**RIGA TECHNICAL UNIVERSITY**
Faculty of Power and Electrical Engineering
Institute of Power Engineering

**Jevgeņijs Kucajevs**

# METHODS AND DEVICES FOR THE CONTROL AND ESTIMATION OF RISKS IN LARGE POWER SYSTEMS

Summary of Doctoral Thesis

**Riga, 2013**

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**RTU Publishing House**
**Riga, 2013**

Kucajevs J. Methods and Devices for the Control and Estimation of Risks in Large Power Systems.
Summary of the Doctoral Thesis. – Riga: RTU, 2012. – 35 pages.

Printed in accordance with decision No.8/13 of RTU Doctoral Board P-05 (Power and Electrical Engineering) dated May 2, 2013

ISBN …

**THIS DOCTORAL THESIS**
**HAS BEEN SUBMITTED FOR THE AWARD OF A DEGREE**
**OF DOCTOR OF ENGINEERING SCIENCES**
**AT RIGA TECHNICAL UNIVERSITY**

This Doctoral Thesis for the Degree of Doctor of Engineering Sciences is to be defended in public on____________, at the Faculty of Power and Electrical Engineering of Riga Technical University, 1 Kronvalda Blvd., Assembly Hall.

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## DECLARATION

I hereby declare that I have worked out this Doctoral Thesis, which has been submitted for review at Riga Technical University for the award of a doctoral degree in the field of engineering. This Doctoral Thesis has not been submitted to any other university for the award of a scientific degree.

Jevgeņijs Kucajevs ................................ (Signature)
Date ............................................

The Doctoral Thesis has been written in the Latvian language and consists of an introduction, five chapters, conclusions as well as a bibliography and an appendix. The total volume of the paper is 124 pages in computer setting. The paper contains 11 tables and 64 figures. The bibliography consists of 78 literature sources.

This paper has been worked out with the support of the European Social Fund within the framework of the project "Support of the development of doctoral studies at RTU" of the National Programme "Support for the implementation of doctoral study programmes and post-doctoral research".

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## TOPICALITY OF THE SUBJECT

The problem of reliability for jointly operating energy producing and consuming systems becomes particularly topical due to the dynamic development of electric power systems and their becoming more complex, the growth of cities, new emerging infrastructures, which rule out even short-term power cuts. This serious reality is testified to by large-scale emergencies in many power systems, which cause immense losses and even loss of human life.[1,2,3,4,5] At the same time, an increase in the energy production costs is observed. Electricity is still unavailable to millions of less privileged population even in the developed countries. The goal of increasing the efficiency of the generation and distribution of electric power leads to the application of tools for the restructuring of power systems and using market conditions. Yet, new problems have emerged as well, namely, the contradiction between reliability (to ensure the required level of which, significant costs are expected) and efficiency. Indeed, the maintenance of various kinds of reserves and an emergency automation system, increasing the throughput capacity of the line, testing and renewing the hardware involves large expenses. The task to maintain the required reliability level is solved at continuously changing conditions. It is a long-known fact that the processes of change in the functioning conditions of power systems develop at a rate that encompasses a considerable timespan. Starting from wave processes developing over a matter of microseconds and to processes of introducing new capacities and consumption, when the time, over which the processes take place, may last for years. Depending on the rate at which the power system functioning conditions change, also the tools for achieving the required reliability level change accordingly. In the case when fast-speed processes emerge, a person is unable to make an appropriate, rational control decision. The control action is generated automatically. On considering the slow processes in order to make substantiated decisions, it is possible to perform complicated calculations and simulation of processes, since it is not necessary to take consideration of the time required for preparing and performing the calculations. In this doctoral paper, we are confining our interest to fast-speed processes, when decisions regarding the generation of control action are made by using automation means. In practice, introduction of market conditions for the operative control modes of power systems leads to contradictions between the aspirations to ensure economic efficiency and reliability. For example, in striving to increase the economic efficiency, it is possible to arrive at recommendations to increase the allowable overloads of line transformers as well as high-voltage and other lines, which will diminish the reserves for the fulfilment of the conditions of static, dynamic and thermal stability. It can be said that the control of a modern power system takes place by solving multicriterial optimization tasks[5,6], which have at least two simultaneous purposes:

