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Faculty of Power and Electrical Engineering

Institute of Power Engineering

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Doctoral Student of the Study Programme "Power and Electrical Engineering"

VIRTUAL-REAL LABORATORY OF POWER SYSTEMS RELAY PROTECTION AND AUTOMATION AND EXAMPLES OF ITS APPLICATION

Summary of the Doctoral Thesis

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DOCTORAL THESIS
PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 9 November 2017 at the Faculty of Power and Electrical Engineering, 12/1 Azenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Edīte Bieļa-Dailidoviča................................ (signature)

Date ....

The Doctoral Thesis has been written in the Latvian language. It consists of Introduction, 4 chapters, Conclusion, Recommendations; the total number of pages is 149. The Bibliography contains 160 titles.

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TOPICALITY OF THE DOCTORAL THESIS

Modern power systems contain millions of elements, cover huge territories and require very large capital investments for the development and maintenance. Many random processes and factors influence the operation of power system [1.1]. A functional control system is required to provide its effective and safe operation. In most of the cases the automatic equipment and devices have a control function. A human being is not able to analyse information and make correspondent decisions quickly enough and is not able to react fast enough to changes in power systems in case of complex damages. New equipment for the generation of energy has been developed and control systems are consantly developing which always requires qualified staff and effective and advanced science. In turn, the staff and science require research laboratories (RL) that can be divided into two RL types:

- real laboratories – for making experiments using real devices or their physical models;
- virtual labs – for the imitation of processes using digital models of devices.

Certainly, a combination of the above mentioned laboratories can exist. The virtual laboratories are applied in many scientific areas [1.2 and are quickly developing with the modern information technologies.

The application of virtual laboratories in the area of power engineering science is much older than of personal computers as it started in the middle of the 20th century with the unification of power systems, when the very first electro-mechanic calculating machines existed. The practical interest to these laboratories can be explained as follows:

- the influence of power systems on the economy indicators that contributed to expensive calculating equipment;
- the essence of the problem regarding the extension and complexity of the power system that finally excludes any opportunity to develop its physical models.

A laboratory for investigation of power systems nowadays is an integrated tool for the work of transmission and distribution operators as well as for the training of young specialists. It is doubtless that the virtual laboratories serve for the training of the dispatcher operators [1.3], [1.4], [1.5].

The opportunities of virtual laboratories are limited in the case of investigation of the behaviour of a real automatic device as the experiments can be realised with the models only. To exclude this disadvantage the application of virtual-real laboratories (VRL) started in the 20th century. It was the result of the development of microprocessors. The complex testing relay protection devices OMICTRONS [1.6], Freja [1.7], ISA DRTS [1.8] can be considered as the basic equipment of VRL.

These relay protection devices are suitable for the testing of manufacturing equipment but are strictly limited in application for research when it is required to generate complex testing signals. The thesis foresees further VRL development and laboratory organisation, and examines the possibilities of making the experiments with real automatic devices. The subject of the thesis is electromechanical transient processes of power systems and the automation suitable for their control (out-of-step protection and recognition of island regime). The existence of such laboratory is important for the improvement of effectiveness of scientific investigations, as well as for the improvement of the education process at the universities.

AIMS AND OBJECTIVES OF THE DOCTORAL THESIS

The main aim of this research is the improvement of the effectiveness and safety of power systems. The following tasks wer solved for the achievement of this aim.

1. The methods and tools of testing and verification of automatic equipment of power systems and its software were analysed.

2. The work proposes, substantiates and realises the structure, equipment and software elements of virtual-real RL including the digital library of the emergency processes, software for the dynamic processes simulation, digital-analogue converters, prototypes of automation equipment.

3. New adapted out-of-step protection automation systems and approaches were synthesised and patented for power systems, and their advantages were proved.

4. While testing and verifying the proposed systems and algorithms, the VRL proved its advantages and estimated opportunities for the effectiveness of the tested equipment.

METHODS OF THE RESEARCH

1. Numerical experiments were made on the basis of the servers of State Insign Centre of Riga Tehnical University and ETAP, MathCad, SMOKY, EUROSTAG software.

2. Testing and verification of automation were realised using the data of generating and transmission network of Latvian power system as well as the IEEE testing system [1.9].

3. Realisation of the automation prototype applies signal processors TMS-320 [1.10] and correspondent software with development opportunities.

4. The records of the emergency processes from the emergency register devices "REMI" in Latvia, Lithuania and Estonia were used for the transient processes generating.

SCIENTIFIC NOVELTY OF THE DOCTORAL THESIS

1. A new structure of a scientific automation laboratory was justified for complex experiments with testing of automation.

2. The opportunities and advantages of the laboratory as well as the ability to examine protective automation complexes were tested and proved in the research; these complexes include terminals with a number of control and executive functions.

3. The research proved the ability of the new protective automation equipment to control a large part of the power system consisting of many terminals connected with the communicative channels and integrating the advantages of local as well as central system.

4. The proved algorithm of the generator voltage modelling can estimate the equivalent resistance of the power system using the modulus value of the generator voltage known in advance.

5. A new algorithm for the control of the generator rotor angle synthesised in the research is not sensitive to the changes of the power system parameters during the emergency processes.

IMPORTANCE OF THE DOCTORAL THESIS

The results of the research were included and applied as follows:

1. in the methodology developed for the State Research Program in Power Engineering;

2. in VRL for the experiments, testing, verification and examining of new methods and approaches, algorithms as well as in the training process: laboratory works regarding the electromechanical transient processes and operation of the relay protection and automation [1.11];

3. in the developed virtual testing and software methodology that can be applied for the testing of the existing relay protection safety, performance and selectivity;

4. in the methodology of virtual testing applied for the execution of the European financial projects PEGASE, ICOEUR and State Research Program in Power Engineering [1.12];

5. in the developed and published training materials for laboratory works "Basics of power system modelling and investigation of short-circuit processes in ETAP environment" and "Laboratory works in ETAP environment for Master study program. Part 1 and Part 2".

BASIC VIEWPOINTS PROPOSED FOR THE DEFENCE

1. The elaborated structure and tools of the virtual research laboratory of power system.
2. New structure and approaches proposed and patented for the effective out-of-step automation equipment.
3. A complex for the examination and verification of the testing equipment synthesised on the base of ETAP and special software.
4. Automation structure for the recognition of island regime and opportunities of its application.

CONTRIBUTION OF THE AUTHOR TO THE RESEARCH

The structure of VRL was proved in collaboration with scientific supervisor Professor Antans Sauhats, using the results of the scientific activities of RTU Institute of Power Engineering in previous years (recording system of the emergency regimes and analytic software SMOKY). A modern analogue-digital simulator was developed on the base of modelling equipment and simulation, testing and verification block of operation processes of power systems and objects. The automation prototype based on signal processor TMS-320 was synthesised together with Associate Professor Andrejs Utāns. The author owns the copyright for most of the numerical experiments and their results described in the thesis; the exceptions are specified in the text.

APPROBATION OF THE RESEARCH

The results of the research were presented and discussed at the seminars and conferences at different levels.

1. The 6th International Conference on Electrical and Control Technologies, Kaunas University of Technology Faculty of Electrical and Control Engineering, May 5–6, 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), Czech Republic, BRNO, May 23–25, 2012.
4. Riga Technical University 53rd International Scientific Conference and the 1st World Congress of RPI-RTU Engineering Alumni on Power and Electrical Engineering, Latvia, Riga, 10–12 October 2012.
5. Electric Power Quality and Supply Reliability Conference (PQ 2012), Estonia, Tartu, 11–13 June, 2012.
6. The 54th International Scientific Conference of Riga Technical University, Section of Power and Electrical Engineering, Latvia, Riga, 14–16 October, 2013.

7. International Conference on Education and Modern Educational Technologies (EMET'13) Recent Advances in Education & Modern Educational Technologies: Educational Technologies, Series 9, Italy, Venice, 28–30 September, 2013.
8. The 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, Latvia, Riga, 14 October, 2015.
9. The 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, Latvia, Riga, 14 October, 2016.

PUBLICATIONS

The following scientific papers about the subject of the research have been published.

1. Sauhats A., Silarajs M., Kucajevs J., Pasnins G., Antonovs D., **Biela E.** Testing of Protection and Automation Devices Using Dynamical Simulation Processes of Power System. Electrical and Control Technologies. Lietuva, 2011, No. 6, ISSN 18225934, 184–189 pp.
2. Sauhats A., Utāns A., Kucājevs J., Pašņins G., Antonovs D., **Bieļa E.** Protection and Automation Devices Testing using the Modeling Features of EUROSTAG. Power and Electrical Engineering. Vol. 28, 2011, 7–12 pp.
3. Survilo J., **Biela, E.** Adverse Currents in Simple Closed Networks. Electrical and Control Technologies, Lithuania, 2011, No. 6, ISSN 1822-5934, 190–195 pp.
4. Survilo J., **Bieļa E.** Extra Losses in Imperfect Closed Grids. Power and Electrical Engineering. Vol. 29, 2011, ISSN 1407-7345, 19–24 pp.
5. Sauhats A., Utans A., Silarajs M., Kucajevs J., Antonovs D., **Biela E.**, Moskins I. Power System Dynamical Simulation Application for Out-of-Step Relay Testing. Scientific Journal of Riga Technical University, Power and Electrical Engineering. Vol. 6, 2012, 1343–1348 pp.
6. Sauhats A., Žalostība D., Bočkarjova G., **Bieļa-Dailidoviča E.,** Dinevičs J. Latvian Project of Smart Grid and Renewables Technological Park. Recent Researches in Environmental Science & Landscaping: Energy, Environmental and Structural Engineering Series 2. WSEAS Press, 2012, ISBN 978-1-61804-090-9. ISSN 2227-4359, Greece, 205–210 pp.
7. Survilo J., Antonovs D., **Biela E.** Non-uniformity Impact of Power Losses in Kurzemes Ring Project Case. Electric Power Quality and Supply Reliability Conference, Estonia, 2012, ISBN 9781467319805, e-ISBN 9781467319782, 137–142 pp.
8. Survilo J., Antonovs D., **Biela E.** The Extent of Network Non-uniformaty Impact on Power Losses. Proceedings of the 13th International Scientific Conference Electric Power Engineering, Czech Republic, 2012, ISBN 9788021445147, 99–104 pp.
9. Sauhats A., Žalostība D., Dolgicers A., Utāns A., Bočkarjova G., **Bieļa-Dailidoviča E.**, Antonovs D. Power System Simulation Laboratory as a Modern Educational Tool. Recent Advances in Education & Modern Educational Technologies, Italy, ISBN 9781618042101, 2013, 103–110 pp.
10. Antonovs D., **Bieļa E.**, Sauhats A., Zicmane I. Laboratorijas darbu komplekss ETAP vidē maģistra studiju programmai. 2. daļa. Rīga, RTU Izdevniecība, 2013. ISBN 9789934104466, 52. lpp.
11. Antonovs D., **Bieļa E.**, Sauhats A., Zicmane I. Laboratorijas darbu komplekss ETAP vidē maģistra studiju programmai. 1.daļa. Rīga: RTU Izdevniecība, 2013, ISBN 9789934104459, 41. lpp.
12. Antonovs D., **Bieļa E.**, Sauhats A., Zicmane I. Energosistēmas modelēšanas pamati un īsslēguma procesu izpēte ETAP vidē. Rīga: RTU Izdevniecība, 2013, ISBN 9789934104053, 42. lpp.

13. Survilo J., Antonovs D., **Biela-Dailidovicha E.** The Stipulation for Orthogonality of the Nodal and Extra Currents. Journal of Energy and Power Engineering. Vol. 31, 2013, ISSN 14077345, 68–73 pp.
14. Sauhats A., Zalostība D., Dolgicers A., **Bieļa-Dailidovicha E.**, Antonovs D. Application of Power System Modelling Software for Educational and Research Purpose. Electrical engineering and information complexes and system, Russia, Vol. 10, No. 1, 2014, ISSN 1999-5458, 5–14 pp.
15. Dolgicers A., **Bieļa-Dailidovicha E.**, Antonovs D., Kozadajevs J. Учебные пособия в лаборатории релейной защиты, Training Facilities in the Relay Protection Laboratory.Electrical Facilities and Systems. Electrical and Data Processing Facilities and Systems, Vol. 11, No. 4, 2015, ISSN 1999-5458, Russia, 5–12 pp.
16. Sauhats A., Zalostiba D., Dolgicers A., **Bieļa-Dailidovicha E.**, Broka Z. University Impact on Power Supply Economy, Reliability and Sustainability Enhancement Decreasing Climate Changes. The 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University: Proceedings, ISBN- 978-1-5090-0334-1, Riga, 2015, 37–42 pp.
17. Sauhats A., Utāns A., **Bieļa-Dailidovicha E.**, Wide-area measurements-based Out-of-Step Protection System, 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University: Proceedings, ISBN- 978-1-5090-0334-1, Riga, 2015, 11–15 pp.
18. Sauhats A., Utāns A., **Bieļa-Dailidovicha E.**, Antonovs, D. Out-of-Step Protection Using Equal Area Criterion in Time Domain, 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University: Riga, 2016, 1–6 pp.

Poster

1. Sauhats A., Antonovs D., Svalovs A., Svalova I., Utāns A., Bočkarjova G., **Bieļa-Dailidoviča E.**, Protective circuit of the out-of-step protectionof power system. (Energosistēmas asinhronā režīma novēršanas aizsardzības shēma. In Latvian). Forums „Latvijas zinātne – kā sasniegt izcilību?" Latvija, Rīga, 9. oktobris, 2015, Rīga.

Patents

1. Antonovs D., Sauhats A., Utāns **A., Bieļa** E. Patents **LV 14832 B**, 05.07.2013.:
   - Asinhronās gaitas novēršanas automātikas ierīce (Out-of-step protective automation device);
   - Asinhronās gaitas novēršanas automātikas paņēmiens (Out-of-step protection approach).
2. Antonovs D., Sauhats A., Utāns A., **Bieļa-Dailidoviča E.** Patents **LV 14912 B**, 27.06.2014.:
   - Asinhronā režīma novēršanas automātikas ierīce (Out-of-step protective automation device);
   - Asinhronā režīma novēršanas automātikas paņēmiens (Out-of-step protection approach).

STRUCTURE AND VOLUME OF THE DOCTORAL THESIS

The thesis is written in the Latvian language, it contains Introduction, four chapters, Conclusion and Recommendations for Further Work and Bibliography. The total number of pages is 149 including 83 figures and 8 tables. The bibliography contains 160 titles.

Introduction proves the topicality of the subject of the research, defines its main aim and tasks and the scientific novelty. It also provides the list of the publications and conferences the research has been presented at.

Chapter 1 contains the analysis of the methods of task solving and means of testing and the verification of a complicated power system automation complex. It considers the operation principles of the automation equipment as well as the applied approaches, methods and means for the examination of it. The development of scientific laboratories is considered and analysed starting with the dynamic-physical models of power systems to the VRL [1.13].

Chapter 2 is devoted to the justification of the necessity of VRL and its structure, as well as to the software and equipment selection.

Chapter 3 describes and analyses two important types of emergency prevention equipment of power systems as examples:

- out-of-step regime recognising and protective automation AGNA;
- Island regime recognising automation (SAA).

Both types of the above mentioned automation equipment use large amount of input processes and relatively complicated algorithms. The chapter describes the present situation, the disadvantages of the applied automation and opportunities for its improvement. It also contains the proposals for new structures and algorithms to exclude these drawbacks.

Chapter 4 contains the description of the testing process of automation algorithm and equipment and the results. Software EUROSTAG, ETAP is applied as well as the data of Latvian power system transmission network and large power stations. Additional testing was carried out using IEEE testing models. The examples of testing results are provided. The library of the testing signals and testing procedure of the power system model validation are considered.

Conclusions and Recommendations for *F*urther *W*ork contain the proposals in two basic directions:

- improvement of power system simulation software with models of new technologies;
- improvement of software with further automation of the experiments.

1. TESTING LABORATORY OF THE POWER SYSTEM AUTOMATIC COMPLEX

Any power system consists of millions of elements that can be divided in two groups:

- power elements generating, transmitting, distributing and utilising energy;
- elements controling the process and, depending on the resulting information, controling the condition and parameters of the system. Most of the controling elements are operating in automatic mode, as the speed of changing of the power system condition and parameters does not give an opportunity to use human resources for these actions.

Part of the possible processes in the system is dangerous for the power elements as it can cause damages, fire, blackouts, etc. Relay protection and emergency automation equipment can break or avoid from these processes. These systems can significantly change the operation of power systems. The testing of scenarios of different types, algorithms and operation can reduce the probability of faulty operation of the automation. Such kind of testing is possible in special laboratories using the equipment and measurement devices suitable for the automation of particular type and performance.

The examining at real power objects can replace laboratory experiments. Such examinations are applied but only at the final stage of the development of the new equipment because of the following reasons:

- it is impossible and too expensive, to create the emergency processes and situations artificially;
- because of low probability of emergency situations at real objects; the testing requires a long time or it has to be made with the help of many samples of new devices; despite the mentioned disadvantages testing of the equipment under real circumstances is an important part of the process of its development.

Unlike the end stage, the testing at the initial stage takes place with the application of models and computer simulation of power systems and new automation equipment. The testing of these cases takes place within the frames of virtual laboratory the structure of which is reflected in Fig. 1.1.

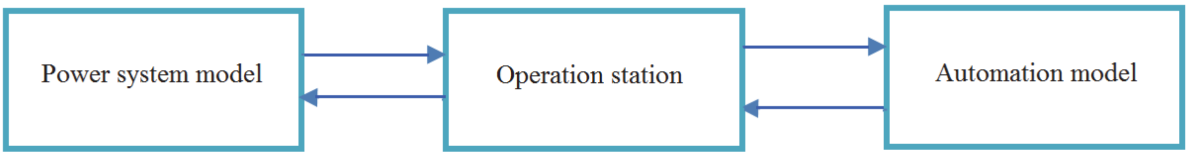


Fig. 1.1. Simplified structure of the virtual laboratory.

Virtual laboratories provide the possibility to experiment with models of power systems as well as with the developed automation. The work with models gives wide opportunities for changes and automation of the experiments. However, there is one but important drawback: a successfully tested model does not guarantee suitability of the device to real working conditions. This statement is topical at the testing of microprocessor devices the realisation of which can allow errors in the development of both software and hardware. Virtual-real laboratories (VRL) are used with the aim to avoid this disadvantage [1.18].

VRL are mass-produced devices applied in power systems realising regular testing of the automation equipment.

The structure and devices of VRL are the basis in this research for further development of testing methods and equipment.

It can be stated that modern power system automation operates using the control of the multidimensional processes. These processes can be avoided (measured) at different geographically distanced places. They are exchanging the information by means of optical high-speed communication channels [1.25], [1.26].

The increasing of the number of processes under control significantly influences the testing process that is becoming more complex.

At the same time, the fact that the signals of microprocessors are of low power significantly simplifies the testing procedure.

The structure of VRL is shown in Fig. 1.2.

