RIGA TECHNICAL UNIVERSITY

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POWER SYSTEMS OUT-OF-STEP MODELLING, CONTROL AND ELIMINATION

Summary of Doctoral Thesis

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DOCTORAL THESIS
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TO OBTAIN A DOCTORAL DEGREE IN ENGINEERING

Doctoral Thesis is proposed for achieving Dr. sc. ing. degree and will be publicly presented on 16th April 2015 at the Faculty of Electrical Engineering of Riga Technical University, Azenes Str. 12/1, Room 306, at 2:00 pm.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Economics, is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Dmitrijs Antonovs ..... (signature)

Date .....

The Doctoral Thesis has been written in the Latvian language. The Doctoral Thesis contains an introduction, 4 chapters, conclusions and proposes, and references. The total volume of the Thesis is 142 pages of computer typesetting, which contains 78 figures and 34 formulas. The list of references consists of 125 literary sources.

CONTENTS

TOPICALITY OF THE DOCTORAL THESIS

Power system is one of the most complex objects that were created by humanity. It provides advanced civilization development process and also relatively high standard of living so that men would be satisfied and could perform daily routines and activities. Dependence on energy has increased by several times for the last ten years, because electricity is used in various electronic gadgets such as smart phones, laptops, etc. It is well known that it is important to ensure uninterrupted and reliable energy supply for customers. In order to achieve this goal, developed power structure is needed. Simultaneously the high quality of electricity must be ensured as well.

At present, the human dependence on electricity is clearly evident and, analysing tendencies of the development, it is possible to conclude that this dependence will only increase. As a result, even a brief power outage could lead to catastrophic consequences that sometimes cannot be precisely assessed and that are difficult to predict due to various reasons. Power outage has direct influence on other critical infrastructures that are heavily dependent on it. Let us mention only the most important of them; these are infrastructures that in case of power outage can paralyse urban and rural life:

- Heat supply;
- All types of communication (phones, Internet, etc.);
- All types of transports;
- Financial systems (banks, stocks, etc.);
- Medical systems;
- Food supply, storage and production;
- Police and civil defence;
- Fuel supply system and so on.

Modern society is extremely vulnerable to power outages. Blackouts, which last for several hours or even days, have significant impact on everyday life and the economy. Major infrastructure operations such as those of communication or transport will be cumbersome; water and heating supply will be stopped, and production processes and stock exchanges will be interrupted. Authorities of accidents (fire-fighting, police and emergency medical treatment) will be unable to communicate because of the collapse of the telecommunications systems. The hospital will remain operational until emergency generators are supplied with fuel. Financial stocks, automated teller machines (ATMs) and shops will be closed, which will lead to a disastrous scenario.

In many cases, the system operating conditions change so quickly that the human can make decisions and carry them out. This fact forms the necessity for automatic control system use. Occasionally, abnormal or emergency modes occur in power systems many of which started with short circuits in power system elements. For short circuits prevention and damaged element fast disconnection, it is necessary to create fast responsive protection systems that would operate independently of human control and whose response time is measured in milliseconds. Relay protection and anti-emergency automatics (RP&EA) terminals are used for making correct decision about disconnection of damaged element in cases of dangerous modes. Unfortunately, terminals may also fail. Therefore, it is necessary to evaluate the complete security of elements. Failures of RP&EA or other elements which are used in control process can promote hazardous process evolving sooner. Thus, the possibility of large scale blackouts still persists. In order to avoid such situations, all types of RP&EA are reserved. In addition, EA is applied, which operates basically only when certain unfavourable conditions happen simultaneously. One of the most important EA is created for the recognition of power system stability disruption and control measures performing for

dangerous mode development elimination and the economic and social damage decreasing. Exactly this kind of automation development – **out-of-step elimination protection (OSEP) – formed the basis for this Doctoral Thesis**.

For the last twenty years, it has been generally accepted to develop secure, economical fully-equipped anti-emergency systems using elements of microprocessor base, high-speed optical communication channels and Global Positioning System (GPS). Usage of the mentioned systems and elements open up new possibilities for creating complex fully-equipped RP&EA devices, which operate in a unified system. In this field of science, a lot of researchers work, and hundreds of publications are available. New equipment is relatively fast put into practice. Making the comparison between the Baltic States and industrially advanced countries in RP&EA, it is possible to conclude that technical level in manufacturing of automatics systems in the Baltic States is decelerating. One of a few exceptions is related exactly to out-of-step elimination protection – "AGNA", because Latvian researchers' (V. Fabrikants, K. Brinkis, A. Sauhats, V. Kreslinsh, A. Utans, A. Svalovs et. al.) studies for the last 50 years have been dedicated to this topic. As a result, modern microprocessor based automatics is used in the Baltic States. It has been devised by RTU, and it has already been manufactured in Latvia for twenty years.

It is important to note that in power industry of the Baltic States there have been significant changes over the last 20 years. These changes are related to restructuring and market mechanism initiation. Demand for energy, its price and standard has changed significantly. Different new technologies of energy generation and distribution have become available (gas-turbo technology, distributed generation, GPS, optical communication channels, alternative energy sources, H_2S devices, new type of wires, electronic devices, control and management terminals, etc.).

These changes have significant impact on OSEP needs and realization possibilities. On the one hand, requirements increase since market mechanism usage leads to power flow adaptation mainly for solving of income maximization task, which in many cases conflicts with stability security. On the other hand, new possibilities of automatics technical level increase arise due to the use of GPS and high-speed communication channels. The main tasks of this Doctoral Thesis include the analysis and consideration of new statements and realization possibilities as well as estimating and defining the resources and ways.

The most topical problems are "N-1" criterion inadequacy for power system control, necessity for probabilistic criterion development, and new generation automatics development to secure better selectivity and more efficient operations.

THE TASKS AND OBJECTIVES SET IN THE DOCTORAL THESIS

The main objective of the thesis is stability and safety level increase in power systems of the Baltic States. To achieve this objective, the following **main tasks** have been set:

1. To analyse the existing OSEP system operation principles, algorithms and device realization techniques.
2. To create the OSEP structure and terminal requested in the Baltic States using microprocessor base, GPS and high-speed communication channels. They are available for testing.
3. To create a model of Latvian power system and to perform appropriate software synthesis for dynamical stability calculations and terminal algorithm validation.
4. To perform the Latvian power system out-of-step mode calculations and to prove their possibility.
5. To perform accuracy verification of new device tests, algorithms and measurements.
6. To develop the OSEP simplified model assessment methodology and to create the library of modelling processes.

7. To develop a new anti-emergency automatics structure that combines local and global system advantages and is capable to operate in cases of GPS and communication channel failures.

RESEARCH METHODS

1. Power system stability and security standards analysis.
2. Modelling of stability loss processes of large power systems using nonlinear differential and algebraic equations implemented in industrial software EUROSTAG and ETAP.
3. Use of digital oscillograms of real emergency processes and protection testing equipment FREJA and ISA DRTS for algorithm and equipment testing.
4. Special software creation for relay protection terminal testing.
5. Refinement of protection devices using Texas Instrument processors and corresponding debugging software.
6. Analysis of emergency processes using digital record processing software SMOKY.

SCIENTIFIC NOVELTY OF THE DOCTORAL THESIS

1. The analysis of out-of-step prevention methods and techniques has been performed and their drawbacks have been defined.
2. New OSEP systems have been worked out; their advantage and implementation possibility in anti-emergency automatics, which combines local and global system advantages and is capable to operate in cases of GPS and communication channel failures, have been proved. Use of OSEP significantly reduces global blackouts risks.
3. New methodology for complex protection terminal verification has been developed.
4. To model stability loss processes for large power system, simplified probabilistic relay protections and automatics operating algorithms have been proved. Verification methodology has been performed as well.
5. Proposed OSEP algorithm provides proper protection functioning in case of voltage circuit failure.
6. The library of modelling processes has been created.
7. OSEP validation has been performed in complex electromechanical processes.
8. To validate protection terminals, ETAP 12.5 software usage possibility in power system mode modelling has been proved.

PRACTICAL APPLICATION OF THE DOCTORAL THESIS

The practical application of the Doctoral Thesis is as follows:

1. Proposed relay protection, automatics terminal structure and new verification methodology is applicable to other numerous terminals as well as to terminal reliability level improvement.
2. The proposed OSEP terminal is being prepared for production in Latvia and in other Baltic States. Synthesized, verified and produced terminal structure solves problems mentioned above. The experiments demonstrate solution efficiency and accuracy.
3. The virtual testing methodology and software have been developed. The methodology may be used for existing elements of relay protection for security, selectivity and high-speed verification.
4. The virtual testing methodology applied to PEGASE and ICOEUR projects financed by the European Community and to national research programmes in Power Engineering has been devised.

DOCTORAL THESIS DEFENDABLE STATEMENTS

1. New effective OSEP structures and algorithms have been proposed and patented. Their advantages have proved in comparison with the ones presently used in Latvia and abroad.
2. OSEP operational algorithm that is indifferent to the voltage circuit failure has been proposed.
3. Structure of relay protection and automatics terminals for testing with additional digital input interface has been applied.
4. The GPS and communication channels for measurement of synchronization and communication channel testing have been used.
5. Hardware verification and testing complex has been worked out using ETAP software and special programmes.

AUTHOR'S CONTRIBUTION TO THE RESEARCH CONDUCTED

The fundamental thesis statements have been formulated using ideas designed in cooperation with scientific supervisors: Dr. habil. sc. ing., professor Antans Sauhats, Dr. sc. ing., associated professor Andrejs Utans and Dr. sc. ing., J. Kucajevs. The Doctoral Thesis may partly be considered the professors' perennial work continuation. The risk management task has been solved together with professor A. Sauhats and J. Kucajevs in the framework of a project financed by the European Community. The idea verification, models, devised software, numerical experiments and their analysis, and recommendations for the effective application belong to the author of the Thesis.

THE APPROBATION OF THE DOCTORAL THESIS

The research results of the Doctoral Thesis have been presented and discussed at seminars and conferences of different levels:

1. The 6th International Conference on Electrical and Control Technologies, Kaunas University of Technology Faculty of Electrical and Control Engineering, 5–6 May, 2011.
2. The 52nd International Scientific Conference of Riga Technical University, Section of Power and Electrical Engineering, Latvia, Riga, October 2011.
3. The 13th International Scientific Conference on Electric Power Engineering (EPE 2012), the Czech Republic, BRNO, 23–25 May 2012.
4. The 53rd International Scientific Conference of Riga Technical University and the 1st World Congress of RPI-RTU Engineering Alumni on Power and Electrical Engineering, Latvia, Riga, 10–12 October 2012.
5. The 54th International Scientific Conference of Riga Technical University, Section of Power and Electrical Engineering, Latvia, Riga 14–16 October 2013.
6. The 9th International Conference on Systems, ICONS 2014, Nice, France, 23–27 February 2014.
7. The 18th Power Systems Computation Conference, PSCC 2014 – POLAND, Wroclaw, 18–22 August 2014.
8. The 9th International Conference on Critical Information Infrastructures Security, CRITIS 2014, Cyprus, Limassol, 13–15 October 2014.

PUBLICATIONS

The following publications have been published on the subject of dissertation:

1. Sauhats, A., Silarajs, M., Kucajevs, J., Pašņins, G., **Antonovs, D.,** Bieļa, E. Testing of Protection and Automation Devices Using Dynamical Simulation Processes of Power System // Electrical and Control Tehnologies. – 6. (2011), 184–189 pp.
2. Sauhats, A., Utāns, A., Kucajevs, J., Pašņins, G., **Antonovs D.,** Bieļa, E. Protection and Automation Devices Testing using the Modeling Features of EUROSTAG // RTU zinātniskie raksti. 4. sēr., Enerģētika un elektrotehnika. – 28. sēj. (2011), 7–12 pp.
3. Dolgicers, A., **Antonovs, D**. Internal Winding Fault Protection for Shunt Reactors // RTU zin. raksti. 4. sēr., Enerģētika un elektrotehnika. – 28. sēj. (2011), 43–47 pp.
4. Sauhats, A., Utāns, A., Pašņins, G., **Antonovs, D**. Out-of-Step Relays Testing Procedure // RTU zin. raksti. 4. sēr., Enerģētika un elektrotehnika. – 29. sēj. (2011), 9–14 pp.
5. Sauhats, A., Utāns, A., Silarājs, M., Kucajevs, J., **Antonovs, D.**, Bieļa, E., Moškins, I. Power System Dynamical Simulation Application for Out-of-Step Relay Testing // Journal of Energy and Power Engineering. – 6. (2012), 1343–1348 pp.
6. Sauhats, A., **Antonovs, D.**, Dolgicers, A., Petrichenko, R., Kucajevs, J. Dynamic Security Assessment and Risk Estimation. Digest Book: Riga Technical University 54th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga, 14–16 October, 2013. Riga: RTU Press, (2013), 56–58 pp.
7. Sauhats, A., Utans, A., Dolgicers, A., **Antonovs, D.**, Pashnin, G. Out-of-Step Protection System Testing by Means of Communication Network Emulator. No: The Ninth International Conference on Systems (ICONS 2014), France, Nice: IARIA XPS Press, 2014, 166–171 pp.
8. **Antonovs, D.**, Sauhats, A., Utans, A., Svalovs, A., Bochkarjova, G. Protection Scheme against Out-of-Step Condition Based on Synchronized Measurements, The 18th Power Systems Computation Conference (PSCC14), September, Wroclaw, Poland, 2014, 8 lpp.

The gained patents:

1. Sauhats, A., **Antonovs**, **D.,** Svalovs, A., Kucajevs, J. Patent **LV 143758 B**, 12.05.2011., Out-of-step relay.
2. **Antonovs, D.**, Sauhats, A., Utans, A., Biela, E. Patent **LV 14832 B**, 05.07.2013.:
    - Out-of-step relay device;
    - Out-of-step protection method.
3. **Antonovs, D.**, Sauhats, A., Utans, A., Biela-Dailidovicha, E. Patent **LV 14912 B**, 27.06.2014.:
    - Out-of-step protection device;
    - Out-of-step protection method.

The author of the book chapter:

1. U. Häger, C. Rehtanz, N. Voropai (Eds.), Monitoring, Control and Protection of Interconnected Power Systems (*Dynamic Security Assessment and Risk Estimation* (Chapter 14), A. Sauhats, E. Kucajevs, **D. Antonovs**, R. Petrichenko, 255–279 pp.), Springer, 2014, 391 p.

STRUCTURE AND CONTENT OF THE DOCTORAL THESIS

The Doctoral Thesis has been written in Latvian; it contains an introduction, four chapters, conclusions and proposals, and references. The total volume of the Doctoral Thesis is 142 pages; there are 78 figures and 34 formulas. The list of references consists of 125 literary sources.

The first chapter is devoted to investigation of the power systems structure and modes, relay protection and automatics, and information exchange principles. Power systems blackouts that happened for the last years have been analysed to comprehend danger of consequences and amount of economic losses. Different factors that initiate the blackouts and allow them to spread making catastrophic losses have been identified. Principal fields that require studies to improve the current situation were formed. The critical overview of "N-1" security criterion has also been performed making the analysis of its lacks, shortcomings and limitations. A certain attention has been focused on risk ideology formation and analysis of risks. Probabilistic management criterion has been proposed. This criterion is directed to maximizing of profit evaluating system structure, parameters and accidental variables. However, main attention has been devoted to the assessment of operational algorithms of out-of-step mode elimination protection: the local type of protection (Alstom (P54x), Toshiba (GRL100), Siemens (SIPROTEC 5), SEL (311L), ABB (REL 512), "AJIAP-M" and "AGNA"), and the global protection (PMU, WAMS). As a result, problem scope that requires certain improvements and development has been formed and discussed in the next chapter.

In the second chapter new OSEP device realization possibilities have been examined. First of all, existing OSEP protection has been analysed and the necessary additions have been defined. Three new OSEP devices and two techniques have been developed and patented, which allow significantly improving selectivity and accuracy and increasing the range of possible actions. One realization example of OSEP scheme with N generators has been analysed to explain recitals principles. Conducting the analysis of modern protection terminals and existing technologies, OSEP function implementation in protection terminal has been analysed using existing differential protection high-speed channels and GPS synchronization. Additionally, OSEP control and blocking algorithms have been proposed such as OSEP operation in case of voltage circuit failure.

In the third chapter power system blackouts and OSEP operation modelling have been performed to verify efficiency and accuracy of proposed solutions. Thus, dynamical transient processes have been modelled using the Latvian transmission system with neighbouring systems model that has been created using modern ETAP 12.5 software. The main attention has been devoted to OSEP operation and efficiency in observed processes making the comparison with "AGNA" device. Also, simplified possible relay protection and automatics operation algorithms have been justified and their verification methodology has been developed for modelling processes of wide power systems transient stability loss.

The fourth chapter is devoted to power systems relay protections and anti-emergency automatics setting selection and verification problems, as well as to investigation of communication channels problems. The proposed setting selection and verification algorithms may be used for a wide range of relay protection and automatics. As a special research field, new automatics operation analysis in different power system modes has been performed to prove the adequacy and functionality of proposed blocking and triggering algorithms.