1. Increasing the efficiency;
2. Increasing the reliability level.

One of all-encompassing methods and which is among the best-known ones, is known under the name "the N-1 criterion". [7,8] This easy-to-apply criterion, which is at the same time complicated in its essence, ensures such sets of power system conditions that allow an unexpected failure of any of the elements. Also, it should not lead to considerable economic losses. As was already mentioned, the simplicity of this criterion is questionable, to put it mildly. When using this criterion, practical contradictions arise and various clarifications are needed. What does "failure of one element" mean? What losses are regarded as "large"? Why should it be N – 1 and not N – 3, for example? It may happen that the probability of three uncertain element failures is higher than the probability of one yet certain element failure!

It can be conceded that it is possible to estimate reliability more strictly, for example, by calculating the possibility of a system emergency. Yet also in this case, the question remains: what kind of a probability value is acceptable?

Theoretically, it is possible to formulate the optimization task in a single-criterion situation. In this case, both objectives (efficiency and reliability) need to be expressed in the same measuring units. One example of such measuring units is money, which reflects profit or loss. Considering the influence of many arbitrary factors on the potential profit or loss, it can be said that the operation of a power system results in profit or losses and that these values are of probabilistic nature. The task of the estimation and management of risks emerges. It has to be noted that the risks emerging in the process of controlling a power system are the subject of a great number of studies [8,9,10,11,12]. A significant contribution to the evaluation of risks, simulation of processes and synthesis of appropriate automatic equipment was also made by Latvian researchers: Jānis Bubenko, Veniamin Fabrikant, Jēkabs Kuzmins, Jānis Putniņš and Voldemārs Putniņš, Jānis Gerhards, Zigurds Krišāns, Vilnis Krēsliņš, Kārlis Brinķis, Jēkabs Barkāns, Antans Sauhats, Vladimir Chuvichin, Anatoly Makhnitko. Yet the majority of the works is dedicated to the evaluation of the reliability level or the methods for increasing it, or calculations of the size of the potential losses. This doctoral thesis looks at reliability and efficiency at the same time. The goal set by the paper is directed towards the minimization of risks and is therefore topical.

## THE PURPOSE OF THE PAPER AND THE SOLVED TASKS

**The main goal** is the diminishing of power systems' risks that emerge due to the disturbance of the dynamic stability of the power systems.

To achieve the set goal, the paper **solves the following main tasks**:

1. An analysis of the methods and algorithms for evaluating power systems' risks has been conducted.
2. The dynamic stability disturbance process in large power systems has been developed and modeled on the basis of simplified automation and distance protection models.
3. A new structure of automation for preventing and eliminating out-of-step operation has been synthesized.
4. An algorithm of distance protection functioning has been developed, which is capable of calculating the actuation risk value in the moment of short circuit.
5. Methods for assessing the validity of simplified models of automation for preventing out-of-step operation have been developed.

## METHODS OF RESEARCH

- For simulating dynamic processes in power systems, the systems of large non-linear differential and algebraic equations have been calculated by using the EUROSTAG software;
- For the purpose of synchronizing geographically distant measurements, a global positioning system (GPS) and optical communication channels have been used;
- The methods of the probability and statistical decision-making theory and the Monte-Carlo method;
- The methods and tools for synthesizing the microprocessor devices.

## THE SCIENTIFIC NOVELTY OF THE PAPER

- An analysis and a comparison of the risk evaluation of possible approaches has been conducted; the probabilistic approach has been substantiated by using the method of reliability and the statistical decision theory as well as the Monte-Carlo method;
- For the purpose of simulating the loss of dynamic stability of large power systems, the simplified probabilistic relay protection and automation functioning algorithms have been substantiated and verification methods for these have been developed;

- Using the global positioning system and optical fiber communication channels, a new structure of out-of-step protection automation has been synthesized;
- The influence of a great amount of dissipated energy sources on the power system's stability has been evaluated;
- A new distance protection algorithm has been proposed, which evaluates the risk level during the elimination of short circuit.

