TALLINNA TEHNIKAÜLIKOOL
Elektrotehnika instituut

ATM70LT

Tanel Sinijärv

ODAV LAHENDUS ELEKTRIENERGIA TARBIMISE MÕÕTMISEKS

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Tallinn 2016

AUTHOR'S DECLARATION

I hereby declare that this thesis is entirely my own work, in my own words, and that all sources used are fully acknowledged and all quotations properly identified. It has not been submitted, in whole or in part, by me or another person, for the purpose of obtaining any other credit / grade.

Tallinn, 23.05.2016.a. .... Tanel Sinijärv

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Odav lahendus elektrienergia tarbimise mõõtmiseks

Tanel Sinijärv, üliõpilaskood 132152AAAMM, mai 2016. – 68 lk.

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Töö konsultant: Stuart Bashford

Võtmesõnad: elektrienergia, vool, efektiivväärtus, mikrokontroller, elektroonika

Referaat:

Lõputöö eesmärk on uurida odavaid lahendusi elektrienergia mõõtmiseks. Ideaalne lahendus mõõdab iga üksikut tarbijat, samas, kui maksumus ühe mõõdetava kohta ei ole rohkem, kui 20 eurot. Soovitud kasutamise kohaks on viljaveskid.

Lõputöö rõhutab elektrienergia mõõtmise tähtsust ja sisaldab põhilisi valemeid ning teooriat. Fookus on suunatud voolu mõõtmisele. Lõputöös on välja toodud mõned tuntumad voolu mõõtmise sensorid. Hinnapäringute tulemusena on esitletud kolme tootja pakkumised ja lahendused.

Lõputöö teises osas on käsitletud mõningaid võimalusi elektrienergia mõõtesüsteemi ehitamiseks. Tutvustatud on mikrokontrolleril põhinevat üldist kontseptsiooni. Testitud on kahe integreeritud analoogskeemi sobivust selle süsteemi tarvis. Uuritud on ka mõningaid andmeside protokolle.

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Inexpensive Solution for Electricity Consumption Metering

Tanel Sinijärv, student code 132152AAAMM, May 2016. – 68 pp.

TALLINN UNIVERSITY OF TECHNOLOGY

Faculty of Power Engineering

Department of Electrical Engineering, chair of Electrical Drives and Power Electronics

Instructor: scientist Heigo Mõlder

Consultant: Stuart Bashford

Key words: electric energy, current, root mean square, microcontroller, electronics

Paper:

The task of this thesis is to investigate inexpensive solutions for electricity metering. The ideal solution will measure every single consumer individually while costing not more than 20 euros per consumer. Desired use of the solution would be in the grain milling industry.

The thesis introduces overall importance of electrical energy metering. Including basic equations and theory behind it. Main focus is on current measuring. Some of the most popular current sensors have been noted in the thesis. The result of the inquiry for ready-made solutions brings out three suppliers and their offers for this solution.

In the second half of the thesis some options for building an electrical metering system are discussed. Overall concept based on microcontroller unit is introduced. Two integrated analog circuits are tested to see their suitability for this measuring system. Few data transmission protocols were explored.

ATM70LT

Nízkorozpočtové měření spotřeby elektrické energie

Tanel Sinijärv, identifikační číslo studenta 132152AAAMM, květen 2016. – 68 str.

TECHNICKÁ UNIVERZITA TALLINN

Fakulta energetického inženýrství

Katedra elektrotechniky, obor elektrické pohony a výkonová elektronika

Vedoucí práce: doktor věd Heigo Mõlder

Konzultant: Stuart Bashford

Klíčová slova: elektrická energie, proud, efektivní hodnota, mikroprocesor, elektronika

Referát:

Cílem této diplomové práce je zkoumat možná řešení nízkorozpočtového měření elektrické energie. Ideální řešení měří každý spotřebič individuálně a nestojí více než 20 euro za spotřebič. Toto řešení bude využito v mlýnském průmyslu.

Práce nás seznamuje se všeobecným významem měření elektrické energie včetně základních rovnic a teorie je vysvětlující. Hlavní důraz je kladen na měření proudu. Práce obsahuje výčet některých v současné době nejpoužívanějších proudových senzorů. Výsledek šetření předpřipravených řešení poskytuje tři dodavatele a jejich nabídky.

V druhé polovině práce jsou diskutovány některé možnosti sestrojení elektrických systémů měření. Je představen všeobecný koncept mikroprocesoru. Dva integrované analogové obvody jsou testovány pro zjištění jejich vhodnosti pro tento měřící systém. Dále bylo testováno několik protokolů přenosů dat.

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TALLINN UNIVERSITY OF TECHNOLOGY

Department of Electrical Engineering

APPROVED BY

Prof. T. Lehtla...............................

.... 2016

TASK OF THE MASTER THESIS

Tanel Sinijärv, student code 132152AAAMM

Master thesis topic: Inexpensive Solution for Electricity Consumption Metering

Task: Find an inexpensive solution how to measure electrical energy in a system where every consumer is being monitored separately.

Input data:

1. Thematic books
2. Scientific articles
3. Price inquiries
4. Internet pages
5. Data sheets
6. Application notes

List of problems that need to be solved:

1. Finding price and suitability of solutions on the market.
2. Measuring motor current, voltage and angle between current and voltage.
3. Choosing appropriate components for making own system.
4. Fast and reliable data transmission between devices.

Instructor: Task received by:

Ph.D. H. Mõlder .... Student T. Sinijärv ....

1 INTRODUCTION

In the modern world the electrical energy has become an inseparable part of life. Wherever we look around us there are either electrical appliances or products that were made with the help of machines that are powered by electricity. The very clothes we wear or food we eat is in one part of its way to us processed with the help of electrical energy. It was about 130 years ago when the first electricity distribution system was set up by Thomas Edison. Back then electricity was used mainly for lights. Over those years the importance of electrical energy has grown into far more important than just a small source of light. Trends are indicating that in the future even more of our daily life will rely on it. Good example is electrical cars that are becoming more common. This has put humanity in front of a question, how to keep the ever expanding electricity consumption constrained and not overuse natural resources. To successful solve the problem it needs to be dealt from both sides. Alternatives for electricity production have to be found and at the same time the efficiency of consumers needs to be optimised to waste less energy [1].

U.S Department of Energy has predicted that world net electricity generation will rise from 20,2 trillion kWh in 2010 to 39,0 trillion kWh in 2040 [2].

From the figure 1.1 we can see that the majority of this growth will be by the use of unrecoverable resources. The report states that electricity consumption by end users grows faster than their other delivered energy sources. Estimated average rise in electricity generation is 2,2 percent from 2010 to 2040. The biggest contributors are non-OECD countries like China, India, Russia [2]. These predictions should not be taken lightly. The fact that most of these growths may happen in countries outside Europe and United States doesn’t mean that it will not affect us. In fact one of the reasons behind this is the higher consumption of goods in western countries.

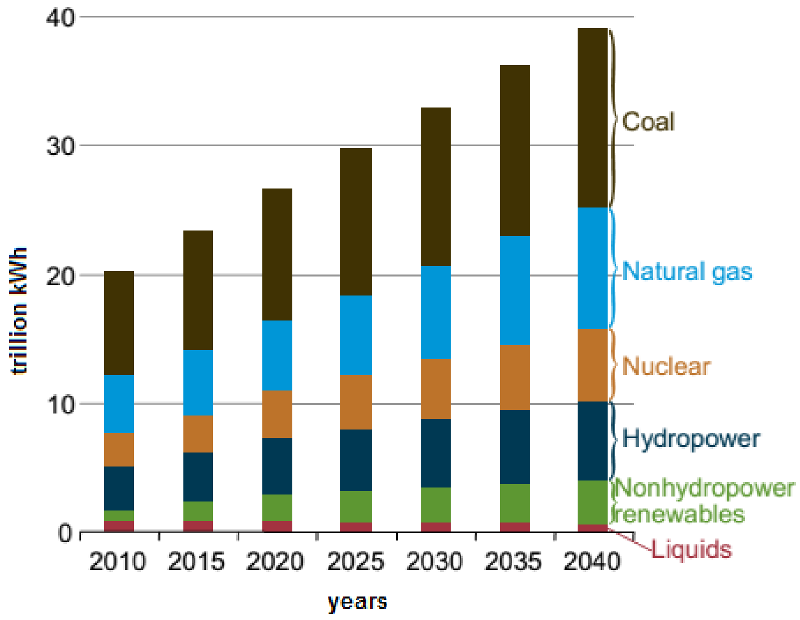


Figure 1.1. World net electricity generation by energy sources [2]

To outweigh the rapid rise of electricity consumption, most of the countries have started regulating the use of electricity. The self awareness is rising. Both people and industries are using more efficient equipment. One of the driving methods towards this energy saving lifestyle has been and will be the pricing of kWh. According to Eurostat news release in May 2015 household electricity prices in the EU rose by 2,9% in 2014 [3].

These factors have made everybody cautious of their electricity consumption including industries. Whenever there is a use of energy we want to know how, where and when it is being used. Having this knowledge will help to improve energy usage and optimise costs. For example, processes that have flexibility to run at any time of a day can be scheduled to night-time or to gaps in regular processes. Planning work in this way helps to reduce electrical distribution equipment costs. Loosing huge peaks in loads will mean smaller substations which cost less. Timing the usage to night times brings lower kWh prices.

1.1 Bühler AG introduction

Bühler AG is a family-owned company with Swiss roots. The beginning of this enterprise dates back more than 150 years. It started as a cast iron foundry with two employees. Today the total number of persons on Bühler AG payroll is about 10600 located in 140 countries around the world. In 2014 the generated sales revenue was 2,3 billion CHF (approximately 2,1 billion EUR) [4]. Bühler AG states that environmental protection is an important business mission. Four to five percent of all annual profits are invested into research and development in order to have innovative and energy efficient solutions that meet the modern needs.

One of the first machines produced by Bühler AG was a cast iron roller mill for flour mills. These roller mills paved the way for industrial-size flour mills. Over the decades Bühler AG has developed and implemented many important machines for food industry. Around 65% of the wheat harvested today is processed into flour by Bühler AG mills. There is more from the food industry. Rice, pasta, chocolate and breakfast cereals are also sectors where the company is well known. Furthermore, Bühler AG is a leading solution provider of die casting, wet grinding, and surface coating technologies.

Here is a list of business areas where Bühler AG is participating:

- Grain milling
- Value nutrition
- Sortex and rice
- Grain logistics
- Consumer foods
- Die casting
- Grinding and dispersion
- Coating solutions

These areas have very different processes and machinery. This thesis will focus on grain milling plants and the electrical energy usage in them. One can think that there is no difference which industry we are talking about. In the end the electricity used by a plant is all the same. That is true, but the way this is controlled varies. And to propose a solution for the electrical energy monitoring we need to know specifics. Elements like panel layout, electrical motor current rating, electrical motor starting mode and control, data transmission lines and protocols, will all affect the properties of electrical energy measurement.

The reason to introduce Bühler AG is to give an understanding how big part of industry and world it touches. As one can see there is no better place to focus on the power efficiency and energy consumption than in the very heart of major industrial equipment and machinery manufacturer.

2 ELECTRICAL POWER MEASURING

Wide scale electrical power measuring started with the development of the first electricity grids. There was a need to know how much has to be paid. When Thomas Edison first started to rate the cost of electricity per lamp. However he soon realized that this is not accurate at all. He developed a chemical ampere-hour meter that consisted of a jar holding two zinc plates connected across a shunt in the customer's circuit. Each month the electrodes were weighed and the customer's bill determined from the change in their weight. This method was also very inaccurate. It took few years and in 1889 Elihu Thomson introduced the first true watt-hour meter, which worked well for both AC and DC circuits [5].

Today the variety of electrical power measuring equipment is very big. Starting from simple one phase watt-hour meter to a multi phase system that does not measure only power, but also analyses its quality. They are able to monitor harmonics, transient events in the system, flickers and tens of other parameters related to electrical power measuring. It doesn’t stop there. In addition these multifunctional meters can trigger digital and relay outputs, read digital inputs, log data, communicate with other field devices and send all this information to a server. There the data will be processed and can be accessed via computer or smartphone.

It seems that everything we want to measure in electrical systems can be measured. Now we have to ask ourselves how much we are willing to pay for these multifunctional devices. Companies which are selling these devices have put a lot of money and time to research and development. Thus the prices of measuring systems are really high. One would never dare to think about using one of these for measuring small single loads. These measuring systems are mainly intended for high current distribution systems or for high value electrical devices. To use them for any other purposes would make no sense. The money paid for extra electricity, losses in the system or additional costs due to not optimizing electricity consumers will, in most cases, be less than the initial investment needed for the whole measuring and monitoring system.

What are the options to measure large number of loads, without high demands on measuring quality and without huge investments?

2.1 Electrical power measuring principles

Electrical power is measured in watts (W). One watt is defined as a power required to do work at the rate of 1 joule per second. In electrical means watt is defined through voltage and current. Meaning also that watt can not be directly measured like voltage and current. By definition one watt of power is transmitted or used when current of one ampere flows through a potential difference of one volt. Mathematically meaning that power P is a result of a multiplication between current I and voltage E, $P = I \cdot E$. A good overview of main electrical calculations, including power, can be seen in the figure 2.1.

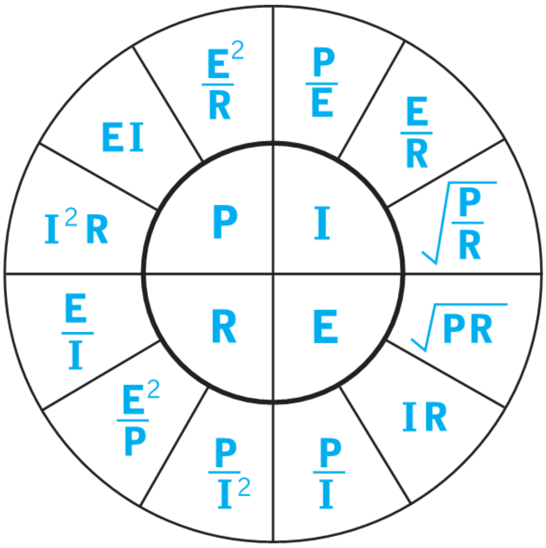


Figure 2.1. Collection of equations to find main electrical parameters [6]

One of the simplest examples of power conversion is a DC circuit with resistive load. In this case the electrical power is converted to heat. We can see that the amount of power turned into heat depends on both current flowing through the resistor and potential difference created by the source. Illustrative schematic is in the figure 2.2.

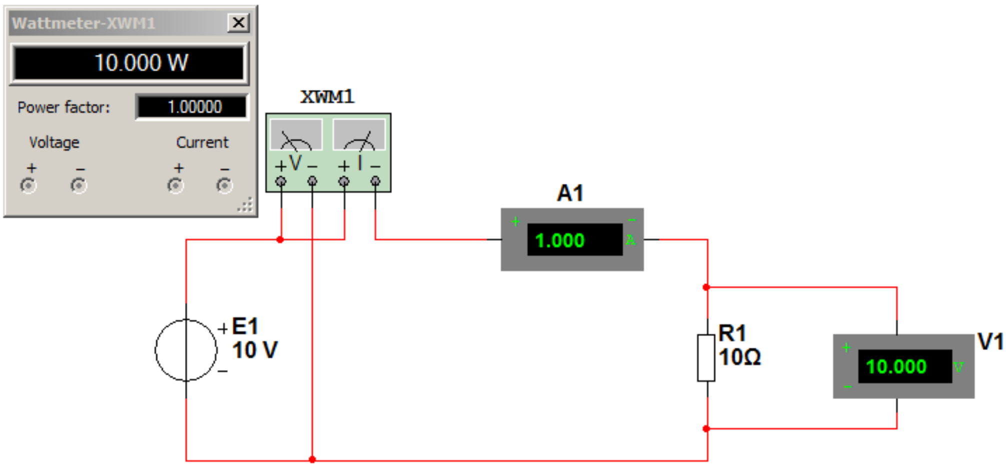


Figure 2.2. Power in simple series circuit

In this circuit we can see that the power shown on wattmeter is equal to current passing through the ammeter multiplied by voltage measured with the voltmeter. In wattmeter it has solved in a way that there are two coils. One of the coils is in series and the other is connected in parallel. The coil that is connected in series with the load is for current and the one in parallel is for voltage. Both of the coils produce magnetic fields which interact with each other resulting in a deflecting torque on the voltage coil which makes the indication needle move. Simple design of a wattmeter is shown in the figure 2.3. This is suitable for both AC and DC circuits.

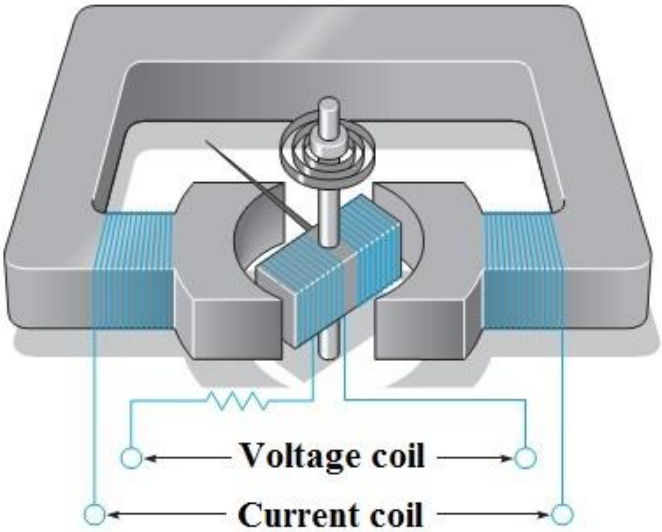


Figure 2.3. Simple wattmeter design [6]

While the simple wattmeter may be suitable for both AC and DC circuits the real physics behind it is a bit more complicated. To understand it better let us take a look at the waveforms of both types and how the power is calculated from them. For DC the equations are already shown in the figure 2.1. For AC waveform we need a bit more. Firstly we have to decide what kind of AC waveform to use. As our AC grid in Europe is 50 Hz sine wave with the RMS (root mean square) value of 230 V between one phase and neutral, we will use the sine wave. Mathematical equation defining the sine wave is [7]:

$$y(t) = A * \sin(2\pi f t + \varphi), \tag{2.1}$$

where t – the time (s),
A – the amplitude (V or A),
f – frequency (Hz),
φ – phase (°).