1. OUT-OF-STEP MODES OF POWER SYSTEM, BLACKOUTS AND THEIR ELIMINATION PROTECTION

Out-of-step mode (OOSM) is one of the most dangerous modes in power system. This mode is associated with parallel operation stability loss of power plants or individual generators, which can cause power systems element damage, customers' power supply interruptions, as well as significant economic and social losses. The OOSM main indicators are considered stable periodic fluctuation of current, power and voltage in transmission lines and in power system objects, and frequency difference existence between separate power system parts, which is troublesome for synchronous operation in spite of electrical connection availability [1], [2], [3].

The lasting OOSM has significant negative consequences such as generator unit damage, stability limit violations, customers who are sensitive to frequency and voltage level changes, and power supply interruption. Hence, selective, timely and secure identification of OOSM is important to eliminate it and to return into normal mode.

The power system mode and operation analysis demonstrates that synchronous mode disruption can occur due to the following reasons:

- impossibility of electricity transmission in the system after loss of one or more power lines;
- generating capacity deficits associated with one or more generator tripping;
- insufficient load amount connected to load shedding automatics.

Due to the use of market mechanism and its development, electrical network capacities practically reach the stability limits. Blackouts risks for the last ten years have significantly increased not only because of the impact of open electric power market. The second important factor is related to renewable energy source increase of the amount and installed capacity. The increase is based on the desire to reduce the effects of climate change, which in general led to the use of renewable energy. The development processes of observed power systems in many cases are caused by necessity of energy transmission over long distances. However, transmission capabilities are always limited.

Certainly, the parallel operation stability in emergency mode is maintained due to the impact of the synchronizing forces. In this case, anti-emergency protection (AEP) devices are used. AEP operates at the beginning of emergency. It makes part of elements, generators, or load trip and implements the power systems division into un-synchronous parts. These devices are called stability elimination/preventive automatics, which help to eliminate a significant amount of emergencies and simultaneously increase transmission capability of transmission lines in normal (pre-emergency or alert) modes. However, there are cases when prevention of stability loss using AEP is impossible or economically unjustified. In these cases, OSEP is employed, which is used for power system division.

Power systems modes which are formed during OOSM are complicated from the point of view of mathematical description and modelling; and almost always OOSM researches should be carried out under partial information circumstances. In practice, OOSM cases exist, when OOSMs of several generators are identified. Usually multifrequency OOSMs have very dangerous consequences, because synchronism restoration probability is negligible and standard OSEP is ineffective. The use of standard OSEP devices to eliminate multifrequency OOSM can take place under certain conditions. For instance, it happens if the connection between the two asynchronous parts and the third one of power system is relatively weak. Division should be carried out so that in the remaining parts there would be not more than two frequencies. Furthermore, OSEP protection must divide complex power system into balanced parts, which have maximal synchronism restoration ability and balance of generation-demand. Certainly, OSEP location choice is a very important and complex task. Its operation

organization is of prior importance evaluating sensitivity degree for certain OOSMs of equivalent generators and for OOSM insensitive to other generators; i. e., it is necessary to ensure selectivity. The multifrequency OOSM existence control and elimination system realization can be carried out by the microprocessor device that defines the angle between equivalent generators e. m. f. vectors and forecasts the possibility of stability maintenance in parts using special algorithms.

To comprehend OOSM consequences, it is enough to analyse blackouts, which have taken place all over the world recently [4]–[11]. From these examples it is possible to conclude that blackouts consequences are variable in volume, length, number of involved people and so on. It is evident that a universal approach to avoid blackouts does not exist. Generally blackouts are not caused due to one event, i. e., usually there is a series of events. In practice, there were no cases when emergencies happened due to one event on adequate and secure network. Analysing blackouts it is possible to conclude that majority of them are related to OOSR, which promotes scale extension of emergency. It is needed to comprehend that protection from natural disasters is almost impossible. That is why utilities must be ready to quickly and efficiently eliminate consequences, i. e., to perform the corrective actions.

The Thesis is focused on prevention of blackouts consequences using OSEP, which can significantly decrease these consequences performing dangerous power system part (-s) tripping. Certainly, selectivity and promptitude are ones of the main requests for modern protections. Capital funds are invested in modern AEP systems, which reduce the probability of blackouts taking different types of control actions.

It is important to note that protections operation begins in case of an already existing dangerous situation. To decrease the probability of this situation in power systems, the security conditions of mode must be met and the structure in selection stage must be made. To achieve this, a widely used “N-1” security criterion is used. “N-1” criterion has already existed for a long time in power system control due to its simplicity of use. However, up to this moment it has not been strictly and precisely defined. This creates significant complications in control principle development and harmonization of unified power systems. To prove the statement mentioned above, it is necessary to consider “N-1” criterion definitions [12]–[15]. Certainly “N-1” criterion plays an important role in power systems management, but it has a number of lacks [12]:

- There is no common “N-1” criterion approach, especially in cases that apply to power system interconnections.
- There is a need for improvement in defence plans (generation increase/decrease, load shedding).
- There is a lack of effective data exchange in real time of the status of neighbouring networks, i. e., this fact leads to sufficient uncertainty in decision-making process.
- “N-1” criterion can vary even within a single power system in different areas.
- There are power system management structure (centralized, de-centralized, horizontal, vertical etc.) main differences which cause significant complication in “N-1” criterion maintaining.
- Interconnection lines capabilities are limited due to historical development impact.
- There are no precisely defined time intervals in which power system must return into normal mode after “N-1” criterion accession to be ready to face new perturbation.
- Unified power system ideology differs (Nordel, UCTE etc.).
- “N-1” criterion cannot be fulfilled in some cases (for instance, Germany).
- There is an impact of uncontrollable power flows on “N-1” criterion (Denmark and Germany).
- Primary reserve amount of power is constant, and it is not optimized correspondingly with existing load amount.

- "N-1" criterion may be changed by requirements till "N-k" or "N-2", which proves "N-1" criterion insufficiency.
- There is a threat of unified power system if one system could not implement "N-1" criterion.
- "N-1" criterion does not include consequences, RP and EA operations.

The summary of the lacks mentioned above show the necessity to make changes in power systems management criteria developing new criteria and ideology that can evaluate dangerous modes and would effectively ensure power system stability (both statical and dynamical) performing mode management using probabilistic approaches.

Nowadays, risk assessment and management are widely used, intensively studied and developed [16]. Risk is associated with complex system functional aspects (applicable to power engineering), including [17]:

- qualitative security assessment for generation, transmission and distribution objects;
- criteria selection for power system planning and management;
- optimal compromise searching between system risk and economic effect in decision-making process;
- equipment aging failure management;
- spare equipment strategy development and selection;
- reliability-centred maintenance;
- load-side (costumer) risk management;
- performance-based rate policy;
- operation risk monitoring;
- interruption damage cost assessment and so on.

Risk management includes at least three aspects:

- performing quantitative risk evaluation,
- determining measures to reduce risk,
- justifying an acceptable risk level.

The severe power outages that have occurred for the last years prove that the single-contingency criterion ("N-1") that has been used for many years in the power industry may not be sufficient to maintain a reasonable system reliability level. However, it is also commonly recognized that no utility can financially justify more rigorous security criteria ("N-2" or "N-3") in power system planning. Evidently, one alternative is to bring risk management into the practice in planning (development and selection of alternatives), design, real-time operation, and maintenance, keeping system risk within an optimal range. It is important to comprehend that risk has both positive (profit) and negative (losses) sides. There are many ways of achieving the management objectives using corresponding methods. There are a lot of "RISK" definitions [18]–[23]. Summarizing the risk definitions, it is possible to divide them in two directions [19], [24]:

- Probability, uncertainty, possibility, and likelihood.
- Consequences, losses, and costs.

As a result, the term "RISK" components (probability and consequences) analysis in first approximation can be expressed as function:

$$R = P \cdot C, \tag{1.1}$$

where P is probability, $P \in [0,\ 1]$;

C is consequences in monetary value, €;

R is risk, €.

The calculation of these two components is a very complex task. In particular, this task becomes insolvable in case of a huge power system, when the number of influence factors, controllable parameters and possible configuration exceeds hundred thousand. Furthermore, it is necessary to keep in mind that all these variables vary in time. Therefore, the task should be limited in order to be able to implement risk assessment and management.

One of possible risk assessment and management structures is depicted in Fig. 1.1. Risk management process helps in decision-making process evaluating the possibility of uncertainty and future events or circumstances (expected/unexpected) and their impact on implementation of objectives.

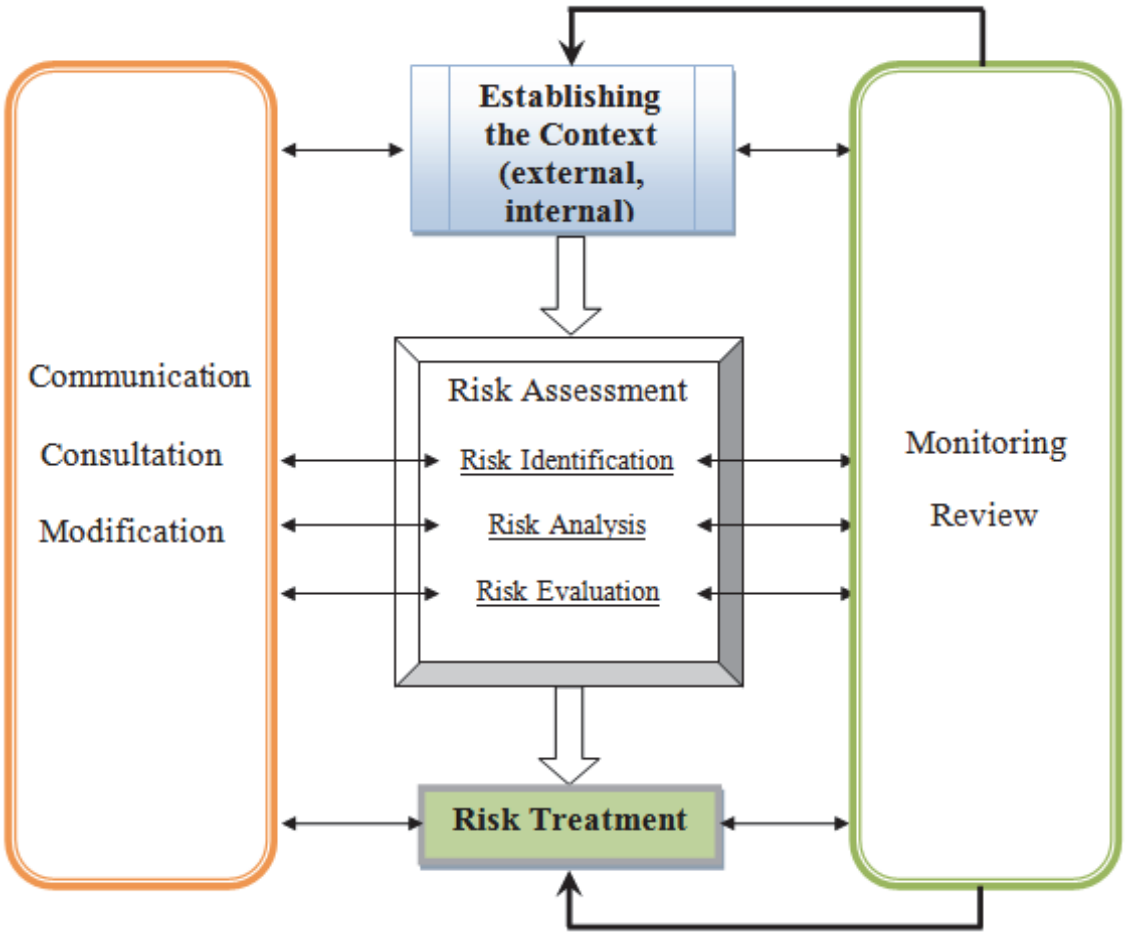

Fig. 1.1. The structure of risk assessment and management processes [25]

Risk assessment is part of risk management process that ensures structured process, which, in turn, identifies possible impact on objectives and analyses risk using consequences and probability expression estimating necessity of further risk treatment (Fig. 1.1). Risk assessment process includes such sub-processes as identification, analysis and evaluation of risk (Fig. 1.1). The principle this process is applied to depends not only on the context of the risk management process but also on the methods and techniques used to carry out the risk assessment. Risk assessment may require a multidisciplinary approach since risks may cover a wide range of causes and consequences. There are often considerable uncertainties associated with the risk analysis. The comprehension of uncertainties is needed to interpret and present risk analysis results effectively. The analysis of uncertainties which is associated with data, methods and models used to identify and analyse risk plays an important role in their application.

An area closely related to uncertainty analysis is sensitivity analysis. Sensitivity analysis involves the size and significance determination of the risk magnitude to changes in individual input parameters. It is used to identify those data that must be accurate and those ones that are less sensitive and, hence, have less effect upon overall accuracy.

Risk assessment is not a stand-alone activity and it is fully integrated in the risk management process with other components (Fig. 1.1). The risk assessment process will highlight factors that can vary over time and could change or invalidate the risk assessment. These factors must be specifically identified for monitoring, so that the risk assessment can be updated when necessary. Risk assessment can be applied at all life cycle stages and is usually applied many times with different levels of detail (accuracy) to assist in the decision-making process. It is important to note that each life cycle phase has different needs and correspondingly appropriate techniques are required. As a result, it is possible to conclude that risk management is a very complicated task that requires comprehensive knowledge of objects and processes which occur in it, as well as the knowledge of external factors which influence it.

Thus, in order to successfully apply the risk assessment and management, one should be able to choose the necessary risk assessment technique [26]. Risk assessment techniques may be classified in different ways to understand relative advantages and disadvantages.

All operations that are associated with probability changes are mainly related to preventive activities such as control of element status, system monitoring, scheduled maintenance, and etc. Certainly, corrective activities also exist. They mainly focus on consequences minimization of undesirable events.

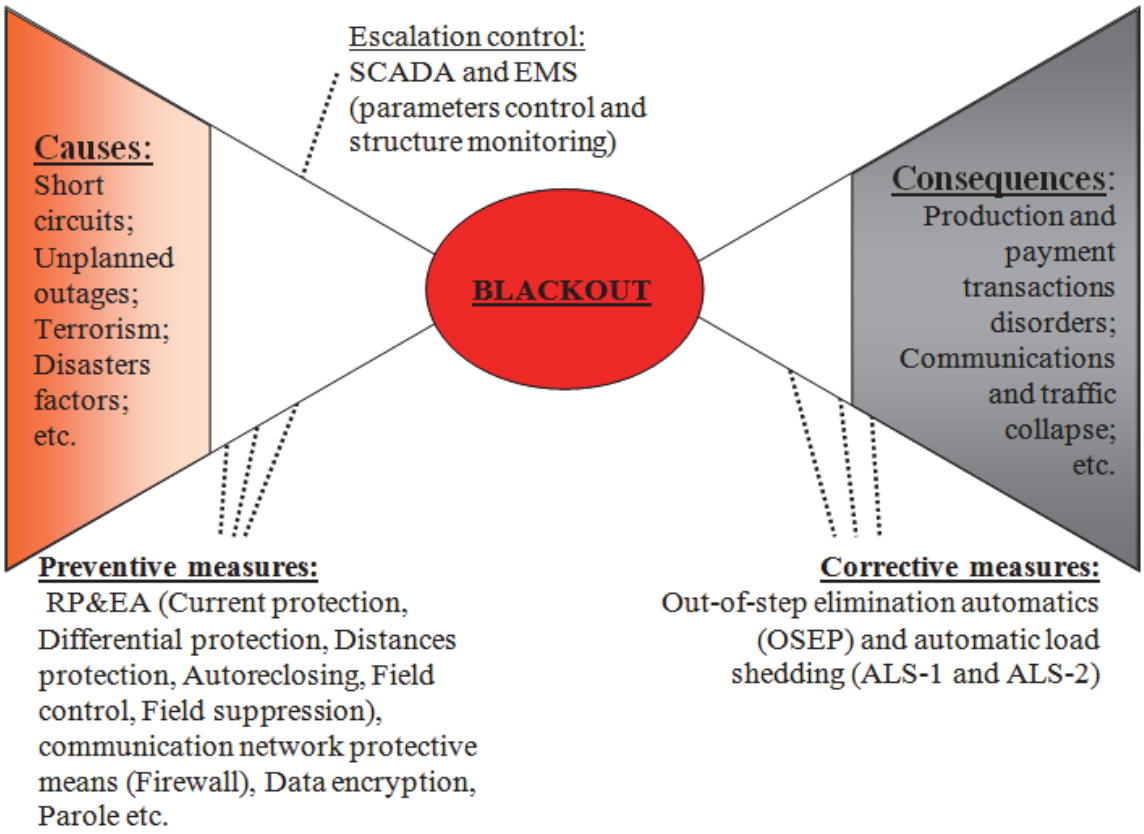

Fig. 1.2. Bow tie diagram technique for a blackout analysis

To comprehend the nature of preventive and corrective measures, it necessary to analyse one example associated with a bow tie diagram technique [26]. This technique forms problem display and comprehension of existing control degree. Using this technique, it is possible to

assess existing control effectiveness, as well. As for its drawbacks, it is important to note that a bow tie diagram could not depict causes that happen simultaneously and lead to corresponding consequences. Thus, this technique will be used for EA effectiveness analysis in case of blackout (Fig. 1.2).

