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MASTER'S THESIS

AUTOMATIC METER READING – BENEFITS AND APPLICATIONS

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Abstract

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In liberalized electricity markets, which have taken place in many countries over the world, the electricity distribution companies operate in the competitive conditions. Therefore, accurate information about the customers' energy consumption plays an essential role for the budget keeping of the distribution company and for correct planning and operation of the distribution network.

This master's thesis is focused on the description of the possible benefits for the electric utilities and residential customers from the automatic meter reading system usage. Major benefits of the AMR, illustrated in the thesis, are distribution network management, power quality monitoring, load modelling, and detection of the illegal usage of the electricity. By the example of the power system state estimation, it was illustrated that even the partial installation of the AMR in the customer side leads to more accurate data about the voltage and power levels in the whole network. The thesis also contains the description of the present situation of the AMR integration in Russia.

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Abbreviations and symbols

AC supply	Alternating Current supply
AMR	Automatic Meter Reading
CAIDI	Customer Average Interruption Duration Index
CIS	Customer Information System
CIS countries	Commonwealth of Independent States countries
DC supply	Direct Current supply
DMS	Distribution Management System
GSM	Global System Mobile
IEEE	Institute of Electrical and Electronic Engineers
LLC	Limited Liability Company
LV-network	Low Voltage network
MAIFI	Momentary Average Interruption Frequency Index
OJSC	Open Joint-Stock Company
OMS	Outage Management System
PLC	Power Line Carrier
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
Smart IMS	Smart Integrated Metering System
TOU tariff	Time-of-Use tariff

I	current
$I_{\lim}$	limit value of differential current
I_S	total (summarized) current of three phases
P	active (real) power
Q	reactive power
t	time
U	voltage
S	apparent power

E	annual energy consumed
k	Velander coefficient
T	temperature
Q	two-week index
q	hour index
R	resistance
X	reactance
l	length of line

Subindexes

rms	root-mean-square
lim	limit value
s	summarized value
r	type of the customer group
i	time
loss	power losses

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1 Introduction

During all time of electricity generation and delivery the energy meters play a role of information source about the energy consumption of end-users. Today's technical advance in sphere of electronics and communication allows to refuse from early used types of energy meters (electromechanical induction meter, solid state meters) because of their insufficient accuracy in the metering and move to the usage of a remote metering system, such as the automatic meter reading (AMR) that can give real-time measurements of the energy consumed.

The AMR system is also able to provide a set of different services, which can be useful for the electric utility planning and operation; they are distribution network management, power quality monitoring, fault and outage reporting, load management, protection against the electricity theft. The main benefit for electricity customers from the AMR usage consists of a possibility to regulate their energy consumption, depending on the off/on-peak time of the whole grid energy consumption, and therefore to pay less for electricity. As a result of the conscious behavior of customers during these time periods, the capital investments into increase of the peak generating capacities will reduce.

This Master's thesis consists from six chapters including Introduction and Conclusion. The second chapter after Introduction contains the description of development of the devices measuring the electric power, development of the AMR technology in particular and examples of the AMR implementation over the world. In this chapter it is also described the technical construction, operating principle of the AMR and some technical recommendations for different parts of the AMR system.

The third chapter is dedicated to the review of possible benefits from the AMR usage for distribution network management, low voltage network (LV network) state-estimation, fault and outage reporting, load modeling, customer service and protection against the electricity theft. This chapter also contains the description of benefits from the AMR usage for different actors of the electricity market and difficulties connected to the AMR integration into the distribution network.

Within a scope of the fourth chapter two methods of the state-estimation of the example 0.4 kV distribution network are described. The first one is based on the load models method, the second one is based on the AMR data usage. Analysis of the results distortion between two methods has been done.

The fifth chapter is dedicated to researching of the present situation connected to the integration of the AMR system in Russia. The chapter contains the review of the AMR application for the residential customers in the Russian power system, the description of benefits and difficulties of the AMR usage in Russia and some forecast of the future development of the AMR technology in Russia.

The results of work are summarized in Conclusion.

2 General description of automatic meter reading system

2.1 History of device development

Throughout the processes of electricity generation and delivery energy meters play a significant role as an information source about the end-users' energy consumption. The most common type of energy meters is a kilowatt-hour meter, which measures the amount of electrical energy supplied to residents or industrial plants. On the basis of these consumption data, the electric utilities submit electricity bills for the customers.

The principle of modern electricity meters is based on continuous measurements of the instantaneous values of voltage and current. These data are used to find the instantaneous value of electrical power, which has to be integrated with respect to time to give the consumed energy.

Some technical descriptions, advantages and disadvantages of different widely used meters in the past and today are introduced and discussed below.

2.1.1 Electromechanical induction meters

At present, many technically developed countries have refused to use this kind of energy meters because of the inaccuracy of measurements. However, these devices are still used in some countries, such as Russia, in houses of old construction.

An electromechanical induction meter is an integrating device, which sums up the instantaneous values of voltage and current. The operation of an electromechanical induction meter is based on counting the revolutions of an aluminum disc which rotates with a speed proportional to the power. The number of revolutions is proportional to the energy consumed. (Trub, 1983)

In Figure 2.1 the electromagnet 1 is connected in a parallel with a load *L*, so its magnetic flux Φ_U proportional to the voltage of a network. The other electromagnet 2 is in a cascade connection with the load, and its magnetic flux Φ_I proportional to the current. As a result, there are eddy currents in the disc such that a force acts upon the disc proportionally to the instantaneous values of current and voltage. The rotation of the disc is caused by electromagnetic forces generated by the interaction of magnetic fluxes and eddy currents of two electromagnets. When power consumption stops, the disc will not carry on rotation, the necessary retarding action by a permanent magnet 7 operating on the aluminum disk is provided. (Trub, 1983)

There are the following designations in Figure 2.1:
1 = potential electromagnet;
2 = current electromagnet;
3 = aluminum disk;
4 = shaft;
5 = top bearing;
6 = lower bearing;
7 = permanent magnet;
8 = worm gear;
L = load.

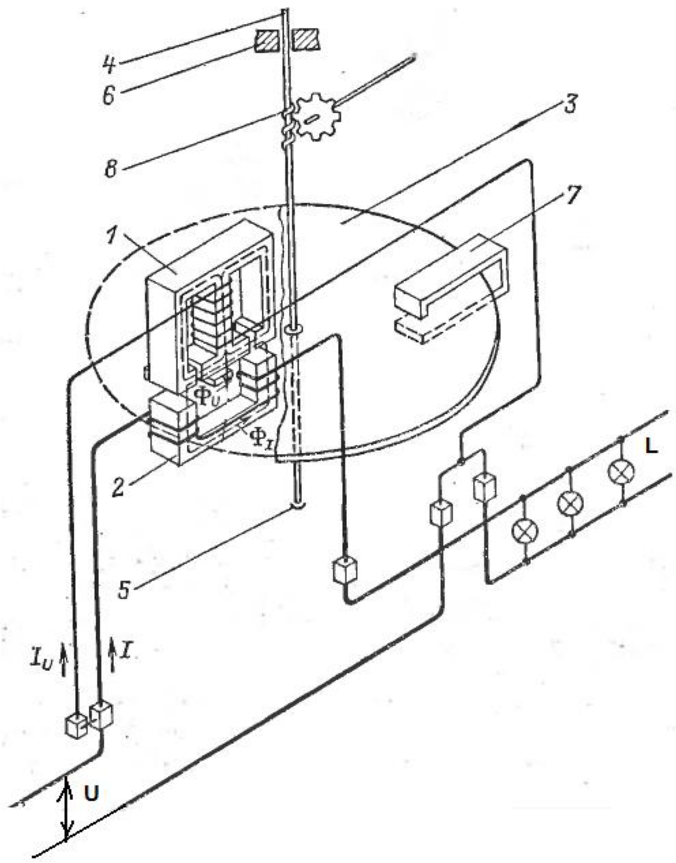

Fig. 2.1 Design of a single-phase electromechanical induction meter (Trub, 1983)

The aluminum disc drives a register by means of a worm gear 8. The register is a series of dials which record the amount of the energy consumed. Each dial has a single digit, which can be seen through the faceplate of the meter, or it can be a pointer type of data reading, where each pointer indicates a digit. Figure 2.2 demonstrates these two types of meters.

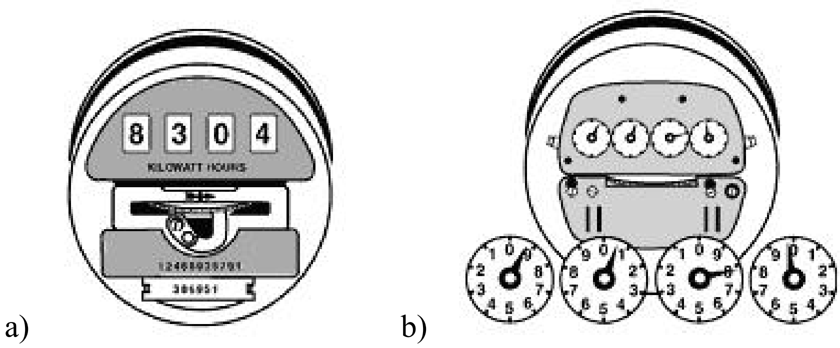

Fig. 2.2 Design of electromechanical meters a) digital type, b) pointer type (SRP, 1996)

An existence of different mechanical parts in the induction meter construction in some cases can lead to reception of inaccurate data because of an opportunity of a dirt penetration in the air gaps. There are some other sources of error which may occur inside or outside the meter (United States department of the interior, Bureau of reclamation, 2000):

- an appearance of magnetic particles in the permanent magnet air gaps;
- an opportunity of a gummy oil or dirt accumulation in the bearing and the increase in friction, as a result;
- a vibration of the all construction;
- an impact of the external magnetic fields which may add to, or subtract from, the normal meter magnetic flux;
- because of overloads and short circuits the magnetization of the permanent magnet can be changed;
- improperly calibrated transformer;
- a creep phenomenon; it occurs when the disc continuously rotates with an applied potential and the load is open circuited.

At domestic customers, the information about energy consumed is read from a meter manually, either by the customer or by a representative of the distribution company. The customers' meter readings can be reported by telephone, post or via the internet. Hence, this system of data reading requires a periodic visit by the controller to verify the customer-supplied data reading and to make the base technical checkup of the device.

These kinds of energy meters are used on single-phase alternating current supplies (AC supplies). Different phase configurations can be accomplished using two or three meters having a common shaft and register, which sums values measured by each element. (Trub, 1983)

A working life of the induction meter is at least thirty years, and it can save its initial accuracy class (2.0 S) after fifty work years. (Akimov, Shuleshko, 2005)

2.1.2 *Solid state meters*

Solid state meters are more developed meters than the electromechanical meters. These meters do not have mechanical parts and power measurement is realized by means of electronic circuits. That is why a solid state meter is often called an electronic meter. Besides measurement of consumed electricity, solid state meters can register parameters such as maximal demand, power factor and reactive power used. These devices can include an electronic clock mechanism to calculate an energy value rather than an energy amount depending on price variation from the time of day, day of week and the season.

The operating principle of the electronic meter is based on a transformation of analog signals metered by current and voltage transformers into a pulse sequence; this action takes place in an analog-signal transformer (Fig.2.3). A pulse frequency is proportional to the energy consumed. A microcontroller processes this information and gives it on a liquid-crystal display. A solid state meter has an opportunity to conserve the measured data in a built-in memory. (Kibitkin, 1999) Because of the absent of any mechanical parts, reliability and accuracy of these meters are at a higher level compared with induction meters.

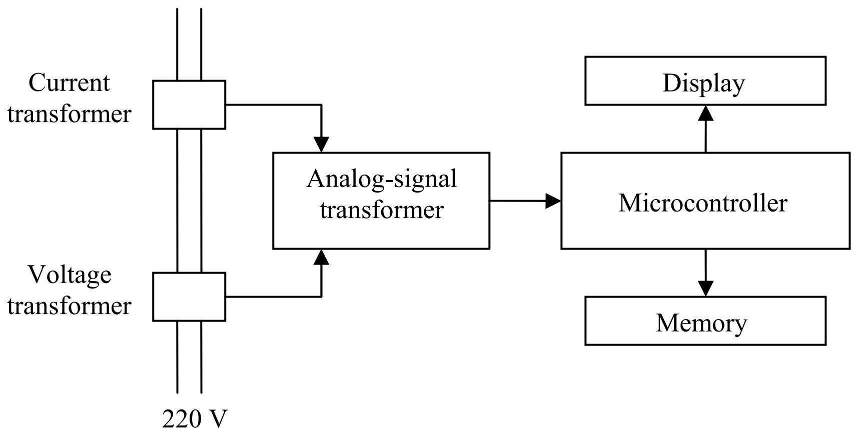

Fig. 2.3 Construction of the solid state meter (Figure is modified from the original source (Kibitkin, 1999)

Using a current transformer for current measurement allows placing this kind of a meter remotely from the main current-carrying conductors; in other words they do not have to pass through the meter itself. This can be an advantage in high power installations in particular.

The electronic meter can keep its accuracy class (0.5 S, 0.2 S) after light and short-term overloads. It is also possible to use one electronic meter for measuring other energy consumed, such as water and gas. The meter can detect attempts of unapproved hacking and electricity theft. Because of their ability of a remote meter reading, these kinds of meters are widely used as a part of the automatic meter reading system. (Akimov, Shuleshko, 2005)

However, the electronic meter has a set of disadvantages, they are:

- a reduction in accuracy during switching and lighting-storm voltage drops;
- a higher cost compared with the induction meter;
- a working life of the electronic meter is about sixteen years, this is less then half that the induction meter has. (Akimov, Shuleshko, 2005)

The solid state meters are able to work in a large frequency range that is why they can operate on AC supplies and also on direct current supplies (DC supplies).

2.1.3 Automatic meter reading

Automatic meter reading (AMR) refers to remote collection of consumption data from electricity users with the target of planning, control and monitoring of electricity consumption by the distribution company. The system of AMR allows cost and labor savings; it is more accurate and also has an ability to execute many other different functions, which are useful not only for electricity supplier, but also for the electricity user.

The modern AMR system is based on two-way communication between the utility and its customer. AMR can be categorized according to the type of technology links used to organize this communication; it can be for instance telephone, radio, power line carrier (PLC) 0.4/22 kV, 0.4/6 kV or GSM. A two-way communication system is not only a method for consumption data exchange, but it also provides a means of electricity tariff submitting, value-added service, interruption and fault reporting, distribution automation, remote meter calibration and detection of electricity theft.

With AMR the distribution companies can obtain more accurate and real-time measurements, further processing of which can lead to improvement in company operation in the sphere of load modeling, distribution management, interruption reporting and customer service. That is why the penetration of the AMR has been increasing rapidly during the last years, and similar development will continue in the future, as many distribution companies have plans to install AMR systems.

2.1.3.1 Development of the AMR

The AMR was first tested by AT&T Corporation (American Telephone and Telegraph Corporation) in cooperation with a group of electric utilities 41 years ago in the USA. It was a successful experiment, after which AT&T offered to provide AMR service based on a telephone communication link. However, from an economical point of view, this project was unprofitable. After nine years, in 1977, a Utility Communication Division was founded in Rockwell International to develop a distribution carrier communication system. Further in 1984, General Electric acquired from Rockwell International an exclusive license to commercialize their project concerning a design of a distribution line carrier link for AMR. The modern era of AMR began in 1985, when several full-scale projects were implemented. Hackensack Water Corporation and Equitable Gas Corporation were the first to execute the wide introduction of AMR technology into the water and gas measurements, respectively. In 1986, the radio-based AMR system was installed for 450 thousands customers. In 1987, Philadelphia Electric Corporation had installed thousands of distribution line carrier AMR units to reach meters that were previously inaccessible. (Tan, Moghavvemi, 2002)

As a result of the technical advance in solid-state electronics, microprocessor components and communication sphere, a modern AMR system allows getting far more useful information beneficial for a distribution company and enables the provision of additional services. The technology is known as Smart Integrated Metering System (Smart IMS), but the basic idea of remote electricity measurement is common for both AMR and Smart systems.