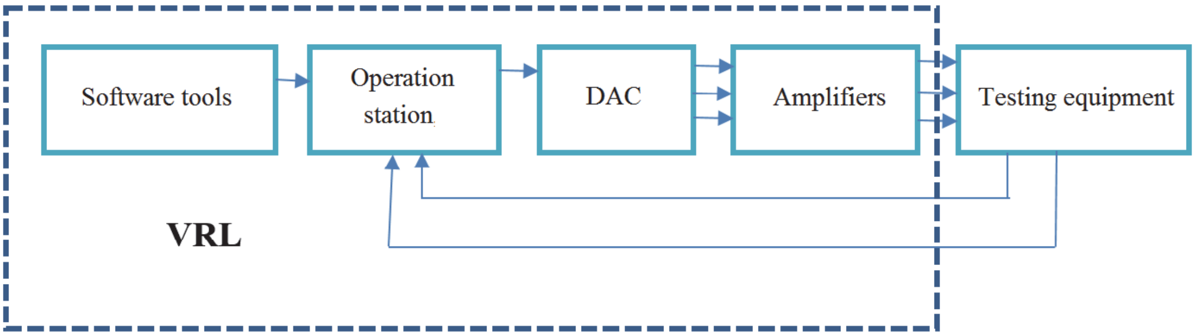


Fig. 1.2. Structure of virtual-real laboratory.

As it is obvious from Fig. 1.2., in comparison with the above mentioned information the virtual laboratory in addition applies blocks: digital-analogue signal converter (DAC) and amplifiers. This enlargement allows the investigation of properties of real automation equipment. The most important disadvantages of this laboratory can be:

- expensive realisation;
- inaccuracy of the digital model of power system.

Virtual laboratory is the complex of software and hardware for making research without the physical presence of equipment [1.28]. The main purposes of a virtual laboratory are illustrated in Fig. 1.3.

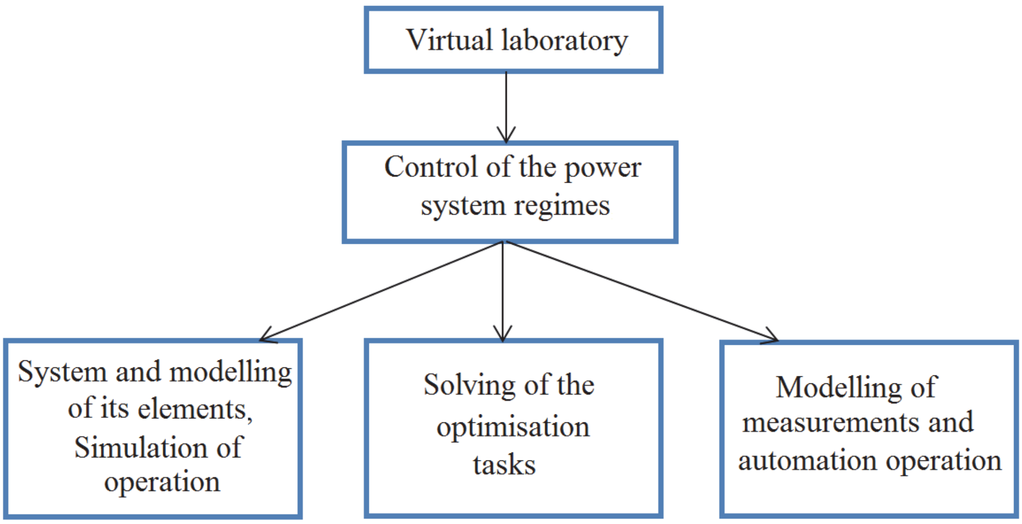


Fig. 1.3. Purposes of virtual laboratory.

The following types of software for power system modelling can be considered:

- *NEPLAN* software [1.37]–[1.39];
- simulators *RTDs* and *NI PXI*. *RTDs* [1.40]–[1.44];

- *ICT* remote high voltage HV laboratory [1.44]–[1.46], [2.17];
- prototype of virtual laboratory (*VEMA*) [1.47], [1.48];
- *e-LABORATORY PROJECT* [1.28];
- *VLABPOWER* virtual laboratory [1.49], [1.50];
- distant labs (distant access) described in [1.23];
- *EUROSTAG* software [1.51]–[1.57];
- *ETAP* (Electrical Transient Analyzer Program) [1.54];
- *PSS/E* (Power Transmission System Planning Software) [1.58].

Summarising of the information about the virtual laboratories gives a conclusion that the programs correspond to the training [1.59] and analysis of the process, but they are not suitable for the application in testing of real equipment [1.60], [1.61].

It is also necessary to pay attention to the analysis of the problems of simulation of emergency processes. Thus, a power system includes (Fig. 1.4) four subsystems: generation, transmission, distribution and load. The purposes of power system are realized with the help of specific control system, which in turn contains the blocks of measurements, prevention and decision making [1.62]. The control system (*CS*) can include a large amount of automation devices as multi-functional control. The relay protection and emergency automation are important in CS subsystem [1.51]. This subsystem supplements the measurements and provides changes in generation, transmission, distribution and loading necessary in the emergency cases [1.63].

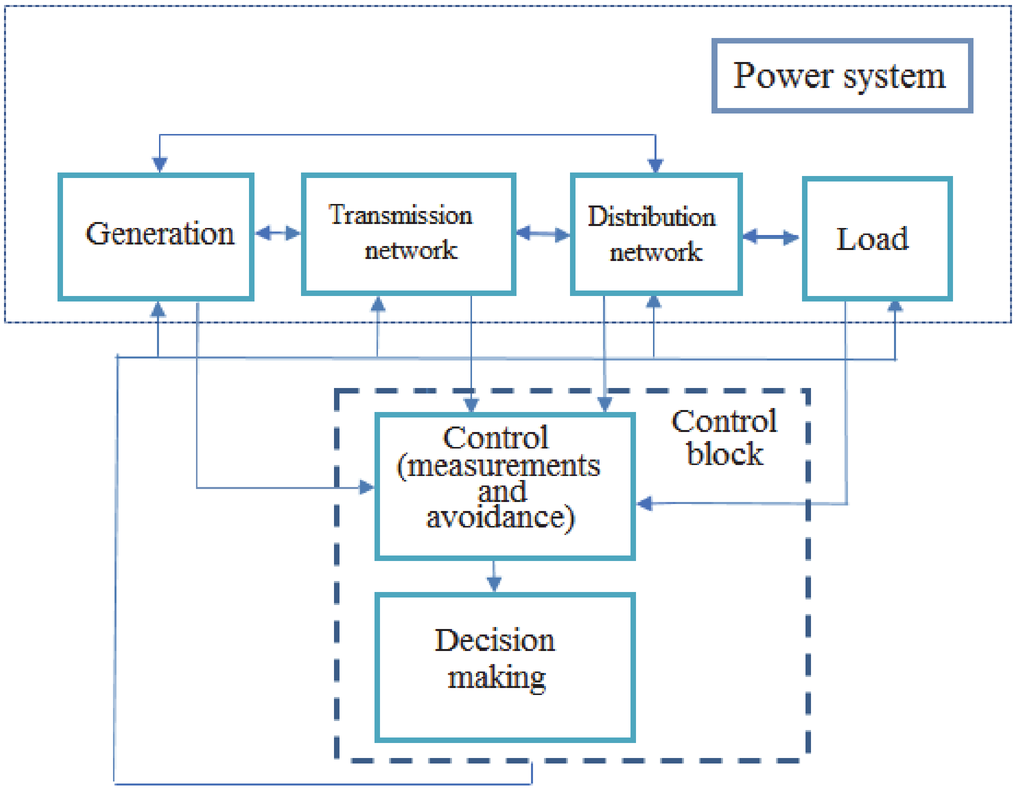


Fig. 1.4. Simplified structure of power system and its control.

The synthesis of algorithms and equipment requires the testing tools that can be realised with two basic principles [2.12]: testing within the area of signal parameters and settings and testing within the area of protective devices parameters.

The procedure of the terminal testing is shown in Fig. 1.5. In this case the testing means the supply of randomly selected signals of the generator of random number and saving of this value in the memory of the tested device with further response from the reference device and the comparison of the response signals. This procedure can be simplified by transferring the functions of the generator of random number and reference device to a researcher who makes the testing.

The above mentioned approach has the following disadvantages:

- possible supply of combination of redundant parameters, that does not occur in a real power system, where the generation of high short currents simultaneously with rated or higher voltage can be considered as an example;
- complex determination of the response of the reference device.

Even a relatively small power system consists of hundreds of thousands of elements that cause difficulties in the modelling process. For the explanation of this statement the structure of Latvian power system should be considered starting with high voltage network. The conclusion is that this network contains tens of 330 kV and more than hundreds of 110 kV PEL, and each should be modelled [1.64].

The high voltage network is connected with a middle voltage network. The middle voltage network contains thousands of elements, but additionally can be enlarged with the elements of low voltage circuits, that in turn enlarges the total network for up to hundred thousand elements together with the loads. The generation sources connected to the high voltage network of the main generation, e.g. hydro station and termo station, as well as to the transmission network with the distributed generation sources, like wind parks, cogeneration, should not be forgotten.

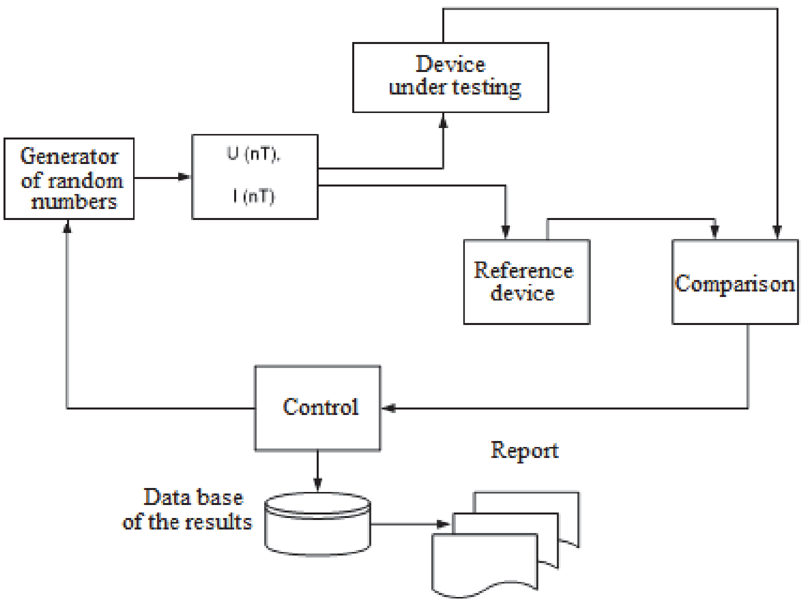


Fig. 1.5. Terminal testing supplying signals directly to the device under testing.

The network of power system supplies the energy sources with hundreds of turbines and generator including the renewable sources [1.65], [2.18], [2.19]. The most difficult is the case when Latvian power system is connected with the neighbour contries (Estonia, Russia, Lithuania) [1.66], [2.20].

The complexity of the power system causes the assumptions in it while modelling.

The following assumptions are conventional in the practice of modelling:

1. the electromagnetic and electromechanical transient processes are modelled separately;
2. the power systems of the neighbour countries are substituted with equivalent generators saving the international transmitting lines;
3. while modelling the electromagnetic transient processes, the networks of one voltage level are separated from those of the other level;
4. modelling of the electromagnetic transient processes takes into account the high voltage network connecting the load to the network terminals [1.67].

The modelling of electromagnetic processes applies the developed theory; the processes are described with algebraic equations; the method of the symmetric components is applied as well as commercial software, e.g. PSS/E [1.68].

The modelling of electronmechanical processes applies the assumption that before any changing the system is stationary and can be characterised by:

- parameters of all turbines TR_l;
- active P_i and reactive Q_i power of generator;
- particular circuits of the transmission network;
- particular values of voltage and current in the elements and branches of the network.

As soon as the oscillations occur in the system, the current and voltage can change that can be described with the following system of differential equations:

$$\left.\begin{aligned} T_1 \frac{di_1}{dt} &= F_1 \\ &\vdots \\ T_j \frac{du_j}{dt} &= F_j \end{aligned}\right] \qquad (1)$$

where $F_j = F_j\left(i_1, i_2, \ldots i_m; u_{m+1}, \ldots u_n; TR_l; P_i; Q_i; P_{cj}; Q_{cj}; \Delta f; \Pi_s\right)$ (2)

where Π_s are the parameters of the system (inductance of the transmission line, resistances, parameters of the turbines, generators and transformers, etc.).

The modelling of the oscillations even in a relatively small power system has significant difficulties because of the large amount of variables and the necessity to take into account a huge amount of generation and load combinations [1.69].

Many data about the loads, generators, line parameters, types of applied automation and parameters are required for the application of (1) and (2). Researchers can distribute the tasks and describe each regime by equation (1). Taking into account the large number of publications regarding the development of the power system tools, modelling the application of this methodology should not cause large difficulties [1.52]. The most complicated challenge is connected with the size of the power system. To overcome these difficulties such soft tools are developed as ETAP, EUROSTAG [1.53]–[1.56]. The application of these tools gives an opportunity for simple, but not cheap, development of a dynamic virtual laboratory of a power system equipped with a user-friendly interface and wide range of tasks to be solved. Unfortunately, the possibilities of existing soft tools are limited. The analysis of such restrictions shows the following.

1. Virtual laboratories do not provide an opportunity to test real equipment and can investigate their own models only. This restriction is significant while a relay protection or protective automation is designed. The mentioned equipment is designed from the models

tested in the virtual laboratory. After the successful testing of the models, the next step is the development and verification of the real equipment.

2. The output proceses of the software under consideration are expressed in the vector from, e.g. for the current *i(t)*:

$$i(t_j) = A_i(t_j)\exp(j\omega(t_j) + \Theta(t_j)) \qquad (3)$$

where A_i; $\Theta(t)$ is modulus and angle correspondingly of the vector.

Such signal cannot be applied directly in the testing of real equipment and investigation process.

This software is not intended for the explicit modelling. For example, the equipment contains analogue-digital converter, digital filter, and large amount of input commands. The modelling of operation of these elements is impossible with industrial software.

2. HARDWARE AND SOFTWARE OF THE VIRTUAL-REAL LABORATORY

To avoid the disadvantages of the VRL described in Chapter 1, an expanded structure of the laboratory is proposed (see Fig. 2.1.)

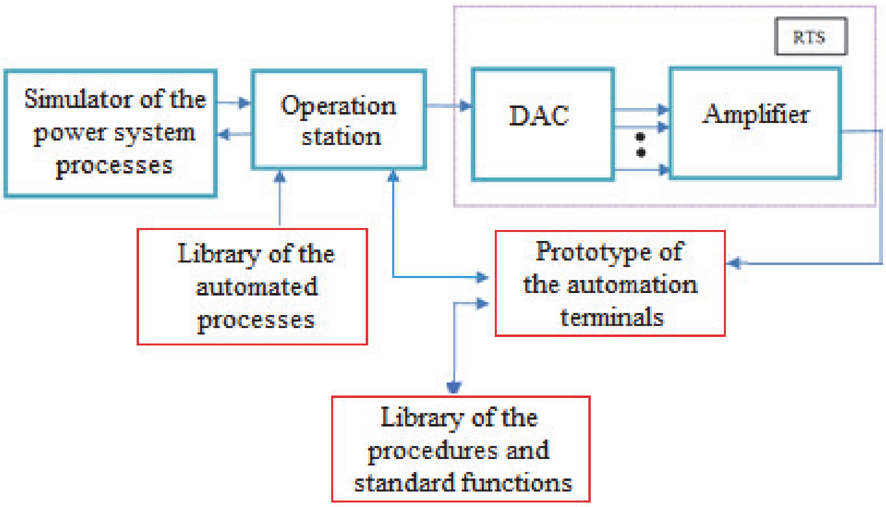


Fig. 2.1. Enlarged structure of the virtual-real laboratory.

VRL consists of a number of blocks.

- A virtual simulator of the processes that simulates the electromagnetic and electromechanical processes is a computer programming complex.
- Operation station equipped with the software for the processes simulation and able to save the processes in a database.
- A library of the procedures and standard functions with a summarised and saved information and database of equipment and its parameters.
- RA testing system (RTS), e.g. ISA DARTS, OMICRON etc.
- A library of real processes that registers the emergency processes (currents and voltages of complex forms). The forming of the library applied the objects of power system that operated and were equipped with the registers of emergency processes. The realisation of

such block for the VRL purposes would be unrealistic due to the capital expenses and volume. The existence of the registers in modern power systems is used as well as RTU participation in projects, connected with the development of registration systems with an opportunity to collect and summarise large amount of information about the emergency processes and enlarge it. As a matter of fact, the power system with emergency processes in its full extent should be a part of the laboratory for the register and saving. This proposal is realised in practice only because of the wide application of the emergency registrators for other purposes (analysis of the relay protection operation, determination of the line damage localisation [2.1], etc.).

- Terminals of automation devices (microprocessors) with a selected structure (the number of controlled processes and output signals, volume of the memory, speed of performance), allowing to realise the most complicated and modern automation systems including relay protection and automation of global type [1.14]. It is possible to include the automation prototype into the laboratory due to the properties of microprocessors. There is an opportunity to provide a universal device for a wide range of equipment that is more expensive and complicated for a low extent only, if to compare it with specific devices for a particular task realisation.

At the end of the century the registrators of the damages on the basis of microprocessors quickly developed. The general operation principle of digital registrators is very simple: at a particulat moment of time, the value of the registered signal is transformed into a digital form. The digital data is saved in the electronic memory and can be sent for further processing by other equipment. The technical indicators of the microprocessor registrators are: accuracy, opportunity to register the prior emergency regimes, uncomplicated utilisation, high enough safety, possibility of further processing of the results, possibility to obtain the results in graphical way, possibilities to calculate power, angles, resistances, frequency, values of current and voltage as well as to recognise emergency situations.

The structure of the microprocessor registration system is much more complicated in comparison to the oscilloscopes mentioned above. Many enterprises working in the field of power engineering apply microprocessor registrators in design and production. Several hundred microprpcessor registrators REMI, developed at the laboratory of RTU Faculty of Power and Electrical Engineering, are used in the Baltic States [2.2].

REMI registrator shown in Fig. 2.2. is able to send the registered data to the computer operator by means of modem with or without internet connection.

Registrator APR serves for the register of the conditions of automation contacts, current, voltage and relay protection of an object under monitoring in an emergency or out of order regime. The registrator transforms up to 15 instant values of analogue input signals into digital form and saves the obtained results in the internal memory. At the same time 32 discrete signals are registered (the conditions of the contacts of the peripherals). The transformation of analogue and discrete signals occurs with 1000 Hz frequency. In the regime of prior emergency, the memory of the registrator saves and permanently renews the values of all the signals and checks the starting conditions. As soon as the conditions are fixed after each of the controlled signals, the memory saves the information of the prior emergency regime, saves the starting time and reason, and the device continues the register of the emergency regime in accordance with the selected duration of the oscilloscope registration. When the registration is completed the registrator gets the waiting mode. The time of the registrator ready condition for the next operation stage does not exceed 5 ms. The results can be sent to the personal computer directly or by means of communication channels for the display and automatic processing (Fig. 2.2.) [1.23].

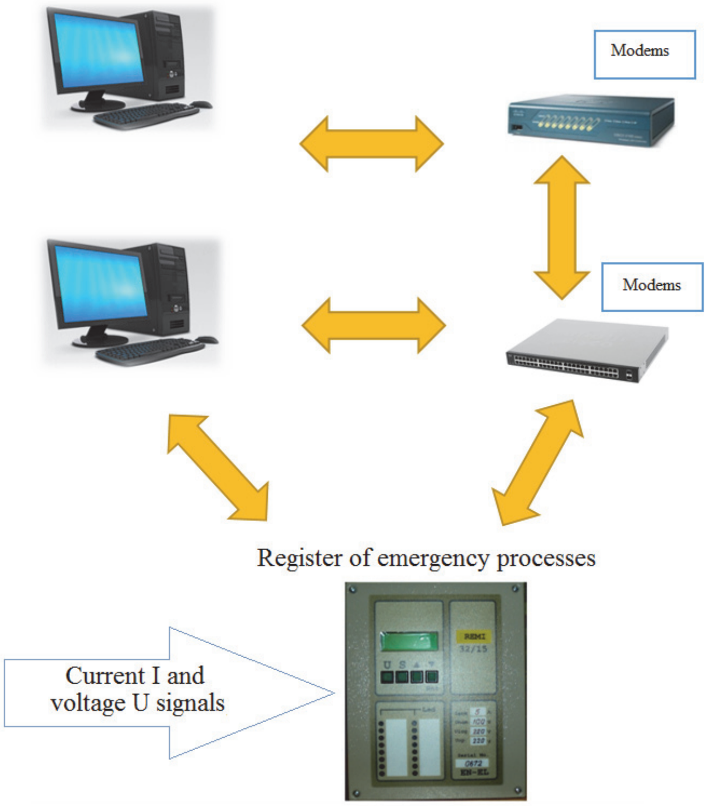


Fig. 2.2. Structure of the information exchange of the emergency processes register (EPR).