## THE PRACTICAL SIGNIFICANCE OF THE PAPER

The practical significance of the promotion paper is expressed as follows:

- The risk evaluation methods have been used in the European project ICOEUR by evaluating the expected opportunities and benefits from the interconnection of the European and Russian power systems.
- The structure of the out-of-step protection automation is implemented by means of microprocessor terminals and will be put into operation in the power systems of the Baltic countries.
- The simplified probabilistic relay protection and automation models can be used by evaluating the risks in the practical tasks of power system control.
- The synthesized distance protection algorithm with real-time risk evaluation will make it possible to improve the selectivity of high-voltage line protection in the case of single-phase short circuits via transient resistance.

## APPROBATION OF THE PAPER

The doctoral paper has been presented and discussed at the following conferences:

1. Riga Technical University. The 49th International Scientific Conference on Power and Electrical Engineering and Environmental Sciences, Riga, 2008.
2. The 3rd International Conference on Integration of Renewable and Distributed Energy Resources, France, Nice, December 10-12, 2008.
3. IEEE Power Tech 2009 International Conference, Romania, Bucharest, June 28 - July 2, 2009.
4. The 5th International Conference on Electrical and Control Technologies, Lithuania, Kaunas, May 6-7, 2010.
5. The 10th International Conference on Environment and Electrical Engineering, Italy, Rome, May 8-11, 2011.

## PUBLICATIONS

The results of the doctoral thesis have been described in the following articles:

1. Sauhats A., Kucajevs J., Svalova I., Svalovs A. Distributed Energy Resources and Power System Stability // RTU zinātniskie raksti. 4. sēr., Enerģētika un elektrotehnika. - 23. sēj. (2008), 54.-65. lpp.
2. Sauhats A., Haļilova N., Kucajevs J., Use of Phasor Measurement for Line Protection // RTU zinātniskie raksti. 4. sēr., Enerģētika un elektrotehnika. - 23. sēj. (2008), 66.-73. lpp.
3. Zima-Bockarjova M., Sauhats A., Kucajevs J., Haļilova N., Pašņins G. Distance Protection Algorithm for Power Transmission Lines Based on Monte-Carlo Method // Thesis of the IEEE Bucharest Power Tech Conference, Rumānija, Bukareste, 28.jūnijs-2. jūlijs, 2009. - 1.-7. lpp.
4. Sauhats A., Kucajevs J., Čuvičins V., Utāns A., Bočkarjova G., Leite L., Antonovs E. Verification of Models of Automatic Devices for Elimination of Asynchronous Operation in Power Systems // The 5th International Conference on Electrical and Control Technologies, Lietuva, Kaunas, 6.-7. maijs, 2010. - 182-186.-5. lpp.
5. Sauhats A., Silarajs M., Kucajevs J., Pašņins G., Antonovs D., Bieļa E. Testing of Protection and Automation Devices Using Dynamical Simulation Processes of Power System // Electrical and Control Tehnologies.5 - 6. maijs(2011) 184.-189. lpp.
6. Sauhats A., Kucajevs J., Leite L., Bočkarjova G., Utāns A., Out-of-step Automation Device Model Validation Methodology // 2011 10th International Conference on Environment and Electrical Engineering, Italija, Roma, 8.-11. maijs, 2011. - 296-301.-6. lpp.
7. 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.
8. 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. (2012) 1343.-1348. lpp.

## THE STRUCTURE AND SCOPE OF THE PAPER

The doctoral thesis has been written in the Latvian language and consists of an introduction, five chapters, conclusions, as well as a bibliography. The total volume of the paper is 124 pages in computer setting. The paper contains 11 tables and 58 figures. The bibliography consists of 78 used literature sources.

