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MODERN TRENDS IN REDUCTION OF POWER LOSSES

BAKALAUREUSETÖÖ

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1. Teema põhjendus

Electric power is one of the basic types of energy consumption. One of the main objective for each state is supplying customers with heat and electricity. Electric power transfer for long distances causes power losses, which means financial losses for network companies. Savings from reduction of losses could be directed to: the technical re-eguipment of networks; the reduction of tariffs for the electric power; increasing personnel salary; the reduction of consumption of natural resources.

2. Töö eesmärk

The work is aimed at studying of modern trends in reduction of power losses. The diploma's aim is to classify power losses and describe methods for reducing of them. Additional task is to perform simulations of one of the methods in DIgSILENT software.

3. Lahendamisele kuuluvate küsimuste loetelu:

Types of losses
Power loss calculation
Ways of solving a problem

4. Lähteandmed

Data for the calculations will be taken from the PowerFactory 2017 data base. For the theoretical part books and other sources will be used.

5. Uurimismeetodid

- *Study of literature*
- *Simulations in DigSilent software*
- *Analysis*

6. Graafiline osa

The graphic part consists of example of power grid and charts obtained during calculations.

7. Töö struktuur

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1. J. D. Glover, S. M. Sarma, and J. T. Overbye, *Power system analysis and design*, no. 5. 2012.
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9. Lõputöö konsultandid

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- *Data collection and processing – 10.09*
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PREFACE

The topic of bachelor thesis is issued by the depatment of Electrical Power Engineering and Mechatronics of Tallinn University of Technology. It has been written to fulfill the graduation requirement of the Electrical Power Engineering and Mechatronics program at the Tallinn University of Technology. Bachelor's thesis was completed in Tallinn University of Technology.

I would like to thank my supervisor for his guidance and support during this process. Also, I would like to thank university faculty of Tallinn University of Technology, for the rendered assistance. Especially, I would like to thank my parents, who helped me to do my bachelor's thesis.

Keywords: distribution systems, losses reduction techniques, VAR compensation, DIgSILENT, power losses.

LIST OF ABBREVIATIONS

AC – Alternating current

CT – Current Transformer

DC – Direct current

DG – Distributed generation

EMF – Electromotive force

EPRI – Electric Power Research Institute

EPS – Electric Power System

FACTS – Flexible Alternative Current Transmission System

3G – Third Generation

GSM – Global System for Mobile communications

HVAC – High Voltage Alternating Current

HVDC – High Voltage Direct Current

PT – Potential Transformer

RES – Renewable energy source

RPS – Reactive power compensation

STATCOM – Static Synchronous Compensator

SVC – Static VAR Compensator

SWER – Single-wire earth return

TCR – Thyristor Controlled Reactor

TCSC – Thyristor Controlled Series Capacitor

TSC – Thyristor Switched Capacitor

1. INTRODUCTION

Electric power is one of the basic types of energy consumption. One of the main objective for each state is supplying customers with heat and electricity. Electric power transfer for long distances causes power losses, which means financial losses for network companies. Savings from reduction of losses could be directed to: the technical re-equipment of networks; the reduction of tariffs for the electric power; increasing personnel salary; the reduction of consumption of natural resources.

The work is aimed at studying of modern trends in reduction of power losses. The diploma’s aim is to classify power losses and describe methods for reducing of them. Additional task is to perform simulations of one of the methods in DIgSILENT software.

2. POWER LOSS CLASSIFICATION

2.1 Distribution systems

There are two types of distribution power losses: technical and non-technical losses. Technical losses are connected with energy, which dissipates in the conductors and equipment for power transmission and distribution.

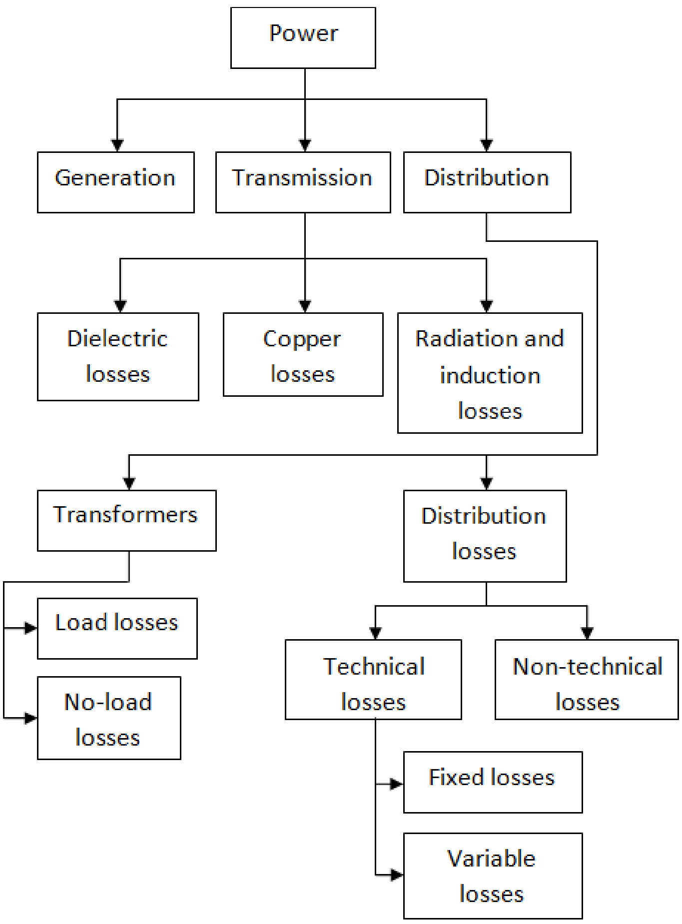

Figure 2.1 Electrical power scheme

The bulk of the technical losses appears because of a heat dissipation or I^2R loss in the distribution conductors. There are also other reasons, which may cause technical losses, for example, low power factor or phase imbalance. Moreover, technical losses can easily be simulated and calculated. Non-technical losses are often related to power theft, meter related problems and billing problems. The majority of non-technical losses are connected with low voltage distribution in networks. Non-technical problems occur during distribution operational problems and it is difficult to measure. The problem is that losses are often not taken into account by system operators and, therefore, do not have recorded information. Non-technical losses are rare and can be neglected at the transmission level. But, even here, questions arise. In the next two paragraphs will be described in details, how technical and commercial losses can be reduced in the distribution system.

2.1.1 Technical losses

In the power system there is a part of the electric losses which is called technical losses. Technical losses occur when the energy is dissipated by the equipment and conductors in the distribution lines. This kind of losses depend on the network characteristics, and mode of the operation [1]. Technical losses can be classified into two categories, namely, the fixed technical losses and the variable technical losses. ın addition, technical losses can be grouped according to the segment of the electric system where it happens [2]. Technical losses can be subdivided into losses in various systems, for example, in the transmission system, primary distribution system and so on.

Fixed technical losses. Even if power was not delivered to customers, the system will still have losses, only because it is electrically energised. These losses are also known as fixed losses or "no-load losses". Fixed losses arise because the steel in the magnetic core of each transformer changes the magnetic polarity in every cycle of alternating current. A quarter or one third of the total losses are fixed losses in distribution lines [3]. These losses usually take the form of heat and noise. When the voltage is applied to the transformer, then there are fixed losses. The fixed losses are affected by such factors as leakage current losses, open circuit losses, crown or dielectric losses.

Variable technical losses. All conductors, whether they are coils in transformers, aluminium or copper wires in overhead lines or cables and even in switchgear, fuses, or metering equipment, have an internal electrical resistance which causes them to heat when carrying electric current [4]. Since energy losses stemming from the dissipation of heat to the environment vary with the current flowing through conductors in electrical networks, these losses are called "variable losses" [5]. These losses are also usually referred as "ohmic losses", "copper losses", "Joule losses" or "resistive losses" [6], [7]. The variable losses are proportional to the square of the load current [1]. For this reason, if peak current is 10 times less than minimum, then peak loss at minimum load will be 100 times greater.

Two-thirds and three-fourths of the technical losses in the distribution system are variable losses [3]. Variable losses occur due to some factors, for example, line resistance, contact resistance and losses to Joule heating. There are multiple choices how to reduce technical losses. Next paragraph describes 5 examples:

Replacement of old equipment. One of the most effective ways to reduce technical losses is to replace old equipment with a new one. High voltage network requires installation of cables with nominal high voltage. Such an installation can largely reduce losses. A thorough load analysis must be carried out If there is a need to replace the power cables. Load analysis helps determine the most effective cable. Also, the replacement of the distribution transformer can significantly save costs [8].

Reduction of transformer losses at design stage. To reduce iron and copper losses, it is necessary to improve transformer´s design. For example, amorphous core transformer can be used to reduce iron loss. More precisely it will be written in chapter 3.

Reduction of transformer’s number. Since the transformers are responsible for almost half of the network losses, the most reliable way to reduce losses is decreasing the number of transformation steps. The significant effect in reduction of distribution losses can be provided by so-called high efficiency distribution transformers [9].

Utilization of feeder on its average capacity. By overloading of distribution feeder distribution losses will be increase. The higher the load on a power line, the higher its variable losses. It has been suggested that the optimal average utilization rate of distribution network cables should be as low as 30 % if the cost of losses is taken into account [10].

Voltage optimization. Carefully re-adjusted voltage levels can reduce current flow in the network [8].

2.1.2 Non-technical losses

The non-technical losses, also referred to as commercial losses, are those related to unmetered supplies, incorrect billing, untimely billing, wrong tariff, defective meters and energy thefts [2]. The majority of non-technical losses are connected with low voltage distribution networks. At medium voltage distribution level, non-technical losses are primarily caused by inaccurate meters and tampering with measurement transformers [11]. Non-technical losses include defective/incorrect metering, human error on installation, administrative processes, and non-metered authorized customers, especially, theft [2]. If the technical losses can vary between 3 and 6 percent, then non-technical losses can increase from 10 to 40 percent.

On the other hand, non-technical losses are caused by loads and conditions that were not taken into account in calculating technical losses. Non-technical losses are more difficult to measure, since these losses are often not taken into account by system operators and, therefore, do not have recorded information. The most likely non-technical losses caused by electricity theft, customers non-payment, errors in technical losses computation, errors in accounting and record keeping. There are also many ways to reduce non-technical losses:

Statistical analysis of electricity meter readings. Statistical analysis of electricity meter readings must be done so that sample data from electricity meters can be analyzed statistically over time to estimate significant deviation from usual meter readings. This will help the operating personnel to keep track the energy usage of its consumers and will have a benchmark in case significant meter reading deviation especially at the totalizing meters is observed [12].

Implementation of energy audits schemes. For all big enterprises, an energy audit should be conducted. Enterprises must make calculations to determine the locations where the losses are greatest with a view to their further elimination. After the carried-out calculations, a realistic assessment is given. This assessment determines the size of the sample. Therefore, it is very important to fix a limit of the sample size in order to quickly determine the loss [13].

Mitigating power theft by proper seal management. All companies associated with the power industry often faced with the problem of electric power theft. Strict government supervision is needed to regulate this problem. Theft affects not only losses of revenue, but also power quality.

This leads to low voltage and voltage dips. To prevent power theft, it is needed to install a proper seal management on the terminal CT / PT at meter terminal box. Installation takes place in medium voltage distribution networks. This installation has a direct connection to the consumer terminal via a low voltage transformer. All unmetered services must be stopped [10].

Replacement of faulty energy meter. It is needed to replace the faulty meter with the distribution agency to reduce unmetered electrical energy. It is periodically necessary to check serviceability of the meter. Old electromechanical meters should be replaced by accurate electrostatic meter. These electrostatic meters will help to measure energy consumption precisely. Meter boxes needs to be properly sealed [9].

2.2 Transmission lines

The main factors affecting losses in transmission lines: the length of the lines, conductor's cross-section, material composition and the number of consumers. It is possible to reduce power losses by reducing the current in conductors or by increasing cross-section of the wires. An increase of cross-section wire leads to an increase in the cost price, therefore it is necessary to find a trade-off between the current strength and the wire cross-section. Losses in transmission lines are divided into three types: copper losses, dielectric losses and induction (radiation) losses.

