TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
34/2019

Research and Development of Electricity Auction for Microgrids

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TALTECH PRESS

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This dissertation was accepted for the defence of the degree 14/05/2019

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Tarmo Korõtko

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ISSN 2585-6898 (publication)
ISBN 978-9949-83-450-1 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9949-83-451-8 (PDF)

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
34/2019

Mikrovõrkude elektrioksjoni uurimine ja väljatöötamine

TARMO KORÕTKO

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KIRJASTUS

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List of Publications

The list of author’s publications, on the basis of which the thesis has been prepared:

I Korõtko, T., Rosin, A., Ahmadi A., R. (2019), “Development of Prosumer Logical Structure and Object Modelling,” 13th IEEE International Conference on Compatibility, Power Electronics and Power Engineering, CPE-POWERENG 2019 (1-6). IEEE.

II Korõtko, T., Rosin, A. (2018), “Search algorithm development for novel electricity auction in microgrids,” 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2018.

III Korõtko, T.; Merisalu, Ü.; Mägi, M.; Peterson, K.; Pettai, E. (2014), “Development of Testing Method for Smart Substations with Prosumers,” Informacije MIDEM-Journal of Microelectronics Electronic Components and Materials, 44 (3), 185−200.

IV Korõtko, T.; Mägi, M.; Peterson, K.; Teemets, R.; Pettai, E. (2013), “Analysis and Development of Protection and Control Functions for Li-Ion Based Prosumers Provided by Low Voltage Part of Distribution Substation,” In: 8th International Conference-Workshop Compatibility and Power Electronics, CPE 2013 (19−24). IEEE.

Author's Contribution to the Publications

Contribution to the papers in this thesis is as follows:

I Tarmo Korõtko, as the main author of the paper researched and developed a novel prosumer logical structure and provided a simplified prosumer logical modelling object.

II Tarmo Korõtko, as the main author of the paper researched existing search algorithms and developed novel search methods to solve a combinatory search problem introduced by an electricity auction.

III Tarmo Korõtko, as the main author of the paper discussed the testing of control algorithms for the central controller of a smart distribution substation with prosumers.

IV Tarmo Korõtko, as the main author of the paper discussed the development of control functions for Li-Ion based prosumers provided by low voltage distribution substations.

Introduction

Electricity generation and distribution is currently experiencing a paradigm shift. The increasing and more effective use of distributed energy resources (DER) is driving the transition from centralized power generation (based on fossil or nuclear fuels) to decentralized generation and unidirectional electricity flow in distribution and transmission grids to bidirectional flow [1]. Projections estimate that from 2010 to 2050, the global need for energy will have doubled [2]. To counter those projections, the European Commission has set ambitious targets in COM (2011) 885/2, which include: reduction of emissions by 40%, reduction of greenhouse gases by over 80%, the decarbonization of the entire energy system, reduction of energy demand by 41% (by supporting strict energy efficiency policies), increased usage of renewable energy sources (RES), etc. [3]. Global policy makers have set the long-term vision for technology development and transfer, which is the improvement of resilience to climate change and the reduction of greenhouse gas emissions [4].

The target of reforming Europe's existing electricity infrastructure shifts end users from passive roles as consumers of electricity to active roles as prosumers (combined user and producer). Prosumers utilize distributed generators (DG), to produce electricity from RES, and controllable loads, to control and schedule their consumption, and are considered as major actors in future electricity grids [5]. More capable and intelligent end-users require the digitalization of the electricity grid with additional and sophisticated services for introducing new revenue streams, encourage private capital investments and drive technology innovation.

Future electricity grids need to enable advanced prosumer management capabilities, sophisticated metering, dynamic pricing options, effortless integration of distributed generation units, incorporation of various types of storage and utilization of large-scale information networking [6]. Simpler grid connection, access to ancillary services, loosened legislation and simplified invoicing encourage greater numbers of consumers to become prosumers. For efficient use of resources, prosumers need to be involved in supporting distribution and transmission grids and balancing generation and demand.

Access to electricity is established within the framework of human rights [7], thus the upgrade from a bulk centralized power grid to a flexible, intelligent, self-healing and distributed Smart Grid needs to be seamless and gradual. New technology needs to be compatible with existing grid infrastructure and prosumers need to be integrated into existing power systems. Prosumer aggregating microgrids can be used as gateways for prosumers to the existing electricity infrastructure.

Microgrids are well suited for integrating prosumers into current distribution grids due to their focus on the locality of operations, limited restrictions on technology, relatively large interest as research subjects and numerous experimental and commercial applications around the world. Microgrids enable the downsizing of a large and complex system into several smaller, localized systems. Local control and optimization problems of prosumers inside a microgrid are less complex than in larger systems. Microgrids are considered as effective means to integrate DER into the electricity grid. Although unpredictable and highly variable output from RES raises challenges in production scheduling, control, forecasting, stability and availability, a microgrid, which utilizes different RES together with electricity storage, has significant potential, since it helps to maximize the use of clean energy [8]. An energy storage system inside a microgrid can greatly increase system stability and provide flexibility.

1.1 Motivation for this thesis

Connections to the electricity grid are currently seen as necessary cost, where the required infrastructure is the responsibility of a large, commonly state owned, distribution system operator (DSO). Policy makers have identified that one way to foster innovation is the active engagement of the private sector [4], which is also the case for electricity infrastructure. A paradigm shift is required in the way electricity supply is perceived: the connection to a larger grid should no longer be considered as a necessity and cost, but as an opportunity and investment. One possible way to introduce private sector funding into the development of the electricity infrastructure is through the implementation of microgrids.

Microgrids serve as aggregators and gateways able to simplify the connection of DERs to the existing bulk electricity grid. Currently, microgrids are purpose-built and case specific. For the commercial success of microgrids, their simple construction and the benefits from predictability and transparency are essential. To include private sector investments into the development of smarter electricity grids, it is required to address the entity responsible for forming a microgrid. For the widespread implementation of microgrids, their formation needs to become simple, transparent and economically beneficial.

The Department of Electrical Power Engineering and Mechatronics of Tallinn University of Technology and the Estonian private company Harju Elekter Elektrotehnika AS have recognized the need for a commercially scalable microgrid application. The concept of a smart low voltage distribution substation (Smart MV/LV) has been developed, which is able to form microgrids between prosumers connecting to the Smart MV/LV. To be successful, the Smart MV/LV needs an effective way to manage prosumers while providing increased possibilities and benefits over the conventional way of connecting to the electricity grid. The Smart MV/LV is required to fulfil the operational targets and achieve higher-level goals of its owner(s), whilst providing a predictable and reliable connection to the utility grid.

Microgrids and their control have been the subject of numerous research papers. The majority of research focuses on primary control, scheduling and optimization of assets, topology etc. Price based asset management has been studied, but commonly focusing on the optimization or scheduling of the utilization of assets with homogeneous ownership. Commercially scalable practical microgrid applications require support for different ownership relations, where the operational goals, and thus the optimization criteria, become more complex and inconsistent.

Electricity auctions are widely used for committing generation and demand from transmission system operators (TSO). The use of electricity auctions for committing smaller DGs has also gained interest, but the majority of auction based research focuses on bid generation and maximizing benefits for individual auction participants. Peer-to-peer energy auctions are also gaining elevated interest from researchers, but the majority of them focus on scenarios where the peer-to-peer market is a complementary part of a larger distribution or transmission system. In order to use an electricity auction as the primary energy management tool inside a microgrid, a novel auction algorithm is required.

While designing energy management between prosumers inside microgrids formed by Smart MV/LVs, a set of requirements and respective assumptions was used for establishing auction design guidelines. A novel auction algorithm is required to:

- maximize revenue for the owner of the smart substation, assuming that benefiting the owner of the smart substation increases commercial interest about them;
- provide economic opportunities for connected prosumers, assuming that the owner of the smart substation uses this to create value for its services and that it encourages an increased number of prosumers to engage in managing their energy consumption and production;
- provide a predictable connection to the point of common coupling (PCC), assuming that microgrids which provide a predictable connection to the PCC gain an advantage from the utility grid over microgrids with an unpredictable PCC connection;
- optimize the use of substation integrated energy storage system (ESS), assuming that the flexibility provided by an integrated ESS provides economic benefits outweighing respective costs.

In addition, there is no standard describing the structure and composition of prosumers. The CEN-CENELEC-ETSI Smart Grid Coordination Group only describes prosumer management systems in their Smart Grid Set of Standards [9], but does not address individual prosumers.

1.2 Thesis objectives

The main objective of this thesis is to provide a method for a Smart MV/LV with an integrated ESS to manage power production and consumption targets for prosumers that connect to the Smart MV/LV and form a microgrid. The proposed method is required to provide a predictable output to the PCC and generate profits to the Smart MV/LV.

Since the proposed method relies on Smart MV/LVs for forming microgrids, emphasis is on the value generation for the owner of the Smart MV/LV. It is required that the method enables energy trading between microgrid participants, complex ownership and price-based control of microgrid assets, business opportunities for microgrid participants and their access to a larger number of grid services. The author aims to provide a management method that helps to resolve limitations of existing energy management approaches and auction methods. The outcomes of this thesis anticipate providing a solid but flexible foundation for energy management inside microgrids, which enable value generation for all parties and thus help significantly increase the integration of DERs into the electricity grid.

1.3 Hypotheses

The main hypotheses of this thesis are:

- Using an auction inside a smart substation for determining prosumer generation and consumption setpoints can increase profits of the owner of the substation, enable prosumers to trade energy and allow the implementation of price-based control of prosumer assets.
- Using a dedicated metaheuristic search algorithm for determining best individual bids from bid sets is an effective method to be used inside an electricity auction for local markets with a limited number of participants.
- A universal logical prosumer structure enables generalization of all electric system components as prosumers and can therefore simplify the logical modelling of electrical systems.

1.4 Research tasks

The main research tasks of this thesis are:

- To research and develop an electricity auction algorithm designed for low voltage microgrids with an integrated ESS. The designed auction needs to meet the objectives of the owner of the substation, but also provide benefits for the utility grid and end users (provide a “win-win-win” scenario).
- To research and develop an algorithm to select the best combination of bids from prosumer bid sets.
- To develop a universal prosumer logical structure for the simplification of modelling microgrid management.
- To prove the concept of the developed electricity auction, it is required to create a new computer program for simulating agent interaction.

1.5 Novelty

The scientific and practical novelties of this thesis are:

1. development of a new electricity auction method, specifically designed for the use in low voltage smart substations, which incorporate an ESS and form a microgrid with connected prosumers;
2. development of a novel search algorithm, which is a key component inside an electricity auction algorithm designed for low voltage distribution level microgrids;
3. definition of prosumer characteristics and the development of a novel logical prosumer structure;
4. construction of a new universal prosumer logical object model based on the developed prosumer structure;
5. development of a novel auction simulator program and a supporting mathematical model for the verification of the auction method and development of prosumer control functions.

1.6 Contribution and dissemination

This research is recommended for microgrid developers who wish to improve the commercial applicability of their systems. It also serves as a good vantage point for information technology (IT) researchers who wish to engage in the field of control and communication of prosumer based electrical networks. Researchers studying bid formation and prosumer behaviour can use the contributed work for proposing innovations and improvements in modelling prosumer behaviour.

The results of this thesis have been introduced in international scientific conferences (2), in an international peer-reviewed journal (1) and in presentations at doctoral schools (2). Direct practical results of this thesis have been applied in a research and development project (Lep14101) carried out between Tallinn University of Technology and AS Harju Elekter Elektrotehnika. This dissertation is supported by another doctoral thesis oriented at the development and control of energy exchange processes between electric vehicles and the utility network [10].

Abbreviations

AI	Artificial intelligence
BDI	Belief-desire-intention
BESU	Battery energy storage unit
BMS	Battery management system
CCU	Central control unit
CPS	Clustering power system
DER	Distributed energy resource
DES	Distributed energy storage
DG	Distributed generator
DOD	Depth of discharge
DR	Demand response
DSO	Distribution system operator
ED	Energy district
EMS	Energy management system
EPS	Electric power system
ESS	Energy storage system
ESU	Electricity storage unit
EV	Electric vehicle
GUI	Graphical user interface
IDA*	Iterative deepening A*
IT	Information technology
JADE	Java agent development framework
LCU	Local control unit
LOAD	Electric load in the experimental microgrid
LV	Low voltage
MAS	Multi-agent system
MGO	Microgrid operator
NZEB	Nearly zero energy building
PAR	Peak to average ratio
PCC	Point of common coupling
PCG	Prosumer community group
PCU	Prosumer control unit
PLC	Programmable logic controller
PoLC	Point of local coupling
PRS	Procedural reasoning system
PSO	Particle swarm optimization
PV	Photovoltaic
R&D	Research and development
RES	Renewable energy source

SESP	Smart energy service provider
SOC	State of charge
SOLAR	Inverter in the experimental microgrid
SP	Setpoint
Smart MV/LV	Smart substation
TSO	Transmission system operator
V2G	Vehicle to grid
VCG	Vickrey-Clarke-Groves
VPP	Virtual power plant

Symbols

B	Bid set
b	Bid
bc	Logical result of balance check
C	Asking/bidding price
C_{SS}	Annual cost of ownership of a Smart MV/LV
d	Depth of search
d_1	Space needed to store the prosumer name indicator
d_2	Space needed to store the prosumer bid indicator
$essC$	Cost for electricity from the ESS
$essPmax$	Maximum allowed output power of the ESS
$essPmin$	Minimum allowed output power of the ESS
$essPopt$	Preferred ESS output power
$essSoc$	SOC of the ESS
ε	Proposed cost for single bid
$G4$	Standard load profile G4
GC_pP	Purchasing price of electricity from the PCC for prosumer
GC_sP	Selling price of electricity to the PCC for prosumer
$H0$	Standard load profile H0
h	Heuristic
K	Number of eligible solutions
Ψ	Optimal solution
n_{max}	Maximum allowed negotiation rounds
O	Time complexity
P	Measured actual prosumer power output
$P\_1 \ldots P\_8$	Load profile peak values for specific prosumer in simulation case
P^{SP}	Prosumer power target for auctioned transaction period
P^{tol}	Allowed deviation between actual prosumer power output and setpoint
$pccSp$	Power setpoint for the PCC
$pccTrsh$	Power setpoint threshold for the PCC
Pr^{+}	Total amount the prosumers are charged with
Pr^{-}	Total amount the prosumers are remunerated with
$Pr^{avgPros}$	Average revenue per prosumer
Pr^{batt}	Total amount of revenue created from using/storing energy from/to the ESS
Pr^{PCC}	Revenue or cost from the PCC
Pr^{p}	Revenue compared to PCC prices
PR_{reg}	Number of registered prosumers
Pr^{util}	Cost of utilization of the Smart MV/LV

$\mathit{PROSUMERS}$	Prosumer information data set
PRSMR	Model instance of prosumer object
$\mathit{SB0}$	Standard production profile SB0
Sp	Space required
$\mathit{solution}$	Search problem solution
$\mathit{stepCnt}$	Number of steps taken for reaching search solution
steps	Set of bids chosen from each registered prosumer
t	Duration of transaction period
U	Utility
u_1	Economic utility component
u_2	DER utility component
u_3	Energy supply utility component
V	Volume of electric energy
V^{+}	Volume sum of highest volume bids of unselected prosumers
V^{-}	Volume sum of lowest volume bids of unselected prosumers
V_{bal}	Electric power balance for the solution of the search
V_i^{+}	Maximum possible volume sum of prosumer i
V_i^{-}	Minimum possible volume sum of prosumer i
V_i^{abs}	Sum of absolute maximum and minimum V values of prosumer i
V_i^{max}	Absolute maximum V values of prosumer i
V_i^{min}	Absolute minimum V values of prosumer i
V_{ESS}	Power prediction to/from the ESS for a transaction round
V_{SP}	Requested total sum of bid volumes
$\mathit{W0}$	Production profile of wind turbine

2 State of the art

This chapter presents the state of the art of prosumers, microgrids and smart substations. Insight and generalizations from various research papers are presented to illustrate current trends in relevant fields. Firstly, the prosumer definition and concept are studied. Secondly, some insight is provided into microgrid technology. The third part of this chapter describes smart electricity substations.

2.1 Prosumers

According to [11] – [15], the original phrase “prosumers” was introduced by Alvin Toffler in his book “The Third Wave” (1980) and encapsulates the meaning of words proactive producer and consumer. As stated by Toffler, prosumers are people who collaborate to enhance goods and services, thus transforming the marketplace and their roles in it. Laconic prosumer definitions focus solely on the concurrent production and consumption capacity, disregarding the cooperation and market communication of the originally proposed definition, e.g. in [16], where a prosumer is defined as a consumer, which concurrently produces the products or services which it consumes or in [17] that defines prosumers as consumers that have their own production capacity. A common example of prosuming is a fast food restaurant, where the customer is involved in providing table service, or the Swedish furniture company IKEA, where the customer is responsible for the assembly of purchased products [12] – [15]. Moving from a generalized definition to a more specific area of interest, electric energy prosumer definitions were studied.

2.1.1 Electricity prosumer

The authors of [18] and [19] lean on the laconic prosumer definition and define electrical prosumers as entities that can act as either power consumers or producers at certain periods; or as end users that at the same time are producers and consumers of electrical energy. In [20], the dimension of energy storage is added, by defining prosumers as hybrid agents that consume, produce and/or store electricity. The authors of [21] add cooperation and restraints to their definition, by declaring the prosumer as an energy user that generates renewable energy and shares the surplus with energy buyers, whilst being constrained by networks. The cooperation dimension is also included in the definition provided in [22], where a prosumer is defined as an energy user that generates renewable energy in its domestic environment and shares the surplus with the energy buyers (e.g. the utility grid). The authors of [6] describe prosuming as active management of energy consumption and production by energy customers, focusing the definition on the intelligence and proactivity of prosumers rather than on their behaviour.

More specific energy prosumer definitions introduce a specified context, operational, cooperation and socioeconomic features. A prosumer definition in the context of a smart grid is provided in [23], where prosumers are described as smart grid customers capable of generating and storing their own energy and thus being key enablers of smart grid energy trading and management schemes. In [5], electricity prosumers are defined as economically active and motivated entities that consume, produce and store electricity, take part in electricity consumption optimization and get actively involved in electricity services. The authors of [24] describe electricity prosumers as consumers with energy production capability, which are able to exchange energy among themselves, while being selfish entities and only wanting to maximize individual payoffs. In [25], the prosumer is defined as an economically motivated entity that consumes, produces, and stores power; operates or owns a power grid and hence transports electricity; optimizes the economic decisions regarding its energy utilization. The prosumer definition is extended in [26] by introducing flexible prosumers that differ from conventional prosumers by co-creating flexibility, e.g. by implementing demand response or flexible timing of consumption.

Based on the analysis of prosumer definitions, structures and models, the need for a novel and universal prosumer logical structure is identified. To establish the demands for a universal prosumer structure, the explicit formulation of prosumer requirements is necessary. A list of prosumer requirements for the composition of a universal structure is composed of:

- ability to produce or consume energy;
- energy transmission between prosumer components;
- optional incorporation of energy storage;
- management and optimization of assets and their use;
- possibility to define operational constraints;
- possibility to define motives, which guide prosumer actions;
- energy transmission between prosumers;
- interaction between prosumers;
- enhancement of product and service use through optimized control, cooperation and communication;
- proactivity to initiate business proposals and actively seek business opportunities;
- implementation of different energy trading and market mechanisms.

2.1.2 Prosumers in electricity markets

Besides technological innovations, the introduction of the prosumer to the electricity grid also introduces new economical and system control possibilities. A prospective concept is the indirect control of prosumer actions based on price signals from electricity markets. Electricity markets can be applied for local management and control of electric power systems (EPS) [17], since markets provide a common interface for participants to interact in a timely and well-informed manner. The authors of [27] state that market-based control frameworks are well suited for implementation as system wide demand and supply management in liberalized energy markets, since they can be applied across legal and organizational boundaries due to their indirect control mechanism.

Three possible markets germinated by prosumers are discussed in [6]: peer-to-peer, prosumer-to-grid and prosumer groups.

- Peer-to-peer markets involve decentralized, autonomous and flexible peer-to-peer networks, where a platform is used to bid and directly sell or buy electricity and services.
- Prosumer-to-grid market models involve brokerage systems for prosumers that are connected to a microgrid.
- Organized prosumer groups connect goal-oriented prosumer community clusters, which are located in geographical proximity of each other, to allow efficient energy sharing among local members.

As stated in [6], local markets are likely to be a key for managing distributed renewable generation and for coordinating decentralized decision models. Nevertheless, predicting and modelling socioeconomic behaviours of prosumers is difficult, since the strategy space of a prosumer depends on other prosumers' strategies [24].

Several research papers address aspects of describing and modelling prosumer interaction. The authors of [24] propose a pricing mechanism for peer-to-peer prosumer markets. In [23], a market interaction method is proposed, where prosumers declare the amount of energy they want to buy or sell at predefined times. Prosumer virtual power plants (VPP) and their on market related costs, forecasting accuracy and resource sharing is studied in [17].

The authors of [28] found that a normal bidding procedure for prosumers in electricity markets is to neglect the price of energy and simply bid their expected load. The mentioned behaviour is mainly due to problems that small end-users are not exposed to time-varying prices, the lack of technical infrastructure for direct load control, small variations in intra-day prices and imbalance penalties; some of which could be solved by grouping and aggregating prosumers and their operations.

2.1.3 Grouping prosumers

Prosumers are recognized as key building blocks of future smart grids, which enable modelling of the entire electricity infrastructure [25]. The positive effects and potential of prosumers are widely recognized. Increasing numbers of prosumers lead to reduction in CO2 emissions, slightly positive macroeconomic effects, significantly positive effects for individual prosumers [29] and an increase in production forecasting accuracy [17]. Prosumers are able to lower their costs for electricity by controlling or rescheduling energy-demanding processes [5] or by exploiting advantages of prosumer coalitions [17].

The change from the existing EPS to a smart grid is achieved by extensive integration of prosumers. There are two paths for prosumers creating a low-carbon energy system: (1) off-grid and self-sufficient agents and (2) agents connected to a grid where prosumers become active providers of energy services [6]. Prosumers and their ability to be self-sufficient will play an important role in the energy network and system [30]. The widespread implementation of prosumers promises significant advantages but introduces stability and safety problems for the operations of the grid [19]. The biggest challenge shall be the management of distributed prosumers, since their control strategies need to depend on behaviours of other prosumers [20]. It is recognized that for the successful management of an EPS with large numbers of connected prosumers, end users need to be involved in the management of the grid [19]. Several methods and philosophies for grouping prosumers into larger electric power systems can be found in literature.

- **Microgrids** are defined as clusters of loads, DG units and ESSs operated to reliably supply electricity and connected to a larger power system at the distribution level [31]. Microgrids are considered as localized connections of DERs through dedicated infrastructure for focusing on local operations and targeting reduced transaction costs. Local energy exchange decreases transmission losses; however, a proper incentive is required for prosumers to exchange energy with each other [24].
- **Virtual power plants** are larger than microgrids and consist of large groups of DERs with aggregated capacity. Management of VPPs is either centralized or decentralized [22], [32]. The variety of DER types inside a VPP portfolio is not limited and VPPs are not subject to geographical limitations (provided the connected DERs are connected to the same TSO. It is reported in [17] that the aggregation of prosumers into VPPs based on key characteristics results in lower forecasting errors and potentially lower risk of market participation. The authors of [32] claim that connecting prosumers through VPPs or

microgrids results in inflexibility and the absence of a common group goal, which leads them to the proposal of prosumer community groups.

- **Prosumer community groups** (PCG) are, according to [33] and [22], similar to VPPs, with the exception that they are made up of prosumers with similar energy sharing behaviours who pursue a mutual goal and jointly compete in the energy market. The authors of [22] state that the key advantage of PCGs is that it increases the accumulated quantity of energy to be auctioned or sold in the energy market, thus attaining higher bargaining power compared to single prosumers or ad-hoc prosumer groups. PCGs can use their accumulated capacity to have a bigger impact on power systems; therefore, by grouping prosumers in PCGs, they receive the necessary negotiating power to compete with large energy providers.
- **Energy districts** (ED) are consumption and production centres, made up of interconnected prosumers that are connected to the grid by the PCC [34]. EDs are managed by aggregators, which apply strategies for improving energy efficiency, manage activities regarding energy purchase and sales within the district [19], maximize the ED utility and reduce the reverse energy flow at the PCC by implementing demand response (DR) programs [34].
- **Aggregating prosumers** with an aggregator entity is described in [28]. The aggregator connects prosumers to the balancing and electricity spot markets and is responsible for delivering electricity to prosumers, trading surplus energy and the net demand in the electricity spot market. Imbalances between commitments in the spot market and real purchase or sales are settled according to prices and rules from a balancing market. In [33], such an aggregator is called the smart energy service provider (SESP), which operates as a broker when local trades are peer-to-peer, as a retailer for over-the-counter sales with bilateral contracts or as a market maker when a call auction is required.
- **Prosumer coalitions** are proposed in [34], where the coalition coordinator, a non-profit entity with the main task of procuring electrical energy for the coalition at minimum cost, is operating in the interests of the whole coalition made up of coalition members (prosumers).
- **Clustering power system** (CPS) is a flexible philosophy that separates the power system into levels based on conventional interconnected grids [35]. CPSs apply the bottom-up strategy and recursive processes for structuring. Consequently, cluster areas are established across the entire power system. The aim of cluster control is to downsize conventional control architectures to the local level, establish advanced control functions in all cluster areas and manage generating units within an area of responsibility by balancing energy within the cluster [36]. The cluster strategy proposed in [35] and [36] is combined with re-adjusted existing structures to provide a compatible, adaptable and sustainable design of future power systems and enable prosumers to actively participate in grid control.

In the context of this thesis, microgrids were chosen as a suitable grouping method due to their focus on the locality of operations, limited restrictions on technology, relatively large interest as research subjects and numerous experimental and commercial applications around the world. A more thorough overview of the state of the art of microgrids follows.

2.2 Microgrids

Microgrids have gained much attention in the last 15 years as research subjects [37] – [40]. There exist numerous experimental microgrids in different locations all over the world: Borrego Springs (CA., USA), University of Hawaii (HI., USA), Illinois Institute of Technology (IL., USA), Gaidouromandra, Kythnos Microgrid (Greece), Bronsbergen holiday park (Netherlands), Bornholm Island (Denmark), LABEIN test facility (Spain), Aichi Micro Grid (Japan), Dong'ao Island (China), Huatacondo (Chile), etc. [41], [42]. Although the term microgrid is common in professional literature, no unified definition exists. In [43], the microgrid is described as a local island grid that can operate either as a stand-alone or as a grid-connected system. The microgrid is powered by the main electricity grid, local small size natural gas powered generators or DGs driven by renewable energy and includes special purpose inverters with filters to overcome problems with harmonics and to improve power quality and energetic efficiency. A link for plug-and-play connectivity to the legacy grid is provided. The definition considers the microgrid as a local power provider with advanced control capabilities.

Another definition is given by the EU research projects [44] and [45], which define a microgrid as an entity that comprises low voltage (LV) distribution systems with DGs, electricity storage units (ESU) and (partially) intelligent or controllable loads. Microgrids can operate in parallel with a larger electric grid, but also in an autonomous way, forming an energy island. DGs can provide considerable benefits if coordinated optimally, but may also introduce new problems, like system stability and security of electricity supply.

A third description of the microgrid states that it is a cluster of interconnected DGs, local loads and EESUs that are managed co-operatively and can be collectively treated by the main grid as a controllable load or generator [37].

For a generalization of microgrid descriptions, various microgrid definitions are summarized as follows:

1. A microgrid is a **platform for integrating local ESSs and prosumers**. Meeting local demand is priority.
2. The area EPS can handle a microgrid as a prosumer (controllable load or generator).
3. A microgrid needs to be **capable of operating in parallel with the area EPS, but also while disconnected from it**. It should be noted that the normal operation mode is in conjunction with the area EPS and islanding is in most cases considered as an emergency operation state. The time a microgrid can sustain an energy island before a blackout occurs varies by the type of local generators, the size and type of the ESSs and the controllability of loads. The microgrid needs to provide a warning of an occurring blackout, giving sensitive devices the opportunity for a controlled shut-down.
4. The microgrid needs a **dedicated feeder to connect to the area EPS** – the PCC.
5. A microgrid must **improve the services and quality of electric energy (distribution)** provided to prosumers. Local filtering and reactive energy compensation devices help to increase the quality of provided electricity. ESSs can aid to prevent faults or give much needed response time at a blackout.
6. The **main objective** of an electrical microgrid is to **provide and manage the flow of electricity between the ESSs, prosumers and the PCC**, but also to **provide ancillary services**.

7. When connected to the microgrid, prosumers need to gain **access** to a wider **variety of services** compared to connecting directly to the utility grid.
8. The microgrid operator (MGO) needs to **effectively manage the ESSs and microgrid prosumers**. The MGO needs to find a locally optimal operating decision, which considers the ambitions of all stakeholders.

Based on the aforementioned conclusions, the definition of a microgrid in the context of this document is as follows: A microgrid is a sophisticated local EPS that has the ability to partially control its electric energy flow to/from the PCC. A microgrid connects prosumers, provides them with electricity and ancillary services and aggregates them to the PCC. The main objectives of a microgrid are to distribute electricity locally, handle energy flow to/from the PCC, improve the quality and security of electricity supply to all connected prosumers and provide prosumers access to various electricity markets.

2.2.1 Point of common coupling

The PCC is the geometric point where a local EPS connects to the area EPS. It can be realized with a dedicated feeder to connect the microgrid to the area EPS. Since the PCC is meant for transferring electricity, an additional communication interface is needed to provide communications with the area EPS. The communication interface between the microgrid and the area EPS can also be used as a communications gateway.

2.2.2 Benefits over the bulk distribution grid

The introduction of microgrids to the commercial electricity distribution market needs to provide advantages, which would justify the substantial investments needed to reform the existing electricity distribution grid.

Similar to the existing bulk distribution grid, microgrids need to provide customers with electricity. In addition, microgrids need also to enhance energy supply reliability, reduce the ecological footprint and carbon emissions, improve power quality, potentially lower costs [46] and provide simpler and more transparent possibilities to sell excess electric energy back to the grid.

The authors of [46] distinguish between three microgrid ownership models:

- The DSO Monopoly Model. In a DSO monopoly microgrid, the DSO owns and operates the distribution grid and also fulfils the retailer function of selling electricity to end consumers. The majority of technical and financial consequences are left to the DSO.
- The Liberalized Market Model. In liberalized markets, a microgrid might have different objectives and various stakeholders. Operational decisions depend on the negotiations of all parties involved. A MGO is responsible for the local electrical energy balance of the microgrid, the import and export of electricity from the PCC, technical performance, maintenance, emission level monitoring etc.
- The Prosumer Consortium Model. In the Prosumer Consortium model, single or multiple prosumers cooperate in order to meet their individual goals. DSOs can only passively influence the operation of a Prosumer Consortium microgrid by imposing requirements and charges on the prosumers, but will not be able to benefit directly from the local trading process.

The ownership of microgrid elements can be much more diverse than in the bulk distribution grid. Residential buildings, instead of connecting directly with the area EPS, could create an energy community which would own the distribution system of a microgrid and aggregate them to the area EPS. Companies with industrial or commercial properties could purchase a distribution system and start integrating DGs onto their premises in order to cover operational costs and produce value.

With regard to the area EPS and the DSO, a microgrid can be considered as one single entity that provides load and generation aggregation, services for generation scheduling, load and generation forecasting and accurate pursuance of forecasts, on demand emergency power options etc., but also a high potential to implement innovative ancillary services for the future smart grid.

2.2.3 Ancillary services

Ancillary services are defined in [47] as services which are all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power. According to the definition, ancillary services are needed to enhance the operation of the electricity transmission system, which would imply actions for physically influencing the distribution network, but could also refer to providing accurate information to distribution system operators DSO for better decision making.

Some examples of ancillary services would be:

- demand response,
- forecasting,
- scheduling,
- frequency control,
- voltage control,
- spinning reserve,
- standing reserve,
- black start capability,
- remote generation control,
- grid loss compensation,
- emergency control actions, etc. [47].

The ancillary service market is emerging as the bulk distribution network is shifting towards a more dispersed distribution network. New DSO needs and innovative control opportunities provide plenty of opportunities for novel business models and techniques to provide a more stable and efficient electricity transmission network. Ancillary services play a large part in the operation of microgrids, and modern microgrids need to be designed not only for the ancillary services available today, but also for potential services of the future.

For the real-time control of microgrids, three different control strategies have emerged: centralized, distributed and decentralized control [48]. The three real-time control strategies for microgrids are depicted in Figure 2.1.

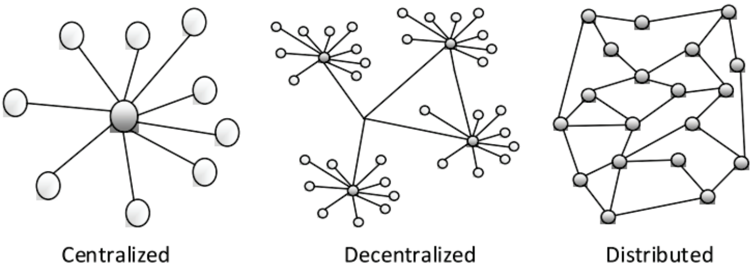

Figure 2.1 – Network types for microgrid control [49].

2.2.4 Centralized control

A centralized control system relies on a central control unit (CCU). The CCU is responsible for maximizing the efficiency and optimizing the operation of the microgrid [50]. Regarding steady-state operation, the basic feature of centralized control is that decisions about the outputs of DGs or the shedding of loads are taken locally by the CCU [51]. The CCU determines the amount of power that the microgrid should import from (or export to) the PCC, whether to store or to use electrical energy from the ESS, shed loads and/or limit DG production.

A centralized system has limitations in system size, since the microgrid CCU has limitations in communication and computational power. The centralized system usually requests direct control over most of the connected devices but needs no specially designed equipment and is thus an attractive option for retrofitting existing infrastructure. The benefits of centralized systems are easier manageability and transparent control hierarchy. The downsides of centralized systems are low flexibility in ownership and the lack of universality.

2.2.5 Decentralized control

Decentralized control is somewhere between centralized and distributed control methods. Hierarchical control can be implemented in decentralized control. There are usually three control levels in such hierarchical control systems; the first level is based on local droop and voltage control, the second level on balance power between the supply and the demand, and the third level is usually based on actions of the electricity market [48].

2.2.6 Distributed control

Distributed control methods enable some level of cooperation between different agents, but the main problem is sharing information and more than that defining the access level of information for different agents [48]. In a distributed control system, the control tasks of different system parts are spread between local control units (LCU). Prosumers compete or collaborate to optimize their operation, making the control problem fuzzy and complex. The distributed control approach is suitable for cases of different prosumer and/or DER ownership.

A distributed system can be viewed as a system of multiple LCUs, which all have their own logic designed to solve local control problems, but in order to be considered a complete system, LCUs also need to communicate with each other and coordinate their actions according to acquired information. A distributed system has no hierarchy, thus solving conflicts of interests between LCUs can become tedious and complex tasks. Communication is essential and a lot of effort is needed to provide a flexible, open and manageable distributed control system. If properly designed, however, distributed control systems provide useful advantages like flexibility, openness, reliability and autonomy.

The distributed approach suggests that such sub-problems are solved locally in each prosumer by the LCU and an interface provides access to control, limits or guides the operation of the prosumer [50]. The interface of a prosumer can be designed to provide services to other prosumers.

Both distributed and decentralized control make use of autonomous intelligent objects called software agents. A control system comprised of multiple communicating agents is referred to as a multi-agent system (MAS).

2.2.7 Multi-Agent Systems

Before extending a multi-agent system, an agent is specified. According to literature, an agent is described as a piece of software or a hardware that can perceive changes in its environment and act upon through actuators. An agent is also described as a special autonomous software component, which provides an interoperable interface to arbitrary systems and is working for some client(s) in pursuit of its own agenda. The characteristics of an agent are stated as autonomy, reactiveness, pro-activeness and social ability. An agent is autonomous because it operates without the direct intervention of others and has control over its internal state; an agent is social because it cooperates with others; an agent is reactive because it perceives its environment and responds to changes in the environment; and an agent is proactive because it is capable of initiating goal-directed behaviour. [52], [53], [54], [55], and [56]

The MAS approach is described as a system of distributed agents. These agents act in an environment to achieve a common goal either by cooperating or competing with each other [57]. MASs can also be defined as systems which consist of groups of agents that are able to interact with each other. The interaction between agents leads towards the system goal, while each agent is optimizing its own objectives [52]. MAS has been applied to a wide range of engineering applications. The application of MASs is to construct robust, flexible and extensible systems [58].

MASs may be deployed in several different architectures. Agent architectures are the fundamental mechanisms underlying the autonomous components that support effective behaviour in real-world, dynamic and open environments [53].

- **Logic-based** architectures have their origins from knowledge-based systems, which use reasoning mechanisms to symbolically represent and manipulate the environment. The main concept of logic-based architectures is the use of background knowledge by agents.
    - The advantages of logic-based architectures are: expressive knowledge representation, which enables description of complex domains; the incorporation of domain knowledge in the learning and reasoning processes; reduction of the hypothesis space, since it can only include those theories that are consistent with prior knowledge; the results of learning and reasoning processes are easy to read and understand. [59]
    - The disadvantages of logic-based architectures are the need for an accurate symbolic description of the environment and the fact that the symbolic representation and manipulation can take considerable time and provide results which often are too late to be useful. [53]
- **Reactive** architectures are realized by mapping situations to actions and are based on a mechanism where sensor data will trigger a response. Instead of designing protocols of coordination or providing agents with complex recognition models, agents are required to work on value-based information that produces social behaviour. The overall behaviour is determined by the interaction of component behaviours. Unlike logic-based architectures, reactive architectures have no central symbolic model and they do not utilize complex symbolic reasoning. The reduction of internal processing allows reactive MAS to achieve quicker response to environmental changes from agents.
    - The advantages of reactive architectures are the shorter response time of agents in dynamic environments and the smaller complexity of agent design than in logic-based architectures.

  - The downsides of the reactive architecture are: sensor data may be insufficient for determining the next action, extremely difficult to design agents that learn from experience, complicated to engineer reactive agents to fulfil specific tasks with a large number of behaviours. [53], [60]
- The **Belief-Desire-Intention** (BDI) architecture was developed based on the philosophical model of human practical reasoning: at first, the agent decides what it wants to achieve and then how to do it. The agent that follows the BDI model intends to display rational behaviour by pursuing the goals it has set, achieving its intentions, using the beliefs it has about itself and about the environment. BDI architectures are probably the most popular agent architectures. They have their roots in philosophy and offer a logical theory which defines the mental attitudes of belief, desire and intention using a modal logic.
  - Two main criticisms have been pointed out against practical implementation of BDI architecture based systems. First, the necessity of having all three attitudes is challenged by planning researchers and the adequacy of only these three is questioned by distributed artificial intelligence researchers. Second, many system designers question the practical relevance of multi-modal BDI logics with incomplete axiomatization which is not efficiently computable.
  - One well-known BDI architecture is the Procedural Reasoning System (PRS) which, alongside with beliefs, desires and intentions, is also based on plans and an interpreter. In a PRS system, beliefs represent the information an agent has about its environment, which may be incomplete or incorrect. Desires represent the goals it is meant to accomplish. Intentions represent desires the agent has committed to. Plans specify courses of action that may be followed by an agent in order to achieve its intentions. These four data structures are managed by the agent interpreter that is responsible for updating beliefs of the environment, generating new desires on the basis of new beliefs, and selecting from the set of currently active desires some subset to act as intentions. The interpreter must select an action to perform on the basis of the agent's current intentions and procedural knowledge. [53], [61], [62], [63], and [64]
- In **hybrid** agent architectures, the agent is made up of subsystems, which are arranged as layers. Hybrid architectures allow reactive and deliberative agent behaviour. There are two types of control flows within hybrid agent architecture: horizontal and vertical.
  - In a **horizontal** control flow, the layers are directly connected to the sensory input and action output. The main advantage of this is the simplicity of design. However, since each layer is an agent, their actions could be inconsistent, prompting the need for a mediator to control the actions. Another problem could arise in the large number of possible interactions between horizontal layers.
  - In **vertical** control flows within hybrid agent architecture, some of the issues are eliminated, because a single layer each deals with each sensory input and action output. The main advantage of vertical

control flows within hybrid agent architecture is that the interaction between layers is reduced significantly. The main disadvantage is that the architecture depends on all layers and is not fault tolerant, so if one layer fails, the entire system will fail. [53]

In the context of this thesis, the distributed control method was chosen for the control of the microgrid formed by the Smart MV/LV. The cooperation of prosumers and other microgrid devices is achieved through interactions of intelligent agents. For the software agents, hybrid agent architectures with horizontal control flows were used, due to their simplicity of design.

2.3 Smart substations

Some vendors use the term "smart substation" for describing electricity distribution or transmission substations, which only monitor and transmit data to a microcontroller or control centre. Such substations neither include devices for improving power quality, e.g. for suppressing harmonics or providing an uninterruptible power supply, nor do they enable sophisticated control and auxiliary services. Although most modern Smart MV/LVs are either in the planning, prototype or field test phase, there are companies that provide Smart MV/LVs with advanced functionalities. [65]

There exist several commercially available solutions for advanced Smart MV/LVs and ESSs, some of which are listed below:

- General Electric's Reservoir is a flexible and compact energy storage solution for ac or dc coupled systems. The solution includes bidirectional inverters for power conversion between ac and dc, battery packs with sophisticated battery management solutions, purpose built enclosures for fast and flexible installation and a dedicated control unit for monitoring batteries and optimizing asset operations. Implemented in power (batteries used to inject a large amount of power into the grid over a short period of time) or energy (batteries used to inject a steady amount of power into the grid for an extended period of time) configuration; the solution enables voltage regulation, frequency response, frequency regulation, renewable integration, black start, back-up, peak management, load, and generation shifting applications. [66]
- ABBs EssPro and Distributed Energy Storage (DES) product families cover a wide range of applications and domains. The EssPro Grid offers integrated turnkey energy storage solutions, ranging from modular, meant to accommodate the requirements specific to each energy storage project, to highly integrated designs. The EssPro PCS is a containerized or pre-packaged outdoor solution for power conversion that enables connection of different battery types or energy storage mediums to provide seamless system integration and battery control. DES systems are outdoor packaged solutions that store energy for later use. The system's batteries and bi-directional inverter are integrated into an enclosure suitable for shipping and withstanding extreme environments. ABB's product portfolio covers the applications of DER integration and output smoothing, load levelling, peak shaving, capacity firming, frequency regulation, voltage regulation spinning reserve etc. [67], [68], [69], [70]
- NEC Energy Solutions has developed the GSS to provide the benefits of energy storage to the grid. GSS offers versatile usage in diverse applications

serving generation, transmission and distribution. Flexible grid-ready design scales from hundreds of kW to hundreds of MW. Different models for long-duration and high-rate container types are available and the number of energy storage racks is customizable. NECs GSS enables frequency regulation, black start, renewable integration, spinning reserve, power plant hybridization, ramp rate management, voltage support, dynamic line rating support, and dynamic stability support. [71], [72]

Although the commercially available applications offer a wide range of products and functionality, they have drawbacks of not having an open design, therefore providing limited access to control algorithms. Limited access to control system functionality is commonly justified by concerns of the user and product safety, but this hinders the development and implementation of novel innovative control methods.

Similar to regular electricity substations, Smart MV/LVs are also used to transmit electricity, distribute power and step up or down the voltage. An example of a smart distribution substation topology for microgrids is presented in Figure 2.2 and a more detailed description about distribution substation topologies can be referenced from [65].