The library of the emergency processes containing a lot of different registered regimes and processes in power system is created by the registrators installed in Latvia, Lithuania and Estonia (due to the relay services of the Baltic States). Examples are shown in Fig. 2.3 [1.23].

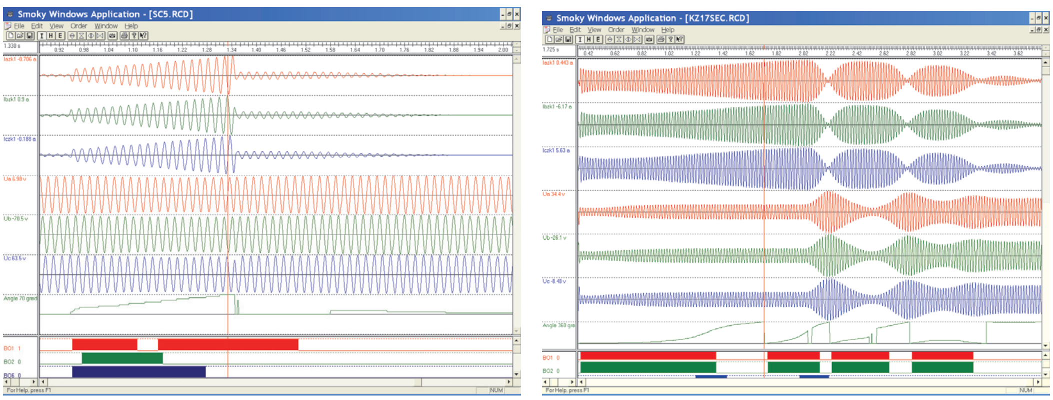


Fig. 2.3. Illustration of the emergency processes oscillograms
by mean of SMOKY software.

By means of the program of the oscillogram drawing SMOKY an additional signal for the effective verification of the algorithms of the device operation can be added to the existing figures [2.3]. An important option is the creation of a vectorgram required by an operator at any time instant. It is important that any oscillogram can be transformed into correspondent voltages and currents and applied in the experiments with real devices.

During the development of the structure of the terminal prototype and selecting the elements of the microprocessors the following factors are important:

- the number of the controlled analogue (currents and voltages) and logical signals;
- the number of the output relays;
- the required volume of the memory (for the saving of programs and data);
- accuracy and frequency of the analogue-digital converter (ADC) [2.4];
- the volume of the data processing and necessary speed.

It is necessary to forsee the maximum number of inputs and outputs in the considered tasks, volume of the memory and power of the processor, as well as to provide a united valid structure for all possible cases. The simplified scheme of the mentioned structures is shown in Fig. 2.4. The structure is based on two 16 bit signal processors TMS 320 [2.5]. It is important to note that the processors are equipped with internal memory of 64 kilobyte volume. 16 output relays and 32 input logical signals are required taking into account the results of the analysis of the line protection and switches control tasks. Two interfaces are foreseen for the conncetion with the external devices: RS 232 provides the connection with personal computer or modem, but RS 422 is for the exchange of data through the optical channels that can be used while realising a differential protection of lines. The operative data are saved in the memory of 1024 kilobytes with an embedded accumulator providing the saving of information even in the case of long-lasting damage of the operative supply source. The volume of the applied memory provides saving of the emergency process register during several minutes. A liquid-crystal four-row indicator generating short messages and explanations is applied for the displaying of information; the control panel consists of four buttons only and allows the recording of the settings in the cases when no external computer is used. The signals are filtered at 50 Hz frequency by means of low frequency filters (LFF) Fig. 2.4. Indication and control block provides the exchange of the information with the external computer. Thus, the terminal can be virtually tested. The presence of two processors and the opportunities of information exchange are easily applied for the realisation of self-testing. If one of the processors is damaged during the calculations of errors or cannot connect with the second one, the serviceable processor can signal about the damage. The terminal structure has a "watch dog" function microscheme for the alarm in the case of both processors damage [2.12.].

The software of the automation terminal prototype is developed taking into account everything described above, realisation of the equipment and contains the following sub-programs:

- ACP processes control;
- digital filters;
- evaluation of electric values; active and inductive resistance, power, angles, vector modules, vector linear combinations are calculated;
- block of the software operation accuracy;
- control block of the memory operation abilities;
- Software SMOKY developed at RTU is adapted for the control, analysis and monitoring of the terminal operation [2.6].

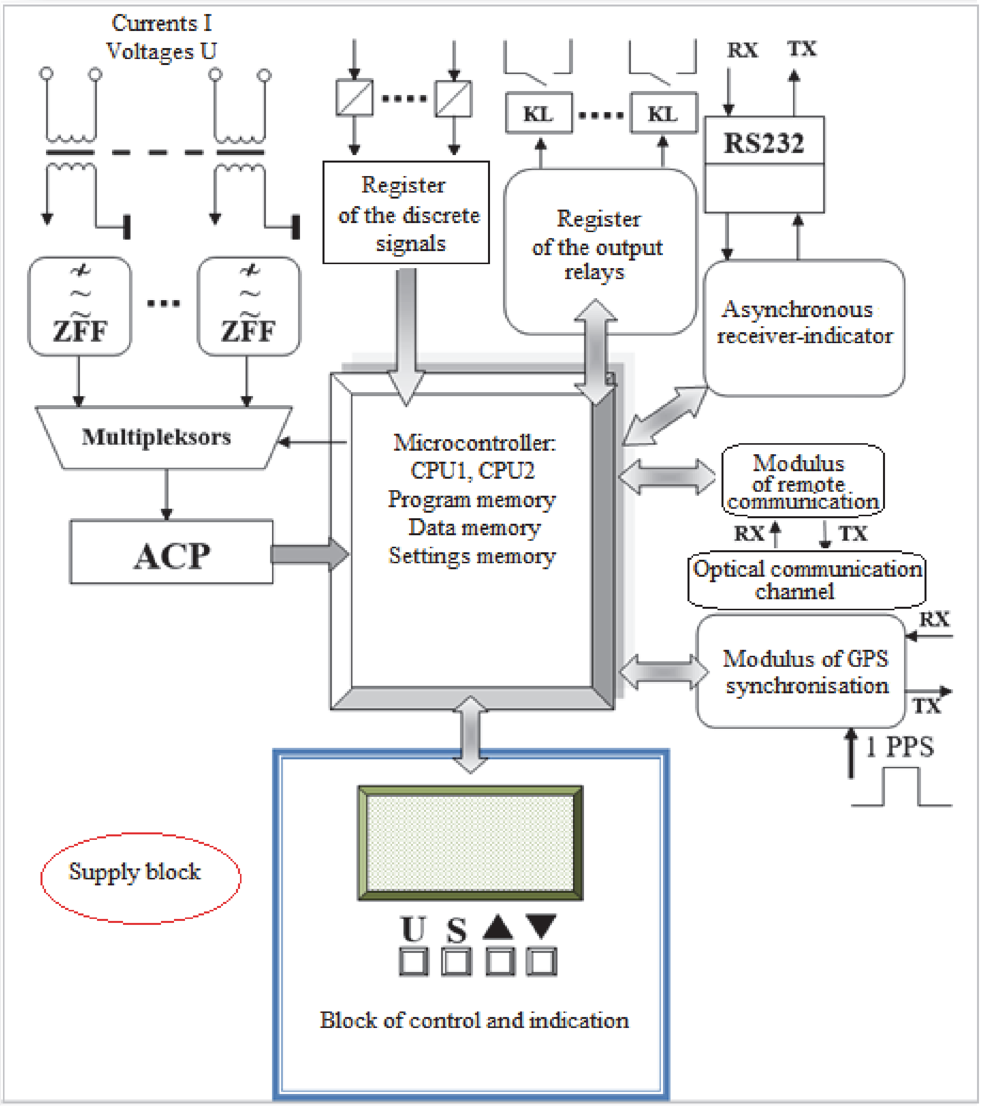


Fig. 2.4. Simplified structure of the device realisation.

A solution with two processors is applied for the realisation of the relay protection and automation terminal of the transmission electric lines. Therefore, a task exists for the distribution of the programs between the processors. The selected structure of the software is shown in Fig. 2.5. The functions of the device are distributed as follows.

The first processor (CPU1) provides the following functions:

- ACP control, processing of input currents and voltages and control of the output relays;
- library of the protective and automation functions;
- registration of the events;
- measurement of the distance till the damage;
- control of the indicating display;
- control of the block of settings input;
- control of RS-232 interface of the oscillograms and settings reading/input.

The second processor (CPU2) provides the following functions:

- control of RS-422 interface of information exchange of both half-sets;
- correction of the second half-set angular error existing during the data transmission;
- timer;

- control program of GPS module;
- protective function (PF).

Measurement of the distance to the location of the damage is realised using the measurements of both terminals. The set of high-speed data transmission realises the exchange of the information between the processors. Both processors provide the function of self-control as well as peer control [2.7].

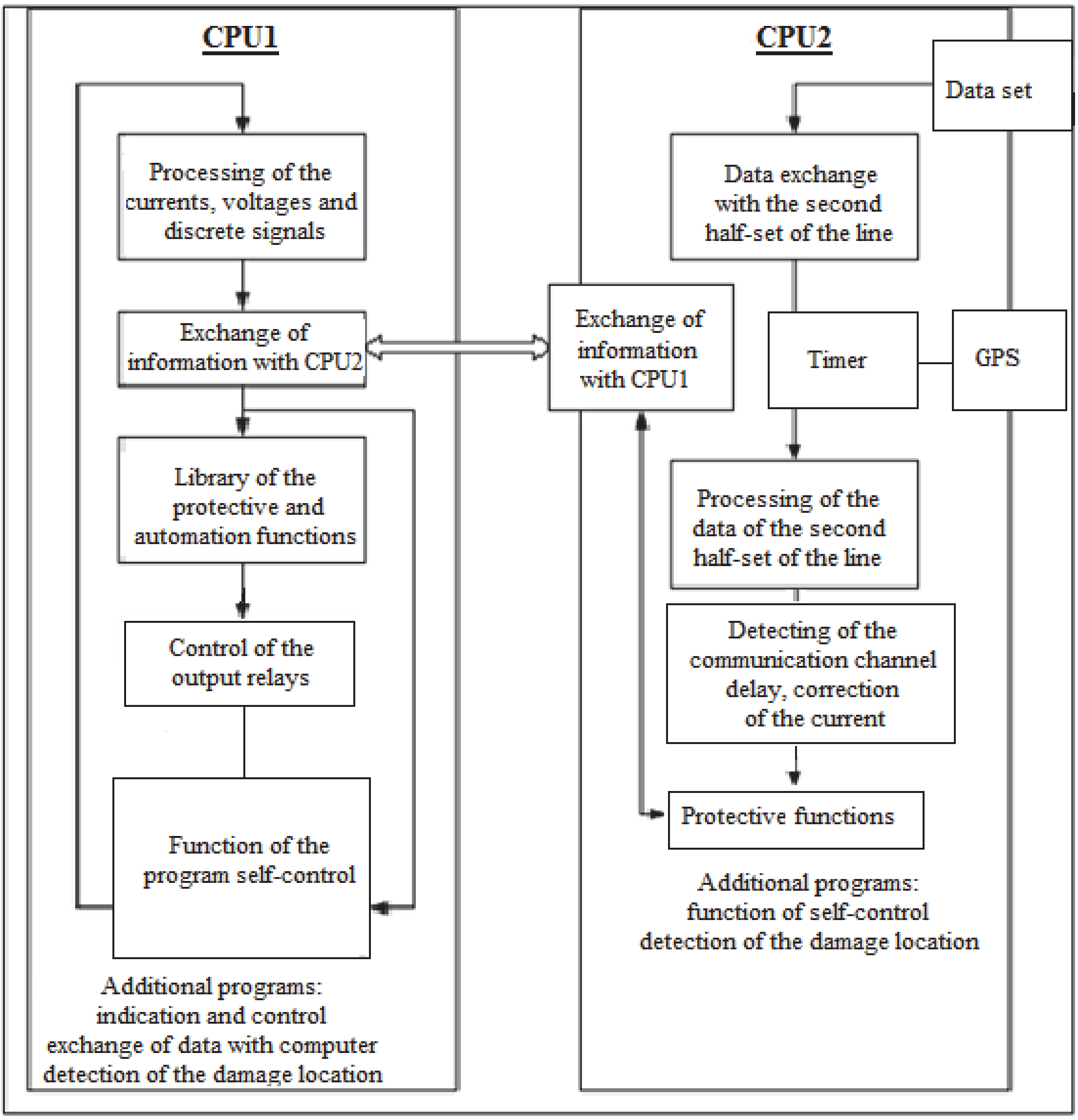


Fig. 2.5. Structure of the program.

3. ANALYSIS OF THE OPERATION OF OUT-OF-STEP PROTECTION AUTOMATION FOR POWER SYSTEMS AND DEVELOPMENT OF NEW APPROACHES TO IT

The power system consisting of two or more synchronous generators can get an asynchronous regime of operation [3.1] (AR). AR characterises the colour change in the regime parameters (e.g. current, voltage), since the angle of EMF of the generator or generators starts to move (accelerates or slows down) in accordance with the angles of the system and other generators, depending on the present power balance. The power systems operating in the conventional steady-state regime provide parameters. The damages of power system, switching on/off of the line, generator or large load switching off cause sudden changes in the electric power, but the mechanical power (water or steam supply) of the generator is relatively constant. It is the reason for the vibrations of the rotor of generator that can result in dangerous oscillations of power. According to the character of the changes and control operations the regime of the power system can stay stable and achieve the balance condition including the stable oscillations of the power system (stable power swings) [3.3].

AR of power system can be classified as a particular dangerous case as the consequences for the power system are catastrophic and result in huge financial losses. To exclude these losses despite the relatively low probability of AR, a special automation AGNA is applied for the avoidance of this regime and reducing of the negative effect.

Different AGNA approaches are developed and realised in the world, e.g. distant relays based on the principles to control the changes of full resistance or angle.

Although the probability of AR is many times lower than that of the single-phase short current regime, the adequate control of AR is significantly important. The purpose is to provide a controlled distribution of the power system and further control in other parts of the power system achieving the power balance and maintaining the rated frequency.

AGNA is tested in this chapter for the realisation of the stated purpose. It should be noted that the achievement of this purpose has a critical importance for the avoidance of the cascade blackout of the power system.

The basic tasks of the out-of-step automation for the asynchronous regime (ARNA) are:

- to fix the emergency changing or controlled parameters within allowable range;
- to estimate the level of perturbation and damage;
- to estimate the condition, data of the regime and parameters of the circuit before the emergency;
- to select correspondent control type, volume and location;
- to realise the control operation according to a particular algorithm and within a particular time interval.

The basic requirements for these devices are selectivity, block in the short-circuit regimes, in the cases of circuits disconnection and during current pause, i.e. the devices should identify AR without operating in other types of damages. It is known that the direct measurement of the angle between the equivalent generators results in particular problems [3.8]. Therefore typical ARNA applies indirect regime parameters like: currents, voltages, resistances, angles between voltage and current, etc. [3.9].

To measure the speed of voltage changing in the epicenter of oscillations is a well-known solution [3.12]. The disadvantage of this approach is connected with time delay. A device determining the feasibility of AR in accordance with calculated acceleration and braking squares comparison [3.12] is known. If the braking square is smaller than that of acceleration the device operates and disconnects the generator from the system. In such case the device makes the decision about an emergency situation and disconnects the generator when AR already starts to develop.

In the simplified cases of the stability estimation a square method is known and widely used [3.14]. This method considers the relationship of energy parameters in the transient process without solution of the differential equations of the rotor motion. Therefore, when the power system is in normal (conventional) operation regime (Fig. 3.1.), the power of the turbine P_{Meh} is in balance with the electric power of the generator, providing the necessary loading requirement. The mechanical and electric powers are intercrossing at angle δ_0 and this point is considered as a steady-state condition. Another “relatively stable” point exists at angle δ_{kr}. This point also describes the balance between the consumed and generated power, however even an insignificant perturbation results in the balance loss and AR in the power system [3.15].

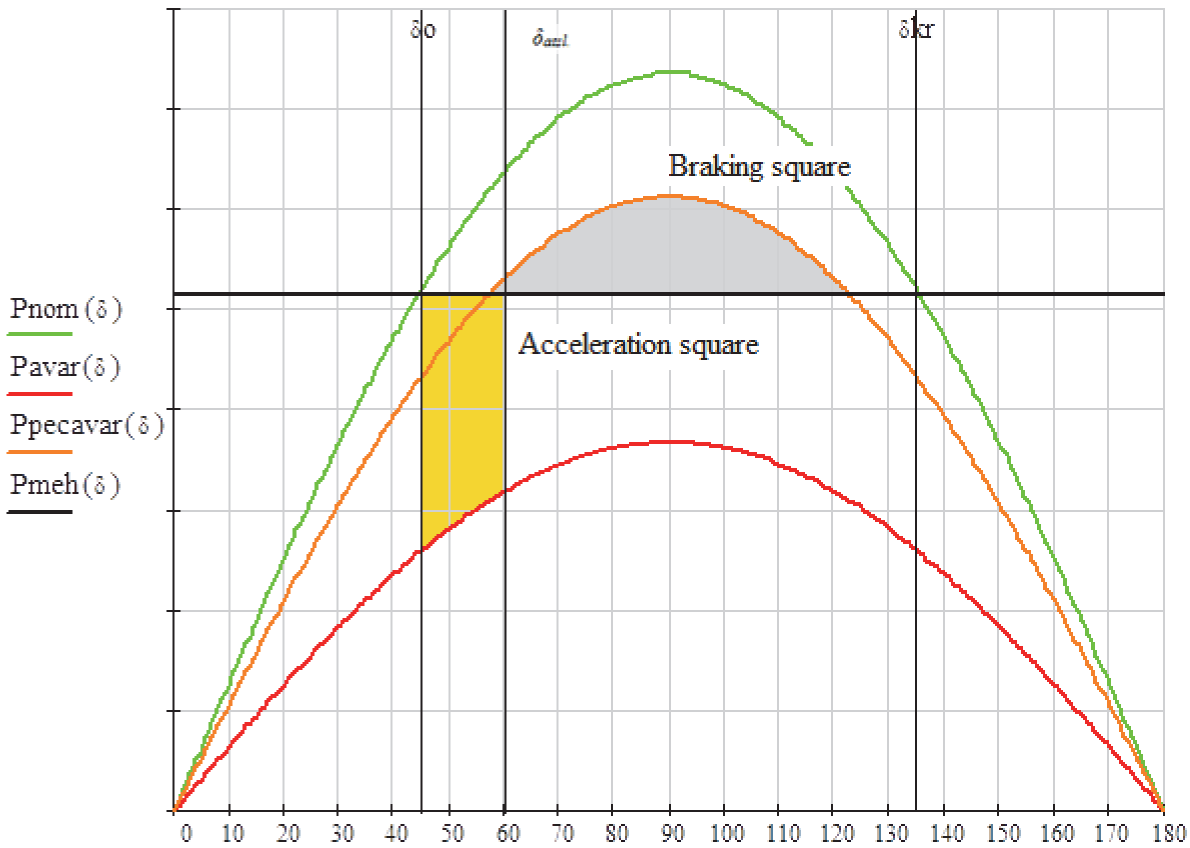


Fig. 3.1. Characteristics of the regimes of the square method (normal, emergency and post emergency regimes).