2.1.3.2 Implementation of the Smart IMS over the world

The most large-scale project of Smart meter deployment at least until 2009 was undertaken by Enel SpA, the dominant utility in Italy with over 27 million customers. The entire integration of this technology for all customers was realized in five years between 2001 and 2005. The communication between elements of the system is based on a low voltage power line provided by Echelon Corporation. (Echelon Co., 2009) In the estimations given in different publications, the total cost of the project was approximately 2.1 billion euros and the savings that Enel is receiving in operation are 500 million euros per year, with a payback of four years. (Smith Bellerby Limited, 2007)

The Ontario Energy Board in Ontario, Canada has been working on introduction the Smart technology into a present country life. The government has set a target of deploying smart meters to 800 000 homes and small businesses by the end of 2007 and throughout the province by the end of 2010. (Ontario Energy Board, 2004)

The California utility Pacific Gas and Electric (PG&E) plans to deploy 10.3 million smart gas and electric meters by the end of 2011 to all of its customers. By employing smart meter technology, PG&E plans to be better able to detect and respond to power outages. In the United States, power outages and interruptions cost 100 billion $ or more per year. According to Electric Power Research Institute (EPRI), California has the greatest losses associated with power outages and interruptions, total amount \$13.2 – 20.4 billion per year. (Green Car Congress, 2008)

In 2004, the Essential Service Commission of Victoria, Australia (ESC) has brought corrections to the Electricity Customer Metering Code and the Victorian Electricity Supply Industry Metrology Procedure to implement an order in the installation of interval electronic meters for Victorian electricity customers. According to a rollout timetable in the ESC's Final Paper entitled "Mandatory Rollout of Interval Meters for Electricity Customers" meters have to be installed by 2013 for all small businesses and residences, starting from 2006. The ESC forecasts that within seven years from the beginning of the replacing, up to 1 million large customers and other customers will have upgraded meters. (ESC, 2004)

In November 2005, the energy supplier Meridian Energy in New Zealand introduced the usage of smart meters in the Central Hawkes Bay area for over 1000 households. The communication link was based on radio and mobile technologies. It was expected to install over 6 300 smart meters by late 2006, as part of the initiated experiment. (Meridian Energy, 2005)

After having conducted a detailed cost-benefit analysis the AMR impact on the nation, in September 2006 the Netherlands government proposed legislation, according to it all residential customers will get a smart meter, starting from 2008. Since that time, two utilities Continuon and Oxxio have been undertaking some pilot projects of the AMR implementation. The smart meters register electricity and gas and communicate through PLC and GSM/GPRS. (Gerwen, 2006)

In Sweden the first studies concerning smart metering started in 2001. In 2003 in order to stimulate the introduction of smart technology, the Swedish government obligated the grid companies to a monthly meter reading for all electricity users by 2009. Since, the investments in this sphere have been going in a faster rate, than the government expected. (Gerwen, 2006)

The Finnish government proposed utilities to deploy smart meters in 80 percent of homes by end 2013. (Business wire, 2009)

According to the report from VaasaETT of October 2008, an energy think tank in Helsinki found that average energy savings thanks to usage of smart meters and in-house displays are 10.3%. The smart meters implementation has a voluntarily character, and is provided by Vattenfal, Fortum, Vantaa Energy utilities. (Business wire, 2009)

2.2 Arrangement of the AMR system

2.2.1 Technical construction of AMR, operating principle

The AMR system is intended to work with three- or one-phase end-customers in 0.4 kV power network environments. The system is used to collect the consumed electricity data for electricity consumption management from separate residential buildings (e.g. one-family and apartment houses), offices, industrial enterprises and public premises. Figure 2.4 demonstrates a principal scheme of communication between a distribution company and customers through the AMR system.

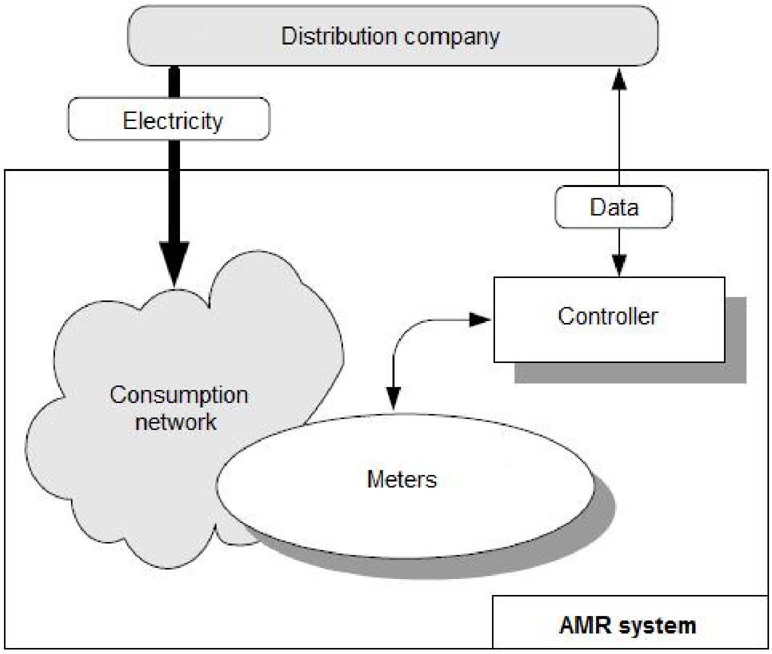

Fig. 2.4 Communication between a distribution company and customers through the AMR system (Figure is modified from the original source (Tele Tec. Co, General description, 2009)

The scope of AMR usage is limited by the size of the administrative center, town, rural area, or region. The application sphere can be extended by increase the number of meter units. One controller is able to accumulate and process data from about one million meter units. Several controller units can be incorporated into the controller of a higher level.

The meters transfer the measured data to a router in the transformer substation via communication links, for example via PLC. The router carries out functions of data acquisition and temporal storage and it has two-way communication with a controller, which is intended for data collection and long-term storage and is installed in the substation. Based on this information the electric utility makes a decision about the distribution automation. The scheme of data transfer between a meter and the controller is shown in Figure 2.5. (Tele Tec. Co, General description, 2009)

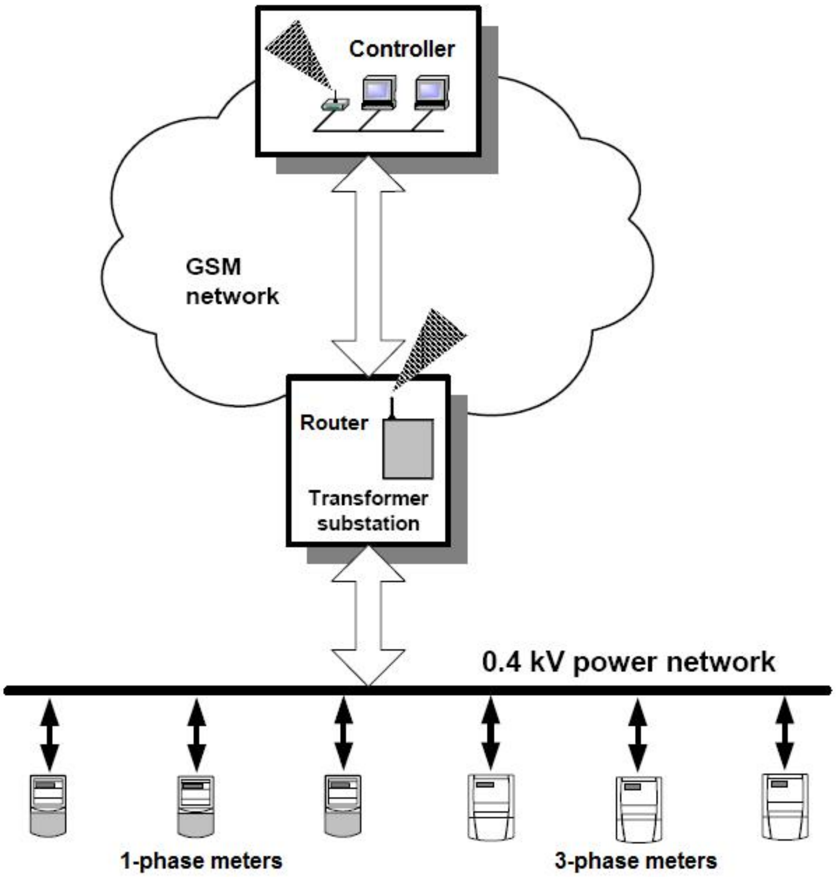

Fig. 2.5 Scheme of data transfer between a meter and the controller (Figure is modified from the original source (Tele Tec. Co, General description, 2009)

In some network constructions, the operation range of the router is not sufficient, in such cases the communication between meters and router has to be based on a principle of multilevel addressing, as shown in Figure 2.3.

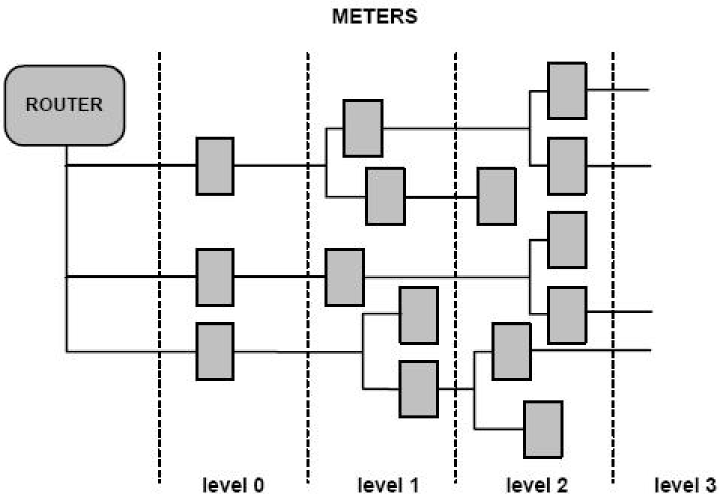

Fig. 2.6 Scheme of multilevel addressing (Tele Tec. Co, General description, 2009)

In the meters equipped with AMR technology, the analog signals of current and voltage are converted into digital signals. Power, consumed energy and a number of other parameters are calculated based on this information. All the data are stored in the non-volatile memory and can be read out remotely. Based on the set electricity tariff and the value-added service, the meters can calculate the electricity value for each end-user. The meters may have a display that provides a user-friendly interface between the system and the customer, giving information about electricity consumption both in kWh and monetary formats. Furthermore, depending on the situation, meters can turn off electricity delivery to a customer by an in-built relay. Such situations are for instance:

- The consumer has broken conditions of contract with the electricity supplier;
- The network condition does not allow electricity delivery because of emergency situation;
- The controller has sent a signal to turn off delivery. (Tele Tec. Co, Technical description and operation manual, 2009)

The meters also contain a scheme of differential current measurement. Differential current is a difference between the value of current in the zero conductor and the value of current in the phase conductor. By means of three-phase meters, it is possible to organize the power balance management. Differential current measurement and power balance management are two ways to detect electricity theft. (Tele Tec. Co, General description, 2009)

2.2.2 Requirements for the AMR system

At present time the standardization of AMR specific communication has not jet settled down. It means that at least equipment, which is installed at the end-users, has to possess a firmware download function to provide an opportunity for the updating of future standards. That is why there are some recommendations for different elements of AMR, which are represented below.

2.2.2.1 Recommendations for the communication network

The structure for communication network is strongly dependent on the communication media, which is chosen to connect elements of AMR system. Such medium links like telephone lines, GSM or Internet require additional wiring at customer premises and in case of GSM specific radio modems with appropriated antennas have to be used. Furthermore these types of communication media are not protected against customer access to the relevant parameters of network that can lead to interrupted connections and an unmanageable AMR system. (Schenk, 2005)

To avoid these mentioned problems it is recommended to use the PLC communication. The communication is provided by already existing distribution network therefore supports a 1:1 replacement of equipment. However, line attenuation phenomena and a noise level are proper to a low voltage distribution network. Detailed measurements and tests in this sphere have shown that the best efficiency of PLC communication can be granted if:

- spread spectrum technologies, which allow to do robust and redundant modulation, are implemented;
- the frequency band between 9 and 95 kHz is used to avoid the attenuation phenomena (European standard EN50065(CENELEC): Signaling on

low-voltage electricity installations in the frequency range 3 kHz to 148.5 kHz);

- every terminal device is used as a repeater for another terminal devices (Fig.2.6);
- electric power substations (or some equivalent stations) are used as a second data concentrator layer. (Schenk, 2005)

2.2.2.2 Recommendations for the terminal equipment

The meters themselves and the load-switching units belong to the terminal equipment in the AMR system. The load-switching unit provides the integration of a monitoring function as the output and the input voltage for the relays and the generation of respective alarm in fault situations. As was mentioned earlier, the terminal equipment has to provide an opportunity to be calibrated and to be able to update functions remotely. The following functionalities are recommended for meters as part of AMR system:

- several tariff register for the active energy consumed depending on time, day or/and actual load criteria;
- several tariff register for the energy delivered, this can be useful in cases of distributed generation;
- tariff register for reactive power consumed/ delivered;
- generation of the load profiles to do a deep analyses the consumption behavior;
- recording of voltage drops and supply interruptions;
- a presence of circuit breaker to disconnect customers from the grid in cases of excess the limit power consumed or a contract failure;
- a possibility for additional slots in the meter for future applications. (Schenk, 2005)

Construction of meters used in the AMR system is based on the following international standards (Table 2.1)

Table 2.1 International standards for meter construction (Tele Tec. Co, Technical description and operation manual, 2009)

Name of standard	Description
IEC 61010-1:2001-02	Safety requirements for electrical equipment for measurement, control and laboratory use. Part 1. General requirements
IEC 62052-11:2003	Electricity metering equipment (AC) - General requirements, tests and test conditions - Part 11: Metering equipment Maintenance Result Date: 2012-02-01
IEC 62053-22:2003	Electricity metering equipment (a.c.) - Particular Requirements - Part 22: Static meters for active energy (classes 0,2 S and 0,5 S)
IEC 62053-23:2003	Electricity metering equipment (a.c.) - Particular requirements - Part 23: Static meters for reactive energy (classes 2 and 3)

2.2.2.3 Recommendations for the data concentrators in the transformer stations

The data concentrator polls the electric meters according to a principle of “master-slave” reserving a specific frequency band for this purpose in case of the PLC link usage. The data concentrator has to provide the connection between a short circuit and ground fault detectors and the control switches based on a digital level. It has to process input analog values of current and voltage measurements. Measurements of a power quality have to be done according to European standard EN50160 (CENELEC): Voltage characteristics of electricity supplied by public distribution systems. The data concentrator has to detect the power theft with following for this disconnection of a customer from the grid. (Schenk, 2005)

2.3 Types of measurements in AMR

On a daily basis, a meter sends to the controller information about the energy (kWh) consumed by the customer and time, during which the energy was used. The dispatcher can also transfer a signal to the meter to submit data measurements at certain time-intervals (an hour, 30 minutes or 15 minutes), which allows getting detailed load profile of each end-user.