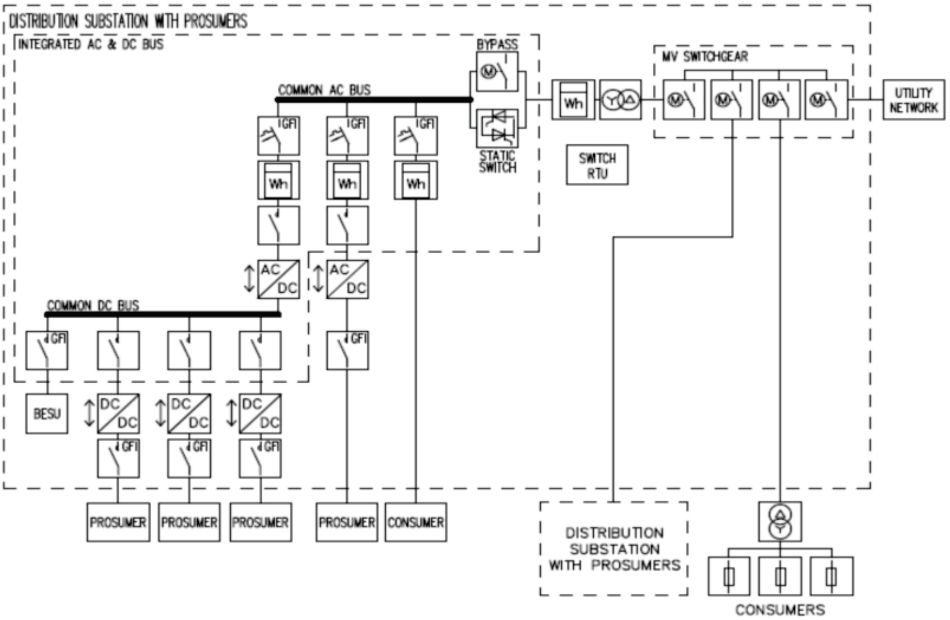

Figure 2.2 – Topology of distribution substation with integrated ac and dc bus and prosumers [65].

Smart substations with advanced functionality are beneficial mainly to owners of the microgrid (e.g. DSOs, manufacturing enterprises, etc.) for controlling energy storage and usage inside the microgrid. The master controller of the substation can be adjusted (e.g. scheduling, trading, optimization) according to the needs of the owner. State of the art distribution substations do not address the management of bidirectional energy exchange between prosumers. It is common to optimize the resources connected to the Smart MV/LV centrally and from the viewpoint of the owner of the microgrid. No commercially available Smart MV/LV offers local energy management that would consider different owners to the prosumers and microgrid.

2.4 Conclusions

This chapter provides an overview of the state of the art in prosumers, microgrids and smart substations.

The research of prosumer definition points towards the lack of a unified definition for an electricity prosumer. Based on the studied prosumer definitions, a list of prosumer requirements was created. Aside from the prosumer definition, prosumers in electricity markets were studied. The participation of electricity prosumers in electricity markets often includes the grouping of prosumers. Various prosumer grouping methods are described and microgrids were chosen as a suitable grouping method in this thesis mainly due to their focus on the locality of operations and limited restrictions on technology.

The general concept and definition of microgrids was researched. Several generalizations from different microgrid definitions were drawn and listed. The benefits of connecting prosumers to the electricity grid via microgrids, instead of direct connections to the bulk electricity grid, are described. Different microgrid control strategies were introduced and a brief overview of MASs, as the control method used inside the Smart MV/LV, is provided in this chapter.

The state of the art of current Smart MV/LV technology was addressed by investigating commercially available systems and their provided functionality. Although commercially available applications offer a wide range of products and functionality, they have several drawbacks as well. Smart MV/LVs are designed to uniformly manage all connected assets. State of the art distribution substations do not address the management of bidirectional energy exchange between prosumers. No commercially available Smart MV/LV offers local energy management, which would consider different owners to the prosumers and the microgrid. The next chapter describes the research and development of an electricity management method in the form of electricity auctions.

3 Research and development of electricity auction

Coordinating electricity production and consumption targets with an electricity auction is an accepted paradigm that has received reserchers' interest in the last two decades. Electricity auctions are common for trading in wholesale electricity markets (e.g. Nord Pool Spot). There has also been interest in using electricity auctions in smaller, local markets to enable direct trading between DGs and consumers.

Due to their locality of operations, microgrids are well suited for local markets. Moreover, microgrids formed by a Smart MV/LV with an integrated ESS have the means to relax requirements for energy auctions by providing storage of the traded good. Microgrids composed of assets with mixed ownership relationships need to provide prosumers with economic opportunities whilst being profitable for the aggregator of prosumers (the Smart MV/LV with and integrated ESS). Aggregated prosumers and an ESS enable balancing the sporadic fluctuations in electricity production and consumption introduced by DERs, which provides greater stability upwards of the grid and lays ground for economic benefits from the Utility. The local market mechanism inside a microgrid is required to serve all prosumers and provide a controlled and predictable connection to the PCC. An electricity auction method for managing power production and consumption targets for prosumers aggregated by a Smart MV/LV with an integrated ESS, whilst providing a predictable output to the PCC and generating profits to the Smart MV/LV is needed.

The following sections describe the research of auction theory and existing electricity auctions. Existing auction methods were investigated to determine the suitability of previously developed auctions for use in a microgrid formed by a Smart MV/LV. The subsequent section provides a detailed description of the development of a novel electricity auction.

3.1 Research of electricity auctions

In the electricity industry, auctions have been used worldwide as the basis for trading energy and capacity, transmission congestion rights, ancillary services etc. [73]. Electricity auctions are a special type of auction whose origins trace back to the traditional auction theory. Nobel Prize laureate William Vickrey first showed a scientific interest in auction theory in the early 1960s. The general definition of auctions describes them as Bayesian games of incomplete information; in fact, auctions are the clearest success story in the application of game theory to economics.

3.1.1 General auction theory

According to [73], auctions are an allocation procedure based on a precise evaluation criterion specified by the auctioneer, and a set of rules designed to award the auctioned good(s) on the basis of presented bids. Most problems in the field of auction theory are concerned with asymmetric information, since under symmetric information, the bidding behaviour and thus the outcome of the auction are relatively easy to predict.

There are multiple ways to categorize auctions. Following is a list of different bases for auction classification:

- number of stages or parallel sessions (single round, multiple round or parallel auction),
- open (bids announced publicly) or sealed (bids announced privately) auction,

- single unit of good for sale (single-unit auction) or multiple units of good(s) for sale (multi-unit auction),
- bidding format and process (structure of bids and asks and their submission procedure) [73],
- clearing method (determination of winning bid(s) and the allocation of auctioned goods) [73],
- pricing rules (which price is used to close the deal) [73].

There are four auction types widely utilized and studied: the ascending-bid auction (also called the English auction), the descending-bid auction (also called the Dutch auction), the first-price sealed-bid auction and the second-price sealed bid auction (also called the Vickery auction). A brief overview of the four basic types of auctions is as follows:

1. **Ascending-bid auction** – a single round open bid single-unit auction. The price is successively raised until only one bidder remains. The final bidder wins the object at the final price. Auctions are carried out interactively in real-time, with bidders present either physically or through a medium.
2. **Descending-bid auction** – a single round open bid single-unit auction. The auction is initiated with a relatively high price, which is then lowered continuously. The first bidder who accepts the current price wins the auctioned good at that price.
3. **First-price sealed-bid auction** – a single round sealed bid single-unit auction. Each bidder independently submits a single bid, without seeing others' bids, and the object is sold to the bidder who makes the highest bid. The price paid for the good is the bidders bid.
4. **Second-price sealed-bid auction** – a single round sealed bid single-unit auction. Each bidder independently submits a single bid, without seeing others' bids, and the object is sold to the bidder who makes the highest bid. However, the price paid is the second-highest bidders bid, or ''second price''.

It should be noted that the bidding strategies of a bidder in the Dutch auction and the first-price sealed-bid auction are equivalent and that the bidding strategies of the second-price sealed-bid auction and the English auction are also equivalent. In addition, the equivalence of the Dutch auction and the second-price sealed-bid auction may break down in the presence of interdependent valuations.

Aside from the four basic types of auctions, there are also other, less common but more application specific auction types. Some less common auction types are described as follows:

1. **Double-auction** – an auction where symmetrically buyers submit bids and sellers asks.
2. **The war of attrition** – a special kind of auction in which all the bidders pay some specified rate, until they quit competing for the good.
3. **Contest** - a widely used phenomenon for allocating goods. In a contest, there are two types of agents—the contest designer (responsible for setting the contest rules) and the contestants. Each contest starts with the contest designer announcing the rules for the next contest (round), which become common knowledge to all contestants. Next, all contestants decide whether to participate in the contest or not. Finally, they perform in the contest according to contest rules until the winner(s) has emerged.

4. **Uniform-price auction** – a multi-unit auction for homogeneous goods. Auction bidders submit one or multiple bids, bidding the price and the quantity for the auctioned good. As a result, the bidders are served in a descending bid price order until the supply of the auctioned good is depleted. All bidders pay the same per unit price, which is usually the lowest per unit price of the served bids. The uniform-price auction emphasizes demand reduction incentives.
5. **Multi-unit auctions** (for heterogeneous goods) – a multi-unit auction where the auctioned goods are heterogeneous. Usually the commodities are close substitutes or complements of one another. Multi-unit auctions can be divided into two:
    a. single (objects sold together in a single round) or
    b. multiple (objects sold separately in parallel sessions or in different auction rounds) round auctions
6. **Single-unit demand multi-unit auction** – a multi-unit auction where several objects are offered for sale, but each bidder is constrained to buy at most one unit.
7. **Combinatorial auctions** – a multi-unit demand auction where bidders have value for multiple units of goods. When bidders are in need of multiple units of goods, they might value a combination of objects more highly than the sum of the values of each individual object. This might drive bidders to place bids for packages of goods, where they indicate a constraint that the bid is to be served for all packaged goods or for none at all.
8. **Sealed bid Vickrey-Clarke-Groves (VCG) auction** – a sealed bid multi-unit auction where the auction system assigns goods to bidders in a socially optimal manner: it charges each individual the harm they cause to other bidders. It is a generalization of a Vickrey auction for multiple items and an extension of the second-price sealed bid auction to a more complex environment. The VCG auction has well-known theoretical properties and is found to be more efficient than two simultaneous second-price sealed bid auctions. [74] – [79].

General auction theory is the foundation for various application specific auctions, e.g. electromagnetic spectrum (bandwidth) auctions, environmental emissions auctions and electricity auctions. The next paragraph discusses research focused on electricity auctions.

3.1.2 Electricity auctions

According to [80], electricity auctions are specific types of auctions where goods are ideally divisible and not storable, which means that transactions need to happen in real time or at least at a predefined point of time in the future. The majority of studies in the field of electricity auctions focus on bidding strategies. For example, the study in [80] presents a bidding strategy for local asymmetric markets, while [81] – [83] propose different risk-based bid formation methods. The discussion in [84] focuses on how DGs or loads would construct their bids in a clearing price auction. A methodology for enabling bidders to estimate their profit-maximizing bid in price uncertainty conditions, considering a multi-unit pay-as-bid procurement auction is reported in [85]. In [86], co-evolutionary bidding strategies, where interacting individuals are evaluated based on their interactions with each other, are analysed. Aside from bidding strategies, some publications also focus on electrical energy auction algorithms.

The continuous double-auction is the preferred auction type for real world trading of equities [87], which also applies to electricity auctions. The study of [83] proposes a risk-based continuous double-auction strategy and a method of determining the optimal generation schedule of DERs using an immune-system-based particle swarm optimization (PSO) method. Although their results have proven the viability and efficiency of the proposed method in comparison with the traditional bidding process, they do not address the predictability of the PCC. Additionally, the method provides no reward, besides a fixed usage rate, for the owner of the microgrid infrastructure. Disregarding the enabler of the microgrid might become a setback, since there would be no incentive for the private sector to invest in such infrastructure.

A spot market model for microgrids reported in [88] can be used to manage distributed energy storage systems without the need for sophisticated production and consumption forecasts.

The discussion in [57] focuses on the problem of profit-based unit commitment and uses of a multi-agent approach to solve it. A multi-agent system has been applied to solve the profit-based unit commitment problem, where a central operator agent commands mobile agents to achieve maximum profits. The described approach focuses on optimizing the unit commitment of DGs.

The authors of [89] present a multi-unit auction to cut the peak to average ratio (PAR) of electrical loads. The proposed auction enables distribution of the load dynamically after the PAR is cut. It focuses solely on managing the demand and does not address generation units or prosumers.

An ESS assisted demand response system based on an online procurement power auction is presented in [90]. The proposed auction enables smart grid participants comprising an ESS to place bids in a demand response online reverse auction. The proposed method is developed for a larger smart grid and is not concerned with optimizing and balancing all connected entities.

The literature search revealed no auction algorithm designed for microgrids that would focus on maximizing profits of the microgrid enabler. Additionally, no reference was found of auction algorithms dedicated to provide a predictable and stable output to the PCC by utilizing an ESS. Based on the studied literature and the objectives stated above, the need for a novel electricity auction algorithm was identified.

3.2 Development of novel electricity auction

The developed electricity auction aims to provide a limited version of a distributed resource allocation method. The limitations are due to the specific nature of the underlying system, e.g. the security of supply and the loading of power lines. A key prerequisite for the developed method is that individual prosumers have means for (limited) control of their power production and consumption, which can be achieved by implementing nanogrids with energy management systems (EMS) [91], nearly-zero energy buildings (NZEB) with EMS-s [92], energy routers [93] and other similar technologies. The following sections provide a detailed description about the auction development process.

3.2.1 Characterization of developed auction

For the development of the electricity auction, several important characteristics need to be defined. The considered requirements for setting up the electricity auction are described in *Table 3.1*, which is composed according to the framework for classifying auctions presented in [94].

Table 3.1 – Definition of required components for the developed electricity auction.

Resources	Multiple units of one single item (electric energy – kWh)
Market Structure	Double-auction in a call market (periodical auction rounds).
Preference structure	Agents communicate preferences using bids.
Bid structure	Multiple bids presented, but only one bid served each auction round.
Supply and demand matching	Multi-sourcing (multiple and single suppliers can be matched with multiple and single purchasers).
Information feedback	Direct protocol mechanism. Agents do not receive feedback about bids of other agents. Agents negotiate bids.

The resource traded in the auction is electric energy for a predefined period in the future (transaction period). The prosumer agent is required to consume or provide the asked or bidden electricity at a constant level. The equations for calculating the prosumer power production (or consumption) setpoint and the condition for prosumer power production range are expressed below:

$$P^{SP} = \frac{V}{t} \tag{1}$$

$$P^{SP} - P^{tol} \leq P \leq P^{SP} + P^{tol} \tag{2}$$

where P^{SP} is the prosumer power target (kW*)* for the auctioned transaction period, V – the volume of electrical energy (kWh) traded in the auction, t – the duration of the auctioned transaction period (h), P – the measured actual prosumer power output, P^{tol} – the allowed deviation of actual prosumer output from prosumer power setpoint (defined by the MGO). If the prosumer is unable to meet condition (2) during the entire transaction period, it may be subject to restrictions or penalties.

The market structure is a periodic call for offers, upon which prosumer agents are able to place bids for purchasing and asks for providing electricity. Each new auction round is initiated by an auction round call. Prosumer agents communicate their preferences only through price signals. The bidding structure allows prosumers to place several bids in one call. According to its preferences, each prosumer can propose bids with different energy volumes and prices. Because the goods are perfectly dividable for electricity auctions, the developed auction is a multi-sourcing option.

The auction method relies on prosumer agents not to share their bidding strategies and market behaviour amongst each other. Market conduct needs to be regulated similar to antitrust or anti-monopoly laws and anti-competitive conduct of prosumers needs to be avoided and/or penalized.

To summarize the main characteristics of the developed electricity auction method, it is a modification of a multi-unit administered continuous double-auction operating in a call market structure. Agents participating in the auction express their preferences by presenting multiple bids for one auction call (auction round). This enables prosumer agents to implement price-based control of their assets, test the market for business opportunities and gain operational flexibility. To manage the auction calls, a dedicated auctioneer agent is required.

3.2.2 Auctioneer agent

The auctioneer agent is an agent residing in the Smart MV/LV responsible for carrying out the auction. It also provides prosumer agents information about current grid prices and communicates with external markets and systems through the PCC. The auctioneer agent aggregates all bids and asks and uses the PCC and ESS to match the PCC setpoint forecasted to the DSO or Utility. Another important task for the auctioneer agent is to restrain and guide prosumers to perform actions which benefit the entire microgrid. Since prosumer agents do not negotiate bids and asks directly, but through the auctioneer agent, it gives the auctioneer agent possibilities to indirectly control the behaviour of the entire microgrid through price signals. The next section describes the agent interaction procedure inside the electricity auction.

3.2.3 Agent interaction procedure

An essential part of auctions is the interaction between participants. The developed auction uses a call market structure, where each new auction round is initiated by the auctioneer agent. For a call market structure, each prosumer agent participating in the electricity auction needs to establish a point-to-point connection with the auctioneer agent, which is presented graphically in *Figure 3.1*. Such communication results in one point-to-point connection for each prosumer agent, which is less complex than, for example, peer-to-peer markets where prosumer agents need to communicate directly with several other prosumer agents. In addition, electricity auctions are specific in terms that the participating agents need to follow strict rules and protocols to provide the safe and reliable operation of underlying infrastructure. Ensuring that each prosumer agent operates within allowed limits requires a dedicated entity, which in the developed electricity auction is the responsibility of the auctioneer agent.

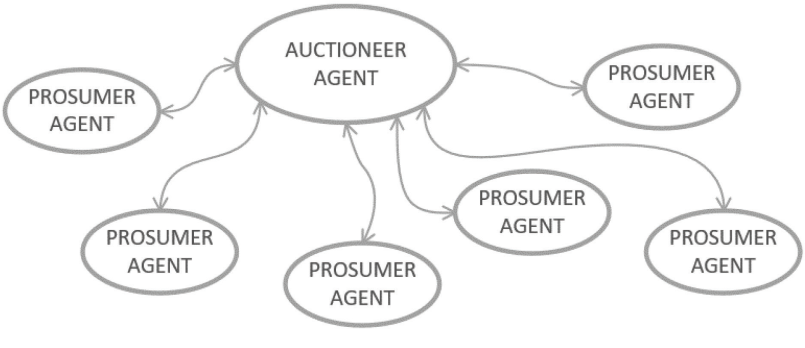

Figure 3.1 – Agent connection topology for the developed electricity auction.

The auction communication mechanism is subscription based, presented graphically in *Figure 3.2*. Each prosumer connecting to the Smart MV/LV needs to subscribe its agent with the auctioneer agent. With the subscription process, the prosumer agent transmits all necessary information about it (e.g. prosumer internal topology, specifics about loads and generation units etc.) to the auctioneer agent that processes this information and either accepts or refuses the subscription. Once the prosumer agent has successfully subscribed to the auctioneer agent, it will start receiving periodical notifications (or calls) each time a new auction round initiates. The prosumer agent composes and presents initial bids upon the notification of a new auction round. The auctioneer agent then replies with an offer, which the prosumer agent may accept or reject. Agent communication during one auction round is finalized with a confirmation message from the auctioneer agent, which states the volume and price of traded electricity for the auctioned transaction round. The next section provides a detailed description of the developed auction algorithm.

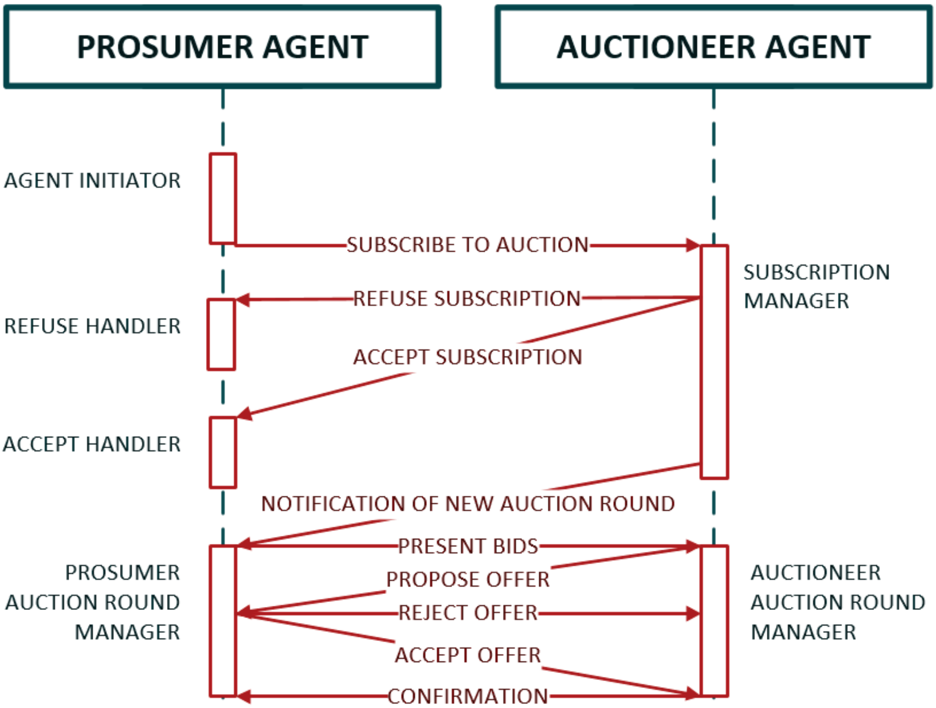

Figure 3.2 – Communication procedure in the developed electricity auction.

3.2.4 Developed auction algorithm

The development of the electricity auction algorithm describes the logic for the auctioneer agent. For the prosumer agents, the logic of composing bids for auction rounds and the decision making for accepting or rejecting proposed offers is not covered in this research and will be a subject of interest for future studies.

The auctioneer agent executes the subscription manager upon initialization. The graphical representation of the subscription manager logic as a flowchart is depicted in *Figure 3.3*. After the subscription server is started, the process divides into two separate threads: one for the periodic auction calls and the other for the handling of subscriptions. The condition for starting a new auction round can be a straightforward periodic timer with a static interval or a dynamic condition dependant on several complex conditions. For each round, a new instance of the auction round manager is created.

The auction round manager describes the logic of a single auction round and negotiations in it. The logic of the auction round manager is represented graphically as a flowchart in *Figure 3.4*. Each time an auction round starts, the total count of negotiation rounds n is initialized and initial data is sent to all registered prosumers. The initial data

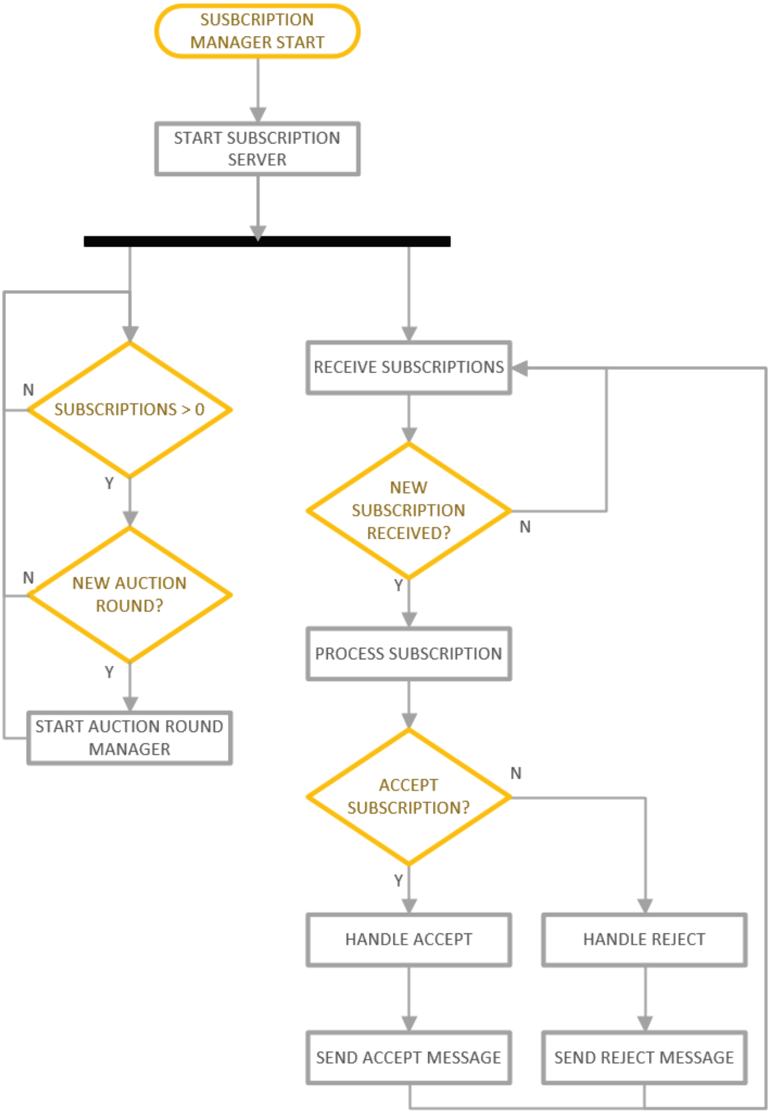

Figure 3.3 – Flowchart of the developed algorithm for the subscription manager.

contains the GC_pP (purchasing price of electricity from the PCC for prosumer) and GC_sP (selling price of electricity to the PCC for prosumer) values for the next auction round. An internal timer is started after sending initial messages. When bids have been received from all prosumers (or the bid timer has expired), the auction advances to find the most suitable combination of bids from presented bid sets. The auctioneer agent processes the optimal bids based on its operation strategy, composes and sends offers for each prosumer. After receiving all replies (or the reply timer has expired), the algorithm checks whether prosumers accepted or rejected their offers. If some of the prosumers replied with a reject message, the negotiation round counter *n* is incremented. While rejecting an offer, the prosumer agent can correct its bid set for the next negotiation round and send it with the reject message to the auctioneer agent. If the negotiation round counter

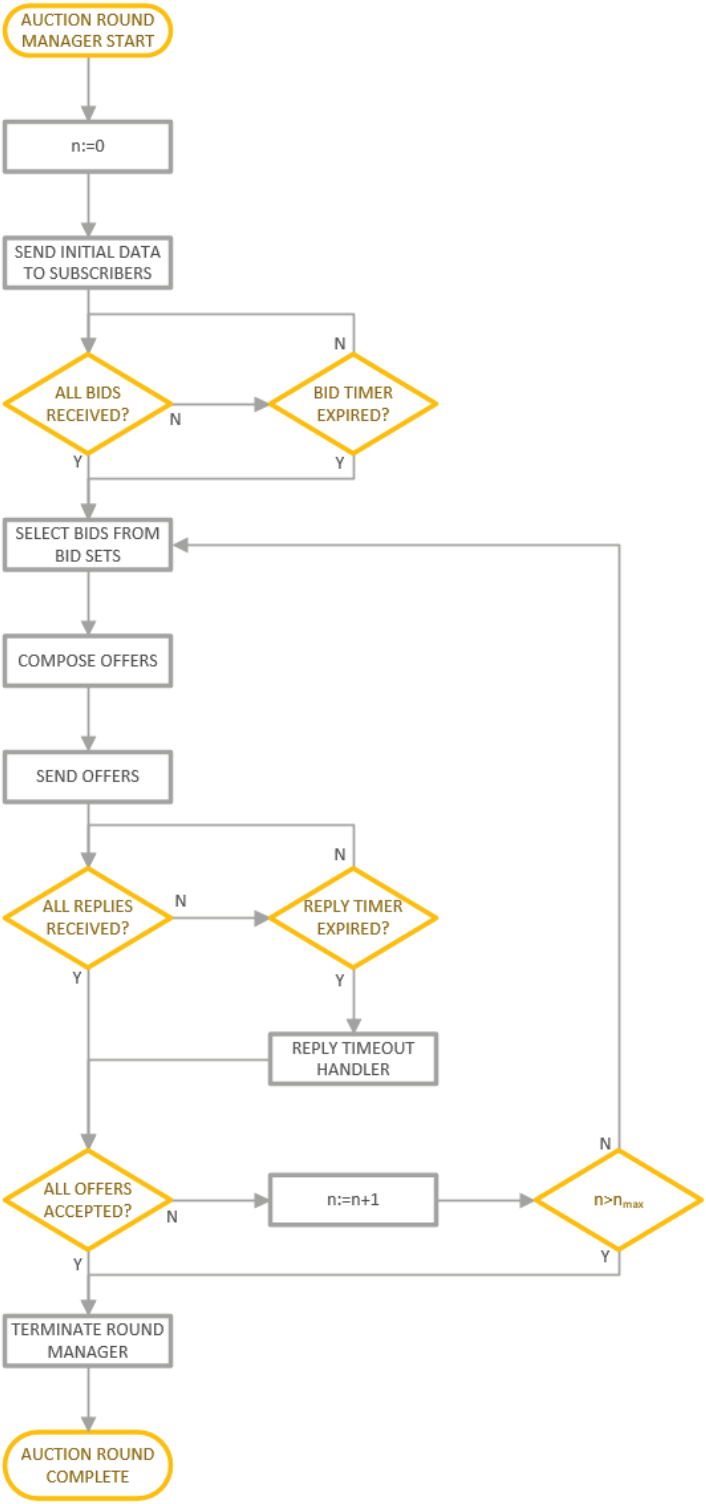

Figure 3.4 – Flowchart of the developed algorithm for the auction round manager.

is less or equal than the maximum allowed negotiation rounds n_{max}, the data from accepted offers (if there are any) is taken as initial data and the logic for finding the most suitable combination of bids from presented bid sets is repeated. If all offers are accepted or the negotiation round counter is higher than the maximum allowed negotiation rounds, the auction is complete. The next section provides a detailed overview of bid presentation in the designed electricity auction.

3.2.5 Bid presentation

The core of any double-auction is the bids and asks the participants present. A bid consists of two values: V – bid volume [1 kWh] and C – bid asking price [$1 \frac{€}{kWh}$]. A bid is considered an ask if the value of V is negative. The prosumer agent needs to determine the amount of energy it requires (or is in excess of) during the next transaction round and the price it would be willing to pay for it (or the price it would request for it).

To enable prosumer agents to look for profitable opportunities, they require the possibility to present several bids and/or asks for one bidding round. For example, in terms of a prosumer that incorporates on-demand production and load shedding in three levels, it would have a maximum of 8 volume levels to bid for (Table 3.2). While the preferable option for the prosumer might be number 1, it might also agree with other options if remunerated accordingly. Similar to the bid composition proposed in [80], the proposed auction mechanism uses a set of bids, all of which are acceptable for the prosumer. A set of bids B for the next round n can be expressed as $B_n = [b_{0_n}, b_{1_n}, \dots, b_{m_n}]$, where b denotes an individual bid and the symbol m is the index of the bid. A bid b is a 2 element array: $[V, C]$. In order to achieve scalable dimensions, the proposed method limits the maximum size of a bid set to 8 bids: $m \in \mathbb{Z}^* \cap m \leq 7$. Reformulated: the set B is a 3-dimensional array, with the maximum size of eight 2-element arrays.

The auctioneer agent is required to determine which bids to choose from prosumer bid sets. The selection of bids from bid sets needs to take into account the power balance inside the microgrid, the forecasted output of the PCC and maximize value generation for the owner of the Smart MV/LV. The selection of best bids from prosumers is a combinatory search problem and a detailed description of the search problem is provided in the following section.

Table 3.2 – Different operational options for a prosumer with on demand production and three level load shedding functionality.

Option number:	1	2	3	4	5	6	7	8
Load shedding level:	0	1	2	3	0	1	2	3
On demand production:	OFF	OFF	OFF	OFF	ON	ON	ON	ON

3.2.6 Search problem

To solve the problem of finding the most suitable combination of bids from prosumer bid sets, a correct problem formulation is required. The problem is described as a series of steps to reach the defined goal. For a formal description of the problem, five characteristics need to be defined: the initial state, possible actions, a transition model, the goal test and a path cost function [95]. The solution of the problem is given as a complex data type (Table 3.3), which includes the set of steps needed to reach the solution and data needed for the goal test.

Table 3.3 – Data structure for the data type solution.

Name	Description	Data Type
steps	Set of bids ($b_1, b_2, \ldots, b_{stepCnt}$) chosen from each registered prosumer enumerated in the order of steps taken.	Array of *b*
stepCnt	Number of steps taken for the solution.	Integer
Vbal	Electric power balance for the solution.	Real

3.2.6.1 Initial state

The initial state of a problem describes the state of the object and the values and constraints at the start of the problem-solving algorithm. For the search problem in the developed electricity auction algorithm, there are several parameters for the initial state. Two key initial state values are the GC_pP and GC_sP. In some cases, available meta-information (e.g. prosumer reputation, transaction history etc.) can also be used to describe the initial state. A complete list of initial state parameters for the developed electricity auction is given in Table 3.4.

Table 3.4 – Initial state parameters.

Parameter	Description
PROSUMERS	A hash table containing prosumer information: bid sets ($PROSUMER_i.B$) and reputation data ($PROSUMER_i.rep$)[1] for each registered prosumer
PR_{reg}	Number of registered prosumers
GC_pP $[\frac{€}{kWh}]$	Purchasing price of electricity from the PCC for prosumer
GC_sP $[\frac{€}{kWh}]$	Selling price of electricity to the PCC for prosumer
essSoc [%]	SoC of the ESS
essPmax [kW]	Maximum allowed output power of the ESS
essPmin [kW]	Minimum allowed output power of the ESS
essPopt [kW]	Preferred ESS output (ESS output setpoint)
essC $[\frac{€}{kWh}]$	Cost for electric energy from the ESS
pccSp [kW]	Power setpoint for the PCC
pccTrsh [kW]	Power setpoint threshold for the PCC
t [s]	Duration of the transaction round

3.2.6.2 Possible actions

Possible actions are the actions available to the problem object at each state. For the search problem in the developed electricity auction algorithm, an action is the choice of one bid from a bid set. For a method named *action(in1)*, which returns a value of data type *b* and takes an input of data type *B*, an action is described according to formula (3).

$$b_n = action(B_n) \tag{3}$$

---

[1] Prosumer reputation data describes the reputation value for each prosumer, where 0 denotes the lowest and 10 the highest prosumer reputation.

3.2.6.3 Transition model

A transition model defines the outcome for each action. The transition model is a function that returns an object state reached as a result of a certain action. The transition model can be described as a method *result(inState, inAction)*, which returns an object state *outState*.

For the search problem in the developed electricity auction algorithm, the transition can be carried out based on several rules: ascending or descending reputation, ascending or descending maximum volumes for bids and asks, ascending or descending prices for bids and asks etc.

For example, if there exist, among others, three prosumers with the following reputation values: *$PROSUMER_3$.rep* = 5; *$PROSUMER_8$.rep* = 4; *$PROSUMER_1$.rep* = 3. If the transition is carried out in descending (from highest to lowest) order of prosumer reputation values, each action taken for *$PROSUMER_3$* will lead to *$PROSUMER_8$* and each action taken for *$PROSUMER_8$* will lead to *$PROSUMER_1$*. Formulas (4) and (5) present the transition model mathematically:

$$\forall a \ \in action(B^{PROSUMER_3}) : result(PROSUMER_3, a) = PROSUMER_8 \qquad (4)$$

and

$$\forall a \ \in action(B^{PROSUMER_8}) : result(PROSUMER_8, a) = PROSUMER_1. \qquad (5)$$

The importance of the prosumer reputation list is described in section 4.2.2.3.

3.2.6.4 Goal test

The goal test determines whether the reached state is a goal state or not. For the search problem in the developed electricity auction algorithm, a goal state is reached, when one bid from each bid set is selected and the total sum of bid volumes, the optimal ESS output and the PCC setpoint is within specified limits. The mathematical formulation of the goal test is given in (6):

$$\begin{cases} solution.stepCnt = PR_{reg} \\ |solution.Vbal + essPopt - pccSp| \leq pccTrsh \end{cases} \qquad (6)$$

The total sum of bid volumes for a solution is calculated using (7):

$$Vbal = \sum_{j=0}^{stepCnt} steps.b_j.V. \qquad (7)$$

3.2.6.5 Path cost function

The path cost function assigns a numeric cost value for each action. For the search problem in the developed electricity auction algorithm, there is a uniform path cost function for each path, since the total cost of the solution is not determined by the sum of individual paths but by a calculation which involves all bids in the solution path. To determine whether the eligible solution is the optimal one, it is required to introduce the utility calculation.

3.2.6.6 Optimality criterion

To determine if one solution is superior to another, an optimality criterion is introduced. The optimality criterion enables quantification of the search result. For electric energy auctions, the optimal solution is commonly defined by economic parameters, for example, by a generated revenue. The developed electricity auction algorithm aims to broaden that approach, since some owners might emphasize other values than revenue generation: maximizing the usage of DERs or for instance, by emphasizing local production. In order to provide the aforementioned flexibility, the utility function shown in (8) is used:

$$U = [u_1\, u_2\, u_3] \begin{bmatrix} k \\ l \\ m \end{bmatrix}, \tag{8}$$

where U is the calculated utility value, u_1 - the economic utility component, u_2 - the DER utility component, u_3 - the energy supply utility component, $k \in \mathbb{R}, 0 \le k \le 1$ - the scale factor for u_1, $l \in \mathbb{R}, 0 \le l \le 1$ - the scale factor for u_2, and $m \in \mathbb{R}, 0 \le m \le 1$ - the scale factor for u_3.

For maintaining focus and simplicity, this thesis concentrates on describing the economic utility component u_1 only and in the remainder of this document, a scaling matrix with values of $k = 1, l = 0, m = 0$ is used. The definition of utility components u_2 and u_3 is outside the scope of this thesis and is subject to future research.

3.2.6.7 Economic utility component

The economic utility component is the revenue the auctioneer agent creates for the owner of the Smart MV/LV. The revenue maximization of each individual prosumer is the task of their prosumer agent. To calculate the generated revenue, the cost of a single bid is calculated. Since the exchanged good is electric energy, not power, the calculation of the proposed cost ε_{i_n} for a single bid b_i for the next round n is calculated using (9):

$$\varepsilon_{i_n} = \frac{V_i C_i t_n}{3600}, \tag{9}$$

where ε_{i_n} is the proposed cost for bid i for the next round n in €, V_i - the electric power requested in bid i for next round n in kW, C_i - the requested price for active power in bid i for next round n in $\frac{€}{kWh}$ and t_n - the duration of the next operation round n in s. In order to calculate a generated revenue for the next round n, formula (10) is used:

$$u_{1_n} = {Pr_n}^{+} + {Pr^{-}}_{n} + {Pr^{batt}}_{n} - {Pr^{PCC}}_{n} - {Pr^{util}}_{n}, \tag{10}$$

where Pr^{+}_{n} is the total amount the prosumers are charged for, Pr^{-}_{n} - the total amount the prosumers are remunerated with, Pr^{batt}_{n} - the total amount of revenue created from using or storing energy from or to the ESS, Pr^{PCC}_{n} - the revenue or cost from the PCC and Pr^{util}_{n} - the cost of utilization of the Smart MV/LV for the transaction period. The equations for Pr^{+}_{n}, Pr^{-}_{n}, Pr^{batt}_{n} and Pr^{PCC}_{n} are as follows:

$${Pr_n}^{+} = \sum_{j=0}^{stepCnt} \begin{cases} V_j > 0, & \varepsilon_{j_n} \\ \quad else, & 0 \end{cases} \tag{11}$$

$$Pr_n^{\ -} = \sum_{j=0}^{stepCnt} \begin{cases} V_j < 0, & \varepsilon_{j\ n} \\ else, & 0 \end{cases} \tag{12}$$

$$Pr_n^{\ batt} = \frac{V_{ESS_n} essC_n t_n}{3600} \tag{13}$$

$$Pr_n^{\ PCC} = \begin{cases} \frac{solution.Vbal * GC_sP * t_n}{3600}; & solution.Vbal > 0 \\ \frac{solution.Vbal * GC_pP * t_n}{3600}; & solution.Vbal < 0 \end{cases} \tag{14}$$

where V_{ESS_n} is the predicted power to be used from or stored to the ESS during the transaction round *n*, *essC*$_n$ - the price for using electricity from or storing to the ESS and *t*$_n$ – the duration of the transaction round *n* in *s*.

The utilization cost of a Smart MV/LV is a complex economic value, which is determined with the production and installation cost of the Smart MV/LV, the development and amortization costs etc. The utilization cost is a variable, which requires case specific evaluation. Calculating or assessing the costs of ownership of a Smart MV/LV is outside the scope of this thesis and is addressed in future research. The initial estimation for C_{SS}, the annual cost of ownership of a Smart MV/LV, is assumed 15 000 €. The cost of the utilization of the Smart MV/LV, Pr^{util}_n, is calculated using (15):

$$Pr_n^{\ util} = \frac{t_n}{31\ 557\ 600} * C_{SS}, \tag{15}$$

To find the optimal solution Ψ, the argument of the maximum *U* is found using (16):

$$\Psi = arg\max_{s} U(s), \tag{16}$$

where *s* denotes the set of solution steps, which are compared (for an universal case: $s \in solution.steps \cap solution.goalState = true$. Formula (16) is the mathematical formulation of choosing the optimal combination of bids from prosumer bid sets.

3.2.7 Example

To illustrate the utility calculation, a simple example case with five prosumers, four bids each, is presented. The example case is intended to demonstrate the utility calculation and does not present any real life scenario. Prosumer bids used in the example are given in Table 3.5 and initial state parameters for the example are presented in Table 3.6.

Table 3.5 – Prosumer information for the example study case.

Name	Bid (*.B = [b$_0$,b$_1$,b$_2$,b$_3$]*)	Reputation (*.rep*)
PROSUMER$_1$	{[5;0,12], [-9;0,17], [2;0,16], [6;0,11]}	5
PROSUMER$_2$	{[8;0,13], [-2;0,17], [5;0,16], [-4;0,16]}	3
PROSUMER$_3$	{[-2;0,15], [4;0,14], [9;0,12], [-6;0,18]}	8
PROSUMER$_4$	{[1;0,19], [6;0,11], [2;0,13], [8;0,11]}	2
PROSUMER$_5$	{[-6;0,18], [-8;0,15], [2;0,14], [6;0,12]}	7

To achieve a clearer representation of possible actions and the transition model, the prosumer information presented in Table 3.5 is sorted in descending reputation order (Table 3.7).

Table 3.6 – Initial state parameter values for the example study case.

Parameter	Value
PROSUMERS	Given in Table 3.5.
PRreg	5
GC_pP [$\frac{\text{€}}{kWh}$]	0,10
GC_sP [$\frac{\text{€}}{kWh}$]	0,20
essSoc [%]	50,0
essPmax [kW]	10,0
essPmin [kW]	-10,0
essPopt [kW]	0,0
essC [$\frac{\text{€}}{kWh}$]	0,15
pccSp [kW]	2,0
pccTrsh [kW]	3,0
t [s]	300

Table 3.7 – Prosumer information for the example study case sorted in descending reputation order.