To present a sine waveform of voltage and current, like in the main AC grid, we need to know the amplitude values. The given RMS value is calculated with equation:

$$y_{RMS} = \sqrt{\frac{1}{T}\int_0^T y^2(t)dt}\ , \tag{2.2}$$

where y_{RMS} – the root mean square of the y function (V or A),
T – period over which the RMS is to be found (s),
t – time (s).

Usually in real life the function of waveform is unknown and instead single measurements are taken and RMS value is calculated over these values with an equation [7]:

$$x_{RMS} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)}\ , \tag{2.3}$$

where x_{RMS} – square root of the arithmetic mean of squares of given values (V or A),
x_n – single value from set of values (V or A),
n – number of values.

In AC theory the RMS value is used to indicate the level of power which is available from this waveform. It refers to the amount of work done by the equivalent value in DC. For the pure sinusoidal waveform the RMS value is 1,41 times smaller than the peak value. To be precise RMS value = peak value / $\sqrt{2}$ [8]. For different waveforms the relation between peak value and RMS value is different. For example triangular or sawtooth waveform has a RMS value $\sqrt{3}$ times smaller than the peak value [9]. This means that any distortion in waveform will change the RMS value making the simple calculation with fixed coefficient inaccurate. Most of the cheap multimeters measure the peak value and from this they calculate RMS, assuming the sinusoidal waveform with RMS coefficient of $\sqrt{2}$ [9]. To see the difference in power lets take a look at three different circuits. One is a DC circuit with 230 V and 2 A. Second is an AC circuit with 230 V RMS and 2 A RMS with no phase shift between current and voltage. Third is an AC circuit with the same current and voltage values as the previous one, but it has a phase shift of 60° between current and voltage. To give a better understanding of these differences a small example was created in Excel. Comparison summary of those three different circuits is shown in the table 2.1. When we look at the sine waveforms in the figure 2.4, left side, with no phase shift between current and voltage then the power produced is always positive varying from 0 W to 920 W. Maximum value comes from multiplying current and voltage peak values. Waveforms that are shifted from one another cause power to have negative values in some parts. Lowering the average (also called real) power. This means that part of the total power (also called apparent power) is used in reactive load. This power is called reactive power. Sometimes the term imaginary power is used, because this power does no work but provides magnetization to enable work in an AC system.

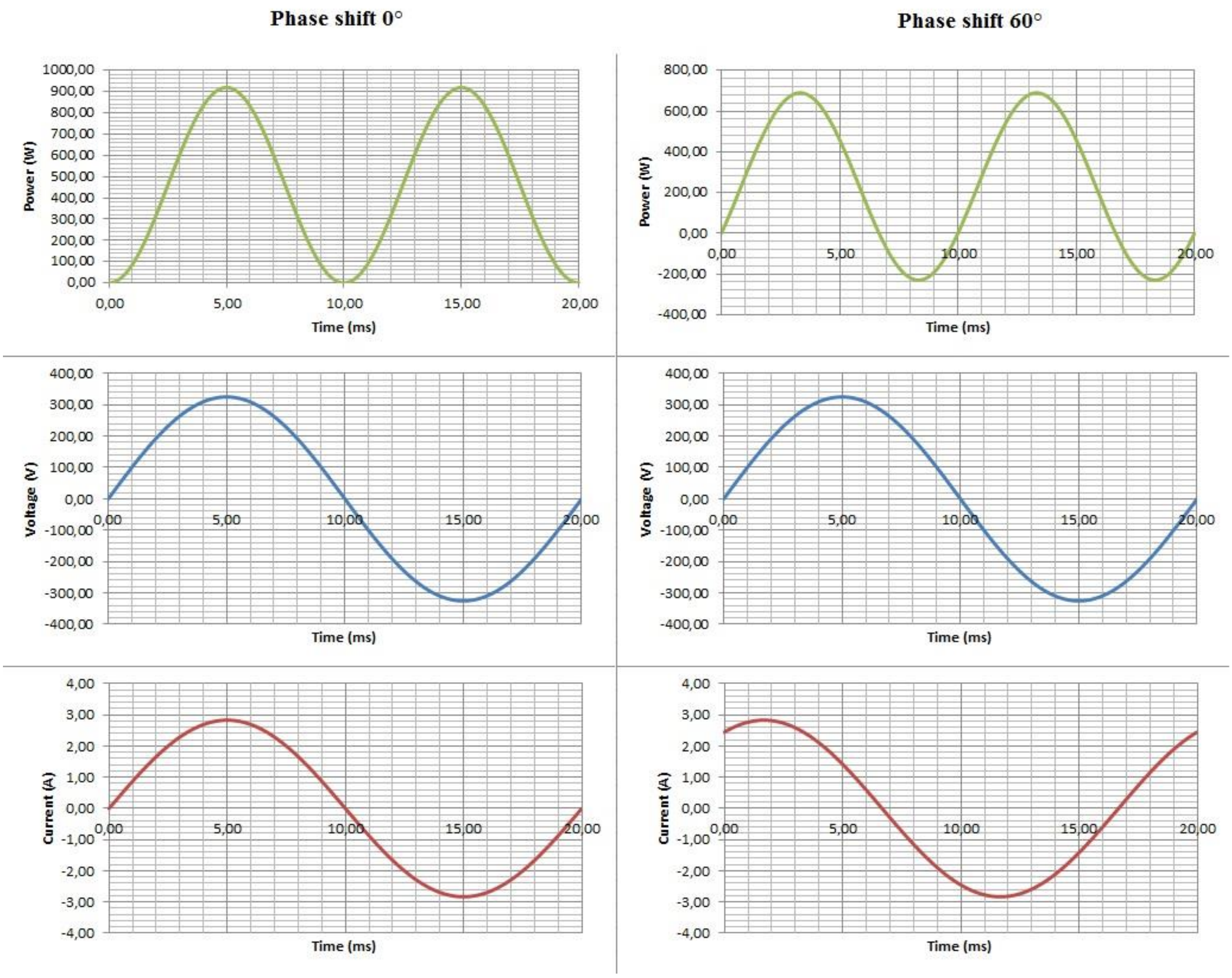


Figure 2.4. Sinusoidal waveforms of AC circuit

Table 2.1. Main values of different circuits

	DC circuit	AC circuit 0°	AC circuit 60°
Peak voltage (V)	230,0	325,3	325,3
Peak current (A)	2,0	2,8	2,8
RMS voltage (V)	230,0	230,0	230,0
RMS current (A)	2,0	2,0	2,0
Peak power (W)	460,0	920,0	689,9
Average power (W)	460,0	460,0	230,0

As the values indicate, in circuit with 60° phase shift the average power (real power) is only half from both DC and 0° AC circuit.

The equations for calculating power:

$$S = \sqrt{P^2 + Q^2}, \tag{2.4}$$

$$P = E * I * cos(\varphi) \text{ [10]}, \tag{2.5}$$

$$Q = E * I * \sin(\varphi) \text{ [10]}, \tag{2.6}$$

where S – apparent power (VA),
P – real power (W),
Q – reactive power (VAR),
E – voltage (V) RMS value,
I – current (A) RMS value.

For the circuit with 60° phase shift the calculations would be:
$Q = 230 * 2 * \sin(60°) = 398{,}4 \ (VAR)$,
$P = 230 * 2 * cos(60°) = 230{,}0 \ (W)$,
$S = \sqrt{230{,}0^2 + 398{,}4^2} = 460 \ (VA)$,

From previous calculations we can see that when measuring power in an AC circuit we also have to know the difference between voltage and current in order to be able to tell how much real power was used by the consumer. For more precise measurements also the distortion power should be included. The distortion power is caused by harmonics. Usually the effect by harmonics is not more than few percent from the total power. That's mainly because the frequencies of different harmonic voltages and currents compensate each other out. The summation of all harmonics in a system is known as total harmonic distortion (THD) [11]. In early electrical distribution systems the harmonics were very small and unnoticeable. During the last half a century rapid growth in use of nonlinear loads has shaped the waveforms of the grid. Main contributors to harmonic distortion are frequency converters, computers, fax machines and most of the household appliances with electronic control [11]. In a grain milling plants there are four main things that fall under the category of nonlinear load:

a) Computers, printers and Ethernet switches that are used for the control systems
b) Switching power supply for 24V devices (PLC, nodes, sensors, valves)
c) Frequency converters
d) Soft starters

All these four have really small impact to the overall power quality. That’s because the amount of power drawn by the switching power supplies is very small. Soft starters have influence on the supply system only during the starting process. Both soft starters and frequency converters power only small part of the motors in grain milling plant. The exact number depends on the clients requirements. Most of the power is consumed by three-phase asynchronous motors with direct or star-delta connection to the mains.

2.2 Measuring current

In previous chapter we saw that for obtaining the power of a certain part of the circuit we need current and voltage. If we want to separate real and reactive power then the angle between voltage and current is also needed. In a grain milling plant all the motors are connected to panel main bus bars through one of the ways shown in the figure 2.5.

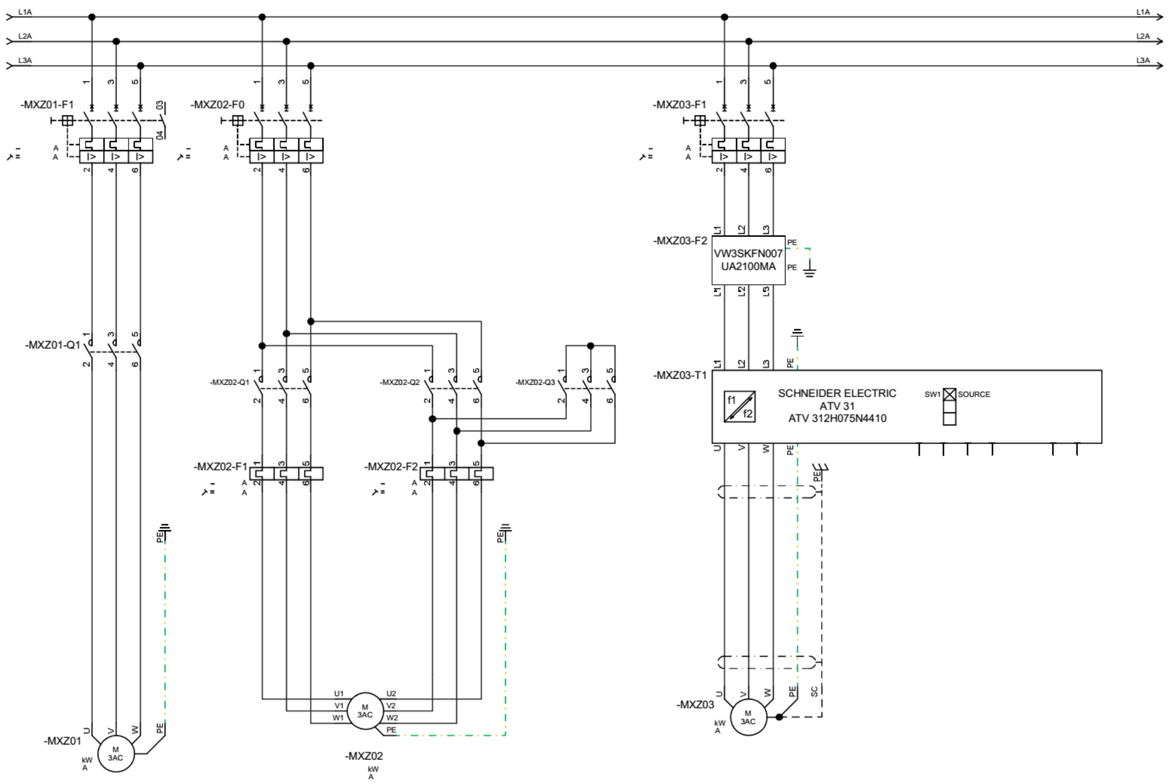


Figure 2.5. Most common motor connection options

Voltage to all the motors behind one panel can be taken as the same and measured only at one point on the bus bars. The voltage drop on the bus bars will be really small and can be discarded. This also means that for the system that measures every motors power separately we will need only one voltage measuring sensor per panel. That makes the voltage sensor less price sensitive. Main emphasis will be on the current sensor. There are various options on the market to choose from. A short overview of these will bring out the best type for this solution.

2.2.1. Shunt

Shunt is a resistor that is connected in series with the load which current we want to measure. The measuring equipment will measure the voltage drop on the shunt which is proportional to the current that is flowing through it. Shunt has a small resistance in order to minimize the effect it is going to have on the main circuit, but not too small because that will make the measuring inaccurate. The biggest downside of using shunt is that it offers no galvanic isolation, making it potentially hazardous to the measurement device and who ever is using it. Another problem known to using shunts is the skin effect. This is not a problem when we measure DC or low frequency AC currents. Only higher frequencies have considerable distortions caused by skin effect [13].

2.2.2. Current transformer

Every current in a conductor generates a magnetic field. A time-varying current in the conductor generates a magnetic field that induces current in the secondary winding [12]. If instead of the simple measuring loop a toroid coil with N turns is placed around the current carrying conductor, the induction effect is enhanced N times. This gives a current transformer where the primary winding is the conductor which current we want to measure and secondary winding is the wire placed around transformers magnetic core. The current in the secondary winding is small enough to be measured by the measuring equipment. In this current transformer the AC current in single-turn primary winding attempts to magnetize the core but in doing so creates an electromotive force and current in the secondary, which tends to cancel the field. If the secondary truly has zero resistance, the current in it exactly cancels the field due to the primary. In result the current in secondary winding is proportional to the current in the main conductor. In real life the secondary measuring circuit is never zero. That adds additional load (known as burden) and phase shift from main current [13]. Never the less current transformers are quite popular for measuring currents in the main distribution grid. It provides galvanic isolation and accuracy around few percent (depends on the specific current transformer) with low price.

Similar to the current transformer is a gapped inductive sensor. It is basically a current transformer which has gap in its core and increased number of secondary turns. The high inductance of the secondary causes the sensor to act like a current source, which generates a voltage across the load proportional to the primary current [13].

2.2.3. Hall effect sensor

Hall effect sensor is based on the semiconductor crystal. When placed into magnetic field this semiconductor starts to conduct creating an electromotive force that is proportional to the field and can be measured. In principle, such a field sensor can be placed near a current-carrying wire and oriented to sense the field created by the current, but the sensitivity is insufficient, and there would always be interfering fields from currents in other nearby wires. Therefore a flux concentrator, which looks like a current transformer with a gap, is used. The device can measure both DC and AC currents [13]. For higher accuracy a compensation winding can be added. This reduces measuring uncertainty to less than one percent. Hall measuring current sensor systems can be used for currents up to 200 kHz frequency region [12].

2.2.4. Rogowski coil

The Rogowski coil for measuring current is an air coil wound around the measured current conductor. The working principle is same as with current transformer, where the mutual inductance between primary and secondary winding generates voltage that is proportional to the current measured. To obtain the AC current waveform a single-chip digital integrator is usually used. Rogowski coils are known for their minor non-linearity, which is due to its lack of magnetic core. Another benefit of Rogowski coil is that it can have a flexible coil design, which makes it easy to use in existing panels and systems. The accuracy of Rogowski coil can be better than 0,1% and frequencies up to few MHz can be measured [13].

There are other less known, more expensive and more complicated current measuring systems on the market, but these previous ones are the most common. Really good solution would be with Rogowski coil, but due to the price of these coils it can’t be considered as an option. Using a low resistance shunt may be a good solution for low current applications, but using it in industrial environment is not the best. Plus it needs to be in series with the motor circuit, creating an unnecessary pair of terminals. This leaves us with current transformer or Hall effect current sensor. Both are suitable for main grid frequencies and come in rather good price. The output of these sensors can be different, but it doesn’t matter as the current can be easily turned into voltage over simple resistor and voltage is what microcontroller units or AD (analog to digital) converters most commonly measure.

3 THREE-PHASE ASYNCHRONOUS MOTORS

As said before the main consumer in grain milling plant is a three-phase asynchronous motor. Lets take a closer look at how the motor works and what are the factors that need to be taken into consideration when measuring motor power.

It is estimated that about 75% of the power in industry is consumed by asynchronous motors (also known as an induction motor) [14]. There are two different designs of asynchronous motors. First one is a squirrel cage motor and the second one is a wound rotor, also known as slip ring motor. Working theory is based on the same, induction, principle. In wound rotor design the speed of the motor is controlled via resistive loads connected to the rotor winding through slip rings [15]. This design is not as reliable as the squirrel cage one. Mainly due to the slip rings that need more frequent maintenance. Before the frequency converters were invented, using this type of the motor was the best way to have an AC motor with variable speed control.

The name squirrel cage refers to a rotor design that is similar to a rodent exercise wheel. When the moving magnetic fields in the stator cut across the rotor conductor bars, a current is produced in them. This current then creates magnetic field around the conductive bars. Similar to the stator the rotor is made out of laminated stack which is filled with either aluminium or copper bars that act as conductors [16]. In the figure 3.1 an overall view of squirrel cage asynchronous motor is shown. As we can see from the picture, the design of this type of a motor is rather robust and compact. Making it ideal for use in solutions which demand high reliability and low maintenance costs.