2.2.1 Copper losses

Copper as a conductor has a certain resistance. When electricity transmission on wires more than 10 m long, the resistance of the wire can not be neglected, since current causes a noticeable voltage drop according to Ohm's law.

$$P = I^2 \cdot R, \tag{2.1}$$

where P – power of electric current, W,

I – current, A,

R – circuit resistance calculated group load, Ohm (Ω).

During electricity transmission through copper wires, part of it goes to heating, also to the forming of electromagnetic fields, which leads to a drop in power. Large voltage deviations leads to power and energy losses. This brings to disruption in electrical equipment and emergency situations. Heating conductors from copper explains the effect of the skin.

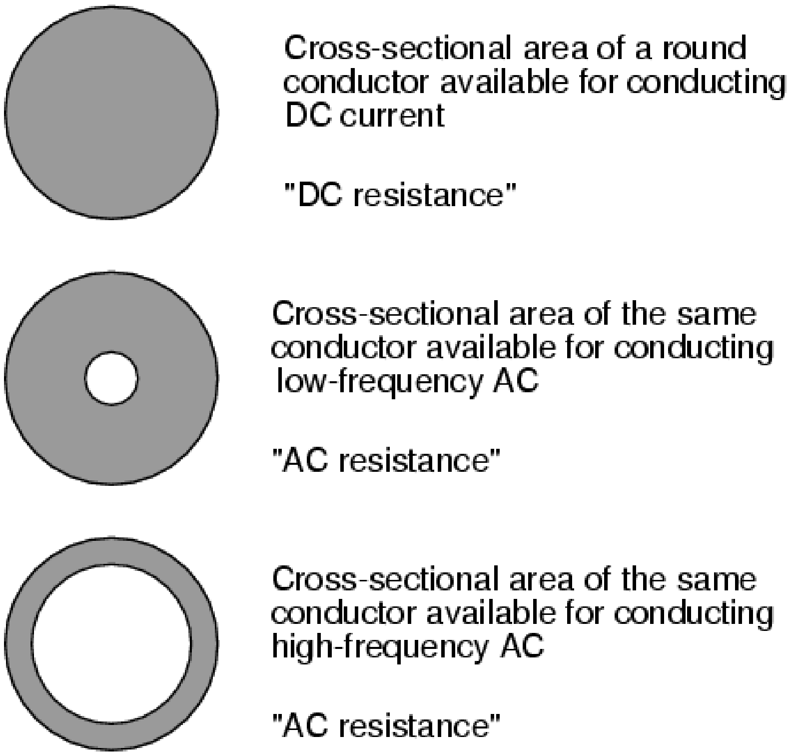

Figure 2.2 Skin effect: skin depth reduction with increasing frequency [14]

Power losses increase as the resistance increases and the frequency changes due to the skin effect. Copper losses can be minimized by covering the line with silver. Since silver is a better conductor than copper, most of the current will flow through the silver layer [15].

2.2.2 Dielectric losses

Dielectric losses is energy that dissipates in a material when electromagnetic field affects on it. There are 3 types of losses: in gases, in solids and in liquid. Each type of losses is calculated by its methodology. If we assume that the isolation system consist of ideal dielectric, then in this case there will be no loss when alternating voltage applied. But in practice, ideal materials do not exist and energy losses always occurs. The only question is how many [16]. In engineering practice, the angle of dielectric losses, as well as the tangent of this angle, are most often used to characterize the ability of a dielectric to dissipate energy in an electric field. The dielectric angle is the angle δ, which adds up to 90 degrees angle of phase shift φ between current and voltage in capacity circuit [17].

2.2.3 Radiation or induction losses

Radiation and induction losses caused by the fields, which are surrounding the conductors. Induction losses occur when the electromagnetic field about a conductor cuts through any nearby metallic object and current is induced in that object. As a result, power is dissipated in the object and is lost. Radiation losses occur because some magnetic lines of force about a conductor do not return to the conductor when the cycle alternates. These lines of force are projected into space as radiation and this result in power losses. That implies power supplied from the source is not fully getting to the load [15].

2.3 Transformers

Voltage transformer is a device designed to change the voltage in an alternating current network. The main parts of the transformer are the magnetic core and coil with windings. The example you can see in Figure 2.3.

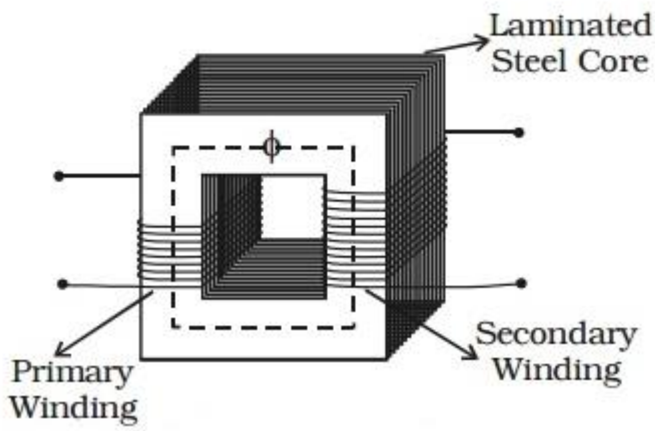

Figure 2.3 Structure of transformer [18]

The principle of the transformer is based on the law of electromagnetic induction. In the primary winding under the influence of the voltage in the core, a magnetic flux is proportional to this voltage, which, in turn, induces the electromotive force (EMF) of self-induction in the secondary windings. The EMF induced in the secondary windings is directly proportional to the number of turns of these windings. The main types of transformers are measuring and power transformers. A power transformer serves to convert an alternating current of one voltage into an alternating current of another voltage with a power conversion at a constant frequency. Measuring transformers are designed to measure large voltages and currents.

Figure 2.4 Power transformer [19]

The losses in transformers are usually divided into two types: losses in copper (copper coils of windings) and losses in steel (core material). “Core” or “no-load” losses are incurred to energize transformers in substations and on the distribution system. No-load losses occur from the energy required to retain the continuously varying magnetic flux in the core and its invariant with load on the transformer. Copper losses are resistive and proportional to load current and are sometimes called “load losses”. “Resistive” or “copper” losses reflect the resistance of the materials themselves to the flow of electricity. Load loss mainly arises from resistance losses in the conducting material of the windings and it varies with loading [2], [20].

2.3.1 Core losses

Core losses are generally from 25 to 30 percent of the total distribution loss. These losses do not change when the load changes. These losses are significantly affected by the characteristics of the steel laminations that are used to manufacture the transformer core. Core losses are the losses incurred to energize the transformer [20]. These losses vary depending on the size of the transformer and the materials used to build the transformer. In order to reduce core losses, it is necessary to use “right-size” transformers.

2.3.2 Resistive losses

The resistive losses are similar to the friction losses that occur both in the lines and in the transformers. As loads increase, the wire material becomes more resistive due to heating, and as a consequence the line losses increase. This is why the resistive losses increase exponentially with the current on the line. In periods of low load, system losses can be considered as core losses. These losses can be as low as three percent. Resistance losses become dominant during peak electrical demand periods. Line losses increase in the range of 10 to 15 percent during peak hours. However, marginal line losses may increase to 20 percent or even more.

At peak extremes, it can take five power plants operating to provide the end-use electricity normally provided by four [20]. Resistive losses are primarily a function of the current flowing through a transformer, heating it up. These losses are exponential with the current. For this reason it is important to not have too small transformer, or it will “run hot” with high losses. One option is for utilities to install banks of three or more transformers at substations, de-energizing one or more during low-load periods, but then switching them on during high-demand periods. Again, there may be trade-offs resulting from increased circuit breaker maintenance costs and risk for decreased reliability [20].

3. MODERN TRENDS FOR REDUCING OF POWER LOSSES

This chapter will describe the most effective methods and events for reducing power losses in distribution systems, electrical networks and reducing transformer losses at the design level. In addition, two methods will be considered that reduce power losses: dynamic compensation of reactive power and high-voltage direct current lines.

3.1 Losses reduction techniques in distribution systems

The most efficient losses reduction techniques in distribution systems are: feeder reconfiguration, distributed generation (DG), VAR compensation and installation of smart metering for non-technical losses [2].

3.1.1 Feeder reconfiguration

Feeder reconfiguration is a very important and usable operation to reduce distribution feeder losses and improve system security. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used:

- normally closed switches (sectionalizing switches);
- normally open switches (tie switches).

By changing the open/close status of the feeder switches load currents can be transferred from feeder to feeder. During a fault, switches are used to fault isolation and service restoration. There are numerous numbers of switches in the distribution system, and the number of possible switching operations is tremendous. Feeder reconfiguration thus becomes a complex decision-making process for dispatchers to follow [21]. Feeder reconfiguration objectives: loss reduction, load balancing, voltage profile improvement, minimization of service interruption, frequency network restoration and balanced service.

Finding the optimal tie switches to make the meshed networks radial is a highly complicated combinatorial optimization problem [22]. There are many ways to use the feeder reconfiguration. Some methods of feeder reconfiguration:

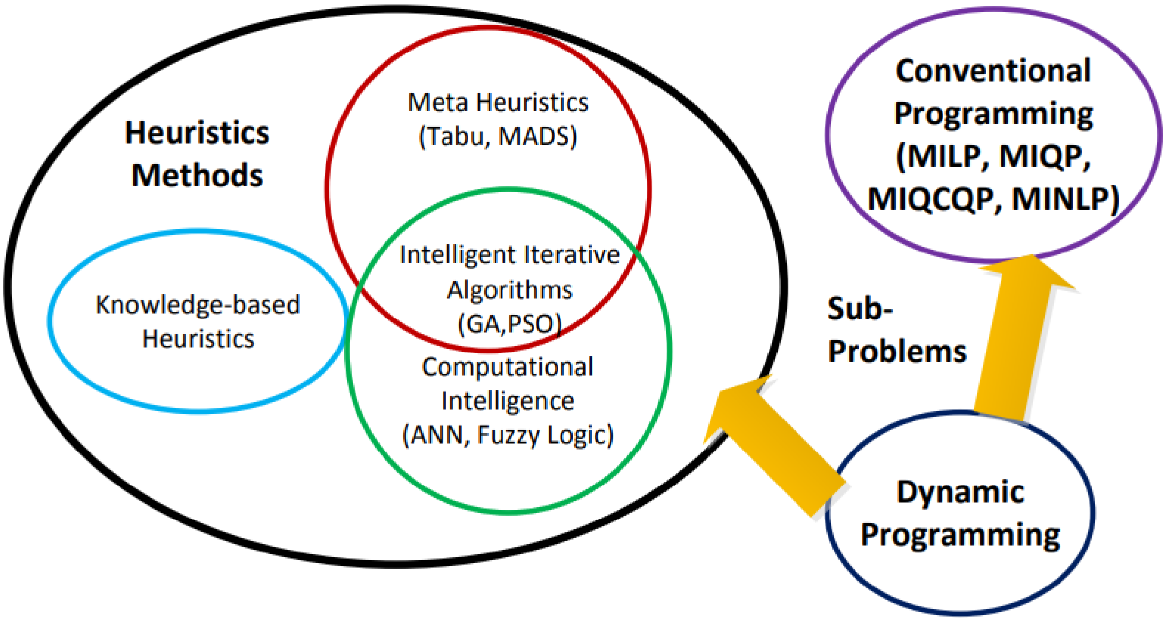

Figure 3.1 Classification of FRC methods [23]

Heuristic methods can be subdivided into two categories: knowledge-based heuristic methods and meta-heuristic methods and computational intelligence.

Knowledge based heuristic methods are frequently put into practice. Heuristic rules are followed for various switch operations. These rules are based on experience of distribution system operation [24]. Examples of heuristic methods: branch exchange method, loop-eliminating method, method where all switches closed and so on. Feeder reconfiguration solutions from knowledge-based heuristics always improve the objectives. However, an optimal solution is not guaranteed for large complex system [23].