Therefore, as an event in this example, power systems blackout is taken. The causes may be different; for instance, they may be long short circuits, unsuccessful autoreclosing, terrorist acts, hacker attacks, natural disasters, and etc. There are also different types of RP&EA and other features used as preventive measures in the course of emergency. Escalation control takes place in dispatchers' centres using SCADA and EMS systems [27]–[29]. Blackout consequences may be decreased using division protection (OSEP) and load shedding protection. In this Thesis, the main attention is paid to OSEP.

All articles on risks, results of scientific studies, risk management methods and techniques can be divided into two main categories [30], [31]:

- first: to reduce the probability of undesirable (cause loses) cases and events;
- second: to reduce the losses which may occur due to these undesirable events.

All publications can also be divided into two groups in another way. The first group includes publications, where risk identification is given, and where possible risks and their consequences are analysed. Unfortunately, it is not possible to apply them to the power management or to further structure development. This part of publications outnumbers the other group. The other group is associated with publications, where numerical solutions are proposed. These solutions can be used in different spheres such as banking, insurance, and logistics. Also in the field of power system there is a relatively small number of publications, which contain proposed solutions that can be used in risk management. Thus, the lack of probabilistic decision-making methods in the risk management is evident. In this Doctoral Thesis a solution is proposed.

Therefore, it is necessary to analyse risk using decision-making theory point of view. To define the risk concept, it is necessary to put forward the following four hypotheses [30], [31]:

- The fundamental objective of considered systems (the term "system" is wider than the power system) is to achieve profit **R**.
- The obtained profit depends on the random **X** case and uncertain parameters $\mathbf{X_n}$ (the case parameters have a probability distribution function; uncertain ones do not have).
- Decision maker (expert) can choose a subjective probability function distribution [32]–[34] to convert uncertain parameters into case parameter class.
- System profit **R** depends not only on independent parameters of the decision maker **X** and $\mathbf{X_n}$, but also on chosen structures **Σ** and their parameters **Π**.

On the basis of the formulated hypotheses, it is possible to conclude that system profit can be expressed by equation:

$$R = F_R\left(X, X_n, \Sigma, \Pi\right) = F\left(X, \Sigma, \Pi\right) \tag{1.2}$$

Function **F(X, Σ, Π)** depends on case parameters X and, thus, knowing (choosing) **Σ** and **Π** it is possible to create profit **R** distribution function such as distribution density. Of course, one can also calculate distribution function numerical variables such as, for instance, expectancy **E(R)**:

$$E\left(R\right) = \int_{\Omega} R\left(X, \Sigma, \Pi\right) d\varphi\left(X\right) \tag{1.3}$$

where φ (X) is parameter X probability distribution function;
Ω is parameter X existence borders;
∫ is multidimensional integral of Stieltjes-Lebesgue.

If equation (1.3) is used, simplified task appears, that is, if the mathematical probability of profit or loss is taken as the risk and optimization tasks criteria of system management. In this case optimization task is expressed as follows [30], [31]:

$$(\Sigma, \Pi)_{opt} = \arg\max E(R(X, \Sigma, \Pi)) \tag{1.4}$$

where $(\boldsymbol{\Sigma}, \boldsymbol{\Pi})_{\mathbf{opt}}$ are optimal maximal profit mathematical probability structures $\boldsymbol{\Sigma}$ and parameters $\boldsymbol{\Pi}$.

From the perspective of risk management problem, the definition of examined optimization task gives an opportunity to use the only criterion – profit mathematical probability. It turns out to be more profitable in usage in comparison with multi-criteria tasks.

Statistical decision theory offers the risk management function effectiveness criterion of mathematical probability [32], [34], which allows describing the optimization tasks as one criterion management statement, at the same time taking into account undesirable event probability, their consequences and decision maker's desire to avoid large losses even if they occur in rare cases.

Essential difficulties are associated with loss evaluation of emergencies (blackouts). *Unsupplied energy costs cannot be used as one indicator in risk management tasks.* In loss evaluation description it is possible to use approved decision making principles of power facility design. Risk assessment is connected with difficulties caused by math (huge variable number, complex structure, etc.) and information (uncertain parameters, loss function representation complexity) features.

Probabilistic power system models and Monte-Carlo method must be used for risk assessment. To reduce high costs of calculation, it is possible to use task simplification and not to do ill-informative process modelling (normal modes).

OSEP must ensure power system division into parts in order to preserve their sufficient viability. It also ensures probability increment of positive emergency outcome reducing possible blackout consequences because there is a relatively high probability that at least one part of the system will be operational. If one examines this problem from the perspective of risk assessment, it is possible to conclude that risk division is being done. As a result, automatics potential effective use can reduce overall risk of power system blackout. OSEP exploitation is a complicated task. The installation of these devices in power system requires the choice of optimal place, operational principle (including control actions) and settings. As a rule, in order to select settings and verify their efficiency it is needed to perform a huge volume of calculations. The accepted solutions depend on different power system modes: importance of transmission line, configuration, regime impact on power plant stability, influence on major load points and common power system mode.

The choice of the calculation algorithm is made on the basis of probabilistic division consequences and stability loss.

All mode parameters are closely interrelated, and different parameters and their combinations are used for OOSM identifications. For OOSM identification the following principles are used:

- Impedance measurement where impedance $Z = R + jX$ and speed changing of this impedance real part dR/dt are calculated. In OOSM vector Z moves fast in complex plane with significant changes R and negligible counteracting changes X. In case of short circuit, speed change of active resistance dR/dt is different from OOSM or power swings mode. Measuring dR/dt it is possible to determine OOSM or swing existence.
- Angle principle where, measuring (modelling) angle between electric values that are modelled by the device, it is possible to determine angle stability loss. Controlled angle transition over critical value means OOSM or dangerous swing existence.

- Parameter variation of transient stability modes that characterizes OOSM; OOSM process parameters – current, voltage, and power – periodically vary. These values can be used for OOSM identification.
- Determination of existence of two or more frequencies in device installation place. Power system generators are operating with different frequencies creating nonsinusoidal parameters of transient processes. Analysis of harmonics allows determining generator rotation frequency.

Nowadays protection terminals (ABB, Toshiba, SEL (Schweitzer Engineering Laboratories), Siemens, Alstom, and etc.) are manufactured all over the world. To understand the principles implemented in protections terminals as well as their limitations and drawbacks, it is necessary to conduct an analysis of devices which now are present on the market. Alstom P54x series protection zones are shown in Fig. 1.3(A) [35]. It is important to note that SEL and Siemens have similar protection zones. ABB terminals have a circular characteristic (Fig. 1.3(B)), but the operation principle is the same for the mentioned manufacturers [36].

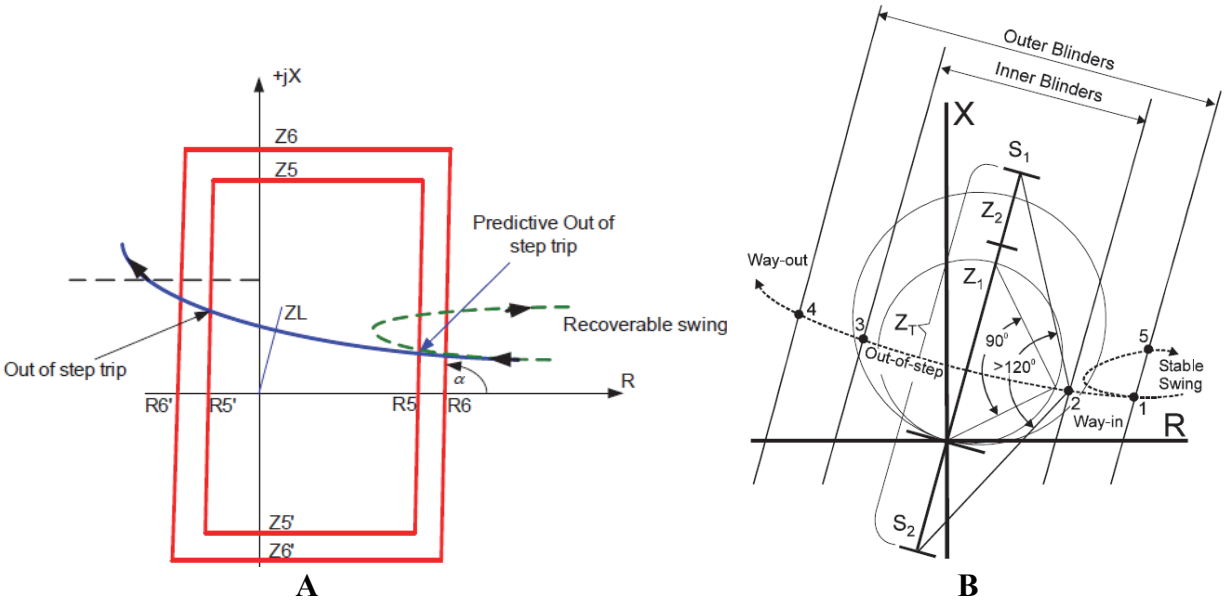

Fig. 1.3. Out-of-step mode identification characteristic (zones): A – Alstom, B – ABB

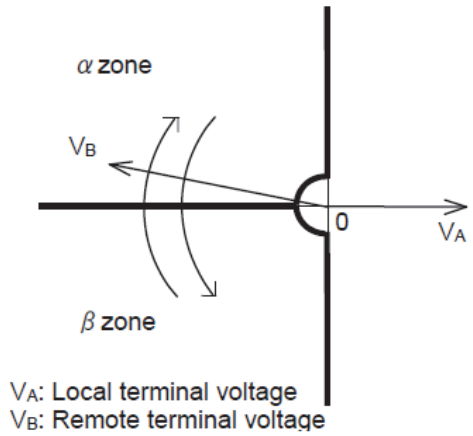

Fig. 1.4. OSEP protection principle [38]:
V_A – local terminal voltage; V_B – remote terminal voltage

In 1980, Toshiba developed and started to produce the first fully numerical differential relay as a transmission line terminal protection [37]. At present, Toshiba has developed a new

relay in which high-speed operations are achieved (typically 16 ms). In [37] different functions of protection combined in one terminal are proposed. Among these functions OSEM is available, as well. This function operates only in case when electrical swing centre (ESC) crosses the protected line and secures power system separation. In OSEP algorithm, the phases of local and remote positive sequence voltages are compared. It detects OOS when the difference between phase angles exceeds 180 degrees. In Fig. 1.4, an operational principle is shown. The protection identifies OOSM by controlling the phasor V_B transition from the second quadrant of zone α to the third quadrant of zone β or vice versa if phasor V_A is used as a reference phasor. Another feature is associated with the requirement that phasor V_B must remain in each quadrant (II or III) for 1.5 period of time to avoid the influence of any VT transient processes.

Conducting the analysis of the protection mentioned above, different drawbacks were revealed. They are mostly associated with settings selection, as well as with the response time. Setting selection is a complicated task, which is related to a set of possible mode research. Of course, relay settings must be intercoordinated to provide selectivity. RP&EA operation coordination allows avoiding uncontrollable separation and its consequences.

Discussing power system protection terminal installation (for instance, A and B, Fig. 1.5), it is possible to conclude that inherently they protect one element (line, transformer, etc.). As a result, it can be stated that they control local parameters (bus voltage, line currents) and using these a decision on corresponding control action implementation is made.

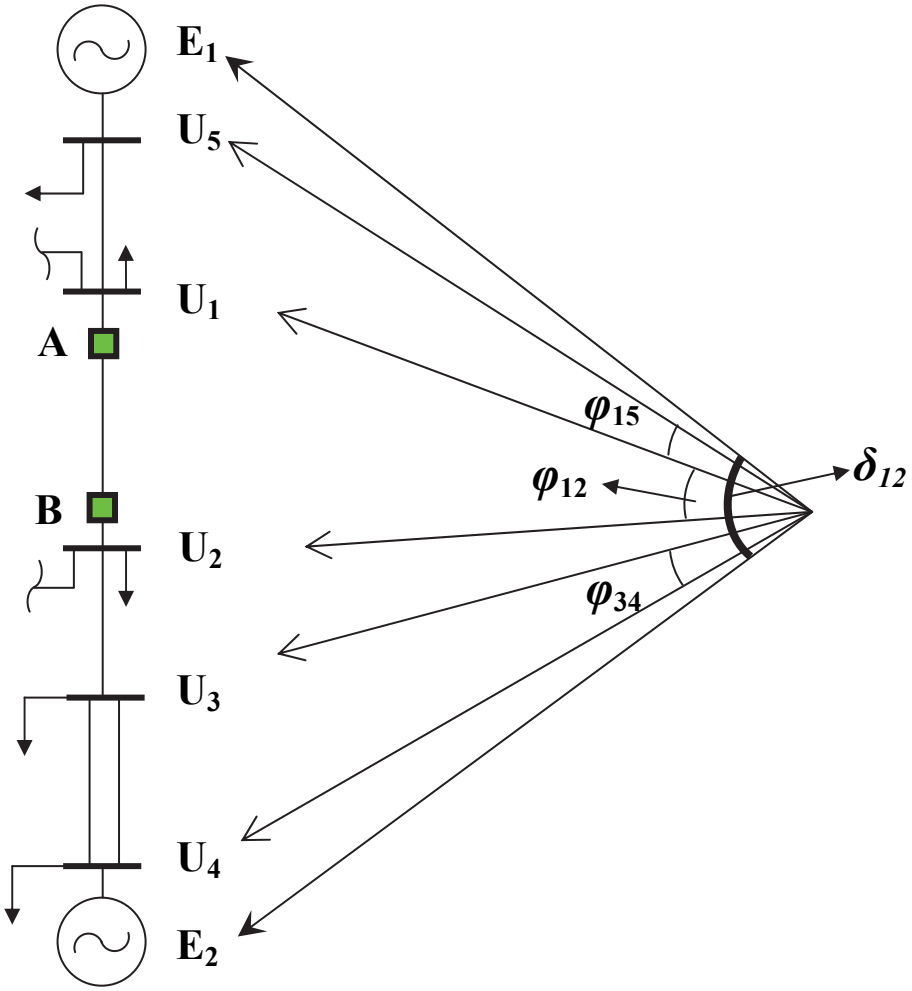

Fig. 1.5. Simplified power system structure and regime parameters

Similarly, there are possible such cases when impedance can change unevenly if an element is switched off suddenly (change of topology and power flows). It is clear that a major part of terminal stands idle when ESC crosses the protected element zone. Any time delay for OOSM identification can unfavourably affect emergency consequences spreading because two frequencies OOSM may transform into multi-frequencies OOSM. Also, in case of bus voltage loss of Toshiba terminals, OSEP function will be blocked in two terminals. Other aspects are concerned with communication channel failures, due to which terminals almost completely lose their functionality.

It is important to point out the main problem which is associated with controlled angles. The observed protections control a local area (A and B (Fig. 1.5)), which generally contains one line. For instance, Toshiba principle (Fig. 1.4.) controls angle φ_{12} between voltages U_1 and U_2 and operates when this angle exceeds 180 degrees [38]. OOSM may appear much earlier. But it is necessary to wait while this will be identified and power system separation will be performed. It is well known that time is one of the most critical factors that can provoke catastrophic consequences if OOSM is not stopped timely. Therefore, it is needed to enlarge the controlled zone, for instance, in Fig. 1.5 it may be buses U_4 and U_5.

Modern security requirements encourage development in OSEP field. As a result, using microprocessors certain devices are developed such as, for instance, "AJIAP-M" [39], [40] and "AGNA" [41], which allow covering a wider control zone (Fig. 1.5).

Presently "AJIAP-M" devices are used as element of EA in a unified power system of Russia. The device performs controlled current and voltage input and control of corresponding mode parameters. Operational principle of the device is based on the use of two equivalent generators OOSM identification algorithm, which uses e. m. f. phasor motion trajectory and ESC recognition in controlled zone. In calculations positive sequence voltages, base line positive sequence current and additional line current of phase "A" as well as corresponding impedances of electrotransmission are used. Simultaneously the device calculates the angle between e. m. f. phasors and the slip sign between power system parts. Selectivity of the device is performed using ESC control in a protection zone.

The device has three stages, and each stage performs output signal formation, which corresponds to surplus and shortage parts. The first stage is high-speed and it operates during the interval when transient process occurs into OOSM till angle exceeds 180 degrees. Other stages operate with time delay, which corresponds to several asynchronous turns. The stages are used consecutively, i. e., at a time moment only one stage operates. Blocking is used to decrease incorrect actions probability for failure, which is not OOSM. It is performed using maximum allowed changes of angle speed and negative and positive sequence of voltages and currents [40].