The main parameters of asynchronous motor are voltage, current, power, frequency, power factor, speed and number of phases. All these parameters have connections to each other and are important in describing the motor.

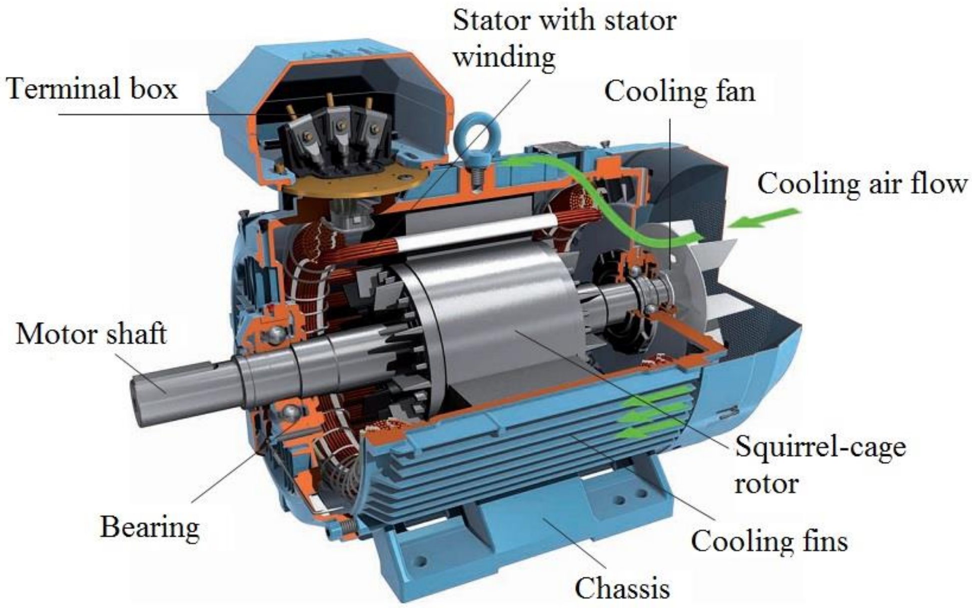


Figure 3.1. Three-phase asynchronous motor view [14]

Electric motor is a device that transforms electrical power into mechanical one. Mechanical power is calculated: $P_2(mechanical) = T * \omega\ (kW)$, where T represents torque and ω rotational speed of the motor shaft. In the motor the output power is always less than the input. That's because some of the energy is lost in the motor. That energy is dissipated as heat. Efficiency of a motor is described as a power ratio in percentages between input and output. Calculated by equation: $\eta = \frac{P_2}{P_1}\ (\%)$, where η is efficiency, P_1 input power and P_2 output power [16]. Different losses are shown in the figure 3.2.

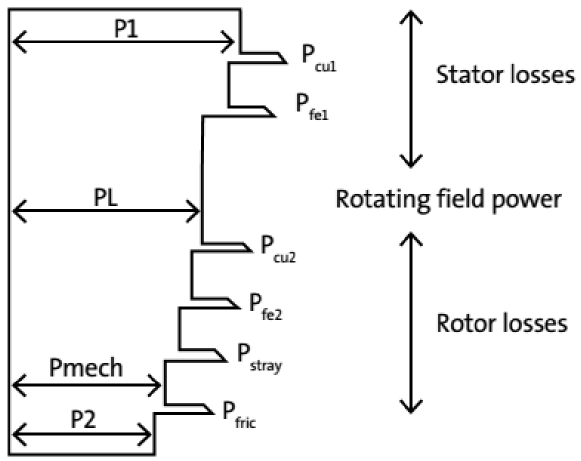


Figure 3.2. Losses in the induction motor [16]

where: P_{cu1} – ohmic losses in stator (W),

P_{fe1} – core losses in stator (W),

P_{cu2} – ohmic losses in rotor (W),

P_{fe2} – core losses in stator (W),

P_{stray} – losses caused mainly by eddy currents in the metal components (W),

P_{fric} – bearing friction losses (W).

Most of these losses are roughly constant. For example the core losses (caused by hysteresis and eddy current losses) depend on the frequency and voltage. Therefore we can say that they are constant during the operation. Ohmic losses are square function of current. Stray losses are usually taken as a fixed percentage from the input power. It may not be completely accurate, but it helps to simplify the calculations. In fact, these losses are usually never calculated separately. The amount of non-mechanical losses is given by the motor power factor cosφ. This depends largely on the load. The magnetization stays almost constant no matter the load. This in partial load range causes the cosφ to drop, meaning that the losses in motor are quite big compared to input power. Power factor is defined as a ratio of active power (W) to apparent power (VA). Numerically this value is the angle of lag of the input current with respect to its voltage [17]. The connection between main motor parameters can be seen in figure 3.3.

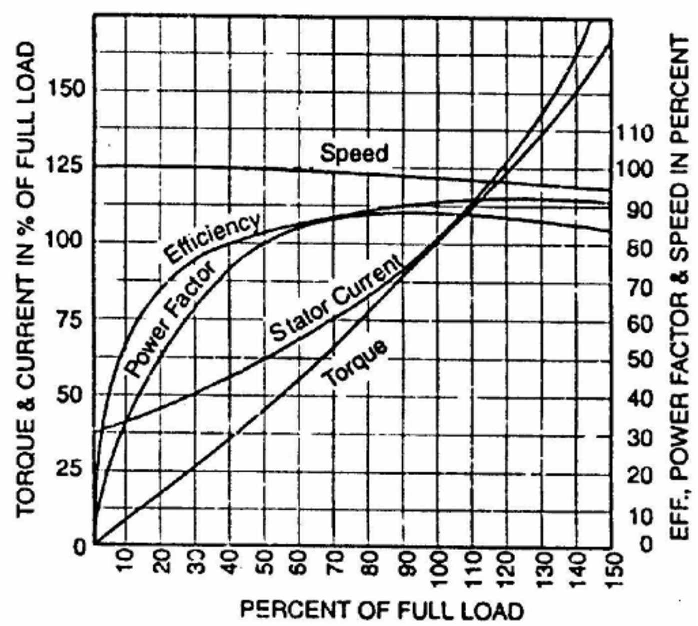


Figure 3.3. Performance curve of a three-phase squirrel cage motor [17]

Power factor on motor nameplate is given for the full load conditions. For a three-phase induction motor the consumed power (real power) is calculated with equation 2.5. To measure that in real time a RMS current, RMS voltage and angle between them is needed. In this preliminary concept the idea is to make this calculation in one main unit so there would be need for only few voltage measuring sensors like said before.

4 SOLUTIONS AVAILABLE ON THE MARKET

The market for automation solutions is wide. New companies and solutions come out every day. The variety of power measuring options is astonishing. Especially if there are no financial constraints. To have a better overview what’s actually out there on the market a small series of inquiries was sent to companies that offer energy measuring solutions. Parameters that were defined in the inquiry:

- Measuring anything else than RMS current is unnecessary
- Current measuring range from 0,5 – 200 A
- All motors are three-phased
- Solution should be able to measure large number of motors, up to 200.
  The number of motors can be bigger, but here it’s used to emphasize how many motors we would like to measure
- Possible to read data remotely
- Possible to communicate with AnywarePro (possible to communicate with third party software applications)
- As cheap as possible

Ideally the cost per one motor power measuring should not exceed 20 euros. This was intentionally not stated in the inquiry. Some companies were already discouraged by the cheapest solution point in inquiry and refused to reply.

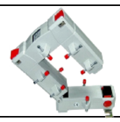
4.1 Electrex

Electrex is an Italian company that designs, develops, manufactures and markets instruments and software for energy measurement, management and control [18]. The solution offered by Electrex consists of following elements.

Currents below 100 A can be measured with three different types of current transformers, dependant on the need. One with 9 mm window diameter, second with 13 mm window and third is a split core with 16 mm window. These will be connected to the energy analyser ATTO D4 70 A ECT RS485 230-240 V. Up to three current transformers can be connected to this unit. Initially made for measuring three phase currents, it can be also used to measure three different three-phase consumers with balanced load. The energy analyser has built in RS485 serial port. This solution is meant to be used only with current transformers by Electrex. It has been developed to measure small currents accurately.

For currents over 100 A they offer ATTO D4 RS485 230-240 V TRANSDUCER / ENERGY ANALYZER. Any third party current transformer can be used with this analyser. Also anything from Electrex split core series can be selected. Both of these analysers can be connected over RS485 to a gateway that provides built in web server. This FEMTO ECT NET D6 WEB 85÷265 V ENERGY ANALYZER & WEB DATA MANAGER can also measure three, less than 100 A, circuits. Summary of devices needed for data acquisition and prices are presented in table 4.1.

Table 4.1. Overview of Electrex offered solution

	Device	Description	Price (net)
1)	FEMTO ECT NET D6 WEB 85÷265 V ENERGY ANALYZER & WEB DATA MANAGER	Gateway that is used to connect all the field analysers. Internet access and up to three current transformers with loads less than 100 A.	405 € 
2)	ATTO D4 70 A ECT RS485 230-240 V TRANSDUCER/ ANALYZER	Analyser for loads smaller than 100 A. Supports up to three current transformers.	97 € 
3)	ATTO D4 RS485 230-240 V TRANSDUCER / ENERGY ANALYZER	Analyser for loads larger than 100 A. Supports up to three current transformers.	97 € 
4)	ECT TA 70/100 A 9 MM POWER QUALITY CURRENT TRANSFORMER	External current transformer to be used exclusively with the instruments of Femto 70A ECT and Atto 70A ECT product families.	16 € 
6)	ECT CTS 16-70/100A SPLIT CORE POWER QUALITY CURRENT TRANSFORMER MINI SERIES	External split-core current transformer to be used exclusively with the instruments of Femto 70A ECT and Atto 70A ECT product families.	27 € 
7)	PFC0205 CTS 23-200	Split-core current transformer for loads up to 200 A. Patented fast snap-on system.	78 € 

Electrex offers also software applications for web server and data managing. Additionally the analysers mentioned earlier are capable of measuring and calculating more than just a RMS current. These are nice features, but as stated before one of the key factors is price, not how many functions are possible.

4.2 DENT Instruments

DENT Instruments designs and manufactures data loggers and energy recorders. Originally from US Oregon, this company has distributors all around the world [19]. They offer full solutions for energy measurement, which include everything from current transformer to software for data managing. Their speciality seems to be data loggers. For this inquiry they offered next solution.

Split-core current transformers from 5 A to 1000 A. For small currents the cheapest would be CT-HSC-020-U. This can measure up to 20 A loads. For higher currents the CT-SCM-0100-U can be used. Both of these are connected to PowerScout 3037 or PowerScout 24. Difference with these energy meters is that first one supports up to three current transformers and is originally meant for use in one three-phase system. It has built in RS485 and optionally Ethernet connection can be added. PowerScout 24 supports up to 24 single circuits. Built in RS485 and Ethernet as an additional feature. Both analysers use same software, ViewPoint, which allows users to set up communication and adjust device options. Summary of equipment is presented in table 4.2.

Table 4.2. Overview of DENT Instrument offered solution

	Device	Description	Price (net)
1)	CT-HSC-020-U	Split-core current transformer. Meant for currents up to 20 A. 10 mm window.	30 € 
2)	CT-SCM-0100-U	Split core current transformer. This one is meant for currents up to 100 A with 32 mm window. From same series and with same price they offer current transformers up to 600 A.	69 € 
3)	POwerScout 3037	Power meter with 3 current transformer inputs. Data connection over RS485 or Ethernet.	595 € 
4)	PowerScout 24	Power meter with 24 current transformer inputs. Data connection over RS485 or Ethernet.	1395 € 

Like with Electrex devices, these can calculate more than RMS current. For this application it would be mostly unutilized. Thus the high price can’t be justified. Good thing about PowerScout 24 is that it has relatively small size compared to the amount of loads it can measure. This will become an important feature when the amount of circuits that needs to be measured is high.

4.3 Contrel Elettronica

Contrel is an Italian company which develops and produces electronic relay protections, systems for efficient usage of electricity and equipment for energy measurement [20]. Their selection of products is the biggest from these three companies. Solution which they offered is as follows.

Current or power sensor that measures every single load is connected over RS485 to a main unit. This data concentrator unit can read from multiple devices. According to the supplier, using MODBUS RTU, the limit of elements will be 247. One limiting factor can be the amount of parameters that the main unit is able to manage. With EMS-96-ETH the maximum number of parameters is 400. This approach helps to save both space and money. Mentioned devices for this kind of application are shown in table 4.3.

Table 4.3. Overview of Contrel Elettronica offered solution

	Device	Description	Price (net)
1)	TTC V-485/50	Current sensor/transformer with RS485 connection, 50 or 25 A (selectable with dip-switch).	32 € 
2)	TTC V-485/300	Current sensor/transformer with RS485 connection, 300 or 150 A (selectable with dip-switch).	62 € 
3)	EMT-1C/300 LV	Power measuring sensor with RS485 connection. Maximum load 300 A.	82 € 
4)	EMS-96-ETH	Network analyser that supports multiple current or voltage sensors over RS485. TFT colour display and internal web server.	280 € 

All three companies offer good solutions for current measuring purposes. Actually these packages have more than is needed and this is the reason why none of these solutions is in a suitable price range. The best option from these three is the Contrel Elettronica. It has a rather cheap and space efficient solution. In addition to the companies already mentioned this inquiry contacted some others as well, however their offers were very similar. Therefore it would be redundant to address all of them individually.

5 MAKING A POWER MEASURING SYSTEM

From the conclusion of previous paragraph it is clear that with the available solutions on the market it is impossible to achieve such a low price. The main reason seems to be that all the solutions that are available offer more than is needed and the simple electricity meters are just not suitable to be used with such a large number of motors. Only option that is left is to make our own power measuring system. The best would be to have a system that uses as many as possible half ready components. Developing something from a scratch can be very costly and time consuming. The final solution may be a perfect fit for what we are searching for, but the time and money spent for the development may not be worth it.

Let’s take for example a simple current measuring transformer. Dependent on the measuring range there are current transformers available from few euros up to few hundreds of euros, depending on what accuracy and additional features are needed. Making even the simplest and cheapest current transformer will require deep understanding of material science, electromagnetism, product development, marketing and probably even more. Even then the end result may not be able to compete with similar products on the market.

When we add something to the simple current transformer and develop a full solution with the features that are needed, we can come up with a product that may compete with other solutions or fill a gap on the market. Also this needs a lot of money and work hours. Definitely a good market analyses is needed and a proper business plan. To come up with a preliminary design and a prototype that uses some ready-made elements can be a task for a single person with limited budget. The outcome is expected to be more a concept for further development or decisions how to proceed, not the blueprints for a finished product, ready to be released for mass production.

5.1 Overall concept

Before we can proceed any further an overall preliminary concept should be set. This way we can see where to start from. It doesn't necessarily mean that the final solution will be the same as established in the beginning. Probably it will be different as most of the problems reveal themselves during the process of solving some others.

The overall concept, as said before, is to have a solution that gives us the possibility to measure electrical energy consumption in a plant on a single motor basis. The measured data has to be accessible from distance. In the figure 5.1 are noted three possible concepts which could provide a solution.

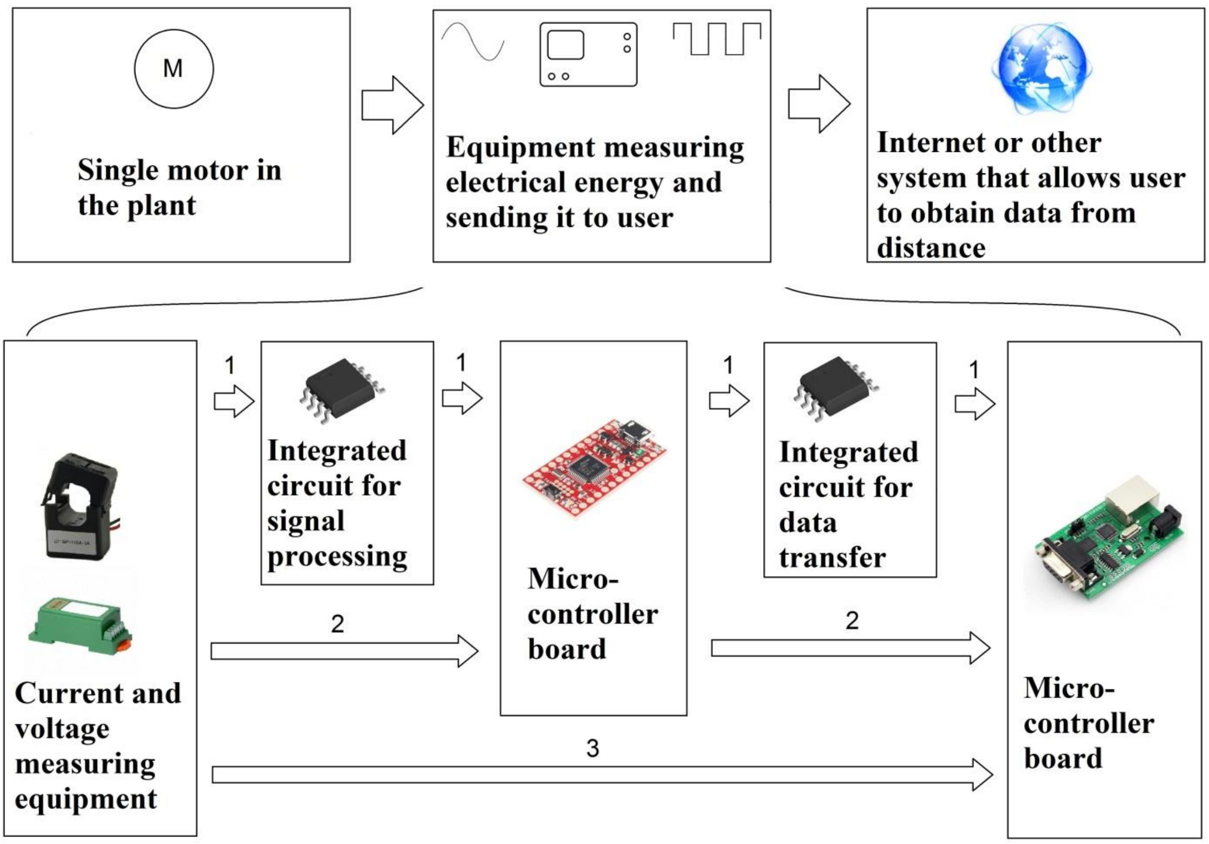


Figure 5.1. Preliminary concept options

In the prototype phase the idea is to use an inexpensive measuring sensors. Similar to the conclusion in paragraph two. The most fitting is either Hall effect current sensor or current transformer (preferably a split-core as it makes the installation to existing plant really easy and fast). Searching for a low cost current transformers leads to a one company called YHDC

Electronics Co. [21]. It is a Chinese company offering a variety of current transformers and Hall effect current sensors. They also have few voltage measuring transformers, but as discussed earlier the main emphasis should be on the current measuring. YHDC has a split-core current transformer series (SCT-013) that ranges from 0-5 A transformer up to 0-100 A one. All are in a same size and come with a 1 m cable that has either 3,5 or 2,5 mm audio plug. The output of these transformers is 0-1 V with an exception of the 0-100 A transformer that has an output of 0-50 mA. There is not much info about the accuracy of the transformer. Only data available is that it has ±3% non-linearity and input can be from 10-120% of the rated current. Looking at the price the expectations should be low. On an online shopping site eBay this split-core current transformer costs around 5 euros.