The main conclusions from the square method are the following: if the braking square is larger than that of the acceleration, the transient process is stable and synchronism is reached after some angle oscillations. If the acceleration square is larger than the braking then AR exists causing the damage of the system if it is not terminated on time.

Therefore, the application of the square method has three stages.

1. Normal regime when the amplitude of the characteristic is within the range of the maximum transmitted power normal (conventional) regime (Fig. 3.1).
2. Emergency regime (short-circuit) when one of the elements of power system is damaged. The conditions of the power transmission are weakening resulting in the decreasing of characteristic amplitude (Fig. 3.1).
3. Post emergency regime that is conventionally harder than the normal regime as the short-circuit localisation results in disconnection of one or some of the electric system elements (line, transformers, etc.). As a result, the range (amplitude) of the transmitted power will be between normal and emergency characteristics (Fig. 3.1.) [3.16].

The method of equivalent square allows to recognise the instant of AR existence in the circuit before the angle between the generators achieves 180 ° value [3.17]. The principle of the method is explained in Fig. 3.2. and Fig. 3.3. In the prior emergency regime (conventional regime) the flow of electric power between two power sources *G1* and *G2* occurs along the two transmission lines *L1* and *L2* (Fig. 3.4.).

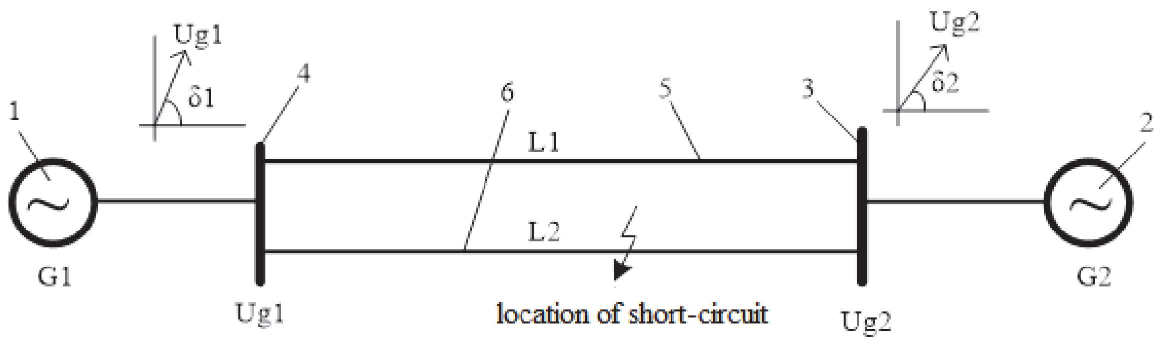


Fig. 3.2. Circuit of the power system under consideration:
1;2 – equivalent generators; 3; 4 – buses of the generators connection; 5; 6 – PEL

Characteristics 1 of power transmission (Fig. 3.3.) corresponds to the conventional regime. In this regime the mechanical power of the generator P_m supplied to the generator turbine is equal to the electric network consumed power $P_e(t)$, the angle is $\delta_0 = \delta_2 - \delta_1$ and the rotor of the generator is rotating with constant speed close to the value of the rated frequency of the electric network. Characteristics 2 (Fig. 3.3.) corresponds to the short-circuit regime of transmission line *L2* (Fig. 3.2.). The short-circuit of line *L2* results in the acceleration of generator rotor because the mechanical power P_m of the generator exceeds the consumed power $P_e(t)$ of the electrical network (Fig. 3.3). The operation of the protective equipment results in the disconnection of line *L2* that corresponds to Characteristics 3 (Fig. 3.3.). The braking of the rotor occurs when electric power $P_e(t)$ exceeds the mechanical power of the generator P_m. The method is based on the comparison of the generator acceleration and braking energy. The "acceleration square" corresponds to the acceleration energy, but the "braking square" – to the braking energy (Fig. 3.3.). In accordance with the method generator loses the synchronism with electric network because with the angle exceeding δ_{cr3} value, the acceleration square is becoming larger than the braking square.

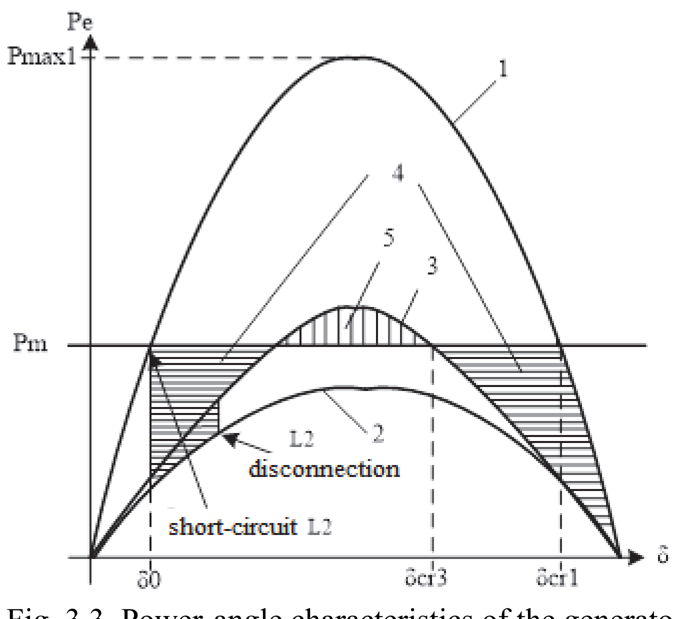


Fig. 3.3. Power-angle characteristics of the generator:
1 – conventional regime, 2 – short-circuit regime;
3 – regime of disconnection of the damaged line L2, 4 – square of the acceleration energy;
5 – square of the braking energy.

The approach of the out-of-order automation operation by means of the equivalent square method is described in [3.18]. For this operation the full energy of generator (braking and acceleration) $A(\delta(t))$ is calculated as well as the critical angle δ_{cr3} (Fig. 3.3.) [3.18.]

$$A(\delta(t)) = \int_{\delta_0}^{\delta_{cr3}} (P_e(t) - P_m) d\delta \tag{4}$$

Testing of the generator synchronism losing in accordance with the considered operation principle with (5) takes place at the time instant when $\delta(t) \geq \delta_{cr3}$:

$$A(\delta(t)) = \int_{\delta_0}^{\delta_{cr3}} (P_e(t) - P_m) d\delta < 0 \tag{5}$$

The disassembly analysis of the power system synchronous regime demonstrated that it is characteristic for the system with the shortage of power that has the following reasons:

- in the case of disconnection of one or more transmission lines the electric energy is not supplied to the power system to a full extent for maintaining the rated frequency and voltage.
- lack of the generated power because of disconnection of one or more generators.

The most effective solution is to measure angle φ and the speed of its changing $d\varphi/dt$. This principle is applied to avoid the asynchronous operation of the automation AGNA. AGNA controls the processes in 110–330 kV transmission electric lines and switches and has the functions of automation. The equipment is realised based on microprocessor elements and uses the digital principle for the information processing.

The decision about starting of AR can be made when the angle φ between the modelled voltages does not achieve the limit when the generator rotor starts turning.

AGNA models the voltages across the generator terminals using the local parameters of the regime (voltage of the buses and line currents) according to the formulas

$$\underline{U}_1 = \underline{U} \pm \underline{I} \cdot Z_{K1} \tag{6}$$

$$\underline{U}_2 = \underline{U} - \underline{I} \cdot Z_{K2} \tag{7}$$

where $\underline{U}$ phase-to-phase voltage at the point of the device installation;

$\underline{I}$ current in the phase;

Z_{K1}, Z_{K2} settings of the compensation resistances.

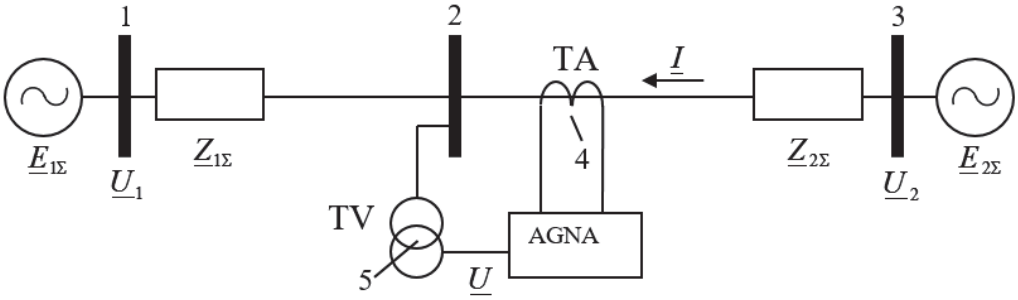


Fig. 3.4. AGNA connection scheme:
1; 2; 3 – buses; 4 – current transformer; 5 – voltage transformer.

From (6) and (7), AGNA models the voltages across the terminals in a complex way, that allows to calculate the angle between them. While modelling angle φ, it is possible to determine the speed of its changing $d\varphi/dt$ and its sign: positive or negative.

The attention is paid to the improvement of ARNA modelling algorithm to increase the potential of the equipment usage, selectivity of the operation and accuracy.

The approach described in [3.21] is noticeably more accurate than the one realised by AGNA, however, each of the selected settings has a significant value. It should be noted that an incorrect selection of settings of one device causes a declination of the controlled AMF angle from its real value and a mistaken operation of the automation can occur. The selection of settings is becoming easier as the possible configuration of the electric station can be relatively simply analysed, simultaneously the changes in the transmission network topology are excluded.

In [3.21] the measurements and accuracy of the modelling depend on the present number and type of generators (as well as transformers) of the station, the circuit of their connection, level of the loading, time constant, etc. Due to that in the device described in [3.21] the realised approach does not provide the necessary accuracy and selectivity of the operation, especially in the cases when the generators and their load differ within the parameter range of one station.

Therefore the device models EDS $\underline{E}_i$ of the i^{th} generator from the voltage of the first bus $\underline{U}_{K1}$ and current $\underline{I}_i$ of i^{th} generator multiplied by the correspondent resistance Z_i. The device is connected to the communication channel by means of which it obtains the information from the second device about the EDS $\underline{E}_j$ of the j^{th} generator. This generator is modelled from the voltage $\underline{U}_{K2}$ of the second bus with the current I_j of j^{th} generator multiplied by the correspondent setting of resistance Z_j, supplied from the second device (indices *i* and *j* correspond to the data of the first and second ARNA devices). The time of the measurements is synchronised by means of GPS satellite signals. One of the main advantages of the approach under consideration is the improved accuracy of measurements and modelling as long as no error occurs from the equivalent generator of different types, time constants and non-uniform type of the load. The measurements are made in the branche "generator-teminal". At the beginning the case of four generators should be considered, and then attention should be paid to the general case with *N* generator. Figure 3.5. presents the realisation example with four generators. Thus, the ARNA equipment is connected to the terminals with the network elements (e.g. transformers, compensators, load, etc.).

EMF of the generators is calculated as follows:

$$\underline{E}_i = \underline{U}_{K1} + \underline{I}_i \cdot Z_i, \qquad \text{i=1.,2} \tag{8}$$

$$\underline{E}_j = \underline{U}_{K2} + \underline{I}_j \cdot Z_j, \qquad j=3.,4 \tag{9}$$

where

$\underline{I}_1, \underline{I}_2, \underline{I}_3, \underline{I}_4$	currents of the generators;
$\underline{E}_1, \underline{E}_2, \underline{E}_3, \underline{E}_4$	EMF of the generators;
$\underline{Z}_1, \underline{Z}_2, \underline{Z}_3, \underline{Z}_4$	resistances of the branch generator – bus;
$\underline{U}_{K1}, \underline{U}_{K2}$	voltages of ARNA input buses.

The out-of-order regime equipment controls the angle δ_{ij} between the vectors of generator EMF and the speed of its changing $d\delta_{ij}/dt$. To improve the accuracy of this operation the device contains a summator that models the EMF $\underline{E}_i$ of the i^{th} generator from the voltage $\underline{U}_{K1}$ of the first bus and current $\underline{I}_i$ of the i^{th} generator multiplied by the correspondent settings of the resistance Z_i. The output of this summator is connected to the first input of the processor. Its second input is connected to the communication channel providing the transmission of the signal of EMF $\underline{E}_j$ of the the j^{th} generator (are modelled from the voltage $\underline{U}_{K2}$ of the second bus and current $\underline{I}_i$ of the j^{th} generator multiplied by the correspondent settings of resistance Z_j).

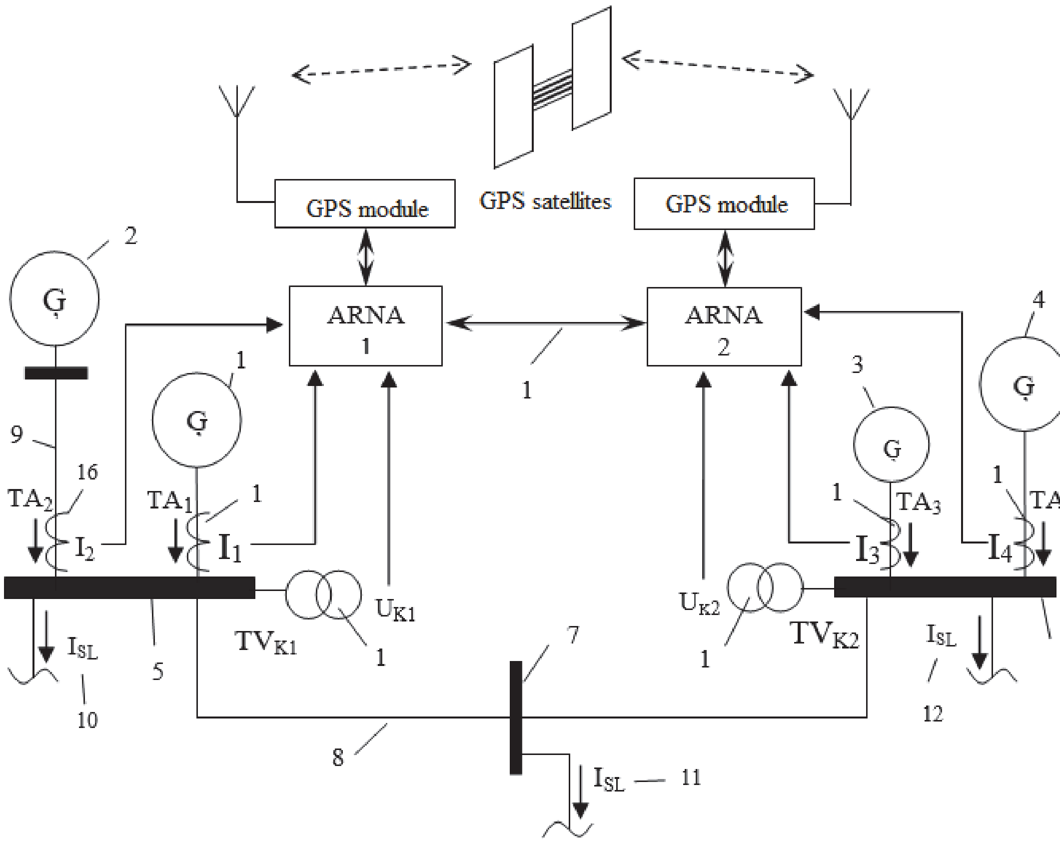


Fig. 3.5. ARNA realisation approach [3.22]:
1; 2; 3; 4 – generators of different types and power; 5; 6 – buses of terminal connections with power consumption; 7 – intermediate bus (intermediate substation) with power consumption; 8; 9 – network lines; 10; 11; 12 – load currents consumed; 13; 14 – voltage transformers; 15; 16; 17; 18 – current transformers; 19 – communication channel.

It should be noted that the EMF $\underline{E}_i$ of the i^{th} generator is sent to the second protective device exactly the same way.

There are six different angles between the vectors of EMF. It is proposed to control the maximum angle between the existing EMF $\delta_{\max k}$ by means of the control of each angle.

The level of the data discretisation should be high enough to avoid fast changes in the power system regime, i.e. the directions of the speed $d\delta_{ij}/dt$ value and EMF vector turning.

The reasons of the changes of angle δ_{mxk} are the normal transient processes (slow changing of the angle) and emergency transient processes (fast changing of the regime parameters, e.g. because of short-circuit or/and other specific perturbations). Therefore, the time interval of the data renovation should be large enough for the accurate and selective operation of the device. Generally, the case of N generators (Fig. 3.5.) is described by the following equations:

$$\underline{E}_i = \underline{U}_{K1} + \underline{I}_i \cdot Z_i, \tag{10}$$

$$\underline{E}_j = \underline{U}_{K2} + \underline{I}_j \cdot Z_j, \tag{11}$$

where

i number of generators controlled with device 1;

j number of generators controlled with device 2;

N total number of the controlled generators ($N = i + j$).

GPS module obtains the information from satellites and produces the synchronisation signals and precise time of the measurements. Both protective devices permanently process the value under control (current and voltage). The necessary corrections of the measurement time take place at the instant of GPS module synchronisation signal approach. GPS module supplies the synchronisation signal each second; thus, if the delay of the information transmission from one terminal to another is less than 1 s, it does not disturb the operation of protective equipment.

The proposed solutions were verified in the promotional paper and publications by *Dr. sc. ing.* Dmitry Antonov [2.6].

This part of thesis describes the AGNA algorithm which can be realised without application of the communication channel. Additional information about the properties of vectors E_1 and E_2 is taken into account. The module of these vectors in a real power system is changed in a wide range and with high accuracy. This approach refers to the euqations (10), (11) and can be described as

$$\begin{aligned} \left|\underline{U} + Z_1 \underline{I}_1\right| &= const. = \left|\underline{E}_C\right| \\ \left|\underline{U} + Z_2 \underline{I}_2\right| &= const. = \left|\underline{E}_C\right| \end{aligned} \quad . \tag{12}$$

To consider only the task of Z_1 estimation

$$\left(U_{1a} + r_1 I_{1a} - x_1 I_{1r}\right)^2 + \left(U_{1r} + r_1 I_{1r} + x_1 I_{1a}\right)^2 = \left|E_C\right|^2 \ . \tag{13}$$

Equation (13) contains two unknown values (r_1 and x_1) and cannot be directly solved. But the fact that the active resistance of the high voltage network is close to zero should be taken into account which allows using of equations (13) and (14) to calculate x_1 and x_2.

The equation (13) is a square equation and it causes difficulties in the realisation of microprocessors. The mentioned difficulties can be solved by applying the algorithm described as base of formula (12) with a simple transposition

$$\begin{aligned}&\left|\underline{U}+Z\underline{I}\right\|_{r\to 0}=\left|\underline{U}+jX\underline{I}\right|=\left|U_A+jU_R+jX\cdot I_A+j^2X\cdot I_R\right|=\\&\left|(U_A-X\cdot I_R)+j(U_R+X\cdot I_A)\right|=(U_A-X\cdot I_R)^2+j^2(U_R+X\cdot I_A)^2;\end{aligned} \tag{14}$$

Let us calculate the left part of the equation using the arithmetic operations only. Variables x_1 (or x_2) can be estimated using one method – the square equations solution.