The similar type of automatics is manufactured in Latvia, owing to the staff of Riga Technical University, the Faculty of Power and Electrical Engineering a new device "AGNA" was developed and patented [41]. This device has proved its competitiveness and potentials in anti-emergency automatics field.

"AGNA" is intended for 110–330 kV line and switch control for power system OSEP. Its operation principle is to measure angle φ and its rate of change $d\varphi/dt$ (Fig. 1.6). This principle is used in the "AGNA" device.

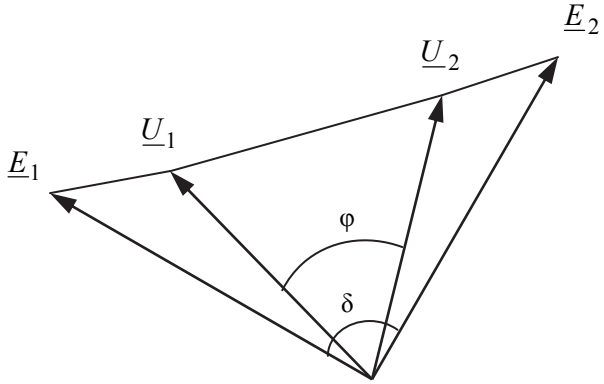

Fig. 1.6. Phasor diagram

"AGNA" models voltages of generator buses using the following formulas (Fig. 1.7):

$$\underline{U_1} = \underline{U} \pm \underline{I} \cdot Z_{K1} \tag{1.5}$$

$$\underline{U_2} = \underline{U} - \underline{I} \cdot Z_{K2} \tag{1.6}$$

where $\underline{U}$ is phase voltage, V;

$\underline{I}$ is phase current, A;

Z_{K1}, Z_{K2} are settings, Ω.

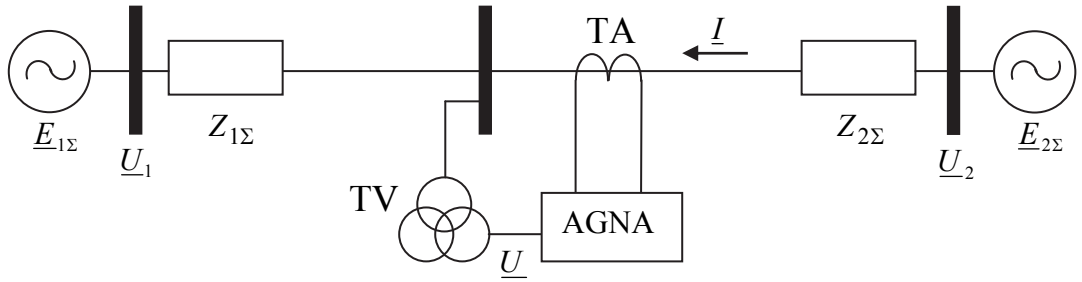

Fig. 1.7. "AGNA" connection scheme

"AGNA" operational conditions are determined using one of two possible algorithms. The first algorithm does not allow the phasor to make a full turn. Operation takes place in the first cycle correspondingly to angle measurement characteristic with two stages in a base zone and one stage in a reserve zone. The second algorithm allows for several cycles. The number of cycles depends on selected setting, which defines the number of operational cycles. This setting automatically assigns operational algorithms.

When GPS systems started to develop rapidly, it became clear that this system proposes the most effective way of remote measurement synchronisation. Nowadays there are other systems similar to GPS systems such as, for instance, GLONASS, BeiDou or DBS, Galileo, which were created in other countries for analogous purposes. As a result, it is possible to conclude that GPS systems are and will be used as a synchronization source for Phasor Measurement Unit (PMU) devices.

Therefore, it is needed to analyse GPS synchronization possibilities in the power system field. In the following cases, precise time synchronisation is needed, which obviously can be achieved using GPS possibilities: relay protection, power system automatic frequency adjustment, load management, load control in power grid over extended areas, and identifying of failure locations [42]. PMU systems are used in modern power systems as part of Wide Area Measurement System (WAMS). Transmission speed of information is not crucial

anymore. This means that data are sent to the control centre at different time according to communication channels transmission speed.

PMUs send measurement using communication channels on a higher hierarchy level. PMU installation place is chosen correspondingly with existing necessities and goals. Phasor measurement system hierarchy is shown in Fig. 1.8. This system structure includes PMU, data concentrator (PDC) and data centre as well as communications links and software. Measurements are stored at local storage for diagnostic and analysis. PDC function is data collection from several PMU simultaneously performing bad data declining, measurement packing correspondingly to time scale and data recording. It is important to note that information flow is bi-directional (PMU configuration and request data) [43].

Communication possibilities of PMU form the base for data transmission from remote locations to the Control Centre. Two data transfer aspects are significant in any communication task [43]. The first aspect is channel capability measured in kbps or Mbps. The second aspect is latency, which is defined as the time lag between the time, at which the data are produced and when they are available for the desired application.

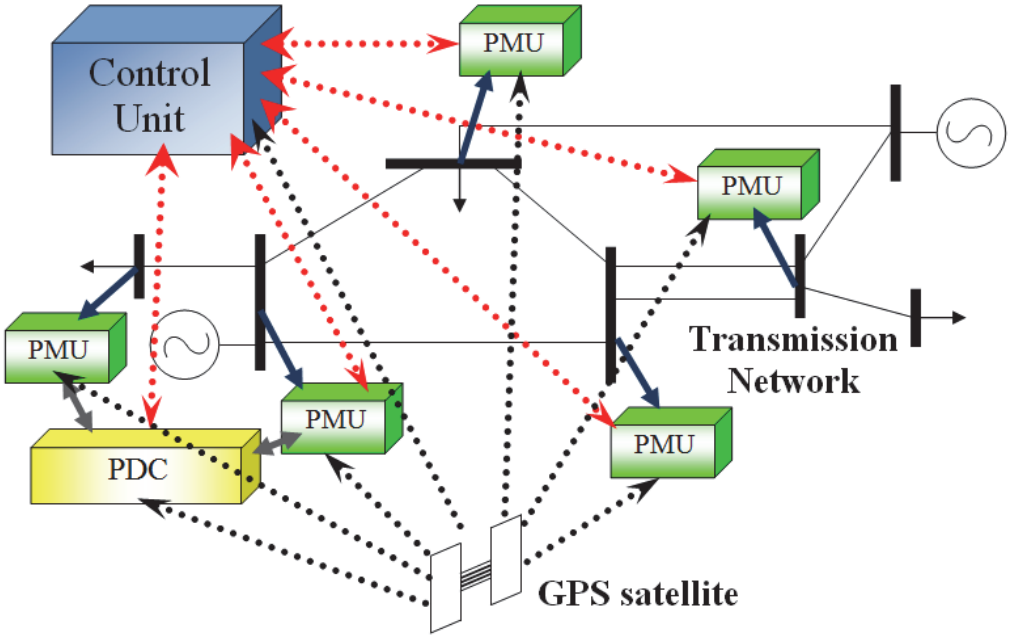

Fig. 1.8. Phasor measurement system hierarchy

PMUs form WAMS, which can perform adaptive restoration mode with minimal losses and time. Power system restoration example is analysed in [44]. PMU systems are used in intelligent islanding, too. Power system separation into islands is a measure of last resort, which performs blackout consequences reduction. Of course, on the island there should be a balance between generation and load. In reality, this requirement is difficult to achieve using classical management methods (previously calculated settings values) because modes and structure are variable parameters in time. As a result, for the precise control information is necessary before disturbance occurs. The information can be provided by the PMU system. Using these data it is possible to implement generation or load switching for achieving balance (keeping the parameters within permissible range).

Undoubtedly, the PMU has several drawbacks, which are mainly associated with time delays [45], [46] and with performing of specified control algorithms. However, the main drawback is GPS signal failure when the whole system loses its functionality. As a result, all data received in PDC and control centres cannot be used for mode control due to the lack of unified time scale. Therefore, technical and economic analysis must be performed using risk

management basics and criteria and after that it is possible to make a final decision about necessary improvements.

It is also important to note that WAMSs are integrated in Energy Management Systems to ensure specified type of signalizing to centre about stability loss or transition in a dangerous mode zone [45]. PMU system data coupled with SCADA and network configuration can be used to identify stable mode limits of power system.

2. OUT-OF-STEP PROTECTION DEVICE REALIZATION

There are possible two OSEP realization variants. In this chapter the two variants are proposed: the first one is device realizations as separate protections; the second one is the function of multifunctional protection terminal. It is clear that the second variant is more beneficial because manufacturing costs would not significantly increase and functionality would not be reduced. Analysing "AGNA" device it was decided to modernize it. It is also necessary to assess expandability of output relay blocks for the OSEP device so that it could fulfil a wide range of relay protections and automatics functions (tripping of the elements and loads, generation units switching on/off, signalization, and etc.). The following structure of the device was designed (Fig. 2.1).

As output signal sources CT and VT, Hall sensors, optical CT and VT can be used. The frequencies spectrum of controlled signals also contains components of higher harmonics (2^{nd}, 3^{rd}, 5^{th}, and etc. harmonics). For the limitations of frequencies spectrum different anti-aliasing filters (AAF) are used. The qualifying standards (type, function, and etc.) may vary for different RP&EA. For this type of automatics narrowband filters must be used (Butterworth filter), which allows limiting the influence of high frequencies on calculations results. Thus, signals are filtered for 50 Hz frequency using anti-aliasing filters (AAF) (Fig. 2.1).

The next stage is the processing of analogue signals, i. e., their transformation into digital signals. To process analogue signals, input signal multiplexing was chosen, which was more effective in case of large controlled variable (signals) number. In this case, multi-channel multiplexor must be used (accordingly to the input signals). In the proposed structure (Fig. 2.1), it is possible to control 16 analogue signals using one multiplexor with 16 channels.

One of the main parameters that defines ADC system is the necessary accuracy of ADC within all range of signals. ADC maximal accuracy will be reached only if the signal level will be coordinated with full ADC input range (the number of degrees quantification). Therefore, processing small input signals (nominal currents or reduced voltages) ADC dynamic range significantly decreases, which causes increase in the noise and error impact in the input signal.

A possible solution is to use pre-scaling of input signal, i. e., its reduction correspondingly to a maximum acceptable input range of ADC. Taking into account hardware minimisation requirement, such a variant was selected where the scale is chosen using software features:

- Preliminary ADC for signal value assessment to select a scale coefficient;
- ADC for signal using a corresponding scale.

Accuracy of convector is defined as a maximal value of all its errors. This value for most of ADC usually does not exceed a lower order. Possibility to use a scale for input signal allows decreasing requirements proposed for ADC order and input range. Using one ADC for processing a large number of analogue signals, factors of time deviation appear for processing signals of different channels. The time deviation is heavily dependent on ADC processing time.

Additionally, the device has an ability to control discrete signals (relay contacts, etc.). To perform this function, a block of discrete signals is used (Fig. 2.1), which provides opto-electric and galvanic isolation to control circuits.

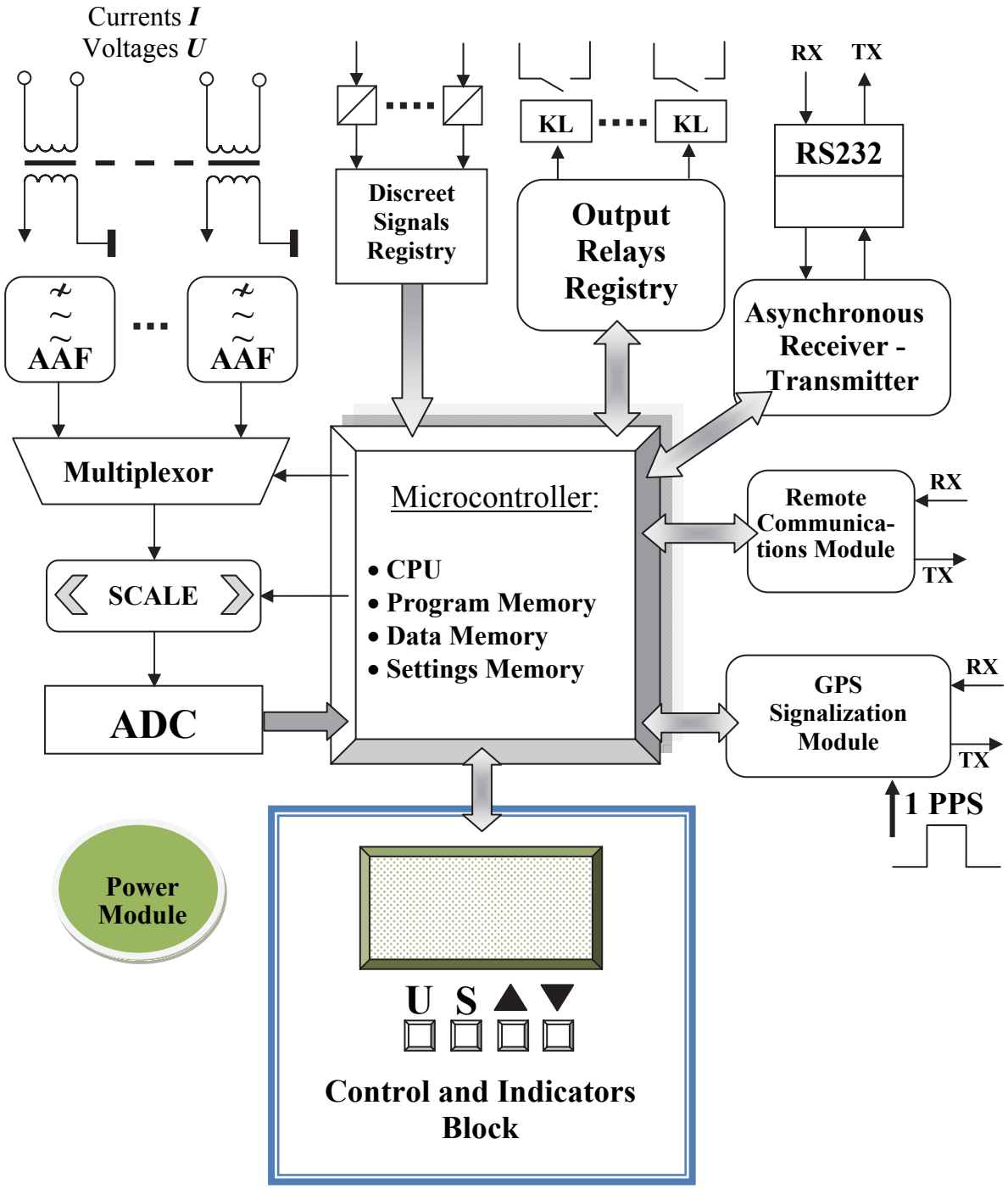

Fig. 2.1. Simplified realization structure of device

Of course, each relay protection and automatics devices have output intermediate relays. For their security strict requests are proposed. Taking this into account, this possibility to control and block must be fulfilled against incorrect operating if there is incompliance between commands given to relay and its real position. The variant may be accepted if it requires the usage of hermetic box relay and operating control of relay winding. The output relay block (Fig. 2.1) provides relay operating in cases if relay control elements (transistor)

are damaged. It also allows controlling coil condition using corresponding software. The number of relays in a block can vary from one to nine.

Usually protection devices have settings and constant sets. These data validity and saving ensure normal operation of a device. The most securable storage element is read only memory (ROM). Settings storage in digital format allows achieving maximum accuracy of settings defined only by this discrete change degree. Furthermore, external factors such as supply voltage variation, temperature, humidity, pressure, and etc. do not affect setting variables. The block is provided with setting storage memory and it ensures the storage in different conditions of the device exploitation.

User interface block (Fig. 2.1) allows displaying settings using indicator and changing them. There are also several solutions, which allow blocking unauthorized access and inputting new settings.

It is clear that the advantage of a microprocessor device over other type devices (analogue and electromechanical) is the information exchange possibility with other hardware or PC. For information exchange RS-232 is used (Fig. 2.1), which allows performing local information exchange. For remote objects communications RS-422 and RS-485 are used, which carry out information exchange among objects or devices.

For measurement synchronization GPS options are used. In the OSEP realization scheme there is a GPS module, which synchronizes measurement using 1 pulse per second (Fig. 2.1).

The running time of large number of service and basic functions is strictly limited (operation in real time) and, as a result, it promotes increased requirements to CPU performance (Fig. 2.1). Multiprocessor structure use significantly increases hardware costs as well as it can influence common device security. As a result, the Harvard structure processor (TMS320Fxxx), which performs operation with fixed point and multiplies 16 digits numbers by one command, was chosen [47], [48].

It is important to note that existing modern OSEP methods have several drawbacks. These drawbacks bring complications in settings selection, and, consequently, unacceptable actions can happen. Moreover, the research results show that there are significant problems associated with equalizing different types of generator equivalentation.