In general the principle is to obtain an AC measurement, process it and send it to the user when requested. As shown in the figure 5.1, transferring this data is the key question here. First let’s have a look at the three suggested options.

Marked with number one is a concept where AC measurement is processed next to the measuring sensor. With the help of signal processing circuit the data is transformed and sent to the microcontroller unit. This can be done with a true RMS to DC converter. In principle it works in a way that the integrated circuit measures analog voltage, processes it and puts out a DC voltage that is equal to the RMS of the measured input. It is still an analog signal and needs to be converted into digital, but there is no need to find the RMS. That gives us the possibility to use simple and cheap microcontroller with its own AD converter without losing much accuracy (usually the inexpensive 8-bit microcontrollers have 10-bit AD converters built in). The obtained value can then be sent over some inexpensive data bus to a more sophisticated and more expensive microcontroller that has a connection to internet or local area network. Choosing the correct data bus and protocol is important. For it has to be simple, cheap and able to connect tens of controllers to the main microcontroller unit. The integrated circuit for data transmitting is an additional chip that helps the low level microcontroller to send data to the main unit. The pros of this concept are:

- Close to the sensor measuring. This is good, because inside the panel there can be frequency converters, soft starters, high current contactors and other devices that cause distortions in longer cables.

- Programming independent RMS calculation. Measurement accuracy is less affected by possible faults in program. MCU (microcontroller unit) is less occupied, which allows it to make faster readings and/or achieve better real time data transfer to the user.

Cons of this concept are:

- Additional circuitry. Firstly there is additional communication circuit needed to make the connection between high and low level microcontrollers possible. Secondly the RMS to DC converter is needed one per every input. So if low level MCU has four CT's it also needs four RMS to DC converters. Another problem with these types of analog circuits is that they are very sensitive to environment and components used to create the circuitry.
- Additional cost. Additional circuitry adds additional costs.

There can be more variations with the low level 8-bit microcontroller. For example we can replace the RMS to DC converter with the AD converter that has higher resolution and connect it to the 8-bit MCU.

Marked with number two in the figure 5.1 is a very similar concept like the first one, but instead of using cheaper MCU it has a bit more expensive unit that doesn't need so much additional external circuitry to accurately read and transmit data. The pros of this concept are:

- No additional costs on external circuitry.
- Smaller size in design which helps to save not only space but money as well.
- When integrated to MCU the elements have faster communication between themselves and we can expect them to perform with less trouble.

Cons of this concept:

- Additional peripherals increase MCU price.
- Without RMS to DC converter the program has to perform RMS calculation.

Then there are other solutions between concept one and two. It will mainly depend on the MCU. What integrated parts and performance level it has. In some cases only one external circuit may be needed.

Marked with number three is a concept where MCU reads the measurement, processes it and sends it to user over the Ethernet cable. The idea itself is good. Pros of this concept:

- Shortest link between sensor and user.
- Smaller amount of different elements results in higher reliability and faster data acquisition.

Cons of this concept:

- Program in the MCU is more complicated.
- Components for data transmission are more expensive. Equipment for data transmission over Ethernet is more expensive than for some of the other bus systems.
- Protocol is more complicated.

The last point needs more clarification to understand why this is in some ways a con. Having a field sensor connected straight to a higher system needs something more sophisticated. For example an OPC UA protocol [22]. OPC UA is a platform-independent standard through which various kinds of systems and devices can communicate by sending Messages between Clients and Servers over various types of networks. It supports robust, secure communication that assures the identity of Clients and Servers and resists attacks [22]. That is a great concept, but implementing it on a low level microcontroller may be harder than it sounds. As it is a lot newer than the other protocols used in field bus applications, there are not so many examples for development boards. If you have a team of people for research and development then it may not be a problem as the benefits of using such a protocol overweigh time and money invested for the development. For a single person project without good existing examples it will be rather hard and complicated to come up with such a solution.

5.2 Root mean square (RMS) to DC converters

Similarly as described in the overall concept, the first option uses inexpensive low level microcontroller and additional circuitry to obtain and transmit data. In the scope of this thesis three options for measuring RMS values were tested, starting with the RMS to DC converter circuits.

LTC1966 is a RMS to DC converter by Linear Technologies. It is one of the cheapest integrated circuits available for this purpose [23]. In the Farnell online electronics store the price is 6,06 euros (for one piece order) [24]. LTC1966 is a true RMS to DC converter that utilizes an innovative patented $\Delta\sum$ (delta sigma) computational technique. The internal $\Delta\sum$ circuitry of the LTC1966 makes it simpler to use, more accurate, lower power and dramatically more flexible than conventional log antilog RMS to DC converters [23]. Some parameters that describe LTC1966 are shown in the table 5.1.

Table 5.1. LTC1966 main parameters

Accuracy	0,1 % gain accuracy from 50 Hz to 1kHz, 0,25 % total error from 50 Hz to 1 kHz.
Linearity	0,02 % linearity.
Supply voltage	2,7 V to 5,5 V single supply, up to ±5,5 V dual supply.
Input	Differential or single-ended, up to 1 V_{peak} differential voltage, voltage range from negative to positive supply.
Output	Output reference pin allows level shifting, voltage range from negative to positive supply.

There is no necessity to bring out the specifics of the LTC1966 work principle and inner architecture. Important are the design notes and limitations that should be kept in mind. First thing that has to be noted out is the linearity and to what extent can we expect the device to be linear. The ideal RMS to DC converter has 1:1 transfer function. Meaning that the output will be exactly the value of input waveform RMS. In real life there are of course some distortions. That can be caused by the input signal shape. A common way to describe dynamic signal wave shapes is crest factor. The crest factor is the ratio of the peak value relative to the RMS value of a waveform. A signal with a crest factor of 4, for instance, has a peak that is four times its RMS value. Because this peak has energy (proportional to voltage squared) that is 16 times (4^2) the energy of the RMS value [23]. The LTC1966 is claimed to work well up to crest factor 4. In normal case, where the load consumes similar to sine waveform, there should be no significant errors, but it should not be forgotten that in cases where the load distorts a lot then the output is no longer accurate.

Design note warns about using ceramic capacitors for the averaging purposes. If a ceramic capacitor is used, it may be necessary to use a much higher nominal value in order to assure the low frequency accuracy desired [23].

For the output a direct connection to AD converter is allowed. Issues to look out for are the input impedance and any input sampling currents. The input sampling currents drawn by ΔΣ ADCs often have large spikes of current with short durations that can confuse some op amps, but with the large CAVE needed by the LTC1966 these are not an issue [23]. A circuit was constructed to test the performance for this application. In the figure 5.2 are shown the connections from 0-100 A current transformer SCT-013-000 through LTC1966 into microcontroller AD converter input. The input part of this circuit copies a data sheet typical application circuit, meant for 50 to 400 Hz current transformer measurement.

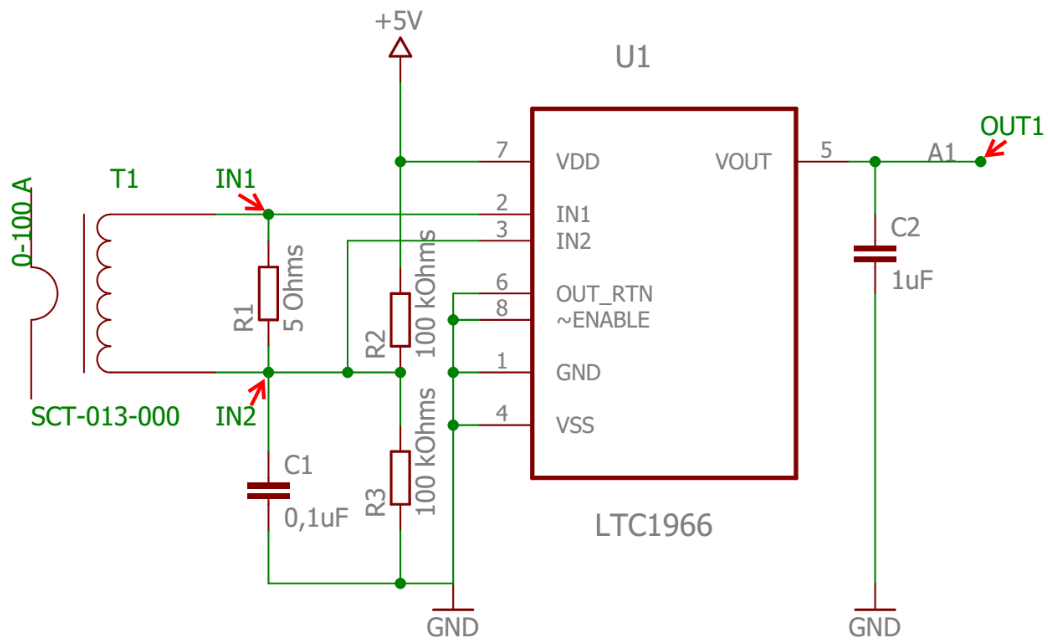


Figure 5.2. LTC1966 connection schematic

In the figure 5.2 the resistor R1 is connected to convert current flow into voltage drop. From data sheet we can see the maximum differential input of the LTC1966 (referred to as maximum input swing) is 1V. This applies to either input polarity, so it can be thought of as ±1V. Because the differential input voltage gets processed by the LTC1966 with gain, it is subject to internal clipping. Exceeding the 1V maximum can, depending on the input crest factor, impact the accuracy of the output voltage, but does not damage the part [23]. The information from data sheet may be a bit confusing. What they are actually saying is that when using single ended signal we shouldn't exceed 1 V peak to peak. With values over this limit the output will be inaccurate. With this specific current transformer we can expect that when primary current is 100 A (RMS), then the secondary will be $50 * \sqrt{2} = 70{,}71\,mA$ in case of pure sine wave. In order to keep it below 1 V peak to peak a 5 Ω burden resistor is used. This way at the maximum allowed load on the current transformer the voltage drop on the burden will be: $2 * 1{,}2 * 0{,}05 * \sqrt{2} * 5 = 0{,}848\,V$ peak to peak. In the case of a single supply we need to lift the current transformer output into proper range so that the input wave doesn't go below 0 and stays unipolar. This is done by the two resistors R2 and R3 which create a voltage divider, splitting the supplied voltage into two. In this particular case when using a 5 V supply the current transformer output will be from $5/2 - 0{,}424 = 2{,}076\,V$ to $5/2 + 0{,}424 = 2{,}924\,V$. In ideal sinusoidal waveform the output of RMS to DC converter with circuit parameters described above, should be around 0,250 V when the current through current transformer is 100 A. To test this theoretical value in practice we first need to find a way to simulate it.

To test out the circuitry a PicoScope 5000 series oscilloscope will be used. This is an USB oscilloscope that has 4 channels and arbitrary waveform and function generator. The output of this generator is rated ±2 V with ±1 % DC accuracy. Instead of measuring actual load the current transformer will be removed along with the burden resistor and the waveform generator output will be connected directly to the circuit input. With this setup we can monitor RMS to DC converter output to see how different values of sine wave are transferred to DC. The connection points for arbitrary waveform and function generator are marked on the figure 5.2 with IN1 and IN2. Output measuring point is marked as OUT1 on the same figure. Actual picture of the measuring is presented in annex 1.

Making the first test with 100% calculated load conditions gives on the output of LTC1966 a DC voltage with small ripple. Comparison between input and output waveforms is shown in the figure 5.3. The waveforms are not on the same y axis. Purpose of this figure is to show the output ripple relationship to the input waveform.

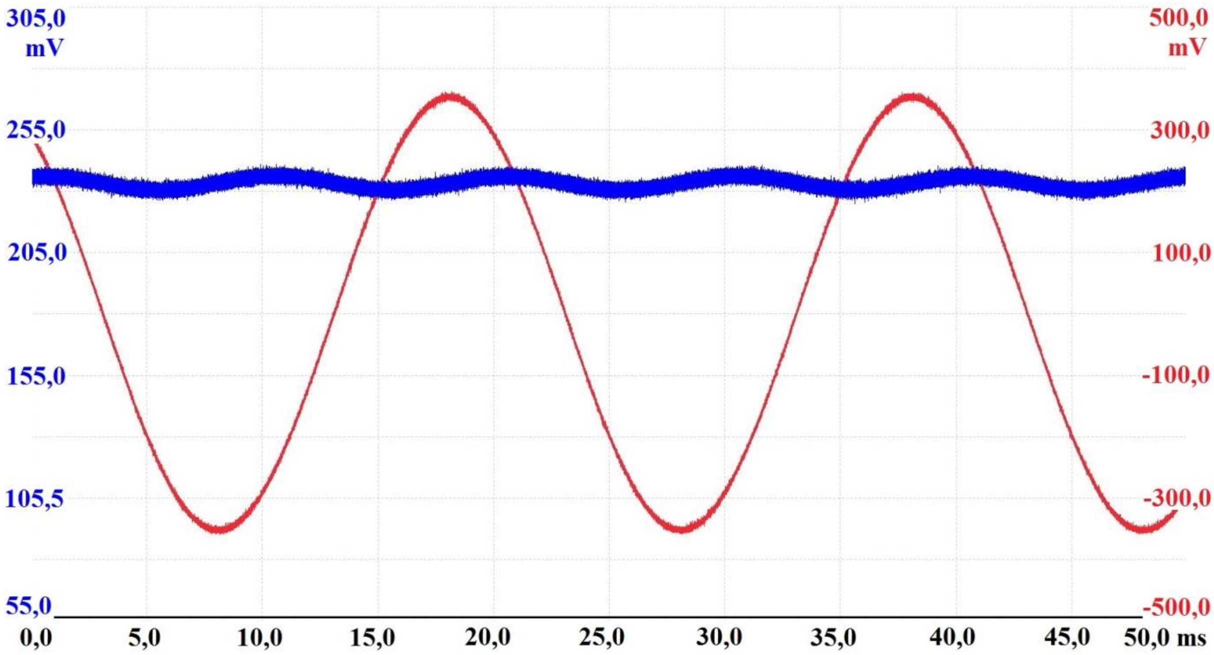


Figure 5.3. LTC1966 test circuit waveform comparison with 1 μF averaging capacitor and 0,707 V peak to peak 50 Hz input

As seen in the figure the ripple in output copies input frequency. To smoothen out this ripple the application note suggests a use of bigger capacitor. Changing the default 1 μF capacitor for 10 μF will solve the problem and stabilize the output. The downside of bigger capacitor is that the output is less sensitive for changes. In the figure 5.4 is shown the output difference between those capacitors. Fast 0,707 V peak to peak sine waveform drop to zero in the input will be smoothed out. For this application it should not be a problem.