Name	Bid (.$B = [b_0,b_1,b_2,b_3]$)	Reputation (.*rep*)
$PROSUMER_3$	{[-2;0,15], [4;0,14], [9;0,12], [-6;0,18]}	8
$PROSUMER_5$	{[-6;0,18], [-8;0,15], [2;0,14], [6;0,12]}	7
$PROSUMER_1$	{[5;0,12], [-9;0,17], [2;0,16], [6;0,11]}	5
$PROSUMER_2$	{[8;0,13], [-2;0,17], [5;0,16], [-4;0,16]}	3
$PROSUMER_4$	{[1;0,19], [6;0,11], [2;0,13], [8;0,11]}	2

Each state is denoted as S_i, where *i* is the state enumerator. In the initial state S_0, the step count is equal to 0 that is less than PR_{reg}, which excludes the initial state as a solution by itself. The transition model states that the prosumer with the highest reputation is $PROSUMER_3$, so the transition from the initial state S_0 to the first state S_1 is a transition to the state $PROSUMER_3$. In order to make the transition from the initial state S_0 to the first state S_1, an action is needed: according to (3), $solution.b_1 = action(PROSUMER_3.B)$. The choice for $PROSUMER_3$ is bid $PROSUMER_3.b_3$*=[-6;0,18]*. Since there has been a transition to a new state, it is required to check whether the reached state is a goal state by using (6):

$$\begin{cases} 1 = 5 & (false) \\ |-6+0-2| \le 3 & (false) \end{cases}.$$

Since the goal check returned *false*, the reached state S_1 is not a goal state. A transition to the next state is initiated. According to the transition model, the transition from S_1 to S_2 is a transition to the state $PROSUMER_5$. Let the action for $PROSUMER_5$ be bid

PROSUMER₅.b₃=[6;0,12]. Again, since a transition to a new state has been made, a goal state check using (6) is required:

$$\begin{cases} 2 = 5 & (false) \\ |((-6+6)+0-2| \leq 3 & (true) \end{cases}.$$

The goal state check returns *false* again. Using analogy, let the actions for the remaining prosumers be: *PROSUMER₁.b₃=[6;0,11]*, *PROSUMER₂.b₂=[5;0,16]*, *PROSUMER₄.b₁=[6;0,11]*. The goal check calculation using (6) for the result *solution.steps = {[-6;0,18], [6;0,12], [6;0,11], [5;0,16], [6;0,11]}*:

$$\begin{cases} 5 = 5 & (true) \\ |((-6+6+6+5+6)+0-2| \leq 3 & (false) \end{cases}.$$

The goal state check for this solution is *false* and the selected prosumer bids are not suitable as a solution. Alternatively, let the actions for the remaining prosumers be: *PROSUMER₁.b₁=[-9;0,17]*, *PROSUMER₂.b₀=[8;0,13]*, *PROSUMER₄.b₂=[2;0,13]*. The goal check calculation using (6) for the result *solution.steps = {[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [2;0,13]}*:

$$\begin{cases} 5 = 5 & (true) \\ |((-6+6-9+8+2)+0-2| \leq 3 & (true) \end{cases}.$$

The goal state check for this solution returns *true* and the combined prosumer bids in *solution.steps* are eligible as a solution, where the electric power balance is *solution.Vbal = 1 (kW)*.

Analysing the eligible solution, it can be stated that *PROSUMER₄.b₂=[2;0,13]* is not the only suitable bid, which, in conjunction with other previously selected bids would output an eligible solution. Using (6), the goal state check results for different solutions for all bids of *PRSOUMER₄* are presented in Table 3.8. The results from Table 3.8 indicate that the eligibility of a solution might depend on the action of the last state.

Table 3.8 – Goal state check results for solutions with different bids of PROSUMER₄.

PROSUMER₄.B.b	*Solution.goalState*
[1;0,19]	*true*
[6;0,11]	*true*
[2;0,13]	*true*
[8;0,11]	*false*

3.2.7.1 Utility calculation example

To demonstrate a utility calculation, the example in 3.2.7 is used. Since the aim of this example is to demonstrate the calculation process, only three eligible solutions are used. The first utility calculation example will be about the solution, where *solution.steps = {[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [1;0,19]}*. Using (11), (12), (13), (14) and (15), the components of *u₁* are calculated: $Pr^{+} = 0{,}1625\ (€)$, $Pr^{-} = -0{,}2175\ (€)$,$Pr^{batt} = 0\ (€)$, $Pr^{PCC} = 0\ (€)$ and $Pr^{util} = 0{,}1428\ (€)$. Using (8) and (10), the value of $u_1 = U = -0.1978\ (€)$. In other words, the Smart MV/LV would make a loss of 19,8 ¢ for the next transaction round of 5 minutes while opting to choose this solution. Using analogy, utility calculations are made for two other eligible solutions and compared in *Table 3.9*. It is clear that none of the three analysed solutions is able to earn profit to the owner of the Smart MV/LV, but nevertheless, using (16), it can be concluded that among these three solutions, the economically most suitable solution is *solution.steps = {[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [1;0,19]}*.

Table 3.9 – Utility calculation values for three suitable solutions.

solution.steps	*U* [€]
{[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [1;0,19]}	-0,198
{[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [6;0,11]}	-0,242
{[-6;0,18], [6;0,12], [-9;0,17], [8;0,13], [2;0,13]}	-0,209

3.2.8 Exceptions in auction rules

After the auctioneer agent has chosen the most rewarding combination of bids from the prosumer bid sets, it composes and sends offers based on those bids. One of the foundations of earning profit is to purchase goods at low prices and sell them at high prices. When both negotiating parties intend to earn profit, both are likely to maximize their profits. Market dynamics suggests that because of negotiations, the purchasing party is willing to raise their buying price and the selling party is willing to lower its asking price. A deal is made when the buying and asking price converge, where the price of the deal is referred to as (market) clearing price. The dynamics of how an agent changes its price during negotiations is referred to as negotiation strategy.

Due to the specific nature of the auction, several exception rules are introduced to provide security of supply for the prosumer agents and encourage active participation and trading in the auction. The following is an incomplete list of enforced exception rules, which will be complemented during future research:

- A price range for prosumer bids and asks. When prosumer agents propose too low *C* values for bids or too high *C* values for asks, it is a more beneficial option to purchase electricity from the PCC. To exclude bids where $C < GCpA$ (purchasing price of electricity from the PCC for aggregator) and asks where $C > GCsA$ (selling price of electricity from the PCC for aggregator), such bids are automatically terminated before the execution of the search algorithm.
- Opportunity to opt-out from the auction. If the prosumer agents are not interested in participating in the auction, they are able to exclude themselves from the auction by providing bids and asks with *C* values of GC_pP and GC_sP respectively. This means that the prosumer purchases electricity with the same price as it would get directly from the DSO and Utility.

3.3 Conclusions

This chapter presents the development of a novel electricity auction for use inside Smart MV/LVs. Research and analysis of literature suggests a need for a novel electricity auction to provide the required functionality. The developed electricity auction is a modification of a multi-unit administered continuous double-auction. Prosumers interact using a subscribed communication method, which provides better manageability of the microgrid. Instead of presenting a single bid, auction participants gain flexibility by presenting a set of bids. The auctioneer agent collects all bid sets, chooses the optimal bids, composes offers and sends offers to participants. Upon receiving an offer, participants either accept the offer or reject it. An auction round runs until the bids and asks of all agents have been served or the auction reaches the predefined number of negotiation rounds.

During the development of the electricity auction, a combinatory search problem for finding the optimal combination of bids from bid sets is identified and analysed. Four conclusions are drawn by analysing the search problem and the problem-solving example:

1. There is no need to perform the goal state check until the final state is reached.
2. There is no explicit way to exclude a solution before the final state is reached.
3. The impact of a single state on the total solution can be determined only after the final state is reached.
4. An eligible solution gives no indication whether it is the optimal one.

The following chapter discusses the research of search algorithms for use in the developed electricity auction.

4 Research and development of search algorithm

The developed electricity auction reveals a combinatory search problem to determine the best combination of bids. Search algorithms have been the subject of numerous books and publications. Existing search algorithms need to be studied to examine their applicability in the developed electricity auction. If no existing search algorithm is suitable for the developed electricity auction, a novel search method is needed.

The following paragraphs describe the research of existing search algorithms. Existing search methods are analysed for use in the developed electricity auction. The subsequent section provides a detailed description of the development of a novel search algorithm for use in the developed electricity auction.

4.1 Research of search algorithms

To solve the search problem described in section 3.2.6, various existing methods were studied. The unconventionality of the search problem lies in the need to calculate the utility for all solutions, which reach the goal state, not just one.

For the quantification of search algorithm performance, a setup of 16 prosumers was used because it is a common number of feeders in low voltage distribution substations. The maximum number of prosumer bids was set to eight. With 8 bids and 16 bidders, the complexity O of the search method is 8^{16}, i.e. there are more than $2{,}81 \times 10^{14}$ possibilities to choose one bid from each prosumer.

According to [95], four parameters are used to evaluate the performance of search algorithms:

1. Completeness – is the algorithm guaranteed to find a solution when there exists one?
2. Optimality – does the strategy find the globally optimal solution?
3. Time complexity – how long does it take the algorithm to find a solution?
4. Space complexity – how much memory is needed to perform the search?

The following section contains a detailed overview of more common search algorithms.

4.1.1 Breadth-first search

A breadth-first search is a method of searching, where first, the initial state is expanded to all of its possible states; then, all the successor states of the initial state are expanded to all of their possible states, which is followed by expanding their successor states to all of their possible states, and so on. The search carries on until it reaches a predefined depth or all states reach the final state.

Since the breath-first search runs all possible combinations, the completeness of the algorithm is *true*. In the presented method, the optimal solution is found from the results of the search and since the breath-first search returns all possible solutions, the optimality parameter is also *true*. For the calculation of time complexity, an assumption is used that the expansion of a node and the takes 10 μs and the goal check calculation another 10 μs. The total number of node expansions is calculated using (17):

$$n + n^2 + n^3 + \cdots + n^d, \qquad (17)$$

where n denotes the number of expandable nodes (for the described setup, $n=8$) and d - the level that the search is expanded to (for the described setup, $d=16$), which results in a total of $3{,}22 \times 10^{14}$ expansions. Using the total number of node expansions and adding the total number of goal checks, the estimated time for the completion of the search would be $6{,}03 \times 10^{9}\ s$, meaning that the time complexity of this solution is immense.

To find the memory required for the search is calculated from the space for storing one solution. A solution is made up of two parameters: the prosumer name and bid number. The prosumer name and the bid number are given by their indexes, both of which are 1 byte integers. The total memory needed to store a breadth-first search is found using (18):

$$Sp = Pr_{reg}(d_1 + d_2), \tag{18}$$

where *Sp* denotes the required space in bytes, d_1 - the space in bytes needed to store the prosumer name indicator and d_2 - the space in bytes needed to store the prosumer bid indicator. For the described setup, *Sp = 32* bytes. The breadth-first search needs to store all results of the penultimate state, meaning that the total amount of required memory is $8^{15}[15(1+1)] = 960$ Terabytes.

The time and space complexity exclude the breadth-first search as a suitable solution. The breath-first search is suitable for smaller datasets.

4.1.2 Uninform-cost search

Uniform-cost search modifies the breadth-first search by always expanding the lowest total path cost node until a final node is reached and no cheaper path is available. The uniform-cost search can be used if the optimal solution is the path with the lowest path cost from the initial node to the final node and where the total path cost is the sum of individual paths costs [95]. Since the search problem states uniform path costs for each path, uniform-cost search is excluded as a suitable search method.

4.1.3 Depth-first search

Depth-first search always expands one of the nodes of the deepest levels. When the search algorithm arrives at a node which is not a solution and which cannot be expanded, it returns to the previous node and either expands to another higher node or heads back to another node. The obvious advantage of the depth-first search against the breadth-first search is that its memory requirements are as low as are memory requirements for one solution. The major disadvantage of the depth-first search is that it might get stuck on a long (or even infinite) path, even when a shallow solution exists on a parallel branch [95]. Also, the depth-first search might result in a suitable solution; there is no way of telling whether it is the global optima.

The completeness parameter of the depth-first search is *false*. The optimality parameter of the depth-first search is also $false$. The time complexity for the depth-first search, considering the worst case scenario, is the same as for the breath-first search. Space complexity for the case at hand is $Sp = 32\ bytes$.

4.1.4 Depth-limited search

The depth-limited search improves the depth-first search by adding the maximum allowed depth of a path [95]. Given the limited depth is inserted correctly, the algorithm can be considered complete (completeness is *true*). Although the problem of incompleteness is tackled, the optimality parameter for depth-limited search remains *false.* Time and space complexity remain the same as for the depth-first search.

4.1.5 Iterative deepening depth-first search

Iterative deepening search uses the depth-limited search, but instead of a fixed-depth limit, the algorithm runs several times while the depth limit is being iterated (depth values: at first 0, then 1, then 2, etc.) [95]. For iterative deepening depth-first search, the completeness parameter is *true*. Also, the optimality parameter is *true*, since the result of the deepest search will return all results. Unfortunately, the time complexity remains the same as for the breath-first search. Space complexity is the same as for the depth-first search.

4.1.6 Bidirectional search

Bidirectional search uses two simultaneous searches: one starting from the initial state and another from the goal state. A result is reached when the searches meet in the middle [95]. The optimality parameter for a bidirectional search is *true* and the completeness parameter is also *true*. The complexity *O* for the bidirectional search method is $2 \times 8^8 = 3{,}36 \times 10^7$. The time complexity for the bidirectional search is $2 \times 8^8 \times 10(\mu s) + 2{,}81 \times 10^{14} \times 10(\mu s) = 2{,}28 \times 10^9 (s)$. The space complexity for the bidirectional search is $2 \times \{8^7[7(1+1)]\} = 56$ megabytes.

4.1.7 Generic best-first search

Best-first search is identical to the uniform-cost search, but instead of expanding the lowest total path cost node, the node to be expanded is selected based on an evaluation function *f(n)*. The choice of *f* determines the search strategy and usually includes a heuristic function *h(n)* as a component [95].

4.1.8 Greedy best-first search

Greedy best-first search is a generic best-first search strategy, where the heuristic function *h(n)* represents the direct distance of the node *n* from the goal node and where such *f* is chosen that *f(n)=h(n)*. In other words, the node closest to the goal is expanded first [95].

The greedy best-first search is similar to the depth-first search, since its completeness parameter and optimality parameter are both *false*, and the worst case time complexity is the same both for the greedy best-first search and the depth-limited search. The greedy best-first search needs to retain all steps, thus the space complexity of the current setup is the same as for the breath-first search. Time and space complexity can be reduced by choosing better heuristic functions.

4.1.9 A* search

A* search combines the greedy best-first search with the uniform cost search, which results in a search strategy that evaluates both: the cost to reach the next node and the cost to get to the goal from the next node. The space complexity of A-Star is exponential since all nodes checked in algorithm steps are stored in memory.

Provided the heuristic function used to determine the cost of directly getting to the goal for each node satisfies certain conditions, the optimality and completeness parameters for the A* search can be considered *true*. The heuristic function needs to be admissible or consistent (depending on the search version used) and have a finite number of nodes with cost lower than or equal to the optimal solution path. The complexity results depend heavily on the assumptions made about the state space and are therefore are not explicitly given. [95], [96]

4.1.10 Recursive best-first search

The recursive best-first search is a simple recursive algorithm that attempts to mimic the operation of a standard best-first search, but using only linear space. Similar to A* search, it utilizes an evaluation function that considers a heuristic function and cost for expanding the next node. It is designed to improve the space complexity of the A* algorithm, its well-known predecessor. The recursive best-first search follows the depth-first search, where only nodes checked in the current step are stored in memory, which results in linear space complexity. Similar to all heuristic search functions, the search efficiency relies heavily on the quality of the heuristic. [95], [96]

4.1.11 Simplified memory-bounded A* search

Simplified memory-bounded A* search proceeds just like A*, by expanding the best leaf until memory is full. Upon reaching the memory limit, an existing node needs to be dropped before a new node can be added, thus the node with the highest *f*-value is dropped.

The complete parameter is *true* for simplified memory-bounded A* search if the depth of the shallowest goal node is less than the memory size. The optimal parameter is *true* if any optimal solution is reachable [95].

4.1.12 Memory-bounded heuristic search

The easiest way to reduce memory requirements for A* search is to adapt the idea of iterative deepening to the heuristic search context, resulting in iterative-deepening A* (IDA*) search. The main difference between the iterative deepening depth-first search and the IDA* search is that the cut-off used is not the depth, but the *f*-cost. For each iteration, the cut-off value is the smallest *f*-cost of any node that exceeded the cut-off in the previous IDA* [95].

4.1.13 Metaheuristic search algorithms

All modern nature-inspired search methods are called metaheuristics (based on Glover’s convention). Some well-known metaheuristic algorithms are: genetic algorithm (based on natural selection), particle swarm optimization (based on social behaviour of bird flocking), cuckoo search algorithm (based on the brood parasitism of some cuckoo species), and bat algorithm (based on echolocation behaviour of microbats). All metaheuristic algorithms use a trade-off of randomization and local search. The performance of a metaheuristic search algorithm depends heavily on its parameter setup [97].

For a better comparison of the search algorithms described in sections 4.1.1 to 4.1.13, their characteristics are summarized in Table 4.1. Due to the specific nature of the problem, none of the analysed search methods can be implemented unambiguously.

4.2 Development of a novel search algorithm

Previous chapter analysed the applicability of more common search algorithms for finding the best combination of bids in the developed electricity auction. Since no researched algorithm proves to be applicable, a novel search algorithm will be composed.

For the development of a suitable search algorithm, a depth-complete search was chosen as a base. A depth-complete search is a depth-first search, which does not stop upon reaching a goal node, but stores it into memory and carries on as it had reached a non-expandable node. The search is complete until it has expanded all nodes. Such a modification provides a complete and optimal search algorithm with better space complexity than the breadth-first search. The space complexity of the depth-complete search depends on the number of solutions. The time complexity of the depth-complete search is too high and a method for filtering out unsuitable branches in the early stages of the search is needed.

Table 4.1 – Comparison of search algorithms.

Parameter	Completeness	Optimality	Time complexity [s]	Space complexity
Breadth-first	*true*	*true*	$6{,}0 \times 10^9$	960 Tb
Depth-first	*false*	*false*	$6{,}0 \times 10^9$	32 b
Depth-limited	*true*	*false*	$6{,}0 \times 10^9$	32 b
Iterative deepening depth-first	*true*	*true*	$6{,}0 \times 10^9$	32 b
Bidirectional	*true*	*true*	$2{,}3 \times 10^9$	56 Mb
Generic best-first	*false*	*false*	N/A[2]	N/A[2]
Greedy best-first	*false*	*false*	N/A[2]	N/A[2]
A*	*true*	*true*	N/A[2]	N/A[2]
Recursive best-first	*true*	*true*	N/A[2]	N/A[2]
Simplified memory-bound A*	*true*	*true*	N/A[2]	N/A[2]
Iterative-deepening A*	*true*	*true*	N/A[2]	N/A[2]
Meta-heuristic	*false*	*false*	N/A[2]	N/A[2]

4.2.1 Development of data filter for reduction of time complexity

To reduce time complexity in the depth-complete search, a heuristic function was used. The heuristic function h aims to filter branches from the search where a solution is impossible.

Before each search, a heuristic h_i is calculated for each state, which is a 2 component array $[V_i^+; V_i^-]$, where V_i^+ denotes the maximum possible sum of *V* and V_i^- the minimum possible sum of *V* available for prosumer *i*. Each time the search reaches a node, the current *V* balance is calculated using (7) and a node termination check is carried out using (19):

$$(-1)(V^+ + pccTrsh) \leq pccSp + Vbal + V_i \leq (-1)(V^- - pccTrsh)\,, \qquad (19)$$

where $pccSp$ denotes the power setpoint for the PCC, $-Vbal$ the sum of already selected bid volumes, V_i - Vi the volume of the bid, V^+ - the volume sum of the highest volume bids of unselected prosumers, V^- - the volume sum of the lowest volume bids of unselected prosumers and $pccTrsh$ - the volume setpoint threshold. In case (19) returns *false*, the node and all its successors are excluded from the search.

The time complexity of the search algorithm depends directly on the expanded nodes. To expand a minimum amount of nodes, the filtering function needs to terminate an unsuitable path as early as possible. To detect a branch which does not pass the

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[2] Since the complexities depend heavily on heuristics and the algorithm constraints, an indicative value is not applicable

termination check (19) early during the search, the input data $PROSUMERS$ requires sorting. The aim of the sorting is to prevent a situation where (one of) the last prosumer bid(s) $PROSUMERS_i.B$ incorporates large V values. The bid sets are sorted in descending V_i^{abs} order, where V_i^{abs} denotes the sum of the absolute maximum and minimum V values (V_i^{max}, V_i^{min}) for prosumer bid set $PROSUMERS_i.B$ and is calculated using (20):

$$V_i^{abs} = |V_i^{max}| + |V_i^{min}|. \tag{20}$$

4.2.1.1 Filter performance evaluation

To evaluate the performance of the filter and its effect on the time complexity of the depth-complete search algorithm, a test computer program was composed. The test program performs the depth-complete search and returns the number of eligible solutions and the time spent for the completion of the search.

For the evaluation, two datasets were used: an 8 by 10 data matrix with randomly generated values (analogy to the example in section 3.2.7 was used); an 8 by 8 data matrix with purposely selected values to simulate a worst-case scenario (a data matrix with the highest number of eligible solutions). The depth-complete search algorithm and the filter depend solely on the V values of prosumer bids, thus only V values of the two evaluation matrices are presented in *Table 4.2* and *Table 4.3*.

Table 4.2 – Bid volume values of a randomly generated data matrix.

$PROSUMER_1$ [kW]	5	-9	2	6	45	58	-25	-16
$PROSUMER_2$ [kW]	8	-2	5	-4	-30	-35	-40	-45
$PROSUMER_3$ [kW]	-2	4	9	-6	-44	33	-22	11
$PROSUMER_4$ [kW]	1	6	2	8	35	-10	35	-10
$PROSUMER_5$ [kW]	-6	-8	2	6	-16	55	-38	3
$PROSUMER_6$ [kW]	5	10	25	8	28	50	35	19
$PROSUMER_7$ [kW]	-30	5	30	35	20	45	-20	15
$PROSUMER_8$ [kW]	-5	8	-100	45	18	13	25	-42
$PROSUMER_9$ [kW]	20	-12	20	14	26	34	17	-12
$PROSUMER_{10}$ [kW]	-15	6	5	26	15	14	17	22

Table 4.3 – Bid volume values of the worst-case data matrix.

$PROSUMER_1$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_2$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_3$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_4$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_5$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_6$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_7$ [kW]	1	-1	2	-2	3	-3	4	-4
$PROSUMER_8$ [kW]	1	-1	2	-2	3	-3	4	-4

First, the depth-complete search algorithm was used to find the solutions of the randomly generated data matrix with 4 columns and 5 rows ($4^5 = 1\ 024$ possible combinations), 8 columns and 5 rows ($8^5 = 32\ 768$ possible combinations), 8 columns and 8 rows ($8^8 = 16\,777\,216$ possible combinations) and 8 columns and 10 rows ($8^{10} = 1\,073\,741\,824$ possible combinations). The number of solutions depends on the value of $pccTrsh$, thus the test program was executed with different $pccTrsh$ values. The results of the experiment are depicted on *Figure 4.1*. In *Figure 4.1*, the value of $pccTrsh$ is presented as a ratio of the absolute maximum V of the data set and the relative solution count refers to the ratio of solutions from all possible combinations.

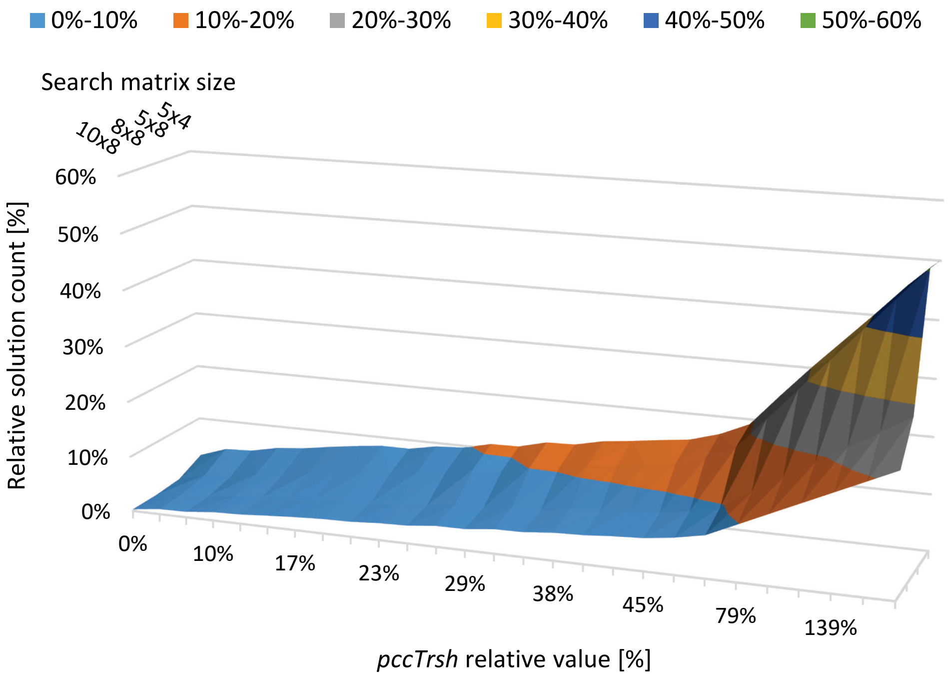


Figure 4.1 – Relative solution count dependency on relative pccTrsh values and search input data matrix size for data matrixes composed from the random data matrix.

Secondly, the depth-complete search algorithm was used to find the solutions of the worst-case data matrices with 4 columns and 5 rows ($4^5 = 1\,024$ possible combinations), 5 columns and 5 rows ($5^5 = 3\,125$ possible combinations), 8 columns and 5 rows ($8^5 = 32\,768$ possible combinations) and 8 columns and 8 rows ($8^8 = 16\,777\,216$ possible combinations). The results of the experiment are depicted in Figure 4.2.

Based on the analysis of Figure 4.1 and Figure 4.2, it is concluded that the solution count increases with the increase of the $pccTrsh$ value. It is suggested to use relative $pccTrsh$ values lower than 5%. The relative solution count decreases as the size of the matrix (and thus, the number of possible combinations) increases. Although the relative solution count decreases, the total number of eligible solutions increases because of the exponential increase of possible combinations.

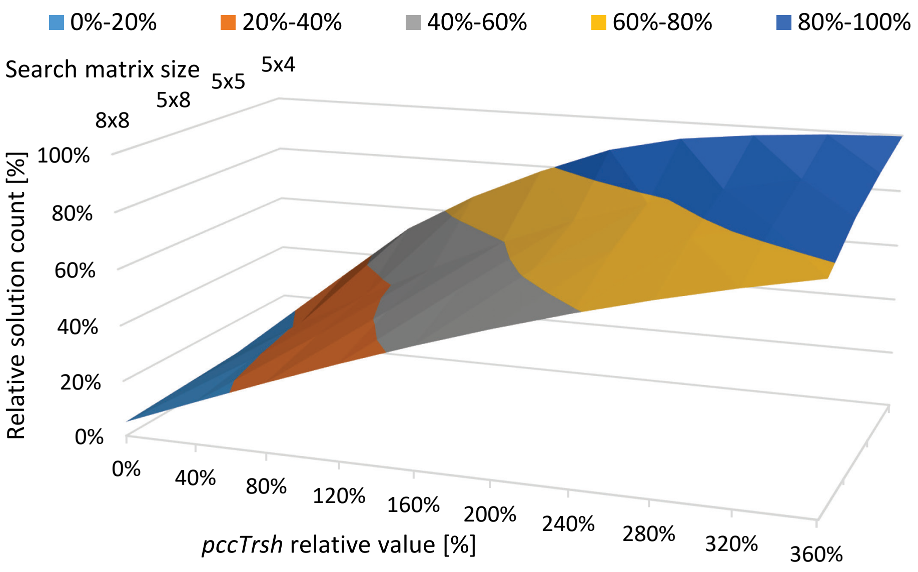


Figure 4.2 – Relative solution count dependency on relative pccTrsh values and search input data matrix size for data matrixes composed from the worst case data matrix.

For a better understanding of filter performance, quantification is required. Since the filter used to decrease the time complexity of the search, it is an objective approach to evaluate filter performance based on the total time for the completion of a search. The time to complete the custom search for finding all eligible solutions was measured with the test program. Based on measured results for searches with and without the filter, the filter efficiency was calculated. The formula for calculating filter efficiency is (21):

$$\eta = 1 - \frac{t_f}{t_w}, \tag{21}$$

where η is the filter efficiency, t_f - the duration of a search with the filter and t_w - the duration of a search without the filter for the same dataset. Similar to *Figure 4.1* and *Figure 4.2*, the dependency of filter efficiency on the $pccTrsh$ and search matrix size is represented in *Figure 4.3* and *Figure 4.4*. The filter efficiency increases with the matrix size and is most effective with low $pccTrsh$ values. The worst-case input data matrix demonstrates how much filter efficiency can vary depending on input data values.

The time complexity of the filtered search of the 8×8 random data matrix with $pccTrsh = 0$ was 1,7 s; and for the worst-case data matrix 3,5 s. The time complexity of the filtered search of the 8×10 random data matrix with $pccTrsh = 0$ was 51,8 s, which is conclusive evidence that the depth-complete search algorithm with filtering is not applicable for use in the developed electricity auction. It is not necessary to measure the time complexity of the filtered search of the 8×16 worst-case data matrix with $pccTrsh = 0$ since it can be calculated.

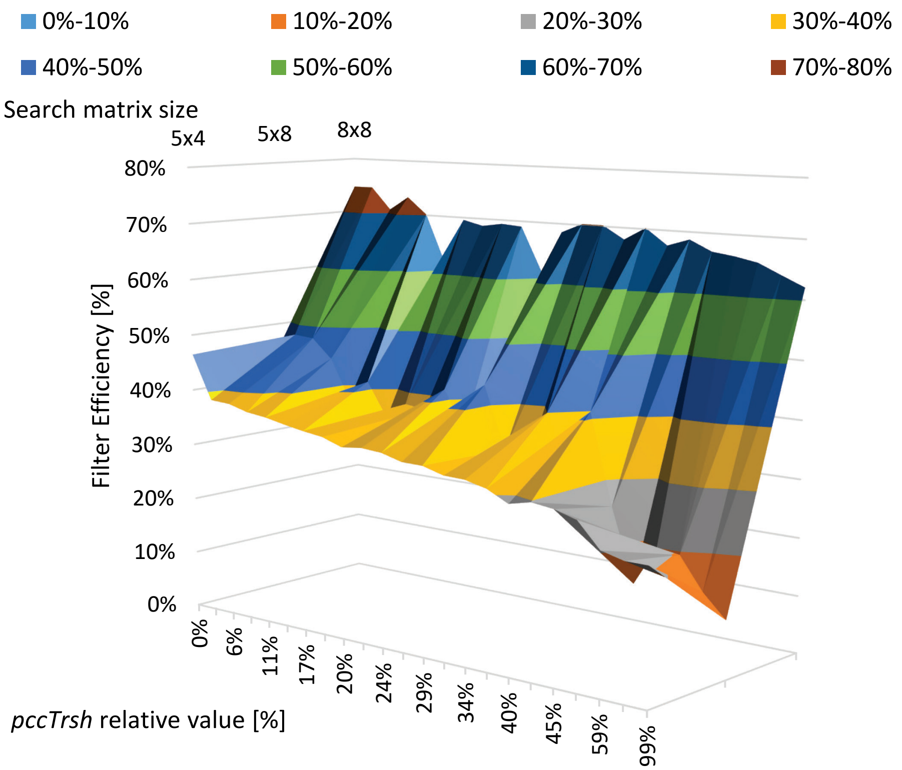


Figure 4.3 – Filter efficiency dependence on $pccTrsh$ *relative value and search matrix size for the random data matrix.*

To calculate time complexity, the time complexities of searches in the worst-case data matrices with different sizes were measured. The measurement results are presented in Table 4.4, alongside with the number of solutions for each matrix. The estimated time complexity is a function of the solution count, which for the worst-case data matrix is a function of the size of the data matrix. The approximate solution count was calculated with (22), which is generated with MS Excel software using measurement results (coefficient of determination $R^2 = 0{,}9999$):

$$K(n, d) = (0{,}075 - 0{,}003 * d)n, \tag{22}$$

where K denotes the number of eligible solutions, n - the total number of combinations and d - the depth of the search. The time complexity was estimated using a linear equation (23), which is generated with MS Excel software using (22) and measurement results (coefficient of determination $R^2 = 0{,}9988$):

$$O\big(K(n, d)\big) = 0{,}0032\mathrm{K}(n, d) + 172{,}2, \tag{23}$$

where O denotes the time complexity in s.

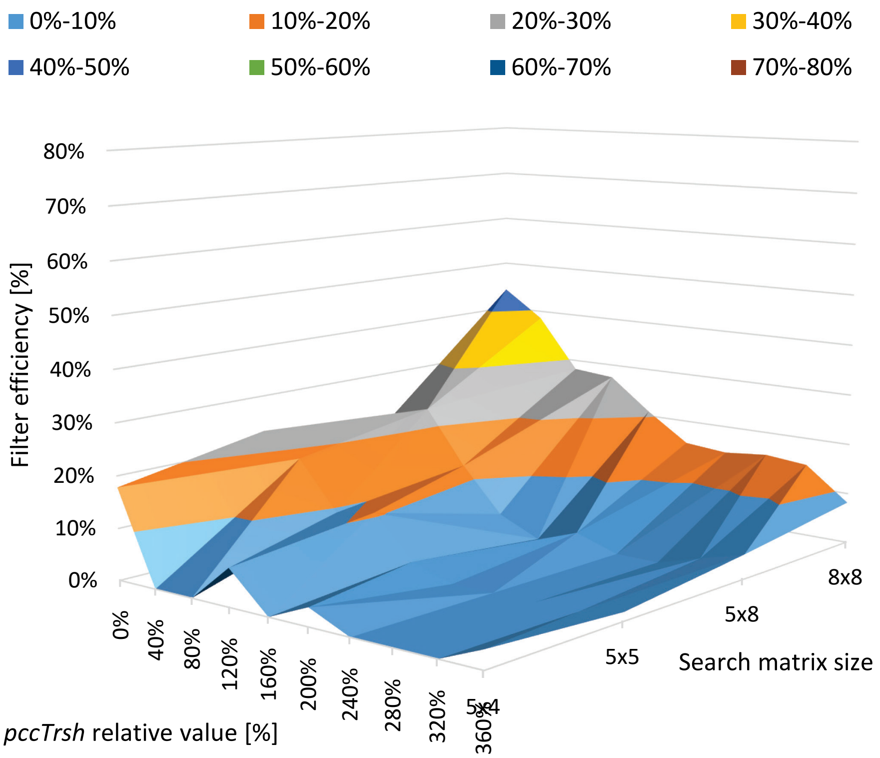


Figure 4.4 – Filter efficiency dependency on pccTrsh relative value and search matrix size for the worst-case input data matrix.

Using (22) and (23), the time complexity of the filtered search of the 8×16 worst-case data matrix with $pccTrsh = 0$ is 2.4×10^{10} (s) was found. It can be concluded that although effective, filtering alone in is not enough to provide acceptable time complexity for the depth-complete search. For the further reduction of time complexity of the depth-complete search, the search was divided into two parts. The first part of the search is the value estimate search and the second part the filtered depth-complete search. The developed search algorithm is called a hybrid two-step search algorithm.

Table 4.4 – Measured search durations and numbers of eligible solutions for different sizes of worst-case data matrixes.

Size	Solution count	Duration [s]
8x3	36	0,005
8x4	296	0,015
8x5	2 030	0,037
8x6	15 200	0,133
8x7	112 308	0,578
8x8	845 320	3,547
8x9	6 386 076	21,020

4.2.2 New hybrid two-step search algorithm

The hybrid two-step search algorithm separates the search into two: the first phase narrows the search by selecting bids from prosumers based on simplified assumptions; the second phase carries out the filtered depth-complete search described in section 4.2 to find the best set of bids. The first phase of the search is executed until the total number of possible combinations is lower than a predefined value. For some search cases, the first part of the search might not be executed at all. In the scope of this thesis, the selected threshold value is $8^8 = 16\,777\,216$, since the completion of the filtered search for the 8×8 worst-case data matrix was acceptable. There are multiple approaches to compose logic for the first phase of the developed algorithm, several of which are described in the following sections.

4.2.2.1 Greedy Two-Step Search Algorithm

The greedy two-step search algorithm aims to select potentially more rewarding bids in the first phase of the search. The logic rests on the assumption that a bid with the highest revenue compared to PCC prices is likely to be a part of the optimal solution. The highest revenue compared to PCC prices was calculated with (24):

$$Pr^p = \begin{cases} V \geq 0; V(C - GC_pP) \\ V < 0; V(GC_sP - C) \end{cases}, \tag{24}$$

where Pr^p denotes the revenue compared to PCC prices, V - the volume of electrical energy of the bid, C - the proposed price of the bid, $GCpP$ - the purchasing price of electricity from the PCC for prosumer, and $GCsP$ - the selling price of electricity to the PCC for prosumer.

For the greedy two-step search, all bids are listed in ascending orders of values calculated by (24) and the number of possible combinations is calculated. While the number of possible combinations remains higher than the predefined setpoint value, the first bid from the list is selected. Each time a bid is selected, all bids from the bid set are removed from the list and the number of possible combinations is recalculated. Once the algorithm reaches the threshold value, the second phase of the search algorithm is executed, with input data outputted from the first phase.

There are several exception scenarios which need to be considered. One of them is a case where selecting the bids with the highest revenue results in an unsolvable problem in the second phase of the search. For example, all prosumers require electricity and offer bids with high volumes and high purchase prices, while there are little or no prosumers to balance the sum of volumes to meet the goal test (6). To prevent the system on committing to bids it cannot serve, a balance check which determines whether the next selected bid is acceptable, is used. The balance check is calculated with (25):

$$bc = \begin{cases} V \geq 0; (V + V_{bal} - V_{SP}) \leq -V^{+} \\ V < 0; (V + V_{bal} - V_{SP}) \geq -V^{-} \end{cases}, \tag{25}$$

where bc denotes the logical result of the balance check, V - the volume of electrical energy of the bid, V_{bal} - the sum of already selected bid volumes, V_{SP} - the requested total sum of bid volumes, V^{+} - the volume sum of highest volume bids of unselected prosumers, and V^{-} - the volume sum of lowest volume bids of unselected prosumers.

4.2.2.2 Volume Difference Based Two-Step Search Algorithm

The volume difference-based two-step search algorithm executes the first phase of the search to select the most rewarding bids from the bid sets with low absolute volume difference. The logic is built on the assumption that there is a higher chance of finding a near-optimal solution when the second phase of the search is executed on a dataset with higher volume variabilities.

The prosumer bid sets are sorted in ascending order of volume difference between the highest and lowest bid. While the total number of possible combinations remains higher than the predefined setpoint value, the bid with the highest (24) value from the first prosumer is selected and a balance check is carried out using (25). If the balance check returns *false*, the bid with the next (24) value is selected and so on. If a bid is selected or no bids from the prosumer return *true* for the balance check, the next prosumer from the list is selected and the number of possible combinations is recalculated.

4.2.2.3 Reputation Based Two-Step Search Algorithm

The reputation based two-step search algorithm executes the first phase of the search by selecting most rewarding bids from prosumers with higher reputation. The logic is built on the assumption that the reputation of prosumers can be used as a reward. If the bid of the prosumer is selected in the first phase, the prosumer agent can use it as an advantage.

The prosumer bid sets are sorted in ascending order of prosumer reputation values. While the total number of possible combinations remains higher than the predefined setpoint value, the bid with the highest (24) value from the first prosumer is selected and a balance check is carried out using (25). If the balance check returns *false*, the bid with the next (24) value is selected and so on. If a bid is selected or no bids from the prosumer return *true* for the balance check, the next prosumer from the list is selected and the number of possible combinations is recalculated.

4.2.2.4 Combined Two-Step Search Algorithm

The combined two-step search algorithm combines the greedy two-step search algorithm and the volume difference based two-step search algorithm in order to combine their benefits and compensate losses in exchange for higher time complexity. The search executes both the greedy and the volume difference based two-step search algorithm and returns the better result.

4.3 Development of an evaluation method for the search algorithm

For a quantitative evaluation of the composed search algorithms, metrics are needed. Using smaller datasets, a revenue comparison between search results, which were carried out in the same dataset, was made for the hybrid two-step and the depth-complete search algorithm. The time complexity of the depth-complete search is too high for larger datasets, thus an estimated value was needed for comparing performance on larger datasets.

A modification of the Monte Carlo method was used for the calculation. All bids in all prosumer bid sets are random variables in a domain of $V \in [-50, 50]$ and $C \in [0{,}1, 0{,}2]$. For the randomly composed dataset, the highest revenue compared to the PCC is calculated from the eligible results of the full depth-first search ($pccTrsh = 2{,}5;$

$pccSp = 0$). The search is iterated 10 000 times for datasets with sizes of 4 to 8 bid sets and 100 times for datasets with sizes of 9 and 10 bid sets. From the collected results, the average highest revenue compared to the PCC is calculated. The average highest revenue per prosumer is depicted in *Figure 4.5*.

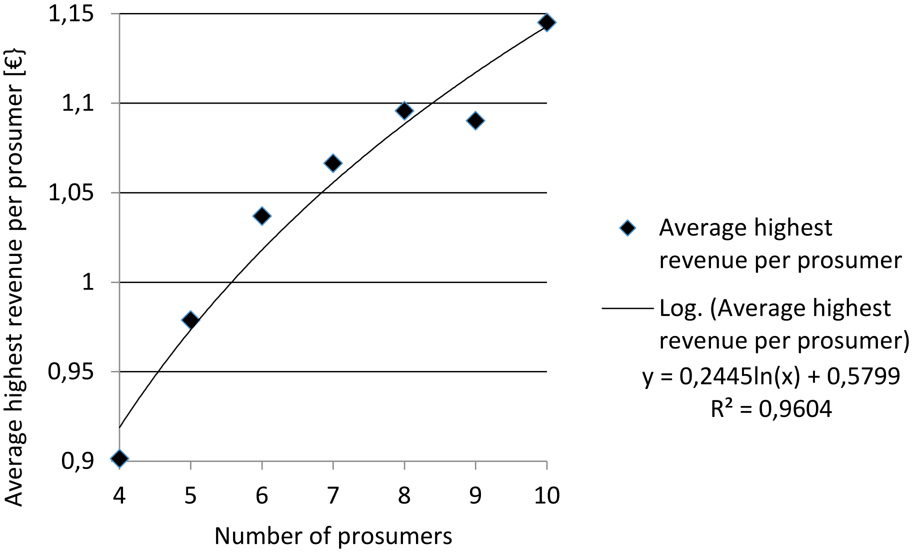


Figure 4.5 - Average highest revenue compared to the PCC per prosumer for datasets with different numbers of prosumers.

Based on average maximum revenues per prosumer for datasets with 4 to 10 prosumers, MS Excel software was used to formulate the relation between the maximum revenue per prosumer and the number of prosumers as a logarithmic equation (26) (coefficient of determination $R^2 = 0{,}9604$):

$$Pr^{avgPros}(d) = 0.2445 \ln(d) + 0{,}5799, \tag{26}$$

where $Pr^{avgPros}$ denotes the average revenue per prosumer and d - the number of prosumers (also the depth of the search). By using (26), it was found that the average revenue per prosumer for a dataset with 16 prosumers is $Pr^{avgPros}(16) = 1{,}2578$, which resulted in an average highest total revenue of 20,125. The average highest total revenue was used as a comparative value for the evaluation of search algorithm performance.

4.4 Evaluation of developed search algorithms

For the evaluation of the developed hybrid two-step search algorithms, experiments were conducted. Each search ($pccTrsh = 2{,}5;\ pccSp = 0$) was iterated 10 000 times. For each iteration, a 16×8 dataset was filled with randomly generated bids in the domain of $V \in [-50, 50]$ and $C \in [0{,}1, 0{,}2]$. An overview of the results of the experiment is presented in *Table 4.1*:

- The **greedy two-step search algorithm** reveals an average total revenue compared to the PCC of 17,804, which is 88,47 % of the average highest total revenue. The average time complexity is 603 ms and the worst time complexity is 3,7 s. The median revenue compared to the PCC is 17,986 (89,37 %) and the average revenue for results below median is 15,749 (78,25 %). The algorithm was unable to find a solution for 15 cases (0,15 %), thus the lowest returned revenue compared to the PCC is 0.