Therefore, making the local measurements, i.e. controlling the current and voltage at the place of protection installation location, the settings of the inductance can be calculated for the modelling of equivalent generators, assuming that the EMF module is constant.

The vector diagram in Fig. 3.6 explains the essence of the proposed method. This diagram shows the vectors of EMF equal to *1.1 U_{nom}* in the complex plane. The voltage and current measurements are used to construct these vectors, i.e. the voltage vector added to the current vectors multiplied by the calculated settings. The points of crossings with *1.1 U_{nom}* are the vectors of EMF equivalent generators.

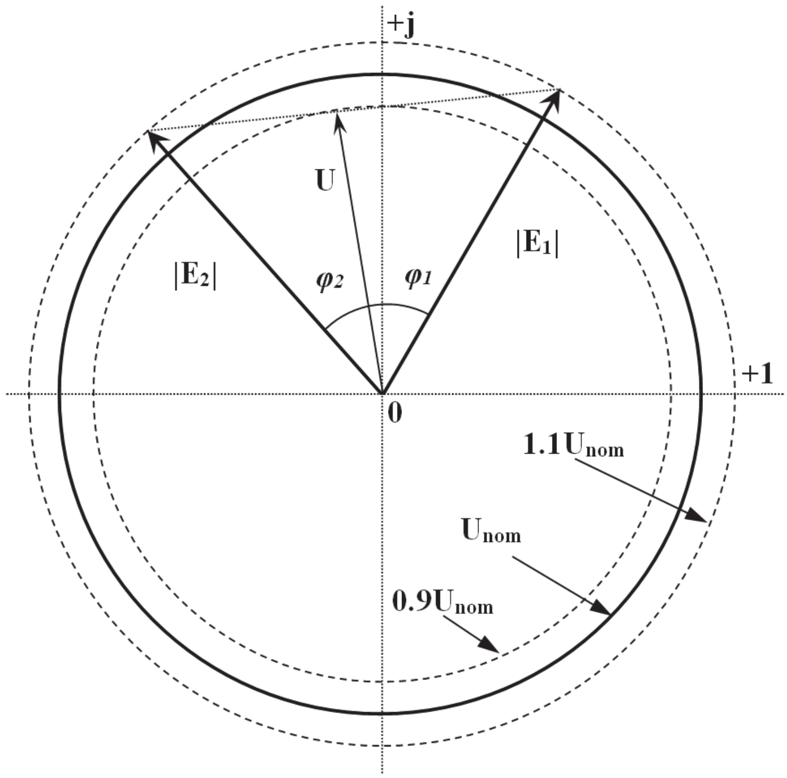


Fig. 3.6. Vector diagram of voltage and generator EMF in the complex plane.

Figure 3.6. demonstrates that the measurements of currents and voltages give an opportunity to estimate unknown resistances and calculate vectors of EMF.

The described algorithm can be applied at the places where the realisation of safe communication channels is impossible.

The disadvantage of the square method is explained in Fig. 3.7. It demonstrates that although at the time instant $\delta(t)\geq\delta_{cr3}$ the total energy of the generator is negative

($A(\delta(t)) < 0$), an opportunity exists that in line L_2 a successful AAI results in an additional braking square leading to the performance of the condition $A(\delta(t)) > 0$ and, therefore, to the returning of the generator into a synchronous operating regime. It is possible that under the condition of different changes in electric network configuration, the prototype can mistakenly recognise the instant of AR existing that can result in an unnecessary operation of the protective equipment.

To improve this situation an approach is proposed that takes into account full energy calculated in real time $A(\delta(t))$, as well as the theoretical value of the possible braking energy $B(\delta(t))$, that can exist in the electric network due to switching of the elements [3.24].

The operation principle of the proposed approach is explained in Fig. 3.5. The following parameters are calculated for the normal regime: $P_{\max 1} = \dfrac{P_e(t)}{\sin \delta_0}$, $\delta_{cr1} = \pi - \delta_0$, $P_m = P_e(t)$,and the starting condition is controlled:

$$\frac{dP_e(t)}{dt} > C1 \tag{15}$$

where C_1 is the constant of the starting condition.

At the instant of existing of "short-circuit L2" the calculation of full energy of the generator $A(\delta(t))$ is started. Simultaneously the calculation of the braking energy $B(\delta(t))$ is also started (16)

$$B(\delta(t)) = \int_{\delta(t)}^{\delta_{cr1}} (P_{\max 1} \cdot \sin \delta(t) - P_m) d\delta. \tag{16}$$

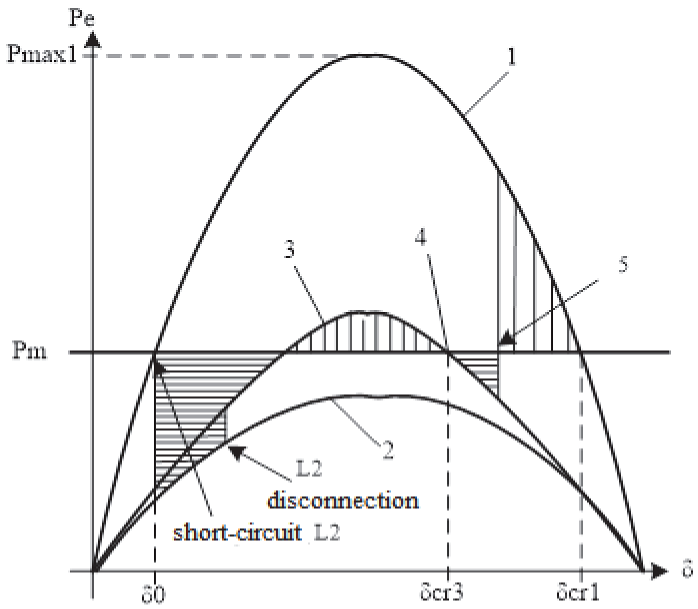


Fig. 3.7. Power-angle characteristics of generators:
1 – conventional regime, 2 – short-circuit regime; 3 – regime of disconnection of damaged line L2; 4 – point of operation; 5 – line L2 AAI.

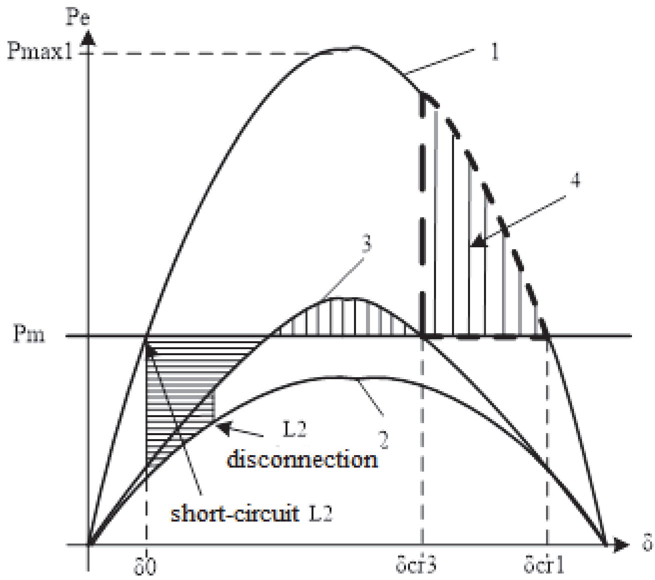


Fig. 3.8. Calculation example of proposed approach for theoretically possible braking square at time instant δ_{cr3}:

1 – conventional regime, 2 – short-circuit regime; 3 – regime of disconnection of damaged line L2; 4 – theoretically possible braking square at time instant δ_{cr3}.

Energy square $B(\delta(t))$ for time instant $\delta(t) = \delta_{cr3}$. The start of AR is fixed at the time instant when the condition (17) is executed. At the time instant of the performance of condition (17) a signal for the division of power system is supplied (relay operation)

$$A(\delta(t)) + B(\delta(t)) < 0 \tag{17}$$

Let us consider an example of the approach realisation for the part of power system which consists of two generators (G1 and G2) and two transmission electric lines (5 and 6). Device *1* (7) and *2* (8) controls the voltages of buses (3 and 4), using voltage trnsformers (9 and 10), and currents from generators (1 and (2), using current transformers (11 and 12). On the basis of these meaurements the active power of the generators is calculated and the starting conditions are examined (3). In the case of short-circuit the calculation and control of the full energy (the acceleration and braking energy of the generator rotor turning) theoretically possible braking energy is excuted. If the conditions are valid then a signal is supplied for the disconnection of power swithes (14; 15; 16; 17) to disconnect lines L1 (5) and L2 (6) and to interrupt AR development. Conmunication channel (13) provides the exchange with information between devices 1 and 2 (7) and (8). The devices supply the control signal to the power switches with signals (18) and (19).

Figure 3.9. and Fig 3.10. present the principal scheme of the considered approach realisation. Block (1) provides the calculation of the generator active power P_{e1} and generator voltage angle δ_1, using the measurements. The values calculated in Block (1) are supplied to the first input of the second block and are sent to the second device by means of communication channel. Data from the 2nd device (P_{e2}, δ_2) are supplied to the second input of Block (2). Block (2) calculates the difference of the generator voltage angles. Block (3) provides the testing of the starting condition performance, i.e. the speed of the generator power changing $dP_e(t)/dt$ exceeds particular setting C_1. Block (4) calculates the accelerating energy and braking energy of the generator $A(\delta(t))$. Block (5) calculates the theoretically possible braking energy of the generator $B(\delta(t))$. Block (6) calculates the sum of the $A(\delta(t))$

and $B(\delta(t))$ energies of the generator testing the existence of AR condition, i.e. $A(\delta(t)) + B(\delta(t)) < 0$.

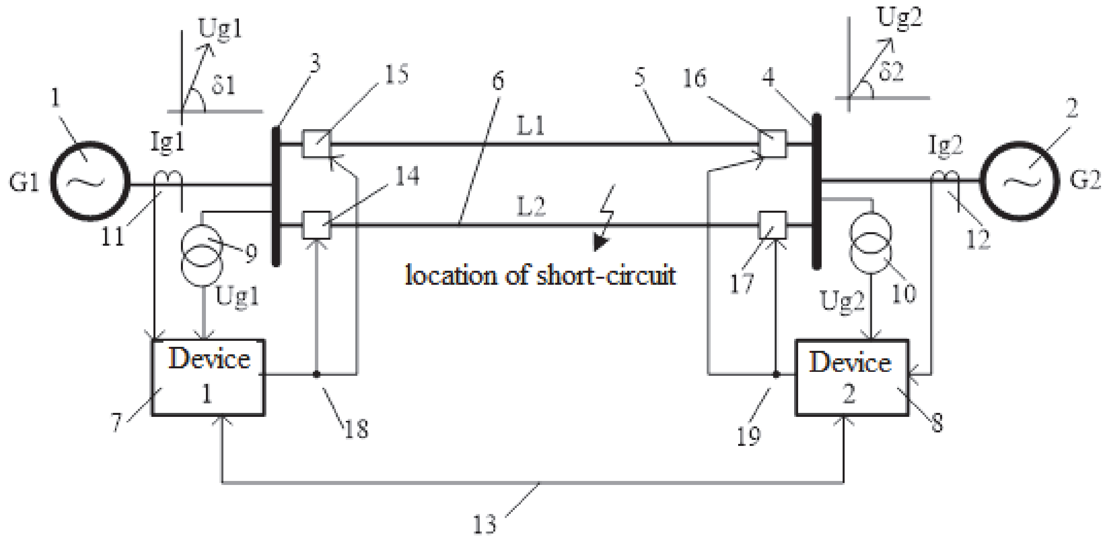


Fig. 3.9. Example of the proposed approach realisation:
1;2 – generators G1 G2; 3, 4 – buses of the generators; 5, 6 – transmitting electric lines L1 and L2; 7, 8 – relay protection devices 1 and 2; 9, 10 – voltage tranformers measuring voltages U_{g1} and U_{g2} across the terminals of the generators; 11, 12 – current transformers measuring currents I_{g1} from G1 and I_{g2} from G2; 13 – communication channel (links the devices of relay protection; 15, 16, 17, 18 – power switches of lines *L1* and *L2*; 18, 19 – control signals of the power switches.

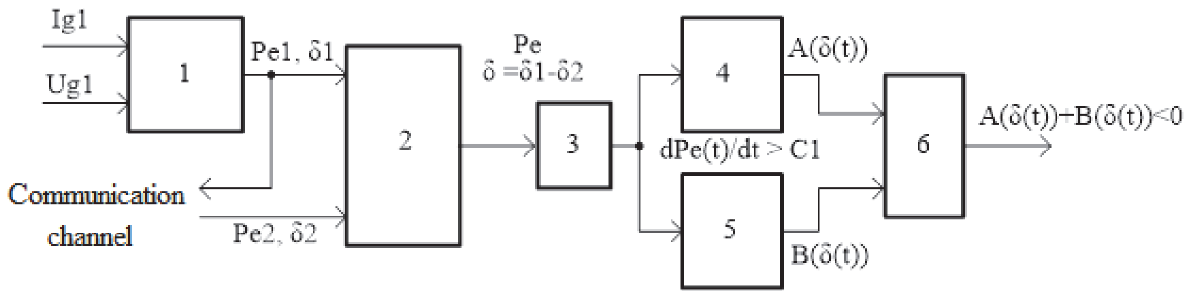


Fig. 3.10. Operation of the relay protection measurement element:
1 – calculation block of generator active power and generator voltage angle; 2 – calculation block of generator voltage angle difference; 3 – testing block of starting conditions existence; 4 – calculation block of generator acceleration and braking energy A(δ(t)); 5 – block calculating theoretically possible braking energy of generator B(δ(t)); 6 – block controlling the existence of AR condition A(δ(t))+ B(δ(t)) < 0.

ARNA control approach is based on the criterion of equivalent squares and especially suits the case when the successful AAI of the transmission line results in the renewal of the prior emergency structure of the electric network. The realisation of the approach takes into account the theoretically possible braking energy of the generator that can additionally exist while renewing of the electric network takes place [3.17], [3.18].

An emergency regime development unfavourably results in a disconnection of one electric station (or a small group) from the total electric system. In this case a developed unbalance of the generated and consumed electric energy can result in disconnection. In order to avoid this problem, it is important to achieve the island regime as soon as possible. The mentioned task is considered further.

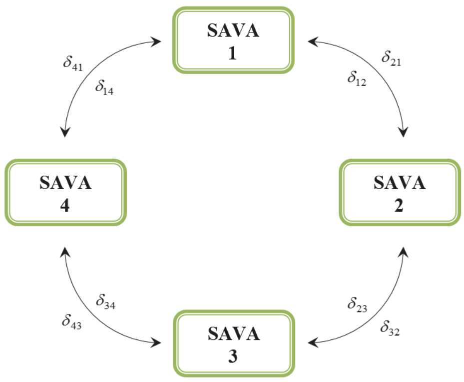
At the beginning the recognition of island regime seems simple taking into account the localisations of the circuit breakers of the electric line. In fact there is a very large number of probabilistic combinations where island regime can exist. This decision should be realised with the central automation equipment that in turn also causes significant difficulties. The attempts to avoid the centralised automation resulted in the proposal of a scheme based on vector control. Figure 3.12. shows the power system of four electrostations.

It is important to note that the number of electrostations can be larger. Let us assume that each electric station is equipped with the units of angle measurement and they are round-connected with high-speed communication channels (Fig. 3.11.).

The general conclusion is that any electric station, e.g. No. 2, loses the synchronism of operation (Fig. 3.12). In this situation three groups of devices No. 1, No. 2, No. 3 can determine the changes of angles. This phenomenon can be applied in synthesising of algorithm for automation.

The basis for a simple algorithm is the following:

1. three devices are able to determine unauthorised prohibited value of δ (or deviation from the angle);
2. SAVA with its two neighbour devices fixing the emergency regime for the unauthorised angles can be applied to determine island regime.



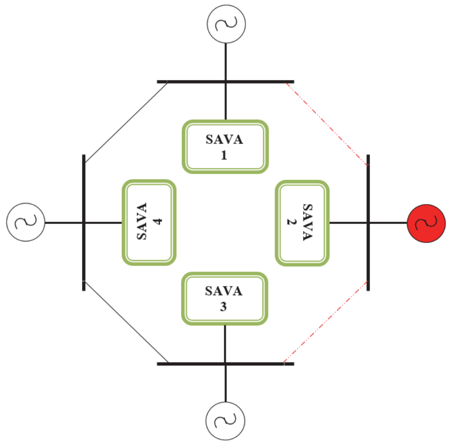


Fig. 3.11. and Fig. 3.12. SAVA round type principle scheme;
electric station 2 operates in island regime.

If the island effect occurs at two or more electric stations, the algorithm becomes more complicated because of the necessity to define the number for two groups of the emergency determination devices and display all SAVA numbers that are within the zone between two groups (Fig. 3.13.).

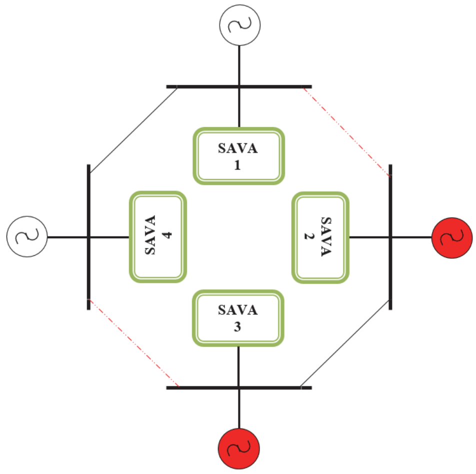


Fig. 3.13. Group 2 – Group 3 and Group 1 – Group 4 of the electrostations in island regime.

Therefore, for the safety of all possible regimes ARNA together with ELK should realise the time method. This gives an opportunity to quickly determine the starting instant of AR and at the same time the method of the angle control recognises the condition when the generator goes to AR. The time and angle control algorithm of the united protective ELK is improved and tested. The structure of the protective system is described in [1.14], which can be applied in case when both methods are being realised simultaneously [3.38.].

The investigation of ARNA identified some cases when the generators returned to the steady-state condition with the angle exceeding 180 degrees in relation to the system balance condition. The analysis of the results allows to state that the stability of the generators operation is provided due to the square method criterion, i.e. the acceleration square was smaller than that of the braking.

For example, a relatively simple system from ETAP library has been investigated. This system contains one generator, loads of different types and terminals.

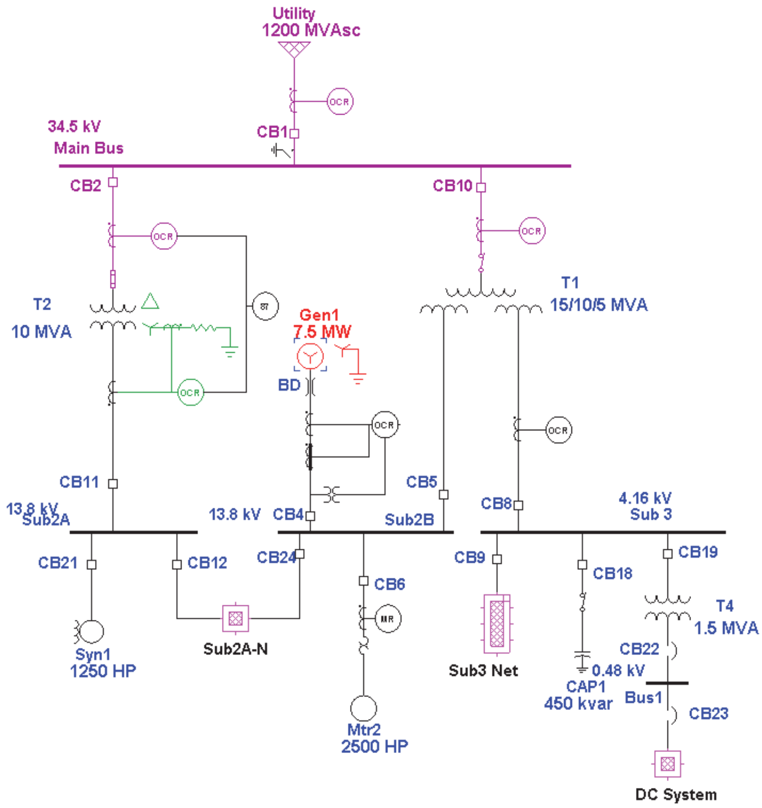


Fig. 3.14. Structure of the power system scheme.