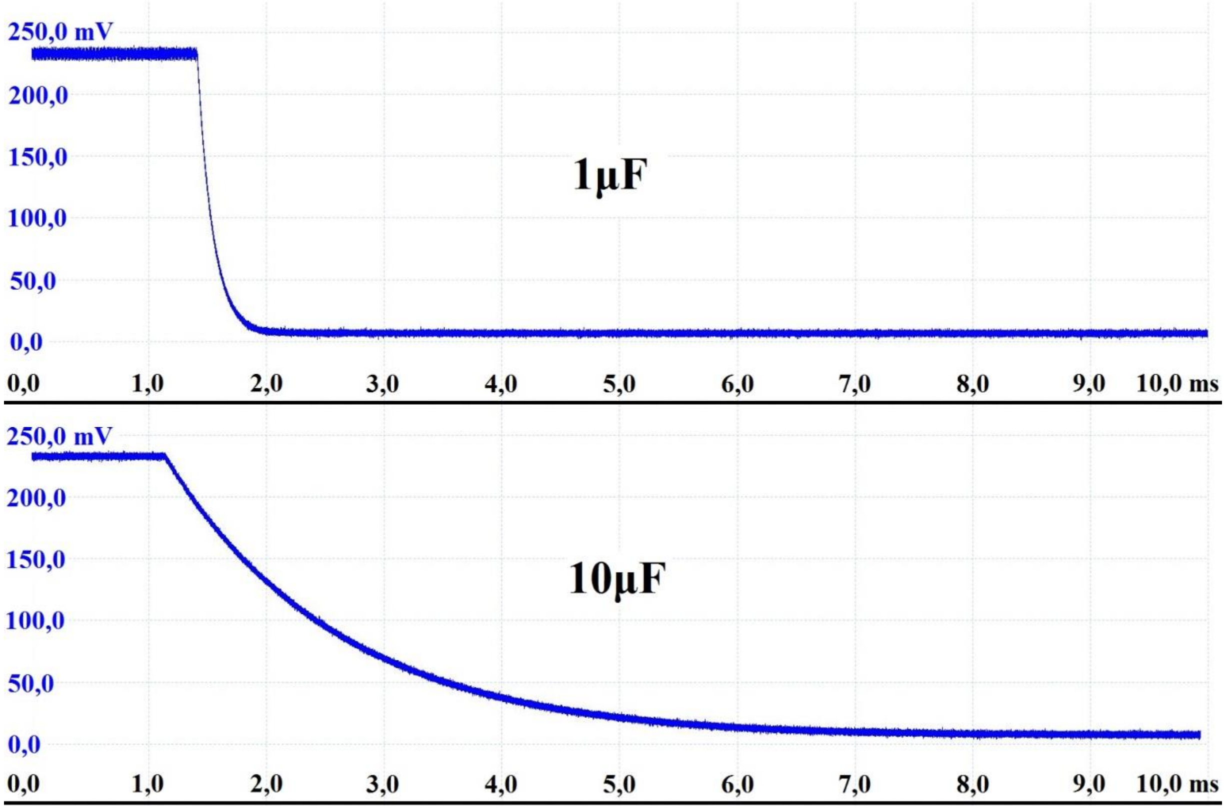


Figure 5.4. LTC1966 circuit output comparison with different capacitors

In the table 5.2 are shown expected values and measured values for the composed LTC1966 circuit in figure 5.2. In the first column is shown the primary current flowing through the current transformer. In the second column is peak to peak voltage of the sine waveform that can be expected on the current transformer output (this is calculated with 5 Ω burden). The values from second row will be entered to the arbitrary waveform generator. Then values of the RMS to DC converter are measured and put into column three. In the fourth column is the calculated output of the RMS to DC converter circuit and the fifth column shows error between theoretical and measured output. In this test the input values are raised above nominal values to see how much and when the output distortion will change drastically.

Table 5.2. Measuring results of LTC1966 circuit

Theor. current (A)	Input (peak to peak) (V)	Output (V)	Expected output (V)	Error (%)
0	0,000	0,001	0,000	-
20	0,141	0,047	0,050	6,0
40	0,283	0,093	0,100	7,0
60	0,424	0,139	0,150	7,3
80	0,566	0,185	0,200	7,5
100	0,707	0,232	0,250	7,6
120	0,849	0,277	0,300	7,7
140	0,990	0,321	0,350	8,3
160	1,131	0,362	0,400	9,5
180	1,273	0,468	0,450	3,3
200	1,414	0,722	0,500	43,2
220	1,556	0,888	0,550	61,1
240	1,697	1,025	0,600	69,2

On the figure 5.5 are plotted measured and expected output values. First thing that can be seen is that till 180 A load the results are close to expected. Error stays under 10%. After 180 A it starts rapidly growing. In the figure it’s not that visible, but from the table the error seems to be present from the very beginning. Error has linear relationship to measured value. That can be corrected analytically in microcontroller unit.

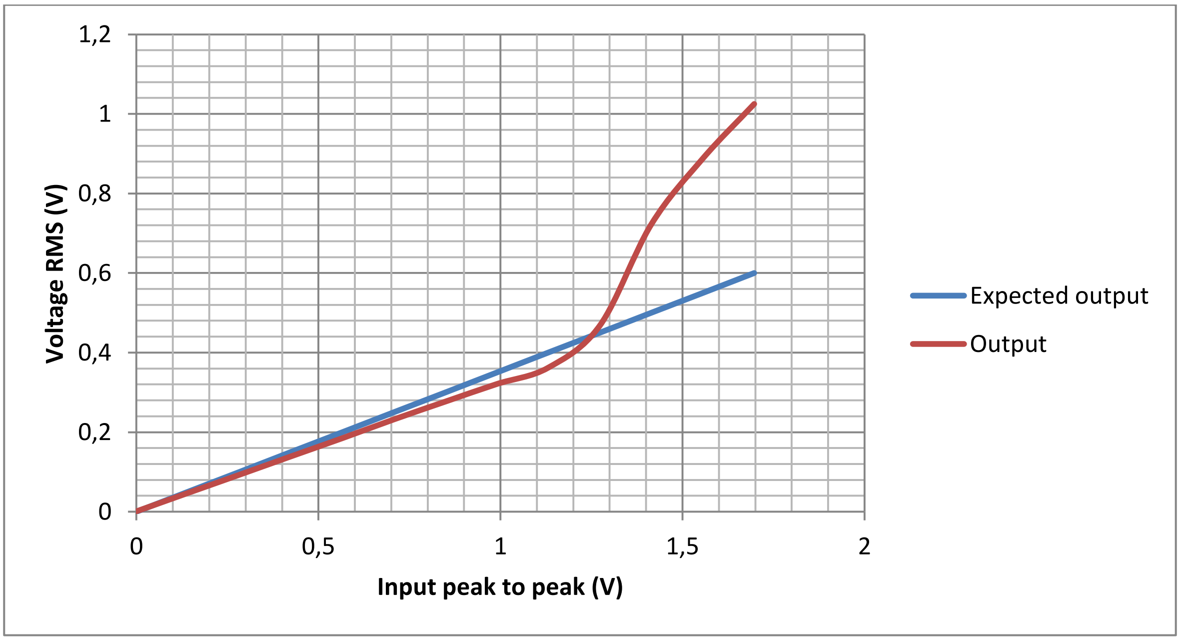


Figure 5.5. LTC1966 output comparison

In conclusion the LTC1966 can be a link between microcontroller and analog measurement, but the circuitry itself has to be well designed and planned. As mentioned before, all the components used in the circuitry have some effect on the output accuracy. In this case the reason for such high error could have been ceramic capacitors or side effects from hand soldering. For this particular price range solution it is not considered as an option to proceed with. The price of RMS to DC converter is quite high and as it became clear, there will have to be good quality additional components included to fine tune the circuit.

Another very similarly integrated circuit is AD736J [25] from Analog Devices. Price in Farnell online store is 6,3 euros [24]. The AD736J is a low power, precise, monolithic true RMS to DC converter. It is laser trimmed to provide a maximum error of ±0.3 mV ± 0.3 % of reading with sine wave inputs. Furthermore, it maintains high accuracy while measuring a wide range of input waveforms, including variable duty-cycle pulses and triac (phase)-controlled sine waves. Waveform with crest factor up to 5 can be measured with only 2,5 % additional error [25]. Main parameters are shown in the table 5.3. Input is described through continuous RMS level. When the input is symmetrical bidirectional sine wave with no DC component then the maximum input can be from -1,414 V to +1,414 V. That is more than the LTC1966 was able to endure.

Table 5.3. AD736J main parameters

Accuracy	Maximum total error ±2,0 % of reading (given at 1 kHz sine wave).
Linearity	0,35% of reading at maximum of 200 mV.
Supply voltage	2,8 V, -3,2 V to ±16,5 V dual supply.
Input	Single-ended, up to 1 V_{RMS} single ended voltage with peak up to ±4 V when powered at 16.5 V
Output	With no load and maximum supply rating up to 12 V.

Comparing these two integrated circuits is not so straightforward as the suppliers show different performance conditions and values. The best is to construct similar circuit with AD736J and measure the same input waveform. In the application note of the AD736J is one schematic that introduces a way how to use this RMS to DC converter with 9 V battery. All others have dual supply (this would mean creating a supply which provides also negative potential). It shouldn’t be a problem to replace the 9 V battery with single ended supply, but to achieve better results the application note circuit was used. The connection schematic of AD736J is shown in the figure 5.6.

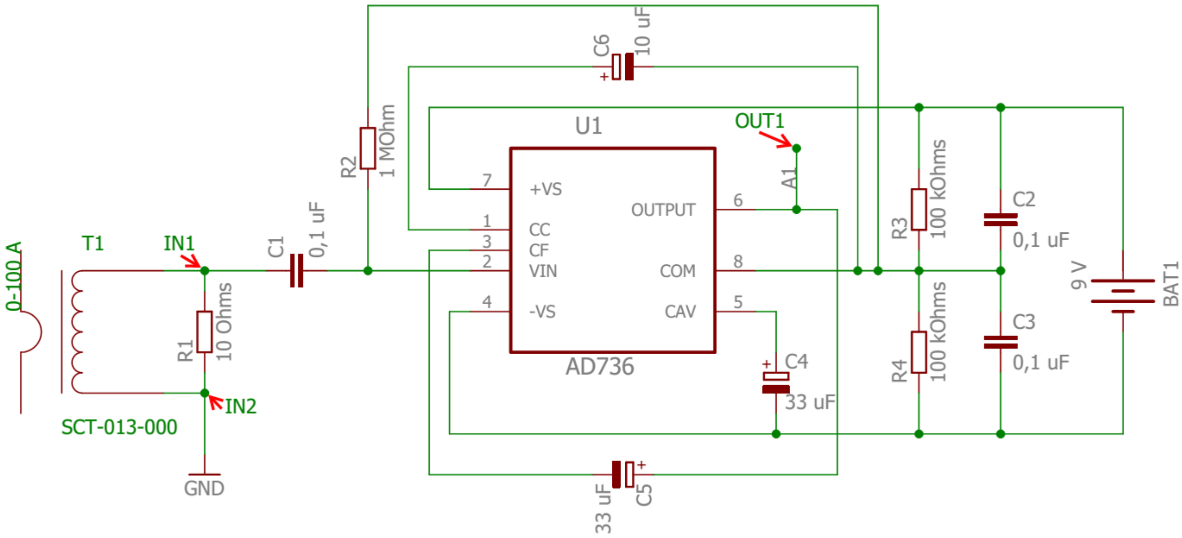


Figure 5.6. AD736J connection schematic

Like with LTC1966 the current transformer along with burden will be removed and arbitrary waveform generator output will be connected instead of it. That way we can perform the same measurements like with LTC1966. Actual picture of the measuring is presented in annex 1. The results are shown in the table 5.4. The output of AD736J is obtained by subtracting half of the battery voltage from the measurement. That’s because R3 and R4 divide battery voltage into two and that is connected to COM pin of AD736J. Integrated circuit ground is no longer 0 V but 4,5 V in case of 9 V battery.

Table 5.4. Measuring results of AD736J circuit

Theor. current (A)	Input (peak to peak) (V)	Output (V)	Expected output (V)	Error (%)
0	0,000	-0,010	0,000	-
20	0,283	0,103	0,100	3,0
40	0,566	0,203	0,200	1,5
60	0,849	0,287	0,300	4,3
80	1,131	0,394	0,400	1,5
100	1,414	0,478	0,500	4,4
120	1,697	0,585	0,600	2,5
140	1,980	0,677	0,700	3,3
160	2,262	0,769	0,800	3,9
180	2,545	0,853	0,900	5,2
200	2,828	0,937	1,000	6,3
220	3,111	1,044	1,100	5,1
240	3,394	1,144	1,200	4,7

Although the burden is different the input is kept same with the LTC1966. This way we have same test conditions for both circuits and as seen from the table the RMS to DC converter has not been pushed over its limits. The figure 5.7 is showing the measured output of AD736J and expected output. Error increases slowly as the input goes higher. The ripple also increases, making readings unstable. This can again be smoothed out with higher capacitor value. Nevertheless a considerable error is present at all times. Error origin is probably the same as in LTC1966 case.

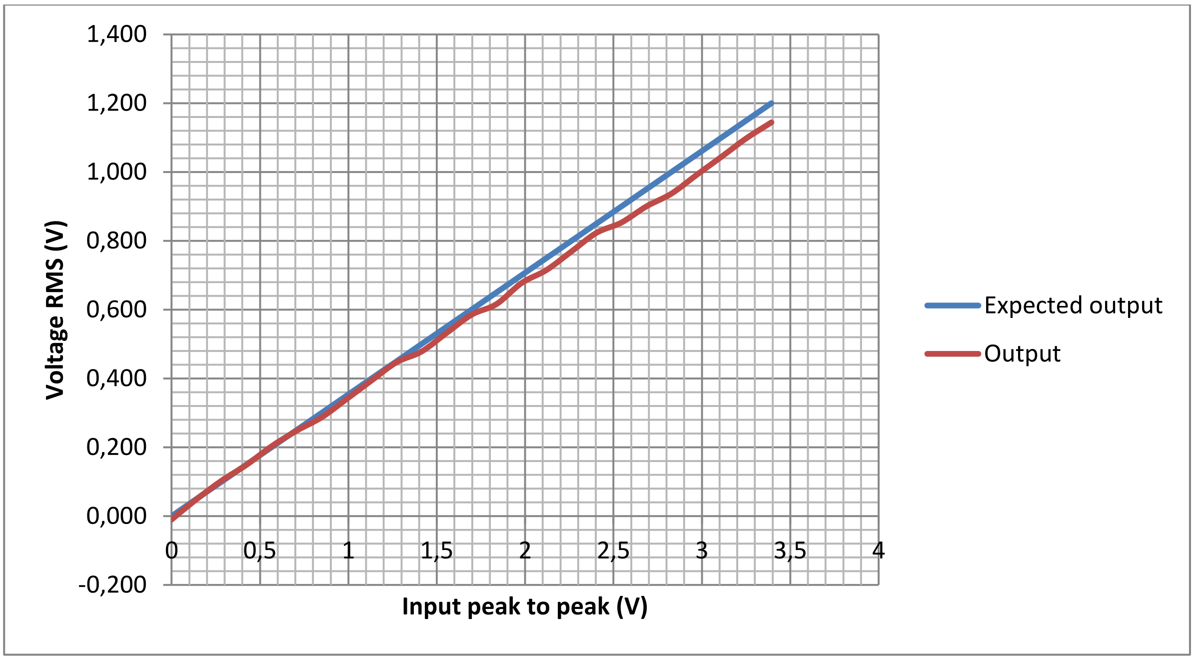


Figure 5.7. AD736J output comparison

Though the AD736J is more accurate than LTC1966, it is also sensitive to selected components. Another downside is that the output is shifted by value of half the supply voltage. An operational amplifier should be used in this case to amplify the measurement and bring it down to a desired region, where microcontroller can effectively read the output values. Analog circuits in general need precise designing and fine-tuning. As stated before, to increase the accuracy of these RMS to DC converters a set of elements has to be added. In order to achieve the right design a series of test circuits will have to be made to determine which elements need to be added or which need to be changed. The result may be that the RMS to DC converter itself is not capable of performing up to the expectations.

There are other RMS to DC converters on the market. Why they are not mentioned here is simply because the price range is too high. The difference between cheap and expensive RMS to DC converters is that more costly units have additional amplification blocks integrated, better crest factors and smaller error.

5.3 Microcontroller

To manage faster prototyping a widely known microcontroller development platform was chosen. Arduino is an open-source prototyping platform based on easy-to-use hardware and software [26]. The choice for Arduino was done due to the reasons:

- Open-source means that the software tools and codes are free to use for everyone.
- Due to high popularity there are a lot of examples on the internet (examples which include both programming codes and circuit schematics).

Reasons given above make the Arduino platform really easy and fast to use. Without knowing all the details of the MCU you can successfully program a development board with example codes and instructions. The Arduino IDE software is free of charge and simple to use. They have a large selection of libraries available that help user to take advantage of additional functions with ease of use. After reaching the desired result with development board, we can discard it and make our own designed PCB that is specially modified for needed purpose.

The Arduino Nano counterfeit is a replica made after original Arduino Nano [26]. The schematic is the same, but the counterfeit uses cheaper components and a bit different USB integrated circuit (different for the reason of cost). But the main unit remains the same (ATmega328P [27]). This way the prototyping can be kept low-cost. For example Arduino Nano V3.0 counterfeit can be bought for 2,5 euros from eBay. That is about four to eight times cheaper than buying an original one.

ATmega328P microcontroller allows the user to connect external analog reference to the AD converter. This helps to obtain better accuracy through using the most of 10-bits. When using the external reference the minimum value is represented by GND and maximum value is represented by the voltage on AREF pin. When the expected value is 0,5 V and as noted before under the current transformer parameters the maximum can be 120 % then the AD converter input should be adjusted to maximum of 0,6 V. Ideally if the V_{REF} is 0,6 V then 120 A current load will give us a maximum value of the 10-bit AD converter which is 1023. In case of normal 100 % load the value would be 852. It would mean that the accuracy of the single measurement is around $120/1023 = 0{,}117\,A$ (this is only the accuracy of AD converter).

Microcontroller input reading is rather simple when RMS to DC converter is used. It will read the analog input and multiply it with a coefficient to get the actual current measurement or use the map function provided by Arduino analog library. When the RMS to DC converter is not used then the measuring process is a bit more complicated. In general the microcontroller should read its analog input as fast as possible, store the read values into register and then calculate RMS value using the equation 2.3. To read AC values the input signal needs to be only positive. A DC component will need to be added. So if for example the input peak to peak voltage is from +0,6 V to -0,6 V then the DC component should be at least +0,6 V to avoid input going negative. Then the input will be from 0 to 1,2 V. In case of 10-bit AD converter the values would be accordingly: +1,2 V equals 1023 and 0 is 0 (in case the Vref is maximum input voltage). This introduces us to another problem. When we read in the amount of values needed, then we can't use these values straight in the equation 2.3. The output would be inaccurate. Instead we need to turn these values into actual current values measured in current transformer.