As a result of continuous metering of the instantaneous values of voltage and current, a meter computes a product of them to give instantaneous real power. Consumed energy can be calculated by integrating real power with respect to time, as it is illustrated in Equation (2.1):

$$E = P \cdot t\,, \tag{2.1}$$

where

P = real power, W;

E = consumed energy, Wh;

t = time, during which the energy was consumed, h.

It is also possible to calculate apparent power as a product of rms voltage and rms current (Eq. 2.2) (Mohan, 2003):

$$S = U_{\mathrm{rms}} \cdot I_{\mathrm{rms}}\,, \tag{2.2}$$

where

S = apparent power, VA;

U_{rms} = root-mean square voltage, V;

I_{rms} = root-mean square current, A.

Then, the electric utility can define a power factor of the load as a ratio of consumed (real) power to apparent power (Eq. 2.3) (Mohan, 2003):

$$PF = \frac{P}{S}, \quad 0 \le PF \le 1 \tag{2.3}$$

where

PF = power factor;

P = real power, W;

S = apparent power, VA.

Apparent power can also be calculated as it is shown in Equation (2.4) (Mohan, 2003):

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

where

S = apparent power, VA;

P = active power, W;

Q = reactive power, VAr.

Furthermore, a sine meter makes it possible to measure reactive energy (kVArh), and it is a good method to determine the efficiency of a large customer's electricity usage. A contract between the end-user and the supplier may specify penalties if the power factor falls below a specified limit. Meters which can record a maximum demand may be similarly used in an attempt to discourage peak surges; this is carried out because of insufficient capacity of the network. (Patrick, 1998)

As was mentioned previously, a meter in the AMR system can define the differential current between a value of current in the zero conductor and a value of current in the phase conductors, thereby helping to detect electricity theft and possible defects in the apparatus.

The AMR system provides automatic detection of outages and online restoration verification. Thanks to real-time access to the information about all points of the distribution system, outages can be located more quickly. The electric utilities no longer have to wait customer calls about outages. Customers report only thirty percent of the outages during the first hour of outage, whereas the AMR provides outage data on a close to real-time basis. (Sridharan, 2001)

3 Benefits and difficulties of the AMR technology

3.1 Benefits for different actors from the AMR usage

The following actors can be regarded in the energy market operation: energy users, network owner, metering company, government, generators, supplier and retailers. Many countries do not make a distinction between network owner and metering company. The AMR usage can provide benefits for all market players.

According to the government policy expectations, the main benefit for electricity customers from the AMR usage consists of a possibility to regulate the energy consumption by customer itself, depending on the off/on-peak time of the whole grid energy consumption. The AMR technology enables energy users to pay the actual price for the electricity at the time that they actually use it. As the result, a customer who usually uses less energy in peak times and/or can increase the energy usage in off-peak times will pay less for energy. Conversely, a consumer who consumes the energy during on-peak time will pay more. In this case the intelligent behavior of a customers group will lead to smoothing the electricity demand curve (Fig. 3.1). Thanks to the automatic data reading, customers no longer need to stay at home waiting for a periodical visit of personal responsible. The modern AMR technology offers a customer the option to manage their accounts online through a special website. (Ontario Energy Board, 2004)

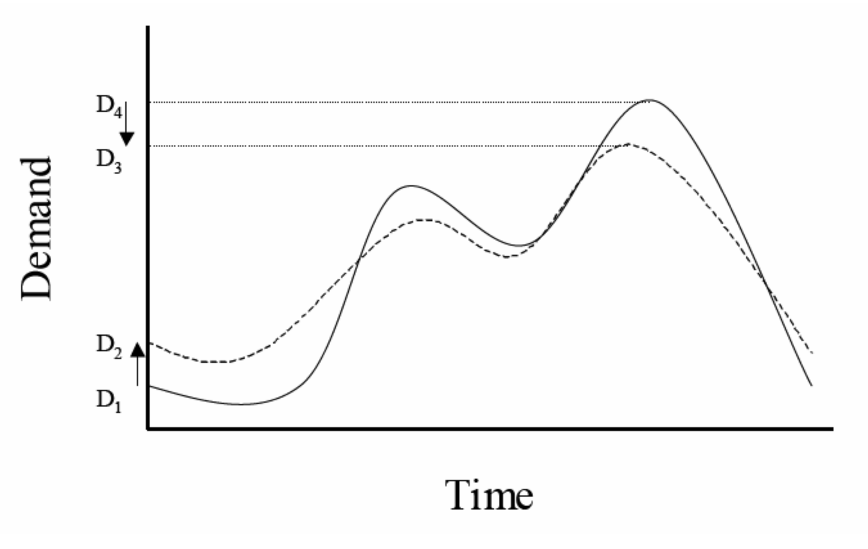

Fig. 3.1 Demand curve changes with shifted load (Ontario Energy Board, 2004)

Conscious behavior of the customers during the on/off-peak time in a large scale can lead to a strengthening of the whole country energy system:

- reliability of the energy delivery will improve;
- required capacity will be lower;
- losses of the whole system will be lower;
- management of the energy delivery will be easier;
- periodical increase of the payment for the electric power will be lower.

It should be waited that the price for the energy recourse will increase for the off-peak time (from $\$_1$ to $\$_2$) and it will decrease for the on-peak period (from $\$_4$ to $\$_3$). But the nature of a price-supply curve means that the price increases in off-peak periods are likely to be less than the price decreases in peak periods (Fig. 3.2).

When the new demand peak (in case of the AMR usage) is lower, some high-margin peak generators may end up being dispatched during few hours. And when the off-peak demand is higher, some base and intermediate plants will operate more.

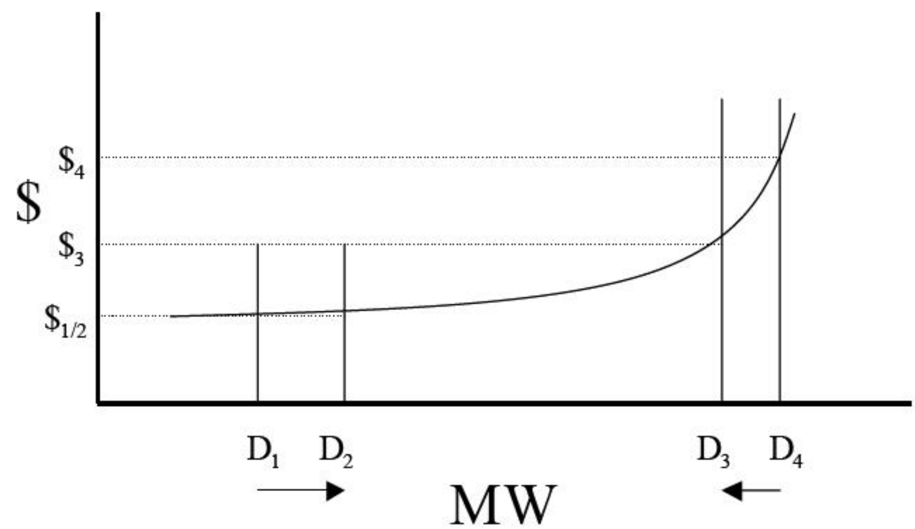

Fig. 3.2 Electricity price-supply curve for shifted load (Ontario Energy Board, 2004)

Getting a comprehensive knowledge about a customer's and a customers group's load profile, retailers and suppliers can mitigate their risk, improving the accuracy of the bids offered in the spot market. In this way, they avoid buying energy at peak periods and can control their costs. Using the AMR as a gateway into the home of the customer, suppliers can offer to end users additional services like Customer Information Service (CIS), Automatic Meter Management (AMM), Time of Use (TOU) tariff, value added service. (MacDonald, 2007)

The AMR technology allows to the distribution company to achieve a much more actual and accurate overview of the energy consumption in their operation region. Therefore, the distribution company can identify suspicious areas where energy consumption is higher than expected. By the way, the AMR system provides a distributor with a tool to detect electricity theft and tamper. The AMR usage leads to decrease the meter reading cost also, as periodical visit of a controller is no longer necessary. An opportunity to use results of the real-time measurements facilitates a process of bills estimation. A customer's ability to observe and manage its energy consumption reduces a possibility of disputes between the distribution company and its end user.

3.2 The AMR usage in the distribution network management

Traditionally the AMR and the Distribution Management System (DMS) have been operated separately without any integration with each other (Fig.3.3). Original role of the AMR technology was a provision of the energy consumption data to the utility for billing and balance settlement purposes. In turn the central idea of the DMS is a monitoring the distribution feeder loads and a controlling the distribution portion of the substation. The DMS usually contains the topology analysis and load flow programs that allow rapid identification of problems and restoration of service. (Ackerman, 1992)

Earlier the automatic monitoring and control center measures as functions of the DMS have been utilized only for operation of 20 kV medium voltage networks.

Whereas on-line information in the low voltage network (LV-network) has been available only from primary substations and from some secondary substations along medium voltage feeders. (Trygg, 2009)

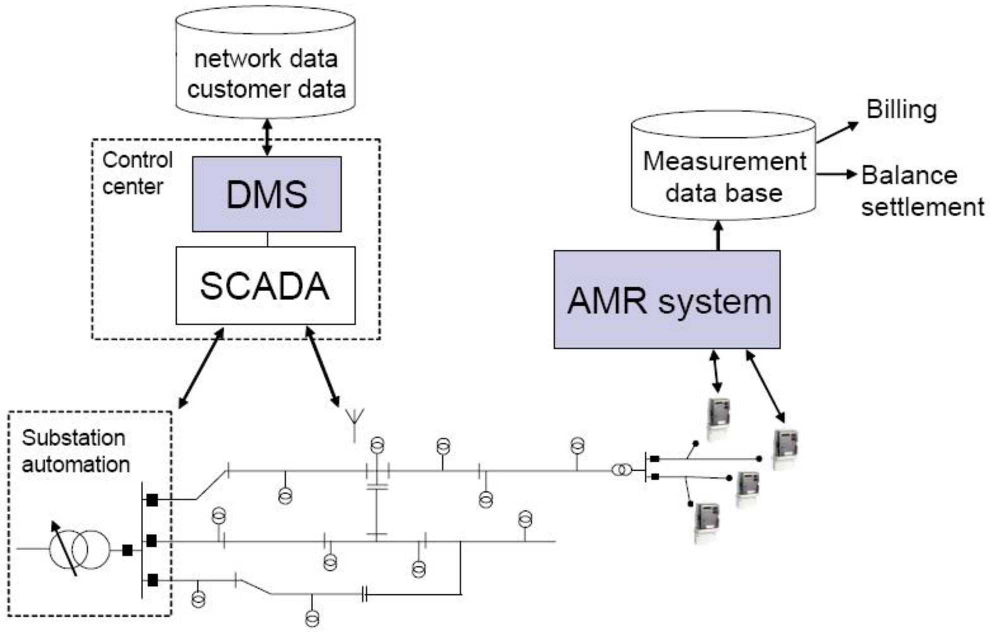

Fig. 3.3 Traditional description of the distribution network management (Trygg, 2009)

The AMR system makes it possible to extend on-line monitoring also to the low voltage network. This allows receipting the timely information about exceptional events, e.g. network faults and voltage violations. Meters can also provide a protection in these situations by means of a disconnecting relay. The AMR integration into the distribution network operation can be seen as an extension of SCADA and DMS action to the low voltage level. The integration of AMR, DMS and Quality Monitoring System (QMS) in network operation, asset management, customer service and other functions is presented in Figure 3.4. (Trygg, 2009)

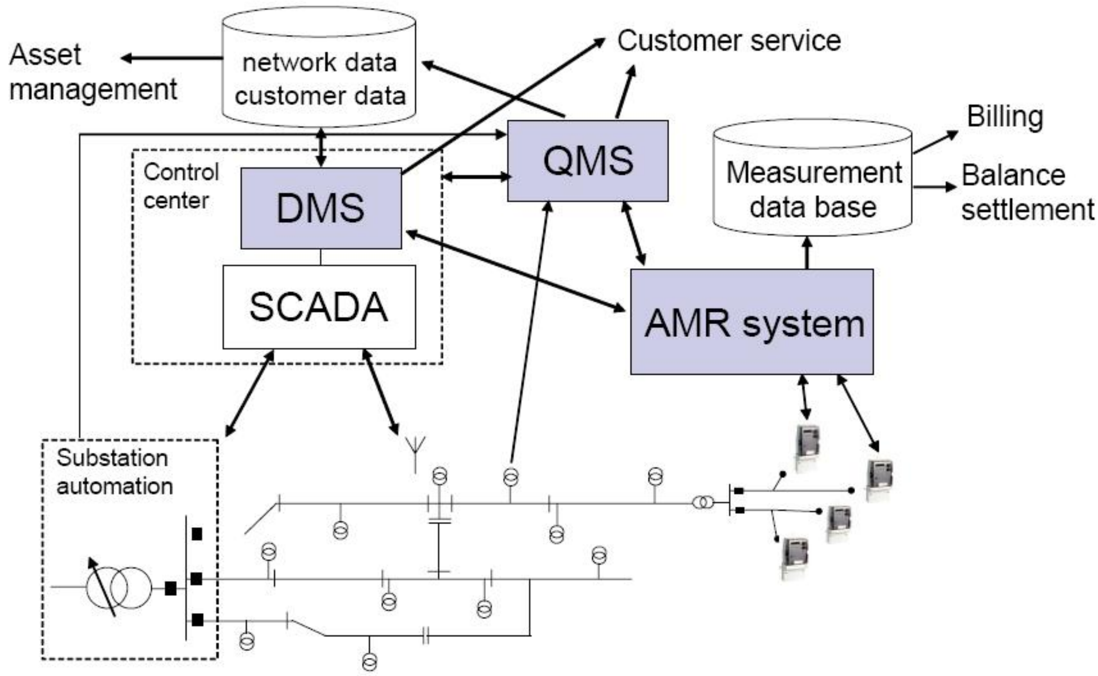

Fig. 3.4 Integrated information systems for comprehensive distribution network management (Trygg, 2009)

Low voltage network management makes it possible to indicate automatically if a fuse in the low voltage network has burnt or a conductor is broken, to locate the fault, to determine a fault type, to provide accurate interruption data, to monitor real-time voltages at customer premises, and provide power quality information for customer service. This new information source allows doing more accurate medium and long term network planning. (Jarventausta, 2007)

3.3 The AMR usage in power quantity monitoring

System with absence of the remote measuring ability can not provide comprehensive and continuous data transfer from the entire distribution network. In such cases, voltage quality is usually monitored temporarily at customer sites based on data reclamations. The present integration of AMR into the low voltage distribution network proposes continues voltage and power quality monitoring, including close to real time measuring of current and voltage variations, active power, apparent power, voltage dips and swells, total distortion of the supply voltage, some harmonic voltages, DC-voltage component, frequency of the supply voltage, voltage unbalance between the three phases. (Jarventausta, 2007)

The development of systematic power quality management improves customer service by providing more accurate power consumed information and by clarifying customer's requests and complaints. In the distribution network design and operation the power quality monitoring allows making more accurate investment plans and management of voltage drops and fluctuations, harmonics and other disturbances. Besides, it provides outage and interruption statistics. (Jarventausta, 2007)

All the measured data about the low voltage network is stored in the power quality database and can be integrated to the network database and different planning and operation systems to increase an amount of available information.