Meta-heuristic methods and computational intelligence. Another type of heuristics formulates feeder reconfiguration into optimization problems and solves them iteratively without derivative information, which is essential for conventional programming. This type of heuristics is called meta-heuristic [23]. All meta-heuristic algorithms use some tradeoff of local search and global exploration. The variety of solutions is often realized via randomization. Despite the popularity of meta-heuristics, there is no agreed definition of heuristics and meta-heuristics in the literature [25].

Several algorithms can be used to solve the problem of feeder reconfiguration, for example, fuzzy logic, intelligent iterative algorithms, genetic algorithms, and particle swarm optimization. These methods were designed for large systems, which have been proved successful in many cases. But they will always be subject to convergence rate, which is largely depends on specific problems and adjustment of searching parameters in the methods.

Conventional programming. For detailed modeling, feeder reconfiguration is a mixed integer nonlinear programming problem, which is formidable. Tremendous work has simplified the problems into linear/quadratic objective and constraints. Commonly used power flow constraints, in which current injection at each node was considered using incidence matrix. This formulation is also popular in heuristic methods [23].

Dynamic programming. In dynamic programming a complex problem is divided into several sub-problems. To achieve overall optimal solution, all the solutions of sub-problems are combined together. No restrictions are faced by programmer while solving each sub-problem [24].

For today, the feeder reconfiguration is a complex task that requires constant optimization with the use of new methods.

3.1.2 Distributed generation (DG)

Distributed generation (DG) is the combination of small objects of power engineering (less than 25 MW) and micro-energy (less than 1 MW). They solve local provision problems of electrical and thermal energy. Traditional primary energy sources (coal, fuel oil, gas) and all alternative energy, based on renewable energy sources (RES) [26]. The concept of distributed generation implies the construction of additional sources of electricity in close proximity to consumers. The power of such sources is selected according to the criterion of expected power of the consumer, where available restrictions are taking into account and can vary widely (from two to three or to hundreds of kilowatts). At the same time, the consumer does not disconnect from the general power supply network [27].

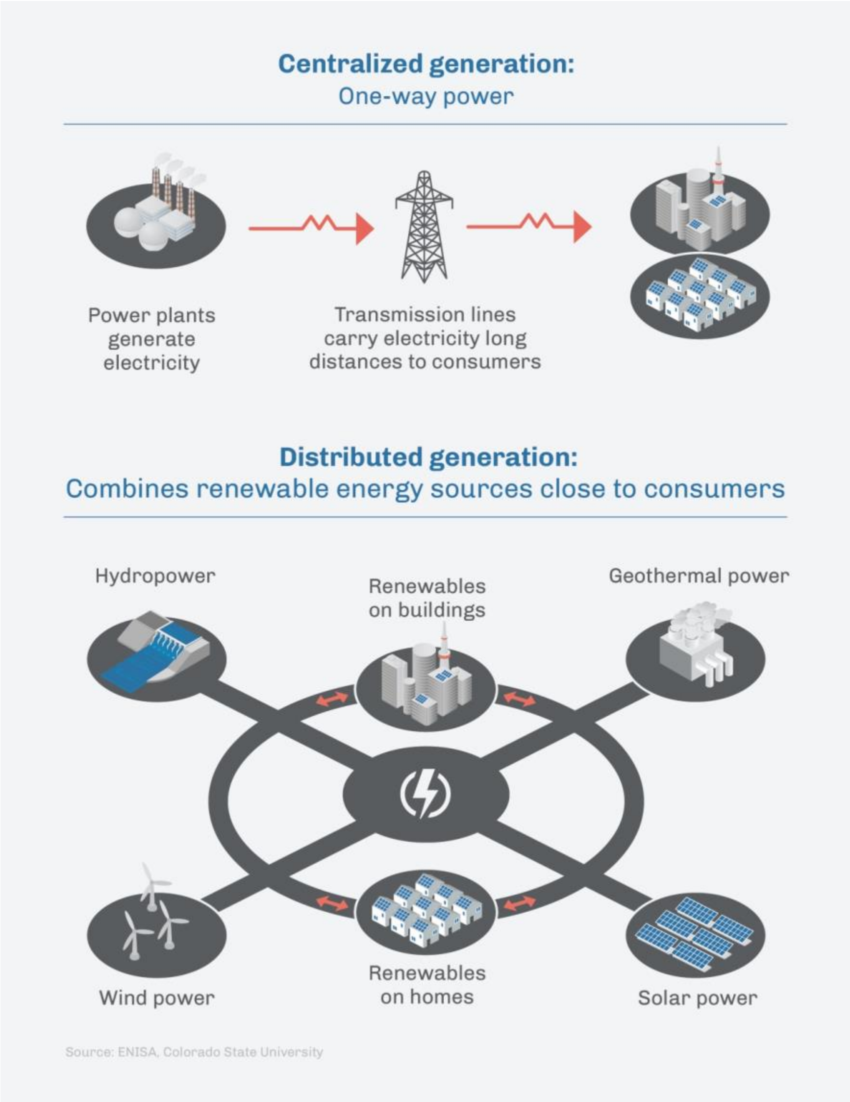

Figure 3.2 Scheme of distributed generation [28]

The presence of a connection to the common electrical network allows to compensate a lack of the electric power due to its consumption from the general network, while in the case of excess electricity production by its own source - to issue it to the network, with the receipt of an appropriate income. This approach allows:

- to reduce electricity losses during transportation due to the maximum approach of electric generators to electricity consumers, up to their location in the same building;
- to reduce the number, length and necessary capacity of the main transmission lines;
- to mitigate the consequences of accidents at central power plants and main transmission lines due to the availability of own energy sources;
- to provide mutual repeated reservation of the electro generating capacities (partially);

- to reduce the impact on the environment through the use of alternative energy, the fuller use of the potential energy of fossil fuels;
- to take part in demand management on the electric power [29].

To achieve the maximum effect from the implementation of the DG network, special attention should be paid to its location and developed power. It is necessary to solve two tasks to achieve the goal:

- the location of the DG source will be determined on the basis of sensor analysis (losses are taken into account).
- determine the optimum power of the DG at minimum losses.

One of the methods is the model of the optimal power search and an installation site of the DG source. The node for connecting the DG source is determined on the basis of the sensory node method. Sensory analysis of network status assessment allows to determine the most sensitive elements without calculating the mode. The main idea of this method is that in the electric power system (EPS) has elements whose mode parameters are relatively more strongly reacting to external disturbances and are changing more with occasional changes in the topology of network's schemes and loadings. These elements are called sensory.

In addition, there are elements in the electrical network, whose the change in the mode parameters causes the strongest reaction of the EPS to disturbances. These elements are called weak points.
The singular analysis of the inverse Jacobi matrix (J-1) was used to determine the sensory and rigid nodes. In nodes which will be the most sensitive to change of load bus it is necessary to establish the DG source. For each separate node with an increase in power of the DG there is a gradual reduction of power losses which is observed up to the size of optimum value. There is losses growth observed at further increase in power source of DG.

The well-known techniques based on minimizing the total losses in the network were used to determine the optimal power of the DG source [30], [31]. As a result of the calculation, there may be several sensory nodes for a particular electrical network.

3.1.3 VAR compensation

Reactive power (VAR) is part of the total power that was not transferred to the load, but resulted in losses for heating and radiation. It does not perform useful work.

Reactive power is defined as

$$Q = U \cdot I \cdot \sin\theta, \tag{3.1}$$

where Q – reactive power, var,

U – voltage, V,

I – current, A,

θ – phase angle.

and can be positive (+ Ue) for the inductive load and negative (-Ue) for the capacitive load. The presence of reactive power is a parasitic factor, unfavorable for the network as a whole.

As a result:

- additional losses occur in the conductors due to the current increase;
- the throughput of the distribution network decreases;
- the mains voltage deviates from the nominal value (voltage drop due to the increase in the reactive component of the mains current).

The main consumers of reactive power:

- asynchronous electric motors, which consume 40 % of all capacity together with domestic and own needs;
- electric furnaces 8 %;
- converters 10 %;
- transformers of all stages of transformation of 35 %;
- power lines 7 % [32].

Reactive power compensation is a key to the solution of a question of energy saving. Correct compensation allows:

- to reduce the total expenses of electric power;

- to reduce the load on the elements of the distribution network (feeding lines, transformers and distributing devices), thereby prolonging their service life;
- to reduce thermal current losses and expenses on the electric power
- to reduce the influence of higher harmonics
- to suppress network interference, reduce phase asymmetry;
- to achieve greater reliability and profitability of distribution networks.

Reactive power can be compensated with synchronous compensators, synchronous motors, cosine capacitors (capacitor installations). At present, capacitor installations are widely used for compensation, which have a number of advantages over other compensation devices:

- small active power losses;
- absence of rotating parts;
- simple installation and operation;
- rather low capital investments / have low cost;
- the ability to select any necessary compensation power;
- possibility of installation and connection at any point of the power grid;
- have a long service life (about 20 years for Legrand capacitors);
- no noise during operating time.

Figure 3.3 Capacitor installation [33]

The choice of compensation equipment depends on the type of power equipment connected to the network. Compensation can be individual (local), centralized (general) and group. In the first case, one or more (battery) of cosine capacitors is connected in parallel to the load. In the second case, a number of capacitors (batteries) are connected to the main switchboard. Group compensation is applied in case of compensation of several located nearby and switched on simultaneously inductive loads connected to one switchgear and compensated by one capacitor battery.

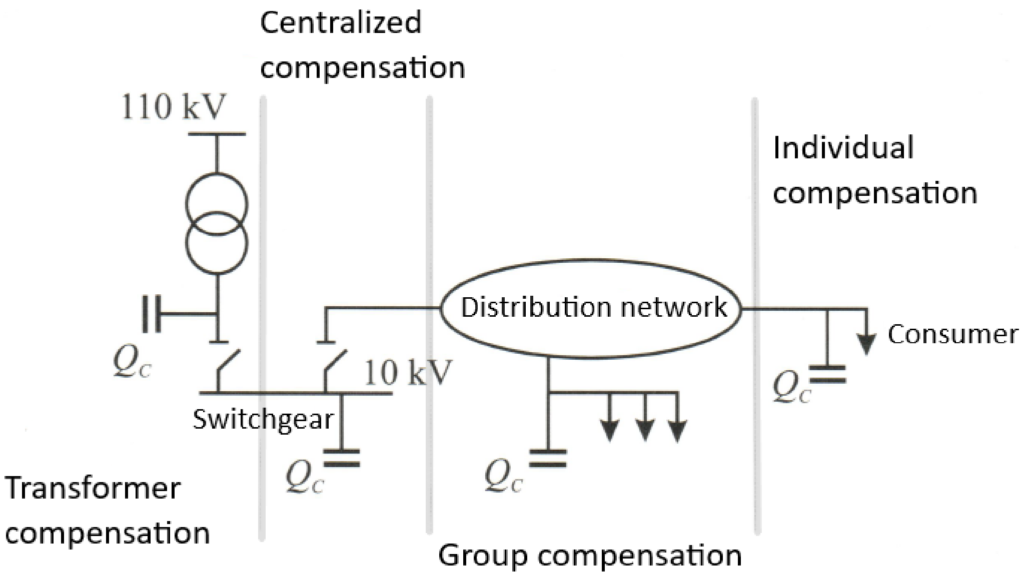

Figure 3.4 Types of compensations [34]

The use of capacitor banks for reactive power compensation allows:

- to unload the power transmission lines, transformers and switchgears;
- to reduce expenses on payment of the electric power;
- using a certain type of installation, reduce the level of the higher harmonics;
- to suppress network interference, reduce phase asymmetry;
- to make distribution networks more reliable and economical

Besides reactive power compensation, there is also such a method as dynamic reactive power compensation, which will be described further.