A three-phase short-sircuit regime at the main bus and its duration (0.1s–0.2s) are modelled. The data from ETAP software is exported to MathCAD [3.39].

The initial model contains a short-circuit that does not damage the stability of the generator (Fig. 3.14.), i.e. the acceleration square is smaller than the braking square. The next scenario considers the case when the generator loses the stability, the oscillations of the electric power exist, like in the first case.

Modelling of some more scenarios gave an oportunity to identify a border case when the stability of the generator is still maintained. In this case the angle passes 180 degrees but after the breaking of the short-circuit it is getting stability (Fig. 3.15.).

Figure 3.15 summarises three cases of the modelling: stable case, when the difference of the angles does not exceed 180 degrees; non-stable case of AR when the difference of the angles exceeds 180 degrees and the generator starts the rotation in accordance with the terminal of the system; stable border case when the oscillations of the generator are getting stability despite the angle exceeding 180 degrees. The conclusion is that the generator can operate in the regimes when the stability can renew even with the angle higher than the limit of 180 degrees.

However, the realised algorithm in each device can significantly differ. Let us consider an example with all three cases using the theoretical data obtained from ETAP software and the samples of ARNA and PMU device (Phasor Measurement Unit) (Fig. 3.16.), (Fig. 3.17.). The basic difference between the theoretical data and the data from the device is the number of the samples within one interval of time, i.e. 10 000 samples from ETAP data, 100 samples from ARNA device and 40 samples from PMU during 1s.

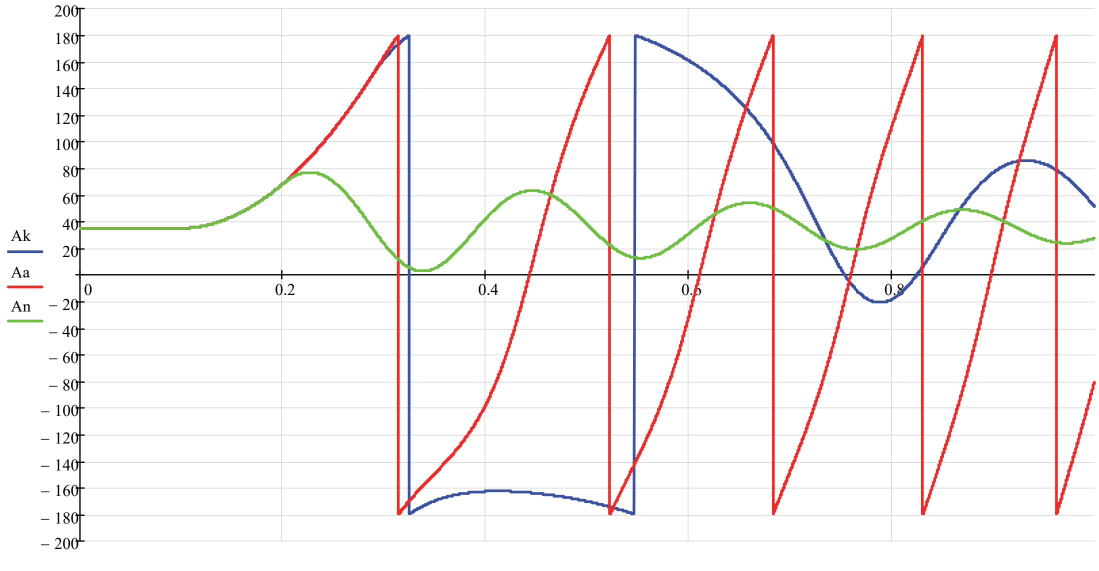


Fig. 3.15. Time changes of the generator angle:
green – Case 1, An (stable); red – Case 2, Aa (non-stable, asynchronous regime);
blue – Case 3, Ak (stable, border case).

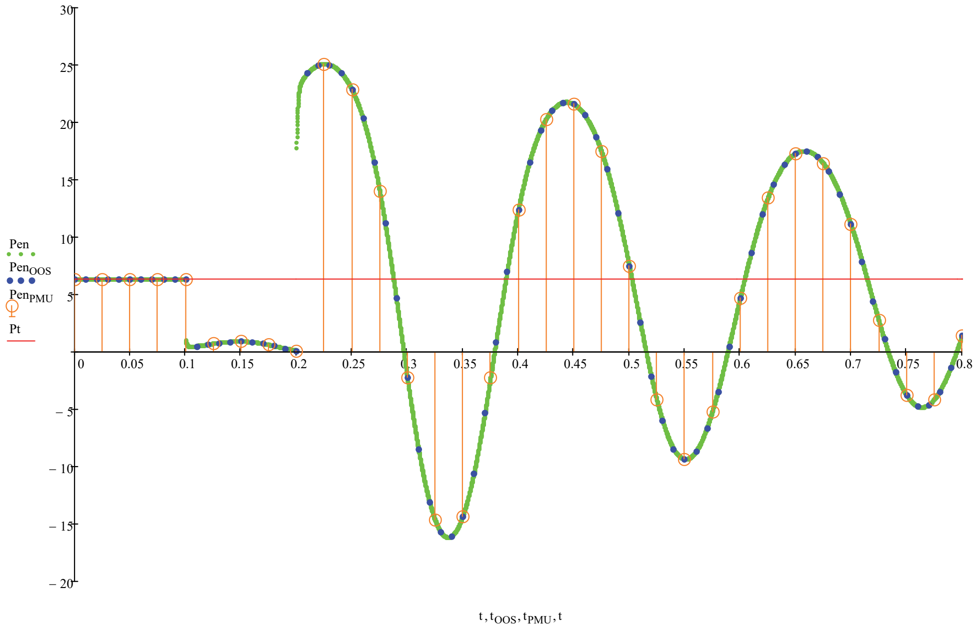


Fig. 3.16. Opportunities of technical and practical problems in Case 1:
green – ETAP modelling data (Pek) (theoretical samples); blue – ARNA samples (P_{ekOOS});
sienna – PMU samples (Pek_{PMU}); red – mechanical power of the generator (P_t, power of the turbine).

The trapeze method is applied for the calculation of the acceleration and braking squares and to compare them for each case.

The calculations in Fig. 3.17 visualise the declinations from the ETAP data for each case and device.

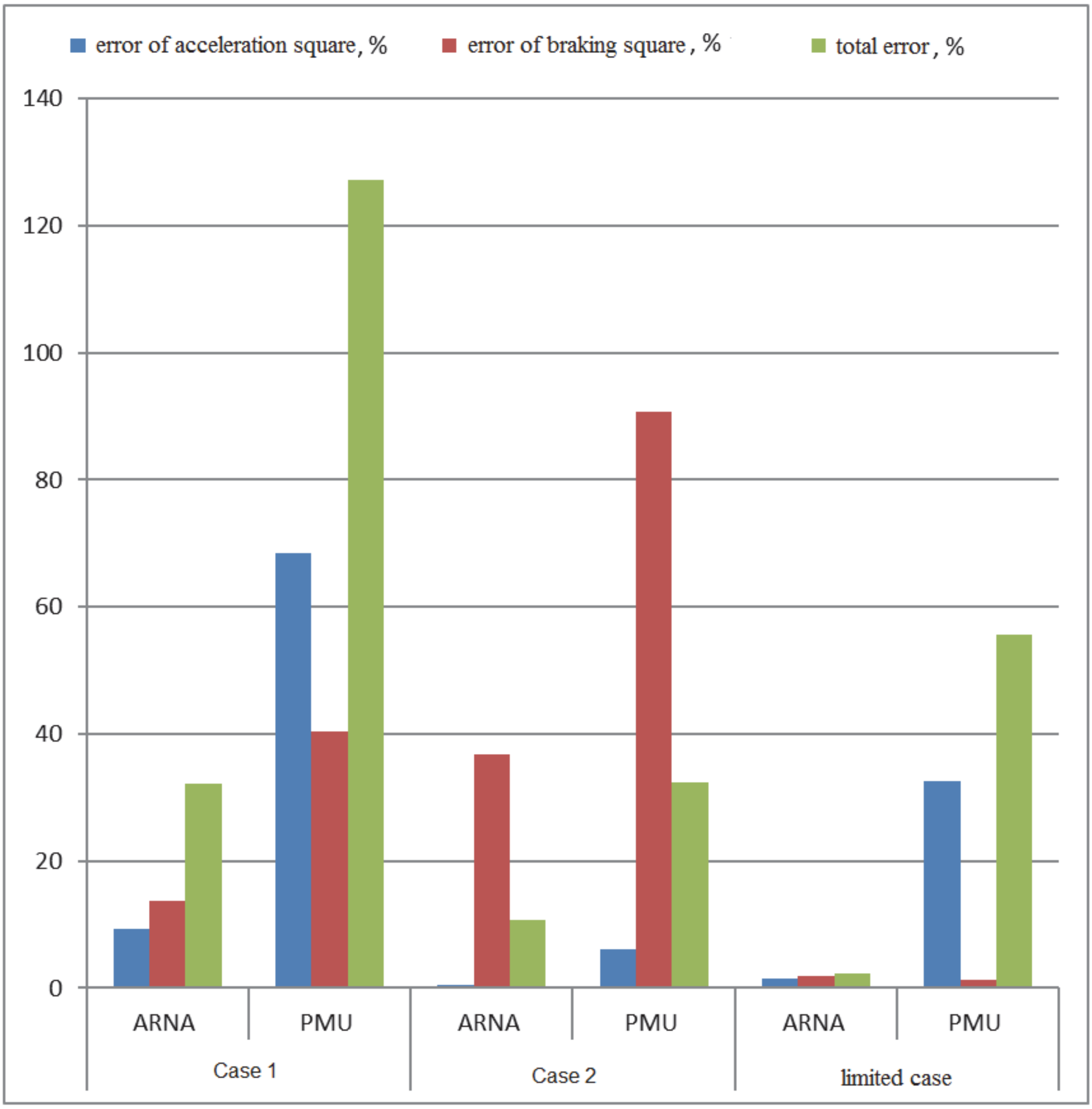


Fig. 3.17. Accuracy of the calculations of squares for ARNA and PMU devices

It is obvious that the difference between ETAP and AGNA data is not higher than the value of 0.02, and the error of the calcualtion squares does not exceed 3 %. It proves a real opportunity of the new ARNA control approach realisation based on AGNA.

4. MODELING OF THE OPERATION OF OUT-OF-STEP PROTECTION AUTOMATION FOR POWER SYSTEMS AND ESTIMATION OF ITS STABILITY USING VIRTUAL-REAL LABORATORY

The application of the virtual-real laboratory in the modelling of ARNA operation is considered as one of the promising directions.

The simplified model of the device is based on the voltage vector control and calculation of the difference of voltage phase angle φ. EUROSTAG software [1.53]–[1.56] is applied for the modelling of power system and simulation of the asynchronous regime. The latter is modelled using the system of three generators and eight buses as well as a complex scheme – IEEE 39 bus system.

Different regimes of power system operation are modelled by means of EUROSTAG [1.53]–[1.56] (short-circuits of PEL, decreasing of load, faults of generators, PEL faults and different loads). One of the testing examples is given below.

An example is selected from the data base of a power system based on the IEEE 39 bus system [4.2] for the modelling of asynchronous regime and testing of the proposed algorithm.

The model is realised in EUROSTAG programming environment [1.53]–[1.56] applying the analysis of the power flow and transient processes [4.4].

The testing scenario is the formation of the events that can influence the stability (Table 4.1.). After its application the behaviour of the power system is analysed and the conclusions on its stability are made. The detailed overview of IEEE 39 bus system is important for the tested part of the system (Fig. 4.1.). Figure 4.1. shows load, generation and power flow [MVA] for the steady-state regime [4.5], [4.6].

Table 4.1

Scenario of the Modelled Events

Time of the event (s)	**Event**	**Element of the power system**	**Notes**
0.00	Start of simulation		
1.00	3-phase short-circuit is formed in line	Line 21-22 22 % for the end of the line	
1.10	Disconnection of power switch 21-22-s	Line 21-22 beginning	Modelling of the protection operation
1.30	Disconnection of power switch 21-22-b	Line 21-22 end	Modelling of the protection operation
1.30	Termination of the short-circuit	Line 21-22	Short-circuit of the transient process
2.5	Connected power switch 21-22-b	Line 21-22 end	Modelling of the automation repetitive switching (AAI)
2.5	Connected power switch 21-22-s	Line 21-22 beginning	AAI modelling
60.0	End of the modelling		

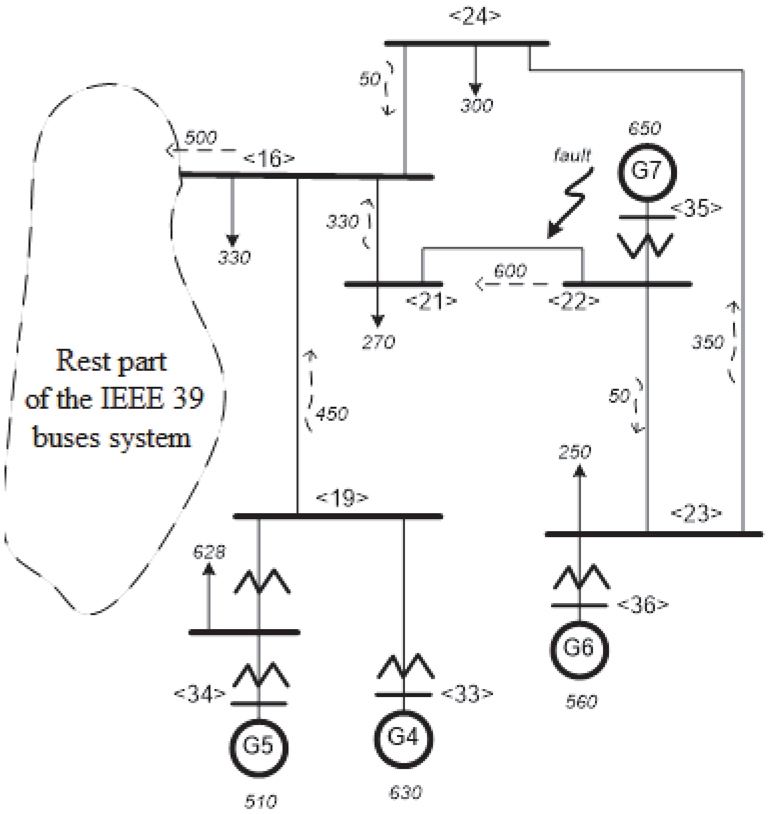


Fig. 4.1. Rest part of the IEEE 39 bus system for the testing scenario

The operation of the protective equipment of PEL as well as AAI is modelled with its switching on/off at a particular time in a correspondent branch.

A similar scenario is applied in two testing cases:

- the first case – the dynamic behaviour of the power system is investigated without ARNA;
- the second case – the model corresponding to ARNA is included into the modelling of the transient processes and the power system is controlled with the help of ARNA.

Figure 4.2. presents the diagrams of the transient processes of the power system [4.7] for the testing case without ARNA application [4.8]. Analysing the diagrams the following can be concluded:

- active power in PEL 21-22 is terminated as a result of short-circuit (1.0 s) and PEL 2122 gets the oscillations after the successful AAI operation (2.5 s) (Fig. 4.4.);
- during the period of PEL 21-22 disconnected condition the active power is distributed, it results in the oscillations in PEL 23-24, (Fig. 4.2. b));
- the oscillations of the power last about 10–11 s from the initial perturbations (1.0 s) that is classified as an asynchronous regime. Starting from the 12th second the oscillations are reduced and the system reaches the normal condition (within the range of the accepted regime);
- the long lasting power oscillations can result in significant damages of the equipment and uncontrolled disconnection of load/generation (the voltage of the buses can reduce below 0.2 from the rated value of the voltage (Fig. 4.2. a));
- despite the power system reaching its normal operation regime in a particular time, the condition of the system is classified as unstable, therefore to avoid the asynchronous regime of the power system the measurements should be taken [4.29].

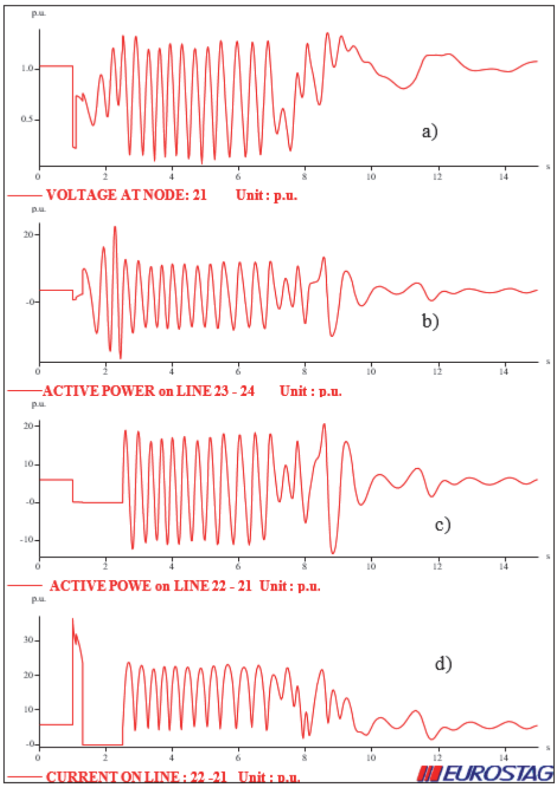


Fig. 4.2. The transient processes of power system in the testing scenario.

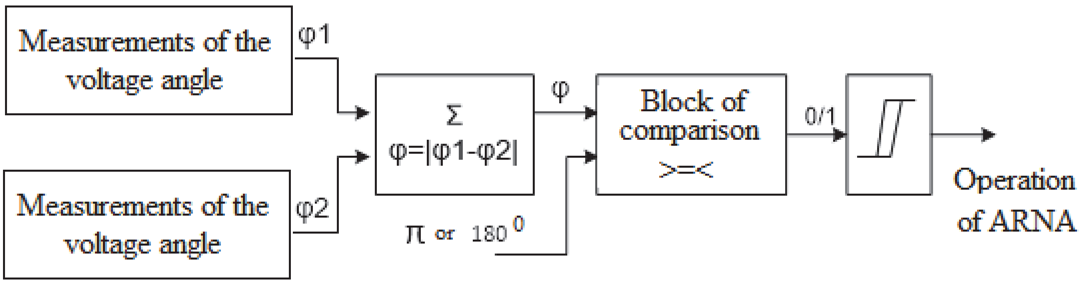


Fig. 4.3. Simplified algorithm of ARNA.

Two ARNA models are integrated into the modelling process. ARNA U2122 controls the voltage angle between <21> and <22> elements and disconnects Line 16-21 as soon as the operation conditions are performed. ARNA U16-24 controls the voltage angles <23> and <24> in the mentioned elements and disconnects the switches of the transmission line 16-24, when the operation conditions are performed (Fig. 4.3.). Systems with the transmission electric lines 16-21 and 16-24 are selected for the comparison of the power systems. After the comparison the balance of power should be reached in the elements of the system (the loads of buses <21> and <24> should be together with generators G6 and G7) [4.10].