3.4 The AMR application for the low voltage network fault indication

Traditionally, a fault protection in the LV-network has been done by blown fuses, and no information about that was received by the control center. In these cases, fault occurrences in the LV-network have been detected by customers' calls. (Trygg, 2009)

An advanced AMR meter operates as an intelligent monitoring device and provides a vital information about low voltage network faults and voltage levels, using the communication infrastructure. Meter includes algorithm to indicate a fault location and a type of the fault. The AMR meters with the in-built switching device are able to isolate automatically the customer from the network in cases, for instance, when neutral conductor is broken. Figure 3.5 illustrates a part of DMS screen in the case of broken neutral conductor in Finland. Yellow line shows the result of localization the broken line-section. (Trygg, 2009)

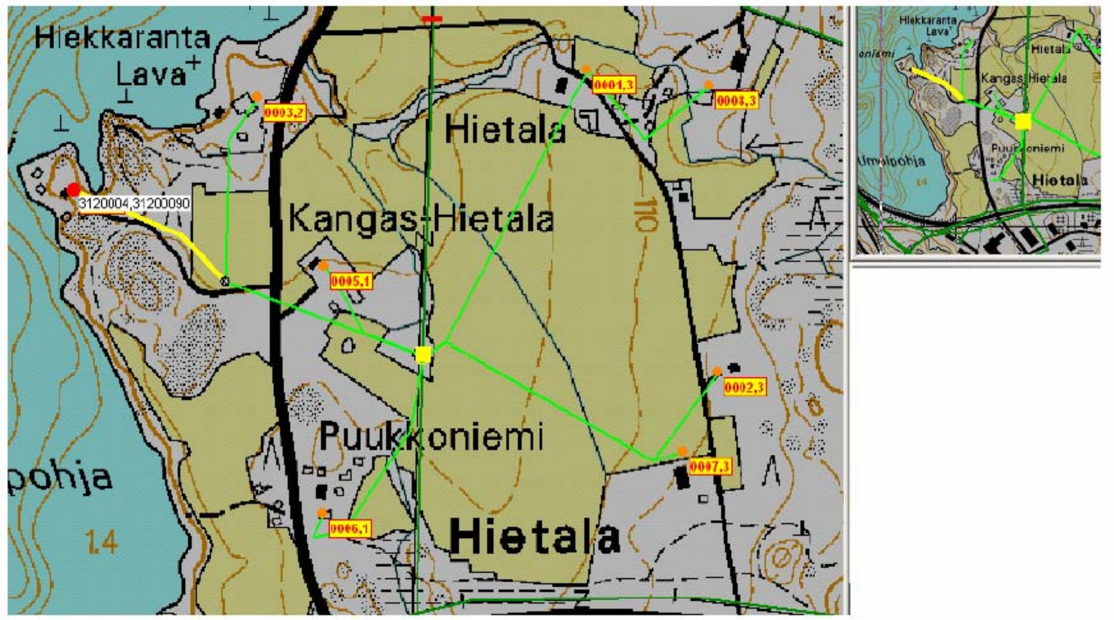

Fig. 3.5 The network localization in case of the broken neutral conductor (Trygg, 2009)

Normally, the distribution network has a radial construction, where a substation is connected to one or more feeders. Primary feeders are protected against faults by means of switches and relays, whereas in the lowest levels fuses are used. (Moreno-Mufnoz, 2007)

3.5 The AMR application for the low voltage network outage management

An Outage Management System (OMS) is one of the main components of the Distribution Management System (DMS), which identifies the location of an outage and providing a technique for quick outage restoration. The OMS provides accurate information about outages, occurred in the medium voltage network. While the DMS has been operated separately from the AMR system, troublous customers’ calls have been used as the primary source of outages in the low voltage distribution network. However customer calls are not completely reliable information source, as they lead to receipt an inaccuracy in the outage duration estimation. (Moreno-Mufnoz, 2007)

The AMR integration with the DMS/SCADA allows receipting actual timely data about outages that helps to save cost of the utility. In some countries, for example, in Finland, the customers are entitled to compensations in electricity interruptions longer than 12 hours. (Jarventausta, 2007)

The algorithm that identifies the outage location is based on the concept of recursion. As a fault in a single component of the radial system will affect all the "downstream" nodes, the first step of outage research consists of crossing upwards to the bottom of the network tree from each nod located in a list "affected nodes", that will contain the nodes affected by the outage. The research will stop when a node, whose further is not affected, is found. In this case the previous nod will be the possible cause of the outage and it will be introduced in a new list "outage cause" in the program. (Moreno-Mufnoz, 2007)

One of the main requirements of the OMS contains the utility has to know the state of each nod in the network and the distribution system topology has to be updated in every cases of the network connectivity and change. Depending on the requirement of the utility, meters can be polled automatically in the intervals of 15 minutes, 30 minutes and 60 minutes or ones per day, no more customers' calls are needed. (Moreno-Mufnoz, 2007)

The following example describes the outage management in an asymmetrical network tree as more representative case in an actual distribution system (Fig. 3.6).

There are faults in the nods 645 and 671. As a result of automatic meter polling, the SCADA system determines the nodes affected by outage:
“affected nodes”: 646, 645, 611, 652, 684, 680, 671, 692, 675.

Based on the outage algorithm research, the SCADA determines the most possible causes of the outage:
"outage cause": 645, 671.

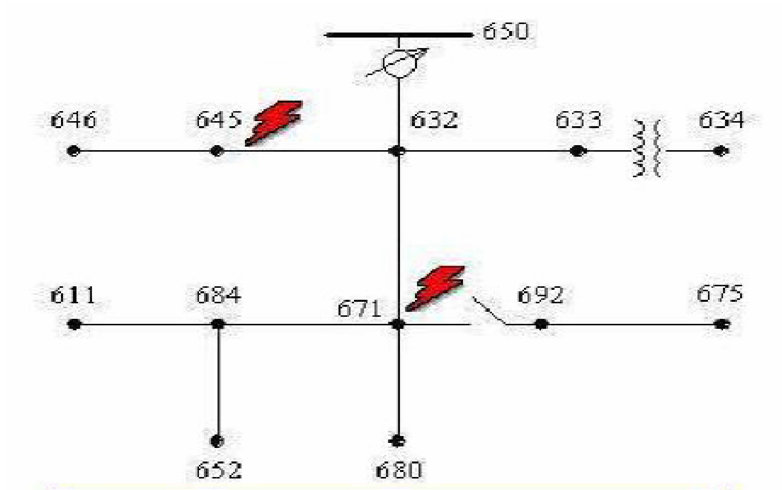

Fig. 3.6 A part of the radial asymmetrical distribution network (Moreno-Mufnoz, 2007)

After the outage locations are found and crew has successfully eliminated all the outages, it is necessary to confirm that power supply is restored for all the customers. Thanks to the meter polling system and the information of the SCADA the utility can know if the restoration has been successful. (Moreno-Mufnoz, 2007)

Indexes of the quality of supply are widely used in the distribution network regulation. They are System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), System Average Interruption Duration Index (SAIDI) and Momentary Average Interruption Frequency Index (MAIFI). Improving the reliability of the interruption reporting, the AMR system also improves the quality and plausibility of the interruption indices. (Jarventausta, 2007)

3.6 The AMR application for the load modeling

The customer load modeling plays an important role for the distribution network state estimation. However, because of a limited ability for real-time measurements in the distribution network, a state estimator could not receive enough real-time measurements, so it was necessary to use pseudo-measurements in the load modeling. The AMR system provides the actual customer load profiles, which can be regarded as the pseudo-measurements in the further load models processing.

Traditionally, load research has been done with monthly billing information and load curves specified for different customer groups. Nowadays, the AMR system enables to provide real-time information, such as:

- *demand information*; it contains the information about energy consumed for the specific time interval;
- *time period* that reflects time, when energy was consumed;
- *customer information* contains the customer group identification and billing information for this customer. (Yu, 2006)

The demand information can be performed for the group of customers, so the general load curve is generated. As the shape of load curves depends of customer type, type of day and season, so the load curve must be generated for at least three customer classes (industrial, commercial, and residential), two types of days (weekday and weekend/holiday), three seasons (spring/fall, summer, and winter). Thus, total 18 curves have to be generated. (Wang, 2001)

Figure 3.7 demonstrates the demand patterns for the weekday in July, 2003, which were obtained in the frameworks of the study of the AMR data influence on the demand patterns analyzing in Korea Electric Power Corporation (KEPCO). The abscissa axis indicates one-hour time intervals and the ordinate axis indicates demand magnitude in the normalized values. (Yu, 2006)

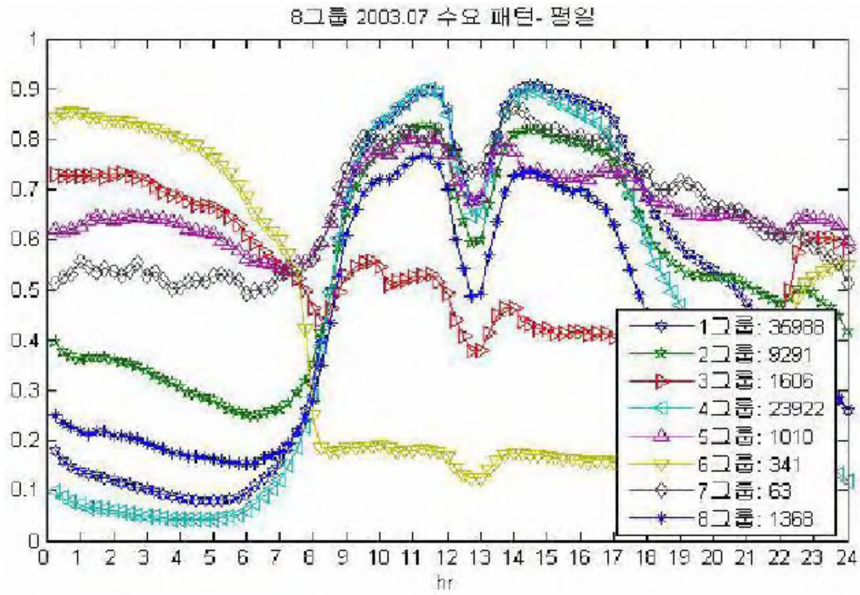

Fig. 3.7 Demand patterns for the weekday in July, 2003, Korea (Yu, 2006)

As it can be seen from the fig. 3.7, the customer groups 1, 2, 4, 8 show a high demand at daytime, the customer groups 3, 5, 7 show a flat demand during all day and the customer group 6 shows a high demand at nighttime. Demand dip during time period from 12:00 till 14:00 indicates on the suspension of production in the dinner time. The individual demand curve of the customer group 1 is depicted in Figure 3.8.

Fig. 3.8 Demand patterns of the customer group 1 for the weekday in July, 2003, Korea (Yu, 2006)

Within the one customer group, for example group 1 (fig. 3.8), customers with different demand contract can be allocated (fig. 3.9). In this example, 70% of customers in the group 1 have demand contracts between 100 kW and 500 kW, they are typical industrial customers.

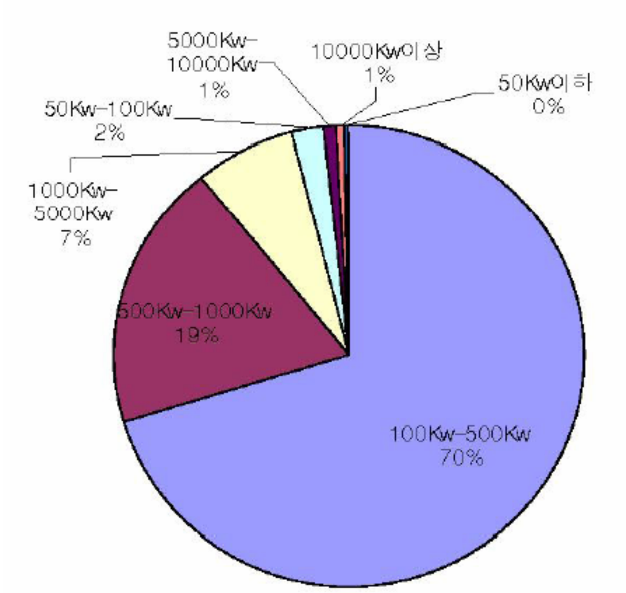

Fig. 3.9 Contractual demand in the group 1 (Yu, 2006)

The data, provided by the AMR, is accumulated in the databases and then it is compared with each other and with additional information to do a deep analysis. There are several databases (DB) for this purpose; they are load profile DB, customer information system (CIS) DB, weather information DB, statistical information DB. Load profile DB contains information about the demand values for certain time interval, quantity of customers, active and reactive power, daily maximum and minimum demand. Customer information system DB has the contract information, billing data, area codes and other business information. Weather information DB has the metrological data from several weather stations. Statistical information DB contains monthly and weekly regional statistics. These databases can be used for tariff design, load forecasting and load management. (Yu, 2006)

3.7 The AMR system and detection of illegal electricity usage

The illegal electricity usage stays a big problem for many countries. It means that customers make an illegal connection to the electricity grid, and this connection does not pass through the electricity meter, so people get the energy without any payment. For example, as Energy and Natural Resources Minister of Turkey said that about 19 % of the energy consumption is illegal in this country. (Pasdar, 2007)

It is cleared that electricity theft is affected on the supply budget cutback. In some cases, illegal energy usage leads to loss up to several billions kilowatt per hour per year. But from the other hand, energy theft causes a problem of technical character. Every electrical grid is designed for specific volume of customers, so it provides specific kilowatt hour energy and electricity theft can cause the problem for the national electricity grid planning and operation. (Pasdar, 2007)

Further it is represented the method for detection of illegal electricity usage, using the AMR system, this method was offered by I. H. Cavdar, member of IEEE. The proposed control system for detection of electricity theft is shown in Figure 3.10. It is intend for PLC signaling over 220 V AC power line. In the Figure 3.10, a host PLC unit and PLC modems named as PLC A1, PLC A2, PLC AN are used for the AMR. They provide communication between each other and send the energy consumption data in kWh value to the host PLC unit. In order to detect energy theft, PLC modems named PLC B1, PLC B2, PLC BN with energy meter chips for every customer are added to the exist AMR system. These additional devices have to be connected between a subscriber and the main distribution line. While this point of connection is located in the area or at underground, it is not available for a human interference. (Cavdar, 2009)

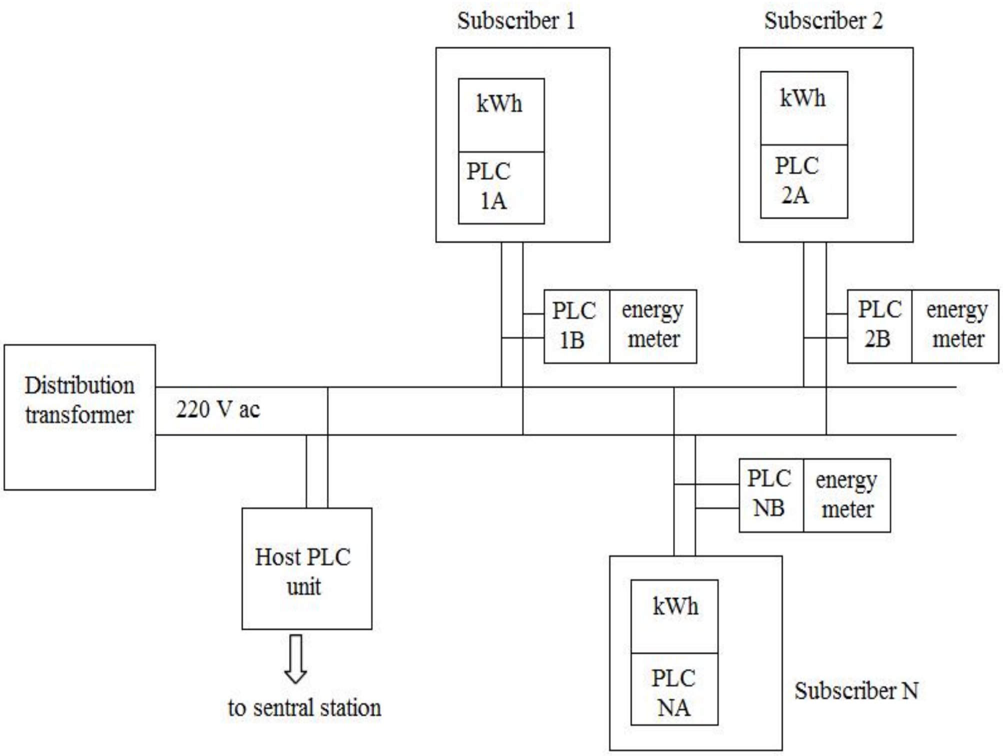

Fig. 3.10 Cavdar's method for illegal usage of electricity (Cavdar, 2009)