Dynamic compensation. This kind of compensation is required when fluctuating loads are present, and voltage fluctuations have to be prevented. The principle of dynamic compensation is to associate a fixed capacitor bank and an electronic var compensator, providing either leading or lagging reactive currents [35]. Essentially, the concept of FACTS (Flexible Alternative Current Transmission System) was formalized by the American Electric Power Research Institute (EPRI). These FACTS for monitor and control of various systems, transport and power consumption uses traditional and new means of power factor correction and improving power quality. Namely: self-switching voltage converters and static thyristor compensators (devices for reactive power compensation with thyristor by switching TCSC (Thyristor Controlled Series Capacitor), TCR (Thyristor Controlled Reactor), TSC (Thyristor Switched Capacitor), SVC (Static VAR Compensator) - combinations of TCR and TSC components , STATCOM (Static Synchronous Compensator), etc [36].

Purpose: Dynamic reactive power compensation systems are used to prevent voltage fluctuations in networks with varying loads. Installations are distinguished by high speed up to 14 commutations per second, in traditional RPC installations one actuation in 5 ... 20 seconds.

Application areas of the solution:

- for systems with fast and abrupt load changes;
- automatic adjustment of centralized compensation in low-voltage main switchboards;
- for use in networks with a high proportion of higher harmonics;
- static converter power (non-linear loads)> 15% of connected power [37];
- filtration of higher harmonics and improvement of voltage quality;
- reduction of costs due to stray currents;
- stabilization of mains voltage.

Main characteristics

- reduces electricity costs;
- reducing the load on the switching equipment by reducing the currents in the circuits;
- improving the voltage quality (i.e., preventing high currents of switching on power capacitors);
- improving the reliability of the entire system (i.e. damage caused by faulty contactors and subsequent explosion of capacitors is prevented);

- ultra-fast power factor compensation, resulting in a consistent reduction in costs caused by stray currents and kWh losses.;
- voltage stabilization (for example, network support at the time of launch of powerful engines);
- optimized energy distribution balance (transformers, cables, switching devices, etc.) by eliminating peak loads.

3.1.4 Installation of smart metering for non-technical losses

Rational use of natural and energy resources is a topical problem today both on the individual and global levels. The smart grid concept aims to solve such key problems as the improvement of electricity supply reliability and energy efficiency, as well as environmental protection. Smart grid uses up-to-date information and communication technologies to acquire, analyze and provide data to energy market players in the automatic mode in order to enhance the efficiency of economic activities in the energy field. The smart grid concept integrates manufacturers and consumers of electric power and electric networks, thus creating a common information and communication space. Smart metering is an integral part of smart grid, which allows determining and analyzing parameters of electric networks and objects. Smart metering includes cutting-edge hardware and software systems which provide a new level of reliability in accounting the consumed energy resources. In its turn, this gives the opportunity to control power consumption and save money, which is important for all companies irrespective of the type of ownership [38].

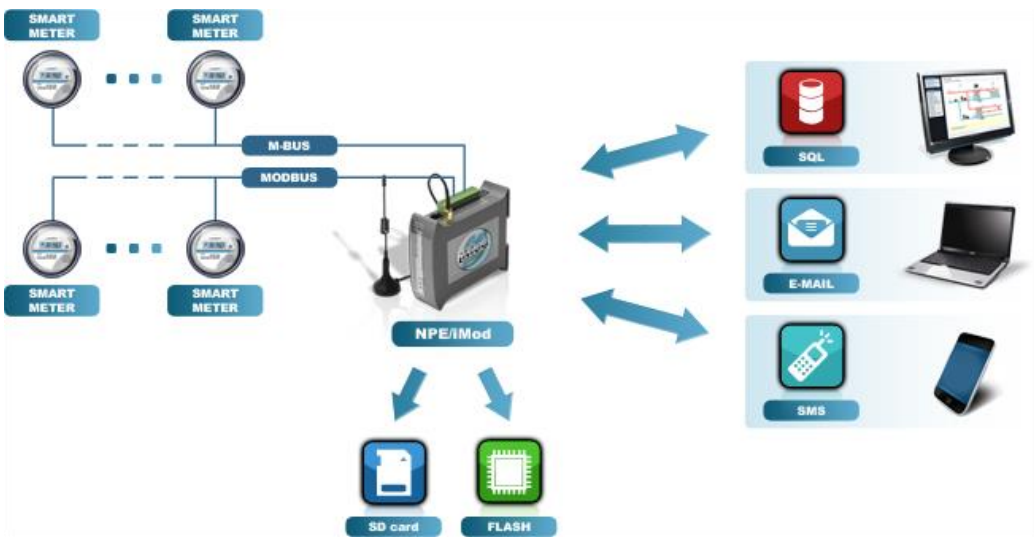

Figure 3.5 Smart metering scheme [39]

Smart metering installation allows to solve the following tasks:

- remote readout of energy meters;
- work with a large (sometimes, multimillion) number of accounting points, while ensuring a high level of productivity;
- remote monitoring of power quality parameters;
- remote control of energy resources metering devices;
- remote control of energy consumption;
- remote power management;
- detection of unauthorized intervention in metering devices operation or changes of power supply connection schemes;
- application of sanctions against malicious defaulters by the method of limiting the power consumption or blackout of power supply;
- analysis of technical condition and failures of metering devices;
- preparation of reporting documents on a power consumption;
- the ability to exchange data with other certified systems;
- the ability to adapt to other tasks provided for by the customer's business processes.

Example of remotely read meters work in Estonia

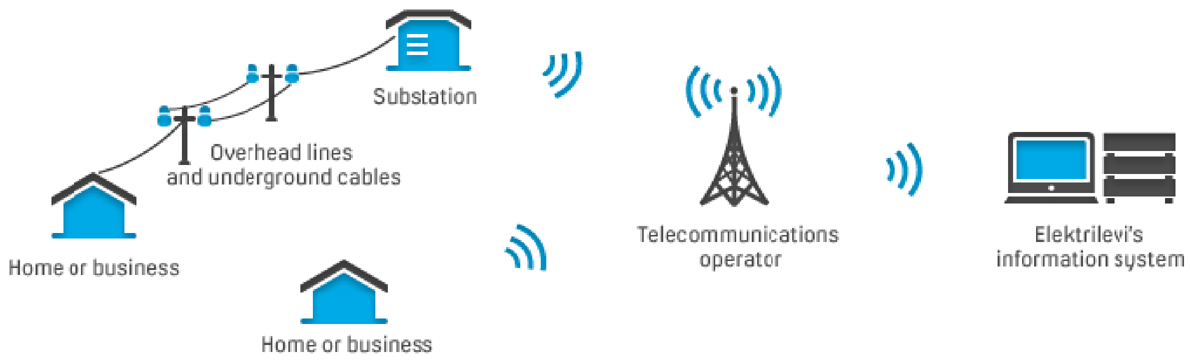

Figure 3.6 Remotely read meters work [40]

Remotely read meters measure the amount of electricity you consume in kilowatt-hours for each hour. The Electricity Market Act sets this as the time interval because the price of electricity on the open market can change for each hour. The meter sends data on how much electricity you consume to the network operator once a day. Most meters use the same power lines that bring electricity to the building to send the data from the meter to the substation. Some meters send the data using mobile communications such as GSM and 3G data communication technology [40].

Advantages of smart metering

For the company itself:

- increasing the efficiency of the existing business;
- opportunities for new types of business;
- ensuring implementation of Smart grid technologies;
- creation and development of software-hardware system.

For energy sales:

- automatic consumption monitoring;
- easy to define the excess of actual indicators over the planned ones;
- to define inefficient production and processes;
- billing;
- power factor monitoring;
- monitoring of quality indicators (voltage and frequency).

For ensuring business – service for the generating, network, sales companies and consumers:

- ready option for all occasions;
- reliability;
- assurance of the quality of services;
- optimal and transparent cost of network company services;
- continual innovation;
- increase of "intelligence" while working in the wholesale and retail market of power supply;
- quality consulting on all issues of power supply and power saving.

3.2 Events for reduction of power losses in electrical networks

According to international experts, the relative losses of electricity during its transmission and distribution in the electrical networks of most countries can be considered satisfying if they do not exceed 4-5 %. Losses of electricity at the level of 10 % can be considered as the maximum permissible from the point of view of physics of transmission of electricity through networks [41].

Based on the features of obtaining effect, events can be divided into the following four groups:

- events for improvement of operating modes of electrical networks;
- events for reconstruction of electrical networks which are carried out for the purpose of decreasing losses;
- events to improve the electricity metering system;
- events to reduce electricity theft.

The main activities of the electrical transmission grid 110 kV and above are the following:

- the establishment of mass production and widespread introduction of adjustable compensating devices;
- construction of new power lines and increasing the capacity of existing lines;
- development of nonconventional and renewable power (small hydroelectric power stations, wind farms, tidal, geothermal hydroelectric power stations, etc.).

The priority measures to reduce technical losses of electricity in distribution networks of 0.4-35 kV include:

- use of 10 kV as the main voltage of the distribution network;
- an increase in the share of networks with a voltage of 35 kV;
- reduction of the range and construction of overhead lines (0.4 kV) in a three-phase version along the entire length;
- use of self-supporting insulated and protected wires for overhead lines with a voltage of 0.4-10 kV;
- use of the maximum allowable wire cross-section in electrical networks with a voltage of 0.4-10 kV;
- development and implementation of new, more economical, electrical equipment;
- use of low power pole-mounted transformers (6-10 / 0.4 kV) to reduce the length of 0.4 kV networks and the loss of electricity in them;
- wider use of automatic voltage regulation devices under load, local voltage regulation means to improve the quality of electricity and reduce its losses;
- complex automation and telemechanization of electrical networks, the use of switching devices of a new generation.

Events for the reconstruction of electrical networks include:

- separation of large substations into smaller ones, input of additional overhead lines and transformers for unloading overloaded sections of networks, replacement of the low-loaded transformers on substations, input of the additional switching devices providing a possibility of switching of sites of networks to food from other substations, etc.;
- input of switching devices at substations of the grid organization;
- input of technical means for regulating power flows along lines.

Events to improve the electricity metering system include:

- replacement of measuring transformers to transformers with higher accuracy classes and nominal parameters corresponding to the actual loads;
- replacement of existing electricity metering devices with new devices with improved characteristics;
- installation of electrical energy metering devices on radial lines extending from substations (head metering).

Events to reduce electricity theft include:

- periodic inspections of the working conditions of electricity meters for settlement accounting at consumers and the detection of electricity theft;
- replacement of 0.4 kV overhead lines of ordinary “bare” aluminum wires with insulated wires, which impede unauthorized connection to the line [42].

3.3 High voltage direct current (HVDC) lines

One of the prospective lines in the development of electric power industry is the use of direct current for the transfer of power over long distances. The processes occurring in such networks are somewhat different from the processes in AC (alternating current) networks. This is due to the fact that the power transmitted by the DC (direct current) circuits has a purely active nature, the inductance and capacitance in such circuits do not exist [43]. The main advantage of HVDC (High Voltage Direct Current) is the ability to transfer more energy over a long distance with lower capital costs and lower losses than in HVAC (High Voltage Alternating Current) lines.

The figure below shows the ground power lines: the area occupied by HVDC is optimal and is about one-third of the area of HVAC. HVDC has two conductors and HVAC has three conductors plus a neutral, as a result, the setup price per mile for HVDC is lower.