ARNA U2122 and U1624 operation results in the power system dividing into two parts. At the island part there were generators G6 and G7 and loads of buses <23>, <21>, <24>. Figure 4.4. demonstrates the models of ARNA operation U2122 and U1624. The signal for operation is supplied when the difference of the angle DLTANGLE exceeds π rad (or 180°) (Fig. 4.4.). Transmission line 1621 will be disconnected when relay U2122 generates its signal for operation. In the same way the branch 16-24 is disconnected from the signal of relay U1624. After the disconnection of the branch (1.58 s) and division of the power system the generators get stability and at the same time the power system also stabilises [4.11]. Thus an island with generators G6 and G7 with the loads on buses 21, 23, 24 is formed.

Therefore the power systems having lost the synchronous regime due to the short-circuit are separated from each other by means of ARNA operation. Due to this operation the power system is protected from the development of asynchronous regime. The separation of the power system takes place at optimal places providing the balance of generation – load at each part at a particular time. A simplified ARNA model accurately determines the condition of the asynchronous regime existence.

In the list of the simulation events the automative equipment U2122 for the avoidance of asynchronous regime, that controls the voltages in elements <21>, <22> should be blocked. It is done in order not to disconnect the transmission line 16-21 at time 1.5828 s as the power in element <21> is from the separated island of the generator (Line 21-22 is disconnected from 1.1 s till AAI operation at 2.5 s). Figure 4.4. illustrates the value of the voltage of element <21>, that is equal to zero within the period from 1.58 s (U2122 operation) to 2.5 s (transmission electric lines 21-22 AAI). Under the conditions mentioned above the real device will not operate in Line 16-21 because vectors $\underline{U1}$ and $\underline{U2}$ are in same phase as the PEL currents do not flow. However, one disadvantage for ARNA model is fixed.

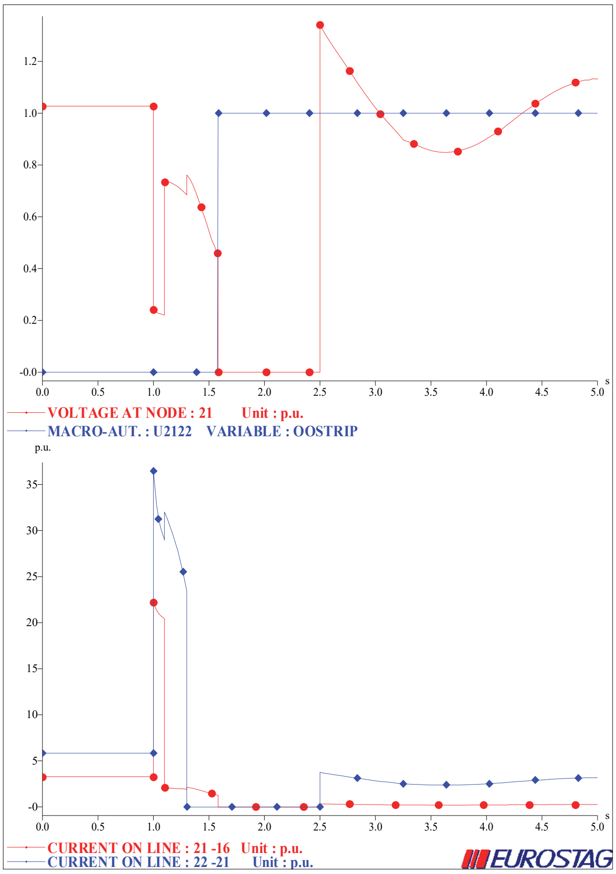


Fig. 4.4. Voltage of the power system in the unit <21>
and currents of PEL 21-16 and 22-21.

For the improvement of ARNA model the operation of the algorithm should be better. The improved ARNA module (Fig. 4.5.) operates if two conditions are in place simultaneously:

- the difference of the voltage angle reaches $\varphi = 180°$;

- the current exists in the controlled transmission electric line (transmission electric line connecting two elements under consideration).

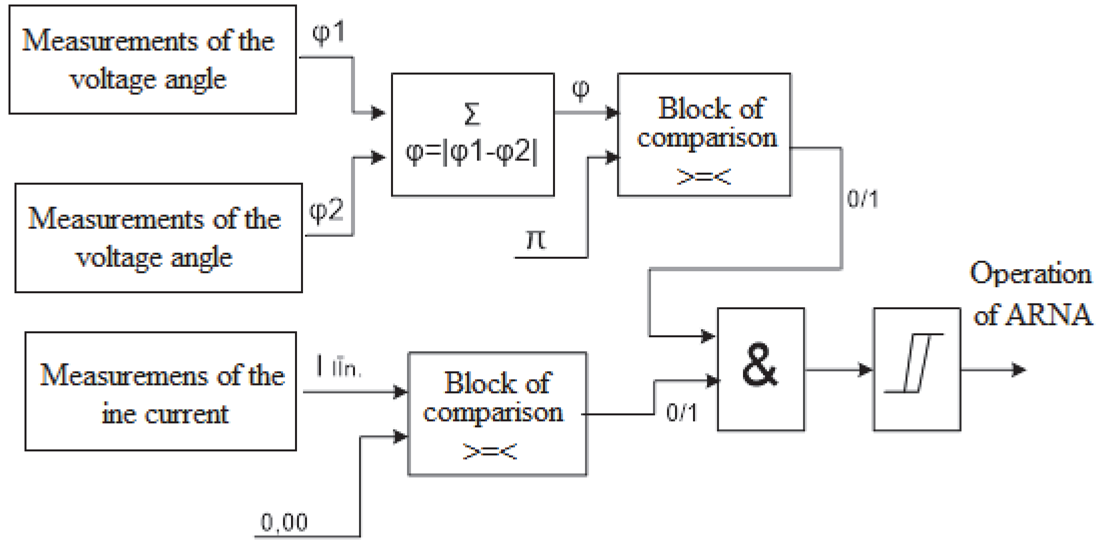


Fig. 4.5. Improved algorithm of ARNA operation.

The same test is applied for the power system with the module with the improved ARNA algorithm. The description of the transient processes events will be performed in EUROSTAG environment in accordance with the testing scenario (example of the scenario):

The list of events contains only one operating ARNA U1624 that separates the power system disconnecting PEL 16-24. ARNA U2122 is blocked at the moment when the angle between elements <21> and <22> reaches 180° degrees. The reason of ARNA blocking is the flow of the current through PEL 21-22, which is a right and accurate relay reaction to the process. As a result the power system is divided into two parts. The quality of AAI is not important for this testing because the successful renewing of the system strongly depends on its type and settings.

The final version of ARNA model is accepted after the simulation of different scenarios. This model accurately identifies the asynchronous regime as well as could be applied for the estimation of the power system stability [4.14].

The testing signals should be presented in digital form (for the testing of the model) as real currents and voltages for the testing of a device. The converted signals are represented as an equivalent of instantaneous values that can be realized by means of any modern system of relay testing (FREJA, ISA-DRTS, etc.). The initial data should be in COMTRADE format. The application of widely used COMTRADE standard allows to organise a library of the tested signals. The library can use the files of the program modelling as well as transient processes registered by the emergency registrators (Fig. 4.6.).

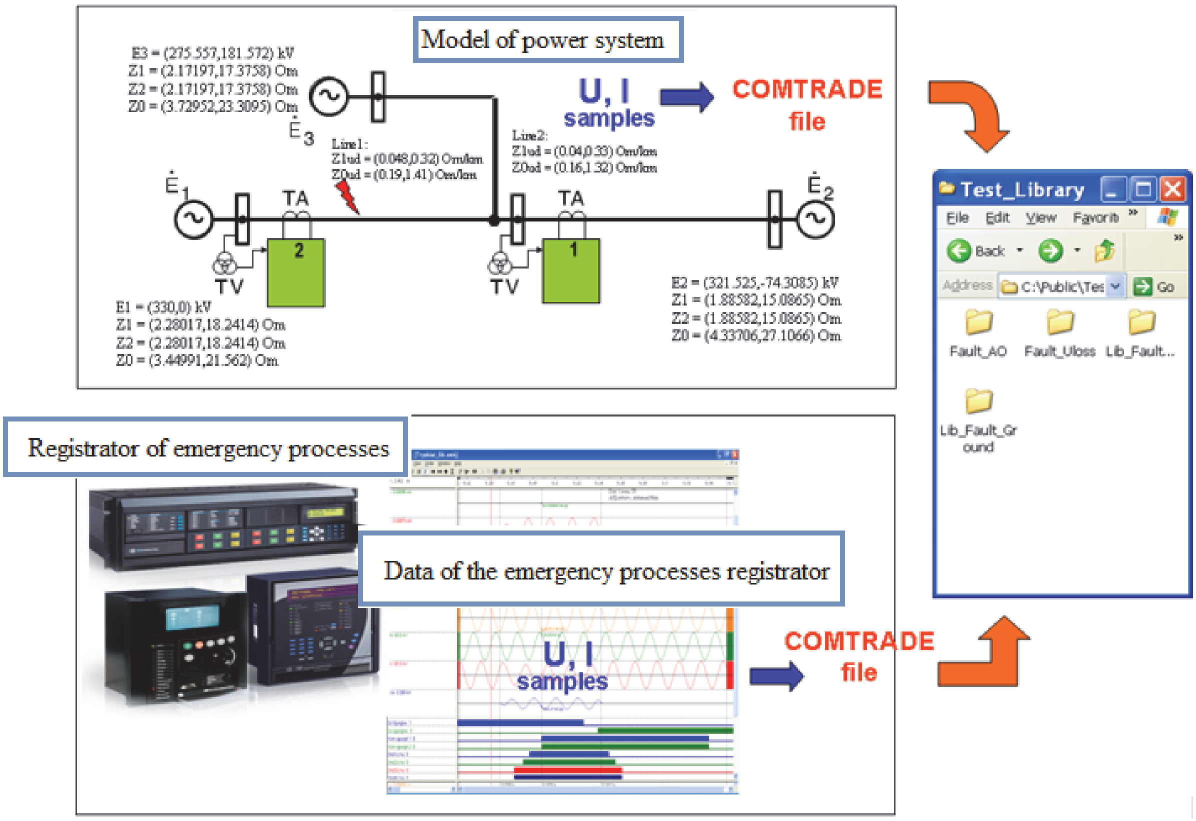


Fig. 4.6. Forming of the testing signal library.

The process of the model validation is illiustrated in Fig. 4.7. This process requires verification of the distant protection model of the high voltage transmission line by applying the proposed methodology. The testing should be realised using a real device (for example, distant protective device REDI) and a mathematical model of the equipment. For the testing procedure the example under consideration uses a simplified model of the device – the process of the signal input is not modelled. The model of the device calculates full resistance of the short-circuit.

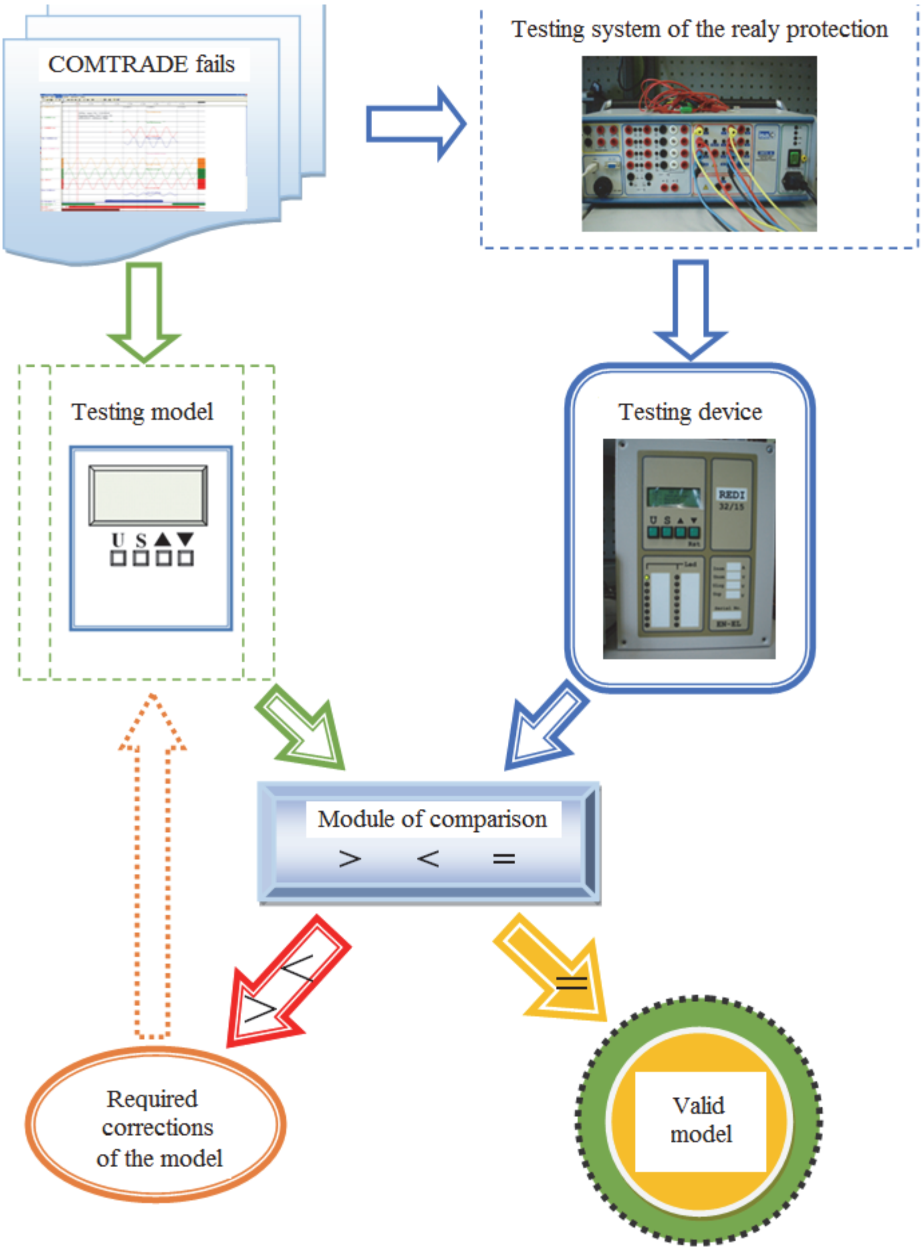


Fig. 4.7. Validation of the model of testing procedure.

Taking into account the results of the testing procedure the error between the device and model is determined: $|P_{1\_device} - P_{1\_model}| = |0.980 - 0.982| = 0.002$.

As it is obvious, the difference is about 0.2 %, that is much less than the error of the device during one year of its operation. Therefore, the conclusion is that the proposed distant protection is valid.

In 2015, RTU Faculty of Power and Electrical Engineering bought new equipment for scientific laboratory – a set of virtual-real laboratory. Two basic interconnected components construct the analogue-digital simulator:

- modelling device of the power systems and objects operation;
- block of the device simulation, testing and verification.

The analogue-digital simulator is a device with wide opportunities providing modelling of power system and operation regimes and processes of its elements and real time simulation; as well as testing and investigation of equipment and automation operation, methods, algorithms and software development and testing. It also allows to analyse the proposed solutions from economic point of view, e.g. modelling the market of electric energy and scenarios of its development. The variety of the analogue and digital input and output channels provides different opportunities of the connection with the simulator. The simulator can model very fast processes (e.g. transient processes that last milliseconds) as well as the long lasting processes (e.g. planning of the power system development). The internet connection provides a remote access of the scientific personnel to the simulator with an opportunity for many people to work with it simultaneously or to start a large simulation using its power.

The main technical components of the terminal equipment are:

1. module of the input of analogue signals;
2. module of the input of discrete (binary) signals;
3. module of the output signals – relay module;
4. module of the analogue – digital converter;
5. inducation and control module;
6. communication module;
7. module of the terminal communication;
8. module of the operative memory;
9. module of the operative energy independent memory;
10. module of the program memory;
11. timer of real time;
12. microprocessor;
13. block of operative supply.

Possible functions and areas of application of the analogue-digital simulator are:

- strategic planning of the power system structure (for 20–30 years), taking into account the development plans of power systems of the neighbour countries and market conditions;
- technical-economic substantiation of large, middle and small power objects (electric stations of different types, conventional and alternative power sources, electrical networks including smart, high voltage substations and lines, sources and networks of heating supply), substantiation of structures and schemes, development and optimisation of sketch designs, business plans, minimisation of fossil consumption, emission into air and capital expenses;
- control of power system safety and risks, elaboration of emergency protective measures, improvement of stability level;
- development of algorithms for the relay protection and automation of power system, selection of settings and testing, testing of the equipment;
- development and testing of the algorithms and software for the automation control of power objects;
- defining and investigation of the emergency situations of power systems.

The principal scheme of the block of equipment simulation, testing and verification is included into the thesis with the indication in the scheme of the links among the basic blocks.

A personal computer with the software necessary for the experiments and algorithms and testing of models provides the work process. Real equipment REMI is applied for this purpose with the ability to realise new algorithms and modify the existing alogrithms and models. The circuit also includes ABB produced protective terminals RED670 [4.39] providing PEL differential protection.

Inputs and outputs of REMI and RED670 are connected to the circuits of currents and voltages, binary inputs and outputs, circuits of operative voltages and signals, to the computer for the exchange with information.

The approbation and verification of the equipment model require a number of experiments. This role is realised by the block of current and voltage generators or testing block of relay protection (RTS), (ISA DRTS), that is controlled by the computer.

The computer stores a data base of the emergency registrator recordings and contains a software for the generation of COMTRADE fails and their downloading into RTS block.

Therefore, the usage of ISA DRTS and its signals allows to investigate the algorithms and to verify the models comparing them with a reference device. A correspondent software controls this process. An additionally developed software SMOKY effectively analyses a relay protection response and constructs the vector diagram. If necessary, the algorithms and model can be improved and corrected.

The analogue-digital simulator can also be used for the training of specialists in relay protection with RED670 device. It is important to improve practical skills and investigate the the algorithms of the device operation because a number of emergency scenarios is available and covers a relatively wide range of faults that cannot be investigated in a real power system.

Another opportunity is the training of dispatchers and special staff using the models of power systems and different emergency scenarios as well as the recordings of the emergency process registrators and theoretically possible transient processes by means of modelling software (e.g. ETAP, EUROSTAG, etc.).

CONCLUSION AND RECOMMENDATIONS FOR FURTHER WORK

❖ Experimental testing of power system automation is an important, mandatory and labour-intensive component of the procedure of the equipment operating ability.

❖ The automation is tested at special laboratories that can provide a generation of complicated signals.

❖ Analysis of the development tendency of power system automation brings to the conclusion that the unification of its functions and the number of controlled processes is increasing. It results in the complications in testing and verification.

❖ Virtual laboratories make only calculative experiments and can test the models of automation devices but not the equipment in general.

❖ A real power system can be used for the experiments but such experiments require very large financial expenses.

❖ A library of the emergency processes, software for transient processes simulation, digital-analogue converters and prototypes of the automation terminals provide the base for a virtual-real laboratory and can provide a wide spectrum of testing.

❖ The round-type structure of the local protective automation applies the advantages of the local and centralised operation principles and generates a soft refusal system.

❖ The round-type protective automation structure gives an opportunity to simultaneously realise the approaches to synchronise two measurements using the global positioning system and the optical communication channels. Its realisation results in high level of safety.

❖ At the initial stage of short-circuit and asynchronous regime processes the equivalent resistances of the power system can be estimated, which provides an opportunity to significantly improve the accuracy of the generator angle control.