Analysing formulas (1.5) and (1.6), it is possible to conclude that modelled voltages can be influenced by various mode factors that vary in time. As an example, equivalent impedance variations of power system can be mentioned (structure variation, existing generator units switching off in minimal load mode, and etc.). Consequently, protection zone limits can significantly change, which would provoke excessive operations or which would not operate timely.

The first solution is suggested in patent **LV 14375 B** [49]. The drawback of "AJIAP-M" and "AGNA" devices is that bus voltages $\underline{U}_1$ and $\underline{U}_2$ are modelled using voltage and current at a device installation place, which can be far away from generator sources. For accurate control of generators, e. m. f $\underline{E}_1$ and $\underline{E}_2$ (Fig. 1.5.) must be used. Moreover, different loads can be connected to buses that provoke additional voltage drop on generators impedance. Therefore, voltages of these buses do not represent equivalent generators angles precisely enough (Fig. 1.6.).

Thus, patent **LV 14375 B** device is modelling angle δ between generator e. m. f. and its rate of change. Generators e. m. f. are calculated using the following formulas [49]:

$$\underline{E}_1 = \underline{U}_{K1} + \underline{I}_{G1} \cdot Z_{G1}, \tag{2.1}$$

$$\underline{E}_2 = \underline{U}_{K1} \mp \underline{I}_L \cdot Z_L + \underline{I}_{G2} \cdot Z_{G2}, \tag{2.2}$$

where $\underline{I}_{G1}$, $\underline{I}_{G2}$ are equivalent generators currents,

$\underline{I}_L$ is line current,

$\underline{E}_1$, $\underline{E}_2$ are equivalent generators e. m. f.,

Z_{G1}, Z_{G2} are generator-bus branch impedance (setting),

Z_L is line impedance (setting),

$\underline{U}_{K1}$ is bus voltage.

The device has more precise generators e. m. f. modelling and, consequently, it has accurate operation because complex load influence is eliminated comparing with "AJIAP-M" and "AGNA" devices. These devices can be used only in relatively simple networks (trunk lines), where they can ensure acceptable accuracy and selectivity.

However, every year the power system structure becomes more complicated because new power sources, lines, customers, and etc. appear. Thus, it is necessary to analyse cases where in transmission lines there are nodes with time variable load. As a result, the drawback of [49] device modelling method is that in case if between buses in a transmission line there appears load node (-s), which considerably changes load value in a day period. In this case, modelled e. m. f. phasor angle deviation from real value (2.2) is observed. There are also cases when modelling is impossible as a confluence point appears in a line. Consequently, the second equivalent generator e. m. f. is not modelled precisely for the device. In this case, to improve modelling accuracy, [50] device models the first generators e. m. f. $\underline{E}_1$ using first bus voltage $\underline{U}_{K1}$ and first generator currents $\underline{I}_{G1}$ (2.3). The device models e. m. f. $\underline{E}_2$ (transmitted using a communication channel) of second equivalent generator using second bus voltage $\underline{U}_{K2}$ and second generator currents $\underline{I}_{G2}$ (2.4). Measurements time difference is eliminated using GPS synchronization pulses. E. m. f. in this case are calculated as follows [50]:

$$\underline{E}_1 = \underline{U}_{K1} + \underline{I}_{G1} \cdot Z_{G1}, \tag{2.3}$$

$$\underline{E}_2 = \underline{U}_{K2} + \underline{I}_{G2} \cdot Z_{G2}, \tag{2.4}$$

where $\underline{I}_{G1}$, $\underline{I}_{G2}$ are equivalent generators currents,

$\underline{E}_1$, $\underline{E}_2$ are e. m. f. of equivalent generators,

Z_{G1}, Z_{G2} are generator-bus branch impedance (setting),

$\underline{U}_{K1}$, $\underline{U}_{K2}$ are voltages of buses.

This method operates quite accurately, but in this case each device settings are extremely important. It must be noted that in case if one device settings are selected incorrectly, the angle deflection from real value of controlled e. m. f. takes place. Another issue is associated with power plant generators equivalentation; for instance, in case of HPP specific problems do not exist because all generators are usually equal in type, power, and etc. Analysing heat-electric generation plants where different types of generators are used, equivalentation is associated with significant errors. It is usually associated with generator inertia constant and loading degree, which sometimes influences directly transient process nature.

Therefore, in [50] the drawback of e. m. f. modelling method is the following: modelling *equivalent generators* e. m. f $\underline{E}_1$ and $\underline{E}_2$ using *equivalent generator* currents $\underline{I}_{G1}$ and $\underline{I}_{G2}$ as well as voltages of the first and second buses $\underline{U}_{K1}$ and $\underline{U}_{K2}$ (2.3, 2.4), angle deflection of real generator e. m. f. phasor is caused. As a result, the patented device [50] cannot precisely model real generators e. m. f. OSEP device modelling precision depends on the number of generators used in power plant, their type and connection scheme, loading degree, constant of inertia, and etc. The method proposed in figure [50] cannot perform acceptable device operation precision and selectivity.

To achieve the goal mentioned above, device [51] models *i*-th e.m.f $\underline{E}_i$ of generators using first bus voltage $\underline{U}_{K1}$ and *i*-th generator currents $\underline{I}_i$ multiplied by corresponding impedance setting Z_i (2.5). E. m. f. $\underline{E}_i$ are transmitted to the first processor input. A communication channel output is connected to the second processor input, where *j*-th generator e. m. f. $\underline{E}_j$ modelled from second bus voltage $\underline{U}_{K2}$ and *j*-th generator currents $\underline{I}_j$ multiplied by corresponding impedance setting Z_j (2.6) are sent from the second device (index *i* and *j* correspond to the 1st and 2nd devices). For measurement time synchronization GPS pulses are used. It is important to note that communication channel becomes an integral part of power system and it has special requirements (processing speed, high reliability degree, and etc.), which must be evaluated. The main advantage of the proposed device is increased precision of measurements and modelling accuracy because the error, which exists making the different types, inertia constant and unequal loading of generators equivalentation, is eliminated. The measurements are made in branches "generator-bus".

First of all, the case of four generators must be examined and after this attention will be paid to generalized case with N generators. In Fig. 2.2, the OSEP device realization example **with four generators** is shown. Thus, the OSEP device is connected to buses, which are connected network elements (transformers, compensation devices, loads and other devices).

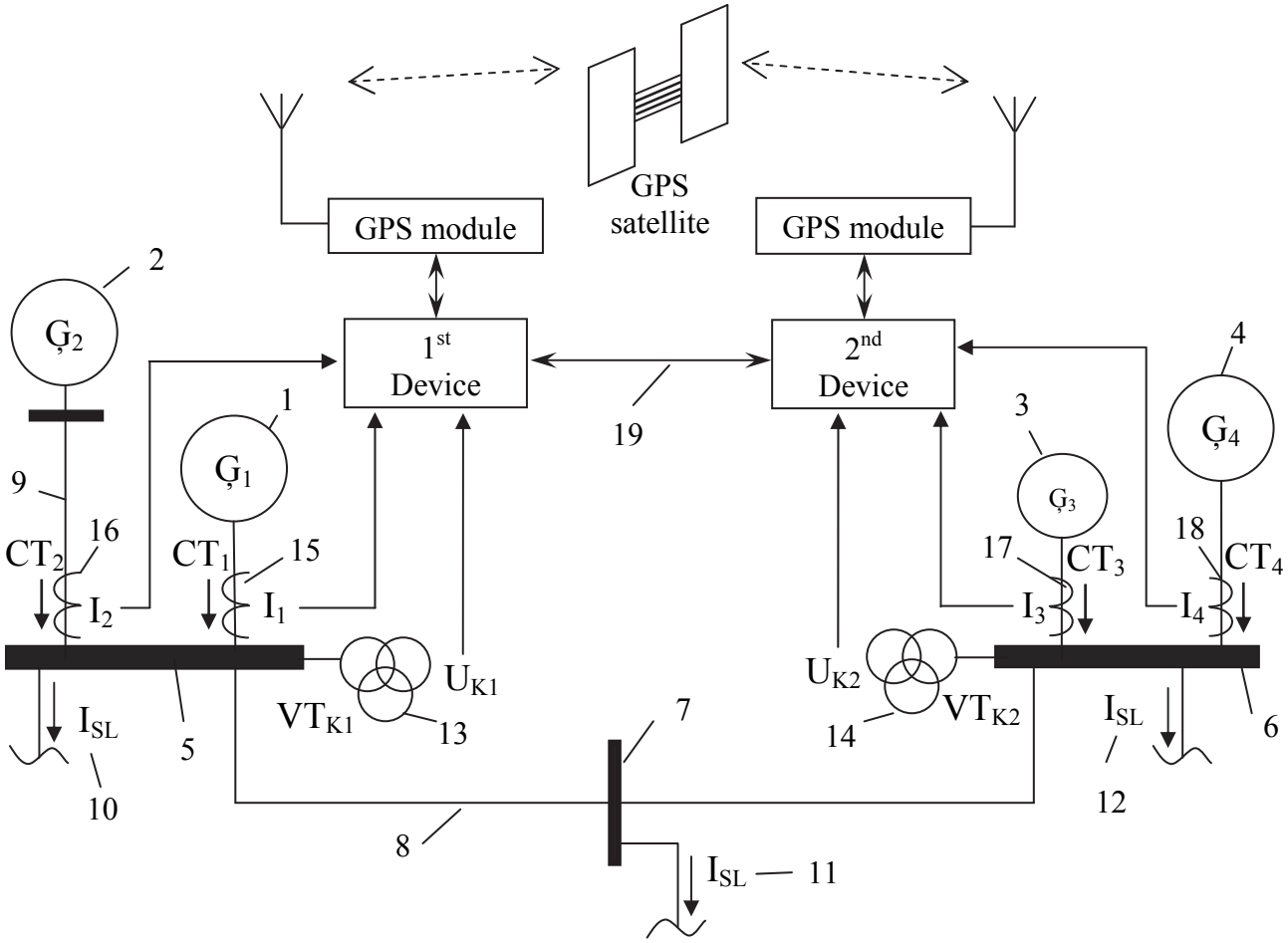

Fig. 2.2. Network scheme with four generators [51]:

1, 2, 3, 4 are different type and power generators; 5, 6 are devices connection buses;
7 is a load node; 8, 9 are network lines; 10, 11, 12 are load currents; 13, 14 are voltage transformers;
15, 16, 17, 18 are current transformers; 19 is a communication channel

Generators e. m. f. devices are calculated using the formulas which are similar to [50]:

$$\underline{E}_i = \underline{U}_{K1} + \underline{I}_i \cdot Z_i, \quad where \quad i = 1, 2 \quad (2.5)$$

$$\underline{E}_j = \underline{U}_{K2} + \underline{I}_j \cdot Z_j, \; where \quad j = 3, 4 \quad (2.6)$$

where $\underline{I}_1$, $\underline{I}_2$, $\underline{I}_3$, $\underline{I}_4$ are generators currents,

$\underline{E}_1$, $\underline{E}_2$, $\underline{E}_3$, $\underline{E}_4$ are generators e. m. f.,

Z_1, Z_2, Z_3, Z_4 are generator-bus branch impedance (setting),

$\underline{U}_{K1}$, $\underline{U}_{K2}$ are voltages of buses.

Between four generators e. m. f. phasors there are six different angles; it is proposed controlling just maximal angle δ_{mxk} among the phasors but not each angle:

$$\delta_{mxk} = \max(\delta_{12}, \delta_{13}, \delta_{14}, \delta_{23}, \delta_{24}, \delta_{34}). \quad (2.7)$$

Certainly, data discretization degree must be enough to observe power system fast changing modes, i. e., $d\delta_{ij}/dt$ rate values and e. m. f. phasors movement directions. Angle δ_{mxk} changes are associated both with normal transient processes (slow angle changing) and with emergencies transient processes (fast mode parameters change, for instance, due to short circuits and other powerful perturbations). The refresh time of data must be enough for the device to operate accurately and selectively. For a general case, i. e., the case with N generators, e. m. f. formulas are the following:

$$\underline{E}_i = \underline{U}_{K1} + \underline{I}_i \cdot Z_i, \quad (2.8)$$

$$\underline{E}_j = \underline{U}_{K2} + \underline{I}_j \cdot Z_j, \quad (2.9)$$

where i is the number of controlled generators by the first device,

j is the number of controlled generators by the second device,

N is a general number of controlled generators ($N = i + j$).

Two protection devices perform continuous processing of controlled quantities (currents and voltages) and at the time of GPS module synchronization pulse arrival necessary corrections of measurement time are performed. GPS synchronization happens in 1 PPS. If information transmission time delay from the first device to the second (and vice-versa) is less than 1 second, then the mentioned time delay does not influence correct protection operations. Last OSEP variant [51] requires an in-depth analysis of possible control actions because there are possible different control actions in order to maintain system stability.

In Fig. 2.3, the OSEP principle scheme with N generators is shown. Transmission network is represented schematically and several power plants are connected to it. In each power plant generators are installed, whose e. m. f. are modelled by OSEOP. In the observed case, six OSEP devices are used, which are connected to the data centre by communication channels using which information exchange is performed. Each device task is to control its own generators e. m. f. As a result, information web includes all power system power plants and forms an informational grid.

It is important to note that one information exchange level exists for protection operations. Of course, it is possible to create more levels for other purposes using, for instance, OSEP measurements for power system mode monitoring and analysis like PMU devices. However, the present Doctoral Thesis is mainly focused on OSEP principles.

Each OSEP models all generators e. m. f., which are in operation conditions and it compares with other OSEP modelled e. m. f. selecting generators with a maximal angle for controlling (2.7). In order to explain the proposed algorithm, one example with the first, second and sixth OSEP must be examined (Fig. 2.3).

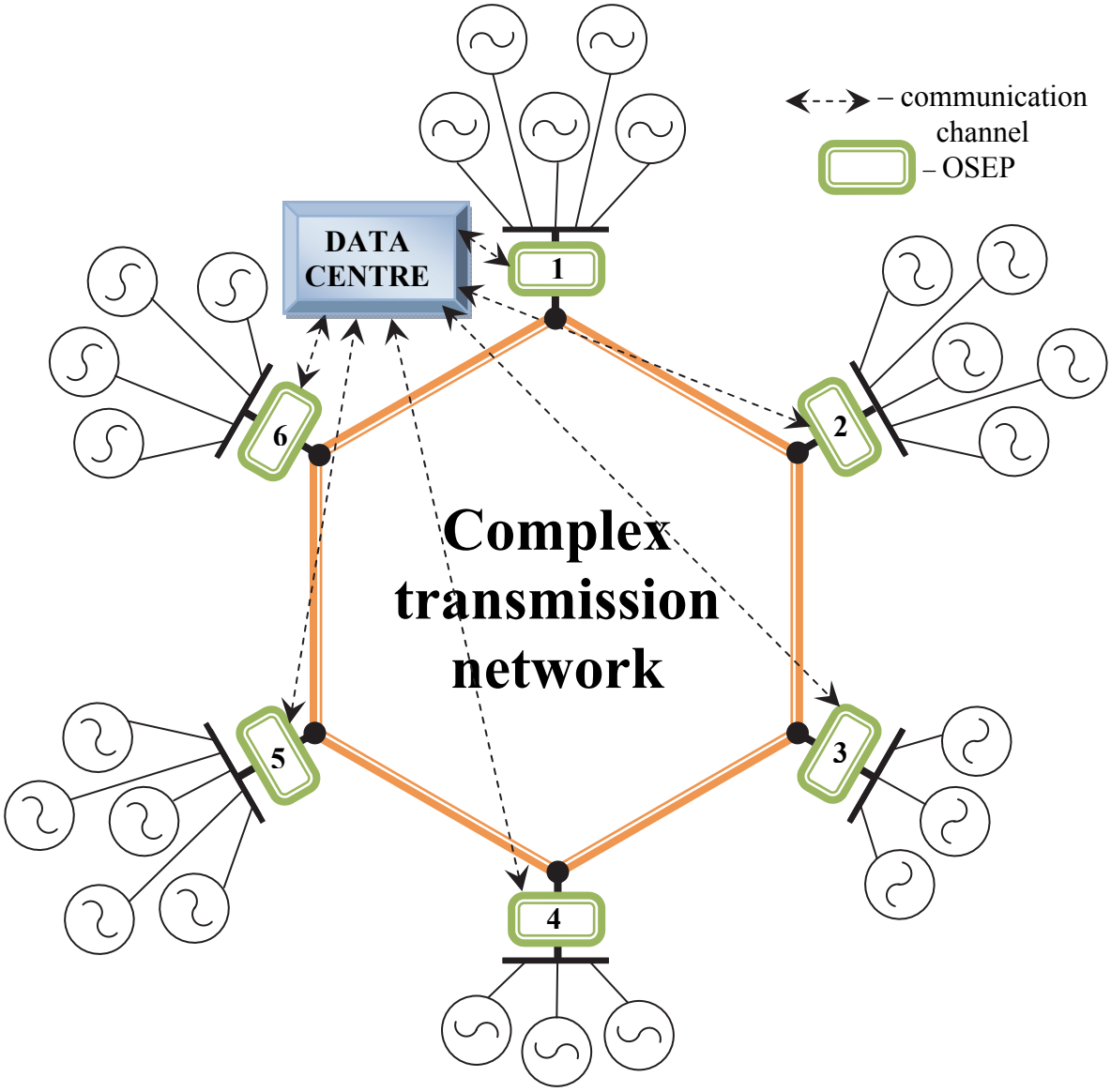

Fig. 2.3. OSEP principle scheme with N generators

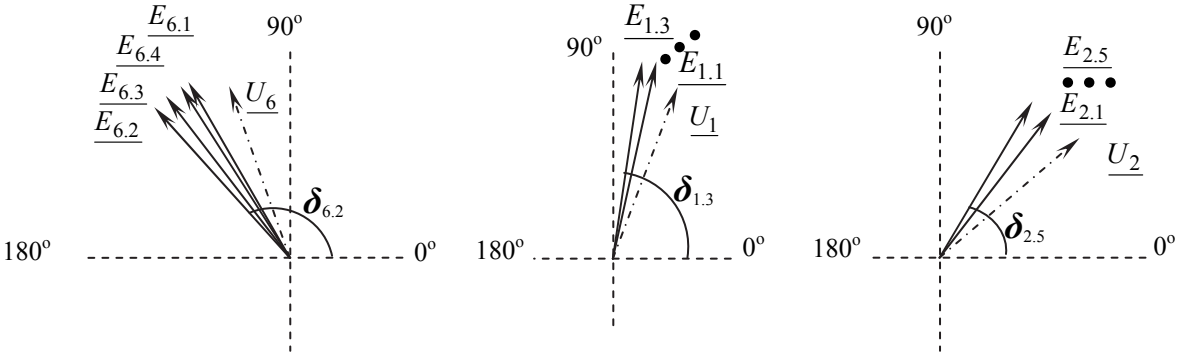

Fig. 2.4. Generators e. m. f. and bus voltages phasors of the 6th, 1st and 2nd OSEP

It is known that voltages phasors for each bus differ and they change according to load and generation amount (power system normal regimes). Let one suppose that in the examined case deviation between bus angles – $\underline{U}_2$ are left behind by $\underline{U}_1$, which are left behind by $\underline{U}_6$.