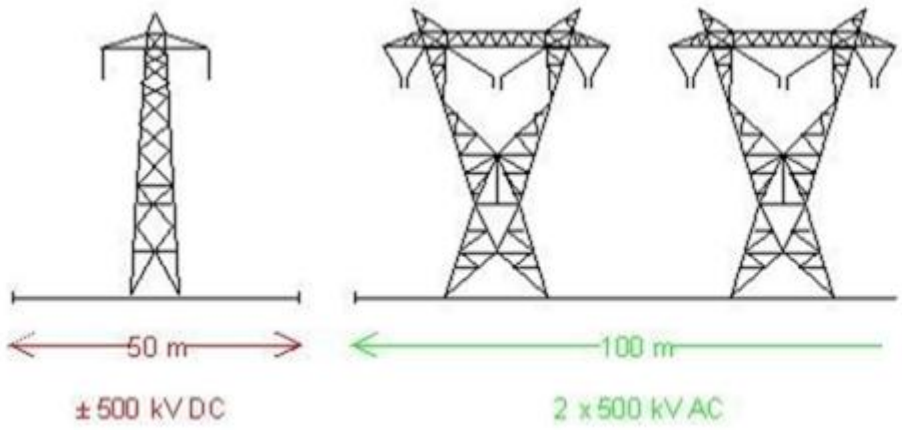

Figure 3.7 Typical Transmission Line Structures For approx. 2000 MW [44]

Advantages of HVDC:

- high transmit power for a conductor of one section (no radiation, no skin effect, etc.);
- more simple line design (no reactive compensators, etc.);
- return through the ground can be used. It means that there is less loss on Foucault's current, etc., since HVAC lines are also used for SWER;
- in the case of SWER, each conductor can be operated as an independent circuit;
- no charging current. Additional current must flow in the cable to charge the cable capacitance. This is especially important in underground / submarine cables. Therefore, in the underwater power lines HVDC has been used for several decades;
- cables may operate at a higher voltage gradient (as there are no Foucault currents);
- the power factor of the line is always equal to one: there is no reactive power, the line does not require reactive compensation;
- less corona and radio interference, especially in bad weather, for a conductor with the same diameter and RMS voltage as in HVAC;
- synchronized operation is not required;
- consequently, the distance of the line is not limited by the requirements of stability;
- can connect AC voltage systems with different frequencies;
- low short-circuit current on DC line;
- does not contribute to short-circuit current of a AC system;
- tie-line power is easily controlled.

Disadvantages of HVDC:

- converters are expensive;
- interface converters with HVAC are faced the problem of reactive power;
- converters generate harmonics, filters are required;
- multiterminal or network operation is not easy.

3.4 Reduction of transformer losses

The degree of loss in the transformer depends on the quality of the construction and the material of the "transformer iron" (electrical steel).

Reduction of losses due to the material:

- application of improved steel grades;
- improvement of the technology of manufacturing the magnetic system (cutting of steel);
- improvement of the core design, sheet joints.

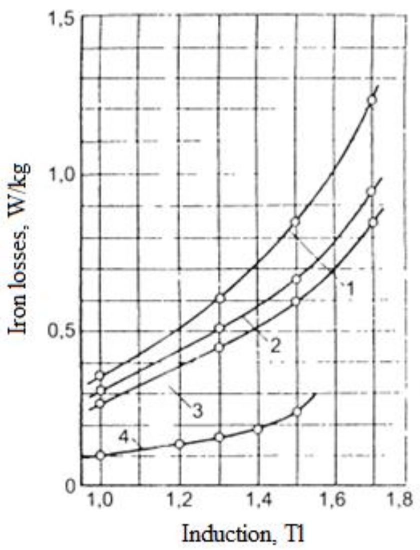

Figure 3.8 Comparative characteristics of some steel grades. Iron losses at voltage 50 Hz:
1 – regular steel (the sheet thickness 33 mm); 2 – Hi-B brand steel (the sheet thickness 0,23 mm); 3 – Hi-B brand steel processed by the laser (the sheet thickness 0,23 mm); 4 – amorphous steel (0,13 mm) [45].

Reduction of losses due to structures:

- improve the orientation of domains;
- reduction of sheet thickness;
- purification of domains by laser treatment of the surface of sheets.

Steel manufacturers offer a wide choice of steel with different characteristics, and the manufacturer of transformers can choose steel depending on the design of the transformer and the required characteristics. A separate place is occupied by amorphous steel. There is a certain rivalry between the two ways of development:

- use of conventional carbon steel with improved orientation and controlled grain size and reduced sheet thickness;
- using a strip of amorphous steel.

Figure 3.9 Toroidal amorphous cores [46]

Amorphous alloy is a metal glass that does not have a crystal lattice. Thanks to amorphous structure this material has more favourable magnetic properties in comparison with traditional electrotechnical steels. Accordingly, the use of this material will reduce power losses.

Figure 3.10 Amorphous Transformer [47]

Cost and manufacturing technique are the major obstacles for bringing to the market a broad assortment of amorphous core transformers. The price of these units typically ranges from 15 to 40 percent higher than that of silicon steel core transformers. A new type of liquid-filled transformer uses ultra low-loss cores made from amorphous metal. The core losses are between 60 or 70 percent lower than those for transformers using silicon steel. To date, these transformers have been designed for distribution operation primarily by electric utilities and use wound-cut cores of amorphous metal [48]. Particular attention should be paid to transformer cooling systems, shunt reactors and microprocessor devices which optimize the life of the coolers.

4. STUDY

The purpose of practical work is to compensate reactive losses in the network with the installation of the RPC on the buses. As a practical part, a modified scheme with 14 bus was taken. Data of scheme was borrowed from the DIgSILENT program.

Input data from the DIgSILENT directory

The scheme consists of: 12 buses, 3 generators, 11 loads, 16 lines and 2 three-winding transformers. Appendix 1 shows a diagram with 12 bus. Nominal voltages:

• Bus 1 - Bus 5: 132 kV;

• Bus 6, Bus 9 - Bus 14: 33 kV.

The nominal frequency of the 12 Bus System is 60 Hz. Load data (active power P and reactive power Q) have been taken from [49] and are listed in the Table 4.1.

Table 4.1 Load data

Load	Bus	P in MW	Q in Mvar
Load_0002	Bus_0002	21,7	12,7
Load_0003	Bus_0003	94,2	19,0
Load_0004	Bus_0004	47,8	-3,9
Load_0005	Bus_0005	7,6	1,6
Load_0006	Bus_0006	11,2	7,5
Load_0009	Bus_0009	29,5	16,6
Load_0010	Bus_0010	9,0	5,8
Load_0011	Bus_0011	3,5	1,8
Load_0012	Bus_0012	6,1	1,6
Load_0013	Bus_0013	13,5	5,8
Load_0014	Bus_0014	14,9	5,0

The machine at the bus 3 is synchronous condenser. The length of each line in the PowerFactory model has been set to 1 km. The rated current of each line is not known and therefore assumed to be 1 kA. The line between bus 1 and bus 2 is a double circuit, and has therefore been modelled as two parallel lines with adapted parameters in the PowerFactory model. The rated power of each transformer is $S_r = 100$ MVA. [49]

Input data from a 12-bus circuit

Data of Bus_0006 and Bus_0009 are presented in tables 4.2 and 4.3.

Table 4.2 Data of Bus_0006

	P, MW	Q, Mvar	I, kA
Laod_0006	11,2	7,5	0,243
Line_0006_0011	16,7	9,7	0,349
Line_0006_0012	9,2	3,2	0,176
Line_0006_0013	22,8	10,6	0,454

Table 4.3 Data of Bus_0009

	P, MW	Q, Mvar	I, kA
Laod_0009	29,5	16,6	0,654
Line_0009_0010	-3,6	-0,8	0,072
Line_0009_0014	3,4	0,4	0,067

4.1 Calculation of reactive power compensation devices

The method of selecting reactive power compensation (RPC) devices is to select devices that allow to improve the power factor of the consumer to the desired value and consists of the following steps:

• selection of installation location of the RPC device;

• calculation of power device RPC;

• carrying out the necessary checks and calculations;

• the actual selection of the RPC device.

4.2 Calculation of the RPC device power and carrying out the necessary checks and calculations

In the general case, the RPC device power in buses 6 and 9 is determined by the formula

$$Q_c = K_c \cdot P, \tag{4.1}$$

where K_c – calculated factor,

Q_c – the RPC device power, Mvar,

P – active power of the total load on the transformer, MW.

There is special table, which can help to determine calculated factor K_c. If $\cos\varphi_1$ and $\cos\varphi_2$ are known than calculated factor can be determined without resorting to mathematical calculations. The $\cos\varphi_1$is a cosine before compensation and $\cos\varphi_2$ is a cosine after compensation.

If in the AC electrical circuit has a purely reactive power than current coincide on phase with applied voltage. If an electric receiver with active and inductive resistances (welding and power transformers) is included in the circuit, then the current will lag in phase from the voltage at angle φ, called the phase angle. The cosine of this angle is called the power factor. The $\cos\varphi$ value characterizes the degree of using source power:

$$\cos\varphi = \frac{P}{S_{nom}}, \tag{4.2}$$

where P – active power of the consumer, MW,

S_{nom} – rated power of the source, Mvar.

The method of calculating the active power P, as well as carrying out the necessary checks and calculations of the RPC device depends on the place of its installation.

RPC devices are selected according to the following specifications:

- rated power;
- nominal voltage;
- rated current.

The following is example of choosing the RPC devices for the network shown in Appendix 1. Distribution busbars 6 and 9 were selected as the location of the installation RPC devices, as shown in Appendix 2. These buses were chosen as an example of calculating the installation of RPC.

4.2.1 Example 1. Calculation of power of RPC device at Bus_0006

At first, it is needed to determine the actual $\cos\varphi$ on the lines when all the installations are working without using compensating devices according to the formula 4.2:

Load_0006:

$$\cos\varphi = \frac{11{,}2}{13{,}4792} \approx 0{,}831$$

Line_0006_0011:

$$\cos\varphi = \frac{16{,}7}{19{,}3127} \approx 0{,}865$$

Line_0006_0012:

$$\cos\varphi = \frac{9{,}2}{9{,}7406} \approx 0{,}945$$

Line_0006_0013:

$$\cos\varphi = \frac{22{,}8}{25{,}1436} \approx 0{,}907$$

Then the total load on the transformer is considered according to the formula:

$$P = \sum_{i=1}^{n} \sqrt{3} \cdot U \cdot I_i \cdot \cos\varphi_i, \tag{4.3}$$

where U – nominal voltage, kV,

I_i – rated load current, A,

$\cos\varphi_i$ – power factor.

or if the active power of each line are known, then it is possible to calculate the total load on the transformer using the following formula

$$P_\Sigma = P_1 + P_2 + \cdots + P_n \tag{4.4}$$

Substituting the values from table 4.2, the total load on the transformer can be obtained:

$$P_{\Sigma 1} = 11{,}2 + 16{,}7 + 9{,}2 + 22{,}8 = 59{,}9 \text{ MW}$$

After that the weighted $\cos\varphi$ for the transformer is determined by the formula:

$$\cos\varphi_{\Sigma 1} = \frac{P_1 \cdot \cos\varphi_1 + P_2 \cdot \cos\varphi_2 + \cdots + P_n \cdot \cos\varphi_n}{P_1 + P_2 + \cdots + P_n} \tag{4.5}$$

$$\cos\varphi_{\Sigma 1} = \frac{11{,}2 \cdot 0{,}831 + 16{,}7 \cdot 0{,}865 + 9{,}2 \cdot 0{,}946 + 22{,}8 \cdot 0{,}906}{11{,}2 + 16{,}7 + 9{,}2 + 22{,}8} \approx 0{,}89$$

The calculated factor K_c is defined using the table in Figure 4.1, given that the required $\cos\varphi_2 = 0{,}95$. It is not recommended to compensate the reactive power in calculations completely (up to $\cos\varphi_2 = 1$), since over-compensation is possible. Thus, the value of $\cos\varphi_2$ generally tend to be 0.90 ... 0.95.