The microcontroller program for calculating RMS values is shown in figure 5.8. It is written in C programming language and the idea is that for two periods of sine wave all values from one AD channel are stored into SRAM memory. Important is to keep the values as integers, because integer value takes 2 bytes of memory whereas float or double type of value takes 4 bytes. This significantly saves space and as AD converter gives anyway integer values from 0 to 1023 then there is no practical need for other types. Using external reference voltage gives the possibility to determine the maximum values what AD converter can read. This way the 10-bit resolution can be used more efficiently. At first the program concentrates on reading as many values as possible to the `Values[400]` array. The actual amount of values is around 360, but as this MCU doesn't allow dynamical memory allocation then the space has to be pre-set. After reading in the values another loop starts to first turn saved value into real measured value through `map()` function, then multiplies the value with itself. In this process integer values are turned into double type values. This is needed, because the result of multiplication exceeds the size what integer can hold. Obtained square value will be added straight to the total sum of squared values. There is no reason to store them and waste precious memory space. Dividing the sum of squared values gives the mean value of squares. And with `sqrt()` function the RMS value is obtained.

```
unsigned long start_time; // 4 byte variable to hold time value
unsigned long stop_time;
double sum;               // variable for the total sum of
                          squared values
double root_mean_square;  // RMS value of the calculation
double mean_square;       // mean value of squared values
double square_value;      // square value
int sensorPin = A1;       // select the input pin
int Values[400];          // select array of 400 integer values
int map_min;              // maximum value for mapping AD
int map_max;              // minimum value for mapping the AD
int i;
int j;

void setup() {            // this part of program runs only once,
                         hence the name setup
  analogReference(EXTERNAL);    // with this statement the AD
                         converter input is measured in
                         accordance to voltage on AREF
  Serial.begin(9600);     // to initialize serial communication
  map_min=-1650;          // minimum value in mA
  map_max=1650;           // maximum value in mA
}
void loop() {             // main program never ending loop
  i=0;                    // reset the i and sum
  sum=0;
  start_time=millis();    // start time equals number of
                         milliseconds since the program started
  stop_time=start_time+40;      // stop time of the upcoming
                         cycle will be 40 ms. This equals with
                         two periods in case of 50 Hz
  while (millis()<stop_time) {  // this cycle reads analog
                          values into SRAM memory
       Values[i] = analogRead(sensorPin);
       i++;
  }
  for (j=0; j<i; j++) {  // calculate sum of square values
      square_value=(double)map(Values[j],0,1023,map_min,map_max)
      *(double) map(Values[j],0,1023,map_min,map_max);
                          // in this equation the values are
                          turned from 10-bit value to a real
                          measurement and then squared
    sum=sum+square_value;// adding up all square values
  }
  mean_square=sum/i;      // mean value from squared values
  root_mean_square=sqrt(mean_square); // calculates RMS
  Serial.print(root_mean_square);
  Serial.println(" [V] RMS");// prints calculated value
}
```

Figure 5.8. Program code to calculate RMS

To estimate the accuracy of this program similar test was done like with RMS to DC converters using lower voltage values. With microcontroller we know that the maximum is 5 V and limiting factors are mostly the program and AD converter performance. Connection of circuitry used in this measurement test is shown in figure 5.8. Like in two previous tests the current transformer was removed and waveform generator was connected to points IN1 and IN2. Similar series of measurements were conducted. Results are presented in the table 5.5.

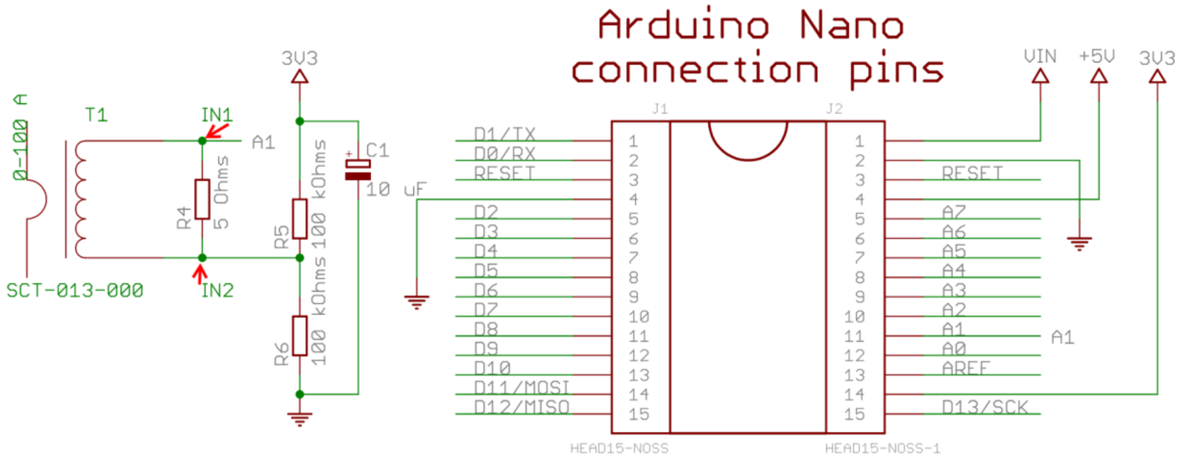


Figure 5.9. RMS measuring circuit based on Arduino Nano

Table 5.5. Measuring results of Arduino Nano

Theor. current (A)	Input (peak to peak) (V)	Output (V)	Expected output (V)	Error %
0	0,000	0,003	0,000	-
10	0,141	0,051	0,050	1,0
20	0,283	0,101	0,100	1,1
30	0,424	0,151	0,150	0,5
40	0,566	0,202	0,200	0,9
50	0,707	0,252	0,250	0,9
60	0,849	0,302	0,300	0,7
70	0,990	0,353	0,350	0,7
80	1,131	0,403	0,400	0,7
90	1,273	0,454	0,450	0,8
100	1,414	0,503	0,500	0,6
110	1,555	0,553	0,550	0,6
120	1,697	0,603	0,600	0,5
130	1,838	0,655	0,650	0,7
140	1,980	0,705	0,700	0,7

Comparing the measured and expected output of Arduino Nano in figure 5.10 will give almost a single line. The difference is very small and the output lines almost exactly cover each other. From the measurement table it's visible that the difference is usually less then 1%. Highest distortion occurs with 20 A theoretical main circuit load. The values calculated by microcontroller were a bit unstable. There was some ripple in the output (values on serial bus) although the input from waveform generator was kept constant. That can be caused by some instability in the input of AD converter input or some calculation errors. In this preliminary design no filters were used. To improve the accuracy of the measurement a hardware low pass circuit may be added to allow only low frequencies to be measured. This would raise the cost of circuitry. Cheaper would be to implement digital filter. For example taking an average of multiple RMS calculations can give better accuracy.

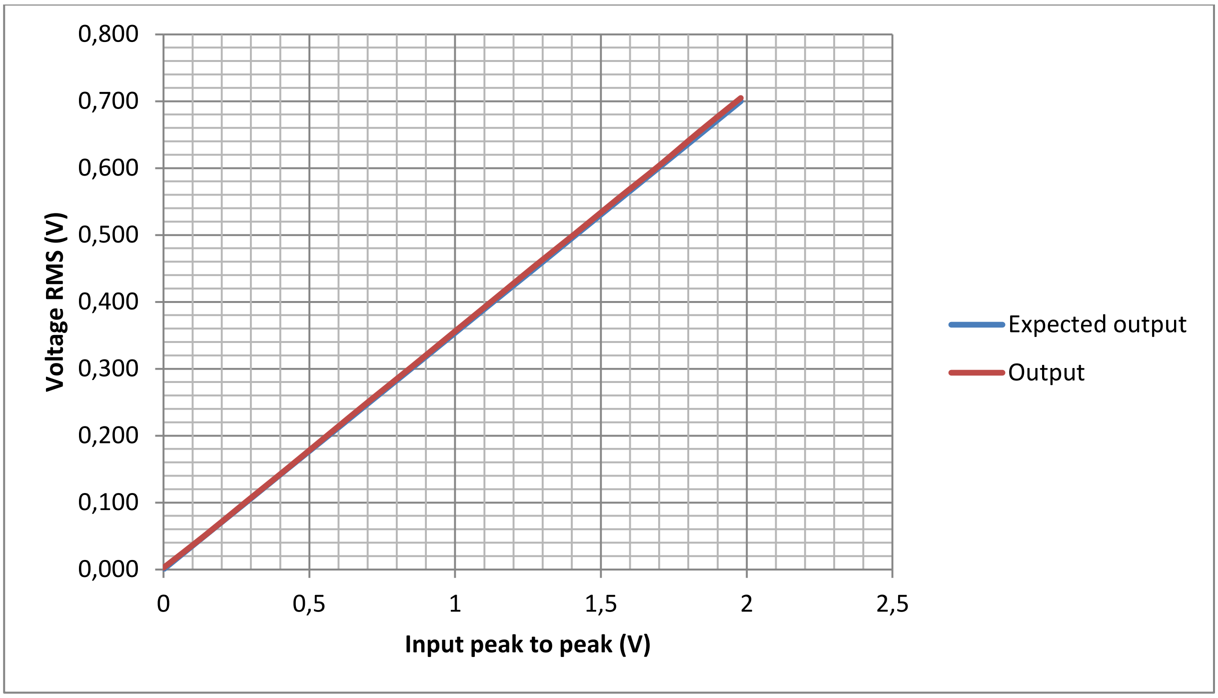


Figure 5.10. Arduino Nano output comparison

After comparing these three AC current measurement methods it is clear that using microcontroller AD converter and calculating the RMS values for 50 Hz waveforms gives better results than using RMS to DC converters. It is also the cheapest as it has the minimum amount of components. Microcontroller itself will be anyway needed for the data transfer no matter what circuitry is used for measuring the AC waveform.

5.4 Data transfer

Transferring data is an important topic that will have a great impact on the final design of this solution. Like previously said the idea will be to gather data from current sensors into one main controller. There may be even a need for multiple main controllers to manage such a big number of motors. This will depend on the type of communication that will be used for data transfer.

The communication between two digital devices can be either parallel or serial. Difference is that in parallel communication all the bits are sent at the same time. This needs a lot of wires. To send 8 bits of data we need 8 signal wires. In serial communication the data is sent from one device to another over single wire in series of bits. That takes multiple cycles, but doesn't need so many wires. In actual applications the serial communication is far more popular than parallel. Use of parallel communication can be seen in some on-board elements and devices like liquid crystal displays, older hard drives, graphic cards and some other devices in personal computers [28].

Like most of the microcontrollers the ATmega328P also has some communication interfaces built-in. Let's first take a look at what options are available in default and if they will be suitable for the power measuring solution.

List of communication options [27]:

- Programmable Serial USART
- Master/Slave SPI Serial Interface
- Byte-oriented 2-wire Serial Interface (Philips I^2C compatible)

5.4.1 USART

USART is a universal synchronous asynchronous receiver transmitter. Asynchronous means that no separate clock signal is provided with the data, so correct reception of data relies on the sender and receiver operating at the same speed, with reception synchronized using a start bit for each byte [29]. When the USART is operated in asynchronous mode, there is a separate data path for send (TX) and receive (RX). One byte of data is transmitted at a time down the serial line, with start, stop and optional error check (parity) bits. A synchronous mode is also available, when the TX pin is used instead to carry a clock (CK) signal. This is sent alongside the data signal to clock the receiver, making the process more reliable. In this mode, the device can still send and receive, but only in one direction at a time [29]. The most common use of the USART in asynchronous mode is to communicate to a PC serial port using the RS-232. Another protocol USART is used for is RS-485. To achieve proper voltage levels (defined by protocol) an interface may be needed to connect TX and RX to bus [30].

5.4.2 SPI

SPI is a serial peripheral interface. It's a single master, multi-slave system, using hardware slave selection [29]. The ATmega328P can work in both master and slave mode. SPI bus has three data pins: SDO - Serial data out, SDI - Serial data in and SCK - Serial clock. Additionally a hardware selection pin is needed. In figure 5.11 are shown the connections in SPI bus. For every slave there has to be an additional SS (Slave Select) pin. This raises the count of wires needed for multi-slave system. SPI is used for on board communication or between peripheral devices that are close (short connection cables).

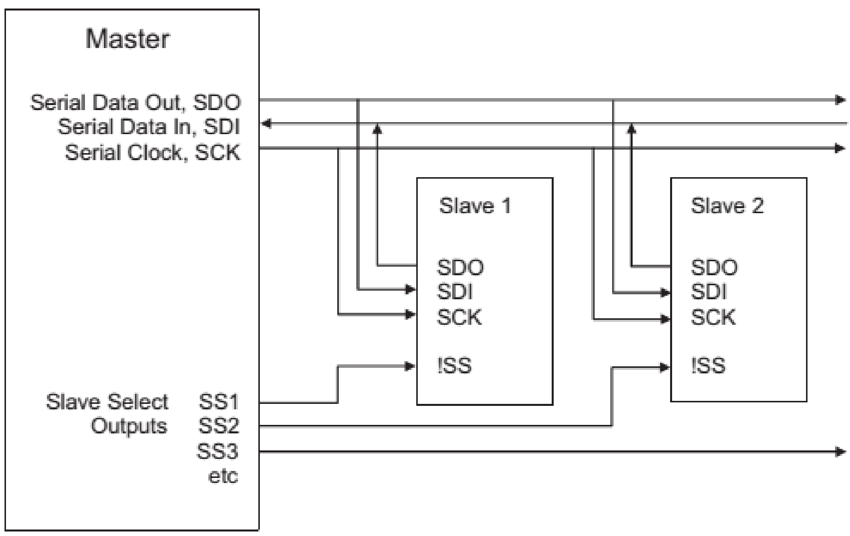


Figure 5.11. Serial peripheral interface (SPI) communication [29]

5.4.3 I^2C

I^2C (inter-integrated circuit, TWI in Atmel microcontrollers) is a system that also uses synchronous master/slave communication, but with a software- rather than a hardware-based addressing system (no additional pin for selecting slave is needed). As in a network, the destination address is transmitted on the same line before the data. This communication uses two pins: SDA - Serial data, SCL - Serial clock [29]. Connection of this bus is shown in figure 5.12. Like SPI this communication is meant for short distances. The TWI protocol by Atmel allows user to interconnect up to 128 devices using only two bi-directional bus lines [27].

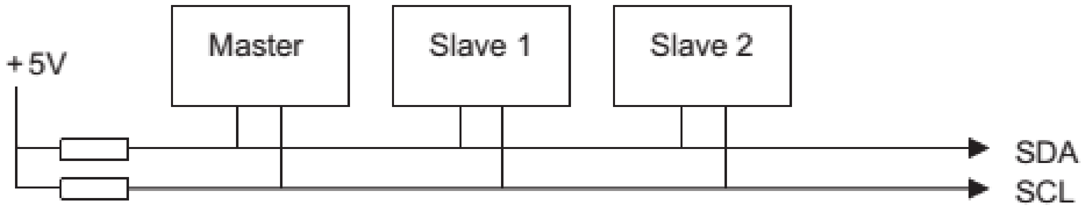


Figure 5.12. I^2C bus connection [29]

The three above mentioned communication options are also very common in other microcontroller brands. Unfortunately the USART, SPI and I^2C can't be considered as good options for longer distances than few meters. In this solution the distance is definitely more plus the electromagnetic disturbance has to be taken into account. These communication interfaces need to have an extra driver or transceiver in order to reach longer distances. Best would be to look into some industrial communication options that might be suitable for this solution.

5.4.4 RS-485

RS-485 is an electrical-only standard. In contrast to complete interface standards, which define the functional, mechanical, and electrical specifications, RS-485 only defines the electrical characteristics of drivers and receivers that could be used to implement a balanced multipoint transmission line [31]. Key features of RS-485:

- RS-485 can have up to 32 unit loads
- 10-Mbps maximum data rate at 12 meters
- At maximum cable length of 1200 meters the data rate can be up to 100 kbps

RS-485 has two structures: full-duplex and half-duplex. The full-duplex implementation requires two signal pairs, (four wires), and full-duplex transceivers with separate bus access lines for transmitter and receiver. Full-duplex allows a node to simultaneously transmit data on one pair while receiving data on the other pair. In half-duplex, only one signal pair is used, requiring the driving and receiving of data to occur at different times [31]. RS-485 uses differential signalling over twisted-pair cable. This gives bigger noise immunity from external sources. Although it was said earlier hat the maximum number of loads is 32, today's transceivers provide reduced unit loading, thus allowing up to 256 units on the bus [31]. The maximum number of bus devices depends on every specific bus design and can't be taken as a rule.

One of the most popular protocols used on RS-485 is MODBUS RTU. The MODBUS addressing space has 256 different addresses from which 1-247 are for slaves, address 0 is for broadcasting and 248-255 are reserved. Meaning that there is only one master and up to 247 slaves. The actual amount may be limited by the physical parameters of the bus. There are actually two different MODBUS transmission modes. RTU mode and ASCII mode. All devices must implement the RTU mode. The ASCII transmission mode is an option. MODBUS RTU includes an error–checking field that is based on a Cyclical Redundancy Checking (CRC) method performed on the message contents. The CRC field checks the contents of the entire message [32]. Two-wire bus topology is seen in figure 5.13. The size of the terminating resistors LT is usually 120 Ω. Depending on environment noise and transmission rates the termination resistance values and principles may differ [31]. Data transfer rates are from 1200 bps to 115 kbps and more. Most commonly used ones are 9600 bps and 19,2 kbps [32].