This system has two energy consumed data records in the host PLC unit, one comes from the AMR-PLC and the other one comes from the PLC modems in the point of connection. Then these data are compared, if there is any difference between them, an alarm signal with the customer address information are sent to the host PLC unit. Modern meters have an opportunity to switch off or switch on the customer after a switching command comes from the host PLC. (Cavdar, 2009)

Another method to detect illegal electricity usage is based on comparing the impedances of lines in time of grid installation and after coming a signal of possible energy theft. This method consists of the following steps:

1) in time of grid installation all loads are disconnected from the grid and test signals is sent to the grid, the signal is a value of current, that follows in the grid, when the grid has specific impedance in its end;
2) all nodes voltages are recorded;

3) based on Ohm's law, impedances of each line that connect to energy meter are calculated and this data with information about node address is saved in the database;
4) in normal situation, value of power sent from each meter is compared with total power that is measured by the main energy meter, if there is difference between two values, energy theft is detected;
5) after detection of illegal energy usage, all load are disconnected from the grid by a command;
6) test signals is sent to the grid again, the value of current is determined;
7) all nodes voltages are recorded and values of impedances are determined;
8) the place of illegal node is found. (Pasdar, 2007)

Modern three-phase smart meters are able to define the differential current between a value of current in the zero conductor and a value of current in the phase conductors. Presence of this current testifies casual or intentional, full or partial grounding of the phase conductor; thereby it helps to detect electricity theft and possible defects in the apparatus. Limit value of differential current I_{lim} lays in the range of 0,15 – 2,5 A, whereas the system will activate, when the current will exceed the value $\frac{I}{I_{\lim}} + 0,04 I_S$ and will be kept over 0,5 seconds. I_S is a total current of three phases. When the value of differential current exceeds a set value, controller can switch off the customer from the grid by means of relay or meter can start to count duration of the differential current presence. (Electrical company "Dialin", 2009)

3.8 The AMR system application in the customer service

With a help of the AMR system the electricity distribution company can offer different tariff services to determine energy consumption for its customers. Customers are entitled to choose any tariff suitable for them from the available ones, herewith setting a tariff type is carried out remotely. Among the flat-rate tariffs it is possible to emphasize prepayment tariff, credit tariff and multi-tariff. Some meters are developed to provide value-added service directly to the end-users. The big hopes of the distribution company are connected with development of remote tariff management.

Electricity suppliers purchase their electricity mostly via the Pool, where the energy cost varies with the hourly period. These prices reflect a total demand on electricity and the bids made by the generating company. Using two-way communication, customer can receive this information and regulate its energy consumption. The customers, who use their appliances in low demand period, will pay for electricity less. And vice versa, the electricity cost in high demand period is higher. (Patrick, 1998)

If customer chooses the operation in prepayment tariff, he or she has to purchase some quantity of electrical energy, expressed in the equivalent units, in advance; usage of magnet card is available. The system informs meter about prepayment coming or customer inserts a magnet card into an apparatus and meter increases the customer's energy balance on a corresponding quantity. In a process of the energy consumption the customer's balance decreases. The extreme allowed value of negative balance (limit) is set by utility and is discussed during a contract formation. A customer receives detailed information from the meter, such as the customer's identifier, current value of the energy consumed, balance, limit; they are constantly available for a customer. When a customer exhausts its limit, meter automatically disconnects it from the grid before new payment will come. (Tele Tec. Co, General description, 2009)

An operation in credit mode is a specific case of the prepayment tariff, when customer has unlimited balance. Meters carry out a measuring the energy consumed and periodically transmit this information to the center. Based on this data, the utility sends to customer a bill for payment. In cases of delayed payment, the customer can be disconnected from the grid. (Tele Tec. Co, General description, 2009)

In case of a multi-tariff operation one time period (day, year) is divided on several ones with different cost of the energy consumed. Usually the system uses 12 tariff plans (4*3 variants) for four types of season and three types of day during a week (workday, weekend and holidays). Some kinds of multi-tariff change its operation type, if fixed maximum of the power consumption is exceeded. (Tele Tec. Co, General description, 2009)

Using meters as a gateway to the customer premises, electricity supply can be remotely disconnected on a date of tenancy ending, and be reconnected when new occupant moved in.

3.9 Difficulties with the AMR integration

One of the biggest obstacles in the process of the AMR integration is a customer's misunderstanding in the questions: how does the AMR work and how a customer can get benefits from the AMR operation. The same, as the electric utility has no clear knowledge on the issue what are the attitudes of the electricity consumers towards the possibilities of new metering technologies offered for them.

The potential of shifting peak load is more significant in households with storage heaters. The resident customers in this case have only 5 - 6 % of a power that can be run by them during the off-peak time. These appliances are dishwashers, washing machines and driers. But from the other hand, a new issue of a noise at the night time appears, when the customers leave these devices till the morning. Furthermore in practice, customers' savings from the consumption shifting are quite modest and customers would need to be given a financial incentive through, for instance, time-of-use (TOU) tariffs or some kinds of automated load management combined with a single rate tariff. (MacDonald, 2007)

But a suggestion of the TOU tariff faces with the customers' misunderstanding also. The fact is that the vast majority of the consumers do not know that electricity price varies hourly. Bob Lieberman, commissioner of the Commerce

Commission of the State of Illinois, before the Subcommittee of Energy and Pure Air (Committee of Energy and Commerce of the House of Representatives of the United States), said in May 3, 2007: *"…95% of all customers – residential, small commercial, municipal – have absolutely no idea that the price of electricity varies by the hour and that the average of the hourly prices is likely to be significantly lower than the hedged retail price they have traditionally seen. And until they know that, they won't realize that there is something in it directly for them; that investing in smart meters will give them access to lower cost electricity."* (Power Encounter, 2009)

Some kinds of the TOU tariff implementation experiences with a voluntary participation of end users in the USA are described further. As a result of the advertising campaign for energy savings *"Flex Your Power"* carried out in the summer 2001 and the California energy crisis, also happening in those dates, it was detected a voluntary reduction of electricity consumption accompanying with switching off lights, reducing air conditioners use or rising thermostats, installing more efficient appliances, using electrical appliances less frequently. This data prove, that many residential consumers are more capable and have greater disposition to change their electricity consumption. (Power Encounter, 2009)

The other experience has taken place with the Puget Sound Energy (PSE), which attracted around 300.000 clients in the program of time-of-use prices between 2001 and 2002. During the West Coast energy crisis occurring in that time, the cost of a power during on-peak periods was much as 145 $ per megawatt-hour higher than the cost of an off-peak power. Many customers reduced their consumption to pay less. But after 2002 the TOU program of the PSE was modified to reflect a calmer wholesale electricity market. As a result, price difference between on-peak and off-peak costs became less than $5 per megawatt-hour, so customers lost any incentives to control their energy consumption. (Power Encounter, 2009)

The metering company faces also the challenge of replacing old meters by smart meters, because this process depends on clients being at home. The example of quite rapid deployment of smart meters can be the work of Eltel company for all Vattenfall customers in Finland, counted 330 000 end user in the May of 2005. This project was carried out during two years with replacing up to 15 000 new meters per month. (Eltel.Co, 2009)

There are two important issues more, hampering the general introduction of the AMR technology. As a result of quite big quantity of actors, who are interested in the AMR deployment, one party can receive benefits from the AMR abilities, when costs for these abilities go from another party. Secondly, there is still much uncertainly about a numerical estimation of the benefits, as practical experiences are lacking. Therefore, an investment in this sphere means taking risks.

At present time, the way to overcome these obstacles is the government regulation by means of setting national and international standards with adopting appropriate national and international rules.

4 The AMR application in LV-network state-estimation

Power quality monitoring plays one of the main roles in the distribution company planning and operation. Actual data about customer electricity consumed and voltage quality are necessary for power supply forecasting and for estimation the electricity procurement by the distribution company, taking into account power losses.

From the other side, low electric power quality leads to some problems occurrence, such as malfunctions, instabilities, reducing the life time of equipment and others. Power disturbances can interrupt sensitive electric devices operation and cause additional costs in the future. For instance, a very short-time interruption or 30% voltage dip of the supply power can reprogram controllers for an entire assembly line. (Chen, 2008)

Voltage quality monitoring is researched as a part of power quality monitoring. The most important parameters are the magnitude of voltage at maximum load at the received side of the line and the voltage drop of the line, that is, the difference of the voltage magnitudes between sending and receiving sides of the line. Low voltage quality is normally detected in cases of voltage impulses, electricity supply interruptions, voltage sags and swells, voltage fluctuations and distortions. Such information as voltage phase, amplitude, and frequency are very important especially for electricity generation systems, where power electronic converters are widely used to adjust an operation of distributed generation units. The correct information about voltage of the grid is necessary for appropriate operation and control of power electronic converters interfacing with the generation units. Nowadays, with the increase of renewable energy generation units, such as solar and wind energy conversion systems, the accurate information about voltage becomes crucial for power system security. (Chen, 2008)

4.1 Load modeling based on the annual energy consumed data

If real-time measurements of power and current in the end-user's side are not available in the distribution network, a value of the customer's annual energy is taken as a starting point for the customer load modeling. The amount of annual energy of each consumer is taken from the electricity billing analysis. Then the value of customer annual energy has to be converted into the peak power (Velander's formula) or into the power at a specified instant (Load models). The methods of conversions are typically based on empiric information about the customer load behavior. (Partanen, 2007)

Velander's formula (Eq. 4.1) was a conventional method to estimate peak loads in distribution networks since it was replaced by the method based on load models. However, the measurements have shown that Velander's formula give the accurate value of the peak power only for a large electricity consumer groups. (Partanen, 2007)

$$P_{\max} = k_1 E + k_2 \sqrt{E}\,, \tag{4.1}$$

where

$P_{\max}$ = peak power, kW;

E = annual energy of the customer, MWh;

k_1, k_2 = Velander coefficients.

Velander coefficients are determined empirically, they are represented in Table 4.1 in values of kW for the peak power and MWh for the annual energy.

Table 4.1 Velander coefficients ($P_{\max}$ [kW], E [MWh]) (Partanen, 2007)

Electricity consumer group	k_1	k_2
Household	0.29	2.50
Electric heating	0.22	0.90
Service	0.25	1.90

The load modeling method gives more accurate results then Velander's formula. Using the load modeling, it is possible to determine the individual consumer's hourly power demand. The idea of modeling is to create load models that describe the electricity consumer's consumption, which varies both temporally and quantitatively. For this purpose, all customers are divided on several groups, in which the electricity consumption can be assumed to be equal with a sufficient accuracy. Measurements of the energy consumed amount and time, during that it was consumed, have to be done for each customer group. On the base of the gathered measurement data, mean powers for each two-week period of the year and two-week indexes for these periods are calculated for each customer group (Fig. 4.2). In the limits of each two-week period daily hour models and hour indexes are calculated (Fig. 4.3). Days of the week are usually divided on a workday, eve (weekend) and holyday. It is also possible to account the electricity consumption dependence from temperature by means of Equation 4.2. (Partanen, 2007)

$$q(t) = q_0(t) + \beta \cdot \Delta T(t), \tag{4.2}$$

where

$q(t)$ = measured electricity consumption at time *t;*

$q_0(t)$ = electricity consumption in normal outdoor temperature at time *t;*

$\Delta T(t)$ = difference of measured and normal outdoor temperature at time *t;*

β = coefficient indicating the temperature dependence of the electricity consumption.

The absolute value of the mean power per hour at time i can be calculated using two-week (external) and hour (internal) indexes according to Equation 4.3 (Partanen, 2007):

$$P_{\mathrm{ri}} = \frac{E_{\mathrm{r}}}{8760} \cdot \frac{Q_{\mathrm{ri}}}{100} \cdot \frac{q_{\mathrm{ri}}}{100}, \tag{4.3}$$

where

P_{ri} = mean power per hour for a consumer group r at time i;

E_r = annual energy consumed of the consumer group r;

Q_{ri} = two-week index (external index) of the consumer group r that corresponds to the time i;

q_{ri} = hour index (internal index) of the consumer group r that corresponds to the time i.

4.2 Example of LV-network state-estimation based on the load models method

In order to analyze power and voltage monitoring based on the load models method, i. e. when the real-time measurements are absent, a part of the example distribution network 10/0.4 kV was regarded (Fig. 4.1). The analyzed distribution network has two customers, which both belong to dwellers of the detached houses.

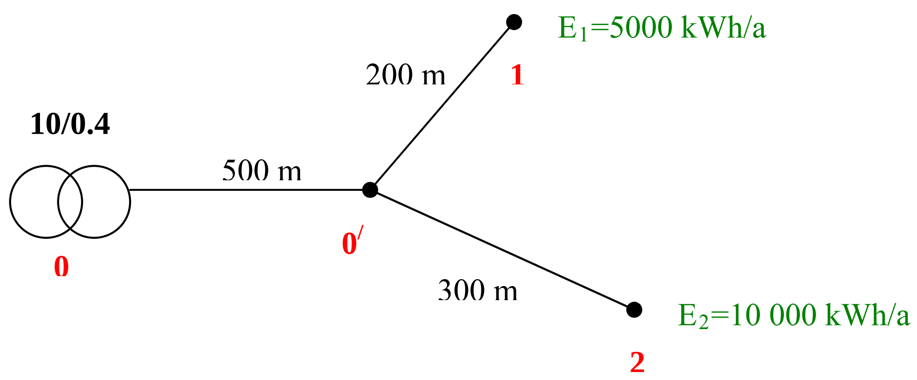

Fig. 4.1 A part of the distribution network 10/0.4 kV with two detached houses customers (situation without the AMR usage)

As a result of absent actual values of annual energy consumed for that kind of customers (E_1, E_2), length of the lines ($l_{00'}, l_{0'1}, l_{0'2}$) and $\cos\varphi$ of loads, these parameters were assumed for the further calculations.

<u>Assumptions:</u>

$$\begin{matrix} l_{00'} = 0.5\,km \\ l_{0'1} = 0.2\,km \\ l_{0'2} = 0.3\,km \end{matrix}, \qquad \begin{matrix} E_1 = 5000\,kWh/a \\ E_2 = 10\,000\,kWh/a \end{matrix}, \qquad \begin{matrix} \cos\varphi = 0.9 \\ U_0 = 0{,}4\,kV \end{matrix}$$

The value of $\cos\varphi$ was assumed close to 1, because the load of detached house can be regarded as almost resistive load.