K_c	$\cos\varphi_2$												
$\cos\varphi_1$	0.80	0.85	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
0.60	0.583	0.714	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.549	0.679	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.515	0.646	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
0.63	0.483	0.613	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.451	0.581	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.950	0.998	1.058	1.201
0.65	0.419	0.549	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.388	0.519	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.358	0.488	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.328	0.459	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.299	0.429	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.270	0.400	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.242	0.372	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.214	0.344	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.186	0.316	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.159	0.289	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.132	0.262	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.105	0.235	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.079	0.209	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.052	0.183	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.026	0.156	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80		0.130	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81		0.104	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82		0.078	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83		0.052	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84		0.026	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85			0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86			0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87			0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88			0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89			0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
0.90				0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484

Figure 4.1 Calculated factor K_c [50]

Thus, the RPC device for Bus_0006 is $K_c = 0{,}184$. Since K_c and P for transformer are known, the required power of the RPC device is determined by:

$Q_c = K_c \cdot P = 0{,}184 \cdot 59{,}9 \approx 11{,}02 \text{ Mvar}$

The compensating installation will be SCB-35-11,4 UHL1 with rated power of 11,4 Mvar. In the same way we calculate Bus_0009. Using same formulas as in Example 1, the following outcomes will be:

The actual $\cos\varphi$ on the lines of Bus_0009 are shown in the Table 4.4:

Table 4.4 The actual $\cos\varphi$ on the lines

Line	$\boldsymbol{\cos\varphi}$
Load_0009	0,871
Line_0009_0010	-0,976
Line_0009_0014	0,994

The total load on the transformer:

$P_{\Sigma 2} = 29{,}5 - 3{,}6 + 3{,}4 = 29{,}3 \text{ MW}$

The weighted $\cos\varphi$ for the transformer is:

$\cos\varphi_{\Sigma 2} \approx 0{,}87$

The calculated factor K_c is defined using the table in Figure 4.1, given that the required $\cos\varphi_2 = 0{,}95$. Thus, the RPC device for Bus_0009 is $K_c = 0{,}238$. Since K_c and P for transformer are known, the required power of the RPC device is determined by:

$Q_c = \mathrm{K}_c \cdot \mathrm{P} = 0{,}238 \cdot 29{,}3 \approx 6{,}97 \text{ Mvar}$

The compensating installation will be SCB-35-7,6 UHL1 with rated power of 7,6 Mvar. After installing RPC on buses 6 and 9, a comparison was made of reactive loss data before and after compensation (Appendix 3 and Appendix 4). These data can be seen in Table 4.5.

Table 4.5 Rreactive loss data before and after compensation

Bus name	Q, Mvar	
	Before compensation	After compensation
Bus_0006	12,215	9,735
Bus_0009	7,608	5,894

DIgSILENT allows to make calculations of the network as a whole (Appendix 1 and 2). The obtained results are placed in Table 4.6.

Table 4.6 Reactive and active losses of grid

Before compensation		After compensation	
P, MW	Q, Mvar	P, MW	Q, Mvar
15,19	42,54	14,52	36,23

Based on the following data, calculations of the total power loss are made by formula 4.6:

$$S_{loss} = \sqrt{{P_{loss}}^2 + {Q_{loss}}^2}, \tag{4.6}$$

where P_{loss} – active power losses of the network, MW,

Q_{loss} – reactive power loss of the network, Mvar,

S_{loss} – total power loss of the network, MVA.

Before compensation

$$S_{loss} = \sqrt{15{,}19^2 + 42{,}54^2} = 45{,}17 \text{ MVA}$$

After compensation

$$S_{loss} = \sqrt{14{,}52^2 + 36{,}23^2} = 39{,}03 \text{ MVA}$$

According to the formula 4.7 the volatge drop calculations had been performed across bus 6 along the lines

$$\Delta U = \frac{P \cdot R + Q \cdot X}{U_n}, \tag{4.7}$$

where ΔU – voltage drop in line, kV,

P – active power of line, MW,

R – active resistance of network, Ω,

Q – reactive power of line, Mvar,

X – reactance of network, Ω,

U_n – nominal voltage, kV.

Next formula will show calculation of voltage at the end of the line

$$U_k = U_0 + \Delta U, \tag{4.8}$$

where U_0 – voltage of transformer at the end of bus and equal to 33 kV.

Active resistance and reactance of lines were taken from DIgSILENT directory of 14 bus system. The table with active resistance and reactance will be presented in Table 4.7.

Table 4.7 Data of lines in the PowerFactory model

Line	From bus	To bus	R in Ω	X in Ω
Line_0006_0011	6	11	1,034	2,166
Line_0006_0012	6	12	1,338	2,786
Line_0006_0013	6	13	0,720	1,419
Line_0009_0010	9	10	0,346	0,920
Line_0009_0014	9	14	1,384	2,944

Table 4.7 shows only the data of busbars 6 and 9. Voltage drop calculations were made on lines based on these data and data from Table 4.8.

Table 4.8 Data of lines in the grid

Lines	Before compensation			After compensation		
	U_n, kV	P, MW	Q, Mvar	U_n, kV	P, MW	Q, Mvar
Line_0006_0011	32	16,7	9,7	33,5	16,7	9,2
Line_0006_0012	32	9,2	3,2	33,5	9,2	3,1
Line_0006_0013	32	22,8	10,6	33,5	22,7	10,3
Line_0009_0010	29,9	3,6	0,8	31,5	3,7	0,5
Line_0009_0014	29,9	3,4	0,4	31,5	3,4	0,7

Numbers in Table 4.8. was taken from Appendices 1 and 2. As an example the Line_0006_0011 was taken for calculation

Before compensation

$$\Delta U = \frac{16{,}7 \cdot 10^6 \cdot 1{,}034 + 9{,}7 \cdot 10^6 \cdot 2{,}166}{32 \cdot 10^3} = 1{,}196 \text{ kV}$$

$$U_k = 32 - 1{,}196 = 30{,}804 \text{ kV}$$

After compensation

$$\Delta U = \frac{16{,}7 \cdot 10^6 \cdot 1{,}034 + 9{,}2 \cdot 10^6 \cdot 2{,}166}{33{,}5 \cdot 10^3} = 1{,}110 \text{ kV}$$

$$U_k = 33{,}5 - 1{,}110 = 32{,}39 \text{ kV}$$

Table 4.9 Active and reactive losses in lines of busbars 6 and 9

Lines	**Before compensation**		**After compensation**	
	$\boldsymbol{P}$, **MW**	$\boldsymbol{Q}$, **Mvar**	$\boldsymbol{P}$, **MW**	$\boldsymbol{Q}$, **Mvar**
Line_0006_0011	0,791	0,378	0,705	0,337
Line_0006_0012	0,259	0,124	0,234	0,112
Line_0006_0013	0,877	0,445	0,791	0,401
Line_0009_0010	0,014	0,005	0,013	0,005
Line_0009_0014	0,039	0,019	0,036	0,017
TOTAL	**1,98**	**0,971**	**1,779**	**0,872**

Table 4.10 Voltage on busbars before and after compensation

Busbars	**Before compensation**	**After compensation**
Bus_0006	32	33,5
Bus_0009	29,9	31,5
Bus_0010	29,9	31,6
Bus_0011	30,8	32,4
Bus_0012	31,3	32,8
Bus_0013	31,0	32,5
Bus_0014	29,7	31,3

As a result of practical work, the following was done:

- the RPC for the scheme in Appendix 1 were calculated, selected and installed;
- after installing the RPC on selected buses, the reactive power on buses was reduced by 34-37 %;
- total power loss in the network decreased by 13,6 %;
- The voltage drop on the lines after compensation decreased;

- Active power on the lines has changed slightly. In the general circuit, the active power loss decreased by 4.4 %. With an increase in $\cos\varphi$, the total power becomes the active power and acquires the maximum value.

Thus, the compensation of reactive power in network was performed correctly.

4.3 Economic justification of RPC devices

Economic benefits due to introduction of capacitor installation consists of the following components:

- Savings on paying for reactive energy.
- For operating objects, the reduction of energy losses in cables due to the reduction of phase currents.
- For projected objects, saving on the cost of cables by reducing their cross-section.

Payment for reactive energy ranges from 12 % to 50 % of active energy. On average, the operating objects in the bringing cables that lose from 10 to 15 % of the consumed active energy. Losses are proportional to the square of current flowing through the cable. For calculations, the loss factor K_{loss} was taken 12 % [51]. Let's consider this component on the example of the operating object Bus_0006 before implementation of capacitor installation $\cos\varphi_1 = 0{,}89$ and after implementation of capacitor installation $\cos\varphi_2 = 0{,}95$. The relative active component of the current I_r (coinciding in phase with the voltage) is taken equal to one. Relative total current before implementation of capacitor installation can be seen on formula 4.9.

$$I_1 = \frac{I_r}{\cos\varphi_1}, \tag{4.9}$$

where I_r – the relative active current, A,

$\cos\varphi_1$ – cosine before compensation of bus 6.

$$I_{1_{0006}} = \frac{1}{0{,}89} \approx 1{,}12\ \mathrm{A}$$

Relative total current after implementation of capacitor installation equals to

$$I_2 = \frac{I_r}{\cos\varphi_2}, \tag{4.10}$$

where $\cos\varphi_2$ – cosine after compensation of bus 6.

$$I_{2_{0006}} = \frac{1}{0{,}95} \approx 1{,}05 \text{ A}$$

The decrease in active energy consumption will be

$$\Delta W_C = \left(\frac{{I_1}^2 - {I_2}^2}{{I_1}^2}\right) \cdot K_{loss} \cdot 100\ \% \tag{4.11}$$

where K_{loss} – loss factor, $K_{loss} = 0{,}12$.

$$\Delta W_{C_{0006}} = \left(\frac{1{,}12^2 - 1{,}05^2}{1{,}12^2}\right) \cdot 0{,}12 \cdot 100 \approx 1{,}453\ \%$$

which means that in this example, the cost of active energy decreased by 1,453 %. Annual savings C in electricity payments will be

$$C = \left(\frac{\Delta W_C}{100\%}\right) \cdot T, \tag{4.12}$$

where T – cost of electricity consumed per year, €.

Cost of electricity consumed per year can be calculated by formula 4.13

$$T = Y \cdot \Delta P_S, \tag{4.13}$$

where Y – the average cost that was calculated for 11 months of 2018 [52], $Y = 46{,}497€/\text{MWh}$.

$$\Delta P_S = (P_B - P_A) \cdot 24\ hours \cdot 365\ days, \tag{4.14}$$

Where P_B – active power before compensation, MW,

P_A – active power after compensation, MW.

$$\Delta P_S = (15{,}19 - 14{,}52) \cdot 24 \cdot 365 = 5869{,}2 \text{ MWh per year}$$

$$T = 46{,}497 \cdot 5869{,}2 = 272900{,}192€$$

$C_{0006} = 0{,}01453 \cdot 272900{,}192 \approx 3965{,}24€$

Payback period of expenses (in years)

$$T_P = \frac{C_{RPC}}{C}, \tag{4.14}$$

where C_{RPC} – cost of condenser installation, €,

C – annual saving for electricity, €.

The cost of capacitors is taken approximately, since installation of these capacitors is made by order. The price of one installation is from 9750 to 25980 euros. In the calculation was taken the average price of 17865 euros. Taking into account the delivery and installation of RPC, the price may increase from 30 % to 50 %. Thus, the maximum installation price is 26797,5 euros.

$$T_{P_{0006}} = \frac{26797{,}5}{3965{,}24} \approx 6{,}758$$

In the same way we calculate Bus_0009 using same formulaes and loss factor but different $\cos\varphi$. In the Bus_0009 the cosine φ before implementation of capacitor installation eguals to $\cos\varphi_1 = 0{,}87$ and after implementation of capacitor installation cosine φ is $\cos\varphi_2 = 0{,}95$. After calculations we got the following outcomes:

Relative total current before implementation of capacitor installation

$$I_{1_{0009}} = \frac{1}{0{,}87} \approx 1{,}15\ \mathrm{A}$$

Relative total current after implementation of capacitor installation

$$I_{2_{0009}} = \frac{1}{0{,}95} \approx 1{,}05\ \mathrm{A}$$

The decrease in active energy consumption will be

$$\Delta W_{C_{0009}} = \left(\frac{1{,}15^2 - 1{,}05^2}{1{,}15^2}\right) \cdot 0{,}12 \cdot 100 \approx 1{,}996\ \%$$

which means that in this example, the cost of active energy decreased by 1,996 %. Annual savings C in electricity payments will be

$$C_{0009} = 0{,}01996 \cdot 272900{,}192 \approx 5447{,}088€$$

Payback period of expenses (in years)

$$T_{P_{0009}} = \frac{26797{,}5}{5447{,}088} \approx 4{,}92$$

This method of calculation is simplified, however, it is recognized in the power industry and is recommended for determining the economic performance of compensating devices at the design stage. Calculation error does not exceed 10 %.