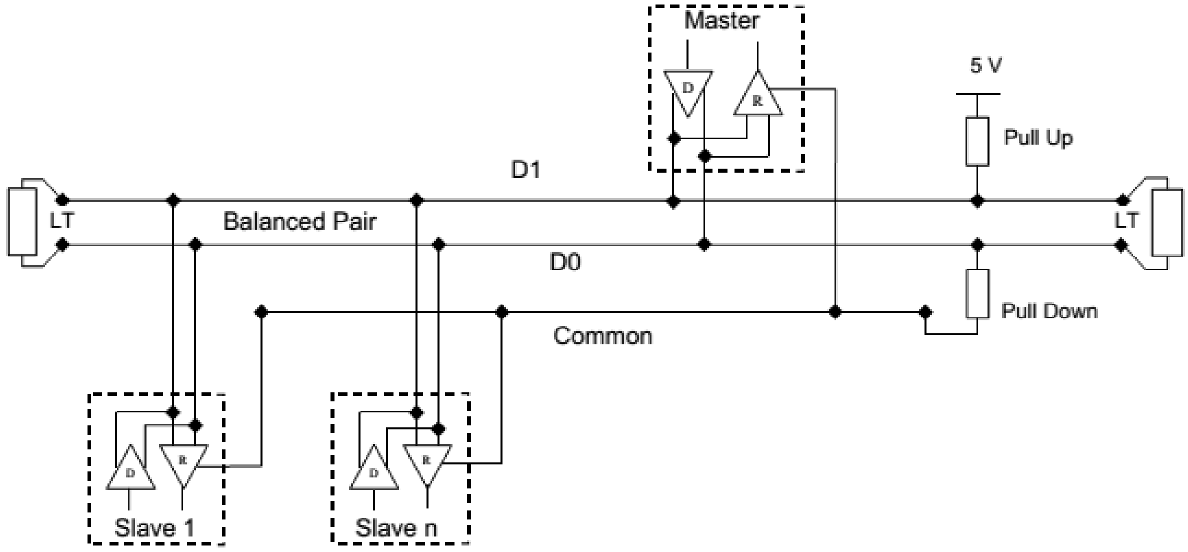


Figure 5.13. RS-485 two-wire (half-duplex) topology [32]

To implement this kind of a topology with Arduino Nano a transceiver unit needs to be added. For example a Maxim Integrated MAX1484CUB+ can be used [33]. It can be bought from Farnell internet store for 2,40 euros [24]. There are also open MODBUS libraries on the internet available for Arduino platform. It is too early to tell if they can be used for this project. These libraries should be tested in real application to see if they work properly. All in all the communication via MODBUS RTU looks like a good and inexpensive solution. The amount of nodes that bus can handle plus the distance seems promising, but like with all protocols an important part lies in the code that will implement it and that has not been tested in the scope of this thesis.

5.4.5 CAN

Controller Area Network (CAN) is a multicast-based communication protocol characterized by the deterministic resolution of the contention, low cost, and simple implementation. It is designed to operate at speeds from 20 kbit/s to 1 Mbit/s [34]. Unlike a traditional network such as USB or Ethernet, CAN does not send large blocks of data point-to-point from node A to node B under the supervision of a central bus master. In a CAN network, many short messages like temperature or RPM are broadcasted to the entire network, which provides data consistency in every node of the system. Bus access is event-driven and takes place randomly. If two nodes try to occupy the bus simultaneously, access is implemented with a non-destructive, bit-wise arbitration. Non-destructive means that the node winning arbitration just continues on with the message, without the message being destroyed or corrupted by another node [35]. CAN is a half-duplex system.

- Number of units on the bus is 32
- 1-Mbps maximum data rate at 40 meters
- At maximum cable length of 1000 meters the data rate can be up to 50 kbps

Standards like ISO 11898-3 and SAE J2411 allow up to 32 nodes [34]. In practice, up to 64 nodes may be connected to a DeviceNet bus, 127 on a CANopen bus and up to 255 nodes may be connected together on a CANKingdom bus. It is recommended to use a transceiver with high bus-input impedance when more than the standard 30 nodes are connected on a bus [36]. CAN bus uses twisted-pair cable like RS-485 with the same 120 Ω termination resistance. CAN bus topology is shown in the figure 5.14. Like with RS-485 the twisted-pair cable is connected to transceiver from where the signal is transmitted to CAN controller. The CAN Controller is the (hardware) component that is responsible for the physical access to the transmission medium. It provides registers for the configuration of the connection to a bus with given characteristics, including the selection of the bit rate, the bit sample time, and the length of the inter frame field. The controller also provides the functionality for managing all the aspects of the CAN protocol, including the management of the transmission modes and the handling of the bus off state. The controller offers a number of data registers for holding messages for outgoing transmissions and incoming data, and provides support for message masking and filtering on reception [34]. There are two possibilities to implement CAN on

MCU. First is to use a microcontroller that has CAN controller built in. Second option is to use stand-alone CAN controller over SPI.

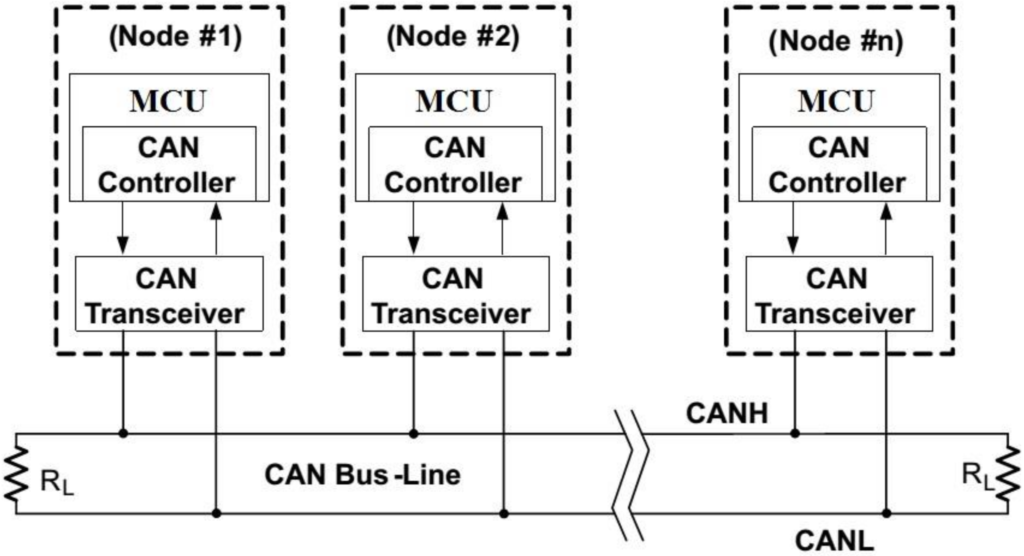


Figure 5.14. CAN bus topology [35]

As the ATmega328P doesn’t have integrated CAN controller a stand-alone unit would have to be used. One of the most popular combinations with Arduino platforms is to use MCP2551 [37] transceiver and MCP2515 [38] stand-alone CAN controller with SPI interface. On Farnell internet page MCP2551 costs 1 euro and MCP2515 costs 1,77 euros [24]. Compared to MODBUS RTU the price for components is very similar. The maximum amount of nodes with the MCP2551 can transceiver is 112 [37]. Transfer speeds and distances are better with MODBUS RTU. CAN is more meant for transferring short single messages. Like with MODBUS RTU there are several open source libraries available for Arduino platform. In order to compare these two options properly both of the libraries should be tested. It may be that one of the ready-made open source libraries will not work as needed for this application.

There are several other industrial protocols available: CANopen, ControlNet, EthetNet/IP, PROFIBUS, PROFINET, INTERBUS, WorldFIP, FoundationFieldbus, HART and many more [39]. It would be redundant to address all of them in this thesis. CAN and MODBUS RTU are one of the simplest protocols. Nevertheless they are enough for this power measuring system.

6 CONCLUSION

The task of this master thesis was to find an inexpensive solution for electricity metering. In the first chapter author looked at the worlds total electricity consumption and its future. Electrical energy is very important in world economy. Using it reasonably and efficiently is becoming more and more essential as the overall consumption rises every year. In order to do so we first have to know when, where and how it is being used.

Being a global machine and plant manufacturer, Bühler AG produces equipment that works solely on electrical energy. It's a company that could definitely use an inexpensive, wide scale electricity metering system.

Measuring electrical energy is nothing new. It has been around for more than hundred years. The theory behind it is in general rather simple. Especially when the aim is not to achieve high precision and tens of parameters. In the second paragraph author takes a look at the main equations that are needed to calculate electrical power consumption. Also the difference in real and apparent power is brought out.

It becomes clear that in a system with numerous motors the main parameter that needs to be measured is RMS current. There are several equipment options available to make the measuring. Most inexpensive from these options are hall effect sensors and current transformers. Both are suitable for this solution. The main subject to be measured is asynchronous motor. A quick introduction of asynchronous motors is given in chapter three. A short overview of the motor power losses is given.

In the scope of this thesis a handful of companies were asked to make an offer for large scale power measuring system. The parameters for inquiry and results are given in chapter four. Three companies are examined in more detail. In general the market for these solutions is rather big. The problem for suitable solutions lies within the price range. Finding something with such a low budget is impossible. Closest to desired range was the solution offered by Contrel Elettronica.

Next step was to look at the options how to make a power measuring system. A preliminary concept was set with few possible options for the overall system. Author started from the motor side. A Chinese company called YHDC Electronics Co. offers a cheap split core current transformer series that can cover most of the needed measurement range. For those few motors that exceed 100 A another measuring transformer has to be selected, but there is no need to do this selecting now as it doesn’t change much in the upcoming parts of design.

One of the sole parts of this thesis was to see if an integrated RMS to DC converter circuit can be implemented in the design. Two elements with the lowest cost were tested. Both were giving inaccurate results. The exact reason of the inaccuracy was not investigated as the RMS to DC converters have already rather high price (taking roughly a quarter of the overall budget for one unit). Most probably the improved accuracy can be achieved with the use of high quality components in the external circuitry of RMS to DC converter and better design of the circuitry itself. Making the total cost on this part of the system too high.

To digitalize the measured values and transmit them to user a microcontroller unit is needed. In order to boost the development process an Arduino open source platform was selected for faster prototyping. Arduino Nano counterfeit with ATmega328P main unit was used. In this thesis the author created a microcontroller program that reads analog values from current transformer and calculates the RMS value. A test was done to evaluate the accuracy of this design. Results were rather good compared to RMS to DC converters. What’s more important is that using the microcontroller units helps to save money and makes the design simpler from the hardware viewpoint.

Transferring data can be rather complicated if the amount of units on the bus is big and environment is filled with electromagnetic disturbances. In this thesis author gives a quick overview of data transferring options available on the selected microcontroller and their suitability for power measuring system. Also two industrial communication protocols are introduced. These are CAN and MODBUS RTU. Overview of these two is brief and doesn’t include details about protocol specifics.

In conclusion this thesis is an introduction to the power measuring system, covering only the input part of the overall concept. It gives a cheap and working solution for measuring current. There is still a lot of research to be done in order to make a fully functional design. In reality the data transmission is far more complex than just few lines presented in the figure. Implementing industrial protocols on open source microcontroller platform should be the next step. After which a hardware design of complete field unit can be made and tested. When it proves to be functional a main unit development can start (unit where all the data comes together and gets passed on to a user). It is too early to tell if the final design will be in the 20 euro limit while delivering proper performance and accuracy at the same time. It is definitely an interesting topic to research.

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RESÜMEE

Elektrienergia on saanud meie igapäevase elu lahutamatuks osaks. Meid ümbritsevad seadmed ja esemed, mis tarbivad otseselt elektrienergiat või on valmistatud elektrienergia kaasabil. Ligikaudu 130 aastat tagasi alustas Tomas Edison esimese elektrijaotusvõrguga. Tol ajal kasutati elektrit pealmiselt valgustamiseks. Aastate jooksul on aga selle tähtsus tunduvalt tõsnud. Trendid näitavad, et tulevikus oleme veelgi enam sõltuvuses elektienergiast. See in seadnud inimkonna küsimuse ette, kuidas tulle toime suureneva elektri tarbimisega ilma, et liig tarbitaks loodusvarasid. Selleks, et olukorda parandada, tuleb probleemile läheneda mõlemalt poolt. On vaja leida alternatiivseid energia allikaid ning samal ajal optimeerida tarbijaid, et ei toimuks asjatut raiskamist.

Ameerika Ühendriikide Energeetika nõukogu on ennustanud, et elektrienergia tootmine suureneb 2010 aasta 20,2 triljonilt kWh 39,0 triljoni kWh 2040-ndaks aastaks.

Kõige rohkem suureneb tootmine selliste riikide arvelt nagu Hiina, India ja Venemaa. Olenemata sellest, et enamus kasvust toimub väljaspool Euroopat ja Ameerika ühendriike ei tohiks sellesse suhtuda kergekäeliselt. Tootmiskasvu pealmiseks põhjuseks on lääneriikide pidevalt suurenev tarbimine.

Selleks, et piirata elektrienergia tarbimise kasvu on riigid hakanud seda reguleerima. Inimeste ja ettevõtete teadvus on samuti tõusnud. Kasutatakse energiasäästlikumaid masinaid. Üheks pealmiseks mõjutajaks on elektrienergia kWh hind. Eurostati andmetel suurenes Euroopa Liidus majapidamiste poolt tarbitava elektrienergia hind 2014 aasta jooksul 2,9%.

Need faktorid on muutnud tarbijad tähelepanelikuks. Kui toimub elektrienergia tarbimine siis soovitakse teada kus, millal ja mille tarbeks. Need teadmised aitavad vähendada kulutusi ja optimeerida tarbimist. Näiteks saab ajaliselt paindlikud protsessid planeerida öisele ajale, kui kogutarbimine on väiksem ja kWh hind madalam. Ka aitab säärane lähenemine kokku hoida investeeringuid jaotusvõrgu väljaehitamisel.

Bühler AG on Šveitsi juurtega ettevõte, mille tegevus on kestnud enam kui 150 aastat. Hetkel annab ettevõte tööd 10 600-le inimesel 140-s erinevas riigis. Bühleri üheks missiooni osaks

on keskkonna kaitsmine ja säästmine. Iga-aastasest kasumist suunatakse 5% arendus ja uurimustöödesse, et tagada innovatiivne ja energiasäästlik areng.

Bühleri pealmiseks tegevusvaldkonnaks on masinate, seadmete ja tehaste tootmine toiduaine tööstustele. Ligikaudu 65% kogu maailmas kasvatatavast viljast läbib töötlemisel Bühleri poolt toodetud seadmeid. Kuid see ei ole kõik. Lisaks vilja jahvatamise tööstustele pakub Bühler seadmeid ka riisi, pasta, šokolaadi ja muude toiduainete tootmiseks. Ollakse üks juhtivamaid ettevõtteid seadmete tootmises sektoritele nagu valud, märgjahvatamine ja katmine.

Seega võib öelda, et elektrienergia säästmiseks ei ole paremat kohta, kui tööstus, mis toodab seadmeid ja lahendusi üle maailma ja väga erinevatele sektoritele. Selleks, et alustada elektrienergia säästmisega peame esmalt teadma, millistes protsessides ja millal tarbimine toimub. Tulenevalt tööstusharust võib tehase ning selles paiknevate seadmete struktuur olla väga erinev. Seetõttu on töö autor võtnud mudeliks vilja jahvatamise tehase.

Elektrienergia tarbimise mõõdistamisega on tegeldud juba üsna kaua. Esimene elektriarvesti, mis suutis mõõta nii vahelduv- kui alalisvoolu leiutati 1889 aastal Elihu Thomsoni poolt. Hetkel turul saada olevad elektrienergia mõõteriistad suudavad teha aga väga palju enamat. Lisaks kWh arvestamisele omavad paljud seadmed erinevaid lisafunktsioone, digitaalseid sisendeid ja väljundeid ning pakuvad võimalust seda kõike distantsilt jälgida ja salvestada.

Kahjuks on aga selliste seadmete hind üsnagi kõrge ning kui soovitakse mõõta mitmeid erinevaid tarbijaid üksikult on lahenduse kogumaksumus niivõrd kallis, et majanduslikult puudub igasugune otstarbekus. Seega tuleb leida võimalus, kuidas paljude seadmete individuaalset elektritarbimist jälgida nii, et see ka majanduslikult kasumlikuks osutuks.

Oma olemuselt on elektrienergia mõõtmine küllaltki lihtne. Alalisvoolu korral leiame tarbitava võimsuse voolu ja pinge korrutisena. Vahelduvvoolu puhul tuleb arvesse võtta ka pinge ja voolu vahelist nurka. Ilma selleta ei ole võimalik öelda, kas tarbitav energia läheb efektiivse töö tegemiseks või on tegu reaktiivenergiaga, millest otsest kasu ei saa. Lisaks sellele on vahelduvvoolus ka harmoonilisi moonutusi. Tavaliselt ei ole nende osakaal rohkem kui mõni protsent koguvõimsusest. Vilja jahvatamise tehastes on põhilisteks elektrienergia tarbijateks kolmefaasilised asünkroonmootorid. Osade seadmete juures kasutatakse ka sujuvkäiviteid ja sagedusmuundureid, mis tekitavad moonutusi. Nende osakaal on aga üsna väike ning sagedusmuundurite korral on kasutusel võrgufiltrid.

Selleks, et mõõta ühe mootori elektrienergia on vaja teada selle mootori voolu ja pinget. Juhul, kui tarbijad on koondatud samasse elektrikilpi, ei ole vaja mõõta pinget iga tarbija juures eraldi. Piisab ühest pinge mõõtmis punktist, sest pingelangu kilbi jaotuslattidel võib lugeda olematuks. Voolu tuleb aga iga mootori jaoks eraldi mõõta. Seega ei ole pinge mõõtmine niivõrd hinnatundlik ning keskenduda tuleb odavale voolu mõõtmise lahendusele.