The values of reactance and resistance of the overhead line 0.4 kV are presented in Table 4.2. (Pasdar, 2007)

Table 4.2 Low voltage power line characteristic (Pasdar, 2007)

Reactance Ω / km, (50 Hz)	Resistance Ω / km, (+20 ^{o}C)	Al/Fe, mm^2	Voltage, kV	Type of line
0.3	1.06	25.0	0.4	Overhead

Calculations of the mean powers per hour and the voltage level in the customers' side were done for the first week of January on Saturday evening between 17h and 18h. Therefore, the value of two-week index for both customers was determined to be equal Q = 123 for the time instant in question (Fig. 4.2).

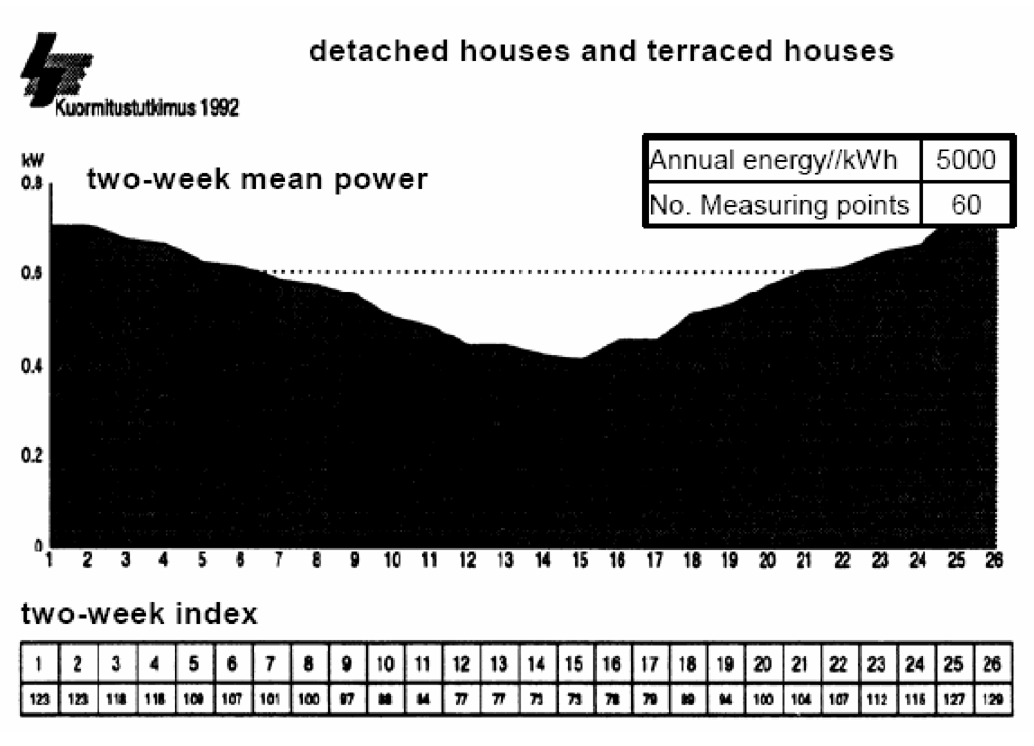

Fig. 4.2 Two-week mean powers and indexes for detached houses and terraced houses (Partanen, 2007)

The value of hour index was determined for both customers for the time instant in question, according to Fig. 4.3. The value of internal index is equal to q = 250 in the first week of January on Saturday evening between 17h and 18h.

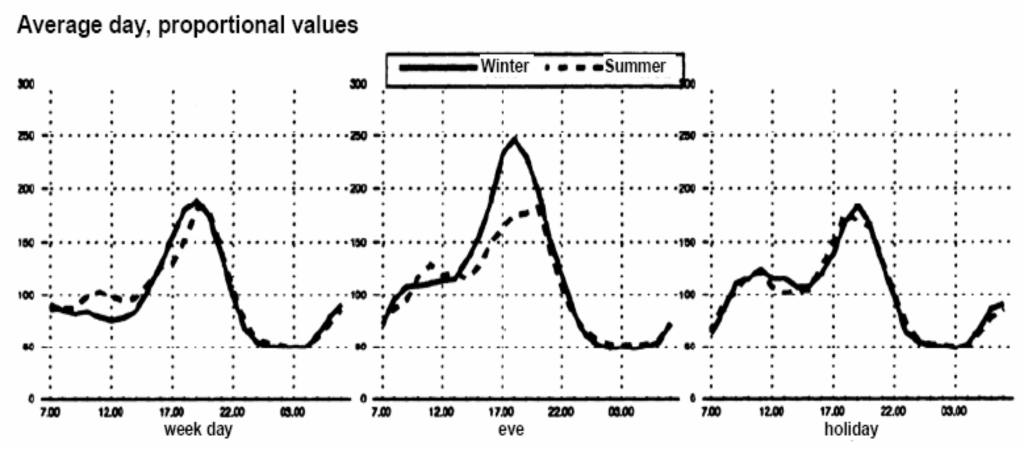

Fig. 4.3: Hour indexes for detached houses and terraced houses (Partanen, 2007)

Values of the mean power per hour for each customer (P_1, P_2) can be calculated according to Equation 4.3.

$$P_1 = \frac{E_1}{8760} \cdot \frac{Q}{100} \cdot \frac{q}{100} = \frac{5000\,kWh}{8760} \cdot \frac{123}{100} \cdot \frac{250}{100} = 1.755\,kW$$

$$P_2 = \frac{E_2}{8760} \cdot \frac{Q}{100} \cdot \frac{q}{100} = \frac{10000\,kWh}{8760} \cdot \frac{123}{100} \cdot \frac{250}{100} = 3.51\,kW$$

Values of the line impedances are calculated according to the length of branch:

$$R_{00'} = r \cdot l_{00'} = 1.06\,\Omega / km \cdot 0.5\,km = 0.53\,\Omega$$

$$X_{00'} = x \cdot l_{00'} = 0.3\,\Omega / km \cdot 0.5\,km = 0.15\,\Omega$$

$$R_{0'1} = r \cdot l_{0'1} = 1.06\,\Omega / km \cdot 0.2\,km = 0.212\,\Omega$$

$$X_{0'1} = x \cdot l_{0'1} = 0.3\,\Omega / km \cdot 0.2\,km = 0.06\,\Omega$$

$$R_{0'2} = r \cdot l_{0'2} = 1.06\,\Omega / km \cdot 0.3\,km = 0.318\,\Omega$$

$$X_{0'2} = x \cdot l_{0'2} = 0.3\,\Omega / km \cdot 0.3\,km = 0.09\,\Omega$$

The value of voltage drop in the line can be calculated using Equation 4.4 (Lakervi, Partanen, 2009):

$$\Delta U = \sqrt{3} \cdot I \cdot \left(R\cos\varphi + X\sin\varphi \right), \tag{4.4}$$

Where ΔU is a voltage drop of the line, I is a value of line current, R and X are resistance and reactance respectively, multiplied by the length of the line; φ is the angle between voltage and current in the received side.

The value of active power P is determined according to Equation 4.5: (Lakervi, Partanen)

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi, \tag{4.5}$$

And the current of each phase of the line is determined as:

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi}, \tag{4.6}$$

So it is possible to modify Equation (4.4) into Equation (4.7):

$$\Delta U = \frac{P}{U} \cdot \left(R + X \cdot tg\varphi \right), \tag{4.7}$$

$$\cos\varphi = 0.9 \quad \Rightarrow \quad \varphi = 25.84^0 \quad \Rightarrow \quad \sin\varphi = 0.436, \quad tg\varphi = 0.484$$

So it is possible to calculate the value of mean power per hour in question in the nod $0^{/}$ (P_{sum}) without taking into account power losses, because of their relatively small values in the short distances:

$$P_{\text{sum}} = P_1 + P_2 = 1.755 + 3.51 = 5.265\ kW$$

In order to determine the value of the voltage in the nod $0^{/}$, the quadratic equation has to be solved, according to Eq. (4.7):

$$\left(U_0 - U_{0^{/}}\right) = \frac{P_{\text{sum}}}{\mathrm{U}_{0^{/}}} \cdot \left(R_{00^{/}} + X_{00^{/}} \cdot tg\varphi\right), \qquad U_{0^{/}} := x$$

$$\left(400 - x\right) = \frac{5265}{x} \cdot \left(0.53 + 0.15 \cdot 0.484\right)$$

$$x^2 - 400x + 3172.7 = 0$$

$$D = b^2 - 4ac = 400^2 - 4 \cdot 3172.7 = 147309.2$$

$$x = \frac{-b \pm \sqrt{D}}{2a} = \frac{400 \pm 383.8}{2}$$

$$x_1 = 391.9 \qquad x_2 = 8.1$$

The value of $x_1 = 391.9$ is a logically relevant, therefore the value of the voltage in the nod $0^{/}$ is $U_{0^{/}} = 391.9\,V$

The voltage drop in the line $00^{/}$ is calculated as:

$$\Delta U_{00^{/}} = U_0 - U_{0^{/}} = 400 - 391.9 = 8.1\,V$$

In order to determine the value of the voltage in the customer 1, the quadratic equation has to be solved, according to Eq. (4.7):

$$\left(U_{0^{/}} - U_1\right) = \frac{P_1}{\mathrm{U}_1} \cdot \left(R_{0^{/}1} + X_{0^{/}1} \cdot tg\varphi\right), \qquad U_1 := x$$

$$\left(391.9 - x\right) = \frac{1755}{x} \cdot \left(0.212 + 0.06 \cdot 0.484\right)$$

$$x^2 - 391.9x + 423 = 0$$

$$D = b^2 - 4ac = 391.9^2 - 4 \cdot 423 = 151893.61$$

$$x = \frac{-b \pm \sqrt{D}}{2a} = \frac{391.9 \pm 389.7}{2}$$

$$x_1 = 390.8 \qquad x_2 = 1.1$$

The value of $x_1 = 390.8$ is a logically relevant, therefore the value of the voltage in the customer 1 is $U_1 = 390.8\,V$

The voltage drop in the line $0'1$ is calculated as:

$$\Delta U_{0'1} = U_{0'} - U_1 = 391.9 - 390.8 = 1.1\,V$$

In order to determine the value of the voltage in the customer 2, the quadratic equation has to be solved, according to Eq. (4.7):

$$\left(U_{0'} - U_2\right) = \frac{P_2}{\mathrm{U}_2} \cdot \left(R_{0'2} + X_{0'2} \cdot tg\varphi\right), \qquad U_2 := x$$

$$\left(391.9 - x\right) = \frac{3510}{x} \cdot \left(0.318 + 0.09 \cdot 0.484\right)$$

$$x^2 - 391.9x + 1269{,}1 = 0$$

$$D = b^2 - 4ac = 391.9^2 - 4 \cdot 1269.1 = 148509.2$$

$$x = \frac{-b \pm \sqrt{D}}{2a} = \frac{391.9 \pm 385.4}{2}$$

$$x_1 = 388.65 \qquad x_2 = 3.25$$

The value of $x_1 = 388.65$ is a logically relevant, therefore the value of the voltage in the customer 2 is $U_2 = 388.65\,V$

The voltage drop in the line $0'2$ is calculated as:

$$\Delta U_{0'2} = U_{0'} - U_2 = 391.9 - 388.65 = 3.25\,V$$

Now it is possible to calculate currents in the each line of the network, using Eq. 4.6:

$$I_{0'1} = \frac{P_1}{\sqrt{3} \cdot U_1 \cdot \cos\varphi} = \frac{1.755\,kW}{\sqrt{3} \cdot 0.3908\,kV \cdot 0.9} = 2.88\,A$$

$$I_{0'2} = \frac{P_2}{\sqrt{3} \cdot U_2 \cdot \cos\varphi} = \frac{3.51\,kW}{\sqrt{3} \cdot 0.38865\,kV \cdot 0.9} = 5.8\,A$$

According to Kirchhoff's law the value of current in the $00^{/}$ line can be calculated as:

$$I_{00'} = I_{0'1} + I_{0'2} = 2.88 + 5.8 = 8.68\,A$$

Three-phase power losses for each line are determined as: (Lakervi, Partanen, 2009)

$$P_{\mathrm{loss}} = 3RI^2, \tag{4.8}$$

Where P_{loss} is the three-phase active power losses;

$$Q_{\mathrm{loss}} = 3XI^2, \tag{4.9}$$

Where Q_{loss} is the three-phase reactive power losses.

According to Equation (4.8), three-phase active power losses for each line were calculated:

$$P_{\mathrm{loss\_00'}} = 3R_{00'}I_{00'}^2 = 3 \cdot 0.53 \cdot 8.68^2 = 119.8\,W$$

$$P_{\mathrm{loss\_0'1}} = 3R_{0'1}I_{0'1}^2 = 3 \cdot 0.212 \cdot 2.88^2 = 5.3\,W$$

$$P_{\mathrm{loss\_0'2}} = 3R_{0'2}I_{0'2}^2 = 3 \cdot 0.318 \cdot 5.8^2 = 32{,}1\,W$$

Three-phase reactive power losses for each line are calculated according to Eq. (4.9):

$$Q_{loss\_00'} = 3X_{00'}I_{00'}^2 = 3 \cdot 0.15 \cdot 8.68^2 = 33.9\,VAr$$

$$Q_{loss\_0'1} = 3X_{0'1}I_{0'1}^2 = 3 \cdot 0.06 \cdot 2.88^2 = 1.5\,VAr$$

$$Q_{loss\_0'2} = 3X_{0'2}I_{0'2}^2 = 3 \cdot 0.09 \cdot 5.8^2 = 9.1\,VAr$$

The results of network calculations by the method based on the load models usage are summarized into Figure 4.4.

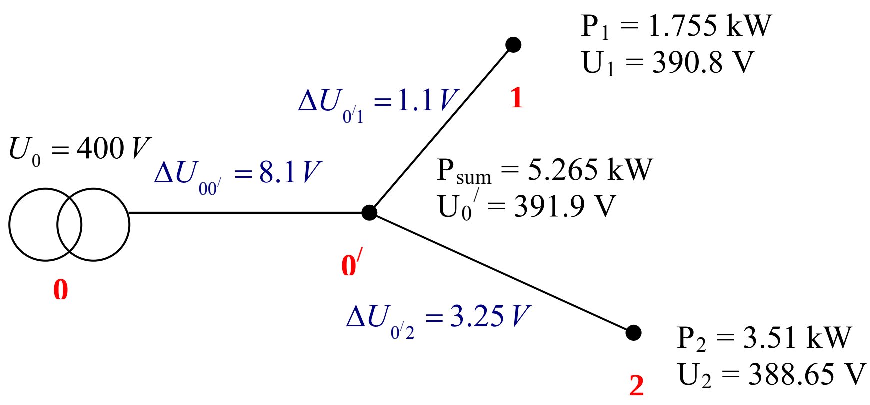

Fig. 4.4 Results of the power and voltage quality calculations by the method based on the load models usage (situation without the AMR usage)

Thus the load models method allows realizing power and voltage quality monitoring based on the annual energy consumed data, which are resolved into the load model for each specific customer group. By means of this approach it is possible to determine the values of power and voltage in the customer side and the voltage drop in the each branch at specific time of season, week and day.

4.3 Example of LV-network state-estimation based on the AMR data usage

Usually, it may be difficult to achieve the total integration of the AMR system for all customers within the bounds of the distribution company operation, if it is certainly not a government regulation. However, in some of countries, which are interested in the AMR system operation, the distribution company entitles the customer to make a decision about the AMR installation in his/her residence. Within the scope of this sub item it is illustrated that even the partial installation of the AMR meters in the distribution network can lead to more accurate data about the voltage and power levels in the whole network.