5. SUMMARY

This diploma presents an overview of modern trends in reduction of power losses in electrical networks. In addition, advantages and disadvantages of these methods were described. Using the DIgSILENT program, the electrical network was modulated and calculated. Reactive power compensators were also calculated and calculations were performed before and after compensation. An economic justification of the RPC installation was made and an assessment of its effectiveness has been carried out.

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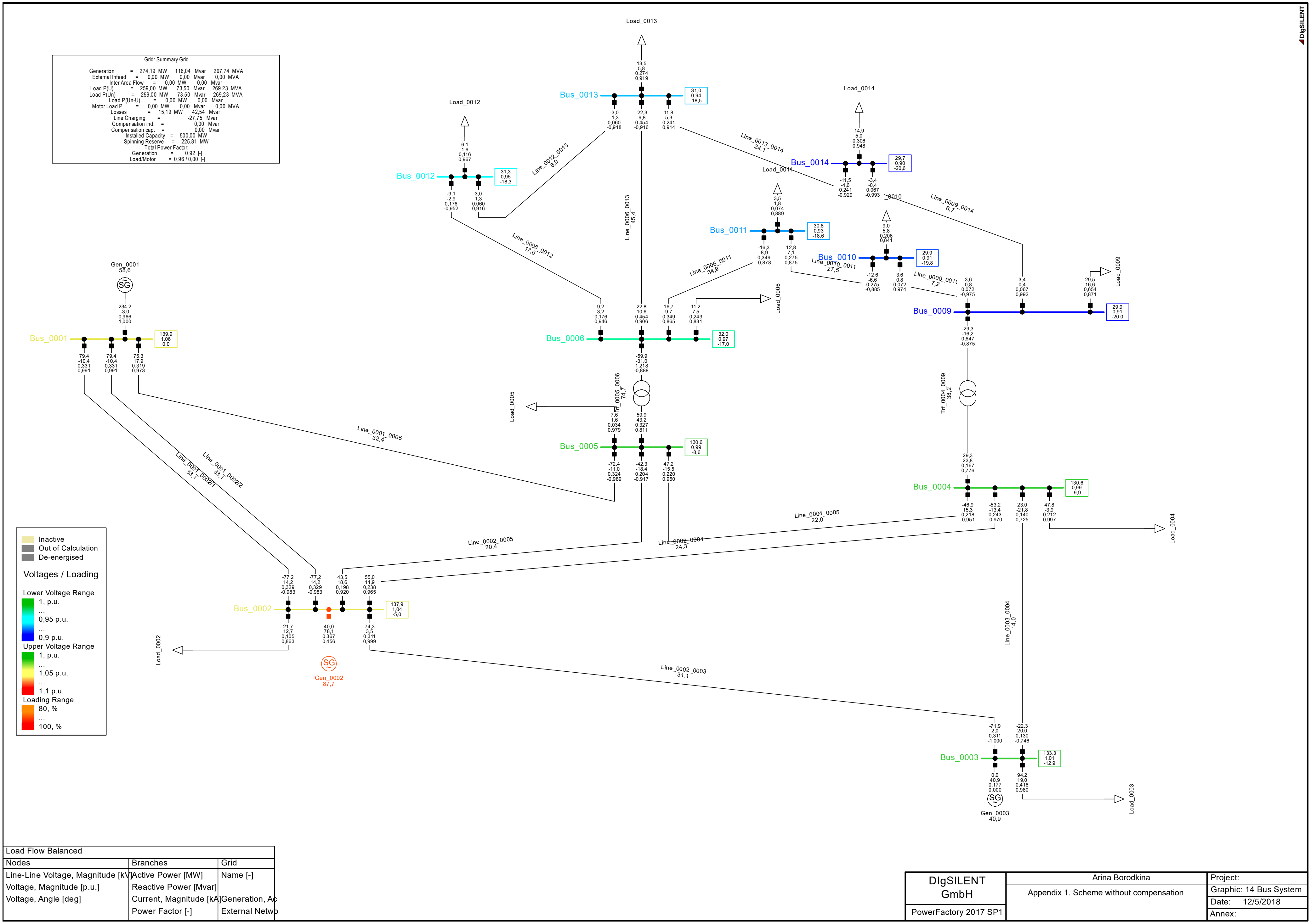
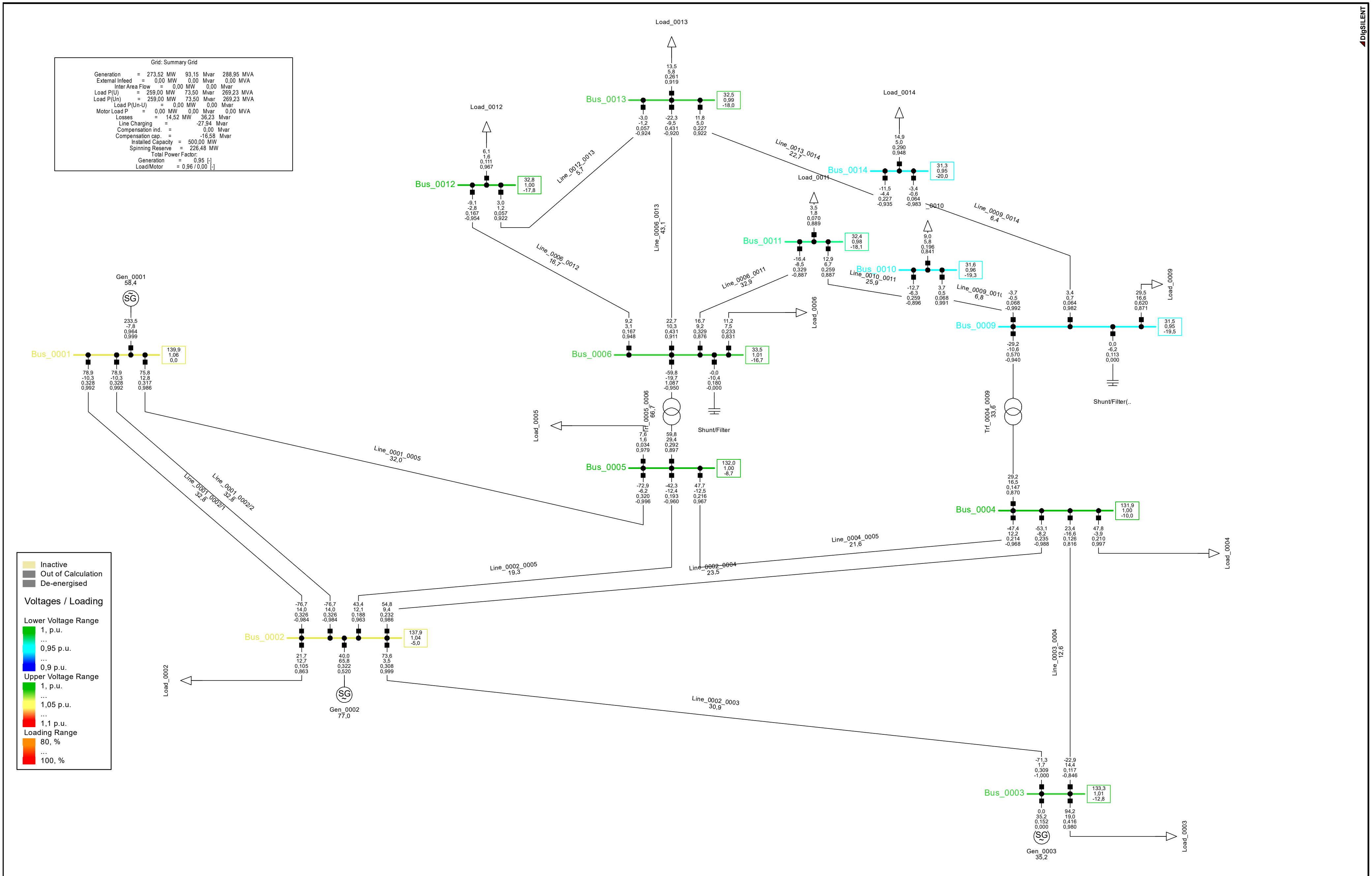
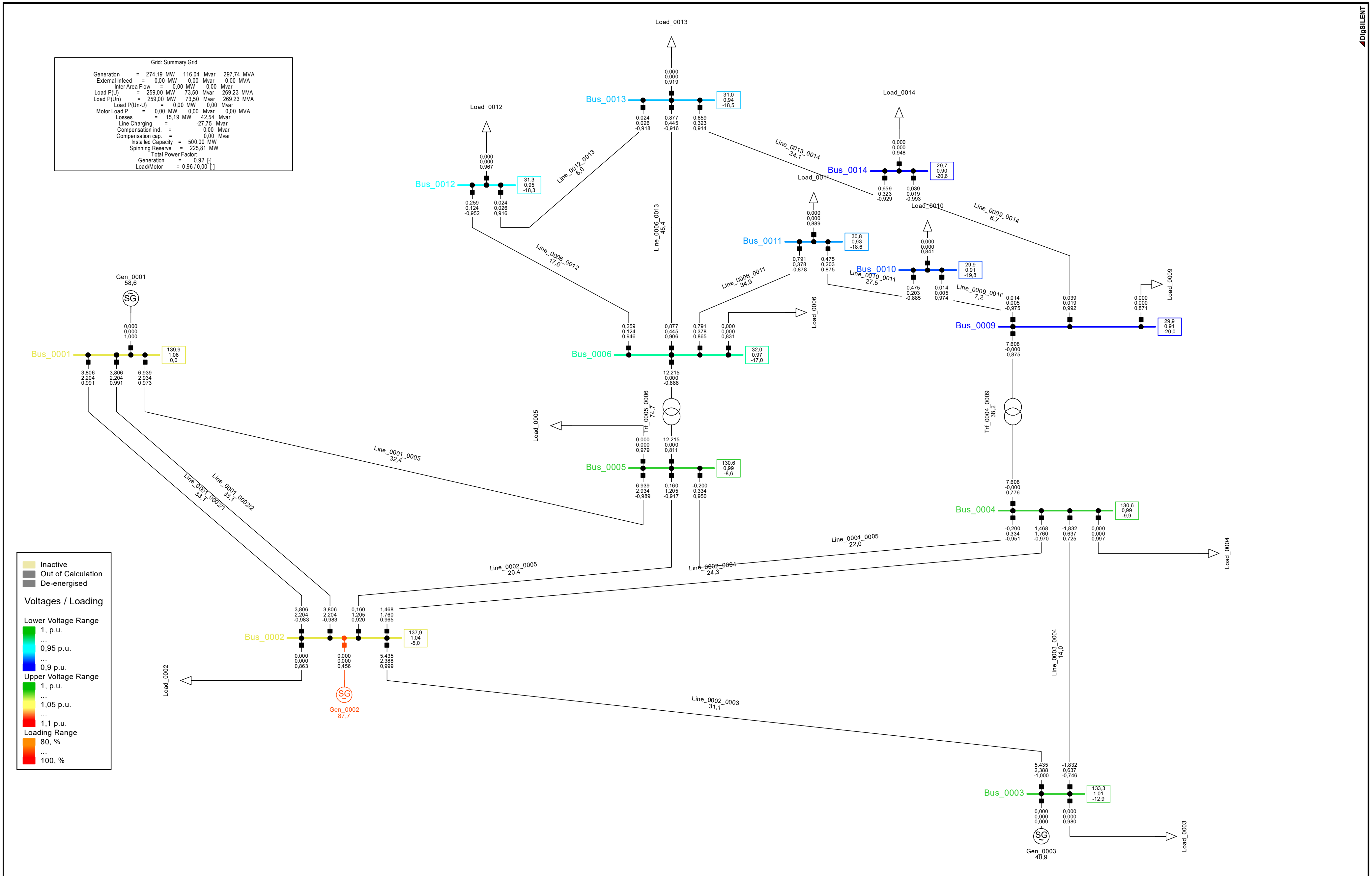
APPENDICES