Table 4.5 – Hybrid search algorithm comparison based on measured results.

Two-step algorithm type	Greedy	Vol. diff. based	Rep. based	Combined
Space complexity	< 1 MB	< 1 MB	< 1 MB	< 1 MB
Avg. time complexity [s]	0,6	1,4	1,5	2,1
Optimal?	No	No	No	No
Complete?	No	No	No	No
Avg. revenue [%]	88,5	85,3	84,7	89,7
Median revenue [%]	89,4	85,6	85,2	90,0
Avg. rev. below median [%]	78,3	75,2	74,2	87,7

- The **volume difference based two-step search algorithm** was able to provide an average total revenue compared to the PCC of 17,159, which is 85,26 % of the average highest total revenue. The average time complexity is 1,44 s and the worst time complexity is 6,0 s. The median revenue compared to the PCC is 17,230 (85,61) and the average revenue for results below median is 15,128 (75,15 %). The algorithm was able to return a solution for all cases and the lowest returned revenue compared to the PCC is 5,013.
- The **reputation based two-step search algorithm** used prosumer reputations in the domain of $PROSUMER_n.rep \in \mathbb{Z}_{10}$. The average total revenue compared to the PCC is 17,041, which is 84,68 % of the average highest total revenue. The average time complexity is 1,50 s and the worst time complexity is 7,5 s. The median revenue compared to the PCC is 17,143 (85,18 %) and the average revenue for results below median is 14,937 (74,22 %). The algorithm was able to return a solution for all cases and the lowest returned revenue compared to the PCC is 4,437.
- The **combined two-step search algorithm** returned an average total revenue compared to the PCC of 18,057, which is 89,72 % of the calculated average highest total revenue. The average time complexity is 2,05 s and the worst time complexity is 6,1 s. The median revenue compared to the PCC is 18,119 (90,03 %) and the average revenue for results below median is 17,641 (87,66 %). The algorithm was able to return a solution for all cases and the lowest returned revenue compared to the PCC is 8,342. The comparison of both searches inside the combined two-step search revealed that the greedy search returned better results than the volume difference based search in 74,1 % of cases.

The comparison of the proposed algorithms showed that the best time complexity with fair average revenue is achieved by using the greedy two-step search algorithm. The volume difference-based two-step search algorithm has higher time complexity and smaller average generated revenue, but the search was able to find a solution for all datasets. The reputation-based two-step search algorithm showed the lowest average revenue but remains an interesting option since it gives opportunities for rewarding prosumers based on their history of behaviour. The best average revenue is achieved by the combined two-step search algorithm, which also has the highest time complexity. An interesting sign of the efficiency of the combined two-step search is that the average revenue for results below median is nearly as high as the average revenue of the greedy two-step search.

An important implication of the test results is that none of the composed search algorithms can be considered either complete or optimal. Near-optimal results mean that the objective of composing an optimal search algorithm has not been met and other approaches can be considered to improve results. Future research is required to compare the results of the developed search algorithm with other promising search methods, e.g. metaheuristic algorithms.

4.5 Conclusions

This chapter describes the development of a novel search algorithm meant for use inside the developed electricity auction. Research of existing search methods suggests that more common search algorithms are not applicable for solving the formulated search problem.

During the development of a novel search algorithm, four hybrid search algorithms were created and analysed. The greedy two-step search algorithm aims to select potentially more rewarding bids in the first phase of the search. The volume difference-based two-step search algorithm executes the first phase of the search to select the most rewarding bids from the bid sets with low absolute volume difference. The reputation based two-step search algorithm executes the first phase of the search by selecting most rewarding bids from prosumers with higher reputation. The combined two-step search algorithm combines the greedy two-step search algorithm and the volume difference based two-step search algorithm in order to combine their benefits and compensate losses in exchange for higher time complexity.

Comparative evaluation results of the developed search methods are given in *Table 4.5*. The selection of an algorithm for a specific application depends mainly on the available resources and the nature of the application. The combined two-step search algorithm while having a drawback of higher time complexity achieves the best average revenue. This thesis recommends the use of the combined two-step search algorithm whenever possible due to its high efficiency.

5 Proof-of-concept for the developed electricity auction

To prove the applicability of the developed electricity auction, it is required to determine the conceptual usability of the developed auction. An effective method for verification is the use of mathematical models and computer simulations. Simulations are required to prove if the developed electricity auction is capable of earning profit. The simulations need to consider that prosumers are able to negotiate prices and indicate which constraints need to be considered. The following restrictions apply to the simulations:

- The auction includes participants with and without DERs.
- The microgrid includes residential and commercial prosumers with standard load and generation profiles.
- Some microgrid prosumers incorporate energy storage (e.g electric vehicles (EV) with vehicle to grid capability).

For the simulations, a computer program and mathematical models are required.

5.1 Design of microgrid model

The state of the art of microgrids is described in section 2.2 of this thesis. The general definition of microgrids refers to them as clusters of loads, DG units and ESSs, which are required to provide a reliable supply of electricity. The loads, generation units and ESSs can be considered as prosumers. The state of the art of prosumers is described in section 2.1. Microgrids commonly connect to a larger power system at the distribution level. If a microgrid connects to a Utility grid, the area EPS can abstract the entire microgrid to a prosumer. Since prosumers are an integral part in describing microgrids, their structuring and modelling will be studied.

5.1.1 Design of prosumer logical structure

The concept of describing producers and consumers as prosumers enables using them as building blocks to model the entire electricity infrastructure. The generalization of the prosumer concept and structure provides prosumer interoperability and greatly reduces the complexity of designing EPSs. A universal prosumer structure enables provision of a framework to describe prosumer behaviour, control, connections and communication to other prosumers, user interaction and prosumer resources. The prosumer logical structure serves as vantage point for prosumer mathematical models and control systems. [98]

A prosumer is an entity made up of two logical elements: the prosumer subject and its resources. Both prosumer components consist of sub-components shown in Figure 5.1. In the following, the prosumer components are described in detail.

5.1.1.1 Prosumer subject

The subject of a prosumer is the proactive owner or delegated manager of the prosumer (this is the abstract conception of the agent; the realization of the agent is a software agent, which resides in the control system of the technological system). The subject needs to have one or several business, operational or miscellaneous goal(s). Prosumer agents are required to consider limitations imposed by prosumer resources in achieving their goals. The needs of a prosumer are classified as goods and services, which are necessary for the prosumer to achieve its goals. The prosumer subject is responsible for managing its resources. To switch between different operations, the subject assumes a role for the prosumer for each transaction round.

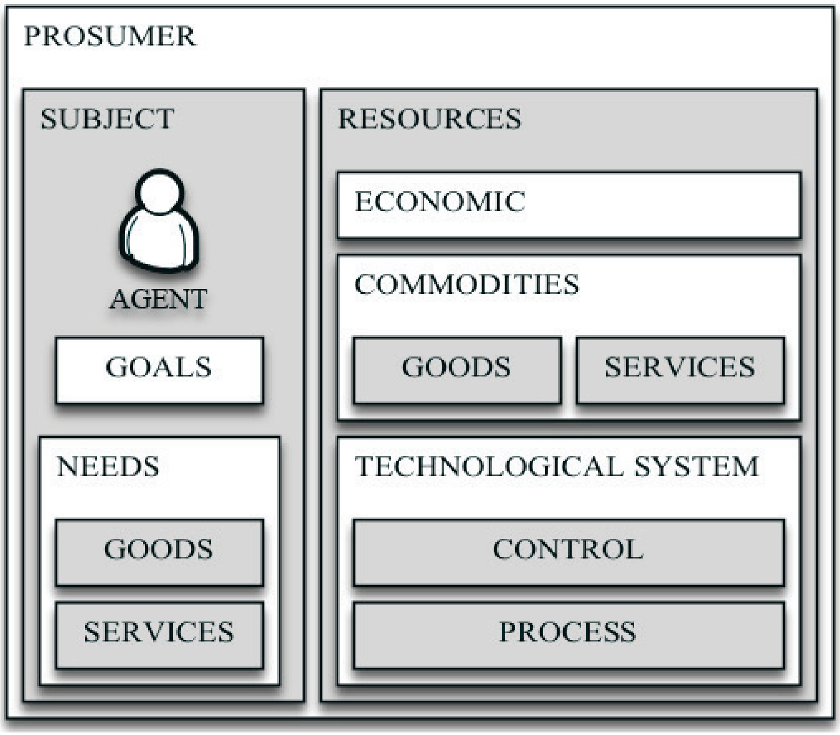


Figure 5.1 – Logical structure of the prosumer [98].

5.1.1.2 Prosumer resources

The resources of a prosumer are the means available to it. Prosumer resources are divided into economic resources, commodities and the prosumer technological system.

Economic resources are, for example, monetary funds (fiat- or cryptocurrency), agreements with other prosumers, energy futures or obligations. Only the subject of a prosumer can manage and contract these resources. Economic resources could also be contracts with TSOs for providing ancillary services or smart contracts with other prosumers concluded in peer-to-peer transaction platforms. [98]

Commodities are goods and services available by the prosumer. The variation of goods provided by an electric prosumer is not limited, but in most cases, it is reduced to two: electricity and data. Prosumers provide services like energy and information distribution, ancillary services and real-time information. A prosumer might not provide any goods at all and serve the sole purpose of energy and information distribution. If a respective technology is present in the prosumer technological system, a prosumer might also provide the service of energy storage. [98]

The prosumer technological system is the set of available technology and software objects. The prosumer technological system is divided into two sub-system layers:

- the process layer that is made up of components residing in the process zone of the SGAM model [9], and

- the control system that consists of prosumer control and communication hard- and software located in the field, station, operation and enterprise zones of the SGAM model [9].

For a clearer perception of the prosumer technological system, the hardware components of an example prosumer are placed onto the SGAM model component layer [9], as depicted in *Figure 5.2*.

The process layer includes process equipment of the prosumer (e.g. generators, loads, power converters, distribution equipment, and measurement points). The distribution process equipment includes all points of local coupling (PoLC) and the PCC. The PoLC is the geometric point where a local EPS connects to another local EPS (or prosumer).

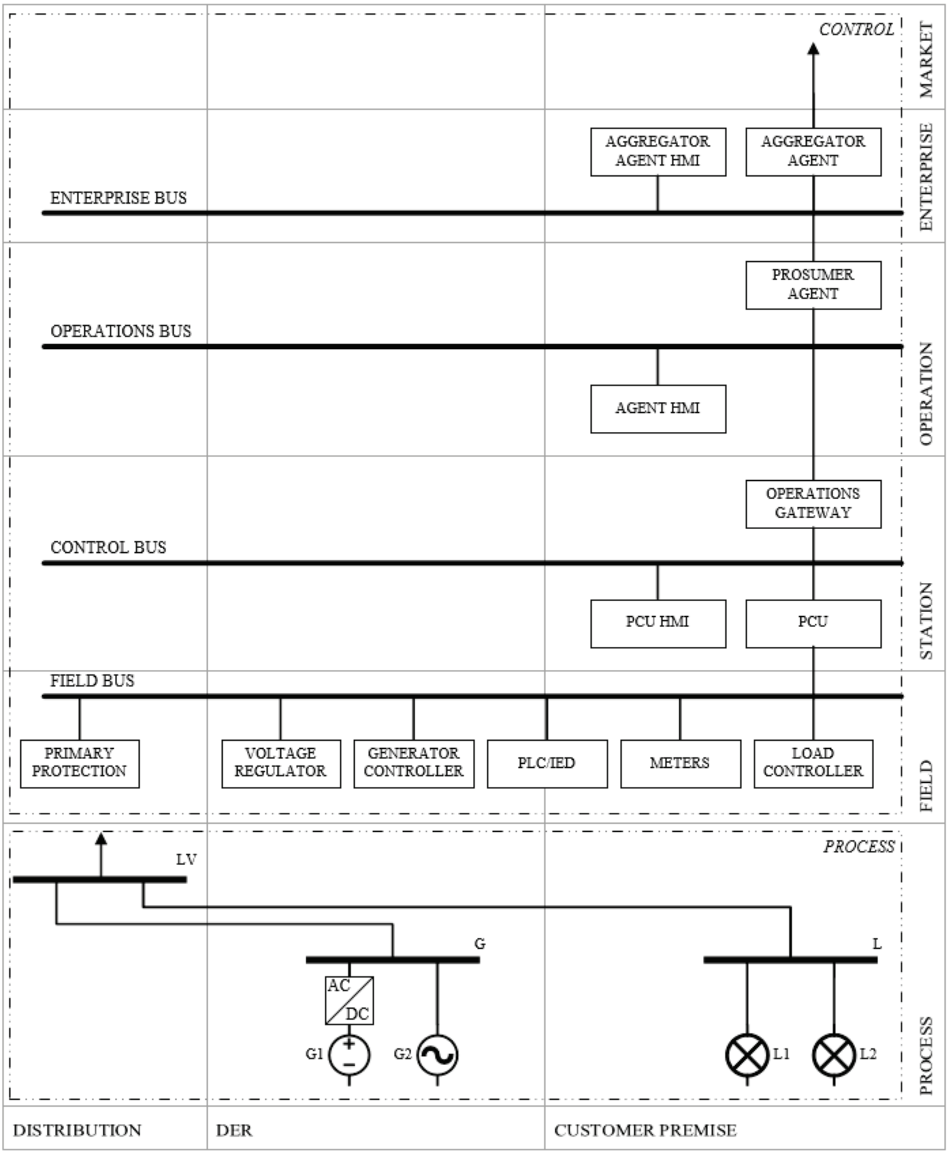


Figure 5.2 – Prosumer technological system mapping onto SGAM component layer [98].

The control system consists of:

- field control devices for primary control of process equipment (e.g. voltage regulators, primary load controllers, metering devices etc.),
- station control devices for prosumer control,
- operation control equipment for management and optimization of the prosumer and
- enterprise level control for coordinating the aggregation of other prosumers.

Enterprise level control is optional and realized when the prosumer is used as an aggregator of prosumers. The control system also includes communication buses and interfaces. [98]

5.1.2 Prosumer roles

The prosumer assumes roles to define its behaviour. A prosumer needs to assume at least one role for a dedicated period in the future. There is no limit for the number of roles a prosumer can assume concurrently but several roles exclude each other. The prosumer roles are classified as conventional and ancillary.

5.1.2.1 Conventional prosumer roles

Conventional roles are prosumer roles required for forming a bulk electric grid. In a bulk electricity grid, there are generators, consumers and distributors. The conventional prosumer roles are listed in *Table 5.1*.

Table 5.1 – Conventional prosumer roles.

Role	Description
Vendor	Obligated to provide electric energy to the PCC. Eligible for remuneration based on economic resources. Excludes the Purchaser role.
Purchaser	Consumes electricity from the PCC and is eligible for billing based on economic resources. Excludes the role of Vendor.
Distributor	Enables the flow of electric energy from one system to another. Might be remunerated based on economic resources.
Island	PCC disconnected.

For instance, a generator, an electric load and a distribution system can be described as two prosumers, one in the role of Vendor and the other in the role of Purchaser. The two prosumers connect to a third prosumer which has assumed the role of Distributor. The flow of electricity is from the PCC of the Vendor to one PoLC of the Distributor and from another PoLC of the Distributor to the PCC of the Purchaser (*Figure 5.3*).

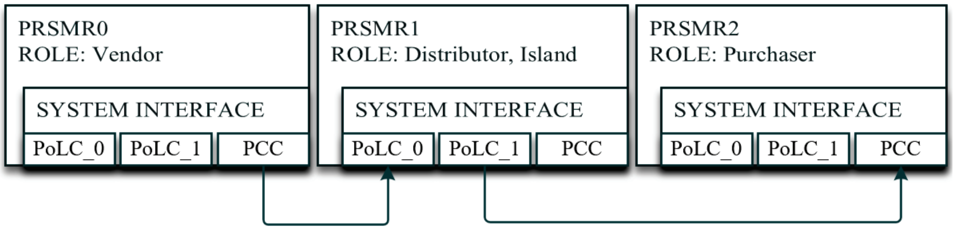


Figure 5.3 – Microgrid described by prosumers [98].

5.1.2.2 Ancillary prosumer roles

Ancillary roles are prosumer roles which, in addition to conventional prosumer roles, are needed to form a sophisticated, intelligent and controllable electricity grid. Some ancillary prosumer roles are described in *Table 5.2*.

Table 5.2 – Ancillary prosumer roles [47].

Role	Description
Frequency controller	Maintains the frequency within the given margins by continuous modulation of active power.
Spinning reserve provider	Increases or decreases generation or reduces consumption that can be provided at short notice, carried out by partially loaded generating units and interruptible customers.
Standing reserve provider	Increases generation or reduces consumption that can be provided by those generating units that are not synchronously on-line, or by interruptible customers.
Black start provider	Provides the capability of starting up a generating unit without an external power supply.
Remote generation controller	Regulates frequency by controlling the output through a centrally-based control system.
Grid loss compensator	Compensates the transmission system losses between the generators and the loads.
Emergency control actuator	Maintains and uses special equipment (e.g. power-system stabilisers and dynamic-braking resistors) in order to maintain a secure transmission system.
Spinning storage provider	Generates or stores electric energy on demand at short notice carried out by charging or discharging energy storage systems.
Communication gateway	Bridges communications between different communication mediums and/or protocols.
Database provider	Provides a sophisticated data archiving and backup service.
etc.	…

While conventional prosumer roles are limited, the ancillary prosumer roles are not. With the emergence of novel technologies and the evolution of the distribution grid, new problems and services are about to arise, which pave the way for future ancillary services.

5.1.3 Microgrid as a prosumer

The prosumer interconnection depicted in *Figure 5.3* represents an islanded microgrid. The subjects of the prosumers inside the microgrid can, but do not have to, be the same for all prosumers. A prosumer can incorporate an aggregator agent used to coordinate the actions of other prosumer agents. Such a prosumer can aggregate other prosumers in a microgrid and represent their summarized needs and commodities to the PCC, becoming thereby the intelligent agent representing the entire microgrid at the PCC. If one delegated agent coordinates the goals and needs of all prosumers inside the microgrid, it forms the microgrid subject. When the microgrid has coordinated behaviour, common economic resources and commodities, they form the microgrid resources. Based on previous reasoning, it can be generalized that a microgrid can be described as a prosumer.

Technological devices (generators, loads, ESSs) can be characterized as prosumers in different roles. When a microgrid is connected to a larger grid, it can also be described as a prosumer. Since a microgrid consists of technological devices, it can be interpreted as a prosumer made up of prosumers. If a microgrid is made up of elements of itself, it can be expanded as a fractal pattern with prosumers as elements (*Figure 5.4*). In theory, the fractal pattern could be limitless, but in practice, this approach is subject to technical limitations (e.g. feeder nominal power, complexity of communication etc.). The minimum size of the microgrid PCC can be evaluated using (27):

$$P_U > \sum_{i=1}^{n} P_i, \qquad (27)$$

where P_U is the nominal power of the PCC, n - the number of prosumers connected to the microgrid and P_i - the nominal power of the feeder of the adjacent prosumer.

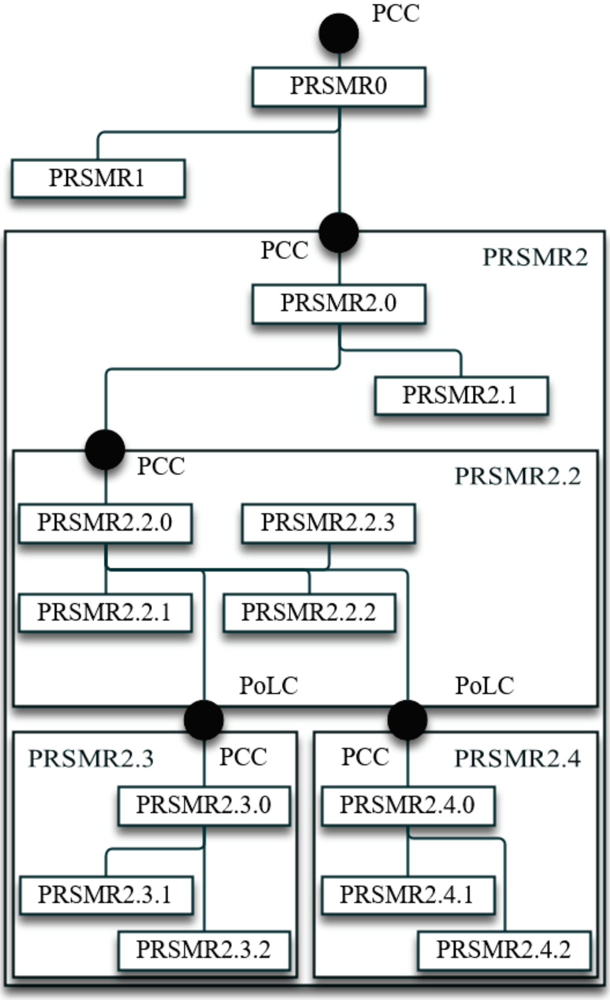


Figure 5.4 – Microgrids as a fractal pattern [98].

To clarify the fractal formation of a microgrid, a complex interconnection structure is depicted in *Figure 5.4*, where a configuration of a microgrid with the prosumers PRSMR0, PRSMR1 and PRSMR2 is presented. PRSMR0 has assumed the role of Distributor, while PRSMR1 and PRSMR2 may have several other roles. PRSMR2 is a more complex microgrid made up of five prosumers: PRSMR2.0 and PRSMR2.2 have assumed the role Distributor, while PRSMR2.1, PRSMR2.3 and PRSMR2.4 are operating in other roles. It is important to note how the PCC of one prosumer can be the PoLC of another. The prosumer PRSMR2.2 is also represented as a microgrid that consists of four prosumers: PRSMR2.2.0 in the role of Distributor and PRSMR2.2.1, PRSMR2.2.2, PRSMR2.2.3 in other roles. Prosumers PRSMR2.3 and PRSMR2.4 are configurations of microgrids, where PRSMR2.3.0 and PRSMR2.4.0 have assumed the role of Distributors and PRSMR2.3.1, PRSMR2.3.2, PRSMR2.4.1 and PRSMR2.4.2 various other roles. [98]

The fractal approach of describing microgrids has advantages over traditional topologies, since it reduces the number of objects required to describe a microgrid to just one, which enables one to apply an object-oriented approach for defining microgrids and EPSs in general. For the practical implementation of the proposed prosumer logical structure in mathematical simulations, a prosumer model object is composed. [98]

5.1.4 Design of prosumer model

Due to its widespread use and large user base, MatLAB Simulink was chosen for the modelling software. The aim of the modelling was to create a model object for the field, station and process zones of the prosumer technological system. The created model is to be used as a building block for EPS models.

The prosumer model is structured according to the prosumer logical structure described in section 5.1.1. The model is divided into the station, field and process zones (*Figure 5.5*). The station zone includes the operations gateway, which is used to handle communications with the operations zone, and the prosumer control unit (PCU), which is used for realizing station level control of prosumer devices.

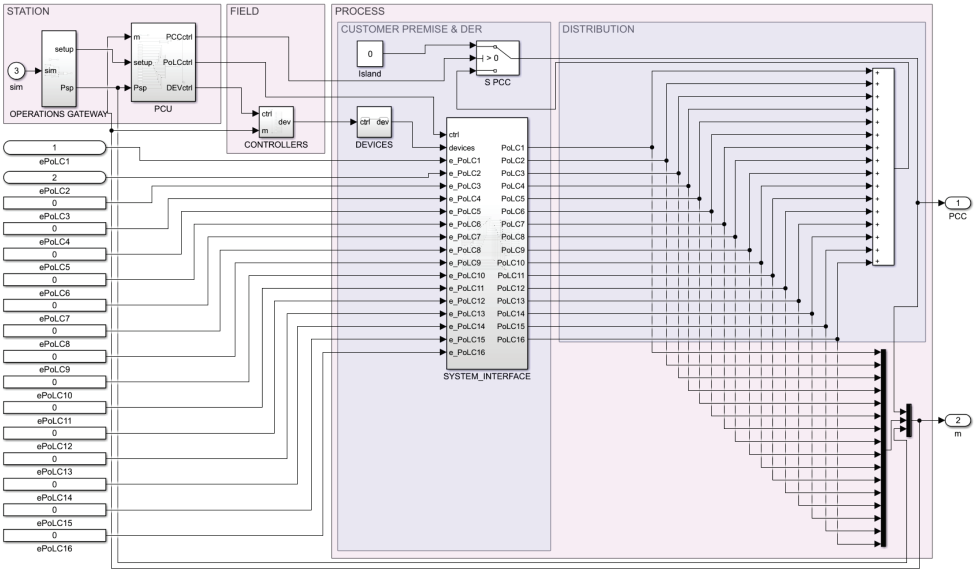


Figure 5.5 – Prosumer object modelled in MatLAB Simulink.

The field zone includes all field level controllers packaged inside one MatLAB Simulink block. The process zone is made up of all prosumer devices, the system interface used for handling PoLC-s and the distribution system.

Since the focal point of this thesis lies in the operations and enterprise level controls, the model is simplified and the detailed process, field and station level modelling are subject to future research. In the current model, active power flow is simulated as floating-point values, which are aggregated by summation. For the simulation of active power output of devices, a load or generation time series is inserted for each device. To simulate the stochastic nature of active power production and consumption, a noise component is added into the output of each device. An example of generated prosumer active power output for a simulation test case with predefined load and production time series is shown in *Figure 5.6*. The load curves and other prosumer parameters are inserted for all object instances via a MatLAB m-file. Once the prosumer model object is created, it will be used for creating a microgrid model, which is described in the next section.

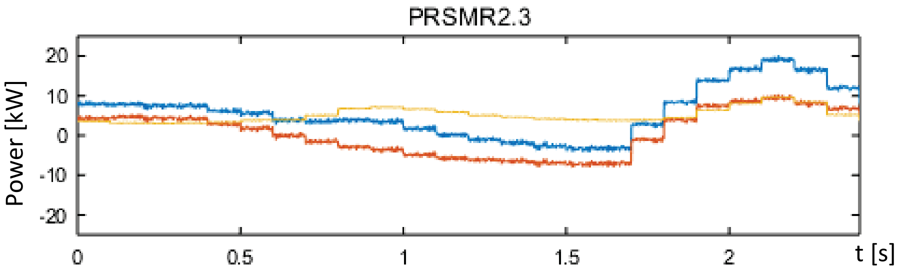


Figure 5.6 – Active power output example of the simplified prosumer model based on predefined load and production profiles.

5.1.5 Design of microgrid logical model

The microgrid fractal pattern in *Figure 5.4* is used as a basis for modelling a microgrid. The aim of the prosumer model object is to use several instances of the same prosumer object for describing EPSs. *Figure 5.7* shows the model of the microgrid fractal pattern described in *Figure 5.4*. For the modelling of the microgrid, only instances of the prosumer object are used.

With the modelling of prosumers and microgrids in place, the behaviour of agents needs to be simulated. For simulating agent behaviour and interaction, a separate auction simulator program is created.

5.1.6 Development of auction simulator program

Prosumer operation and enterprise level control is realized with a dedicated computer program. Programming of prosumer software agents is done using the Java programming language and utilizing the Java Agent Development Framework (JADE). One consideration in the design process of the software agent is the reuse of code for implementation in physical prosumers. For the simulation, a dedicated simulation communication agent was composed to handle communications between JADE agents and MatLAB Simulink.

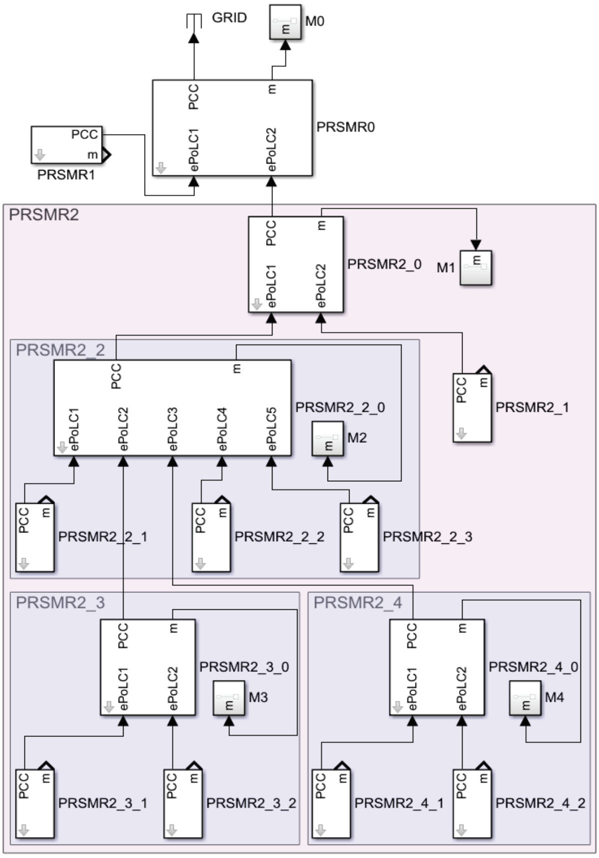
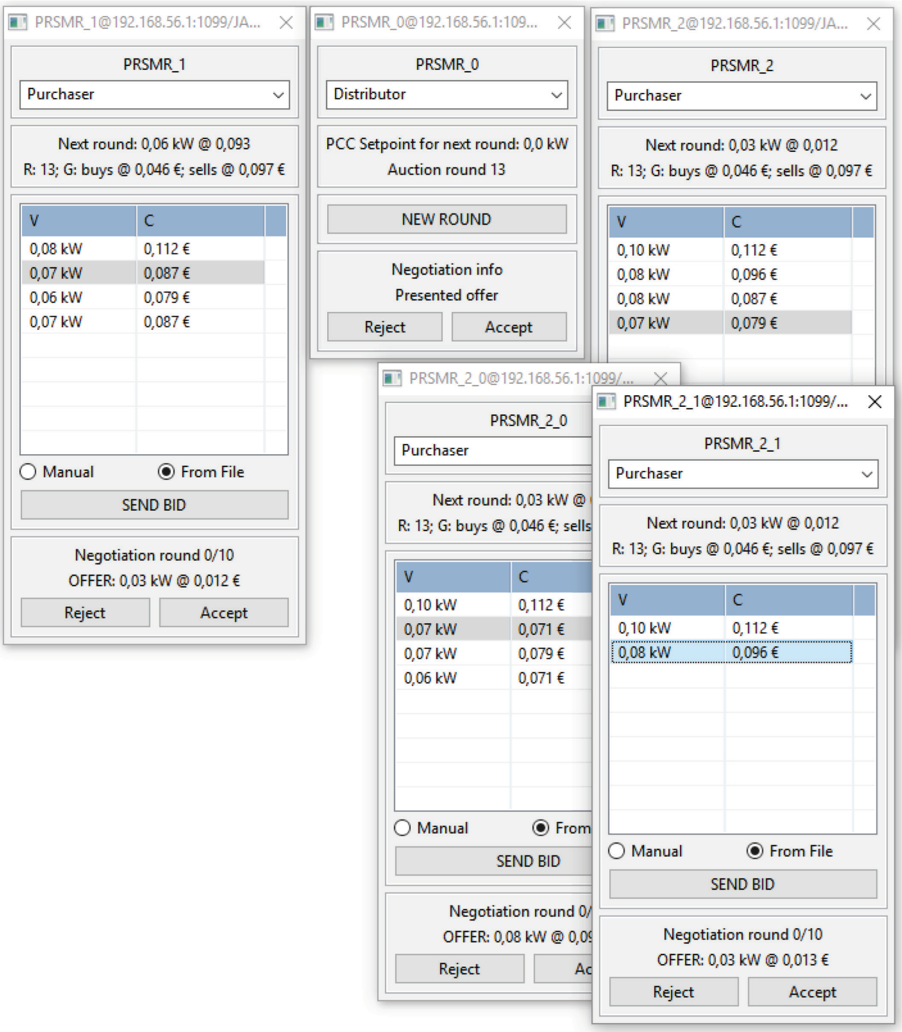


Figure 5.7 – Microgrid model composed of prosumer blocks [98].

A graphical user interface (GUI) is provided for each software agent (*Figure 5.8*). The GUI is used to communicate prosumer goals and parametrize the prosumer agent. During a simulation, the user can choose the role for each prosumer. Based on the role the prosumer has assumed, the user can initiate a new auction round or compose prosumer bids and carry out negotiations. For speeding up the simulations, an option is included to read bids for auction rounds from a predefined excel spreadsheet, which needs to be formatted according to a predefined template.

The use of intelligent software agents enables the implementation of complex machine learning and artificial intelligence (AI) algorithms. Since the focus of this thesis lies on the design of the auction algorithm, the design of algorithms for software agents is outside the scope of this research. The design of prosumer agent behaviour will be of elevated interest in future research. The current solution uses the combination of a user and the prosumer GUI to carry out computer simulations of the electricity auction. The next paragraph describes the simulations carried out to verify the concept of the developed electricity auction.



PRSMR_1

Purchaser

Next round: 0,06 kW @ 0,093
R: 13; G: buys @ 0,046 €; sells @ 0,097 €

V	C
0,08 kW	0,112 €
0,07 kW	0,087 €
0,06 kW	0,079 €
0,07 kW	0,087 €

○ Manual ● From File

Negotiation round 0/10
OFFER: 0,03 kW @ 0,012 €

PRSMR_0@192.168.56.1:109...

PRSMR_0

Distributor

PCC Setpoint for next round: 0,0 kW
Auction round 13

Negotiation info
Presented offer

PRSMR_2@192.168.56.1:1099/JA...

PRSMR_2

Purchaser

Next round: 0,03 kW @ 0,012
R: 13; G: buys @ 0,046 €; sells @ 0,097 €

V	C
0,10 kW	0,112 €
0,08 kW	0,096 €
0,08 kW	0,087 €
0,07 kW	0,079 €

PRSMR_2_0@192.168.56.1:1099/...

PRSMR_2_0

Purchaser

Next round: 0,03 kW @
R: 13; G: buys @ 0,046 €; sells

V	C
0,10 kW	0,112 €
0,07 kW	0,071 €
0,07 kW	0,079 €
0,06 kW	0,071 €

○ Manual ● From

SEND BID

Negotiation round 0/
OFFER: 0,08 kW @ 0,09

Reject Ac

PRSMR_2_1@192.168.56.1:1099/...

PRSMR_2_1

Purchaser

Next round: 0,03 kW @ 0,012
R: 13; G: buys @ 0,046 €; sells @ 0,097 €

V	C
0,10 kW	0,112 €
0,08 kW	0,096 €

○ Manual ● From File

SEND BID

Negotiation round 0/10
OFFER: 0,03 kW @ 0,013 €

Reject Accept

Figure 5.8 – Prosumer agent user interface.

5.2 Initial verification of developed auction algorithm

In order to decide whether to continue with the development of the current auction algorithm, it needs to be verified with a marginal cost of resources. To prove the viability of the concept of the designed auction method, an experimental microgrid setup was created. The experimental microgrid consists of eight prosumers and is meant to evaluate the simulator and auction logic and not to reproduce a certain real life scenario.

A graphical representation of the topology of the experimental microgrid is depicted in *Figure 5.9*. The load profiles used for composing prosumer outputs are BDEW standard load profiles obtained from [99]. The data used for characterizing wind generator output is collected from [100]. A random date of 14th of May 2014 was selected as the simulation period. In the following, the prosumers chosen for the experimental microgrid are described in brief.

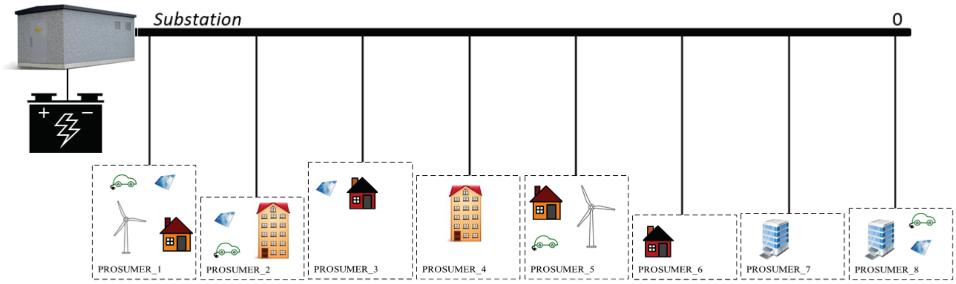


Figure 5.9 – General topology for fictional microgrid used in the simulation example.

5.2.1 Prosumer 1

Prosumer 1 is a residential household with solar panels and a small wind turbine. A smart vehicle to grid (V2G) enabled domestic charger to be installed at the residence; one of the tenants owns an electric vehicle that enables bidirectional power flow. Besides the electric vehicle, there are three load groups that can be shedded when deemed necessary. The owner of the prosumer is keen on using DER for power generation. While the power produced from DER is mostly consumed by local loads, there may be a need to sell excess energy to the grid during some periods.

The household load characteristic is composed of using the standard load profile H0, with the peak value of P_1_{H0} in kW. The solar panel production consists of using standard production profile SB0, with the maximum nominal output of P_1_{SB0} in kW. The maximum nominal output power of the wind turbine is P_1_{W0} in kW. There are restrictions on EV availability and the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.2 Prosumer 2

Prosumer number 2 is a residential household with solar panels. A smart V2G enabled domestic charger to be installed at the residence; one of the tenants owns an electric vehicle that enables bidirectional power flow. Besides the electric vehicle, there are two load groups that can be shedded when deemed necessary. The owner of the prosumer is keen on using DER for power generation. While the power produced from DER is mostly consumed by local loads, there may be a need to sell excess energy to the grid during some periods.

The household load characteristic is composed of using the standard load profile H0, with the peak value of P_2_{H0} in kW. The solar panel production consists of using standard production profile SB0, with the maximum nominal output of P_2_{SB0} in kW. There are restrictions on EV availability and the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.3 Prosumer 3

Prosumer number 3 is a residential household with solar panels. There are three load groups that can be shedded when deemed necessary. The owner of the prosumer is keen on using DER for power generation. While the power produced from DER is mostly consumed by local loads, there may be a need to sell excess energy to the grid during some periods.

The household load characteristic is composed of using the standard load profile H0, with the peak value of P_3_{H0} in kW. The solar panel production consists of using standard production profile SB0, with the maximum nominal output of P_3_{SB0} in kW. There are restrictions on the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.4 Prosumer 4

Prosumer number 4 is a residential household. There are three load groups that can be shedded when deemed necessary.

The household load characteristic is composed of using the standard load profile H0, with the peak value of P_4_{H0} in kW. There are restrictions on the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.5 Prosumer 5

Prosumer number 5 is a residential household with a small wind turbine. A smart V2G enabled domestic charger to be installed at the residence; one of the tenants owns an electric vehicle that enables bidirectional power flow. Besides the electric vehicle, there are three load groups that can be shedded when deemed necessary. The owner of the prosumer is keen on using DER for power generation. While the power produced from DER is mostly consumed by local loads, there may be need to sell excess energy to the grid during some periods.

The household load characteristic is composed of using the standard load profile H0, with the peak value of P_5_{H0} in kW. The maximum nominal output power of the wind turbine is P_5_{W0} in kW. There are restrictions on EV availability and the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.6 Prosumer 6

Prosumer number 6 is a residential household. The household load characteristic is composed of using the standard load profile H0, with the peak value of P_6_{H0} in kW.

5.2.7 Prosumer 7

Prosumer number 7 is a commercial building. There are two load groups that can be shedded when deemed necessary.

The load characteristic for the commercial building is composed of using the standard load profile G4, with the peak value of P_7_{G4} in kW. There are restrictions on the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.8 Prosumer 8

Prosumer number 8 is a commercial building with solar panels. The company has a fleet of three EVs, which are stationed on company premises after working hours. The EVs and their chargers enable V2G operation. Besides the EV fleet, there are two load groups that can be shedded when deemed necessary. The owner of the commercial building is keen on using DER for power generation. While the power produced from DER is mostly consumed by local loads, there may be a need to sell excess energy to the grid during some periods.

The load characteristic for the commercial building is composed of using the standard load profile G4, with the peak value of P_7_{G4} in kW. The solar panel production consists of using standard production profile SB0, with the maximum nominal output of P_7_{SB0} in kW. There are restrictions on EV availability and the flexibility of certain loads, but for simplification purposes, only some of them are taken into account.

5.2.9 Forecasting

An integral part of the connection with the PCC is to provide predictions to the operator of the larger grid about power consumption and production. The forecasted PCC output for each time step of the simulation period is denoted as $STAB\ PCC\ SP$. For simplification purposes, the PCC output forecast is composed manually, based on the experience of the user of the simulator program. For future applications, the PCC output forecast is composed on the basis of forecasts received from prosumers, received through web services or automatically generated using dedicated AI algorithms. The initial $STAB\ PCC\ SP$ values for the simulation period with a time-step of one hour are presented in *Figure 5.10*.

5.2.10 Simulation setup

Simulation cases described in this document were all carried out with operation round durations of one hour. The following parameters were manipulated for different simulation cases:

- ESS capacity and nominal power output,
- ESS depth of discharge (DOD),
- cost of ownership,
- cost margin,
- PCC setpoint forecast, and
- prosumer nominal values.

ESS capacity denotes the energy storage capacity of the ESS in *kWh*. ESS nominal output presents the nominal output power of the ESS in *kW* for charging and discharging. Maximum DOD indicates the lowest acceptable value in per-cent for the state of charge (SOC) of the ESS. The annual cost of ownership is an estimate of cost for the utilization of the Smart MV/LV. The prosumer cost margin is used to define the margin, which the Smart MV/LV adds to the prices it receives from the PCC for purchasing or selling electricity from the PCC. The prosumer cost margin can also be interpreted as markup of the Smart MV/LV or distribution fee of the Smart MV/LV.

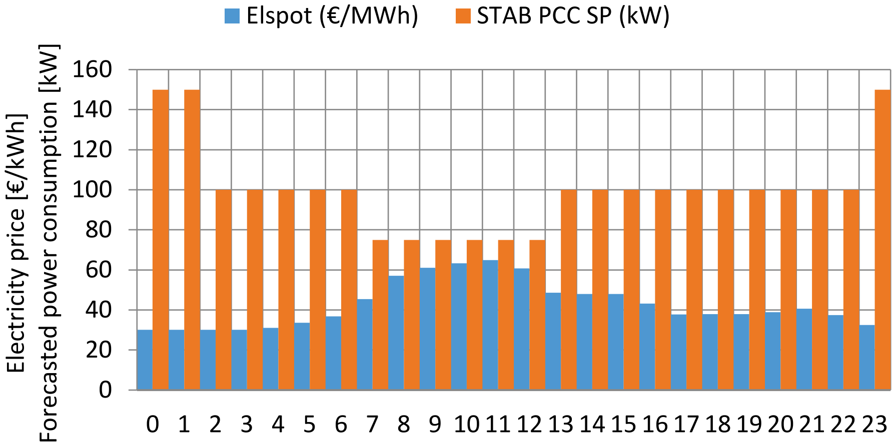


Figure 5.10 – Initial PCC output forecast and day ahead Nordpool Elspot prices for the simulation period.

5.2.10.1 Simulation Case 1

The parameters of the first simulation case are displayed in *Table 5.3* and *Table 5.4*. The aim of this simulation case is to evaluate whether such a microgrid setup is able to earn profit. In order to evaluate if a configuration is feasible or not, the most rewarding case was studied. In case the most rewarding simulation scenario fails to earn profit, the setup is non-feasible. The most profitable case is where all prosumers agree to operate with grid prices, hence all prosumers accept to operate with GC_pP and GC_sP prices. The initial SOC parameter describes the SOC of the ESS at the beginning of the simulation case. The final SOC parameter describes the target SOC of the ESS at the end of the simulation case.