# 1. METHODS AND TECHNIQUES FOR ASSESSING THE CONTROL RISK OF LARGE POWER SYSTEMS

## *1.1. Emergencies and risks in power systems; their consequences*

The main task of the management of a power system is to guarantee reliable and efficient power supply conditions to the consumers. As a result of the influence of many accidental events, the parameters, configuration and conditions of the power system change continuously. Elements of the power system, for example, loads, generators, transmission lines, are switched on and off, which causes changes to the energy flows. Such changes, probably initiated by the power system operator due to the need to comply with the technical limitations and to ensure the quality and efficiency of energy. On the other hand, the changes are affected by a number of external factors, which can be regarded as indeterminate and probabilistic. A significant part of the control action is generated as a result of protection and power system automation devices. At any operating condition, emergency situations may arise, leading to economic, social and ecological losses [1,2,3,4]. It is important to point out that the losses depend on arbitrary factors and indicators, which therefore in their turn can be regarded as probabilistic values. It can be said that the risk of a power system is a combination of the probability rate of an emergency and its consequences [8,9]. The wish to minimize losses is evident. It is this wish, along with the arbitrary nature of the losses, that constitutes the basis of the synthesis of the risk estimation and control methods.

One of the most important tasks, the solution of which is directed towards eliminating the large losses, is to develop a risk estimation methodology, which characterizes the possible losses and their probability. The next task is to generate actions to diminish the risk of the condition. The large scale of power systems and the number of equipment units and subsystems explains the complicated nature of the risk estimation task. Yet there are a number of methods and means dedicated to the estimation and elimination of power system control risks [10].

There are many possible risk indicators, which are foreseen for various purposes. Most of them are calculated as the mathematical expectation of probabilistic laws; in other cases, the probability distribution is used, which can be calculated in a number of ways. The risk indicators reflect several factors, including the capacity and interruption components, the indeterminations of forecasts, the configuration and condition of the system, etc.

### *1.2. Criterion N-1. Advantages and disadvantages*

The criterion (N-1) can be defined as follows:

The condition of the system is regarded safe if interruption of the operation of any of the system's elements does not result in considerable loss of load, voltage collapse or loss of synchronism.

The brief and – at first sight – clear definition of the criterion raises a multitude of issues when applied.

In order to remove these issues for the definition of the criterion "N-1", in practice, lengthy instructions and rules for the work of operators are added. As a result, it can be said that there is no unified approach. In different power systems, the application of the criterion "N-1" is different.

### *1.3. The probabilistic approach to the assessment of risk and reliability*

As shown in [8], probabilistic methods can be regarded as a powerful tool that can be used for solving problems in various power systems. Every two years, for the application of probabilistic methods, the worldwide PMAPS conference is organized (Probabilistic Methods Applied to Power Systems).

On the other hand, the variety of risk assessment approaches in complicated systems has yielded grounds for turning to theoretical works that were dedicated to the discussed problem.

The most substantiated approach, in our opinion, has been developed within the statistic decision-making theory [6].

### *1.4. Risks from the point of view of statistical decision-making theory*

In order to define the concept of risk, let us assume the following four hypotheses:

1. The main objective of the discussed system (in this paragraph, the concept of a system is broader than that of a power system) is to gain profit R.
2. The profit to be gained depends on the case X and the indeterminate parameters $X_n$ (for arbitrary parameters, the probability distribution function is known; for indeterminate parameters, the distribution function is not known).
3. For indeterminate parameters, the decision-maker can choose subjective probability functions and, by this method, to move indeterminate parameters to the class of arbitrary parameters.
4. The system's profit R depends not only on the parametersX and $X_n$ that are independent of the decision-maker, but also on the selected structuresΣ and their parameters Π.

Based on the formulated hypotheses, we can say that the system's profit R can be described by the following function:

$$R=F_R(X, X_n, \Sigma, \Pi) = F(X, \Sigma, \Pi) \qquad (1.1)$$

The function (X, Σ, Π) depends on arbitrary parameters X, thus it can be stated that by selecting Σ and Π, it is possible to calculate the distribution function for the profit R, let us say, in the form of distribution density [6]. Of course, it is also possible to calculate the numerical values of the distribution function, for example, the mathematical expectation E(R):

$$E(R) = ( \int_{\Omega} R(X,\Sigma,\Pi)d\varphi(X)' \qquad (1.2)$$

where φ(X) – the probability distribution function of the parameters X;

Ω – the limits for the existence of the parameters X.