Grid: Summary Grid
Generation = 274,19 MW 116,04 Mvar 297,74 MVA
External Infeed = 0,00 MW 0,00 Mvar 0,00 MVA
Inter Area Flow = 0,00 MW 0,00 Mvar
Load P(U) = 259,00 MW 73,50 Mvar 269,23 MVA
Load P(Un) = 259,00 MW 73,50 Mvar 269,23 MVA
Load P(Un-U) = 0,00 MW 0,00 Mvar
Motor Load P = 0,00 MW 0,00 Mvar 0,00 MVA
Losses = 15,19 MW 42,54 Mvar
Line Charging = -27,75 Mvar
Compensation ind. = 0,00 Mvar
Compensation cap. = 0,00 Mvar
Installed Capacity = 500,00 MW
Spinning Reserve = 225,81 MW
Total Power Factor:
Generation = 0,92 [-]
Load/Motor = 0,96 / 0,00 [-]
Load_0013
Bus_0013
Load_0012
Bus_0012
Line_0012_0013 6,0
Line_0013_0014 24,1
Load_0014
Bus_0014
Load_0011
Bus_0011
Line_0009_0014 6,7
Line_0006_0013 45,4
Line_0006_0012 17,6
Line_0006_0011 34,9
Bus_0010
Line_0010_0011 27,5
Line_0009_0010 7,2
Load_0009
Bus_0009
Load_0006
Gen_0001 58,6
Bus_0001
Bus_0006
Trf_0005_0006 74,7
Trf_0004_0009 38,2
Load_0005
Bus_0005
Line_0001_0005 32,4
Line_0001_0002/1 33,1
Line_0001_0002/2 33,1
Bus_0004
Line_0004_0005 22,0
Line_0002_0005 20,4
Line_0002_0004 24,3
Load_0004
Inactive
Out of Calculation
De-energised
Voltages / Loading
Lower Voltage Range
1, p.u.
0,95 p.u.
0,9 p.u.
Upper Voltage Range
1, p.u.
1,05 p.u.
1,1 p.u.
Loading Range
80, %
100, %
Bus_0002
Load_0002
Gen_0002 87,7
Line_0003_0004 14,0
Line_0002_0003 31,1
Bus_0003
Gen_0003 40,9
Load_0003
Load Flow Balanced
Nodes
Line-Line Voltage, Magnitude [kV]
Voltage, Magnitude [p.u.]
Voltage, Angle [deg]
Branches
Active Power [MW]
Reactive Power [Mvar]
Current, Magnitude [kA]
Power Factor [-]
Grid
Name [-]
Generation, Ac
External Netwo
DIgSILENT GmbH
PowerFactory 2017 SP1
Arina Borodkina
Appendix 1. Scheme without compensation
Project:
Graphic: 14 Bus System
Date: 12/5/2018
Annex:



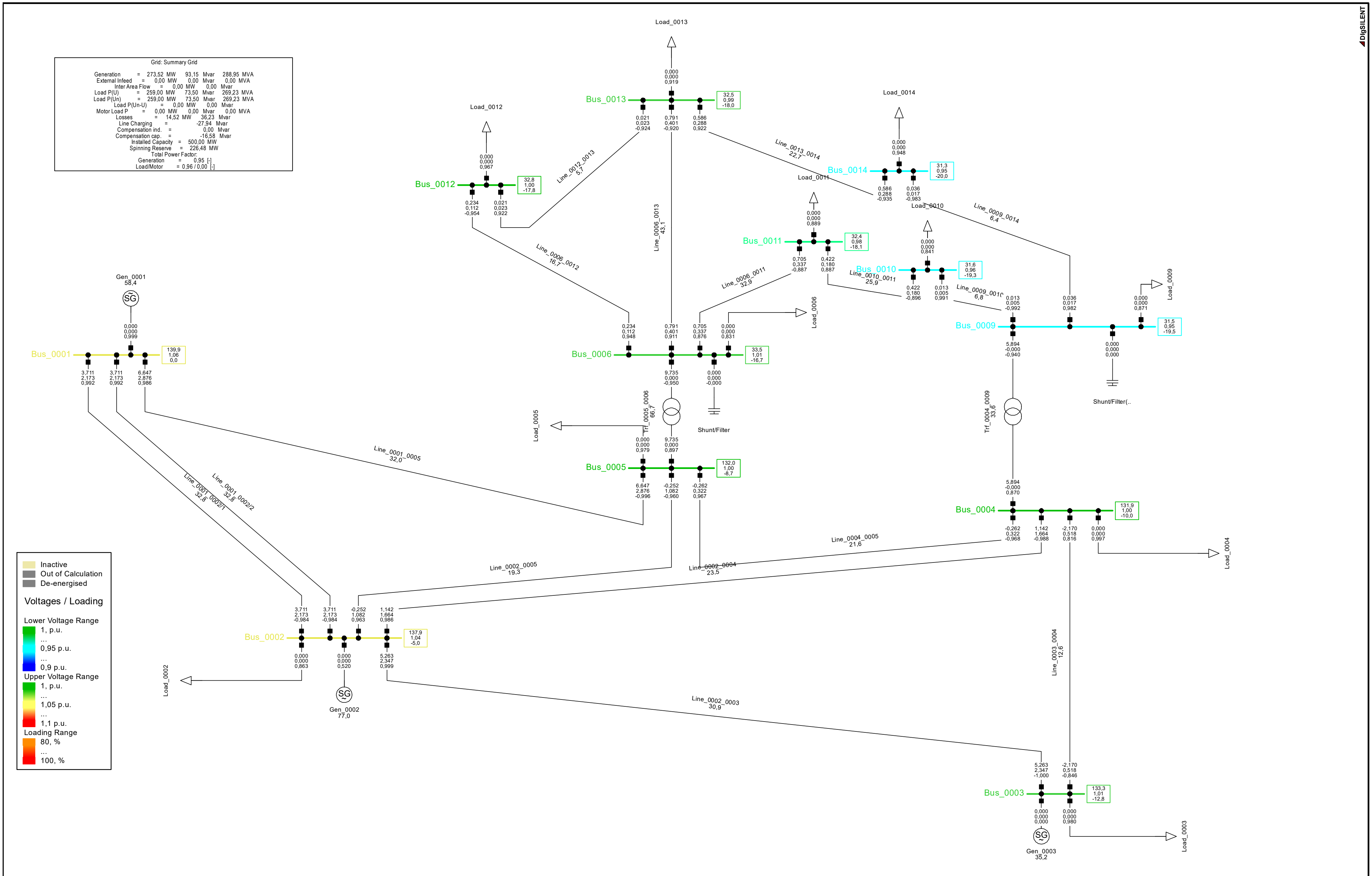
Load Flow Balanced		
Nodes	Branches	Grid
Line-Line Voltage, Magnitude [kV]	Active Power [MW]	Name [-]
Voltage, Magnitude [p.u.]	Reactive Power [Mvar]	
Voltage, Angle [deg]	Current, Magnitude [kA]	Generation, Ac
	Power Factor [-]	External Netwo

DIgSILENT GmbH	Arina Borodkina	Project:
	Appendix 2. Scheme with compensation	Graphic: 14 Bus System
		Date: 12/10/2018
PowerFactory 2017 SP1		Annex:



Load Flow Balanced		
Nodes	Branches	Grid
Line-Line Voltage, Magnitude [kV]	Reactive-Losses (total) [Mvar]	Name [-
Voltage, Magnitude [p.u.]	Losses (total) [MW]	
Voltage, Angle [deg]	Power Factor [-]	Generat
		Externa

DIgSILENT GmbH	Arina Borodkina	Project:
	Appendix 3. Scheme without compensation with active and reactive losses	Graphic: 14 Bus System
		Date: 12/10/2018
PowerFactory 2017 SP1		Annex:



Load Flow Balanced		
Nodes	Branches	Grid
Line-Line Voltage, Magnitude [kV]	Reactive-Losses (total) [Mvar]	Name [-
Voltage, Magnitude [p.u.]	Losses (total) [MW]	
Voltage, Angle [deg]	Power Factor [-]	Generat
		Externa

DIgSILENT GmbH	Arina Borodkina	Project:
	Appendix 4. Scheme with compensation with active and reactive losses	Graphic: 14 Bus System
		Date: 12/10/2018
PowerFactory 2017 SP1		Annex:

APPENDIX 5. SUMMARY OF THE DIPLOMA WORK

Author: Arina Borodkina	*Type of the work:* Bachelor Thesis
Title: Modern trends in reduction of power losses	
Date: 20.12.2018	*65 pages*
University: Tallinn University of Technology *Faculty:* Faculty of Engineering *Department:* Department of Electrical Power Engineering and Mechatronics	
Tutor(s) of the work: Victor Astapov *Consultant(s): -*	
Abstract: The main goal of the bachelor's thesis is to study modern trends in reduction of power losses. During the work, power losses were classified and methods for reducing them were described. One of the method of reducing power losses was chosen, which was modulated in the program DIgSILENT and calculated. In this thesis work was selected method of VAR compensation. After the simulation, calculations of capacitor installations on buses 6 and 9 were carried out. After installing RPC on separate buses, the reactive power on buses was reduced by 34-37 %, and the active power decreased by 1-4 %. Total bus losses decreased by 6-8 %. Despite insignificant changes in active power in buses, the total power loss in the network decreased by 13.5 %. On the basis of these data, an economic justification was made for RPC installation and an assessment of its effectiveness was carried out. From the data obtained it can be concluded that RPC installation was done correctly.	
Keywords: distribution systems, losses reduction techniques, VAR compensation, DIgSILENT, power losses.	

APPENDIX 6. LÕPUTÖÖ KOKKUVÕTE

Autor: Arina Borodkina	*Lõputöö liik:* Bakalaureusetöö
Töö pealkiri: Kaasaegsed trendid võimsuse kadude vähendamisel	
Kuupäev: 20.12.2018	*65 lk*
Ülikool: Tallinna Tehnikaülikool *Teaduskond:* Inseneriteaduskond *Instituut:* Elektroenergeetika ja mehhatroonika instituut	
Töö juhendaja(d): Victor Astapov *Töö konsultant (konsultandid): -*	
Sisu kirjeldus: Bakalaureusetöö peamiseks eesmärgiks on uurida kaasaegsed trendid võimsuse kadude vähendamisel. Töö käigus oli liigitatud võimsuskaod ja kirjeldatud nende vähendamise meetodeid. Valitud meetod voolukadude vähendamise eest oli moduleeritud ja arvutatud programmis DIgSILENT. Selles lõputöös oli valitud välja VAR kompensatsiooni meetod. Pärast simulatsiooni oli tehtud 6. ja 9. lattides olevate kondensaatorseadmete arvutused. Pärast reaktiivvõimsuse kompenseerimise paigaldamist erinevates lattides oli vähendatud reaktiivvõimsust 34-37 % võrra ja aktiivvõimsus vähenes 1-4 % võrra. Kogu rehvi kaod vähenesid 6-8 %. Hoolimata väikesest lattides aktiivvõimsuse muutumisest, kogu kaod vähenesid kokku 13,5 % võrra. Sellese andmete põhjal oli tehtud reaktiivvõimsuse kompenseerimise paigaldamiseks majanduslik põhjendus ja oli viidud läbi selle tõhususe hindamine. Saadud andmetel võib järeldada, et reaktiivvõimsuse kompenseerimise paigaldamine toimus korrektselt.	
Märksõnad: jaotussüsteemid, kadude vähendamise tehnikad, VAR kompensatsioon, DIgSILENT, võimsus kaod.	