Table 5.3 – PCC and ESS configuration values for simulation case 1.

Parameter	Value
BESU capacity [kWh]	450
ESS minimum and maximum output [kW]	-75; 75
Maximum DOD [%]	20
Initial SOC [%]	40
Final SOC target [%]	40
Annual cost of ownership [€]	15 000
Prosumer cost margin [%]	10

Table 5.4 – Prosumer specific values for simulation case 1.

	P_1	*P_2*	*P_3*	*P_4*	*P_5*	*P_6*	*P_7*	*P_8*
H0 [kW]	24	28	20	28	20	20	-	-
SB0 [kW]	10	6	10	-	-	-	-	10
W0 [kW]	10	-	-	-	8	-	-	-
G4 [kW]	-	-	-	-	-	-	45	24

The total revenue for the simulation period (1 day) was -15,62 €. The amount of electricity purchased from the PCC was 2,4 MWh. Clearly, such a setup is not feasible.

For a better understanding of the impact the simulation parameters have on simulation results, the effect of prosumer cost margin on the generated revenue was studied. Simulations were carried out with parameter values presented in *Table 5.5* but with prosumer cost margin values of 0 %, 5 %, 30 %, 40 %, 50 % and 70 %. The simulation results are presented in *Table 5.5* and *Figure 5.11*. The simulation results display an increase of 0,025 ¢ in revenue for one *kWh* for a 1 % increase of the prosumer cost margin. Reformulating, the revenue for the simulation period can be increased by increasing the prosumer cost margin or increasing prosumer output volumes.

Table 5.5 – Total daily revenue for different prosumer cost margin values.

Prosumer cost margin [%]	0	5	10	20	30	40	50	70
Total daily revenue [€]	-22,2	-18,8	-15,6	-8,9	-1,9	4,5	11,4	25,5
Total energy traded [*kWh*]	2692	2692	2687	2685	2690	2680	2680	2691

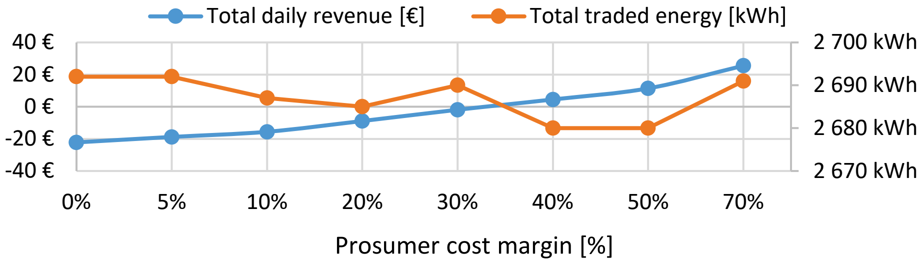


Figure 5.11 – Dependency of the generated daily revenue on the prosumer cost margin and total traded electricity.

5.2.10.2 Simulation case 2

Another way to increase revenue is to decrease operation costs. In the first simulation case, the operation costs are set to 15 000 €. This simulation case decreases the operation costs to 5000 € (which is roughly the cost of a 450 *kWh* battery pack purchased at 90 €/*kWh* and has a useful life span of 8 years) and uses a prosumer cost margin of 20 %. The detailed input parameters to the third simulation case are displayed in *Table 5.4* and *Table 5.6*. Simulation case 2 generated a total daily revenue of 18,5 €, by trading 2685 *kWh*.

Table 5.6 – PCC and ESS configuration values for simulation case 2.

Parameter	Value
BESU capacity [kWh]	450
ESS minimum and maximum output [kW]	-75; 75
Maximum DOD [%]	20
Initial SOC [%]	40
Final SOC target [%]	40
Annual cost of ownership [€]	5 000
Prosumer cost margin [%]	20

5.2.10.3 Simulation case 3

One way to increase the generated revenue is to increase the amount of traded electricity. The input parameters for the third simulation case are presented in *Table 5.7* and *Table 5.8*. A new PCC setpoint forecast was created along with Nordpool Elspot prices for the simulation period depicted in *Figure 5.12*.

Table 5.7 – PCC and ESS configuration values for simulation case 3.

Parameter	Value
BESU capacity [kWh]	450
ESS minimum and maximum output [kW]	-75; 75
Maximum DOD [%]	30
Initial SOC [%]	40
Final SOC target [%]	40
Annual cost of ownership [€]	5 000
Prosumer cost margin [%]	20

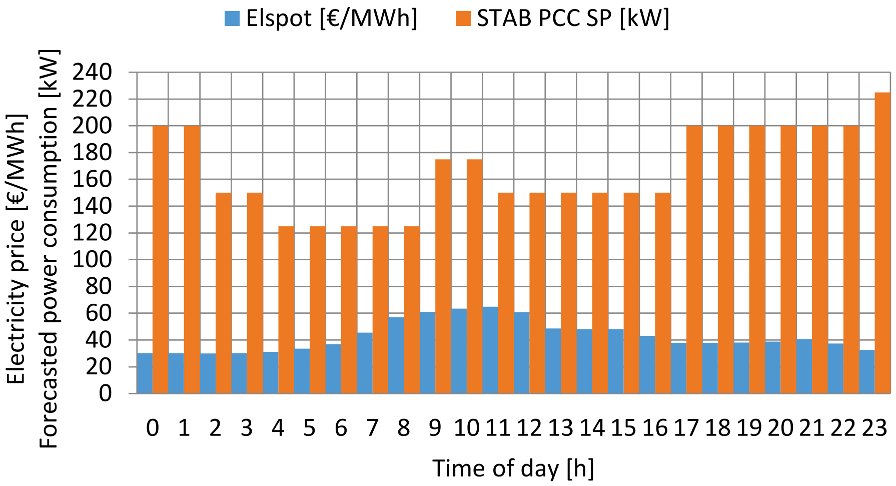


Figure 5.12 – PCC output forecast and day ahead Nordpool Elspot prices for the simulation period.

The simulation generated a total daily revenue of -8,30 €, by trading a total of 4134 *kWh*. The results show that for a 54 % increase in traded electricity, the increase of revenue was just 0,6 €. To investigate this, an alternative simulation with an alternative PCC output forecast was executed. The alternative forecasts of PCC output and Nordpool Elspot prices are depicted in *Figure 5.13*. The simulation with the alternative PCC output forecast generated a total daily revenue of -3,51 €, by trading a total of 4084 *kWh*. The simulation case with the alternative PCC forecast was able to generate 4,79 € higher revenue by trading 50 *kWh* less energy.

This simulation displays the relevance of PCC output forecasting. Forecasting has a higher role in increasing revenue than the plain increase of energy throughput, which in turn sets high demands on prosumers to provide accurate forecasts of their outputs and accurate forecasting algorithms.

Table 5.8 – Prosumer specific values for simulation case 3.

	P_1	*P_2*	*P_3*	*P_4*	*P_5*	*P_6*	*P_7*	*P_8*
H0 [kW]	36	42	30	42	30	30	-	-
SB0 [kW]	15	9	15	-	-	-	-	15
W0 [kW]	15	-	-	-	12	-	-	-
G4 [kW]	-	-	-	-	-	-	68	36

5.2.10.4 Simulation case 4

In this simulation case, prosumers are also able to reject offers and thus negotiate prices. The simulation case uses input parameters shown in *Table 5.4* and *Table 5.9* and the forecasted PCC output presented in *Figure 5.13*. Simulations were carried out with three different prosumer cost margins: 30 %, 20 % and 10 %.

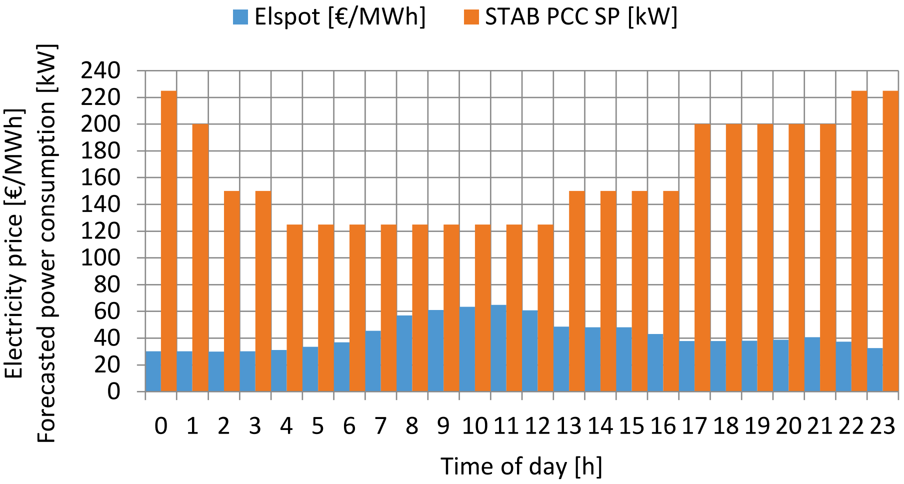


Figure 5.13 – PCC output forecast and day ahead Nordpool Elspot prices for the simulation period.

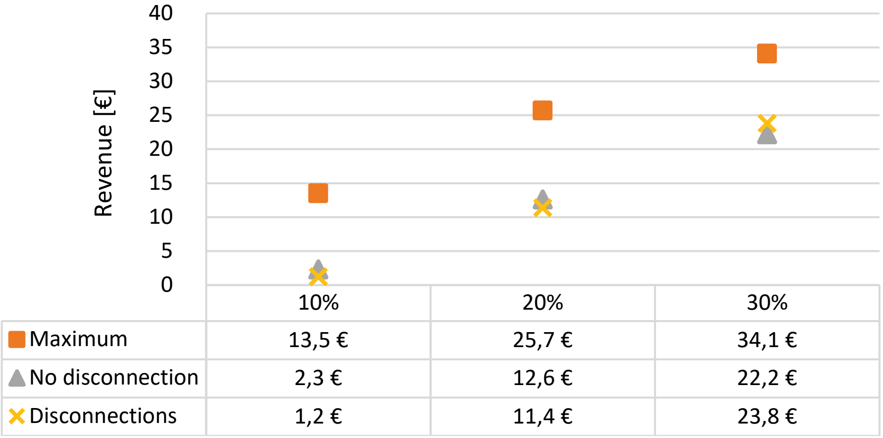
First, the theoretical maximum revenue was found for all simulation setups, using the method described in section 5.2.10.1. Next, two simulations were carried out with different behaviours: the first assumes the prosumer agents will eventually accept offers with grid prices to avoid disconnection; the second simulation strictly follows the predefined maximum limits defined by prosumer agents, disregarding the threat of being disconnected. To reward prosumers in a controllable fashion, the minimum accepted revenue parameter was introduced. For each simulation period, a value for the minimum accepted revenue was generated. If the minimum accepted revenue for a period is not reached, it will accumulate in the next periods. For all simulation setups, the target is to break even, so the total minimum accepted revenue is 0 €. The results for the different setups of simulation case 4 are presented in *Table 5.10* and *Figure 5.14*.

Table 5.9 – PCC and ESS configuration values for simulation case 4.

Parameter	Value
BESU capacity [kWh]	450
ESS minimum and maximum output [kW]	-75; 75
Maximum DOD [%]	20
Initial SOC [%]	40
Final SOC target [%]	40
Annual cost of ownership [€]	5 000

Table 5.10 – Generated revenues for different simulation setups of simulation case 4.

Prosumer cost margin [%]	30	20	10
Maximum total daily revenue [€]	34,1	25,7	13,5
Total daily revenue (prosumers not disconnecting) [€]	22,2	12,6	2,3
Total daily revenue (prosumers disconnecting) [€]	23,8	11,4	1,2



	10%	20%	30%
■ Maximum	13,5 €	25,7 €	34,1 €
▲ No disconnection	2,3 €	12,6 €	22,2 €
✕ Disconnections	1,2 €	11,4 €	23,8 €

Figure 5.14 – Dependency of generated daily revenue on the prosumer cost margin.

5.2.11 Simulation results

Simulation results show how different prosumer agent behaviours can affect the total generated revenue. The importance of PCC setpoint forecasting is demonstrated through the simulations carried out. Simulation case 4 shows that the created electricity auction method can generate revenue for the owner of the Smart MV/LV while allowing prosumers to negotiate prices. These results are used as an indication that the composed electricity auction is viable and should be developed further.

Based on the simulation results, it can be recognized that the generated profit depends on a number of variables, some of which are case specific, while others can be dynamically modified in the smart substation. For maximizing economic returns, the following recommendations are given:

- The higher the capacity of the ESS, the higher the generated revenue, but also the cost for initial installation. Optimal sizing of the ESS capacity and the nominal power needs a case specific approach. Methods for optimal sizing of the ESS are in the scope of future research.
- Maximizing prosumer cost margins generates higher revenues, but presumably discourages prosumers in participating in the auction. The margin needs to be dynamic, taking into account the reactive behaviour of participating agents. Further research is needed to determine best strategies for maximizing prosumer cost margins, which will be addressed in future studies.
- Decreasing installation and operation costs has immediate effect on generated revenue.
- Accurate prosumer forecasts enable one to provide a more accurate PCC output forecasting, thus it is recommended to use measures to motivate prosumers for providing accurate consumption and production forecasts.
- An increased number of participating prosumers provides a larger variation of bids, which provides for combining a more rewarding result.
- The larger the quantities of traded energy, the larger the generated profits, thus maximizing the total usage rate of the substation helps to increase generated revenue.

- Combining prosumers with dissimilar consumption and production patterns provides greater opportunities to avoid peaks in consumption and production, which enables avoiding penalties and maximizing the usage rate of the substation.

The next step in developing the electricity auction algorithm is to verify it experimentally, which requires dedicated testing equipment. The development of an experimental ESS is described in the next section.

5.3 Development of experimental energy storage system and microgrid

Tallinn University of Technology and the Estonian private company Harju Elekter Elektrotehnika AS carried out a research and development (R&D) project Lep14101, titeled “Energy storage system.” The aim of the project was to research and develop a low-voltage energy storage system and technical documentation for electric substations. The following section provides an overview of the ESS developed as a result of the R&D project Lep14101.

5.3.1 Development of experimental ESS

The ESS is meant for use in low-voltage distribution substations, thus the required power connection is three-phase ac. The ESS consists of three main components: a battery pack with a battery management system (BMS), a bidirectional 3-phase ac to dc converter with reactive energy compensation and advanced filtering options, and an industrial grade programmable logic controller (PLC) with IEC61850 and IEC60870 communication capability. The general topology of the developed ESS is depicted in *Figure 5.15*.

The battery pack of the experimental ESS consists of 216 consecutively connected WB-LYP40AHA [101] Li-Ion batteries, which limits the theoretical operating range from 604,8 VDC to 864 VDC. In practice, the operation range is narrower than the theoretical operating range due to inconsistencies in battery chemistry. The battery pack is designed for experimental purposes and elements with a capacity of 40 Ah are used. The batteries are managed by two separate BMSs. In the designed ESS, Orion BMS [102] devices are used (a 144 cell and a 72 cell device).

The energy flow is managed using a bidirectional ac/dc converter NXA02615G0T02SGA1A2D700CI+MASG [103] from Vacon. It comprises an active front end converter to control the dc output voltage, an integrated LCL filter, sophisticated control functions for ac active and reactive current control etc.

The ESS is controlled by the Brodersen RTU32 PLC [104]. A PLC with a 32-bit 500 MHz real time operating system, it supports all utility protocols and several other standardized communication protocols like IEC61850, DNP3, IEC60870, DNP3 WITS, Modbus, Profibus, Profinet, DF1, DLMS etc. The RTU32 PLC is responsible for field level control of the ESS. For user interaction, the RTU32 PLC is connected to a graphical operator panel Siemens TP700 Comfort. The main technical characteristics for the ESS are presented in Table 5.11.

In the scope of the R&D project LP14101, the ESS was designed, built and programmed. For demonstrating the operation of the ESS, an experimental microgrid was designed and constructed. The following chapter provides more insight into the details of the experimental microgrid. The constructed ESS and the experimental microgrid are displayed in *Figure 5.16*.

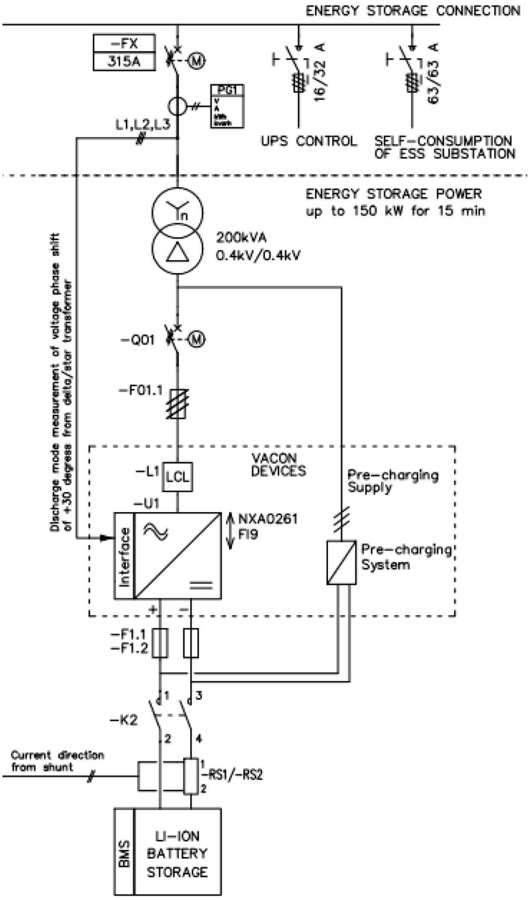


Figure 5.15 – Experimental ESS single line diagram [105].

Table 5.11 – Main technical characteristics of the developed experimental ESS.

Nominal power [kW]	150
Ac voltage [V]	400
Ac maximum current [A]	217
Galvanic isolation	200 kVA transformer
Installed battery storage capacity [kWh]	60
Guaranteed charge-discharge cycles (DOD = 100%)	500
Guaranteed charge-discharge cycles (DOD = 50 %)	2000
Battery modules in series	216
Battery module voltage [V]	2,8 … 3,7
Battery module capacity [Ah]	90
Battery pack nominal current [A]	232
Bidirectional ac/dc converter maximum dc voltage [V]	797
Bidirectional ac/dc converter nominal dc current [A]	308
Bidirectional ac/dc converter nominal dc power [kW]	176
Bidirectional ac/dc converter nominal ac current [A]	261

Figure 5.16 – Experimental ESS built in cooperation with the Department of Electrical Engineering of Tallinn University of Technology and Harju Elekter Elektrotehnika AS.

5.3.2 Construction of experimental microgrid

In the development process of the experimental microgrid, protection and control functions of the low voltage part of a distribution substation were designed and simulated. A detailed overview of the design and simulation results of the protection and control functions of the low voltage part of a distribution substation is published in [106].

In addition, practical issues regarding bidirectional energy exchange were studied during the development process of the experimental microgrid. A novel testing method for substations was created, which includes computer simulations and practical verification for automated exchange of electricity. The concept of designing and realizing a testing method for low-voltage distribution substations that form a microgrid with prosumers, is reported in [65].

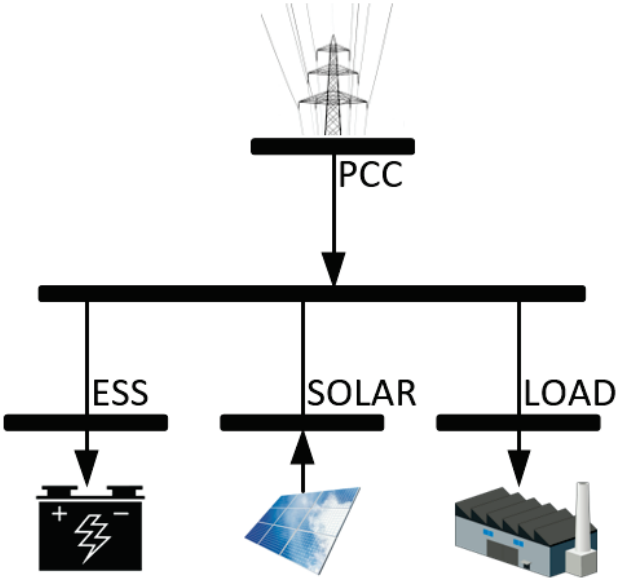


Figure 5.17 – Generalized topology of the experimental microgrid.

The experimental microgrid built for demonstrating the experimental ESS is a microgrid with a common ac bus that includes four main participants: the ESS, the PCC, a photovoltaic (PV) panel with an inverter (SOLAR) and an electric load (LOAD). The generalized topology of the experimental microgrid is depicted in *Figure 5.17* and a more detailed single line diagram in *Figure 5.18*.

The PCC is the connection to the grid. The grid is the low voltage distribution grid of the campus of Tallinn University of Technology.

The SOLAR participant of the microgrid is a programmable dc power supply connected to a three-phase ac/dc converter. The programmable power supply enables one to emulate solar power production and the ac/dc converter is used for the connection to the common ac bus. The programmable dc power supply is controlled by the control unit of the ESS (the microgrid control system is realized in the RTU32 PLC of the ESS).

The LOAD participant of the microgrid is a ventilation blower and an electric heater. Both electrical loads are controlled using two-point control, providing three load levels (off, half and full load). The loads are switched using the control unit of the ESS.

5.3.3 Demonstration of experimental ESS and microgrid

The experimental microgrid was used to demonstrate the operation of the ESS. The aim of the experiment was to demonstrate three cases of use: load shedding, storing of electricity and electricity management. For each use case, the microgrid participants are switched into different states, which emulate real-life situations in a microgrid with prosumers. For the visibility of the processes, the duration of each situation selected was one minute. The demonstration test case is described by 21 steps and by SOLAR, LOAD and PCC setpoints (SP) for each step. The ESS production or consumption is regulated to match the PCC output with the PCC setpoint. The setpoints for each test case step are presented in *Table 5.12*. The experiment results are depicted in *Figure 5.19* as time series.

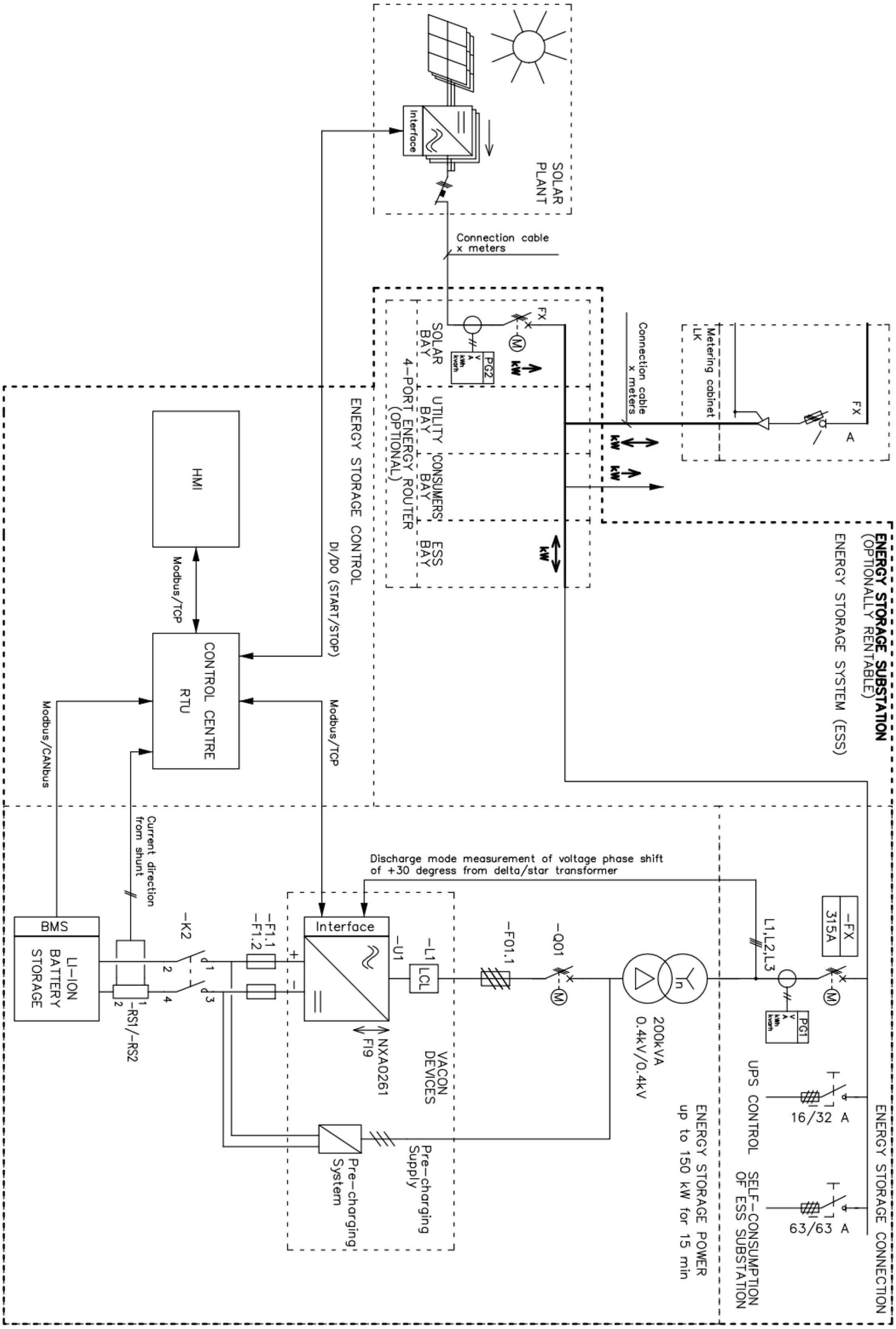


Figure 5.18 – Single line diagram of the experimental microgrid.

Table 5.12 – Setpoints for microgrid demonstration test case.

Step	USE CASE	SOLAR SP [kW]	LOAD SP [kW]	PCC SP [kW]
0	LOAD SHEDDING	0,0	0,0	0,0
1	LOAD SHEDDING	0,0	0,0	8,0
2	LOAD SHEDDING	0,0	2,1	3,0
3	LOAD SHEDDING	0,0	4,0	3,0
4	LOAD SHEDDING	0,0	4,0	4,0
5	EL. STORAGE	0,0	2,1	2,1
6	EL. STORAGE	-1,0	2,1	1,2
7	EL. STORAGE	-3,5	4,0	1,2
8	EL. STORAGE	-6,0	4,0	0,0
9	EL. STORAGE	-1,0	2,1	1,1
10	EL. STORAGE	0,0	4,0	-3,0
11	EL. MANAGEMENT	0,0	2,1	2,1
12	EL. MANAGEMENT	-1,9	4,0	2,1
13	EL. MANAGEMENT	-6,0	4,0	2,1
14	EL. MANAGEMENT	-1,0	4,0	2,1
15	EL. MANAGEMENT	0,0	4,0	2,1
16	EL. MANAGEMENT	0,0	2,1	-5,0
17	EL. MANAGEMENT	0,0	0,0	-5,0
18	EL. MANAGEMENT	-3,5	0,0	-5,0
19	EL. MANAGEMENT	-5,0	0,0	-5,0
20	ESS CHARGING	0,0	0,0	8,0

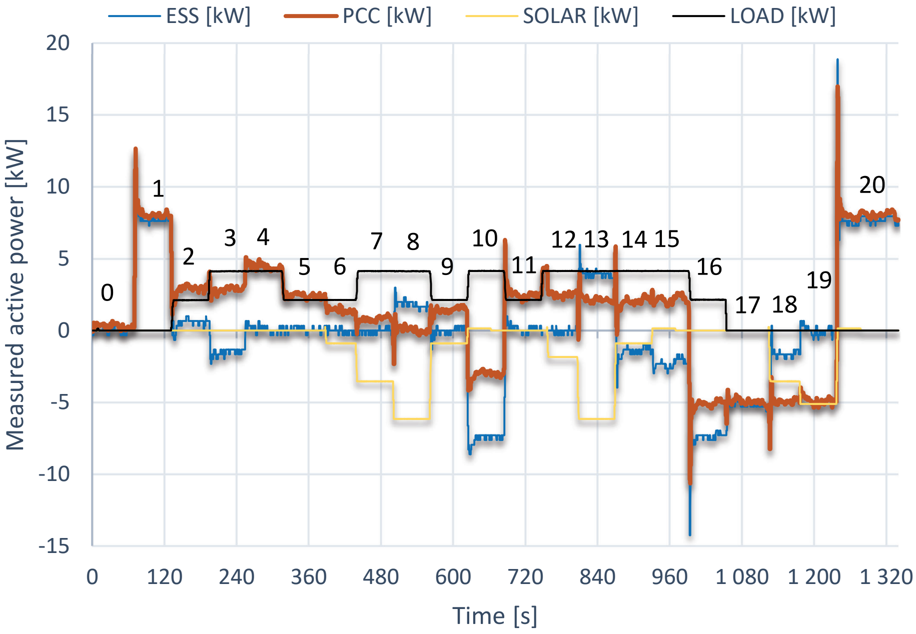


Figure 5.19 – Measured active power of the experimental microgrid for the test case.

Based on the measurement results of the experiment, several conclusions were drawn. First, it is concluded that a microgrid with an integrated ESS is adequately able to provide the functionality of load shedding, electricity storage and electricity management to the PCC. It can be identified from *Figure 5.19* that during test case steps 11 to 15 and 16 to 19, the measured PCC output values are close to the PCC SP.

Second, the regulator controlling the ESS output requires tuning to provide a better dynamic response to changes in the measured values. Substantial overshoot for larger changes in the regulator setpoint can be seen in *Figure 5.19*. The manual or automatic tuning of the regulator of the ESS is a subject of future research.

The third conclusion drawn from the experiment is that the used bidirectional three-phase ac/dc converter is over-dimensioned for the current application. The nominal power of the converter is 150 kW, but the maximum load of the microgrid is 4,1 kW. A higher output power means lower regulation accuracy. For the experimental microgrid, an ac/dc converter with nominal active power output of 20 kW should be used or the consumption and production capacity of the loads and generators up-scaled.

The conducted experiments proved the viability of the design of the ESS and pointed out shortcomings in the experimental microgrid. For better operation, it is required to review ESS, SOLAR and LOAD sizing. In addition, the regulator controlling the ESS needs to be tuned, which is outside the scope of this research. In the following, further enhancements needed for the experimental microgrid are described in detail.

5.3.4 Future advancement of the experimental microgrid

In subsequent R&D projects, the following aspects need to be considered:

- Replacement of existing microgrid participants with loads and generation units with higher nominal active power consumption and output;
- Expansion of the microgrid with the addition of new participants;
- Design and implementation of autonomous agents for microgrid participants with the aim of conducting experiments with agent interaction and local electricity auctions.

At the point of publication of this thesis, there are no ongoing R&D projects regarding the advancement of the experimental microgrid.

5.4 Conclusions

Chapter 5 described the proofing of the developed electricity auction concept. Before the initial verification through computer simulations, the microgrid and the prosumer objects were modelled.

For describing prosumers, a novel universal prosumer structure was developed. The developed prosumer logical structure concentrates on more common prosumer definitions and their constraints and enables universal use for describing electric prosumers. Based on the developed prosumer structure, a model object for the field, station and process zones of the prosumer technological system were created. Using only elements of the prosumer object type, a microgrid logical model was created. The microgrid model was linked with a computer program, built for realizing the operation and enterprise level control prosumer in the prosumer technological system. The auction simulator program combined with the microgrid model enabled simulations for interactions between microgrid prosumers.

An experimental fictional microgrid was created for simulating prosumer interactions inside a microgrid. Various simulation cases were conducted and analysed. The results of the simulations showed that the developed electricity auction is capable of earning profit. It was identified that the generated profit depends on a number of variables, some of which are case specific, while others are dynamically modifiable in the Smart MV/LV. The results indicate that the composed electricity auction is viable and should be developed further.

After the concept of the electricity auction has proved to be viable, the next step is to back up simulation results with experimental results. For these purposes, an experimental ESS and microgrid were developed in cooperation with Estonian private company Harju Elekter Eletrotehnika AS. Initial experiments with the ESS and experimental microgrid have been conducted, which demonstrate the applicability of the designed concept. Further enhancements to the ESS and experimental microgrid are due, in order to use them for experimental verification of the electricity auction.

6 Conclusions and future work

This doctoral thesis provides a novel energy management method for electrical microgrids formed by prosumers connecting to a Smart MV/LV with an integrated ESS. The developed method enables managing power production and consumption targets for prosumers, which connect to the Smart MV/LV and form a microgrid. The developed method uses an administered auction mechanism for energy distribution between microgrid prosumers and energy balance management for the PCC. By creating a local market for the microgrid, the auction method enables prosumers to implement price-based control of their assets. Microgrid connected prosumers also gain access to innovative grid services by using the power of aggregation and communication. Furthermore, the developed electricity auction leaves room for improvements and development, making it a valuable and practical method to be used in future-proof microgrid applications.

The developed electricity auction is a modification of a multi-unit administered continuous double-auction, which is managed by the auctioneer agent inside the Smart MV/LV. Prosumers interact using a subscribed communication method and present multiple bids for each auction round. The auctioneer agent chooses one bid for each prosumer and creates an offer for each prosumer, which will be subject to negotiations. The auction round is executed until all bids and asks of all agents have been served. During the development of the electricity auction, a combinatory search problem for finding the optimal combination of bids from bid sets is identified.

Research of existing search methods indicates a need for a customized search algorithm. Based on the conducted research and experiments, a novel hybrid two-step search algorithm was composed. The thesis describes and analyses four different variations of the hybrid two-step search algorithm. All four algorithm variations were analysed by using a developed quantitative method. The analysis of the developed search algorithms led to the following conclusions:

- It enables determining if a solution is the global optimum that requires calculation of the utility function of all eligible solutions, which has unreasonably high time complexity for modern computer based solution, i.e. it cannot be confirmed if the result returned by the search algorithm is the global optimum (the optimality criterion of the search algorithm cannot be verified).
- The performance of the search algorithm can be assessed by comparing it with an estimated value of the global optimum.
- The combined hybrid two-step search algorithm provides good practical applicability due to its relatively high efficiency (an average revenue of 89,7 % compared to the estimated highest total revenue), acceptable time complexity (2,1 s for the formulated search problem) and completeness (the algorithm is guaranteed to provide a solution whenever there exists one).

The electricity auction concept was proved. Before the initial verification of the developed auction algorithm, the microgrid and prosumer objects were modelled. A novel prosumer structure was developed by concentrating on more common prosumer definitions and their constraints. Based on the developed prosumer structure, a model object for the field, station and process zones of the prosumer technological system was created. Using only elements of the prosumer object type, a microgrid logical model was created. The microgrid model was linked with a computer program used for simulating interactions between microgrid prosumers. A microgrid setup was created for the simulations. It can be concluded from the simulation results that the generated profit depends on a number of variables, some of which are case specific, while others can be dynamically modified in the smart substation. The results of the simulations demonstrate that the developed electricity auction is capable of earning profit.

For further evaluation of the developed electricity auction, an experimental ESS and microgrid were developed in cooperation with Estonian private company Harju Elekter Eletrotehnika AS. Initial experiments with the ESS and experimental microgrid showed the applicability of the designed concept. Further enhancements to the ESS and experimental microgrid are due, in order to use them for experimental verification of the electricity auction.

6.1 Future research

Future challenges lie in the advanced development of the electricity auction algorithm. Due to the reactive nature of the problem, it is required to conduct substantial research on real-world objects and in real-life situations. The author has identified the following directions for further research and development of this topic:

- Replacement of experimental microgrid participants with loads and generation units with higher nominal active power consumption and output;
- Expansion of the microgrid with the addition of new participants;
- Research on the cost of ownership of Smart MV/LVs;
- Research and development of autonomous agent controllers for microgrid prosumers;
- Development of an optimal ESS sizing and regulator tuning method for smart substations;
- Research and development of prosumer cost margin optimization algorithms; further development of the electricity auction algorithm by defining other components of the utility calculation function (8) and complementing auction exception rules;
- Research and development of additional metaheuristic search algorithms;
- Development of prosumer object field and station level models;
- Research and development of prosumer and microgrid forecasting methods.

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Acknowledgements

Primarily I would like to thank my family for their support and patience. I thank Birgit for believing in me – this thesis would not have been possible without backing from you. I thank my children, Emili Loviise, Loore and Kasper, for providing me motivation and inspiration – I hope this work will contribute to building a better, sustainable world for you. I thank my mother Tiiu for raising me as a personality I am today and I thank my brother Karpo for his guidance and support throughout my life. I thank the rest of my family and friends for their support and being there for me.

I would like to thank my supervisors for their guidance and counselling. I would like to thank Associate Professor Emeritus Elmo Pettai for encouraging me to take up doctoral studies. My thanks go to Professor Argo Rosin for guiding and mentoring me – this work would not have been completed without the counsel I got from you.

I would like to thank my colleagues in Tallinn University of Technology for fruitful discussions and meaningful conversations.

This research work has been supported by European Social Fund (project ”Doctoral School of Energy and Geotechnology II“), Estonian Ministry of Education and Research (project SF0140016s11), Estonian Science Foundation (Grant ETF9350), Estonian Archimedes Foundation (project AR10126 and program for doctoral studies and internationalisation “DoRa”), SmartGrids Era-Net (project GERA1), Estonian Research Council grant PUT (PUT1680), Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts ZEBE (grant 2014-2020.4.01.15-0016) and European Regional Fund.

Abstract

Research and Development of Electricity Auction for Microgrids

Global leaders have identified the need for improvement of resilience to climate change and the reduction of greenhouse gas emissions. A microgrid, which utilizes different renewable energy sources together with electricity storage, helps to maximize the use of clean energy. Microgrids serve as aggregators and gateways, which are able to simplify the connection of distributed energy resources (DER) to the existing bulk electricity grid. The concept of a smart low voltage distribution substation (Smart MV/LV) capable of forming microgrids has been developed. To be successful, the Smart MV/LV needs an effective way to manage prosumers while providing increased possibilities and benefits over the conventional electricity grid. The main objective of this thesis is to provide a method for a Smart MV/LV with an integrated energy storage system (ESS) to manage power production and consumption targets for prosumers, which connect to the Smart MV/LV and form a microgrid.

Prosumer definitions and their use in electricity markets were analysed. The participation of electricity prosumers in electricity markets often includes the grouping of prosumers. Various prosumer grouping methods were described and the general concept and definition of microgrids were studied. Several generalizations from different microgrid definitions were drawn and listed. Different microgrid control strategies were introduced and a brief overview of multi agent systems is presented. The state of the art of current Smart MV/LV technology studied by investigating commercially available systems shows that they are designed to uniformly manage all connected assets. State of the art distribution substations do not address the management of bidirectional energy exchange between prosumers.

Research and analysis of literature suggest that a novel electricity auction to provide the required functionality is necessary. An electricity auction was developed, which is a modification of a multi-unit administered continuous double-auction. Prosumers interact using a subscribed communication method that provides better manageability of the microgrid. Instead of presenting a single bid, auction participants gain flexibility by presenting a set of bids. The auctioneer agent collects all bid sets, chooses the optimal bids, composes offers and sends offers to participants. Upon receiving an offer, participants either accept the offer or reject it. During the development of the electricity auction, a combinatory search problem for finding the optimal combination of bids from bid sets was identified and analysed.

Research of existing search methods suggests that more common search algorithms are not applicable for solving the identified search problem. During the development of a novel search algorithm, four hybrid search algorithms were created and analysed. The greedy two-step search algorithm aims to select potentially more rewarding bids in the first phase of the search. The volume difference-based two-step search algorithm executes the first phase of the search to select the most rewarding bids from the bid sets with low absolute volume difference. The reputation based two-step search algorithm executes the first phase of the search by selecting most rewarding bids from prosumers with higher reputation. The combined two-step search algorithm combines the greedy two-step search algorithm and the volume difference based two-step search algorithm in order to combine their benefits and compensate losses in exchange for higher time complexity. Comparative evaluation results of the developed search methods are

presented. This thesis recommends the use of the combined two-step search algorithm whenever possible due to its high efficiency.

For describing prosumers, a novel universal prosumer structure was developed. The developed prosumer logic is to be used universally for describing electric prosumers. Based on the developed prosumer structure, a model object for the field, station and process zones of the prosumer technological system was created. Using only elements of the prosumer object type, a microgrid logical model was created. The microgrid model was linked with a computer program, built for realizing operation and enterprise level control prosumer in the prosumer technological system. The auction simulator program combined with the microgrid model enabled simulations for interactions between microgrid prosumers.

An experimental fictional microgrid was created for simulating prosumer interactions inside a microgrid. Various simulation cases were conducted and analysed. The results of the simulations demonstrated that the developed electricity auction is capable of earning profit. It was identified that the generated profit depends on a number of variables, some of which are case specific, while others are dynamically modifiable in the Smart MV/LV. The results indicate that the composed electricity auction is viable and should be developed further.

For further evaluation of the developed electricity auction, an experimental ESS and a microgrid were developed in cooperation with Estonian private company Harju Elekter Eletrotehnika AS. Initial experiments with the ESS and the experimental microgrid showed the applicability of the designed concept. Further enhancements to the ESS and experimental microgrid are due, in order to use them for experimental verification of the electricity auction.

Lühikokkuvõte
Mikrovõrkude elektrioksjoni uurimine ja väljatöötamine

Maailma riikide poliitiline juhtkond on tuvastanud vajaduse kliimamõjude ohjamise ning kasvuhoonegaaside emissioonide vähendamise järgi. Elektriline mikrovõrk, mis kasutab erinevaid taastuvenergia allikaid ning energiasalvesteid, võimaldab suurendada puhta energia kasutamist. Mikrovõrgud toimivad kui tarbijate ja tootjate koondajad ning lüüsid, mille kaudu on võimalik lihtsustada taastuvenergial töötavate elektritootmisseadmete liitumist elektrivõrguga. Ettevõtte Harju Elekter Elektrotehnika AS ning Tallinna Tehnikaülikooli Elektroenergeetika ja mehhatroonika instituudi koostöös on arendatud nutika alajaama kontseptsioon, mis võimaldab alajaamal temaga ühendatud prosumerite vahel moodustada elektrilise mikrovõrgu. Nutikate alajaamaade edu tagamiseks on tarvis uudset moodust prosumerite haldamiseks, mis tagaks prosumeritele laiemad võimalused ning eeliseid kui iseseisvalt elektrijaotusvõrguga ühendumisel. Kuna prosumerite vaheline elektrienergia vahetus saab võimalikuks läbi nutikate alajaamade, käsitleb antud töö alajaama omanike huvide teenimist. Käesoleva töö peamiseks eesmärgiks on arendada välja meetod prosumerite tootmise ja tarbimise haldamiseks, mida on võimalik kasutada nutika integreeritud energiasalvestiga alajaama koosseisus ning mis muudaks alajaama rajamise atraktiivseks erinevatele huvigruppidele.

Antud töö uurib erinevaid prosumeri definitsioone ning nende tegutsemist elektriturgudel. Kuna prosumerite osalemine elektriturgudel nõuab tihti nende grupeerimist, uuritakse erinevaid viise prosumerite grupeerimiseks ning keskendutakse mikrovõrgu üldise kontseptsiooni ning definitsiooni uurimisele. Loetletakse erinevaid mikrovõrkude juhtimise viise ning antakse lühike ülevaade mitmik-agendi süsteemidest. Uuritakse ka nutikate alajaamade ja energiasalvestite tehnoloogia hetkeseisu ning leiti, et turul leiduvate lahendused on piiratud. Olemasolevad nutikad alajaamad ei võimalda kahesuunalist energiavahetust alajaamaga ühendatud prosumeri vahel ning selle haldamist.