Further analysis of modelled generators e. m. f. phasors must be performed for each plant (Fig. 2.4). In Fig. 2.4, three separate phasors diagrams for each OSEP device are shown. Let us suppose that maximal angles are the following: the sixth OSEP – $\boldsymbol{\delta_{6.2}}$; the first OSEP – $\boldsymbol{\delta_{1.3}}$; the second OSEP – $\boldsymbol{\delta_{2.5}}$. When maximal angles are found for each device, it is possible to calculate angles for control: $\boldsymbol{\delta_{61}}$ and $\boldsymbol{\delta_{12}}$. Controlling these angles and their rate of changes, generators which start to operate asynchronously can be selectively switched off, and if this operation is ineffective, they can perform power system separation using selected algorithms.

In the observed cases, the OSEP device is analysed as separate protection. However, it is necessary to assess the case when OSEP is one of protection terminal functions. At RTU, another protection device "LIDA" was developed. This device includes relatively large number of protection functions [52]. Similarly, it is realized using microprocessor principles and digital information processing algorithms. This protection consists of two devices, which are installed at line ends and of communication channels that link them. The protection is ensured using "Master/Master" principle, i. e., the devices are equal. For differential currents calculation, phase current phasors at line ends are used. For information exchange among devices, optical communication channels are used.

It is well known that "AGNA" model voltages phasors $\underline{U}_1$ and $\underline{U}_2$ (1.8, 1.9). The modelled phasors can differ from real and if the difference is significant, "AGNA" may operate incorrectly (not to operate or to operate with unacceptable time delay). Correspondingly with "AGNA" operational principle, it must be located in power system part where separation must be performed. It means that "AGNA" operation efficiency depends on selection of installation place: extensive power system modelling of different modes and scenarios must be performed. Certainly, to measure voltages precisely it is necessary to be as close to the generators as possible, and calculation of angles between real voltage phasors is required as well. If it is possible to measure voltages in different power system locations, the angle between any two voltage phasors can be calculated and the algorithm similar to "AGNA" can be employed because in this case the angle is measured. Thus, the OSEP becomes the distributed system where measurements are made in all critical power system nodes.

To implement the examined variant, the following things are required:

- measurement equipment that measures voltage phasor on buses, which operates in real time and is located closer to the generators;
- the device that would perform measurement transmission though a communication network in real time;
- communication network that would be fast enough to carry out real time data transmission;
- all measurements that would be synchronized in time precision 10–50 μs;
- transmission of "trip" command on circuit breakers for realizing power system separation in case of OOSM.

It is suggested to use high voltage line protection terminal opportunities for realizing OSEP. Consequently, at present there already are measurements that are made in real time and synchronized; high-speed channels for transmitting measurements and commands (trip, block, and etc.). Protection terminals are installed practically at all ends of high voltage lines (Fig. 2.5); this allows performing measurements in real time conditions for different points of power system. These measurements will be synchronized and for their transmission high-speed communication channels will be used and, as a result, it will be possible to trip any element of the controlled network.

In addition, the following things are required:

- voltage angle transmission in one data package together with currents whose differential protections usually transmit from one device to another. It is important to

note that the time delay of a communication channel would not significantly increase because data amount of angle values takes only several bits (angle value is in the interval from 0..360 degrees, so information is 9 bits). Additional amount is 4–5 % from the total package size.

- Software block that would compare angle difference with settings ($\varphi_n - \varphi_k >$ const).
- OSEP function blocking due to short-circuits (un-symmetry, overload currents), minimal voltage and fast voltage angle changes (***dφ/dt* > const**).
- Option to switch-off OSEP function operatively (with setting/command).

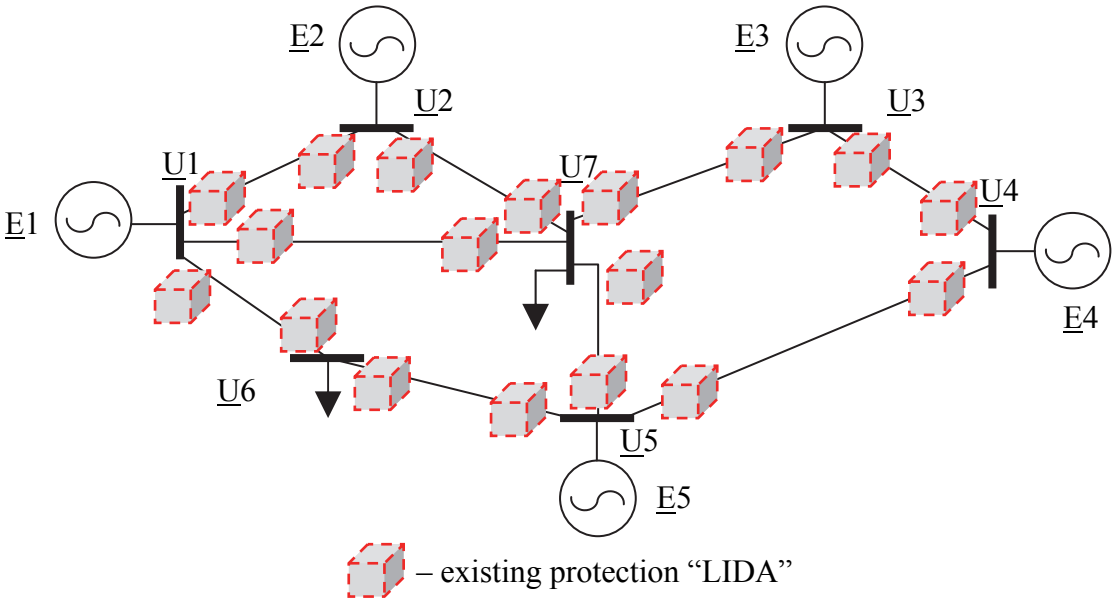

Fig. 2.5. Protection terminal installation in power system network

It is necessary to analyse the case when the proposed system can operate in a unified system. For example, it could be a power system with three generation units, loads and lines (Fig. 2.6), which connect separate power system parts. At lines ends terminals with differential and distant protection ("LIDA") are installed.

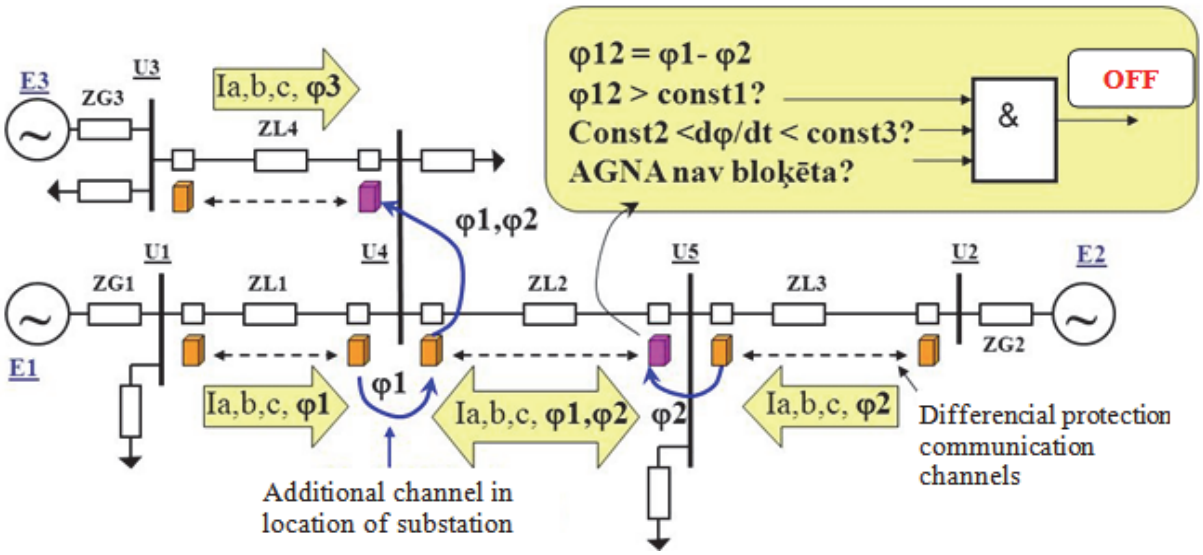

Fig. 2.6. Power system protection configuration and information transmission network

For protection operation high-speed communication channels that link devices are used. Each device measures line current and bus voltage; after that it transmits current and angle of bus voltage to the opposite end using a communication channel. This configuration allows calculating the angle between voltage phasors of line ends (φ14, φ45, φ52) (Fig. 2.6.). According to the operational principle of OSEP, it is needed to control angles difference among voltages that are closer to generators units (φ12, φ13, φ23). To ensure this, it is needed to create additional communication channels (in location of one substation). Channels construction allows transmitting information within a communication network and it is available for each protection device. Local channel can be performed as a direct connection between devices communication interfaces.

Let us suppose that in case of OOSM power system must be separated in two points: when OOSM is between (E1, E3) and (E2) generators, line ZL2 must be tripped; and when OOSM is between (E1, E2) and (E3) generators, line ZL4 must be tripped. Thus, OSEP function of the devices, which protect lines ZL2 and ZL4 and marked with purple colour, is activated and they calculate φ12 and φ13, φ23 angles, respectively.

The OSEP can be realized as a wide area system that allows measuring and comparing voltages angles in power system critical points. The conditions of system creation are the following: measurement synchronization, high-speed data transmission channel existence, voltages measurement and data transmission in real time. To realize wide area system multifunctional line protection, device possibilities and differential protection communication channels are proposed to use. Therefore, the proposed variant is economically sound in comparison with other wide area systems, because existing communications channels and protection terminals are employed.

Of course, it is extremely important to note new OSEP specific possibilities. Communication channels and GPS modules are provided with operability control systems. However, the proposed structure of protection allows to realize additional control functions. For the purpose mentioned above, it is possible to use:

- Algorithms that allow identifying errors, which appear in communications channels due to jams.
- Automatic re-configuration (losing part of useful features) when failures are detected. There are two possible variants:
    - The first case is when GPS failure is detected – the device automatically operates using a back-up algorithm based on measurement synchronization using a communication channel (time delay of channel is calculated).
    - The second case is when a communication channel failure is detected – the device automatically operates using a “classical” (local) OSEP principle (for instance, “AGNA”).

It is known that failures in voltage measurement circuit happen relatively often in power systems EP&EA. For that reason, the devices that can operate non-selectively have special blocking. OSEP devices can operate incorrectly in case of false voltage measurements. To avoid these situations, it is enough to provide devices with fast operating block that would respond to non-symmetry appearance in controlled voltages and could block protection operation. The further chapters deal with how to use limitations of automatics functioning (only symmetrical modes), how to set up protection terminals that would be resistant to most failures, which can occur in voltage circuits.

- Voltage circuits non-symmetry (launch condition not decision-making feature as in an analogous device).
- Currents circuits non-symmetry checking. If non-symmetry is not fixed in current circuits, the failure of voltage circuit is registered.

- If the previous condition is fulfilled, the faulted phase is identified.
- If base phase (A) is faulted, this is exchanged with another phase, which is rotated by 120 degrees (B or C phase).

3. POWER SYSTEM BLACKOUTS AND OUT-OF-STEP PROTECTION OPERATION MODELLING

To verify the proposed solution efficiency, the modelling and analysis of power system modes and protection operations must be performed. For this purpose, the transmission system of Latvia (330 kV) and neighbouring systems (Lithuania, Estonia, and Russia) were chosen. The main task is to model dynamic transient processes and to obtain the necessary data for verification of OSEP operational modelling parameters.

In the present Doctoral Thesis, the analysis was based on the high-voltage transmission grid of the Latvian power system (330 kV) [53], including all important power plants (Plavinu HPP (PHPP), Riga HPP, Riga TEC-1 and TEC-2, Imanta heat power plant). Modern software ETAP 12.5 was chosen for OSEP testing. The Latvian power system is interconnected with neighbouring networks of Russia (Velikoreckaja) and Estonia (Tsirguliina and Tartu), which were taken as equivalent generators (power systems) in the model. Lithuania interconnections were modelled as four powerful load nodes (Klaipeda, Sauli-Teslai, Panevezus, Ignalinas_AES) (Fig. 3.1). The scheme and its data were used as a basis [53].

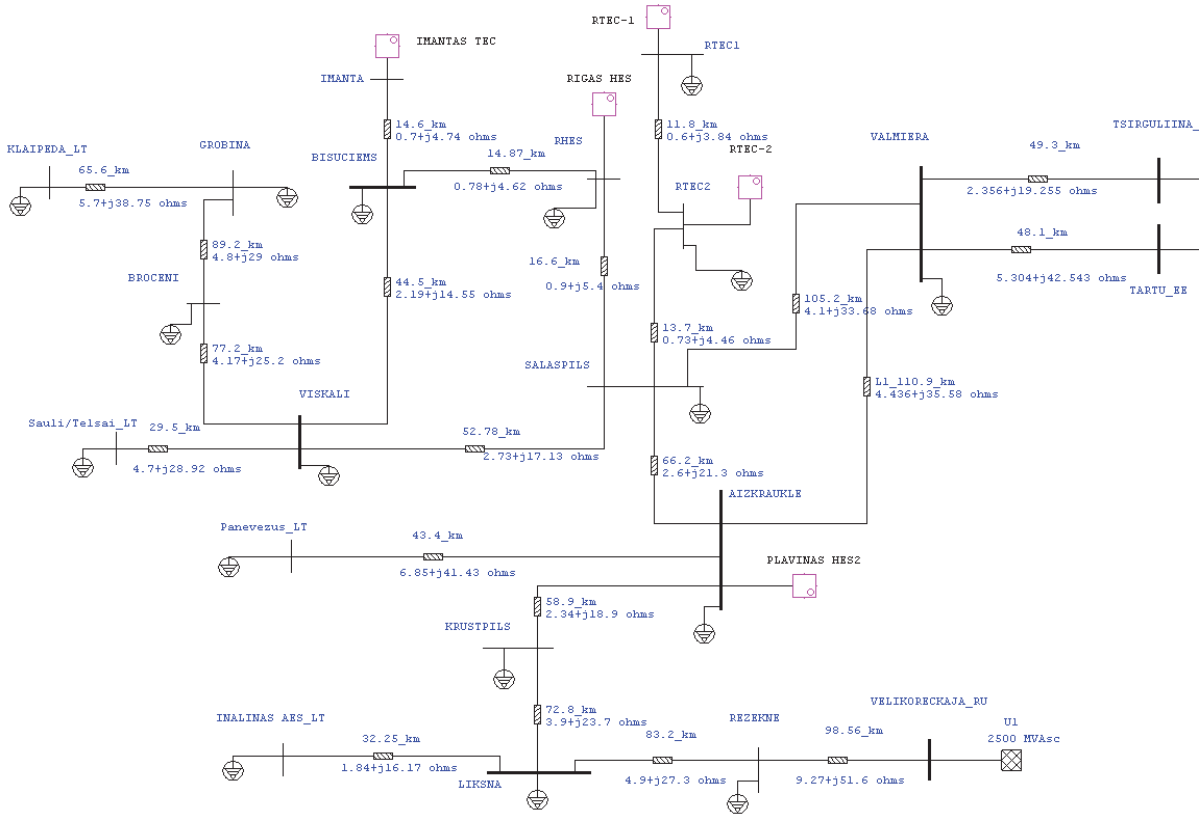

Fig. 3.1. The Latvian power system model in ETAP

To perform verification of the selected automatic structure, algorithm and settings, it is needed to select the most characteristic possible modes of the observed power system. It is known that in terms of stability a three phase short-circuit is the most severe single fault. This fault is taken as a base case, which can cause OOSM. In the examined case, a three-phase fault occurs at a transmission line connecting Viskali and Bisuciems buses at 95 % of its

length. The short-circuit duration is deliberately assumed to comprise 0.53 seconds, which is longer than operation time of main RP because there are cases when the main protection does not operate due to some reasons. Hence, this time delay is possible if short-circuit is eliminated using back-up protections. This simplification is assumed to perform complex cascading events modelling within the grid. In case of base scenario, instability processes can be observed on the whole network, i. e., all operating generators one by one lose stability and start operating asynchronously (wide scale OOSM). Additional complication is associated with the fact that instability develops both between Latvian and the external systems as well as within the Latvian system itself. The generators connected to the grid lose their stability and various transient groups are formed. However, further analysis focuses on inter-system observations under this complex instability pattern; paying the main attention to Latvia and Russia connection. This perturbation forms the basis for selection of corresponding settings for the above-mentioned protections ("AGNA" and OSEP [50]). However, first of all, it is needed to check possible action efficiency, which can be done by decreasing the fault time. In the course of experiment, such a mode is achieved (fault time is 0.35 s) when it is possible to define the generator that first starts to operate asynchronously (Fig. 3.2). In the observed case, all generators still operate in OOSM. Using the most dangerous generator, it is possible to perform its tripping [51] (for example, Imanta generator Gen9). The generator tripping is performed after short-circuit trip with 0.05s time delay, but OOSM still appears after a longer time period. It can be seen that there is another dangerous generator that must be tripped (RTEC1 generator G1) (Fig. 3.3).