Voolu mõõtmiseks on mitmeid erinevaid lahendusi. Üheks neist on šunt. Šunt on takistus, mis ühendatakse jadamisi seadmega, mille voolu soovitakse mõõta. Tema takistus on väike, et vähendada mõju mõõdetavale süsteemile. Samas ei tohi ta olla aga liiga väike, sest see muudab mõõtmise ebatäpseks. Üheks suurimaks miinuseks šundi juures on see, et puudub galvaaniline eraldatus mõõtesüsteemi ja mõõdetava vahel.

Voolutrafo on üsna levinud vahend vahelduvvoolu ahelat läbiva voolu mõõtmiseks. Tema tööpõhimõte seisneb selles, et voolujuhti läbiv vool loob juhi ümber magnetvälja, mis omakorda indutseerib voolu sekundaarmähisesse. Sekundaarmähisesse indutseeritud vool on proportsionaalne mõõdetavat vooljuhti läbiva vooluga. Selline lahendus on üsna täpne ning eraldab mõõtesüsteemi galvaaniliselt.

Halli efektil töötav mõõtesensor on loodud pooljuhtidest. Kui sensor asetada magnetvälja siis hakkab pooljuht juhtima elektrit, mille suurus on proportsionaalne magnetvälja suurusega. Asetades halli sensori voolujuhi lähedale saab mõõta seda juhti läbivat voolu. Selleks, et parandada sensori täpsust kasutatakse konsentraatorit, mis näeb välja nagu voolutrafo. Veelgi suurema täpsuse saavutamiseks võib lisada kompenseeriva mähise.

Rogowski vöö on nagu õhksüdamikuga voolutrafo, kus vastastikuse induktiivsuse tulemusena sekundaarmähisesse tekkiv pinge on proportsionaalne mõõdetava vooluga. Rogowski vöö on ebalineaarne, mis tuleneb magnetsüdamiku puudumisest. Tema suureks eeliseks on aga mehaaniliselt paindlik disain, mis muudab tema kasutamise olemasolevates süsteemides väga lihtsaks ja mugavaks.
Lisaks eelnimetatud lahendustele on ka muid, kuid nende eraldi välja toomisel ei ole mõtet, sest erilahenduste korral on hind enamasti liiga kõrge. Odava mõõtesüsteemi tarvis on

parimaks valikuks mõõtetrafo või halli sensori kasutamine. Mõlemad on hinna poolest soodsad ning mõõtevahemikud sobilikud.

Turul on väga palju erinevaid lahendusi elektrienergia mõõtmiseks. Selleks, et saada paremat ülevaadet, saadeti hinnapäringud mitmetele erinevatele ettevõtetele. Päringut täpsustavad punktid olid järgmised:

- Oluline on vaid voolu efektiivväärtuse mõõtmine, kõik muu on üleliigne
- Mõõtevahemik peaks olema 0,5 – 200 A
- Kõik mootorid on kolmefaasilised
- Lahendus peab olema võimeline mõõtma suurt hulka mootoreid. Suurusjärgu väljatoomiseks oli ette antud kogus 200 mootorit
- Võimalus andmete kauglugemiseks
- Võimalik ühendada kolmanda osapoole tarkvaralahendustega
- Nii odav kui võimalik

Ideaalne oleks, kui pakutava lahenduse maksumus ühe mõõdetava mootori kohta ei ületaks 20 eurot. Seda aga ei toodud sihilikult hinnapäringus välja. Osad ettevõtted keeldusid pakkumise esitamisest juba seetõttu, et mainitud oli lahenduse odavust.

Lõputöös on välja toodud kolme ettevõtte poolt pakutud lahendused koos hindadega. Nendeks ettevõteteks on Electrex, DENT Instrument ja Contrel Elettronica. Kõigi lahenduste puhul olid põhinõuded täidetud, kuid vaieldamatult odavaimat lahendust pakkus Contrel Elettronica. Siinkohal ei ole põhjust ülejäänud ettevõtete pakkumisi eraldi välja tuua, sest nende lahendused olid väga sarnased ja hinnaklass sama või isegi kallim.

Seega tuleb uurida võimalusi ise soovitud lahenduse väljatöötamiseks. Parim viis oleks kasutada juba osaliselt valmis tooteid, et hoida kokku arendus kuludelt. Luues midagi täiesti rohujuure tasandilt võib lõpptulemuseks olla küll ideaalne toode, mis vastab kõigile seatud nõuetele, kuid aeg ja raha, mis kulusid selle väljatöötamiseks võivad üle kaaluda isegi parima idee. Selle lõputöö eesmärk ei ole pakkuda lõpliku lahendust, mis oleks valmis masstootmiseks. Pigem on tegu esimeste sammudega säärase lahenduse väljatöötamiseks, mis võivad tulla kasuks tulevikus.

Selleks, et uurida lähemalt võimalusi säärase mõõtesüsteemi loomiseks tuleb esmalt paika panna visioon, milline võiks lahendus olla. Töös pakub autor välja kolm lahendust, kus süsteemi keskseks osaks on mikrokontroller. Esimene ja teine lahendus kasutavad kahe erineva tasandi mikrokontrollerit. Voolu mõõtmise ja esmaste arvutustega tegeleb odavam ja väiksema jõudlusega mikrokontrolleril põhinev lahendus, mis edastab andmed järgmisele mikrokontrollerile, mis on kallim ja suurema jõudlusega. Seal toimub andmete kogumine, salvestamine, töötlemine ja edastamine kohalikku võrku või Internetti. Kolmanda pakutud lahenduse korral oleks kasutusel ainult üks mikrokontrolleri tasand, mis võimaldaks lugeda mõõteandmeid otse, ilma kesk-seadet kasutamata. Sellele siin töös aga pikemalt ei keskenduta.

Voolu mõõtmiseks on autor otsustanud valida Hiina tootja YDDC Electronics poolt pakutavat tootesarja, mille mõõtevahemik ulatub 100 A-ni. Tegemist on voolutrafoga, mille südamik on poolitatav. Valiku pealmisteks põhjusteks on soodne hind ja võimalus paigaldada seade ilma mootorite tööd katkestamata. Lisaks sellele on voolutrafo kompaktses juhtme ja ühenduspistikuga varustatud valmislahenduses.

Esimese lahenduse idee seisneb selles, et kasutades integreeritud skeemide abi, ei ole mõõtetulemuste täpsus niivõrd sõltuv mikrokontrolleri programmi koodist ja jõudlusest. Lõputöös on testitud kahte erinevat integreeritud analoogskeemi. Esimene on LTC1966. Tegu on integreeritud analoogskeemiga, kus väljundiks on alalispinge, mille suurus on võrdeline sisendsignaali efektiivväärtusega. Toote andmelehel on välja toodud mõningad võimalikud skeemi lahendused ja juhised, kuidas LTC1966-t kasutada. Lõputöö raames on ühte neist testitud, et näha, kas antud toode võiks sobida soovitud lahenduse väljatöötamiseks.

Selleks, et analoogskeeme testida kasutab autor PicoScope 5000 seeria USB ossilloskoopi. Lisaks neljale sisendkanalile on selle ossilloskoobiga võimalik luua ka erineva kujuga väljundsignaale vahemikus ±2 V. Tänu sellele ei ole tarvis otsida reaalset testimisobjekti. Voolutrafo sekundaarmähise signaali on võimalik simuleerida ossilloskoobi signaaligeneraatori abiga.

Testimise käigus kasutab autor ideaalset 50 Hz sagedusega siinus signaali. Muutes sisendsignaali amplituudväärust mõõdetakse analoogskeemi väljundit ning võrreldakse seda ideaalse arvutusliku efektiivväärusega. Saadud tulemused on näidatud tabelis ja graafikul.

Paraku on LTC1966-e väljundi viga üsnagi suur. Võib vaid oletada, miks selline viga tekib. Põhjuseks võib olla analoogskeemile lisatud komponentide kehv kvaliteet või, et käsitsi koostatud skeemi jooterajad põhjustavad häiringuid. Eelnimetatud ebatäpsus ja komponendi küllaltki suur hind etteantud 20 eurose kogumaksumuse juures muudavad LTC1966-e mittesobilikuks selle lahenduse tarvis.

Lisaks LTC1966-le katsetas autor ka konkureeriva ettevõtte poolt pakutavat integreeritud analoogskeemi AD736J. Selle toote hind on ligilähedane LTC1966-e omale. Skeemi sisendsignaalina kasutatakse jällegi PicaScope-i signaaligeneraatorit. Katsetuse tulemused on veidi paremad. Vea suurus on veidi väiksem kui eelmise analoogskeemi korral. Paraku samadel põhjustel ei pea autor AD736J integreeritud analoogskeemi heaks komponendiks, mida mõõtesüsteemis kasutada.

Need kaks analoogskeemi olid ühed odavaimad, mida säärase funktsiooniga toodete grupis võib leida. Analoogsignaali efektiivväärtust mõõtvate integreeritud skeemide hinnad ulatuvad väga kõrgele. Tulenevalt hinnast on ka suurem täpsus ning skeem sisaldab lisaks efektiivväärtuse mõõtmisele ka võimendavaid lülisid. Siinkohal ei pea autor vajalikuks neid eraldi välja tuua, sest hinna tõttu ei saaks neid kasutada.

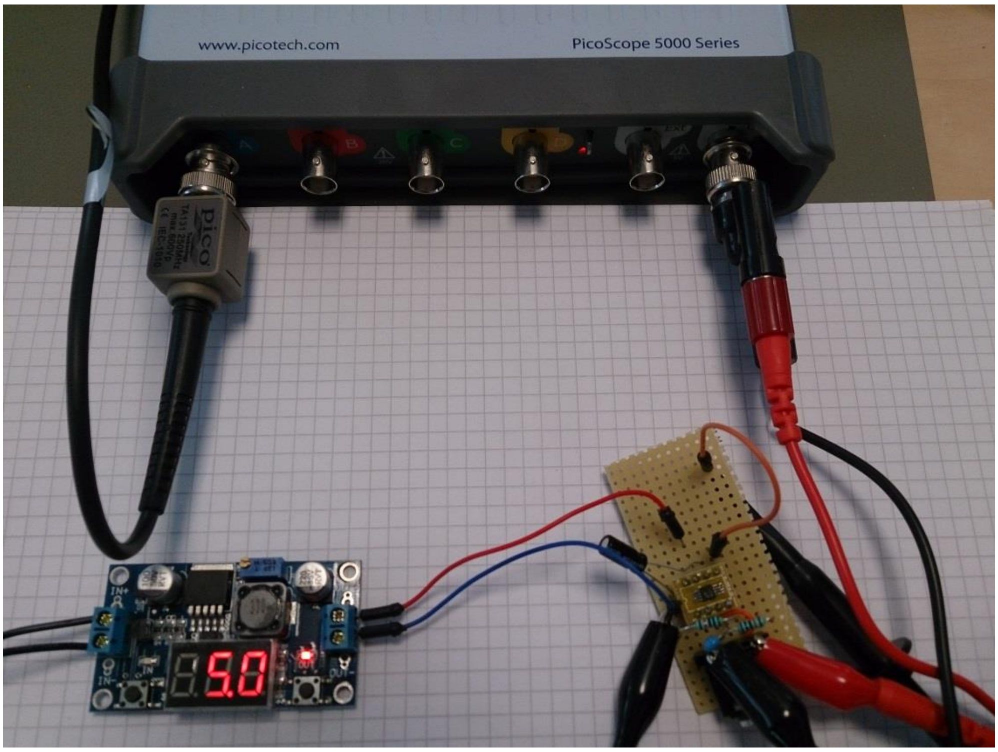
Olenemata sellest, kas kasutada sisendi teisendamisel analoogskeemide abi või mitte on andmete edastamisel oluliseks lüliks mikrokontroller. Selleks, et esmaseid katsetusi oleks võimalikult lihtne teostada, kasutab lõputöö autor Arduino arendusplatvormi. Tegemist on vabavaralise tarkvara ja riistvara lahendusega, mis võimaldab kasutajal väga lihtsa vaevaga kasutada olemasolevaid programmikoodi näidiseid oma ideede teostamiseks. Otsustatud on kasutada järele tehtud Arduino Nano-t. Mikrokontrolleriks sellel plaadil on ATmega328P. Sama, mis originaalil. Ülejäänud komponendid on aga madalama kvaliteediga ning kasutusel on veidi teine USB draiver.

Kolmanda praktilise katsena luuakse programmi kood Arduino Nono jaoks. Eesmärk on testida, milliseid tulemusi annab mikrokontrolleri kasutamine analoogsignaali otsemõõtmisel. Jällegi kasutatakse signaaligeneraatorit, et simuleerida voolutrafo väljundit. Selle lahenduse tööpõhimõte on järgmine: loetakse 40 ms jooksul mikrokontrolleri mälusse nii palju mõõtesuuruseid, kui võimalik. Arvud salvestatakse eelnevalt defineeritud asukohta. Euroopas kasutusel oleva võrgusageduse juures salvestab mikrokontroller sisendsignaali kahe perioodi väärtused. Seejärel arvutatakse salvestatud väärtuste alusel efektiivväärtus. Tulemusi võrreldakse ideaalse arvutusliku efektiivväärtusega. Viga on tunduvalt väiksem, kui analoogskeemide korral. Kasutatud ei ole digitaalseid filtreid, mis võiksid mõõtmistulemusi veelgi täpsemaks muuta ilma lisakulutusteta.

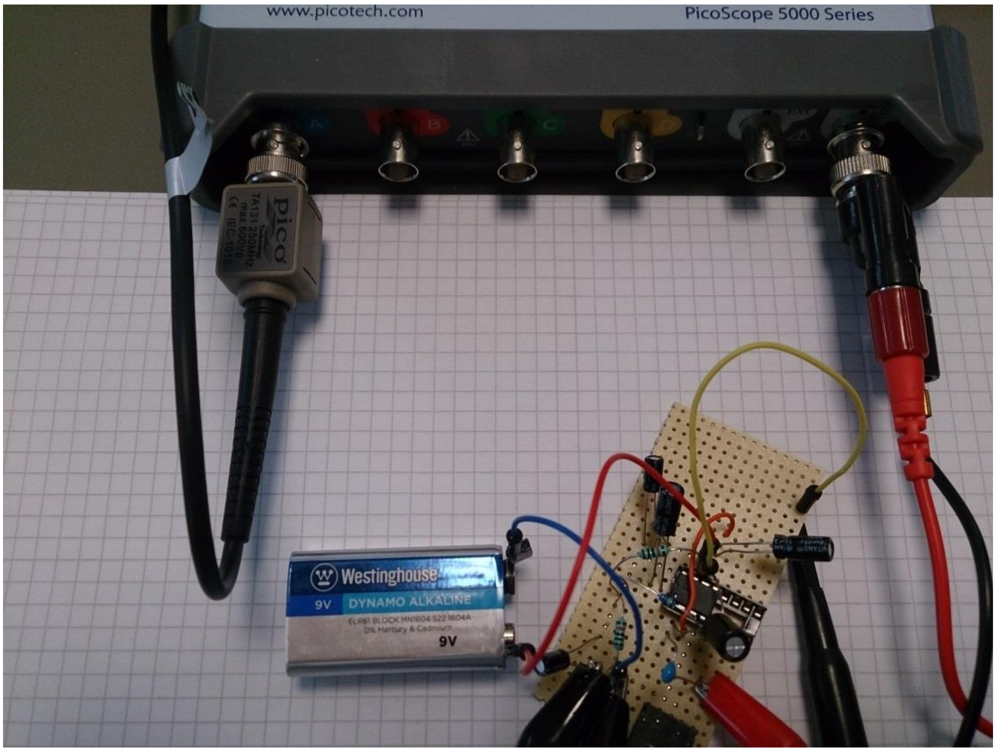
Üheks oluliseks osaks terviklahenduse juures on andmeside. Selleks, et mõõdetud tulemusi edastada on vaja kasutusele võtta andmeside protokoll. Paljudel mikrokontrolleritel on integreeritud andmeside draiverid. Atmega328P omab näiteks USART, SPI ja I^2C draivereid, kuid kahjuks sobivad need vaid väga lühikeste vahemaade juures. Tuleb mõelda tööstusliku protokolli kasutamisele. Selleks võiks olla näiteks CAN või MODBUS RTU. Kuna andmeside mahud ei ole suured, sest kõrgema astme mikrokontrollerile edastatakse vaid arvutatud efektiivväärtus, ei ole põhjust keerulisemaid protokolle kasutada. Mõlemad eelnimetatud andmeside protokollid on väga levinud.

Lõputöö ülesandeks oli uurida odavaid lahendusi elektrienergia mõõtmiseks. Maksumus ühe mõõdetava kohta ei tohiks ületada 20 eurot. Paraku ei ole sellise hinnaga võimalik juba valmis lahendust soetada. Seega tuleb leida võimalus ise soovitud süsteemi väljatöötamiseks. Lõputöö raames on katsetatud kahte analoogskeemi ja ühte mikrokontrolleril põhinevat lahendust, mis võiksid olla üheks osaks terviklikust süsteemist. Tutvustatud on ka mõningaid andmeside protokolle. Selleks, et jõuda lõpliku lahenduseni on veel palju tööd tarvis teha. Ennekõike tuleb leida sobilik lahendus andmeside teostamiseks. Siinkohal on väga oluline osa mikrokontrolleri programmikoodil.

ANNEXE



Measuring LTC1966 RMS to DC converter



Measuring AD736J RMS to DC converter