Kirjanduse uurimine ja analüüs osutab uudse elektrienergia oksjoni vajadusele. Käesolev töö kirjeldab elektrienergia oksjoni arendamist, milleks on kohandatud mitmik-ühiku modereeritud järjepidev paralleeloksjon. Prosumerite omavaheline suhtlus toimub tellimusel põhineva meetodi alusel, mis tagab mikrovõrgu parema hallatavuse. Selle asemel, et esitada oksjonil üks pakkumine, esitavad prosumerid igas pakkumiste voorus mitu pakkumist. Moderaator, e. Oksjonipidaja-agent kogub kokku kõik pakkumised ning valib esitatud pakkumistest sobivaima kombinatsiooni. Valitud kombinatsiooni alusel koostatakse prosumeritele individuaalsed pakkumised, millega prosumeritel on võimalus nõustuda või nendest keelduda. Oksjoni algoritmi keskseks osaks on kombinatoorne otsingu probleem leidmaks sobivaim pakkumiste kombinatsioon.

Olemasolevate otsingualgoritmide analüüsi tulemusena on võimalik järeldada, et nende otsene kasutamine otsinguprobleemi lahendamiseks ei ole otstarbekas. Lähtudes konkreetsest probleemist on välja arendatud uudne otsingumeetod. Käesolevas dokumendis kirjeldatakse otsingumeetodi arendamist ning loodud nelja erinevat otsingualgoritmi. Ablas kaheastmeline otsingualgoritm valib esimeses otsingu etapis potentsiaalselt kõige kasumlikumad pakkumised. Mahupõhine kaheastmeline otsing valib esmajärgus madalamate mahtudega pakkumised. Mainepõhine kaheastmeline otsing teenindab kõigepealt prosumereid, mis omavad süsteemi silmis kõrgemat mainet. Kombineeritud kaheastmeline otsing kasutab nii ablast kui mahupõhist otsingut ning valib mõlema otsingu tulemustest kasumlikuma. Algoritmide töö hindamiseks on töös

esitatud võrreldavad andmed. Käesolev töö soovitab kõrgema efektiivsuse tõttu kombineeritud kaheastmelise otsingu kasutamist kus vähegi võimalik.

Prosumerite paremaks kirjeldamiseks on loodud uudne prosumeri struktuur. Loodud struktuur võimaldab universaalselt kirjeldada elektrilisi prosumereid. Tuginedes loodud struktuurile on koostatud ka prosumeri tehnoloogilise süsteemi välja, jaama ning protsessi tsooni esitav mudel. Kasutades uudset prosumeri loogilist mudelit on võimalik loogiliselt esitada mikrovõrke kasutades selleks ühe objekti struktuuriga komponente. Mikrovõrgu loogiline mudel liidestatakse arvutiprogrammiga, mille abil teostatakse prosumeri operatiivjärelvalve ning vajadusel ka ettevõtte tsooni juhtimine. Arvutiprogramm koos mikrovõrgu loogilise mudeliga võimaldab viia läbi simulatsioone mikrovõrgu prosumerite omavahelise suhtluse ning energiavahetuse simuleerimiseks.

Loodud meetodite ja algoritmide hindamiseks on loodud kujutletav eksperimentaalne mikrovõrk. Erinevad simulatsioonid näitavad, et arendatud elektrienergia oksjon on võimeline kasumlikult toimima. Tuvastatakse erinevad muutujad, mis mõjutavad mikrovõrgu kasumlikust. Simulatsioonide tulemused viitavad, et koostatud elektrienergia oksjon on elujõuline ning sobiv lahendus kasutamaks nutikates integreeritud elektrienergia salvestitega alajaamades.

Elektrienergia oksjoni algoritmi edasiseks arendamiseks on Tallinna Tehnikaülikool koostöös ettevõttega Harju Elekter Elektrotehnika AS arendanud ning ehitanud prototüübi eksperimentaalsest energiasalvestist ning mikrovõrgust. Esmased eksperimendid näitavad loodud kontseptsiooni rakendatavust. Oksjoni algoritmi ning nutika alajaama kontseptsiooni edasiseks arenduseks on vajalik eksperimentaalse mikrovõrgu ning energiasalvesti täiendamine ja edasiarendamine.

Appendix

Publication I

Korõtko, T., Rosin, A., Ahmadi A., R. (2019), “Development of Prosumer Logical Structure and Object Modelling,”13th IEEE International Conference on Compatibility, Power Electronics and Power Engineering, CPE-POWERENG 2019 (1-6). IEEE.

Development of Prosumer Logical Structure and Object Modeling

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Abstract— **The emergence of distributed generation (DG) has paved the way for transforming consumers into prosumers. Prosumers are entities, which are able to consume and produce energy. Prosumers are building blocks of future smart grids, which help to integrate distributed energy resources (DER) into existing electric power systems (EPS). Prosumers are the subject of multiple research papers, where most of them use case-specific structures or models of electricity prosumers. Since prosumers can be used to represent any EPS and interactions in it, a universal prosumer object is of key importance of modeling novel EPS topologies. The key challenge for the composition of a universal prosumer structure is the assurance of flexibility. In this paper, prosumer definitions are studied and a set of prosumer properties is determined. We propose a novel logical structure for prosumers, which serves as a vantage point for creating an universal prosumer object. The usage of the prosumer model is described and demonstrated by composing microgrids from instances of the prosumer object. For practical implementation in mathematical simulations, a model of the prosumer object is constructed.**

Keywords—prosumer, microgrid, modeling, simulation, smart grid, electricity auction.

I. INTRODUCTION

The sprawling and more effective use of distributed energy resources (DER) introduces a change from the centralized power generation paradigm, which is mainly based on fossil or nuclear fuels and bulk distribution [1], [2]. Bulk distribution grids are reformed to flexible, self-healing, and intelligent distributed smart grids. Simplified grid connection and access to new energy markets and services help encourage greater numbers of consumers and businesses to produce electricity to cover their consumption and sell excess energy to the Utility grid. End users will shift from passive roles as consumers of electricity to active roles as prosumers and are likely to become major actors in smart grid development [3].

The positive effects and potential of introducing prosumers to EPS-s are widely recognized. An increasing number of prosumers leads to reduction in CO_2 emissions, has slightly positive macroeconomic effects, provides significant positive effects for individual prosumers [4] and increases production forecasting accuracy [5]. There are two paths for prosumers creating a low-carbon energy system: (1) off-grid and self-sufficient agents and (2) agents connected to a grid, where prosumers become active providers of energy services [6]. The ability of prosumers to be self-sufficient will play an important role in smart grids [7]. Prosumers enable new energy management options, reduce their impact on the environment and access innovative procedures to reduce energy costs [3]. The concept of describing all producers and consumers as prosumers enables to use them as smart grid building blocks and model the entire electricity infrastructure with prosumers [8].

In context of the Smart Grid Architectural Model (SGAM) described in [9], prosumers cover all zones from process to market level and span across the domains of distribution, DER and customer premises. To address control and management problems of the prosumer, a generalized abstraction, which allows isolating problems for each zone, is required. The abstraction provides the basis for modeling the prosumer object.

The aim of this paper is to propose a universal prosumer logical structure and a simplified modeling block, which enables to model active power flow inside EPS-s using instances of a single object. The proposed logical structure provides a framework to describe prosumer behavior, control, connections, communication, user interaction and prosumer resources. For the creation of a universal prosumer logical structure, existing literature was studied to determine the state of the art in prosumer research.

II. STATE OF ART

The concept of prosuming has become of elevated interest in electrical engineering due to the widespread implementation of DERs. There exist numerous definitions for electrical prosumers in literature. The authors of [12] and [10] define electrical prosumers as entities, which can act at certain periods as either power consumers or producers. In [11], the former definition is expanded by adding the dimension of energy storage. The authors of [13] and [14] add cooperation and restraints to the definition. The authors of [6] describe prosuming as active management of energy consumption and production by energy customers, focusing the definition on the intelligence and proactivity of prosumers rather than their behavior. More specific energy prosumer definitions introduce specified context, cooperation, operational and socioeconomic features. A prosumer definition in the context of a smart grid is provided in [15], where prosumers are described as smart grid customers capable of generating and storing their own energy and thus being key enablers of smart grid energy trading and management schemes. In [3], electricity prosumers are defined as economically active and motivated entities, which consume, produce and store electricity, take part in electricity consumption optimization and get actively involved in electricity services. The authors of [16] characterize prosumers as selfish entities only wanting to maximize individual payoffs. There exist numerous proposals on prosumer structures and modeling.

A. Modeling of prosumers

For practical and experimental purposes, the prosumer has been subject to modeling. In [17], the authors propose

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the modeling of prosumers according to four elements: action set, communication, intelligence, and performance. Prosumer interactions are simulated in an Environmental Social Technical System (ESTS). Although provided simulation results show the cooperation of prosumers, the proposed model lacks a clear overview of prosumer assets and the expansion of the prosumer model is unclear. Furthermore, the proposed method segregates prosumer agents from distribution system operator (DSO) agents and retailer agents, which should not be the case for the desired level of abstraction.

In [10], prosumers are modelled into energy districts, which are made up of the former, a centralized aggregator and a cloud service provider. Each prosumer hosts a nanogrid system, a home automation system and a smart energy box. Whilst addressing control and optimization of prosumer assets and higher-level optimization with a cloud service, interactions between prosumers for cooperation are not introduced. The proposed model lacks the functionality to define prosumer motives and model proactive behavior for pursuing business opportunities.

The authors of [18] divide the power system into clusters, which can also be interpreted as prosumers. They propose a smart grid architecture made up of superordinate, ordinate and subordinate clusters, each cluster operated and managed by a smart grid cluster control unit (SGCC). The proposed method succeeds in providing a universal building block for clusters. The authors focus on grid structure rather than the prosumer structure and the proactivity and trading between prosumers remains unclear.

In [11], a layered architecture of the prosumer is proposed, where each layer is agnostic about the implementation of other layers and their interactions are based on service interfaces. The defined layers are device, local control, system control and market layer. This concept is expanded in [8], where a web services infrastructure and service oriented architecture (SOA) of prosumers and the cyber-physical energy system is discussed. Further development is presented in [19], where the prosumer model is expanded with an additional cyber layer and a business analytics layer for the valuation of products and services is introduced. The authors of [8] claim that the proposed prosumer-driven and web services-based distributed control architecture is suitable for supporting all emerging smart grid applications. The prosumer structure described in [11], [8] and [19] is the most detailed and comprehensive among researched literature, where the focus lies on defining prosumer interfaces. Although the research carried out has been substantial, we recognize that the model proposed in [19] lacks universality, as it is too case specific, and therefor does not meet our required level of generalization.

Based on the analysis of different prosumer definitions, structures and models, the need for a novel and universal prosumer logical structure is identified. To establish the demands for a universal prosumer structure, the explicit formulation of prosumer requirements is needed. Based on researched literature, a list of prosumer requirements for the composition of a universal structure is composed:

- Ability to produce or consume energy.
- Energy transmission between prosumer components.
- Optional incorporation of energy storage.
- Management and optimization of assets and their use.
- Possibility to define operational constraints.
- Possibility to define motives, which guide prosumer actions.
- Energy transmission between prosumers.
- Interaction between prosumers.
- Enhancement of product and service use through optimized control, cooperation and communication.
- Proactivity to initiate business proposals and actively seek business opportunities.
- Implementation of different energy trading and market mechanisms.

In the following paragraph, the development of a universal prosumer logical structure, which would meet the aforementioned requirements, is discussed.

III. DEVELOPMENT OF UNIVERSAL PROSUMER LOGICAL STRUCTURE

We recognize that a prosumer is an entity, which is made up of two logical elements: the subject and its resources. Defining only resources is insufficient for describing a prosumer and a subject by itself cannot be considered a prosumer. The prosumer subject is made up of an intelligent agent, prosumer goals and needs. Prosumer resources are its economic resources, commodities and technological system. To clarify the logical building blocks of a prosumer, the novel prosumer logical structure is depicted in Fig. 1. Following is a detailed description of the two logical components of a prosumer.

The subject of a prosumer is the proactive owner or delegated manager (autonomous agent) of the prosumer. The subject defines abstract goals (e.g. maximize profit, emphasize renewable generation, maximize user comfort), which are used to formulate the interests and preferences of the owner of the prosumer. Prosumer needs are classified either as goods or services and are formulated with respect to the prosumer technological system. To define the general behavior of the prosumer for the next operation period,

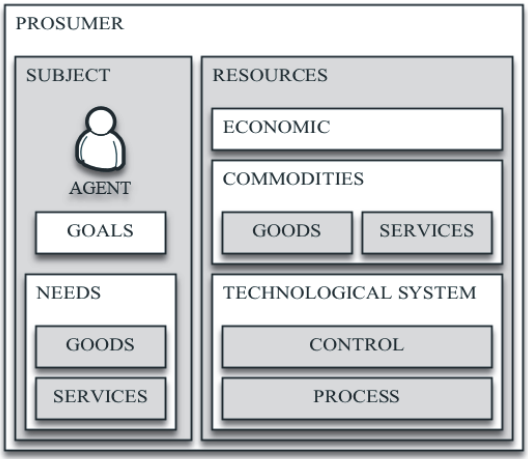

Fig. 1. Proposed prosumer logical structure.

the subject assumes one or several roles or delegates the prosumer control unit (PCU) to designate roles dynamically.

The resources of a prosumer are the means available to it for fulfilling its needs and achieving its goals. Each prosumer has economic resources e.g. monetary funds (fiat- or cryptocurrency), agreements with other prosumers, energy futures or obligations. Only the subject of a prosumer can manage and contract these resources. Economic resources could also be contracts with TSO-s for providing ancillary services or smart contracts with other prosumers concluded in peer-to-peer transaction platforms.

Commodities are goods and services available by the prosumer. The variation of goods provided by an electric prosumer is not limited, but in most cases, it is reduced to two: electric energy and data. Prosumers provide services like energy and information distribution, ancillary services and real-time information. A prosumer might not provide any goods at all and serve the sole purpose of energy and information distribution. If respective technology is present in the prosumer technological system, a prosumer might, also provide the service of energy storage.

The technological system of the prosumer resources is the set of technology and software objects available to the prosumer. The system is divided into two sub-systems:

- **process**, which is made up of components from the process zone, and
- **control**, which includes hard- and software for communication and control of the field, station, operation and enterprise zones.

The mapping of the prosumer technological system hardware onto the SGAM [9] component layer is depicted on Fig. 2.

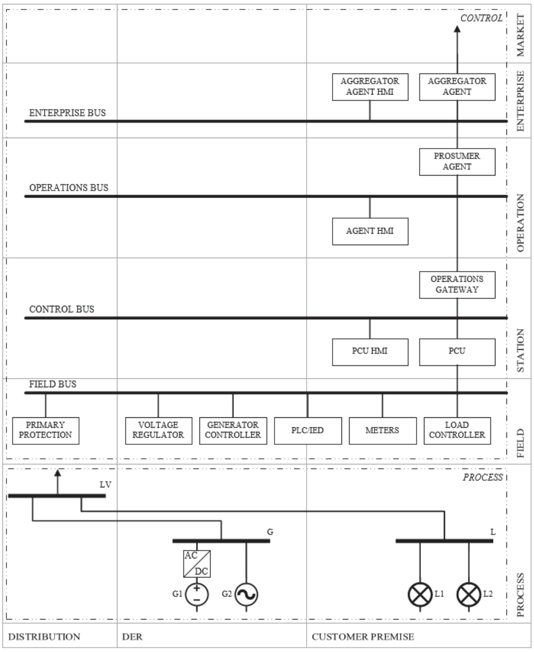

Fig. 2. Prosumer technological system mapping onto SGAM component layer.

The process sub-system includes the process equipment of the prosumer (e.g. generators, loads, power converters, distribution equipment, and measurement points). The distribution process equipment includes all points of local coupling (PoLC) and the point of common coupling (PCC). The control system consists of:

- **field control** devices for primary control of process equipment (e.g. voltage regulators, primary load controllers, metering devices etc.),
- **station control** devices prosumer control,
- **operation control** equipment for management and optimization of the prosumer and
- **enterprise level control** for coordinating the aggregation of other prosumers.

Enterprise level control is optional and realized when the prosumer is used as aggregator of prosumers. The control system also includes communication buses and interfaces

The PoLC is the geometric point where a Local EPS connects to another Local EPS (or prosumer). The PCC is the geometric point where a Local EPS connects to the Area EPS. The PCC can be realized with a dedicated feeder to connect the microgrid to the Area EPS. Since the PCC is meant for transferring electrical energy, an additional communication interface is needed to provide communications with the Area EPS. The communications link is realized by the prosumer, which has assumed the role of aggregator. The communication interface between the microgrid and the Area EPS can also be used as a communications gateway.

A. *Prosumer roles*

Depending on the goals and needs of the prosumer subject, its resources and interactions with other prosumers, it needs to assume at least one role for each dedicated time period in the future. The prosumer role defines its general behavior. There is no limit for the number of roles a prosumer can assume concurrently, but there are several roles which exclude each other. The prosumer roles are classified as conventional and ancillary.

Conventional roles are prosumer roles which are needed for forming a bulk electric grid, where there are generators, consumers and distributors. The conventional prosumer roles are described in TABLE I. For example, a generator, an electric load and a distribution system working as an energy island could be described as follows: prosumer PRSMR0 in the role of Vendor and prosumer PRSMR2 in the role of Purchaser are connected to prosumer PRSMR1 in the role of Distributor and Island. The flow of electricity would be from

TABLE I. CONVENTIONAL PROSUMER ROLES

Role	Description
Vendor	Provides electricity to the PCC. Shall be remunerated according to the terms stated in prosumer bindings. Excludes the Purchaser role.
Purchaser	Consumes electricity from the PCC and will be invoiced according to the terms stated in prosumer bindings. Excludes the Vendor role.
Distributor	Enables the flow of electricity from one system to another. Might be remunerated according to the terms stated in prosumer bindings.
Island	PCC disconnected.

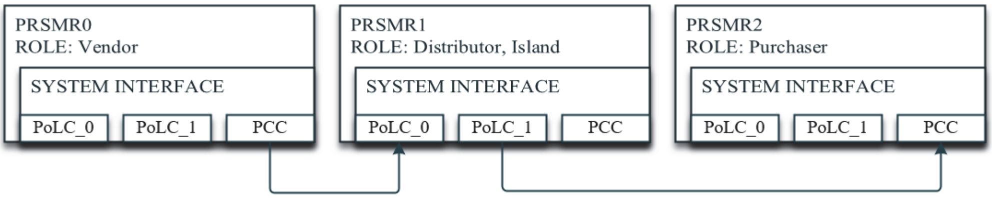

Fig. 3. Proposed prosumer logical structure.

the PCC of PRSMR0 to a PoLC of PRSMR1 and from another PoLC of PRSMR1 to the PCC of PRSMR2 (a graphical example is presented on Fig. 3).

Ancillary roles are prosumer roles, which, in addition to conventional prosumer roles, are needed to form a sophisticated, intelligent and controllable electricity grid. As the conventional prosumer roles are limited, the ancillary prosumer roles are not. With the emergence of novel technology and the evolution of the distribution and transmission grid, new opportunities, services and problems are about to arise, which all have their role in forming future ancillary services.

With the prosumer structure in place, a prosumer object can be composed. The following paragraph describes the use of the proposed prosumer logical structure for building a universal prosumer object and its instances for defining an EPS.

IV. DESCRIBING EPS-S USING PROSUMERS

Prosumers are used as building blocks for novel EPS architectures. It is noted in [8] and [11] that the prosumer concept can be used to represent electrical interconnections, independent system operators (ISO), utilities, microgrids, industrial facilities, commercial buildings, residential dwellings etc. In fact, the authors of [8] emphasize that the prosumer abstraction allows to represent any EPS as a prosumer and to model all interactions associated with electricity through interactions between prosumers.

There are various ways prosumers can be added to an existing EPS or even form a new one. Common methods to interconnect prosumers or connect them to the existing Utility grid include virtual power plants (VPP), prosumer community groups (PCG), microgrids, energy districts, prosumer coalitions, aggregators and clusters [5], [10], [14], [16], [18], [20] – [24]. The authors of this paper consider the formation of microgrids as effective means to transition the existing EPS to a smart grid, due to the emphasis on the locality of operations and the scalability of the concept.

Microgrids are defined as clusters of loads, distributed generation (DG) units and energy storage systems (ESS) operated to reliably supply electricity and connected to a larger power system at the distribution level [25]. A simple configuration of a microgrid is made up of technological devices: generators, loads, distribution systems and the PCC. Externally, prosumers have the same characteristics as technological devices, meaning the technological devices inside a microgrid can be represented as prosumers in different roles. For example, the prosumer interconnection presented in Fig. 3 represents an islanded microgrid.

If a microgrid is connected to a Utility grid, the microgrid itself can be considered as a prosumer, which means a microgrid can be described as a prosumer, which is made up of prosumers. Since a microgrid is made up of elements of itself, it can be expanded as a fractal (Fig. 4) pattern with prosumers as elements. In theory, the fractal pattern could be limitless, but in practice, this approach is subject to technical limitations (e.g. feeder nominal power, complexity of communication etc.). The minimal size of the PCC can be evaluated by (1):

$$P_U > \Sigma^n_{i=1} Pi, \tag{1}$$

where P_U is the nominal power of the PCC, n the number of prosumers connected to the microgrid and P_i the nominal power of the feeder of the adjacent prosumer.

To clarify the fractal formation of a microgrid, a complex interconnection structure is depicted in Fig. 4, where a configuration of a microgrid with the prosumers PRSMR0, PRSMR1 and PRSMR2 is presented. PRSMR0 has assumed the role of Distributor, while PRSMR1 and PRSMR2 may have several other roles. PRSMR2 is a more complex microgrid made up of five prosumers: PRSMR2.0 and PRSMR2.2 have assumed the role Distributor, while PRSMR2.1, PRSMR2.3 and PRSMR2.4 are operating in other roles. It is important to note how the PCC of one prosumer can be the PoLC of another. The prosumer PRSMR2.2 is also represented as a microgrid, which consists of four prosumers: PRSMR2.2.0 in the role of Distributor and PRSMR2.2.1, PRSMR2.2.2, PRSMR2.2.3 in other roles. Prosumers PRSMR2.3 and PRSMR2.4 are configurations of microgrids, where PRSMR2.3.0 and PRSMR2.4.0 have assumed the role of Distributors and PRSMR2.3.1, PRSMR2.3.2, PRSMR2.4.1 and PRSMR2.4.2 various other roles.

The fractal approach of describing microgrids has advantages over traditional topologies, since it reduces the number of objects required to describe a microgrid to just one, which enables to apply an object-oriented approach for defining microgrids and EPS-s in general. For the practical implementation of the proposed prosumer logical structure in mathematical simulations, a prosumer model object is composed.

V. MODELING OF THE PROSUMER OBJECT

For the initial verification of the proposed prosumer structure, a mathematical model of the prosumer object was created using MatLAB Simulink software. The aim of the model is to simulate active power distribution inside prosumers for building prosumer control systems and use it for the development of distributed intelligent agents. We have identified that the detailed simulation of electrical parameters is not necessary for designing prosumer higher-

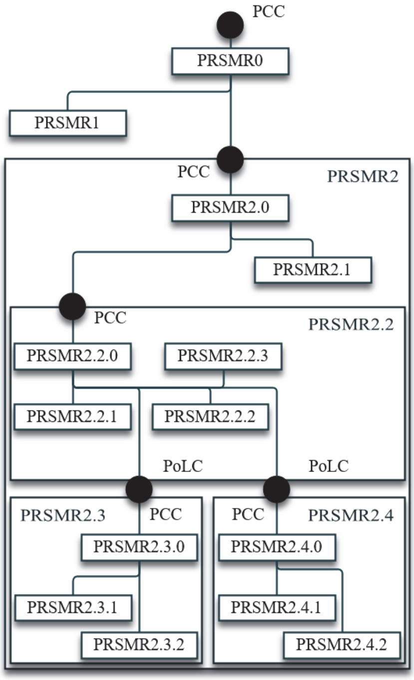

Fig. 4. Microgrids as a fractal pattern.

level control and therefor, for simplification purposes, only active power as a floating-point value was used in the prosumer model. A generalized prosumer model with a detailed electrical system will be the subject of future research.

The model of the prosumer technological system comprises all modules presented in the prosumer logical structure in Fig. 1. The prosumer model is constructed to have 16 PoLC's, which can be either internal or external. Internal PoLC's are for prosumer devices and external PoLC's are for external devices. The distinction between internal and external devices is made based on device control: if the higher-level control of the device is to be carried out by the PCU, it is considered as a prosumer technological device. For each prosumer, a class needs to be defined in the MatLAB Workspace, which parametrizes the prosumer and its elements. Prosumer classes also define the load profiles of prosumer technological devices.

Prosumer subjects and their intelligent agents are modelled using the Java programming language and utilizing the Java Agent Development Framework (JADE). For the simulation, a dedicated simulation communication agent was composed to handle communications between JADE agents and MatLAB Simulink.

A graphical user interface (GUI) is provided for each prosumer subject. The GUI is used to formulate prosumer subject goals and parametrize the prosumer subject intelligent agent. The formulation of intelligent agents enables the implementation of complex machine learning and artificial intelligence (AI) algorithms, which will be of elevated interest in future research.

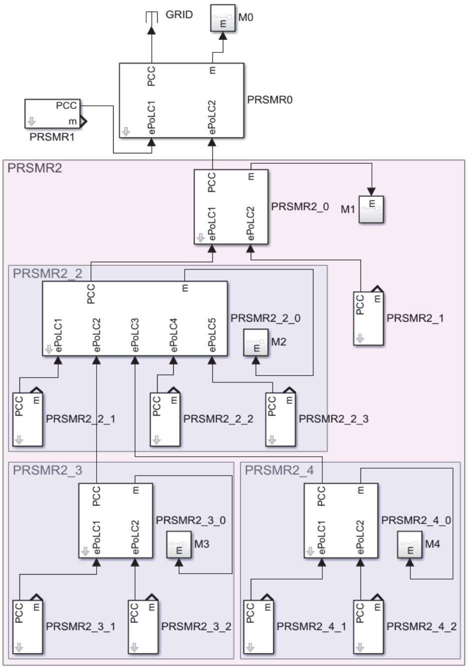

Fig. 5. Microgrid model composed of prosumer blocks.

To verify the prosumer model and the fractal approach for describing microgrids, the complex interconnection depicted in Fig. 4 is modelled in MatLAB Simulink using the composed prosumer model blocks (Fig. 5). Initial simulations show promising results for the proposed model for use in simulating prosumer behavior and interactions on a simplified active power production and consumption level.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a novel prosumer logical structure was proposed. The proposed structure aids in composing prosumer mathematical models and developing control systems, but also unifies the prosumer concept. Based on the proposed structure, a simplified mathematical model for the prosumer technological system was composed Using the mathematical model, the grouping of prosumers into microgrids as a prosumer fractal pattern was also demonstrated. The composed modeling block enables to simulate the following:

- active power production or consumption;
- using and managing energy storage;
- power distribution between prosumers and their devices;
- behavior and control of prosumer devices;
- control and optimization algorithms for prosumers and their devices;
- agent communications and cooperation;
- multi-agent EPS-s
- prosumer trading schemes and methods;

Future research will focus on further development of the proposed prosumer structure and the prosumer mathematical model. The next steps are the modeling of the prosumer control systems and designing a multi agent system (MAS) environment for prosumer interaction. Concurrently, the hardware prototype of a prosumer control system is to be developed, to enable the verification of the control system and mathematical models on physical equipment.

ACKNOWLEDGMENT

This work was supported by the Estonian Research Council grant PUT (PUT1680), and Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts ZEBE, grant 2014-2020.4.01.15-0016 funded by European Regional Development Fund.

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Publication II

Korõtko, T., Rosin, A. (2018), “Search algorithm development for novel electricity auction in microgrids,” 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON 2018.

Search algorithm development for novel electricity auction in microgrids

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Abstract—**This paper describes the development of a novel search algorithm to be used as a key component inside an electricity auction algorithm for electrical microgrids. Electricity auctions and common search algorithms are reviewed. Since no common search algorithm proves eligible for an optimal solution of the search problem inside the novel electricity auction, a custom two-step search algorithm is developed. The developed search algorithm divides the search into two: first, the search is narrowed based on simplified assumptions, and second, a filtered search algorithm is used to find the optimal set of bids. Comparative results for different search algorithm variations and insights to future research are presented at the end of this paper.**

Keywords—microgrid; electricity auction; search algorithm; smart grid

I. INTRODUCTION

Managing distribution of electrical energy between agents using an electricity auction is a widely accepted paradigm, which has attracted researchers' interest in the last two decades. Auction algorithms proposed in literature mainly use modifications of the continuous double auction for unit commitment in microgrids [1] – [8]. The majority of research considers microgrids with homogeneous ownership. However, practical implementations of microgrids contain complex prosumer (combined user and producer) ownership relations. For the widespread implementation of microgrids, the entity responsible for enabling the formation of microgrids needs to be favored. Since generation and consumption forecasting has become of elevated interest due to the sprawling use of distributed energy resources (DER), it is highly likely that microgrids, which provide a predictable connection to the point of common coupling (PCC), gain an advantage over microgrids with an uncontrollable PCC connection. Energy storage systems (ESS) at the disposal of the prosumer responsible for microgrid formation promise to provide greater flexibility for the operation of the microgrid.

The following paper briefly introduces a novel electricity auction, developed in TalTech University. The developed auction is designed explicitly for a microgrid with an ESS and to maximize profits for the entity enabling the formation of the microgrid. As outlined in Chapter II, the key component of the novel electricity auction is the search algorithm for selecting the optimal set of bids. The main focus of this paper is to describe the research and development of the search algorithm for the novel electricity auction.

II. STATE OF THE ART

A. Electricity auctions

According to [9], electricity auctions are specific types of auctions where goods are ideally divisible and not storable, which means that transactions need to happen in real time or at least at a predefined point of time in the future. Most studies in the field of electrical energy auctions are conducted on bid formation. The study in [9] presents a bidding strategy for local asymmetric markets, while [4], [5] and [6] propose different risk-based bid formation methods. The discussion in [10] focuses on how distributed generators (DG) or loads would construct their bids in a clearing price auction. A methodology for enabling bidders to estimate their profit-maximizing bid in price uncertainty conditions, considering a multi-unit pay-as-bid procurement auction is reported in [11]. In [12], co-evolutionary bidding strategies. where interacting individuals are evaluated based on their interactions with each other, are analyzed. Aside from bid formation, some publications also focus on electrical energy auction algorithms.

The continuous double-auction (an auction where symmetrically buyers submit bids and sellers asks [7]) is the preferred auction type for real-world trading of equities [8] and electrical energy auctions are no exception. The study of [6] proposes a risk-based continuous double-auction strategy and a method of determining the optimal generation schedule of the distributed energy resources (DER) using an immune-system-based particle swarm optimization method. Although their results have proven the viability and efficiency of the proposed method in comparison with the traditional bidding process, they do not address the predictability of the energy consumed from or produced to the PCC. Additionally, the method provides no reward, besides a fixed usage rate, for the owner of the microgrid infrastructure (which makes the exchange of energy possible in the first place). Overlooking this aspect might become a setback, since there would be no major incentive for stakeholders to invest in such infrastructure.

A spot market model for microgrids reported in [14] can be used to manage distributed energy storage systems without the need for sophisticated production and consumption forecasts.

The discussion in [13] focuses on the problem of profit-based unit commitment and use of a multi-agent approach to solve it. An auction algorithm for unit commitment is presented, which considers the total output of the multi-agent system and uses a dedicated agent to sort out the most profitable solution for the entire system. The algorithm assumes that the highest profit for a prosumer is also the highest profit for the entire system, which might not be the case for microgrids, which are formed of prosumers with different owners.

In researched literature, there is no auction algorithm designed for microgrids, which would focus on maximizing profits of the microgrid enabler. Based on studied literature and the objectives stated above, a novel electricity auction algorithm is currently being developed at TalTech University. Fig. 1 shows the flowchart of the designed electricity auction. The designed electricity auction is a modification of a multi-unit administered continuous double-auction. Instead of presenting a single bid, auction participants gain flexibility by presenting a set of bids. A bid consists of two values: V – bid volume [1 kWh] and C – bid asking price [1 €]. The auctioneer agent collects all bid sets, chooses the optimal bids, composes offers and sends offers to participants. Upon receiving an offer, participants either accept the offer or reject it. While rejecting the offer, a participant can correct its bid set and send it to the auctioneer agent for the next negotiation round. An auction round runs until the bids and asks of all agents have been served or the auction reaches the predefined number of negotiation rounds (R_{MAX}). This paper describes the research and development of a novel search algorithm designed to solve the problem of finding the optimal combination of bids from bid sets in the developed electricity auction.

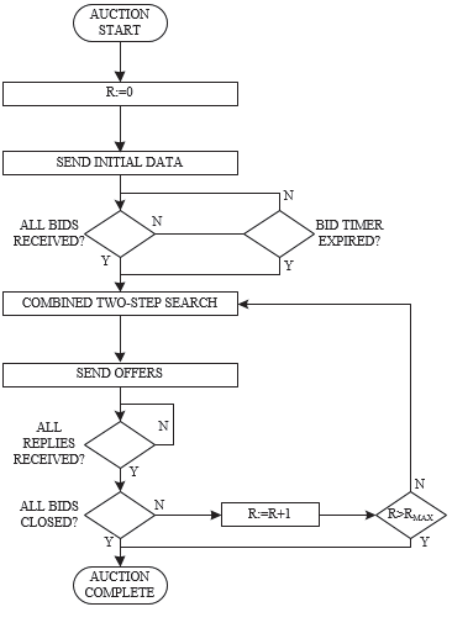

Fig. 1. Electricity auction flowchart.

B. Search Algorithms

A breadth-first search is a method of searching, where, at first, the initial state is expanded to all its possible states, then, all the successor states of the initial state are expanded to all of their possible states, next, their successor states are expanded to all of their possible states, and so on. Uniform cost search modifies the breadth-first search by always expanding the lowest total path cost node until a final node is reached and no cheaper path is available [15]. A method based on the breadth-first search for making demand response decisions in microgrids is reported in [16].

Depth-first search always expands one of the nodes of the deepest levels. When the search algorithm arrives at a node that is not a solution, and that cannot be expanded, it returns to the previous node and either expands to another higher node or heads back to another node. The depth-limited search improves the depth-first search by adding the maximum allowed depth of a path. Iterative deepening search uses the depth-limited search, but instead of a fixed depth limit, the algorithm runs several times while the depth limit is being iterated (depth values: at first 0, then 1, then 2, etc.) [15].

Bidirectional search uses two simultaneous searches: one starting from the initial state and another from the goal state. A result is reached when the searches meet in the middle [15].

The best-first search is identical to the uniform-cost search, but the node to be expanded is selected based on an evaluation function $f(n)$. The recursive best-first search is a simple recursive algorithm that attempts to mimic the operation of the standard best-first search but using only linear space. Greedy best-first search is a generic best-first search strategy, where the heuristic function $h(n)$ represents the direct distance of node n from the goal node and where such f is chosen that $f(n) = h(n)$. In other words, the node closest to the goal is expanded first [15].

A* search combines the greedy best-first search with the uniform cost search, which results in a search strategy that evaluates both, the cost to reach the next node and the cost to get to the goal from the next node. Simplified memory-bounded A* search proceeds just like A*, by expanding the best leaf until memory is full. Since the memory is full, an existing node needs to be dropped before a new node can be added, thus the node with the highest f-value is dropped. To reduce memory requirements for A* search, the idea of iterative deepening is adapted to the heuristic search context. The main difference between iterative deepening the depth-first search is that the used cutoff is not the depth, but the f-cost [15].

All modern nature-inspired search methods are called metaheuristics (based on Glover's convention). Some well-known metaheuristic algorithms are: genetic algorithm (based on natural selection), particle swarm optimization (based on social behavior of bird flocking), cuckoo search algorithm (based on the brood parasitism of some cuckoo species), bat algorithm (based on echolocation behavior of microbats). All metaheuristic algorithms use a tradeoff of randomization and local search. The performance of a metaheuristic search algorithm depends heavily of its parameter setup [17].

For a better overview of more common search algorithms, a comparative evaluation table is given in TABLE I. All search algorithms were evaluated by solving the problem for the novel electricity auction: finding the global optima of the sets of bids from 16 prosumers, where each prosumer submits 8 bids. It was also required to consider the following four problem-specific characteristics:

- There is no need to perform the goal state check until the final state has been reached.
- There is no explicit way to exclude a solution before the final state has been reached.
- The impact of a single state on the total solution can be determined only after the final state has been reached.
- An eligible solution gives no indication whether it is the optimal one.

III. DEVELOPMENT OF CUSTOM SEARCH ALGORITHM

It was found that none of the search methods compared in TABLE I. is ideal for solving the search problem. The breadth-first and a complete depth-limited search method remain the two to be considered, but some important approaches can be transposed from other strategies. A complete depth-limited search does not stop when it reaches a goal node but stores the goal node into the solution hash table and carries on as it had reached a non-expandable node. The search continues until it has expanded all nodes. Such a modification makes it possible to return all solutions. Since the space complexity of the breadth-first search is worse than for the depth-limited search, the complete depth-limited search was chosen as the basis of the custom search algorithm.

A. Search Algorithm Evaluation

For the evaluation of composed search algorithms, metrics are required. For smaller datasets, a revenue comparison can be made between the search results of the composed search algorithm and the full depth-first search for the same dataset. Since the time complexity of the full depth-first search is too high for larger datasets, an estimated value was used.

A modification of the Monte Carlo method was used for value estimation. All bids in all prosumer bid sets were randomly generated values in a domain of $V \in [-50;\ 50]$ and $C \in [0.1;\ 0.2]$. For the randomly generated dataset, the highest revenue compared to the PCC was calculated from the eligible results of the full depth-first search ($pccTrsh = 2.5$; $pccSp = 0$). The search was iterated 10 000 times for datasets with sizes of 4 to 8 bid sets and 100 times for datasets with sizes of 9 and 10 bid sets. From the collected results, the average highest revenue compared to the PCC was calculated.

Based on average maximum revenues per prosumer for datasets with 4 to 10 prosumers, the relation between the maximum revenue per prosumer and the number of prosumers is found. The average revenue per prosumer for a dataset with 16 prosumers is $Pr^{avgPros}(16) = 1.258$, which results in an average highest total revenue of 20.13. The average highest total revenue is used as a comparative value for evaluating the performance of composed search algorithms.

TABLE I. COMPARISON OF SEARCH ALGORITHMS

Parameter	Completeness	Optimality	Time complexity	Space complexity
Breadth-first	*true*	*true*	$6{,}0 \times 10^9\ s$	960 Tb
Depth-first	*false*	*false*	$6{,}0 \times 10^9\ s$	32 b
Depth-limited	*true*	*false*	$6{,}0 \times 10^9\ s$	32 b
Iterative deepening depth-first	*true*	*true*	$6{,}0 \times 10^9\ s$	32 b
Bidirectional	*true*	*true*	$2{,}3 \times 10^9 s$	56 Mb
Greedy best-first	*false*	*false*	N/A[a]	N/A[a]
A*	*true*	*true*	N/A[a]	N/A[a]
Recursive best-first	*true*	*true*	N/A[a]	N/A[a]
Simplified memory-bound A*	*true*	*true*	N/A[a]	N/A[a]
Iterative-deepening A*	*true*	*true*	N/A[a]	N/A[a]
Meta-heuristic	*false*	*false*	N/A[a]	N/A[a]

[a] Since the complexities depend heavily on heuristics and the algorithm constraints, an indicative value is not applicable.

B. Input Data Filter

Similar to the generic best-first search, heuristics are used in the custom search algorithm. In the generic best-first search, a heuristic function h is used to determine the node nearest to the goal. For the custom search algorithm, a heuristic function h is used for filtering out branches, where a possible solution is impossible. Before the search is performed, a heuristic h_i is calculated for each state, which is a 2 component array $[V_i^+;V_i^-]$, where V_i^+ denotes the maximum possible sum of V and V_i- the minimum possible sum of V available for prosumer i. Each time a node is reached, the current V balance is calculated, and a node termination check is performed using (1):

$$\begin{cases} pccSp + Vbal + V_i \geq (-1)(V^+ + pccTrsh) \\ pccSp + Vbal + V_i \leq (-1)(V^- - pccTrsh) \end{cases} \tag{1}$$

where $pccSp$ denotes the power setpoint for the PCC, V_{bal} the sum of already selected bid volumes, V_i the volume of the bid, V^+ the volume sum of highest volume bids of unselected prosumers, V^- the volume sum of lowest volume bids of unselected prosumers and $pccTrsh$ the volume setpoint threshold. In case the check returned *false*, the node, and all its successors, are terminated and the search carries on.

The time complexity of the search algorithm depends directly on the nodes expanded. To expand the minimum number of nodes, the filtering function needs to terminate an unsuitable path as early as possible. To detect a branch that does not pass the termination check as early as possible, the input data *PROSUMERS* needs to be sorted. The aim of the sorting is to prevent a situation, where (one of) the last prosumer bid(s) $PROSUMERS_i.B$ incorporates large *V* values. The bid sets are sorted in descending V_i^{abs} order, where V_i^{abs} denotes the sum of the absolute maximum and minimum *V* values (V_i^{max}, V_i^{min}) for prosumer bid set $PROSUMERS_i.B$ and is calculated using (2):

$$V_i^{abs} = |V_i^{max}| + |V_i^{min}| \tag{2}$$

To evaluate the performance of the filter and its effect on the time complexity of the search algorithm, a test program was composed. The test program performs the custom search and outputs the number of eligible solutions and the time spent for the completion of the search. Two datasets were used for the evaluation: a randomly generated data matrix with 8 elements and 10 data rows and a worst-case data matrix (a matrix with the highest number of eligible solutions) with 8 elements and 8 data rows. The custom search algorithm and the filter depend entirely on the *V* values of prosumer bids.

At first, the custom search algorithm was used to find the values of data matrices with different numbers of rows and columns (up to 8 columns and 10 rows – a total of 8^{10} combinations), which are composed from the random data matrix. The number of eligible solutions depends on *pccTrsh*, thus the search was run with different *pccTrsh* values. To achieve a comparison, the custom search algorithm was also used to find the values of data matrices with different numbers of rows and columns (up to 8 columns and 10 rows – a total of 8^{10} combinations), which were composed from the worst-case data matrix.

In the analysis of the test results, it is evident that the solution count increases with the increase of the *pccTrsh* value. The solution can be considered linear for relative *pccTrsh* values up to 50% of the absolute maximum *V* of the used data set. It is recommended to keep the relative *pccTrsh* lower than 5%, which gives a gain in flexibility and results in a slight increase of the solution count. The relative solution count decreases as the size of the data matrix (and thus, the number of possible combinations) increases. It should be noted that although the relative solution count decreases, the total number of eligible solutions increases because of the exponential increase of possible combinations.

To evaluate the filter, it is required to measure the filter performance. Since the filter is meant to decrease the time complexity of the search, it is an objective approach to evaluate filter performance based on the total time for the completion of a search. The time to complete the custom search for finding all eligible solutions was measured with the test program. Based on the measured results for searches with and without the filter, the filter efficiency was calculated using (3):

$$\eta = 1 - \frac{t_f}{t_w} \tag{3}$$

where η is the filter efficiency, t_f the duration of a search with the filter and t_w the duration of a search without the filter for the same dataset. Filter efficiency depends on the relative value of *pccTrsh* and search matrix size. The filter efficiency increases with the matrix size and is more effective with lower *pccTrsh* values. The worst-case input data matrix demonstrates the variation of filter efficiency depending on the input data values. Filter evaluation results are presented in TABLE II.