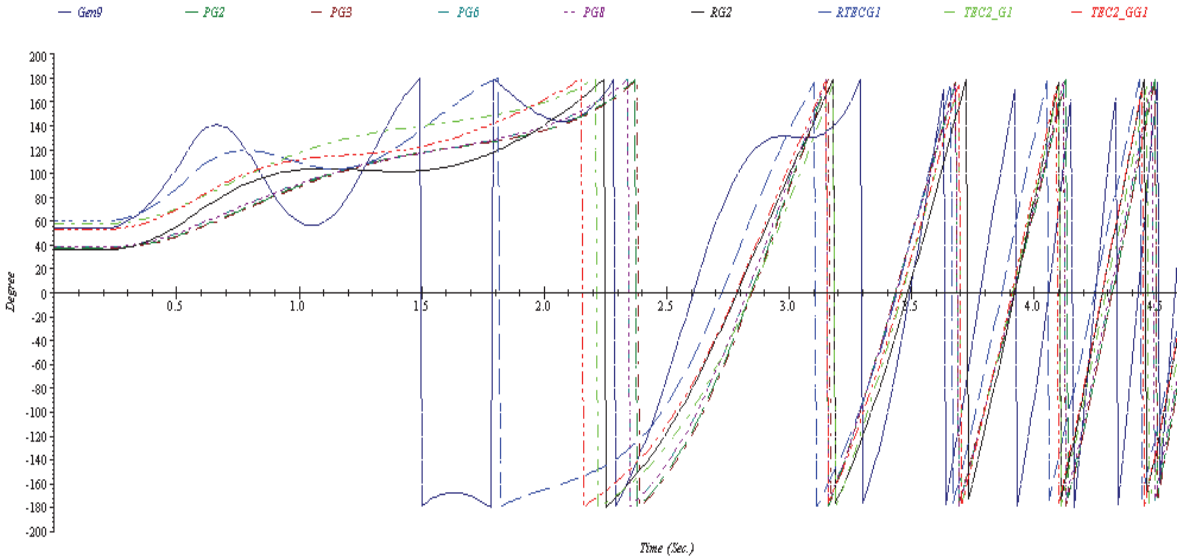

Fig. 3.2. The Latvian power system wide scale OOSM of generators

Comparing Figs. 3.2 and 3.3, it is possible to conclude that other generators do not start to operate asynchronously. This fact proves corrective action efficiency and opportuneness, which allows avoiding undesirable consequences (power system blackout).

Reverting to the base case and performing dangerous generators tripping, it can be observed that this action unfortunately does not have a significant effect because other generators start to operate in OOSM (Fig. 3.4). This process can be explained by the fact that perturbation impact was too powerful and the existing reserve was not enough. The observed results allow performing protections, which have different action degrees starting with the disconnection of the most dangerous generator and only in cases where the dangerous process will continue to perform system separation.

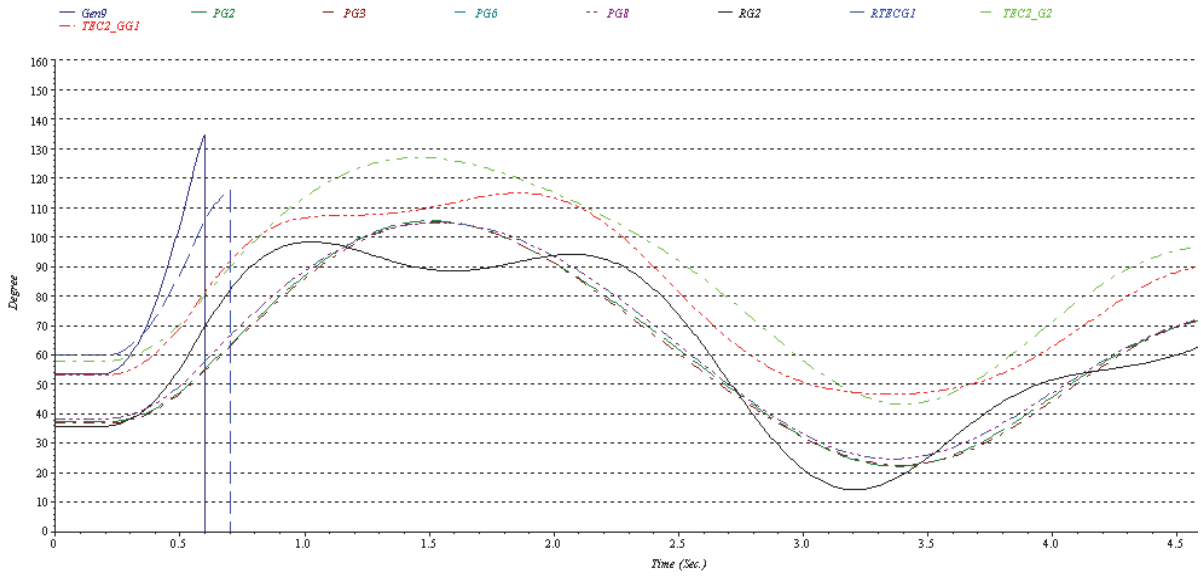

Fig. 3.3. Transient process with two "dangerous" generators tripping

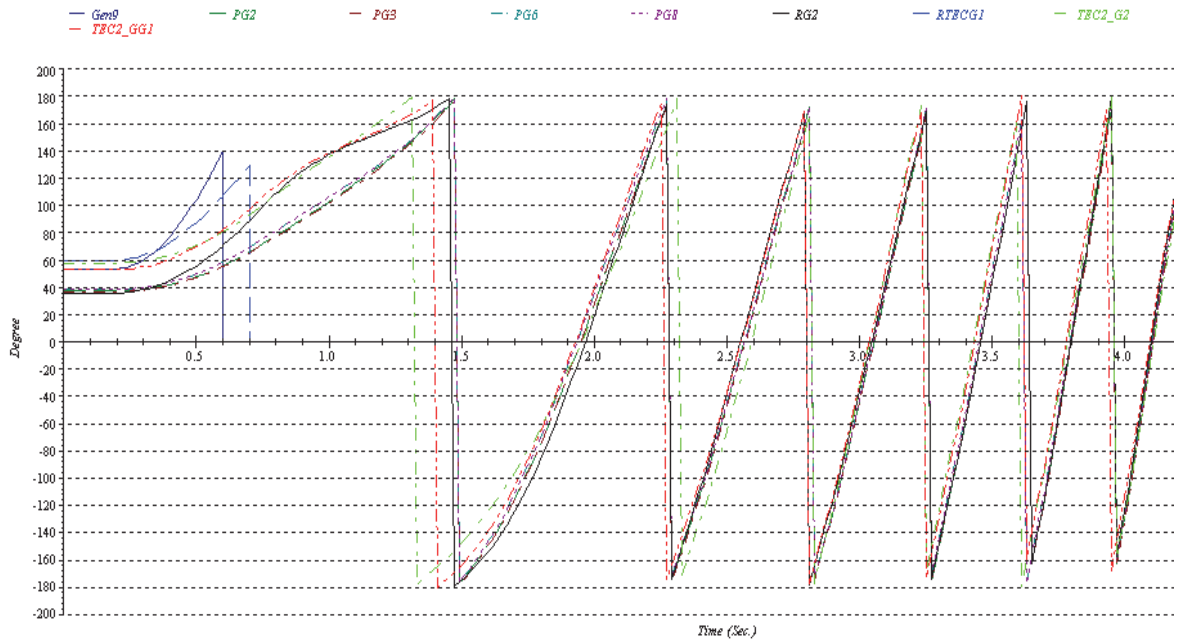

Fig. 3.4. Inefficient tripping of generators

To compare protection operations, installation places of devices must be chosen. According to the analysis set out above, it is possible to conclude that one of the most hazardous interconnection of the Latvian power system is the area between Latvia and Russia. Thus, Plavinu HPP and the Russian power system buses were chosen as the protection zone (Fig. 3.1). "AGNA" was installed at bus "Liksna", where it measures voltage and currents in lines. "AGNA" device monitors the angular difference between phasors associated with Plavinu HPP generators and the Russian power system derived from the local measurements. In case of two terminals, the first one was installed at "Aizkraukle", and it additionally measures the current associated with the Plavinu HPP generators. The second terminal is located identically with "AGNA" device. The observed power system part includes a number of concentrated load nodes, for instance, bus "Aizkraukle", etc.

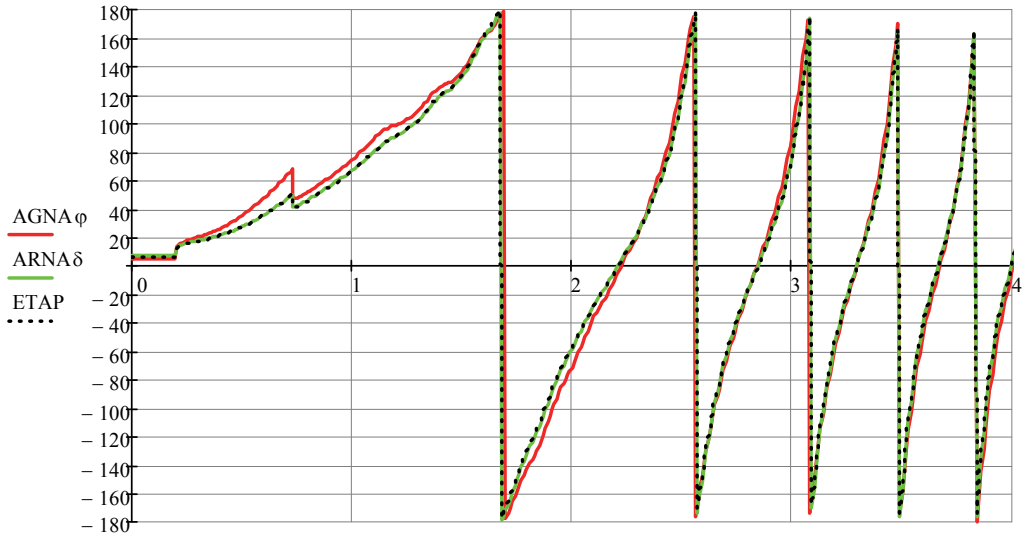

Fig. 3.5. "AGNA" and ARNA modelled angles comparison with ETAP angle between buses PHPP and Velikoreckaja (base case) [54]

Analysing calculated OOSM and graphs it is possible to evaluate setting correctness. Therefore, the comparison of the presented graphs (AGNA and ARNA vs. ones calculated in ETAP) leads to the conclusion that settings were chosen properly (Fig. 3.5.).

It is necessary to observe the case that is associated with reduced load and generators number (PHPP only two of ten generators are in service). According to the mode, impedance settings were corrected, i. e., equivalent impedance of power plant was increased by 4 times comparing with the base case (eight generators are in service). In this case, significant error of "AGNA" angle modelling is observed in comparison with theoretical data (ETAP data). It means that "AGNA" will respond incorrectly, and this can lead to more severe consequences (losses). Analysing OSEP operation, it is possible to conclude that it will operate very closely to real regime data (Fig. 3.6).

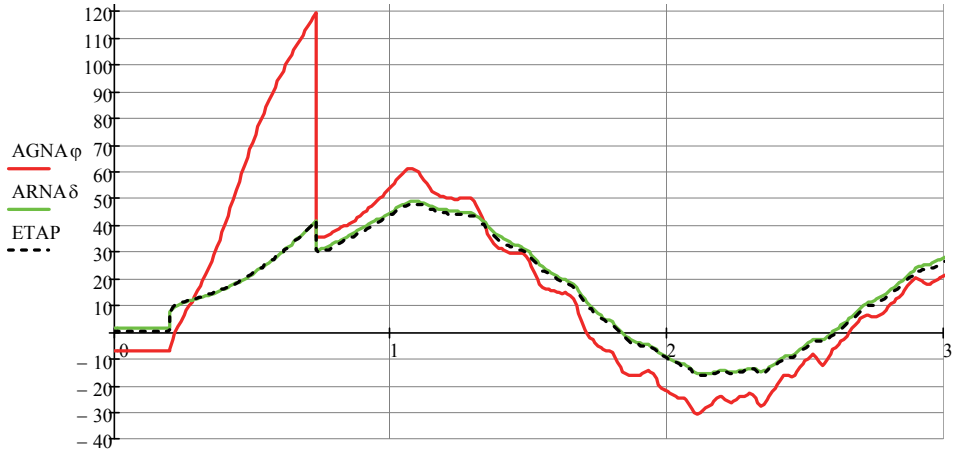

Fig. 3.6. "AGNA" and ARNA modelled angles comparison with ETAP data (minimum load mode – night mode) [54]

All calculations and modelling were made in a specially designed simulator ("Analog-Digital Power System Simulator") with a remote control possibility. This was very helpful and useful, because all necessary software was in one place and it was available at any time.

Changes in power system topology and structure may lead to dangerous consequences which are mainly associated with changes in protection zones. Therefore, they have significant influence on correct recognition of "AGNA" unstable conditions. This will cause

dangerous consequences for both power plant equipment and system integrity, if addressed incorrectly. During analysis and modelling, a number of "AGNA" disadvantages and imperfections were identified: potential incorrect operations due to settings selection complexity (power system structure changes); high dependency on power flows (especially if flow direction varies), etc. The proposed OSEP scheme [50] avoids these limitations, due to the fact that any changes in the network structure do not have any significant influence on the correct terminal operation. As an example, controlling a local situation (a plant scheme) where it is possible to evaluate all possible variants can be mentioned. Therefore, the settings were not affected due to mode or topology changes as "AGNA". Modern software use allows verifying a new protection algorithm. The analysis proved its efficiency and viability in different modes. It is useful to substitute "AGNA" for new protection OSEP, especially in cases of complex power system structure, when it is almost impossible to observe all possible modes and settings.

4. OUT-OF-STEP PROTECTION TESTING

For many years the problem of settings selection has existed. During this time different settings selection and calculation methodologies have been developed, which are now used in power system RP [39]. However, it is very difficult to assess the selection accuracy of these settings because new elements (power unit, lines) appear in the course of the development of power system structure, topology changes, and etc. Modern system structure is complex and liable to similar failures and perturbations. The impact of destabilising effect has been developed, too, causing unpredictable and uncontrolled consequences.

Another aspect that is associated exactly with settings of RP&EA is verification or adequacy validation. It is clear that the selected settings of the protection devices cannot be checked in real conditions. This problem requires effective and accurate solution to ensure power system mode security and adequacy.

To model emergency modes, it is possible to use different data sources; however, in this Thesis EUROSTAG software was used, which calculated signals as a signal effective value and a phase angle. However, these results cannot be used at once, because for RP devices verification, the signals must be in COMTRADE format [55]. Therefore, special conversion in COMTRADE format software was developed [57]. After conversion signals are transformed into real current and voltages values used for devices validation.