For that purpose, the previously regarded part of the example distribution network 10/0.4 kV was used but with the other assumption. In that case, it was assumed that only the customer 2 has the AMR system installation (Fig. 4.5).

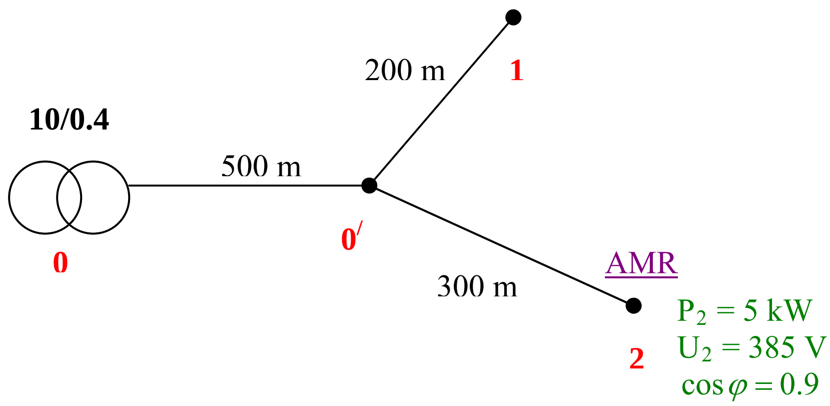

Fig. 4.5 A part of the distribution network 10/0.4 kV with two detached houses customers (situation with the AMR usage in the customer 2)

As a result of absent the actual data measurements, which could be done by the AMR meter in this special case of the network configuration, such parameters as the mean power per hour in question P_2, the magnitude of the voltage in the customer side U_2 and $\cos\varphi$ of the load, were assumed.

Assumptions:

$P_2 = 5$ kW

$U_2 = 385$ V

$\cos\varphi = 0.9$

Using these assumptions, it is possible to calculate the value of the current in the line $0'2$ from Equation (4.6):

$$I_{0'2} = \frac{P_2}{\sqrt{3} \cdot U_2 \cdot \cos\varphi} = \frac{5\,kW}{\sqrt{3} \cdot 0.385\,kV \cdot 0.9} = 8.3\,A$$

The voltage drop in the line $0'2$ is determined according to Equation (4.4):

$$\Delta U_{0'2} = \sqrt{3} \cdot I_{0'2} \cdot \left(R_{0'2} \cdot \cos\varphi + X_{0'2} \cdot \sin\varphi\right) =$$
$$= \sqrt{3} \cdot 8.3 \cdot \left(0.318 \cdot 0.9 + 0.09 \cdot 0.436\right) = 4.7\,V$$

So the value of the voltage in the nod $0'$ can be calculated as:

$$U_{0'} = \Delta U_{0'2} + U_2 = 4.7 + 385 = 389.7\,V$$

The voltage drop in the line $00'$ is determined as:

$$\Delta U_{00'} = U_0 - U_{0'} = 400 - 389.7 = 10.3\,V$$

Now it is possible to calculate the summary power in the nod $0'$ from Equation (4.7):

$$P_{\text{sum}} = \frac{\Delta U_{00'} \cdot U_{0'}}{\left(R_{00'} + X_{00'} \cdot tg\varphi\right)} = \frac{10.3 \cdot 389.7}{\left(0.53 + 0.15 \cdot 0.484\right)} = 6.66\,kW$$

Without taking into account power losses the mean power per hour of the customer 1 can be calculated as:

$$P_1 = P_{\text{sum}} - P_2 = 6.66 - 5 = 1.66$$

The value of the current in the line $00'$ is determined from Equation (4.6):

$$I_{00'} = \frac{P_{\text{sum}}}{\sqrt{3} \cdot U_{0'} \cdot \cos\varphi} = \frac{6.66\,kW}{\sqrt{3} \cdot 0.3897\,kV \cdot 0.9} = 10.96\,A$$

According to Kirchhoff's law the current in the line $0'1$ can be calculated:

$$I_{0'1} = I_{00'} - I_{0'2} = 10.96 - 8.3 = 2.66\,A$$

So the voltage drop in the line $0'1$ is determined according to Equation (4.4):

$$\Delta U_{0'1} = \sqrt{3} \cdot I_{0'1} \cdot \left(R_{0'1} \cdot \cos\varphi + X_{0'1} \cdot \sin\varphi \right) =$$
$$= \sqrt{3} \cdot 2.66 \cdot \left(0.212 \cdot 0.9 + 0.06 \cdot 0.436 \right) = 1\,V$$

The voltage in the side of the customer 1 is calculated further:

$$U_1 = U_{0'} - \Delta U_{0'1} = 389.7 - 1 = 388.7\,V$$

The following calculations of the three-phase active power losses were done according to Eq. (4.8):

$$P_{\text{loss\_00'}} = 3R_{00'}I_{00'}^2 = 3 \cdot 0.53 \cdot 10.96^2 = 191\,W$$
$$P_{\text{loss\_0'1}} = 3R_{0'1}I_{0'1}^2 = 3 \cdot 0.212 \cdot 2.66^2 = 4.5\,W$$
$$P_{\text{loss\_0'2}} = 3R_{0'2}I_{0'2}^2 = 3 \cdot 0.318 \cdot 8.3^2 = 65.7\,W$$

Three-phase reactive power losses for each line are calculated according to Eq. (4.9):

$$Q_{\text{loss\_00'}} = 3X_{00'}I_{00'}^2 = 3 \cdot 0.15 \cdot 10.96^2 = 54.1\,VAr$$

$$Q_{\text{loss}\_0'1} = 3X_{0'1}I_{0'1}^2 = 3\cdot 0.06\cdot 2.66^2 = 1.27\ VAr$$

$$Q_{\text{loss}\_0'2} = 3X_{0'2}I_{0'2}^2 = 3\cdot 0.09\cdot 8.3^2 = 18.6\ VAr$$

The results of network calculations by the method based on the partial AMR system installation are summarized into Figure 4.6.

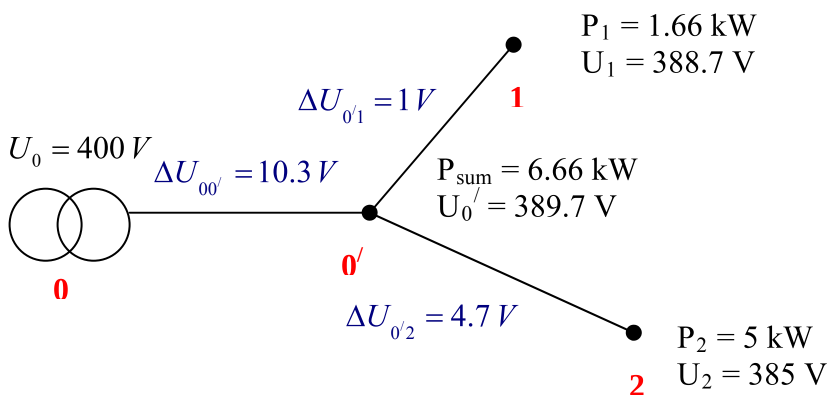

Fig. 4.6 Results of the power and voltage quality calculations by the method based on the partial AMR system installation (the AMR is in the customer 2)

Thus the AMR system suggests another approach to realize power and voltage quality monitoring based on the real-time measurements of the power and voltage values in the customer side.

4.4 Analysis of the results distortion between two methods

Theoretically, the approach of LV-network state-estimation based on the AMR system offers the more accurate data about the power and voltage characteristics of the network in comparison with the way based on the load models.

The possible reason of getting inaccuracy in LV-network state-estimation based on the load models, first of all, is connected with the usage of empirical data in the power and voltage quality processing. Secondly, a division of all customers on several groups, in which the electricity consumption can be assumed to be equal with a sufficient accuracy, always will lead to receive an inaccuracy in the calculations in the scope of one customer. The temperature correction of electricity consumption just complicates the calculations and can be also the reason of getting an inaccuracy.

The real-time measurements provided by the AMR eliminate these problems supposing the actual data transfer from the each customer's side. The AMR usage method is free from the empirical data usage in the power and voltage quality processing. Besides, even the partial installation of the AMR in the customer side leads to more accurate data about the voltage and power levels in the whole network.

Particularly, as the second example of the network calculations illustrates, the value of the power consumed by the customer 2 can be higher at a specific hour of data measurements than it was estimated at the moment of the load model production. As a result there is the higher magnitude of voltage drop in the lines and the lower magnitude of voltage in the side of customer 1. These corrections are able to improve the distribution company planning and operation.

5 The AMR technology in the Russian power system

5.1 Present situation with energy meters in Russia

The electronic meters started to be used in the European countries already in the 1960's. However, to the 1980's the induction meters were still used in the most part of the Russian electric power system. They were cheaper, long lived and sufficed to the required accuracy class index 2.5. In that time the electric power system has been staying under the Russian government budgeting without any regulations by the electricity market mechanisms, the energy production was at the high level, and the cost for electricity was quite cheap, that is why there were not any incentives to make the electricity usage more economical and to invest into the new measuring devices. (Consulting company "Step", 2006)

The first mass production of the electronic meter began in Russia in the beginning of the 1980's. So Russia has lagged behind in the measuring system development the European countries more than twenty years.

The undertaken liberalization of the Russian electricity system and reformation of the RAO "UES of Russia" during 2003-2008 have been setting up claims for the accuracy of the energy metering, the usage of the multi-tariff system in the pay estimation of energy consumed and the transition to the automatic meter systems utilization. In such situation, with the help of the market competition increase and the rising of the energy source cost the correct energy consumed measuring stays a main means to decrease costs and to increase profitability of the distribution company business. The Russian electric utilities usually do not have authentic information about the energy consumed data. According to different estimations, until recently the unaccounted energy in Russia was about 10 – 20 % of the delivered energy. (Consulting company "Step", 2006)

For the last years the replacing of the induction meters by the electronic meters in Russia has been going with fast rates that can be seen in Figure 5.1. During six years from 2000 till 2005 the rate of the electronic meters usage by the residential electrical customers has raised more then twice.

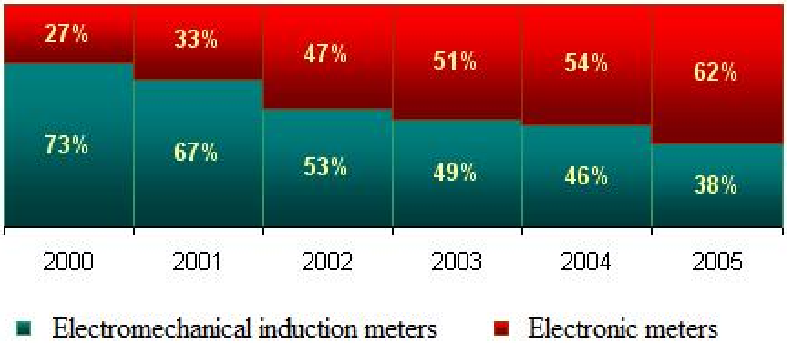

Fig. 5.1 Replacing of the induction meters by the electronic meters during 2000 - 2005 years in Russia (Consulting company "Step", 2006)

The volume of the electric meters production in 2008 in Russia accounted 7 016 363 meters, where the most part of production (32 %) belongs to the open joint-stock company “Концерн Энергомера” (“Consern Energomera”), the second place is taken by the limited liability company “Инкотекс” (“Inkoteks”). The third place is divided between the open joint-stock companies “Ленинградский электромеханический завод” (“Leningrad electromechanical factory”) and “Московский завод электроизмерительных приборов” (“Moscow factory of electric metering devices”). Fig. 5.2 demonstrates the dividing of the electric meters production between the leading Russian manufacturers.

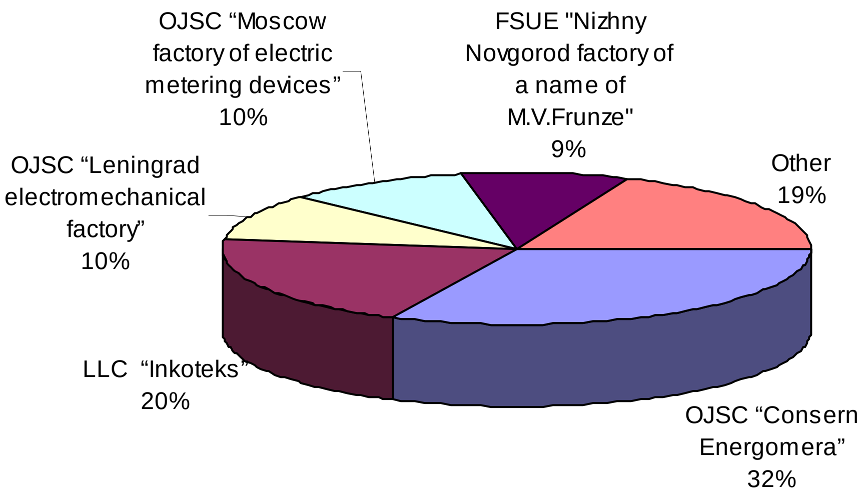

Fig. 5.2 Dividing of the electric meters production between russian manufacturers (Adercade consulting, 2009)

In 2008 in Russia the electronic meters production was 87.2 % of the total electric meters production, whereas the production of the induction meters was 12.8% accordingly. The production of the one-phase meters accounts 77.4 % of the total electric meters production, while the rate of the three-phase meters production was 22.6 % of the total electric meters production. (Adercade consulting, 2009)

In the structure of meters import it is possible to allocate three basic countries-suppliers of the electric meters into the Russian Federation; they are China, the USA and Sweden. Share of these countries in the Russian import of meters is 82.5 %. The largest supplier of the electric meters of the Chinese production is a company Lodestar Int’l Co. Electric meters from Sweden are provided by ABB, the company Elster Electriciti LLC takes a leading position in this question in the USA. A presence of such importing suppliers in the Russian electricity market leads to reduction of cost of the national electric meters. (Adercade consulting, 2009)

The CIS countries stayed in 2008 the main buyers of the electric meters of the Russian production. 72 % of the meters export were delivered into Ukraine and Kazakhstan in 2008. (Adercade consulting, 2009)

At present time there are a number of disputes concerning the question of reasonableness of the total replacement of induction meters by electronic meters. The electronic meters with a high accuracy index (0.2, 0.5) undoubtedly are needed in the places of the high electricity transfer capacity, but in the residential customers side the accuracy index 2.0 is sufficient. The ability of an electronic meter to keep a required accuracy index in cases of the fast changing loads is also more important for industry, not for the residential users. Also taking into account the bad condition of the rural electricity network in Russia, the electric utilities usually decide to install the induction meters in such territories due to their reliability in comparison with the electronic meters. Besides, the multi-tariff system is still ignored by the end-users, who prefer to install one-tariff electronic meters. Such multi-tariff system is much more needed in industry, where it helps to make a load smooth. (Akimov, Shuleshko, 2005)

Therefore some manufactories, for instance OJSC "Moscow factory of electric metering devices", begin to produce induction meters with an accuracy index 0.2 with inbuilt electronic module, which can be used as a detector element for the remote reading system. Such kind of device is cheaper than an electronic meter. (Tubinis, 2009)

5.2 Review of the AMR application for the residential users in the Russian power system

There are about ten developed variations of the AMR system for the residential users using the PLC-technology in Russia. The most known of them are created by OJSC "Moscow factory of electric metering devices" and CJSC "Informational-analytical center of scientific and technical researches "Континиум" ("Continium") (Moscow).