The time complexity with *pccTrsh* value 0 for the filtered search of a 8 × 10 randomly generated data matrix was 51.8 s, which is conclusive evidence that the custom search algorithm with filtering alone is not suitable for solving the search problem at hand.

Although sorting and filtering can substantially improve the performance of the custom search algorithm, the maximum number of searched nodes, and thus the time complexity, is still ineligible. To decrease the time complexity of the search, some simplifications need to be introduced. As the next step, the search was divided into two parts: the value estimate search and the filtered custom search, thus resulting in a new search algorithm: the hybrid two-step search algorithm.

IV. NEW HYBRID TWO-STEP SEARCH ALGORITHMS

The hybrid two-step search algorithm divides the search into two phases: the first phase narrows the search by selecting bids from prosumers based on simplified assumptions; the second phase carries out the filtered custom search to find the most suitable set of bids. The first phase is executed while the total number of possible combinations of the remaining dataset is higher than a threshold value, meaning in some cases that the first part might not be executed at all. For the problem at hand, the threshold value was selected to be 8^8, since the completion of the filtered search for the 8 × 8 worst case data matrix was acceptable. There are several approaches to compose logic for the first phase of the hybrid two-step search algorithm.

A. Greedy Two-Step Search Algorithm

The greedy two-step search algorithm executes the first phase of the search to ensure that the most rewarding bids are selected. The logic is built on the assumption that a bid with the highest revenue compared to PCC prices is likely to be a part of the optimal solution. The highest revenue compared to PCC prices was calculated with (4):

$$Pr^p = \begin{cases} V \geq 0; V(C - GCpP) \\ V < 0; V(GCsP - C) \end{cases} \tag{4}$$

where Pr^p denotes the revenue compared to PCC prices, *V* the volume of electrical energy of the bid, *C* the proposed price of the bid, *GCpP* the purchacing price of electrical energy for the PCC, and *GCsP* the selling price of electrical energy for the PCC. For the greedy two-step search, all bids are listed in

TABLE II. FILTER EVALUATION RESULTS

Data matrix size	Random data	Worst-case data
8x8	1.7 s	3.5 s
8x10	51.8 s	-
8x16	-	2.4×10^{10} s

ascending order and the total number of possible combinations is calculated. While the total number of possible combinations remains higher than the selected threshold value, the first bid from the generated list is selected. Each time a bid is selected, all bids from the selected prosumers bid set are removed from the generated list and the total number of possible combinations is recalculated. Once the algorithm reaches the threshold value, the second phase of the search algorithm is executed, with input data output from the first phase.

There are several exception scenarios to be considered. One is a case where selecting bids with highest revenue (compared to PCC prices) results in an unsolvable problem in the second phase of the search. For example, prosumers offer bids with high volumes and high purchase prices while there are no prosumers to balance the sum of volumes. To prevent the system on committing to bids it cannot serve, a balance check is required, which determines whether the next bid to be selected from the most rewarding bids list is acceptable. The balance check is calculated using (5):

$$bc = \begin{cases} V \geq 0; (V + V_{bal} - V_{SP}) \leq -V^{-} \\ V < 0; (V + V_{bal} - V_{SP}) \geq -V^{+} \end{cases} \quad (5)$$

where *bc* denotes the logical result of the balance check, V the volume of electrical energy of the bid, V_{bal} the sum of already selected bid volumes, V_{SP} the requested total sum of bid volumes, V^{+} the volume sum of highest volume bids of unselected prosumers, and V^{-} the volume sum of lowest volume bids of unselected prosumers.

B. Volume Difference Based Two-Step Search Algorithm

The volume difference-based two-step search algorithm executes the first phase of the search to select the most rewarding bids from the bid sets with low absolute volume difference. The logic rests on the assumption that there is a higher chance of finding a near-optimal solution when the second phase of the search is executed on a dataset with higher volume variabilities.

The prosumer bid sets are sorted in ascending order of the difference of the highest and lowest bid. While the total number of possible combinations remains higher than the selected threshold value, the bid with the highest (4) value from the first prosumer is selected and a balance check is carried out using (5). If the balance check returns false, the bid with the next (4) value is selected etc. If a bid is selected or no bids from the prosumer return true for the balance check, the next prosumer from the list is selected and the total number of possible combinations is recalculated.

C. Reputation Based Two-Step Search Algorithm

The reputation-based two-step search algorithm executes the first phase of the search by selecting the most rewarding bids from prosumers with higher reputation. The logic is built on the assumption that the reputation of prosumers can be used as a reward. If a bid of a prosumer is selected in the first phase, the prosumer agent can adjust its behavior to use it as an advantage.

Prosumer bid sets are sorted in ascending order, based on prosumer reputation values. While the total number of possible combinations remains higher than the selected threshold value, the bid with the highest (4) value from the first prosumer is selected and a balance check is carried out using (5). If the balance check returns false, the bid with the next (4) value is selected etc. If a bid is selected or no bids from the prosumer return true for the balance check, the next prosumer from the list is selected and the total number of possible combinations is recalculated.

D. Combined Two-Step Search Algorithm

The combined two-step search algorithm combines the greedy two-step search algorithm and the volume difference-based two-step search algorithm to benefit from the efficiency of the former and the completeness of the latter in exchange for higher time complexity. The search executes both, the greedy and the volume difference-based two-step search algorithm and returns the better result.

V. RESULTS

The composed hybrid two-step search algorithms were evaluated using a test program. Each algorithm was iterated 10 000 times with values of *pccTrsh* = 2.5 and *pccSp* = 0. For each iteration, a dataset with 16 prosumer bid sets filled with randomly generated bids in the domain of $V \in [-50; 50]$ was used. The generalized results of the performed simulations are outlined in TABLE III.

The comparison of the proposed algorithms shows that the best time complexity with fair average revenue is achieved by using the greedy two-step search algorithm, though it has an important drawback of being incomplete. The volume difference-based two-step search algorithm has higher time complexity and smaller average generated revenue, but it is complete in return. The reputation-based two-step search algorithm shows the lowest average revenue but remains an interesting option since it gives opportunities for rewarding prosumers based on their behavior history. The best average revenue was achieved by the combined two-step search algorithm, which also has the highest time complexity. An interesting sign of the efficiency of the combined two-step search is that the average revenue for results below median was nearly as high as the average revenue of the greedy two-step search.

An important implication of the test results is that none of the composed search algorithms is optimal. Near-optimal results mean that the objective of composing an optimal search algorithm has not been met and other approaches can be considered to improve results.

TABLE III. SEARCH ALGORITHM SIMULATION RESULTS

Two-step algorithm type	**Greedy**	**Vol. diff. based**	**Rep. based**	**Combined**
Space complexity	< 1 MB	< 1 MB	< 1 MB	< 1 MB
Avg. time complexity	0.6 s	1.4 s	1.5 s	2.1 s
Optimal?	No	No	No	No
Complete?	No	Yes	No	Yes
Avg. revenue[a]	88.5 %	85.3 %	84.7 %	89.7 %
Median revenue[a]	89.4 %	85.6 %	85.2 %	90.0 %
Avg. revenue [a] bel. med.	78.3 %	75.2 %	74.2 %	87.7 %

[a] Revenue compared to calculated average highest total revenue.

VI. CONCLUSIONS AND FUTURE RESEARCH

A brief description of an electricity auction, designed for microgrids and purposed to maximize benefits of the microgrid forming entity, has been provided. A detailed description of research and development of a search algorithm for the described auction was presented.

Four different hybrid search algorithms were discussed. Preference in algorithm selection relies mainly on the available resources and the application. We recommend the use of the combined two-step search algorithm whenever possible due to its high efficiency. Although the time complexity is roughly the sum of the two search algorithms, the outcome is a complete search algorithm with average revenue of nearly 90% of the calculated average highest total revenue.

Future research will focus on the simulation of electricity auctions inside microgrids to evaluate and improve the auction method. Auction implementation on physical objects is also necessary for further algorithm development. Future research is required to compare the results of the developed search algorithm with other promising search methods, e.g. metaheuristic algorithms.

ACKNOWLEDGMENT

This work was supported by the Estonian Research Council grant PUT (PUT1680), and Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts ZEBE, grant 2014-2020.4.01.15-0016 funded by European Regional Development Fund.

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Publication III

Korõtko, T.; Merisalu, Ü.; Mägi, M.; Peterson, K.; Pettai, E. (2014), “Development of Testing Method for Smart Substations with Prosumers,” Informacije MIDEM-Journal of Microelectronics Electronic Components and Materials, 44 (3), 185−200.

Original scientific paper

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 44, No. 3 (2014), 185 – 200

Development of Testing Method for Smart Substations with Prosumers

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Abstract: The paper presents a concept of design and realization of a new testing method for distribution substations which form a microgrid with prosumers. The distribution substation acts as a service provider for distributed resource units in a microgrid and can be used for bidirectional energy exchange between prosumers, such as electric vehicles, battery pack energy storage devices and utility networks. Use of distribution substations equipped with energy storing and bidirectional energy exchange capability enable peak load shaving and demand response, which will reduce the need for new investments into building new power sources or electric power grids to meet peak demand. While the state of the art in the field analyses mainly different theoretical microgrid topologies and integration of unidirectional distributed energy resources, focus in this paper is on practical issues regarding bidirectional energy exchange, which can provide solutions to microgrid manufacturing enterprises. Protection and control functions of the low voltage part of the distribution substation must be tested prior to exploitation. The new testing method for substations includes both computer simulations and practical verifications for automated energy exchange. Simulation results can be used to define and optimize parameters for protection and control functions before constructing a real microgrid. Functions of an experimental microgrid application were simulated with MATLAB, which showed that several prosumers can be served simultaneously and effectively utilized for peak shaving of utility network loads. The results of the simulations were used to develop sample control algorithms and program modules for the substation controller of the experimental microgrid prototype.

Keywords: bidirectional power flow, electric vehicles, microgrids, smart substation, substation testing methods

Razvoj testnih metod za pametne postaje s proizvajalci-porabniki

Izvleček: Članek predstavlja koncept načrtovanja in realizacije novih testnih metod za distribucijske postaje, ki oblikujejo mikro omrežje s proizvajalci-porabniki. Distribucijske postaje nastopajo kot ponudniki storitve za distribuirane enote virov v mikro omrežju in so lahko uporabljene za dvosmerni pretok energije med proizvajalci-porabniki, kot so električna vozila, hranilne enote in omrežja. Uporaba distribucijskih postaj s hranilniki energije omogoča rezanje vrhov porabe in odzivnost porabe, kar zmanjšuje potrebo po novih investicijah v nove proizvodne kapacitete, ki bi pokrivale vrhno porabo. Medtem ko se trenutne analize osredotočajo na različna teoretična mikro omrežja z enosmernim pretokom energije, ta članek opisuje praktične vidike dvosmernega pretoka energije in nudi rešitve proizvajalcem mikro omrežij. Pred uporabo distribucijskih postaj je potrebno testirati zaščite in kontrolne funkcije. Nove testne metode vključujejo računalniške simulacije in praktična preverjanja avtomatiziranega prenosa energije. Simulacijski rezultati so lahko uporabljeni za načrtovanje in optimizacijo zaščit in kontrolnih funkcij realnih mikro omrežij. Funkcije poskusnega omrežja so bile simulirane v MATLABu. Rezultati so pokazali, da se lahko oskrbuje več proizvajalcev-porabnikov hkrati, ki učinkovito omogočajo rezanje vrhov porabe energije. Rezultati so bili uporabljeni za razvoj kontrolnih algoritmov in programskih modulov za kontrolo postaj prototipnega mikro omrežja.

Ključne besede: dvosmerni pretok energije, električna vozila, mikro omrežja, pametne postaje, testne metode

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1 Introduction

Smart Grids and microgrids have attracted much attention due to the increasing awareness of energy conservation and environmental problems. Use of different prosumers (e.g. modern electric vehicles) and their effective integration into electric power grids depends on the technologies applied around distribution substations. The concept of a prosumer has two common meanings: a union of words of a producer with a con-

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sumer or a professional consumer [1]. "Producing consumer" type of a prosumer either generates energy or consumes energy. A "professional consumer" is a well-educated, skilled consumer who commonly makes smart purchasing or selling decisions using additional information [1], [2]. Integration of prosumers to electric power grids is beneficial both to utility networks and prosumers. Prosumers can consume or generate electric energy and improve reliability of electric power supply (e.g. peak shaving, frequency regulation, voltage sags) by integrating renewable energy resources to electric power grids more efficiently. Prosumers can earn additional money with selling ancillary services to utility networks.

In energy trading, the role of distribution substations will increase when different types of prosumers are connected to their output bays. In this paper, mainly electric vehicles (EV) with Li-Ion batteries or battery energy storage unit (BESU) applications are considered as prosumers. EVs with vehicle-to-grid (V2G) capability can be charged or discharged through substations. Other types of prosumers that could be connected with distribution substations are generators (e.g. photovoltaic), energy storage units (e.g. supercapacitors, electrolyser, flywheel) or different subsystems (e.g. other bidirectional distribution substations, microgrids or smart homes).

The aim of this paper is to develop a new testing method for the next generation distribution substations (smart substations), which includes optimization of requirement validation algorithms and testing scenarios (defined according to the rules of testing functions), and selecting proper parameter values for protection and control functions. The method can be applied in the construction of new distribution substations (existing substations are typically designed for given purpose and do not have reserve space to expand to include energy storage).

The developed method will be used in the construction of an experimental microgrid prototype. For transparency, example control topologies for the substation controller are presented.

The paper is divided into ten main parts. Parts 2 and 3 describe the state of the art of smart substations and the proposed topology for smart distribution substation. Part 4 describes the state of the art of substation testing methodology. Part 5 introduces the new approach to substation development methodology. The substation organization and control architecture are firstly described and simulated according to the requirements, then saved for reuse in a repository. The results are practically verified during the experiments, using the experimental microgrid, and production cycle of the smart substation, and finally accepted by prosumers. General functional requirements and parameters are defined for distribution substations with prosumers (BESU and EV). Part 6 discusses the principles of the development and testing of control algorithms for the central controller of the distribution substation. Part 7 describes simulation of the control functions for bidirectional energy exchange between Li-Ion prosumers and the utility network with MATLAB Simulink. Parts eight and nine discuss the principles of testing novel distribution substations and the data required during the tests from prosumers. Finally, future studies and conclusions are presented.

2 State of the art of smart substations

Several papers have addressed microgrid (distributed resource island systems according to IEEE 1547.4) architectures [3]-[8], V2G architectures [9], [10] and bidirectional converter topologies [11], [12]. However, research papers regarding testing of microgrids or presenting technical analysis about control functions for automated bidirectional energy exchange between distribution substations and several prosumers are scarce. Several papers have addressed the concept of virtual power plants (VPP) [13], [14], but no technical analyses show how the concept could be realized in real applications.

Some reports address the testing of distributed resource units [15], PV [16] or V2G [17] applications and energy storage systems [18], [19], but not regarding prosumers in general.

Some companies are using the term "smart substation" [20] to describe substations, which only monitor and transmit data to a microcontroller or outside server. These types of substations include no devices e.g. for suppressing harmonics [21] or providing uninterruptible power supply.

Today's smart substations are either in the planning or in the prototype phase. Few projects can be found in field testing [22], [23].

It can be concluded that distribution substations for integrating prosumers to electric power grids are still in the development phase. IEEE 1547 standard presents mandatory requirements [24] for interconnection itself and testing. IEEE 1547 standard is not a design handbook or application guide. Thus, it is necessary to solve how to construct next generation distribution substations and how to test these substations.

3 Topology of distribution substation for integrating prosumers with utility network

Transformer substations are part of the electric power system concentrated in a given place to transmit electric energy, distribute power and step up or down the voltage. Substations for medium voltage grids (typically 6-24 kV) transform 3-phase medium voltage to 3-phase AC low voltage (typically 400 V AC).

State of the art distribution substations do not include bidirectional energy exchange capability between prosumers, LV side consumers and utility network. Next generation distribution substations could control electric power quality in a local area, maximize benefits for prosumers and owners of microgrids, integrate several prosumers to electric power grids (e.g. large EV parking lots).

An example of a distribution substation topology for microgrids is presented in Fig. 1.

The substation consists of a MV switchgear, a transformer and a low voltage (LV) switchgear (with switches, smart meters, contactors and power converters). The substation allows bidirectional energy exchange between all the prosumers and consumers that are connected with the integrated AC & DC bus, and transfer energy to the utility network. Prosumers are connected either to behind AC/DC power converter with a common DC bus or to a common AC bus. For every prosumer in the common DC bus separate protection and switching apparatuses are available at the DC side.

The BESU in the substation is connected with the common DC bus. The DC bus voltage can float in the specified voltage range to increase the efficiency of energy conversion. For example, the BESU can support fast charging of EVs, provide backup energy and power capability for a utility network power outage. As the number of renewable energy sources is increasing in the grid (e.g. wind and solar energy), the balancing of excess generation sources and load demands can be controlled through the substation. This enables stabilization of the grid AC voltage and frequency [23].

The presented distribution substation topology is beneficial mainly to the future owners of a microgrid (e.g. manufacturing enterprises) for controlling energy storage and usage inside the microgrid. The master controller of the substation can be adjusted (e.g. scheduling, trading, optimization) according to the needs of the future owners of the microgrid.

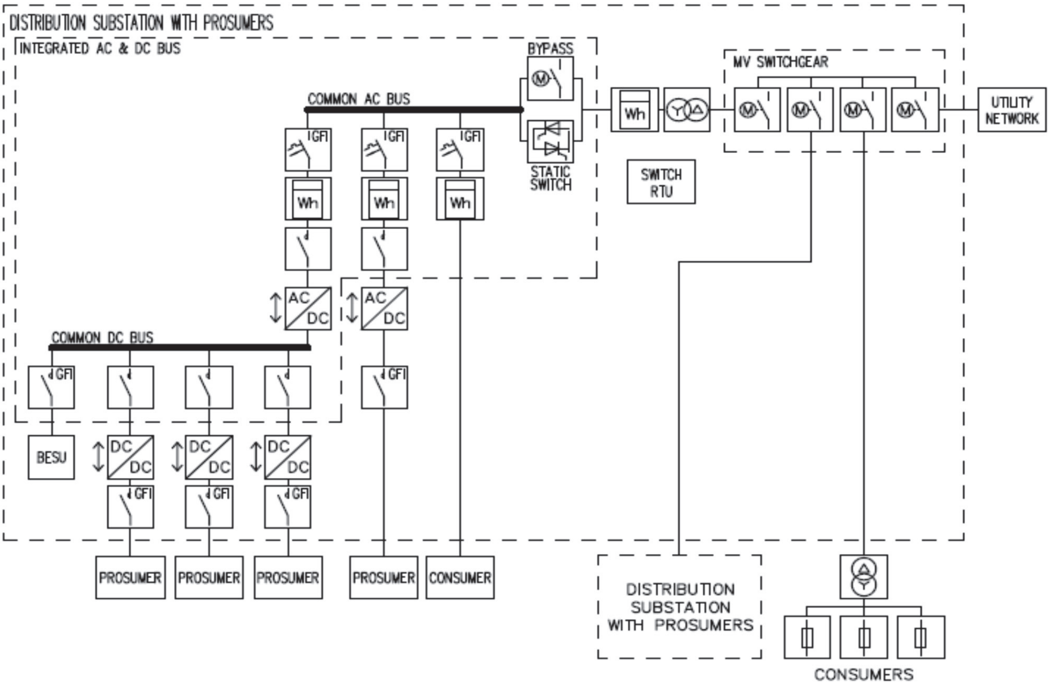


Figure 1: Topology of a distribution substation with an integrated AC & DC bus and prosumers for microgrid applications.

4 State of the art of substation testing methodology

Ordinary substation testing is divided into factory routine tests and field tests [25]. Factory routine tests are divided into visual tests, mechanical tests and electrical tests.

During visual factory tests, a general check is carried out to ensure the hardware is in accordance with project documentation, there exist no errors of assembly and all labels are correct. Also the absence of leakages will be checked.

The tightness of all electrical and mechanical connections will be checked during factory tests.

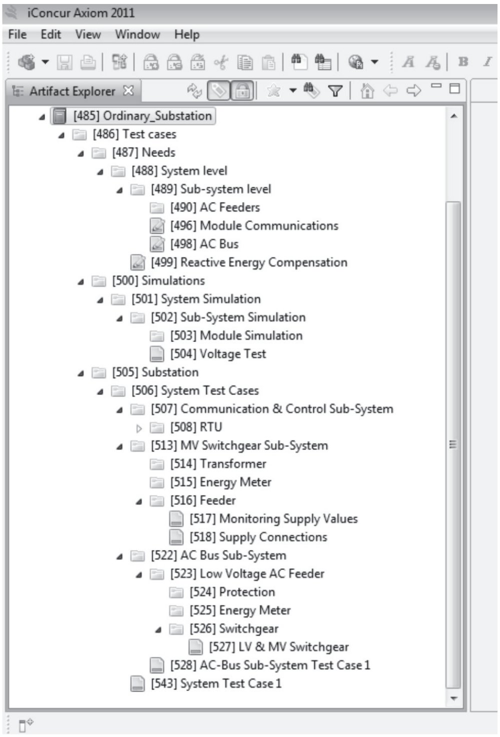
Electrical factory tests include: installation correctness (topology), wire insulation resistance and tests of protection and switching apparatus. Transformer parameters will also be checked [25]. A very important part is to test the substation under nominal current and voltage (separately).-

Substation field tests are is similar to factory tests. During mechanical field tests, only the connections installed on site will be tested. Electrical field tests measure the insulation resistance of only those cables which are installed on site. Protection systems and switchgear will also be tested on site. The testing methodology details will vary in different countries and legislative areas. [26], [25], [27].

The information structure (testing requirements, testing methods, test cases, functional descriptions and other detailed views as source texts of control programs) of an ordinary substation can be represented using a requirements definition software e.g. Axiom (Fig. 2).. The collected information is used as reference during optimization, validation, and verification processes.

The software allows parallel use of requirements information, simulation and verification data enable faster validation of microgrid projects.

Independent certification of specified and tested microgrid modules, such as energy storage systems, can reduce installation time at customer site from weeks to hours, since certification transforms energy storage from a nascent technology into a safe plug-and-play appliance. After the integration of the system (substation, prosumers and utility), main use cases need to be tested. The verification process commonly demands rigorous testing and evaluation and is a time consuming and costly process.



- [485] Ordinary_Substation
  - [486] Test cases
    - [487] Needs
      - [488] System level
        - [489] Sub-system level
          - [490] AC Feeders
          - [496] Module Communications
          - [498] AC Bus
        - [499] Reactive Energy Compensation
    - [500] Simulations
      - [501] System Simulation
        - [502] Sub-System Simulation
          - [503] Module Simulation
          - [504] Voltage Test
    - [505] Substation
      - [506] System Test Cases
        - [507] Communication & Control Sub-System
          - [508] RTU
        - [513] MV Switchgear Sub-System
          - [514] Transformer
          - [515] Energy Meter
          - [516] Feeder
            - [517] Monitoring Supply Values
            - [518] Supply Connections
        - [522] AC Bus Sub-System
          - [523] Low Voltage AC Feeder
            - [524] Protection
            - [525] Energy Meter
            - [526] Switchgear
              - [527] LV & MV Switchgear
          - [528] AC-Bus Sub-System Test Case 1
        - [543] System Test Case 1

Figure 2: Screenshot of testing requirements for ordinary distribution substation.

5 New approach to substation development methodology

The substation testing methods, which were described in the previous part of this paper, are included in the construction of a new methodology. The new methodology is based on a software development methodology (X-model) and is visually represented in Fig. 3. During software testing, it is useful also to follow IEEE standard 829-2008 recommendations. The Requirements box (including e.g. application software functional requirements, substation user requirements, use cases etc.) is visualized in the left-upper part of Fig. 3. Documentation and repositoring is visualized in the left-lower part of Fig. 3. Prototype construction is visualized in the right-lower part of Fig. 3. Producing is visualized in the right-upper part of Fig. 3.

Next chapters of the paper introduce some control aspects of the smart substation and their testing methods.

Functional requirements and parameters for distribution substations with prosumers are described in different standards (e.g. IEEE 1547.1 and VDE-AR-N 4105 [28]).

IEEE 1547.1 standard describes test procedures for equipment interconnecting distributed resources (e.g. prosumers) with electric power systems. In addition, the German standard VDE-AR-N 4105 provides for the improved network integration of decentralized power generation (in particular, inverter-based generators).

During normal operation, the magnitude of the voltage change caused by the generating prosumers must in any connection point not exceed a value of 3 % compared to the voltage, when the generating prosumers were not connected. Voltage change of 3 % in the connection or disconnection with the distribution substation should not occur more frequently than once every 10 minutes.

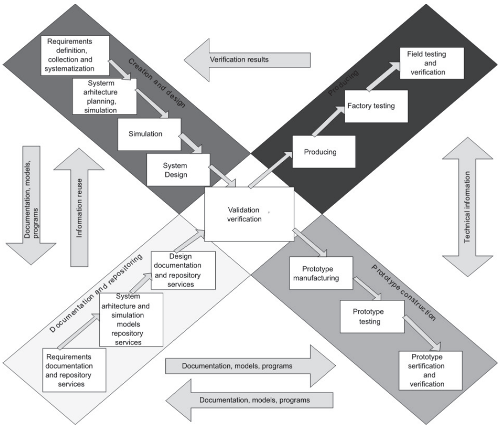


Figure 3: Substation testing methods in the developed methodology.

VDE-AR-N 4105 specifies the disconnection of inverters connected to the LV network due to grid side disturbances [29]. When the voltage variation (undervoltage, overvoltage) exceeds the limits $80\%U_n<U_{pcc}<110\%U_n$, disconnection is necessary within 100 ms. In case the upper limit is exceeded, according to EN 50160, inverters must shut down. If the frequency limits $47.5Hz<f_n<51.5Hz$ are exceeded, the inverters must disconnect in 100 ms. The inverters are allowed to reconnect after a fault, when the following conditions are satisfied: $85\%U_n<U_{pcc}<110\%U_n$, $47.5Hz<f<50.05Hz$, minimum delay of 5 s. The specific behaviour of the inverters and controlled rectifiers under a grid faults is very important, since it is desired that the system avoids disconnection as much as possible.

Frequency variation is a common problem which affects power systems. To avoid unbalanced conditions, distribution substations serving prosumers must be capable of adjusting power production by means of frequency regulation. Generating substations with the capacity over 100 kW have to reduce their real power in steps of at most 10 % of the max. active power [29]. Generating bays have to reduce their power output with a gradient of 40 % Hz, when a 50.2 Hz frequency limit is surpassed. The output power is allowed to increase again when the frequency is below 50.05 Hz. Outside the frequency limits, the bays have to disconnect from the grid. Controllable substations have to reduce the power output to the target value within a maximum period of time of 1 minute. If the set point is not reached in the mentioned time period, the generating prosumers must be disconnected.

6 Testing of control algorithms for the central controller of the distribution substation

The Remote Terminal Unit (RTU) acts as a central controller in the substation and also as the master in a microgrid. Each prosumer might include its own control unit handled as a slave device that serves the purpose of controlling prosumer related lower level tasks. The RTU operates the substation in general, while the functionality of safe and fast fault response is handled by protection apparatus (fuses, circuit breakers etc.). The purpose of the powerful RTU is to read the status and operational parameters of microgrid prosumers, to send control values and configuration information to the slave devices, to control bidirectional energy exchange between prosumers and the utility network (control of prosumer and utility bays), and to perform the following functions: scheduling, electricity trading (with electricity retailer), grid constraints observer (retrieve information from distribution system operator) and interface provider to EV owners (e.g. departure time, energy prices). In regard to the topology (e.g. integrated AC & DC bus) chosen, each bay for a prosumer might include its own slave controller or the central RTU could control all prosumer bays itself.

Communication between intelligent electronic devices (IEDs) of the next generation substation, including RTU and prosumers, should be realized with the IEC 61850 protocol [1] as much as applicable. The IEC 61850 protocol uses Ethernet as the basic communication technology, currently at a speed of 100 MBit/s. Different protection and control functions should be scattered between substation devices in order to speed up data flow between the devices [30].

Control algorithms for the RTU have to be tested prior to the exploitation of the distribution substations. This requires verification of the protection and control algorithms both in the simulation and laboratory environment, and then in factory testing.

Before any energy exchange in either direction can be executed, the communication side must be tested with data retrieval and sending. If the communication link is available and safe, data is being polled by RTU from the prosumer. For example, for EVs it is required to monitor the battery current and temperature in order to protect the prosumer during charge and discharge, thus it is necessary to gather the following data about the battery of the prosumer: state of charge (SOC), state of health (SOH), battery pack open circuit voltage, measured temperature values and nominal values of various BMS predefined parameters (rated capacity, maximum and minimum values of battery pack voltage, SOC levels, current and temperature).

To provide the best service to the prosumer (e.g. owner of the EV), the RTU needs data about the maximum possible time period the prosumer could stay connected to the microgrid, minimum SOC level required before departure and an agreement from the prosumer to allow partial discharge of the battery, which would be compensated according to the agreement with the service provider. This information can either be received remotely by the RTU or partially entered using a user interface (human to machine interface (HMI) panel, smartphone application etc.).

After testing the communication, protection functions have to be tested in order to evaluate and determine whether it is safe to proceed or not. This requires the presence of the main supply for testing. The algorithm for the RTU contains many protective functions:

- AC side protection functions are mainly realized by intelligent bay controllers (e.g. modern smart meters), ensuring that voltage and frequency are in the determined range and current values do not exceed defined maximum values. Digital input data from smart meters for the RTU:
  - automatic or manual mode of charge,
  - AC side circuit breaker closed,
  - positions of AC side contactors,
  - positions of the isolation monitoring devices
  - power related quantity values,
  - faults.
- DC side protection functions realized by the RTU for each bay ensure that DC side primary and auxiliary voltage values are in the determined range, current values do not exceed maximum values. Digital input data:
  - positions of DC side circuit breakers and contactors,
  - positions of isolation monitoring devices,
  - EV connector locking.
- General protection functions realized by the RTU ensure that parameter values of prosumers' BMSs and power converters are in the determined range, active monitoring of AC and DC side protection inputs, emergency stop pushbuttons not activated, connection termination not required by EV owners.

It must be verified that all data is being collected and logged by the RTU in order to generate operation and error reports.

If any of the criteria set by the protection functions is not met, the charge or discharge of prosumers must not be allowed and should be interrupted (soft stop) if a fault occurs during a process. All critical protection functions are carried out redundantly, independent of the RTU, and will be triggered automatically (hard stop) when fault conditions occur.

When the general protection functions have been tested, the RTU processing side can be tested. When no error conditions are present, the RTU must calculate the process values using polled and user defined data. Data used from processing must activate the AC/DC and DC/DC power converters in the predefined sequence and parameters values are to be downloaded to the power converters. Contactors behind DC/DC converters (at DC bus side) allow the switching of DC voltage to prosumers when DC/DC converters are ready in the buck mode. Contactors before DC/DC converters allow the switching of DC voltage to the common DC bus when DC/DC converters are ready in the boost mode. The position and status data of prosumer bay devices are transferred to the RTU for signalling purposes, for example, which substation bays are currently online and exchanging energy with prosumers (offline bays are reported in error reports).

If it has been verified that protection functions and operation of power converters run according to the control algorithm in RTU, predefined control algorithms for the system can be tested. The tests are based on typical use cases.

6.1 Charge

Figure 4 presents an example of an action flow chart for a prosumer charging use case (operation) [31]. Table 1 specifies the abbreviations and parameters used in Figs. 4 and 5. The command for charging is initiated by the prosumer (EV or BESU user). Some EVs need to follow the CHAdeMO protocol [32]. For EVs, the charging start signal is sent to the EV. If protection functions are fulfilled, AC contactors for AC/DC converters positioned in front of the common DC bus are closed. AC/DC converters will receive target output voltages and power values from the RTU and will be set to rectifier mode. DC/DC converters are operating in the buck or boost mode. The DC/DC converters will receive target secondary side output voltage and power values from the RTU. If the common DC bus voltage is in range by the AC/DC converter, contactors on the primary side of the DC/DC converters are closed. When the DC/DC converter output voltage is in range, the BESU's BMS is set to the charge mode. For EVs, the connector is locked and the isolation test is performed, also contactors of the secondary side of DC/DC converters are closed. At the beginning of the charging process the SOC level of prosumers will determine whether the charge is performed with a slow current value, constant maximum current value or with constant voltage. The choice of the charging mode will be adjusted in accordance with the battery SOC value. For EVs charging is stopped at the zero current signals or timeout from the EV side. Depending on the location of fault detection, fault events will immediately open the adjacent switching apparatus.

6.2 Discharge

Figure 5 presents an example of an action flow chart for a discharging use case (operation) [31]. The command for discharge initiates the function for the selection of a prosumer type (EV or BESU user). For EVs the connector is locked and the isolation test performed. Contactors of the secondary side of the DC/DC converters are closed, the DC/DC converters receive a target for the primary side output voltage and power values from the RTU. When the output voltages of DC/DC converters are in range, the contactors of the primary side of the DC/DC converter are closed. Active power is transferred to the common DC bus. AC contactors for AC/DC converters (that are installed before the common DC bus) are closed if energy flow is directed from DC bus to AC bus side.

AC/DC converters will be set to the inverter mode and the RTU determines the target output power value for the AC/DC converter. The AC/DC converter synchronizes with the common AC bus voltage and power is transferred to the common AC bus. The time of discharge of prosumers (EV, BESU) depends on the quantity of resources acquired from the substation to perform its service providing. Discharging of prosumers is stopped when the depth of discharge, maximum discharge current or temperature is exceeded or the SOC value drops below the value defined in the manufacturer specifications [33]. Switching apparatuses are opened and operation of power converters stopped according to the determined sequences (determined stop or fault detection).

Table 1: Abbreviations and parameters in figs. 4 and 5

START	program cycle start
Check. Comm	communication check function
Status.Comm	communication status data object
Status.Comm.Err	communication error status
Poll	function to poll data from the prosumer
Data	RTU internal database for process values
Protection	function for carrying out protection functions
Calculate Process Values	function for calculating process values
Data.Prot.AC_B_err	AC bus error data object
Data.Prot.DC_B_err	DC bus error data object
Data.Pros.Chrg	prosumer charge command data object
Data.Pros.DsChrg	prosumer discharge command data object
Wake BESU	BESU wakeup function
Sleeping P-conv. to stand-by	function for setting power converters currently in sleep mode to stand-by
Close AC contactor	AC contactor closing function
Write process data to conv.	function for writing process data to converters
Write DC/DC conv. val	function for writing DC/DC converter process values
Write AC/DC conv. val	function for writing AC/DC converter process values
Set AC/DC conv. To Rectifier m.	function for setting the AC/DC converter to operate in the rectifier mode
Set AC/DC conv. to Inverter m.	function for setting the AC/DC converter to operate in the inverter mode
Set DC/DC conv. to Buck m.	function for setting the DC/DC converter to operate in the buck mode
Set DC/DC conv. Boost m.	function for setting the DC/DC converter to operate in the boost mode
Data.Pros.DC_PBus_U_OK	DC prosumer primary bus voltage status data object
Close DC/DC conv. prim. Cont.	function for closing the DC/DC converter primary side contactor

Data.Pros.DC_ SBus_U_OK	DC prosumer secondary bus voltage status data object
Data.Pros.DC/ DC_Rdy	prosumers DC/DC converter ready state status data object
Data.Pros.Cap_DisCh	prosumers DC/DC converters capacitors need for discharge status data object
Data.Proc.Synch_OK	AC/DC converter AC output in synchronization with the AC bus status data object
Close DC/DC conv. sec. cont.	function for closing the secondary contactor of the DC/DC converter
Open DC/DC contactors	function for opening the primary and secondary contactors of the DC/DC converter
D.chrg DC/DC conv. cap	function for discharging the DC/DC converter capacitors
Close AC/DC Conv. AC cont.	function for closing the AC contactor of the AC/DC converter
END	end of program cycle

7 Simulation of bidirectional energy exchange between prosumers and utility network

Before microgrid system integration tests, (typical) use cases are to be simulated (visualized in left part of Fig. 3). This is done before prototype, factory and field tests, which are carried out using real hardware (visualized in right part of Fig. 3). Computer simulations provide a first testing environment for different control algorithms, allow optimization of energetic parameter values and a selection of devices for protection and control functions. Figure 1 shows a distribution substation topology that is similar to the topology simulated using the MATLAB Simulink model (Fig. 6) [31]. The model consists of 24 kV utility network supply through an MV switchgear, a 250 kVA voltage transformer 24/0.4 kV and an LV switchgear, which interconnects consumers and prosumers. The LV switchgear is divided into a common AC bus and a common DC bus. In this paper the BESU, (including Li-Ion battery pack with the nominal voltage of 460 V DC) is considered as prosumer in the MATLAB Simulink model. Other prosumers are connected with the common DC bus through bidirectional DC/DC power converters DCDC1-DCDC3 (double-leg full bridge DC/DC power converter topology with galvanic isolation). Contactors are included in the bays before and after the bidirectional DC/DC power converters. The common DC bus is supplied through a 100 kVA bidirectional AC/DC power converter ACDC1 (three-level neutral point clamped voltage sourced converter). The common DC bus voltage can be adjusted up to 800 V DC. Consumers consuming 100 kVA to 200 kVA are connected with the common AC bus.

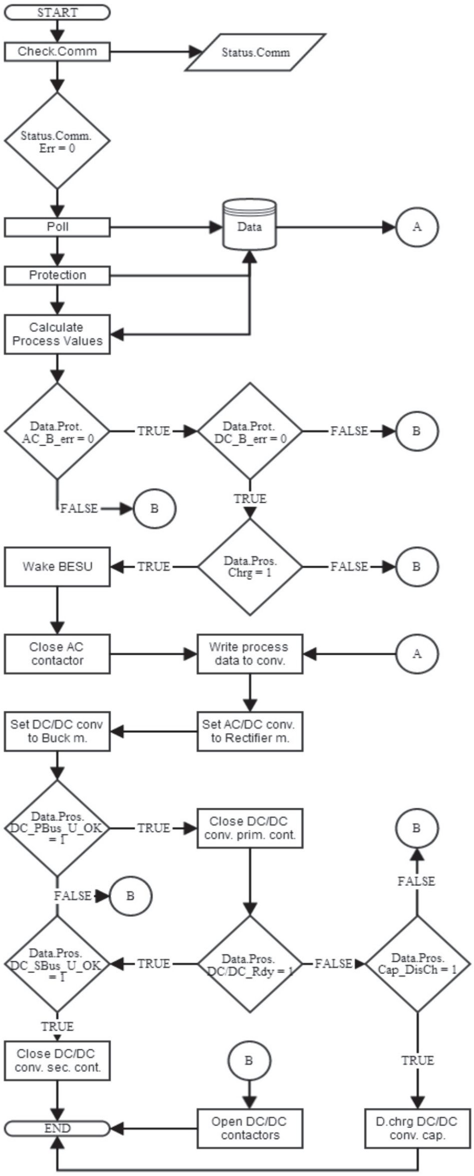


Figure 4: Action flow chart for the prosumer charging operation.

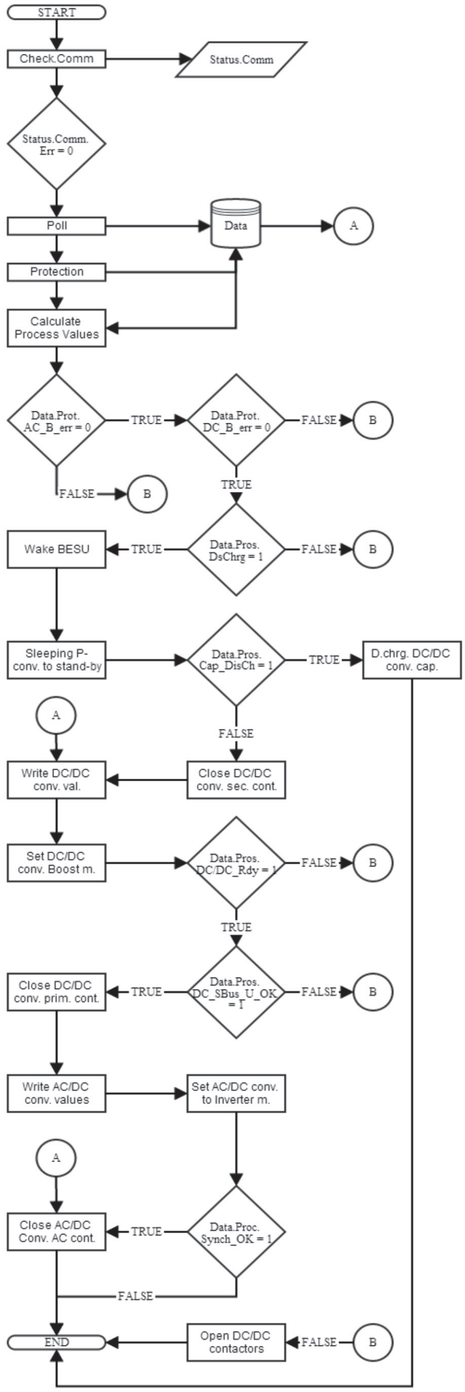


Figure 5: Action flow chart for the prosumer discharging operation.

The purpose of the MATLAB Simulink model is not to simulate a particular bidirectional AC/DC or DC/DC power converter, but rather to evaluate control functions (scripts) for bidirectional energy exchange and power distribution between the prosumers and the utility network. The simulated, tested (using the experimental prototype in laboratory) and verified control algorithms describing the control functions will be downloaded to a substation controller during the production of such a smart substation.

Some important systems integration tests can be carried out out much faster if user requirements, data models (systematized by developers) and the data values collected during simulations, laboratory experiments and factory tests are available also during site tests. Parallel recording and using the requirement information, simulation and verification data enable faster validation and approval of a microgrid project.

Independent certification (described in part 4 and visualized in lower right part in Fig. 3) can significantly reduce installation time spent at customer site.

During simulations, firstly, the consumer stage of a single prosumer (PROSUMER1) is examined. The bidirectional AC/DC converter ACDC1 operates in the rectifier mode and supplies the common DC bus.

The bidirectional DC/DC power converter DCDC1 in the prosumer bay operates in the buck mode. The results from the simulated model are presented in [31]. The charging current is ramped up smoothly and maintained at constant current level with the rising of the internal voltage of the Li-Ion battery pack.

Secondly, the producer stage of prosumers is examined. All three prosumers (PROSUMER1-PROSUMER3) provide support to the common DC bus. The support is utilized, for example for the peak shaving of the 200 kW load of the consumers for the utility network. The target goal is to reduce the load of the consumers for the utility network to 100 kW. The bidirectional DC/DC power converters DCDC1-DCDC3 operate in parallel in boost mode. The bidirectional AC/DC power converter ACDC1 operates in inverter mode and supplies the common AC bus. The results from the simulated model are presented in [31].