It is needed to discuss an example of the proposed concept. In EUROSTAG power system a model is created which consists of two generation zones connected by high voltage line (110 and 330 kV) [56]. The power system can become unstable when short term loss of 330 kV transmission link occurs. This condition can arise as a result of a short circuit on 330 kV line with subsequent successful auto reclosing. Varying the short circuit clearing time, the load, type and location of short-circuit, different scenarios can be simulated. Analysing them it is possible to get the information about system behaviour. Depending on the selected scenario, the cases from stable power swing toward the synchronism loss and OOSM can be simulated.

"AGNA" device is used to protect power system from OOSM influence. OOSM identification is based on angle control. The EUROSTAG allows any signal of dynamic simulation to be exported in the ASCII format. Thus, 3ph currents and voltages obtained during simulation can be saved in an external file and used for real device testing. The relay test system (RTS) (ISA DRTS) is used to playback the simulated signals. When the COMTRADE file is obtained, it can be used with any modern Relay Test Equipment, which allows playbacking the waveforms of signals.

After the simulation it is needed to analyse the reaction of verified testing relay. For this purpose SMOKY2 software was created [58]. SMOKY2 allows showing analogue and digital

signals, constructing vector charts (in dynamic and static studies), increasing the accuracy of signal displaying, finding digital signal changes, as well as several other features. Briefly, the methodology is summarized in Fig. 4.1 [59].

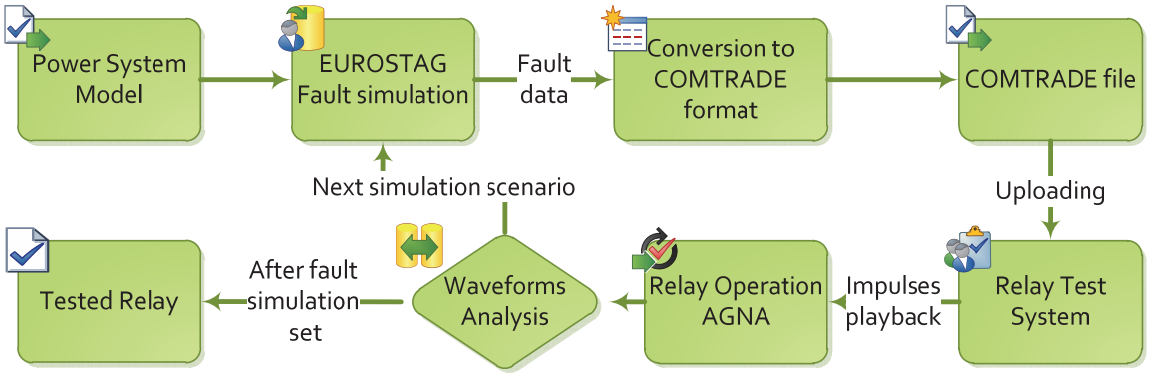

Fig. 4.1. OOSM modelling and terminal operation verification [59]

Of course, "AGNA" device realization is associated with a simplified algorithm in comparison with new types of protection [49]–[51]. To perform OSEP device operation functional verification, the above-mentioned methodology is used. Additionally, in this case two OSEP devices settings, communication channel and GPS operability must be evaluated. Further several cases will be analysed using oscillograms and SMOKY software. In Fig. 4.2, OOSM oscillogram is shown, which occurs after long lasting 3ph short-circuit trip. The angle between modelled e. m. f. and its change of rate exceeds the 1st stage of the main zone triggering settings for the 1st and 2nd outputs. The operation of these outputs is shown in oscillogram as digital signals "Pam1p1iz" and "Pam1p2iz" (Fig. 4.2).

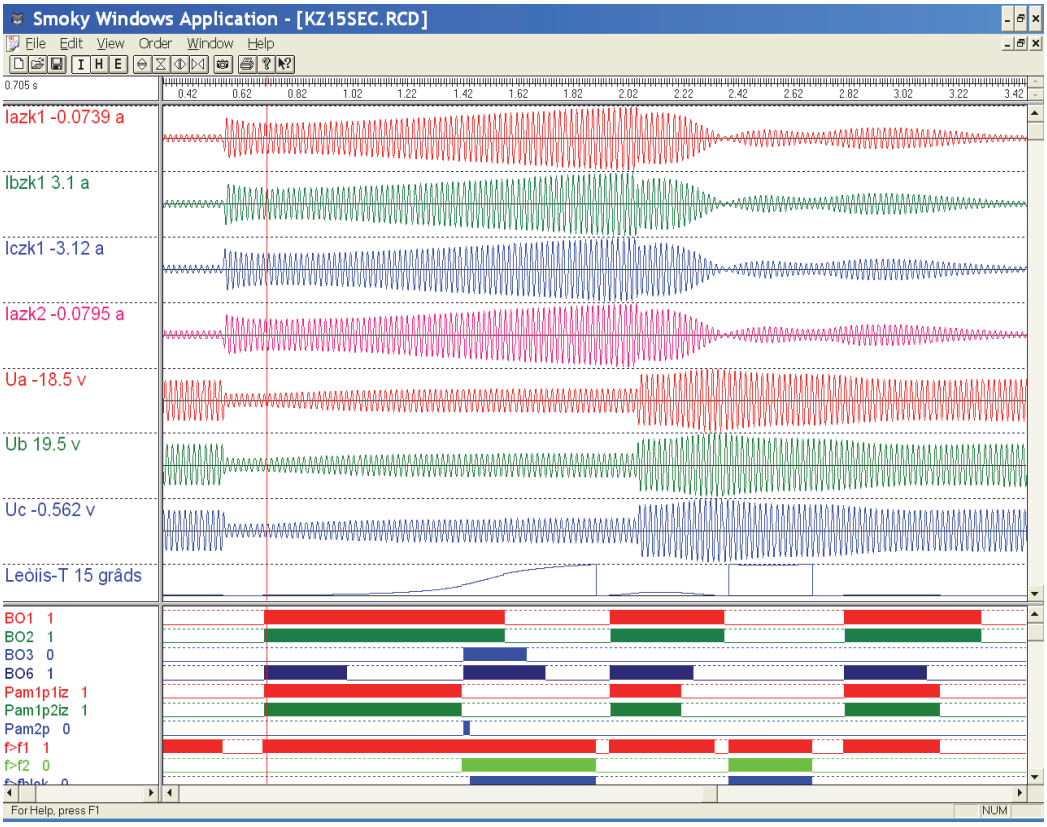

Fig. 4.2. OOSM oscillogram after long lasting 3ph short-circuit

There is also the device output relay operation, i. e., digital signals BO1, BO2, BO6, caused changes in power system mode, but OOSM continued to develop. As a result, operational conditions remain and the 1st stage of the main zone output relays of the device operates again.

One of the main requirements to OSEP device operation is incorrect operation impossibility, i. e., excessive tripping in case of short-circuit in the power system. The device is blocked in case of currents and voltages asymmetry.

However, in cases of 3ph short-circuits, additional blocking is activated because blocking using asymmetry cannot be sensitive enough. It is known that 3ph short-circuit asymmetry is short-term, and if this is not fixed, the device is blocked using other conditions: **$d\delta/dt > d\delta/dt_{max}$ and $I1>I_{blok3}$ or $U1>U_{blok3}$**. This case is shown in oscillogram (Fig. 4.3). In case of 3ph short-circuit currents and voltages, which are used to calculate modelled e. m. f., are changed unevenly, and the angle between them changes correspondingly. This condition is fixed by the device if operational condition **$d\delta/dt > d\delta/dt_{max}$** is fulfilled. Simultaneously, if voltage is less than setting **U_{blok3}** or current is more than **I_{blok3}** setting, the device will be blocked, i. e., angle calculation will be stopped. Operational condition will be resumed in case when voltage and current will return to normal limits.

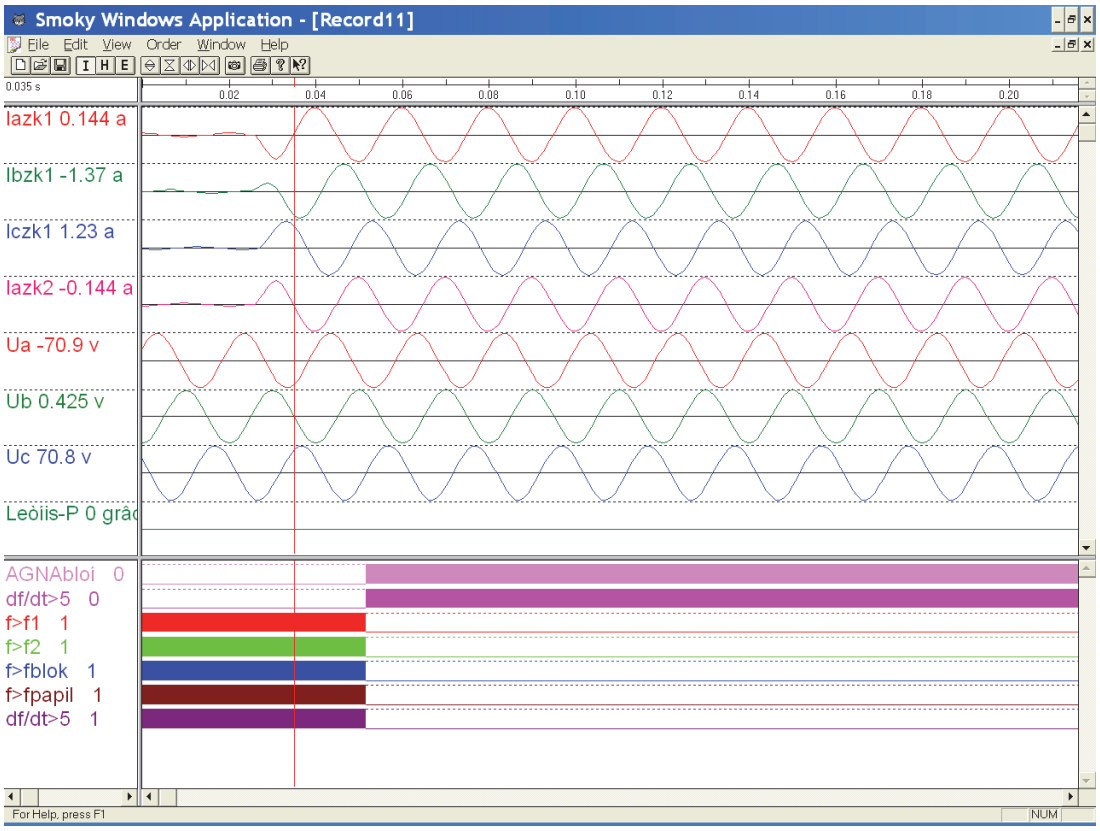

Fig. 4.3. Device blocking in 3ph short-circuit case

This blocking is shown in oscillogram as a digital signal "dϕ/dt>5" (in a new algorithm φ must be changed to δ) (Fig. 4.3). At the same, time device blocking signal "AGNAblok" is given (Fig. 4.3). In Fig. 4.4, there is oscillogram where the case of incorrect operation is shown. In this case, blocking (3ph short-circuit existence fact) is deactivated. Despite the fact that asymmetry conditions were active, short-term 3ph short-circuit asymmetry was too small. As a result, blocking was fixed and its conditions were not provoked due to current and voltage negative sequences. Therefore, the device operated incorrectly identifying short-

circuit mode as OOSM, which is absolutely unacceptable. Thus, special attention must be paid to OSEP blocking settings.

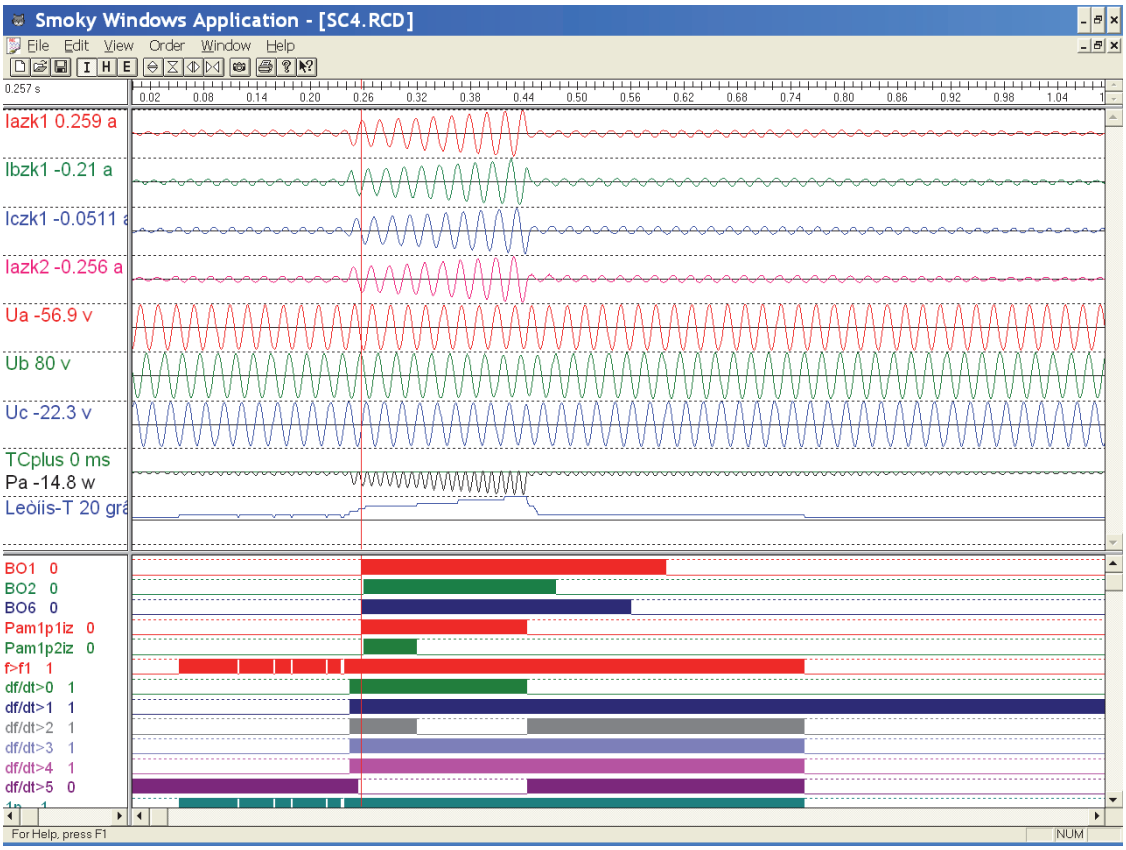

Fig. 4.4. The case of device incorrect operation

CONCLUSIONS AND PROPOSALS FOR FUTURE RESEARCH

- OOSM can take place in any power system and it can provoke system blackout, power plants stoppage and long-term power supply interruption. Statistics of blackouts (emergency) proves this statement.
- "N-1" criterion can neither evaluate power system and anti-emergency automatics behaviour in case of instability nor evaluate probabilities of elements failures, weather condition impact, sudden changes of load and other stochastic factors, which in total play a decisive role in power system management.
- Analysis and comparison of possible risk assessment techniques have been performed; a stochastic approach has been proved employing security and statistical decision theory methods and Monte-Carlo technique.
- To model stability loss processes for large power system, simplified probabilistic relay protections and automatics operating algorithms have been justified. Verification methodology has been worked out as well.
- The new OSEP structures have been synthesized using GPS and optical communication channels.
- New protection algorithms have been developed and their efficiency has been proved.
- The possibility of ETAP 12.5 software use has been proved to model power system modes for protection terminal verification.
- It is needed to put new OSEP into practice and to research the influence of control actions.

- ❖ New protection integration possibilities in WAMS and necessary modification must be assessed.
- ❖ The changes in the power system topology and structure can provoke dangerous consequences that are mainly associated with protection zone changes. These changes inevitably affect modes recognition by "AGNA" and corresponding control actions.
- ❖ The imperfections and drawbacks of "AGNA" device have been determined in the course of analysis and modelling: incorrect operation due to settings selection complexity (changes in the power system structure), high dependence on power flow directions especially in cases when the flow changes its direction in several branches of the protection zone. OSEP scheme does not have this kind of limitations because power system structures changes do not hinder its proper operations. Thus, it is possible to control a local situation (plant scheme) where it is relatively simple to consider all possible cases. Consequently, there is no impact on impedance settings due to modes or topology changes as in case of "AGNA".
- ❖ It is possible to realize new protection algorithm verification using modern software. The proposed analysis has proved its efficiency and viability in different modes.
- ❖ It is worthwhile to substitute "AGNA" for new generation of OSEP protection, especially in cases of complicated power system structures when it is impossible to evaluate all possible modes and the corresponding settings.
- ❖ OSEP effective functioning is possible in case when two conditions are met: there are high-speed and secure communication channels and GPS synchronization.
- ❖ New OSEP possible action range contains relatively large range that allows performing complicated control action algorithms ("dangerous" generator or interconnection tripping, disconnection of customers, and etc.) to ensure power system stability.

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