❖ The power system configuration can significantly change its configuration during the asynchronous regime. The impact of these changes is not taken into account in the presently applied automation algorithms. The opportunity to control the angle acceleration and braking square reduces this drawback significantly.

❖ The digital recordings of avoidance of the emergency processes in power systems is successfully applied in the testing and new devices and at different steps of training process.

❖ Analogue-digital simulator is applied in the training of RA specialists using the possibilities of RED670 device. The training gives the possibility to investigate the algorithms and significantly improve practical skills because together with the emergency scenarios this complex includes a wide range of faults that cannot be investigated at a substation of real power system.

❖ The complex gives the possibility to train dispatchers and special staff using the models of power system and different types of the emergency situations including the recordings of the emergency registrators as well as theoretically possible transient processes by means of the modelling software (e.g. ETAP, EUROSTAG etc.).

BIBLIOGRAPHY

[1.1] El-Hawary, M., E. Electrical Energy Systems // CRC Press 2000 by CRC Press, LLC, p.365.
[1.2] Xuemin Chen, Gangbing Song, Yongpeng Zhang. Virtual and Remote Laboratory Development: A Review. Earth and Space 2010: Engineering, Science, Construction and Operation in Challenging Enviroments: PP 3843-3852.
[1.3] Miller, G., Storey, A., Vadari, S., V., Brewer, K. Experiences Using the Dispatcher Training Simulator as a Training Tool // IEEE Transactions on Power Systems, Vol. 8, No. 3, August 1993, pp. 1126-1132.
[1.4] Hwang, P.-I., Ahn, S.-J., Hur, S.-I., Yoon, Y.-T., Moon, S.-I. Adaptive Step Size Method for the Power System Model of Dispatcher Training Simulator // IEEE PES General Meeting, 25-29 July 2010, p.7.
[1.5] Nesterenko, M. Multi-Control Center Dispatcher Training // 2011 EMS Users Conference Philadelphia, PA, 18-21 September, 2011.
[1.6] https://www.omicronenergy.com/en/support/technical-support/
[1.7] Programma. Freja 300 / Freja Win 4.0 Relay Testing System. User's Manual. Sweden : Programma, 2001. 154 lpp.
[1.8] http://www.isatest.com/products-container/protective-relay-testing/drts-6
[1.9.] IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems, IEEE Std C37.111-1999, Institute of Electrical and Electronics Engineers,15 October 1999, 55 p.
[1.10] http://www.ti.com.cn/cn/lit/ds/symlink/tms320c25.pdf
[1.11] Rosloniec, S., Fundamental Numerical Methods for Electrical Engineering // Springer-Verlag Berlin Heidelberg, 2008.
[1.12] Strelkovs, V., Chuvychin, V., Sauhats, A., Lubarskyi, D., Rubtsov, A., Scheufeld, O., Shewarega, F., Vennegeerts, H., Panciatici, P., Utans, A., Leite, L., Kucaevs, J., Erlich, I. Modeling requirements for the ETN // PEGASE Pan European Grid Advanced Simulation and state Estimation, 2011, p. 286.
[1.13] Sauer, P., W., Hajj, I., N., Pai, M., A., Trick, T., N. Computer Methods in Electric Network Analysis // IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No. 6, June 1983, pp. 1726-1731.
[1.14] Sauhats A., Utāns A., Bieļa-Dailidovicha E., Wide-area measurements-based Out-of-Step Protection System, 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University
[1.15] http://www.arcelect.com/rs232.htm
[1.18] Khaitan, S., K., ed., Gupta, A. ed. High Performance Computing in Power and Energy Systems // Springer-Verlag Berlin Heidelberg 2013, p.378.
[1.23] AGNA apraksts: http://remi.eef.rtu.lv/docs/AGNA_eng_2008_lil.pdf
[1.24] Transmission Line Reference Book 345 kV and Above // General Electric Company, Electric Power Research Institute, Second edition, 1982.
[1.25] Siemens AG, SIPROTEC 5 Distance Protection, Line Differential Protection, and Overcurrent Protection for 3-Pole Tripping, V 5.00, 2014, 1460p.
[1.26] ABB Inc., REL 512 Numerical Transmission Line Protection System, Substation Automation and Protection Division, Coral Springs, FL, Allentown, PA, 2011, 8p.
[1.28] http://kpfu.ru/docs/F324157708/Virtualnye.laboratorii.pdf
[1.37] D.Bica, "Performant software in Power Engineering Education", Proceedings of Romanian National Symposium on Electrotechnics, Bucharest, October 2007, pp.231-234.
[1.38] BCP Busarello Cott Partner Inc., NEPLAN Planning and optimization system for electrical network, http://www.neplan.ch.
[1.39]http://ieeexplore.ieee.org.resursi.rtu.lv/xpl/articleDetails.jsp?arnumber=4651684&queryText=Power+Engineering+Education+using+NEPLAN+software&newsearch=true&searchField=Search_All
[1.40] RTDS hardware and RSCAD active line as on 06/10/2008. http://www.rtds.com
[1.41]http://ieeexplore.ieee.org.resursi.rtu.lv/xpl/articleDetails.jsp?arnumber=5307318&queryText=Real+Time+Power+System+Simulation+using+RTDS+and+NI+PXI&newsearch=true&searchField=Search_All
[1.42] NI-PXI Controller, Active link as on 06/10/2008 http://zone.ni.com/devzone/cda/tut/p/id/4811
[1.43]Sunil Palla, Anurag K Srivastava, and Noel N. Schulz, "Hardware in the loop test for relay model validation," Proceedings of the IEEE Electric Ship Technologies Symposium, May 2007 Page(s): 449 – 454
[1.44]http://ieeexplore.ieee.org.resursi.rtu.lv/xpl/articleDetails.jsp?arnumber=5442686&queryText=ICT+Enabled+High+Voltage+Laboratory%3A+Cost+Effective+Tool+for+Engineering+Education&newsearch=true&searchField=Search_All
[1.45]J. Campos, "Development in the application of ICT in condition monitoring and maintenance", Computers in Industry, vol. 60, pp. 1-20, 2009
[1.46] Kikuchi, H., Matsufuji, Y., Kashiwagi, T., Takebayashi, T. Development of Technologies to Simulate Power Flow for Power Grid // FUJITSU Sci. Tech. J., Vol.50, No. 2, April 2014, pp. 92-99.

[1.47] M. Travassos Valdez, C. Machado Ferreira and F. P. Maciel Barbosa, "Distance Education Using a Desktop Virtual Reality (VR) System", 24th EAEEIE Annual Conference, EAEEIE2013 (European Association for Education in Electrical and Information Engineering), Chania, Crete, Greece, May 30 - 31, 2013
[1.48]http://ieeexplore.ieee.org.resursi.rtu.lv/xpl/articleDetails.jsp?arnumber=6715005&queryText=Electrical+Engineering+Teaching+and+Distance+Learning+using+a+Desktop+Virtual+Reality+System&newsearch=true&searchField=Search_All
[1.49] C. M. Ionescu, E. Fabregas, S. M. Cristescu, S. Dormido, and R. De Keyser, "A Remote Laboratory as an Innovative Educational Tool for Practicing Control Engineering Concepts," Education, IEEE Transactions on, vol. 56, pp. 436-442, 2013.
[1.50]http://ieeexplore.ieee.org.resursi.rtu.lv/xpl/articleDetails.jsp?arnumber=6715005&queryText=Electrical+Engineering+Teaching+and+Distance+Learning+using+a+Desktop+Virtual+Reality+System&newsearch=true&searchField=Search_All
[1.51] 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.lpp.
[1.52] Sauhats A., Zalostība D., Dolgicers A., Bieļa-Dailidovicha E., Antonovs D. Power System Modeling Software for Educational and Research Purpose. Electrical engineering and information complexes and system, Vol.10, No.1, 2014, ISSN 1999-5458, Russia, 5.-14.lpp.
[1.53] 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.lpp.
[1.54] Antonovs D., Bieļa E., Sauhats A., Zicmane I. Laboratorijas darbu komplekss ETAP vidē maģistra studiju programmai. 2.daļa. Rīga, RTU Izdevniecība, 2013. ISBN 9789934104466, 52.lpp.
[1.55] Antonovs, D., Bieļa, E., Sauhats, A., Zicmane, I. Laboratorijas darbu komplekss ETAP vidē maģistra studiju programmai. 1.daļa. 1.daļa. Rīga: RTU Izdevniecība, 2013, ISBN 9789934104459, 41.lpp.
[1.56] Antonovs, D., Bieļa, E., Sauhats, A., Zicmane, I. Energosistēmas modelēšanas pamati un īsslēguma procesu izpēte ETAP vidē. Rīga: RTU Izdevniecība, 2013, ISBN 9789934104053, 42.lpp.
[1.57] Halilova N. Eurostag Softweare as Tool for Stability Study of the Power Sistems, Power and Electrical Engineering, RTU, ISSN 1407-7345, 2008, pp 29-32
[1.58] http://w3.siemens.com/smartgrid/global/en/products-systems-solutions/software-solutions/planning-data-management-software/planning-simulation/pages/pss-e.aspx
[1.59] L.19-PowerWorld; Unified Power System Models through Integrated Topology Processing (ITP) // PowerWorld Corporation http://www.powerworld.com, Champaign Illinois USA. p.13.
[1.60] Overbye, T.J., Sauer, P.W., Marzinzik, C.M., Gross, G. A User-Friendly Simulation Programm for Teaching Power System Operator // IEEE Transactions on Power Systems, Vol. 10. No. 4, November 1995.
[1.61] Zhou, E., Z. Object-oriented Programming, C++ and Power System Simulation // IEEE Transactions on Power Systems, Vol. 11, No. 1, February 1996, pp. 206-215.
[1.62] Duncan Glover, J., Sarma, M.S., Overbye, T.J. Power System Analysis and Design // Cengage Learning, Fifth edition, 2012.
[1.63] Sauer, P., W. On The Formulation of Power Distribution Factors for Linear Load Flow Methods // IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 2, February 1981, pp. 764-770.
[1.64] Balodis, M., Ekmanis, J., Gavars, V., Kuņickis, M., Zeltiņš, N., Žīgurs Ā. The Latvian Electricity Supply Trilemma: Security, Social equity, and the Environment.// WEC Central and Eastern Europe Regional Energy Forum - FOREN 2014 "Tomorrow's Energy: From Vision to Reality", 24 June, 2014. Bucharest, Romania, Palace of the Parliament.
[1.65] Sauhats, A., Chuvychin, V., Gurov, N., Strelkovs, V., Svalova, I., Svalovs, A., Linkevics, O., Rivkins, J. The Latvian Experience and Problems of the Grid Integration of Renewable Energy Sources in the Power System // IEEE Russia Power Tech, 27-30 June 2005, p.7
[1.66] Ayuyev, B., I., Yerokhin, P., M., Shubin, N., G., Neujmin, V., G., Alexandrov, A., A. Unit Commitment with Network Constraints // IEEE Russia Power Tech, 27-30 June 2005, p.5.
[1.67] Powell, L. Power System Load Flow Analysis // McGraw-Hill 2005 by the McGraw-Hill Companies, Inc., p.183.
[1.68] http://w3.siemens.com/smartgrid/global/en/products-systems-solutions/software-solutions/planning-data-management-software/planning-simulation/pages/pss-e.aspx
[1.69] Bakken, D. ed. Smart Grids. Clouds, Communications, Open Source, and Automation // CRC Press 2014 by Taylor & Francis Group, LLC, p.446.
[2.1] Realization of Distance Relay Algorithm using EMTP MODELS J.Y. Heo, C.H. Kim, K.H. So, N.O. Park, International Conference on Power Systems Transients – IPST 2003 in New Orleans, USA.
[2.2] 2014 Key World Energy Statistics // OECD/IEA, Paris, 2014.

[2.3] Almeida, A., B., Reginatto, R., da Silva, R., J., G., C. A Software Tool for the Determination of Dynamic Equivalents of Power Systems // VIII IREP Symposium Bulk Power System Dynamics and Control, 1-6 August 2010, Buzios, RJ, Brazil, p.10.
[2.4] L.22-Sauhats, A., Chuvychin, V., Antonovs, E., Zicmane, I., Strelkovs, V., Interconnection of power systems with different under-frequency load shedding schemes // EEEIC 2011: Rome, Italy, 8-11 May 2011, pp. 1- 4.
[2.5] A. V. Zhukov, A. N. Komarov, A. N. Safronov, I. V. Barsukov, Experience in connecting the power generating units of thermal power plants to automatic secondary frequency regulation within the united power system of Russia, Journal Article: Power Technology and Engineering 04/2012; 43(3):185-193. DOI:10.1007/s10749-009-0089-0
[2.6] D. Antonovs, Promocijas darbs - Energosistēmu asinhronā režīma modelēšana, vadība un novēršana, Rīga, RTU, 2015.
[2.7] Dolgicers A., Bieļa-Dailidovicha E., Antonovs D., Kozadajevs J. Electrical Facilities and Systems. Electrical and Data Processing Facilities and Systems, Vol.11, No.4, 2015, ISSN 1999-5458, Russia, 5.-12.lpp.
[2.12] M. Silarājs, Promocijas darbs - Statistiskā pieeja energosistēmu aizsardzības algoritmu sintēzē un testēšanā Relejaisardzības un automātikas kompleksu pārbaudes metodes un līdzekļi, RTU, 2012
[2.17] Sauhats A., Zalostiba D., Dolgicers A., Bieļa-Dailidovicha E., Broka Z. University Impact on Power Supply Economy, Reliability and Sustainability Enhancement Decreasing Climate Changes. 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University: Proceedings, ISBN-978-1-5090-0334-1, Riga, 2015, 37.-42.lpp.
[79] R. Varfolomejeva, I. Umbrasko and A. Mahnitko “Algorithm of smart control system operation of small hydropower plant” EEEIC 2013, no. 6549537, pp. 330-334
[2.19] Varfolomejeva, R., Sauhats, A., Kucajevs, J., Petričenko, R., Jankovskis, N. Stochastic Aproach to Economical Analysis of Biomass Power Plants. In: Environmental Biotechnology and Engineering — 2014: The Fourth Int. Symposium on Environmental Biotechnology and Engineering. Vol. 1, Mexico, México, 9–12 September, 2014. México D.F., México: Cinvestav, 2014, pp. 281–293. ISBN 978-607-9023-28-7.
[2.20] A. Vanags, Z. Krišāns, Elektriskie tīkli un sistēmas, II daļa, Rīga, RTU, 2005, lpp. 270 – 272.
[3.1.] В. А. Веников, Переходные электромеханические процессы в электрических системах, М., 1985. – 536 стр.
[3.2] Ruiz, P., A., Sauer, P., W. Voltage and Reactive Power Estimation for Contingency Analysis Using Sensitivities // IEEE Transactions on Power Systems, Vol. 22, No. 2, May 2007, pp. 639-647.
[3.3] Rubcovs, S., Smart Under-Frequency Load Shedding System // III Smart Communications & Technology Forum, June 5, 2013, W., Poland, pp. 88 - 103.
[3.4] http://alephfiles.rtu.lv/TUA01/000035993_e.pdf
[3.8] https://books.google.lv/books?id=y3Zs7-R4hKsC&pg=PA303&lpg=PA303&dq=angle+between+two+equivalent+generators&source=bl&ots=lMBcZjs8pE&sig=oACMMETcMxsnEuLEmSSKWF27bTc&hl=en&sa=X&ved=0ahUKEwioxq2smIHUAhUKjSwKHTl1BMkQ6AEIIDAA#v=onepage&q=angle%20between%20two%20equivalent%20generators&f=false
[3.9] L.93- Fan, S., Li, X., Zuo, L., Li, Y. A New Asynchronous Parallel Load Flow Calculation Algorithm // IEEE Conference on Robotics, Automation and Mechatronics, 21-24 September 2008, pp. 1027-1031.
[3.12] http://library2.usask.ca/theses/available/etd-06272008-100122/
[3.14] H. Ito, I. Shuto, H. Ayakawa, P. Beaumont, K. Okuno, Development of an Improved Multifunction High Speed Operating Current Differential Relay for Transmission Line Protection, Developments in Power System Protection, Conference Publication No. 479, IEE 2001, 511–514 pp.
[3.15] Yeu, R., H., Sauer, P., W. Post-Contingency Equilibrium Analysis Techniques for Power Systems // 37th Annual North American Power Symposium, 23-25 October 2005, pp. 429-433.
[3.16] Papkovs, B., Zicmane, I. *Elektromagnētiskie pārejas procesi elektriskās sistēmās*. Rīga: RTU Izdevniecība, 2007. 306 lpp. ISBN 978-9984-32-181-3.
[3.17] Kimbark, E. W. „*Power System Stability*”, vol. 1, 1995, IEEE, Inc. New York: Wiley, pp. 122-132. ISBN 0–7803–1135–3
[3.18] B. Alinezhad, H. K. Karegar „Out-of-Step Protection Based on Equal Area Criterion”, IEEE Transactions on Power Systems (Volume: PP, Issue: 99), 23 June 2016, 9 p. ISSN: 0885-8950, DOI: 10.1109/TPWRS.2016.2584121. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7498682.
[3.21] D. Antonovs, A. Sauhats, A. Utāns, E. Bieļa, Patents LV 14832 B, 05.07.2013., Asinhronās gaitas novēršanas automātikas ierīce un paņēmiens.
[3.22] Antonovs D., Sauhats A., Utāns A., Bieļa-Dailidoviča E. Patents LV 14912 B, 27.06.2014.: Asinhronā režīma novēršanas automātikas ierīce. Asinhronā režīma novēršanas automātikas paņēmiens.
[3.24] Yang, Z., Kui, W., Buhan, Z. A Real-time Dynamic Equivalent Solution for Large Interconnected Power Systems // 4th International Conference on Electric Utility Deregulation and Power Technologies (DRPT), Year 2011, pp. 871-875.

[3.38] http://www.nordpoolspot.com/
[3.39] http://www.ptc.com/engineering-math-software/mathcad
[4.2] Poon, K., K., Y., Emami, R., Bose, A., Abur, A. External Data Exchange Issues for State Estimation in Power Systems // IEEE Transactions on Power Systems, Vol. 27. No. 2, May 2012, pp.849-856.
[4.4] Villella, F., Leclerc, S., Erlich, I., Rapoport, S. PEGASE Pan-European Test-beds for Testing of Algorithms on Very Large Scale Power Systems // 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Berlin, 2012, p.9.
[4.5] Korn, G., Korn, T., “Mathematical handbook”, McGraw-Hill Book Company, 1968.
[4.6] 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 Technologies. - 6. (2011), 184.-189.lpp.
[4.7] Vempati, N., Silva, C., Alsac, O., Stott, B. Topology Estimation // IEEE Power Engineering Society General Meeting, 12-16 June 2005, p.5.
[4.8] http://www.scribd.com/doc/19864620/39-New-England
[4.10] Zhao, L. Multi-Area Network Analysis // Dissertation, Texas A&M University Doctor of Philosophy (subject Electrical Engineering), 2004.
[4.11] Sauer, P., W., Pai, M., A. Steady-state Stability and Load Flow // 27th IEEE Conference on Decision and Control, 7-9 December 1988, pp. 2110-2113.
[4.14] Ivanov, V., Rimarev, V., Gerhards, J., Mahnitko, A. Calculations of Steady And Transient States In The Complex Power Systems According To The Program “Mustang”// Control of Power & Heating Systems, 5th International Conf. CP&HS 02, Zlin, Czech Republic, May 21-22, 2002, p.116.
[4.29] http://new.abb.com/substation-automation/products/protection-control/line-differential-protection/red670