The simulations also help to define value ranges of resistances of possible electrical circuits. Internal resistance R_i of generating/consuming prosumers can be calculated and later tested from the voltage drop/rise ΔU during energy exchange with a constant current I. Designed BESU energy density can be predetermined by simulations. Effective gravimetrical energy density

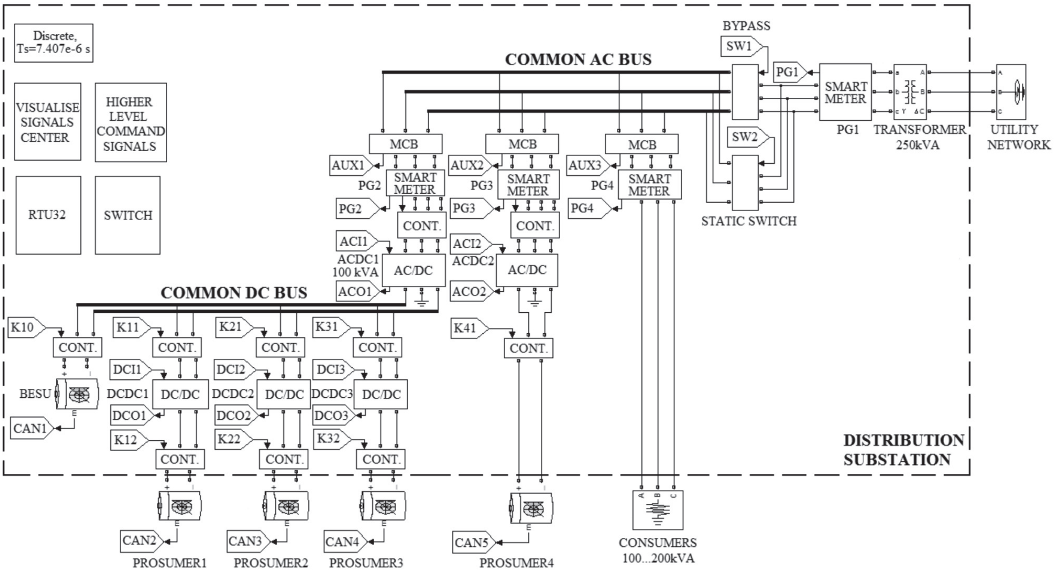


Figure 6: MATLAB Simulink model of a distribution substation with prosumers.

of modern lithium-ion batteries is about 100 to 265 Wh/kg.

Power density or the time rate of energy transfer is either measured gravimetrically (kW/kg) or volumetrically in kilowatt per litre (kW/l). Power density combines the energy density with the speed at which the energy can be delivered from one prosumer to the other or can be absorbed by a load. The actual speed is characterized by electric current.

The maximum power of an electric circuit is given by the formula $P_{max} = U^2/R_i$, where U is voltage applied and R_i, is the internal resistance of the circuit. The P_{max} specifies the power of a rectangular single maximum current peak of a given voltage. In reality the current peak is not rectangular caused by time constants and the voltage change is caused by the voltage drop. For supercapacitors the IEC 62391–2 standard therefore proposes a formula to calculate a more reality oriented effective power P_{eff} for power applications:

$$P_{eff} = \frac{1}{8} \times \frac{U^2}{R_i} \qquad (1)$$

8 Test method for smart substations

Protection and control functions of smart substations have to be tested prior to exploitation. This includes running computer simulations, factory testing and onsite tests. Table 2 presents an example testing protocol for distribution substations that includes BESU and providing services for prosumers. For factory testing of the substation a variable voltage and frequency supply unit, load simulator and a test prosumers (e.g. EV and emulated PV plant that is based on programmable DC source) are required.

The testing method sequence begins with general routine tests for LV & MV switchgears, RTU and distribution substation. Settings and parameters need to be downloaded to devices and HMI.

Computer simulations verify the designed control algorithms and provide dynamic values (e.g. voltage and current values), which can be used for adjusting settings for protection and control devices. Differences between simplified computer simulations and practical test results should not exceed 10 %.

When the testing has been prepared, test supply unit can be connected and the behaviour of the system monitored.

Before connecting test loads, bays of the distribution substations must be prepared. This requires verification that protection functions run properly. Protection functions should be dependable (will operate when required), secure (will not operate when not required), selective (respond to events within their zones). Bay parameters have to be inserted and control of bays through RTU has to be verified. At the end of the preparation of the bays the operation of power converters has to be tested.

After preparations and supply connection, test loads can be connected. Data retrieval and controllability of the prosumer's local controller (BMS) must be verified. Consumption and production stages (e.g. charging and discharging of the test EV) can be then tested for test prosumers and BESU.

IEEE 1547.1 type (design) tests are included in Table 2. The temperature stability test verifies that interconnection equipment maintains measurement accuracy of parameters over its specified temperature range. Abnormal voltage and frequency test verify that the system ceases to energize the area electric power system (EPS) in abnormal conditions. The synchronization test demonstrates that interconnection equipment will accurately and reliably synchronize to the area EPS. Interconnection integrity tests include verification for protection from electromagnetic interference (EMI), surge withstand performance and dielectric tests on the paralleling device. DC injection test verifies that the system complies with the DC current injection limit. Function tests include means to determine that the system ceases to energize the area EPS in unintentional island condition and loss of phase. Reconnect time test verifies the functionality of the reconnect timer in trip event. Harmonic tests measure individual current harmonics and total demand distortion (TDD).

IEEE 1547.1 production test verifies the operability of every unit of the interconnection equipment manufactured for customer use. Commissioning tests (onsite tests) are conducted after the interconnection system is installed and is ready for operation. Flicker tests are site dependent.

Onsite testing is vital prior to exploitation to verify that all the protection and control functions run properly. Specific functions like peak shaving, frequency droop control, reactive power compensation and intentional islanding can be monitored and test results protocolled. Time response to unintentional islanding should be 2 s according to IEEE 1547 requirement. During onsite testing the remote controllability of the distribution substation for the utility network can be verified. Some functions of the distribution substation have to be monitored over a longer period of time. These functions include ambient temperature tests to verify how much the prosumers and BESU can actually support in the production stage at different ambient temperatures (e.g. in winter and summer periods). The data can be used for accurate forecasting. The operations of data storing and scheduling functions must be verified.

Table 2: Testing protocol for distribution substation

No.	Description of test sequence	Status
	Factory tests	
1.	**Preparation for testing**	
1.1.	Routine tests for LV & MV switchgears and distribution substation	
1.2.	RTU testing (data retrieval, control of outputs)	
1.3.	Computer simulations for protection and control settings	
1.4.	Download of parameters and settings to power converters and smart meters	
1.5.	HMI set-up	
2.	**Connection of test sources and communications**	
2.1.	Supply connection	
2.2.	Monitoring of supply values (e.g. voltage, frequency)	
2.3.	Communication set-up and data flow	
3.	**Preparation of bays**	
3.1.	Protection ensured, interlocking of bays	
3.2.	Nominal, max. and min. values inserted for bays	
3.3.	RTU connection sequences (e.g. operation of contactors)	
3.4.	Activation of AC/DC and DC/DC power converters	
3.5.	Control response and data retrieval of AC/DC and DC/DC power converters	
4.	**Connection of test loads and BESU**	
4.1.	Data retrieval and controllability of prosumer controller (BMS)	
4.2.	Execution of example charging test sequence	
4.3.	Report from charging sequence (protection status, control functions, power quality)	
4.4.	Execution of example discharging test sequence	
4.5.	Report from discharging sequence (protection status, control functions, power quality, voltage rise, time responses)	
4.6.	DC input mismatch wiring test	
4.7.	First full charge of BESU	
4.8.	BESU functions testing (charge, discharge)	
5.	**IEEE 1547.1 type (design) factory tests**	
5.1.	Temperature stability	
5.2.	Responses to abnormal voltage	
5.3.	Responses to abnormal frequency	
5.4.	Synchronization in production stage	

5.5.	Interconnection integrity	
5.6.	DC injection	
5.7.	Unintentional islanding	
5.8.	Ceases to energize functionality and loss of phase (simulated fault sequences, emergency stop sequence)	
5.9.	Reconnect time and sequence	
5.10.	Harmonics	
6.	**Onsite (Field) testing of complete system behaviour**	
6.1.	Download of parameters and settings of the end user to devices	
6.2.	Peak shaving functional test	
6.3.	Frequency droop control in production stages	
6.4.	VAR management (reactive power compensation)	
6.5.	Power conditioning (PQ) and harmonic suppression	
6.6.	Intentional islanding and resynchronization	
6.7.	Power balancing in islanding mode	
6.8.	Blackstart management	
6.9.	Flicker test (site dependent)	
6.10.	Network communications (control from utility network)	
6.11.	Utility network supply accordance to EN 50160	
6.12.	Ventilation verification for heat extraction	
6.13.	Data storage (metering) and access through cloud applications	
6.14.	Scheduling tests	
6.15.	Ambient temperature tests (production stages of the prosumers and BESU)	
7.	**Conclusions**	
7.1.	Compliance with different international standards (EN 50160, IEC 61000, IEEE 1547.1 etc)	
7.2.	Remarks and limitations	
	Verification	

Table 3 presents an example of a generalized test report of the testing protocol for distribution substations. Different parameters have to be monitored and protocolled at consumption stage and production stage of the prosumers and also during different ancillary functions. The measurement values can be divided into three main categories: prosumer side, common DC bus side and utility network side.

Table 3: Test report with measured values

No.	Description of measurements	Value
	Field testing	
1.	**Prosumer DC side and BESU measurements both for consumption and production**	
1.1.	DC side voltage (start, end)	
1.2.	DC side current (max., average)	
1.3.	SOC values (start., end)	
1.4.	Active power (max., average)	
1.5.	Transferred energy (kWh)	
1.6.	Temperature of prosumer elements and DC/DC power converters (max., average)	
1.7.	Efficiency of DC/DC conversion	
1.8.	Specific energy (gravimetric mE, volumetric VE)	
1.9.	Specific power (gravimetric mP, volumetric VP)	
1.10.	Ambient temperature	
1.11.	Duration of full test and cycle times (e.g. constant current, constant voltage). Sampling rates.	
2.	**Common DC bus measurements during consumption or production of energy by prosumers**	
2.1.	Common DC bus voltage (max., min., average)	
2.2.	Common DC bus voltage unbalance (max., min., average)	
	Field testing	
2.3.	Common DC bus current (max., average)	
2.4.	Temperature of AC/DC power converters (max., average)	
2.5.	Efficiency of AC/DC conversion	
2.6.	Active power (max., average)	
2.7.	Transferred energy (kWh)	
3.	**Utility side measurements during consumption or production of energy by prosumers**	
3.1.	AC voltage (max., min., average, unbalance)	
3.2.	AC current (max., average)	
3.3.	AC frequency (max., min., average)	
3.4.	Active power, Reactive power, Apparent power (max., average)	
3.5.	Power factor (max., average)	
3.6.	Transferred energy (kWh)	
3.7.	Harmonic distortion (THDU, THDI, TDDI) with 1 to N activated prosumers at DC or AC side	
3.8.	Voltage flicker	
3.9.	Total efficiency of energy conversions	

3.10.	Duration times to load/production reduction: 25%, 50%, 75%	
3.11.	Inrush max. current and duration	
3.12.	Isolation monitoring and leakage currents	
4.	**Additional utility side measurements during production of energy by prosumers**	
4.1.	Max. continuous output power	
4.2.	DC current injection	
5.	**Functional test reports**	
5.1.	Clearing time to abnormal voltage (<U, >U)	
5.2.	Clearing time to abnormal frequency (<f, >f)	
5.3.	Clearing time unintentional islanding	
5.4.	Clearing time to simulated faults	
5.5.	Duration time for recovery (from abnormal area EPS values to nominal values)	
5.6.	Duration time for recovery (fault trip clearance)	
5.7.	Duration time to intentional islanding	
5.8.	Duration time to resynchronization	
5.9.	Duration time to blackstart	
5.10.	Duration time to peak shaving (target value, duration time and reference signal tracking error)	
5.11.	Ramp rate to active power production	
5.12.	Active power reduction gradient in frequency regulation	
5.13.	Duration time for VAR Management (target value, duration time, reference signal tracking error)	
5.14.	Duration time for harmonic suppression (target harmonic content, duration time and reference signal tracking error)	
5.15.	BESU roundtrip efficiency	
5.16.	BESU scheduling execution	
5.17.	Standby losses	

The key measured parameters in the test report are the efficiency values of the power converters, overall energy conversion efficiency and maximum continuous output power of the prosumers.

Other important parameters are the stress values for prosumers (current, temperature), power quality measurements at the utility network side (accordance to IEC 61000), clearing times and duration times of different IEEE 1547.1 determined functions and ancillary tasks. From the measured parameters energy density and power density values can be calculated for prosumers and BESU.

9 Configurable values for prosumers

While the main parameters of bays are defined in the designing phase, some of the bay parameters and ancillary services can be adjustable for the prosumers. Table 4 presents an example configurable value list for the bays of the distribution substation, which can be adjusted through HMI. These parameters include nominal, maximum and minimum values of different prosumer side parameters, price and scheduling options when to consume or produce (charge or discharge). Maximum values cannot exceed the limits of the selected devices. Minimum values, in most cases, are limited due to economic reasons or capabilities of the devices. Positions 1.1-1.7 in Table 4 can be inserted and simulated in the MATLAB simulation environment.

Functional settings include different ancillary tasks, threshold values, time delays, time synchronization, BESU side preferences, event/history logging and status reporting/reading. Time delays should provide ride-through for low/high voltage and frequency values.

Table 4: Configurable values for prosumers

No.	Description of values	Value
1.	Prosumer parameter values	
1.1.	Nominal/min/max voltage	
1.2.	Nominal/min/max current	
1.3.	Nominal/min/max charging power	
1.4.	Nominal/min/max discharging power	
1.5.	Maximum capacity (e.g. Ah)	
1.6.	Capability selection for bay: V2G	
1.7.	Maximum DOD (%)	
1.8.	Nominal/min/max temperature	
1.9.	Nominal/min/max prices for charging	
1.10.	Nominal/min/max prices for discharging	
1.11.	Scheduling preferences for prosumers	
2.	Functional settings	
2.1.	Peak shaving option activation	
2.2.	PQ preferences (VAR management or harmonic suppression)	
2.3.	Target cos φ	
2.4.	Individual harmonic compensation list	
2.5.	Load balancing activation	
2.6.	Non-islanding voltage and frequency range	
2.7.	Time delays for ride-through of abnormal conditions	
2.8.	Response times to abnormal conditions	
2.9.	Time synchronization	

2.10.	Scheduling preferences for BESU management	
2.11.	Event/history logging	
2.12.	Status reporting/reading	

10 Future studies

Tallinn University of Technology currently develops a smart substation development methodology and constructing an experimental microgrid that enables us to study energy flows and data communication. Parts of the smart substation development methodology that are not covered in this paper need future studies. The basic functions and operation modes (including protection algorithms) such as energy transmission from the power grid to the energy storing system, EV battery charging, balancing power loads and other functions have to be developed, tested and analysed. The simulated management and control algorithms have to be fine-tuned and will be transferred to the substation RTU (Fig. 7). Data will be collected for further analysis using an iConcur Axiom software. Primary goals are to analyse the quality of energy flow, energy efficiency and harmonic levels during EV charging through the microgrid, electromagnetic compatibility related issues and to improve and apply the testing methodology. The analysis will indicate needs for modifications to be made in the microgrid structure to optimize and improve the overall efficiency and power factor levels in the system to ensure the quality of electricity in accordance with international standards.

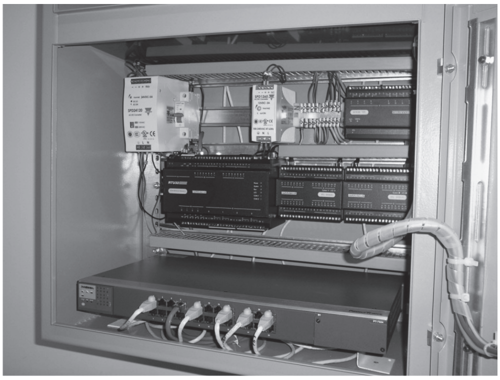


Figure 7: View of an experimental setup with RTU devices for microgrid experimentations.

Practical applications will show possible drawback areas in the communication between the devices, which will then have to be solved with different control algorithms. Future studies will focus on development of a prototype microgrid and on possibilities to transfer energy to the common AC bus or to the power grid with synchronization related issues. Results from microgrid experiments will be published in future papers. Advice and warnings of issues to be aware of for smooth and accurate testing will be provided.

11 Conclusions

This paper has reviewed a developed testing method for distribution substations which form a microgrid with prosumers. Topology of the substations has been presented with an integrated AC and DC bus. The topology enables providing simultaneously services to prosumers, consumers and utility network. It has been proven through simulations that an integrated AC and DC bus (Fig. 1) can be the main topology solution for integrating prosumers with different nominal voltages to electric power grids. Simulation results have verified that bidirectional energy exchange between the utility network and prosumers can be used for peak shaving of utility networks loads.

In microgrid applications a distribution substation can be viewed as an energy router and it is the function of the substation's main controller in the higher level to determine when to utilize prosumers for ancillary services.

This paper has presented a new testing protocol for distribution substations. The testing procedure includes running computer simulations, prototype tests (using laboratory tests for substation and microgrid integration), factory tests and onsite tests.

Before constructing a real life substation, a smaller stand has to be constructed and examined. An experimental microgrid is being constructed at Tallinn University of Technology. Experiments with the microgrid will give vital data about charging/discharging algorithms and communication between the devices. These studies will enable us to construct a larger real life substation capable of supplying power to several prosumers that will be part of a microgrid or even a viable module of Smart Grid solutions.

Acknowledgment

This research work has been supported by European Social Fund (project "Doctoral School of Energy and Geotechnology II"), Estonian Ministry of Education and Research (project SF0140016s11), Estonian Science Foundation (Grant ETF9350), Estonian Archimedes Foundation (project AR10126), SmartGrids Era-Net (project GERA1) and European Regional Fund.

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa conducted by Foundation Archimedes.

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Arrived: 17.9.2013
Accepted: 8.5.2014

Publication IV

Korõtko, T.; Mägi, M.; Peterson, K.; Teemets, R.; Pettai, E. (2013), “Analysis and Development of Protection and Control Functions for Li-Ion Based Prosumers Provided by Low Voltage Part of Distribution Substation,” In: 8th International Conference-Workshop Compatibility and Power Electronics, CPE 2013 (19−24). IEEE.

Analysis and Development of Protection and Control Functions for Li-Ion Based Prosumers Provided by Low Voltage Part of Distribution Substation

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***Abstract*-This paper presents a design and simulation results of protection and control functions of the low voltage part of a distribution substation. The substation acts as a service provider for distributed resource units in a microgrid and can be used for bidirectional energy exchange between prosumers, such as electric vehicles, battery pack energy storage devices and utility networks. Improved functions for automated energy exchange are described. Functions of an experimental microgrid application are simulated with MATLAB. The aim of the modelling and simulation is to define and optimize parameters and functions for construction of a microgrid prototype. Sample control algorithms and program modules for the substation controller are developed and described. Use of the IEC 61850 communication protocol in the communication between prosumers and a substation is analyzed.**

I. INTRODUCTION

Smart Grids and microgrids have attracted much attention due to the increasing awareness of energy conservation and environmental problems. Use of modern electric vehicles (EV) and their effective integration into power grids depends on the technologies applied around distribution substations. EVs with vehicle-to-grid (V2G) capability are charged or discharged through substations. In energy trading, the role of substations will increase when different types of Li-Ion prosumers are connected to their output feeders. In this paper EVs with Li-Ion batteries or battery energy storage unit (BESU) applications are considered as Li-Ion based prosumers. The concept of a prosumer has two common meanings: a union of words of producer with a consumer or a professional consumer [1]. “Producing consumer” type of a prosumer either generates energy or consumes energy. A “professional consumer” is a well educated, skilled consumer, who commonly makes smart purchasing or selling decisions using additional information [1], [2].

Several papers have addressed microgrid architectures [3], [4] and bidirectional converter topologies [5], [6]. However, technical analysis about control functions for automated bidirectional energy exchange between distribution substations and several Li-ion based prosumers is scarce. The aim of this paper is to develop, optimize and define functions and parameters for the construction of a substation prototype for microgrid applications. Sample control topologies and program modules of the substation controller are presented. The paper is divided into three main parts. The first part describes the topology of the proposed substation. The second part presents the simulation results of control functions for bidirectional energy exchange between Li-Ion prosumers and the utility network with MATLAB Simulink. The third part discusses the principles for the development of substation control algorithms.

II. TOPOLOGY OF DISTRIBUTION SUBSTATIONS FOR LI-ION PROSUMERS

Substations are used to transmit electrical energy, distribute power and step up or down the voltage. Transformer substations for medium voltage (MV) grids (typically 6-24 kV) transform 3-phase medium voltage to 3-phase AC low voltage (typically 400 V).

An example of a distribution substation topology for microgrids is presented in Fig. 1. The substation consists of a MV switchgear, a transformer and a low voltage (LV) switchgear (with switches, smart meters, contactors and power converters). The substation allows bidirectional energy exchange between all the prosumers and consumers. Substation topology is implemented with an integrated AC and a DC bus. Prosumers are connected either to behind AC-DC power converter with a common DC bus or to a common AC bus [7]. For every prosumer in the common DC bus, separate DC-DC converters, protection and switching apparatuses are available at the DC side. The BESUs in substations serve several purposes. For EV filling stations, the BESU can be an additional buffer between the EV and the utility network. The BESU can support fast charging, while drawing near-average power from the grid and reducing the series of charging peak loads for the utility network, which can delay the capital upgrades for the utility network. In the case of an utility network power outage, the BESU will ensure backup power capability and the substation can operate in an island mode using the BESU to power consumer loads. As the number of renewable energy sources is increasing in the grid (e.g. wind and solar energy), the balancing of excess generation sources and load demands can be controlled through the substation. This enables stabilization of the grid voltage and frequency.

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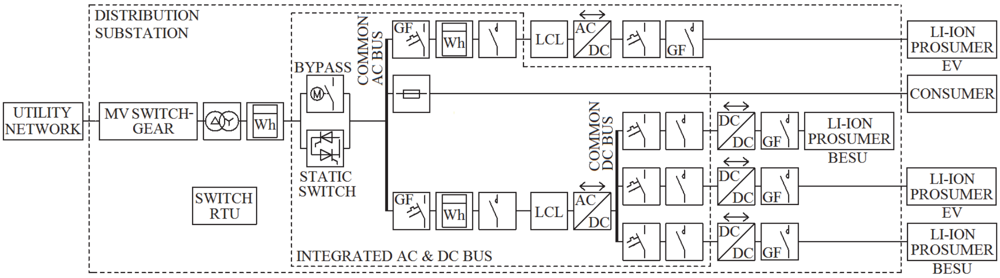


Fig. 1. Topology of a distribution substation with an integrated AC & DC bus and Li-Ion prosumers for microgrid applications.

The necessary amount of stored energy required from the BESU ($E_B(t_{ch})$) to support common DC bus output feeders in fast charging can be deduced as follows:

$$E_B(t_{ch}) = \sum_{j=1}^{n_P} \frac{E_{p,j} \cdot (SOC_{f,j} - SOC_{i,j})}{\eta_{bexc,B} \cdot (\eta_{bexc,j})} - \frac{E_{gr}(t_{ch})}{\eta_{bexc,B}}, \quad (1)$$

$$E_{gr}(t_{ch}) = P_{gr} \cdot t_{ch} \cdot \eta_{acdc}, \quad (2)$$

where $E_{p,j}$ is the full energy capacitance (kWh) of a particular prosumer's battery pack; $SOC_{f,j}$ is the final battery state of charge (SOC) value (%) at the end of the charging; $SOC_{i,j}$ is the initial battery SOC value (%) at the beginning of the charging; $\eta_{bexc,j}$ is the total efficiency of a prosumer's DC-DC converter and the charging efficiency of its battery; n_p is the number of connected prosumer output feeders with the substation; $\eta_{bexc,B}$ is the total efficiency of BESU DC-DC converter and the discharging efficiency of its battery; P_{gr} is the maximum available grid active power (W); η_{acdc} is the efficiency of the AC-DC converter; and t_{ch} is the charging time (h). $P_{gr,max}$ value can be lower than the total required charging power for a common DC bus.

III. PARAMETERS FOR START AND END OF BIDIRECTIONAL ENERGY EXCHANGING BETWEEN PROSUMER AND UTILITY NETWORK

To control bidirectional energy exchange with an EV or a BESU output feeder, it is necessary to gather information from a prosumer battery management system (BMS) [8]. The required information is described in more detail in section V. The data is gathered for a substation from a prosumer BMS through CANbus, whereas an additional gateway is required to communicate with the substation's remote terminal unit (RTU). A dedicated and manageable Ethernet switch is required for IP-based communications between the RTU and the substation devices.

Smart meters in the substation are used for AC load online management and for overvoltage and undervoltage protection. DC side backup measurements (in the case of BMS failure) in common DC bus topology are sent to the RTU for processing. Smart meters positioned in front of the AC-DC converter control the physical switching of the AC side apparatuses (e.g. contactors), but wait for the initiating signals from the RTU. The RTU controls the physical switching of all DC side apparatuses and transfers input parameter values for power converters.

The charging process of the EV is initiated when an EV is connected to a charging station and a request is given by the owner of the EV. The process stops automatically when the target SOC value has been reached. The discharging process of the EV is initiated (option allowed and selected by the owner of the EV) when active power is needed by prosumers or additionally reactive power compensation is required on the AC side. In a common DC bus topology, the discharging of EVs requires scheduling algorithms. EVs with sufficient SOC levels are chosen for discharging. The discharging is stopped when the SOC level of the EV battery has dropped below the set threshold value or the RTU has determined that the calculated time for recharging the battery to the owner's specified departure time cannot be matched.

The charging process of the BESU is initiated when its SOC level drops below the lowest set threshold value. The process stops automatically when the SOC reaches its highest set threshold value. The discharging of the BESU is initiated in addition to EV discharging initiation, when fast charging support is necessary for substation's common DC side output feeders. The discharging is stopped when the SOC level of the BESU has dropped below the set threshold value.

IV. SIMULATION OF BIDIRECTIONAL ENERGY EXCHANGING BETWEEN PROSUMER AND UTILITY NETWORK

Figure 1 shows a distribution substation topology that is similar to the topology simulated using the MATLAB Simulink model (Fig. 2). The model consists of 24 kV utility network supply through an MV switchgear, a 24/0.4 kV transformer and an LV switchgear, which interconnects consumers and prosumers. In this paper, the control of the BESU (with nominal voltage of 460 V DC) through the common DC bus (up to 800 V) is analyzed in more detail. The purpose of this model is not to simulate a particular bidirectional AC-DC or DC-DC converter, but rather to evaluate control functions for bidirectional energy exchange between the BESU and the utility network. The tested and verified control algorithms are used for the programming of an experimental substation controller.

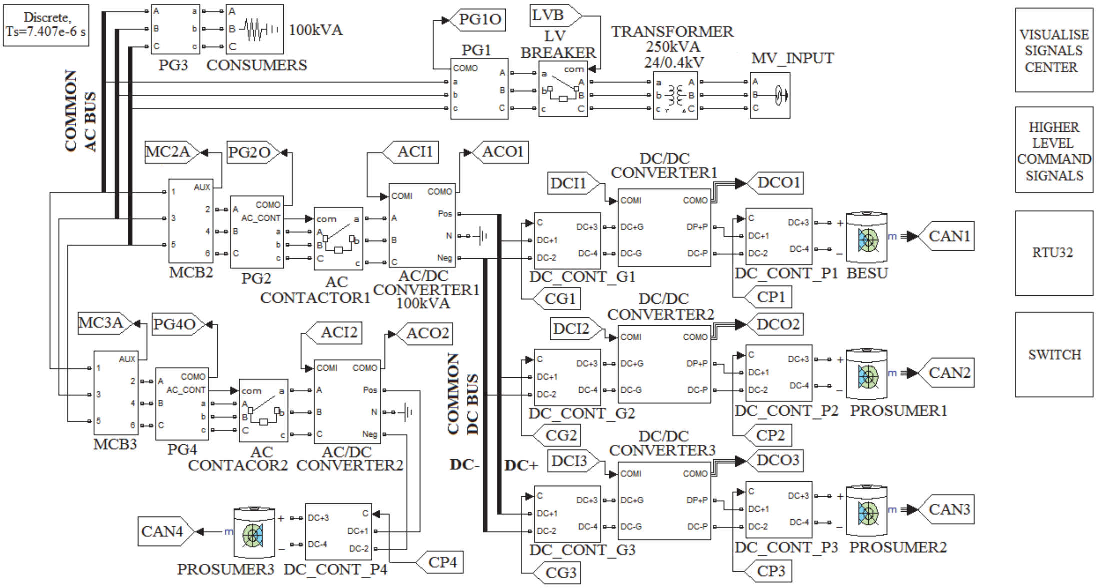


Fig. 2. MATLAB Simulink model of distribution substation with Li-Ion prosumers.

Firstly, the consumer stage of prosumers (BESU) is examined. The bidirectional AC-DC converter 1 operates in rectifier mode (charging). The bidirectional DC-DC converters operate in buck mode. The results from the simulated model are presented in Fig. 3. The BESU is charged with constant current (e.g. maximum current 120 A) and the SOC level of the BESU starts to rise.

Secondly, the producer stage of prosumers is examined. All three bidirectional DC-DC converters operate in parallel in boost mode to equally support the common DC bus. AC-DC converter 1 operates in inverter mode. The results from the simulated model are presented in Fig. 4. Active power (100 kW) from the DC bus is transferred to the AC side and the current from the utility network to AC consumers decreases.

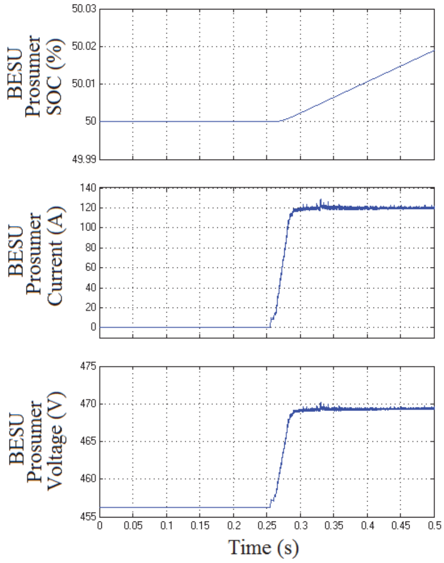


Fig. 3. State of charge, current and voltage of the BESU in the MATLAB Simulink model at the consumer stage of the BESU.

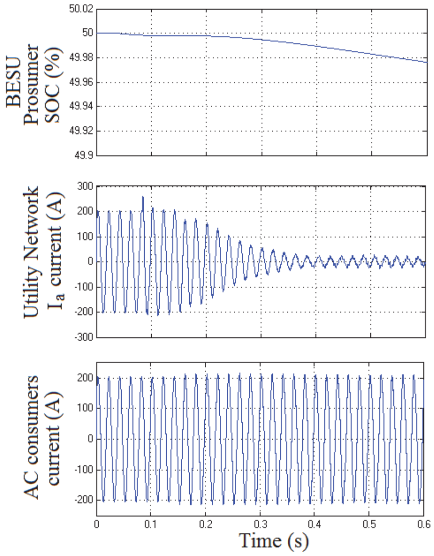


Fig. 4. SOC of the BESU, current of utility network and AC consumers in the MATLAB Simulink model at the producer stage of prosumers.

V. SUBSTATION CONTROL ALGORITHM FOR CHARGING AND DISCHARGING PROSUMERS

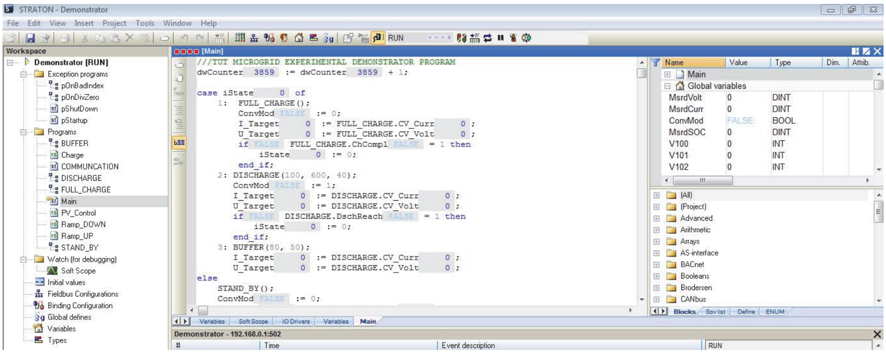
The RTU acts as a central (master) controller in the substation (Fig. 5). Each prosumer might include its own control unit handled as a slave device that serves the purpose of controlling prosumer related lower level tasks. The purpose of the RTU is to read the status and operational parameters of microgrid prosumers, to send control values and configuration information to the slave devices, to control bidirectional energy exchange between prosumers and the utility network (control of prosumer and utility feeders), and to perform the following functions: scheduling, electricity trading (with electricity retailer), grid constraints observer (retrieve information from distribution system operator) and interface provider to EV owners (e.g. departure time, energy prices). In regard to the topology chosen, each feeder for a prosumer might include own slave controller or the central RTU could control all prosumer feeders itself.

Communication between intelligent electronic devices (IEDs) of the next generation, including RTU, and prosumers should be realized with the IEC 61850 protocol [1] as much as applicable. The IEC 61850 protocol uses Ethernet as the basic communication technology, currently at a speed of 100 MBit/s. Different protection and control functions should be scattered between substation devices in order to speed up data flow between the devices [9].

Before any energy exchange in either direction can be executed, it is necessary to gather data from the prosumer's BMS about its state of charge (SOC), state of health (SOH), battery pack open circuit voltage, temperature measurements, and nominal values of parameters (rated capacity, maximum and minimum values of battery pack voltage, SOC levels, current and temperature). To provide the best service to the prosumer, the RTU needs to acquire data about the maximum possible time period the prosumer could stay connected to the microgrid, minimum SOC level required before departure and an agreement from the owner of the prosumer to allow partial discharge of the battery, which would be compensated according to the agreement with the service provider. It is required to monitor the battery current and temperature in order to protect the prosumer during charge and discharge. For Li-Ion batteries, the active monitoring of battery pack voltage and SOC levels will determine whether a constant current or a constant voltage stage of battery charging is used. Discharge has to be stopped if the SOC value drops below the value defined in the manufacturer specifications [10].

In the common DC bus topology, feeders for prosumers are equipped with DC circuit breakers (overcurrent and short circuit protection), DC-DC bidirectional converters, DC current sensors (in the case of BMS failure for backup monitoring of current value and direction), ground fault interrupter [11] and contactors before and after the DC-DC converter (Fig. 1). Contactors behind DC-DC converters allow the switching of DC voltage to prosumers when DC-DC converters are ready in buck mode. Contactors before DC-DC converters allow the switching of DC voltage to the common DC bus when DC-DC converters are ready in boost mode. The position and status data of prosumer feeder devices are transferred to the RTU for signalling purposes, for example, which substation feeders are currently online and exchanging energy with prosumers (offline feeders are reported in error reports).

The entire microgrid algorithm should contain many protective functions. AC side protection functions realized by smart meters: ensure that voltage and frequency are in the determined range, current values do not exceed maximum values. Digital input data of smart meters: automatic or manual mode of charge, AC side circuit breaker closed, positions of AC side contactors, monitoring of isolation. DC side protection functions realized by the RTU for each feeder: ensure that DC side primary and auxiliary voltage values are in the determined range, current values do not exceed maximum values. Digital input data for the RTU is as follows: positions of DC side circuit breakers and contactors, isolation monitoring, and EV connector locking. General protection functions realized by the RTU: ensure that parameter values of prosumers' BMSs and power converters are in the determined range, active monitoring of AC and DC side protection inputs, emergency stop pushbuttons not activated, connection termination not required by EV owners. All data needs to be collected and logged by the RTU in order to generate reports and report errors.



```
///TUT MICROGRID EXPERIMENTAL DEMONSTRATOR PROGRAM
dwCounter  3859  := dwCounter  3859  + 1;

case iState     0  of
    1:  FULL_CHARGE();
        ConvMod FALSE  := 0;
        I_Target      0  := FULL_CHARGE.CV_Curr      0 ;
        U_Target      0  := FULL_CHARGE.CV_Volt      0 ;
        if FALSE  FULL_CHARGE.ChCompl FALSE  = 1 then
            iState      0  := 0;
        end_if;
    2: DISCHARGE(100, 600, 40);
       ConvMod FALSE  := 1;
       I_Target      0  := DISCHARGE.CV_Curr      0 ;
       U_Target      0  := DISCHARGE.CV_Volt      0 ;
       if FALSE  DISCHARGE.DschReach FALSE  = 1 then
           iState      0  := 0;
       end_if;
    3: BUFFER(80, 50);
       I_Target      0  := DISCHARGE.CV_Curr      0 ;
       U_Target      0  := DISCHARGE.CV_Volt      0 ;
else
    STAND_BY();
    ConvMod FALSE  := 0;
```

Name	Value	Type	Dim.	Attrib.
Main				
Global variables				
MsrdVolt	0	DINT		
MsrdCurr	0	DINT		
ConvMod	FALSE	BOOL		
MsrdSOC	0	DINT		
V100	0	INT		
V101	0	INT		
V102	0	INT		

Fig. 5. View of programming software for substation central controller (Brodersen A/S).

The command for charging is initiated by the prosumer (EV or BESU). Some EVs need to follow the CHAdeMO protocol [11]. For EVs, the charging start signal is sent to the EV. Power converters enter standby mode if not currently operating, and the BESU is awakened. If protection functions are fulfilled, AC contactors for AC-DC converters positioned in front of the common DC bus are closed. AC-DC converters will receive target output voltages and power values from the RTU and will be set to rectifier mode, while DC-DC converters are operating in buck mode.

The DC-DC converters will receive target secondary side output voltage and power values from the RTU. If the common DC bus voltage is in range by the AC-DC converter, contactors on the primary side of the DC-DC converters are closed. The RTU waits for the ready state status of the DC-DC converters or determines whether the capacitors of the DC-DC converters have to be discharged from overvoltage. When the DC-DC converter output voltage is in range, the BESU's BMS is set to charge mode. For EVs, the connector is locked and the isolation test is performed, also contactors of the secondary side of DC-DC converters are closed. Energy measurements are being recorded for billing purposes. At the beginning of the charging process the SOC level of prosumers will determine whether the charge is performed with a slow current value, constant maximum current value or with constant voltage. The choice of the charging mode will be adjusted in accordance with the battery SOC value. For EVs the EV side demand current is analyzed by the RTU and the charging current is adjusted accordingly. To avoid current peaks, the starting and stopping of charging is executed using the soft-start and soft-stop.

For EVs charging is stopped by receiving the zero current signals from the EV side. Depending on the location of fault detection, fault events will immediately open the adjacent switching apparatus. When the charging stops, DC-DC converter primary and secondary side contactors will be opened and the recording of measuring consumed energy is stopped. For EVs, the connector is unlocked and the total charging cost is sent for billing. If the common DC side requires no further power supply, AC-DC converter operation is stopped and the contactor of the AC side of the AC-DC converter is opened. Power converters are set to sleep mode.

The command for discharge initiates the function for the selection of a prosumer type (EV or BESU). For EVs, the connector is locked and the isolation test is performed. The discharge start signal is sent to the EV and the BESU is awakened from sleep mode. The parameters from the BMSs are gathered and analyzed. Power converters will go to standby mode if not currently operating. AC and DC side circuit protection inputs and parameters are analyzed. The RTU determines whether capacitors of DC-DC converters have to be discharged from overvoltage. Contactors of the secondary side of the DC-DC converters are closed, the DC-DC converters receive a target for the primary side output voltage and power values from the RTU and are set to boost mode. The RTU waits for a ready status from the DC-DC converters. When the output voltages of DC-DC converters are in range, the contactors of the primary side of the DC-DC converter are closed. Active power is transferred to the common DC bus and energy measurements are being recorded for further processing. AC contactors for AC-DC converters before the common DC bus are closed, AC-DC converters will be set to inverter mode and the RTU determines the target output power value for the AC-DC converter. The AC-DC converter synchronizes with the common AC bus voltage and power is transferred to the common AC bus. The time of discharge of prosumers depends on the quantity of resources acquired from the substation to perform its service providing [1], [7]. Discharging of prosumers is stopped when the depth of discharge, maximum discharge current or temperature is exceeded. Switching apparatuses are opened and operation of power converters stopped according to the determined sequences (due to determined stop of discharging or fault detection). The recording of energy measurements is stopped.

VI. PRINCIPLES FOR THE DEVELOPMENT OF A SUBSTATION CONTROLLER FOR COMMON DC BUS POWER MANAGEMENT

Energy flow in a common DC bus topology can follow four different ways: from the utility grid (through an AC-DC power converter) to prosumers at the common DC bus, from prosumers at the common DC bus to the AC grid and between prosumers themselves at the common DC and AC buses. Some important aspects for the development of common DC bus power management:

- For higher total efficiency of the distribution substation, the AC-DC converter in front of the common DC bus has to be with AC-DC-DC topology. The output DC voltage of the AC-DC converter should be adjustable during the charging of prosumers for a wide range (e.g. from 300 V to 800 V DC), in order to acquire the maximum total efficiency of the DC-DC converters. The selection of the optimal DC bus voltage is decided through RTU algorithms.
- Equations (1) and (2) are used in order to determine the use of battery energy storage units' resources to support the common DC bus.
- When BESU resources are exhausted, the local substation operator will have an opportunity for intervention in order to decrease the total charging power required by the common DC bus to decrease power consumption in the utility network for a short term (the prosumers are charged with less current compared to their maximum values).
- Energy transfer from the common DC bus to the AC grid will not be executed until a sufficient number of DC-DC converters of prosumer feeders are ready in boost mode.
- The control of data and energy exchange shall be possible between different substations in the utility network.

VII. FUTURE STUDIES

Tallinn University of Technology is constructing an experimental microgrid that enables us to study energy flows and data communication during EV charging. The microgrid consists of a fast charging station for EV charging and a battery pack for storing electrical energy. The basic functions and operation modes (including protection algorithms), such as energy transmission from the power grid to the energy storing system, EV battery charging, balancing power loads and other functions have to be developed, tested and analyzed. Management and control algorithms for the RTU (Fig. 6) have to be fine-tuned. During experimentation, data values will be collected for further analysis. Primary goals in the construction of the microgrid are to analyze the quality of energy flow, efficiency and harmonic levels during EV charging through the microgrid and electromagnetic compatibility related issues. The analysis will indicate needs for modifications to be made in the microgrid structure to optimize and improve the overall efficiency and power factor levels in the system to ensure the quality of electricity in accordance with international standards. Practical applications will show possible drawback areas in the communication between the devices, which will then have to be solved with different control algorithms. Future studies will focus more on V2G and microgrid solutions. Further studies will address possibilities to transfer energy to the common AC bus or to the power grid with synchronization related issues. Results from microgrid experiments will be published in future papers.

Fig. 6. View of an experimental setup with RTU devices for microgrid experimentations.

VIII. CONCLUSIONS

Distribution substation topology for microgrid applications with Li-ion based prosumers was reviewed. Through simulations it has been proven that integrated AC and DC bus is the main topology solution for integrating prosumers with different nominal voltages. Simulation results have verified the principle of control algorithms for bidirectional energy exchange between the utility network and prosumers. These control algorithms will be transferred to the experimental substation controller (RTU). IEC 61850 protocol will be used between smart meters, RTU, AC-DC power converters, and Ethernet switch.

The substation for microgrid applications with prosumers should be ready to simultaneously serve AC and DC prosumers. This means that core control program in its main controller should integrate control and protection functions for AC bus, common DC bus and the link from AC bus to the utility grid. The chosen substation topology can be used, e.g., for constructing EV fast filling stations. Before constructing a real life substation, a smaller prototype has to be constructed and examined. Experiments with the microgrid will give vital data about charging algorithms and communication between the devices. From these studies it will be possible to construct a larger real life substation capable of supplying power to several EV charging stations and that will be part of a microgrid or even a viable module of Smart Grid solutions.

ACKNOWLEDGMENT

This research work has been supported by Estonian Archimedes Foundation (projects “Doctoral School of Energy and Geotechnology II” and “Optimization of the functioning of the energy system to balance changeable loads“).

This research was supported by European Social Fund’s Doctoral Studies and Internationalisation Programme DoRa conducted by Foundation Archimedes.

This research was supported by Estonian Science Foundation Grant. ERA-Net Smart Grids/Quality and Safety.

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