Tens already implemented pilot projects proved their efficiency in the increase of gathered payments for the electricity. The payback period of these projects is estimated in 3-4 years, like in Italy. According to report of OJSC "System operator of Unified Energy System of Russia", the electric power generation in 2008 is estimated in 1 006.8 TWh. Taking into account that the unaccounted energy in Russia is on the average 15 % of delivered energy, the amount of unaccounted electric power in 2008 year are 151.02 TWh. Having the electricity tariff of 0.02 €/kWh the economical losses of the electric power delivery is 3.02 billions € in 2008. So that amount of money could be saved by getting the actual value of the energy consumed and by protection against the illegal electricity usage, which are provided by the AMR technology. (Tubinis, 2005), (OJSC "System operator of Unified Energy System of Russia", 2009)

The AMR technologies that are developed by OJSC "Moscow factory of electric metering devices" and CJSC "IAC STR "Continium" are named "ЭМОС-МЗЭП" ("EMOS-MZEP") and "АСКУЭР "Континиум" ("ASCUER "Continium") respectively. They have a similar functional scheme, which is presented in Figure 5.3. The difference between two technologies is contained in the type of used communication link. "EMOS-MZEP" is based on the radio system, "ASCUER "Continium" uses the PLC connection.

The information about consumed energy comes from meters into the controller that is allocated on the each floor of the building; these data are jointed with the information about time of use and are fixed in the non-volatile memory according to the program set from the outside. This information is transferred to the concentrator that is allocated either in the transformer substation or inside of the building. The control room receives these data through the two-way communication channel.

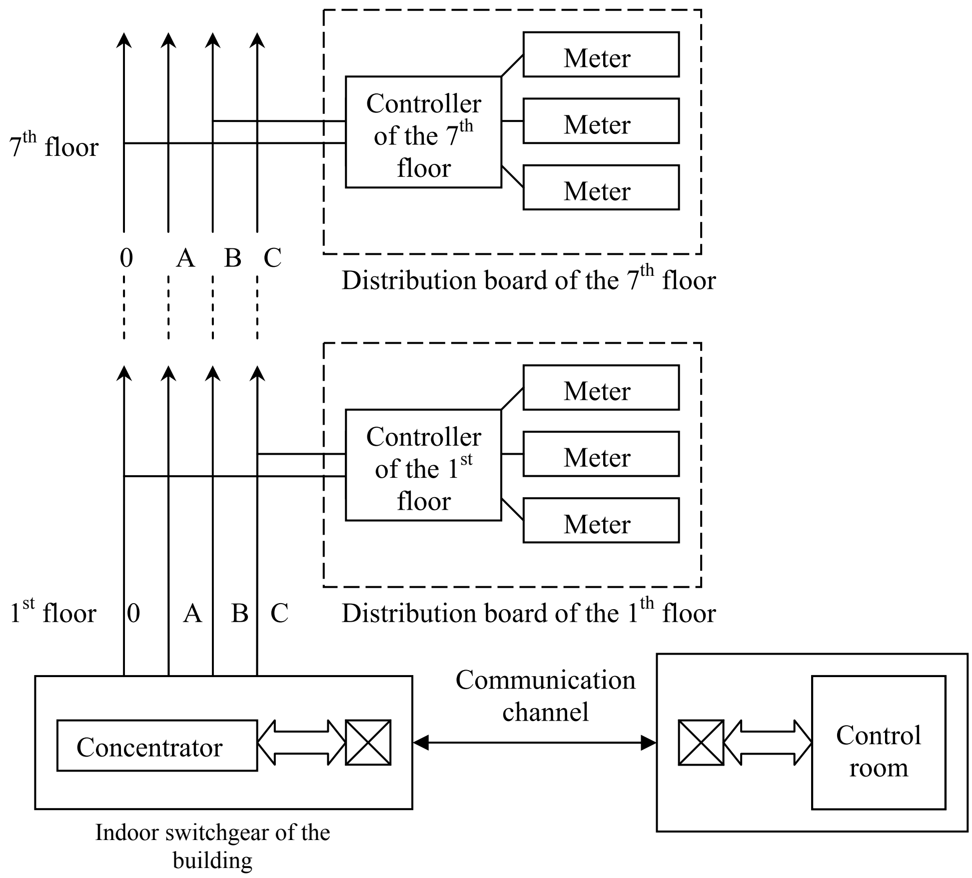

Fig. 5.3 Functional scheme of the AMR technology of “EMOS-MZEP” and “ASCUER “Continium” (Figure is modified from the original source (Tubinis, 2005)

This AMR technology is most widely used in many pilot and life projects in the Russian power system and has proved its efficiency. However, a comprehensive scientific analysis has showed that “EMOS-MZEP” technology is less expensive, but it also has disadvantages. In particularly, it is less protected from the signal interferences, and it does not assure the required continuous communication between meter and controller. “ASCUER “Continium” technology is free from these kinds of disadvantages; therefore this technology was chosen for realization of the largest life project of the AMR implementation in Russia, which is rolling out in Khabarovsk city. (Tubinis, 2005)

The project the AMR implementation in Khabarovsk is carrying out according to instruction of the municipal authorities and OJSC “Khabarovskenergo”. The system is constructed basing on the PLC-communication link of 0.4 kV distribution network. The project is financed by the tariff component, when the cost of system development is contained in the customer's tariff. The estimated payback period is four years. (Tubinis, 2005)

As a result of a pilot project carrying out in the Twer region of Russia by OJSC "Twerenergo", the AMR system will be installed in the settlement Yurievo-Devichie with a population of 300 people. All technical preparations have begun in 2005. The rate of energy losses in this place before the AMR system integration was more than 60 % of total energy delivered. After the first month of the system operation the energy losses were reduced up to 8 % of total energy delivered. (MRSC Center, 2008)

One of the highest tariffs for the electric power takes place in the Sakhalin area of Russia. Therefore, occurrences of the electricity theft are wide-spread in this region and that brings essential losses for the electric power branch. During the last years OJSC "Sakhalinenergo" takes measures to reduce the power losses rolling out a set of pilot projects of the AMR integration for residential customers. The working parameters of one of such pilot projects for 60-apartments house during January – May of 2005 are summarized into the Table 5.1 and compared with the data of 2004 in the same time period.

Tabl. 5.1 The working parameters of the pilot project of the AMR integration for 60-apartments house during January – May of 2005 with comparison to data of 2004 (LLC "Matrix, 2006)

Year	2004	2005
Electricity consumption, $*10^3$ kW/h	48.6	65.2
Electricity payment, €	1472	2111.4
Electric power losses, % of delivered energy	47	4
Electricity delivery, $*10^3$ kW/h	71.4	67.8

As a result of such pilot project the electric power losses were reduced on 43 %-units, the electricity payment was increased almost at 1.5 times.

The increasing amount of Russian energy companies start to undertake pilot projects of the AMR integration for the residential customers. During the projects realization the AMR technology proved the costs saving and improvement of the distribution companies operation. Table 5.2 contains a list of several Russian energy companies, which started to use the AMR technology for the residential customers, as pilot projects.

Table 5.2 The volume of the AMR system integration into the residential side in Russia (APLM, 2009)

Name of energy company	**Amount of meters in points**	**Total amount of customers**	**% of AMR integration**
OJSC “Orelenergo”	30 654	900 000	3,4
LLC “Balashihinskie electroseti”	10 456	-	-
OJSC “Astrahanenergo”	23 225	-	-
OJSC “Omskenergo”	1470	774 900	0,19
OJSC “Altayenergo”	350	-	-
OJSC “Sakhalinenergo”	249	514 000	0,05
OJSC “Mordovenergo”	125	-	-
OJSC “Ryazanenergo”	50	1 325 000	0,004
OJSC “Belgorogenergo”	417	1 513 100	-
OJSC “Smolenskenergo”	136	-	-
OJSC “Pskovenergo”	583	412 366	0,14
OJSC “Troitskie electroseti”	910	-	-

The information about a total amount of customers was not available from websites of several energy companies. But according to this statistics, the larger scale pilot projects in Russia were undertaken by OJSC “Orelenergo”, OJSC “Astrahanenergo”, LLC “Balashihinskie electroseti”.

5.3 Benefits of the AMR usage in Russia

The main benefits of the AMR usage for Russia, like in other countries, are spread on customers and the electric utilities, and are connected with a demand side management. First of all, the main economical effect for customers includes the idea of the pay reduction for the electricity and power consumed. For the electric utilities the AMR usage is a way of reduction of the energy consumption peaks and reduction of capital investments on increase of the peak generating capacities. With a help of the AMR usage there is no longer necessary to visit the customer's residencies by the distribution company's staff in order to record the energy consumed data. The AMR system allows to poll energy meters of one apartment house for several seconds remotely. Therefore the possible casual and deliberate mistakes of controller are eliminated.

The electricity theft stays an essential problem of the network distribution system in Russia that leads to the electric power losses in average 20-40 % (in several regions up to 60 %) of the total delivered energy. The AMR technology allows reducing the electric power losses till 5-10%, getting the information about balance of the electric power delivery in the distribution network. (Energy future, 2009). Especially, during the current period of elimination of the cross-subsidization in the Russian power system, when the electricity tariff for the residential users becomes to be equal to the cost price of electricity production, it is forecasted that the electricity tariff for the residential users will increase in two or three times, therefore the electricity theft occasions will increase also. In such situation the AMR system is enable to detect the electricity theft and even to disconnect the trespasser from the network.

The network state-estimation based on the AMR data improves a control over the distribution network, getting the actual values of power and voltage of the whole network. These data are widely used for distribution company planning and operation.

The correct information about the customers' power consumed provided by the AMR system allows formation of the economically justified prices and tariffs for the electricity power consumption for different regions in Russia.

The replacement earlier used meters by new smart meters in the AMR structure usually is accompanied by renewal of infrastructure of the whole distribution network 0.4 kV.

Systems of data transmission, which are used in the AMR technologies are universal and can be added by other functions, for instance, by the security and fire alarms. These combinations even can lead to the pay back period reduction.

5.4 Difficulties with the AMR integration in Russia

The automatic systems for commercial accounting of the power consumption of the industrial customers are used a lot of time both in Russia and abroad. Because of a growing amount of the residential users, their low energy consumption and low rate into the distribution company budget until the last years, the AMR integration for the residential customers was economically unreasonable. As a result of systematic elimination of the cross-subsidization in the Russian power system, when the electricity tariff for the residential users was quite low due to the higher tariff for the industrial customers, the electricity tariff for the residential users became to be equal to the cost price of electricity production. As a result, the rate of the residential customers in the distribution company budget formation have increased recently up to 20 %. Therefore, the accurate information about the customers' consumed energy becomes necessary for the distribution company cost saving. (Tubinis, 2004)

One of the fears of the electric utilities in case of the all-round AMR integration is that customers will pay for the real energy consumed, and the problem of the energy reserve payment appears. The energy reserve is necessary for correct managing of the power processes; it is estimated as 10-15% of the total energy delivered. One of ways to solve this problem consists in the increase of the electricity tariff for customers at the coefficient of the energy reserve (1.1 – 1.15). (Tubinis, 2004)

Nevertheless the present technologies of the AMR system are efficient and justified, at the certain moment in the future they will need to be modified by additional functions. The AMR systems producers have to take it into account in their production. Besides, the elements of AMR system are complicated and need a service of qualified staff.

Characteristics of the Russian distribution networks become one more problem for the AMR system producers, if the target is 100 % area covering with PLC-communication. These characteristics are a big extension, a high level of noise and a high speed of attenuation of the high-frequency signals.

As a result of elimination of the cross-subsidization in the Russian power system, the electricity tariff for the residential users will increase in two or three times, therefore the electric utilities have to develop different tariff systems for customers, offering tariffs based on the volume of energy consumed, the time of usage, the time of payment and others.

The main feature of every AMR system is an accuracy of measurement, which depends not only of meter itself, but also of current and voltage measuring transformers and of losses in the wire between transformers and meter. As the current and the voltage measuring transformers presently are produced in Russia with the accuracy index at 0.5, it is not reasonably to produce meters with the higher accuracy index that is why the production of the electric meters has stopped at the accuracy index 0.2. There are two ways to solve this problem. One of them is an improvement of the meter construction and operation conditions. The other one consists in the requirement strengthening for transformers exploitation, their standard calibration and creation of transformers with a higher accuracy index. (Tubinis, 2004)

One of the main features of every project is it's payback of cost. One possible way in this question is a using of system of the project financing through a tariff component. Besides, the electric utilities use so called "active" tariff system, when the price for electricity in "active" time differs from the price for electricity at basic time on about 40 %. The relatively new method of the payback increase means that the electric utility gives the AMR system to customer in a leasing purpose; the tariff of the customer, who does not have the AMR technology, is higher. (Tubinis, 2009)

5.5 Forecast of the future development of the AMR usage in Russia

The present situation with the Russian power system described by the market liberalization and systematic elimination of the cross-subsidization are quite suitable for the rolling out the AMR projects for the residential users. In order to keep a competitive position in the electricity market and to minimize costs the electric utilities will have to seek ways to receive more accurate data about the electricity delivered and consumed. The AMR technology is able give this information.

As the electromechanical meters are still used in many regions in Russia, the transition to the AMR technology with the smart meters usage can be done without going through a period of the solid state meters usage. That undoubtedly will save costs of the distribution company for the network infrastructure renewal.

However, there is no any structure coordinating a technical policy in the field of the electric utilities operation in the retail market of the electric power in Russia. Therefore, each region of Russia acts in this question separately from others that may lead finally to mistakes and the overexpenditure of costs. Besides, the situation is complicated by the fact that the Russian scientific centers of the AMR technology development are located far from each other and their developments are insufficiently financed. In such situation the most reasonable way means that the one of the existing Russian organization has to undertake a role of a coordinator. For instance, it can be non-commercial partnership “АСКУЭ” consolidating the leading Russian manufacturers of the electric measuring systems or it can be association of potential users of the AMR systems presented by household consumers, for example, "Роскоммун-энерго". (Tubinis, 2005)

6 Conclusion

In liberalized electricity markets, which have taken place in many countries over the world, the electricity distribution companies operate in the competitive conditions. Therefore, accurate information about the customers' energy consumption plays an essential role for the budget keeping of the distribution company and for correct planning and operation of the distribution network.

The AMR technology allows getting real-time measurements of the customers' energy consumed and also provides a set of different services, which can be useful for the electric utility planning and operation. Major benefits of the AMR were illustrated in the thesis; they are distribution network management, power quality monitoring, load modelling, fault and outage reporting and detection of the illegal usage of the electricity. By the example of the power system state estimation, it was illustrated that even the partial installation of the AMR in the customer side leads to more accurate data about the voltage and power levels in the whole network.

In the scope of the thesis the situation connected with AMR integration in Russia was researched. The electricity market liberalization and systematic elimination of the cross-subsidization in Russian power system represent rather suitable time period for the rolling out the AMR projects for residential users. In order to keep a competitive position in such electricity market and to minimize costs the electric utilities will have to seek ways to receive more accurate data about the electricity delivered and consumed. The AMR technology can be used for this purpose. That is why, nowadays there are many pilot projects of the AMR integration for residential users undertaken in the Russia, and the main target of most of them is the electric power losses reduction. Besides, these pilot projects have already proved their efficiency in the Russian power system.

The penetration of the AMR in the world has been increasing rapidly during the past years, and similar development will continue in the future, as many distribution companies have plans to install AMR systems.

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