∫ – the multi-dimensioned Stieltjes-Lebesgue integral.

If the task to calculate the probability distribution function for profit R, then this function ∫ (R) can be expressed as follows:

$$f(R) = \int_{\Omega} XR(X,\Sigma,\Pi)d\varphi(X) \qquad (1.3)$$

The expression (1.2.) and (1.3.) can be used for risk assessment and management purposes.

A simplified task emerges in the case of using (1.2.), that is, if the mathematical expectation of profit (or loss) is assumed as a risk and a criterion for the optimization of the system's management. In this case, the optimization task can be set in the following way:

$$(\Sigma, \Pi)_{opt} = argmaxE\,(R(X, \Sigma, \Pi)), \qquad (1.4)$$

where $(\Sigma, \Pi)_{opt}$ stand for the structures Σ and parameters Π of the mathematical expectations of the optimum maximizing profit.

The discussed optimization task, from the point of view of a risk management problem, makes it possible to use a single criterion – the mathematical expectation of profit. In this sense, it is very convenient in use (unlike multicriterial tasks).

Sadly, as is proven by the statistic decision-making theory (supported by real-life evidence), the application of the expression (1.2) is limited. The mathematical expectation of profit is unable to describe a very significant phenomenon: decision-makers in many cases and due to a variety of reasons prefer solutions characterized by lower mathematical expectations of profit, on condition that those profits will be received with a higher degree of reliability than others, even if higher in size on the average.

The mentioned phenomenon is particularly clearly expressed in insurance business. It can be said that on the average, all insurance takers suffer losses. That is to say, the mathematical expectation of the insurance taker is negative. This statement is proven by the viability of insurance companies.

In order to avoid the above-described difficulties, one more function is introduced, describing the “taste” of the decision-maker by comparing various density functions and giving preference either to an increase in the average profit or to a decrease in the large losses. This function is termed the utility function $L_F$.[6]

By using experts’ experience and the results of solving decision-making tasks, the character of the utility function can be reflected as shown on Figure 1.1.

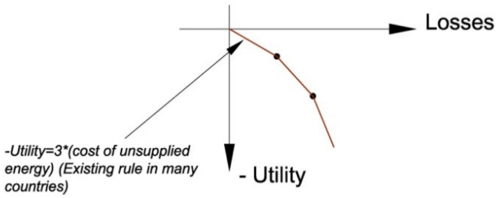


Figure. 1.1. The character of the utility function

The graph in Figure 1.1 shows, which is the main aspect in the character of the utility function, that utility at a negative profit R decreases faster than the respective profit. (the negative profit actually means losses). If the utility function L† is known:

$$L_F = L_F(R) = L_F(X, \Sigma, \Pi), \qquad (1.5)$$

then it is very easy to define the risk assessment criterion:

$$E(L_F) = \int_{\Omega} L_F(X, \Sigma, \Pi)\, d\varphi(X) \qquad (1.6)$$

and set the risk management task:

$$(\Sigma, \Pi,)_{opt} = argmax\, E(L_F(X, \Sigma, \Pi)). \qquad (1.7)$$

It is obvious that (1.4) and (1.7) make it possible to respect the decision-makers’ wish to diminish the possibilities of large losses occurring.

### *1.5. The simplified methods and criteria of risk assessment*

**The technical risk**. For assessing the risks of technical systems, the concept of technical risk is used relatively widely:

$$R_T = \Sigma P_i R_i , \quad (1.8)$$

where $P_i$ – the probability of an undesirable event related to negative profit $R_i$;

i=1,..... the numbers of the undesirable events in their list.

The technical risk is the mathematical expectation of losses and this concept has the above-mentioned drawbacks. Of course, if the utility function $L_F$ is known, then also (1.6.) can be transformed for discrete cases:

$$E(L_F)= \boldsymbol{\Sigma} P_i L_{Fi} (X, \Sigma, \Pi) , i=1 \quad (1.9)$$

### *1.6. Game theory criteria and methods*

The above-described methods for formulating risk criteria were substantiated by the adopted hypothesis that the probability distribution function for the influencing parameters and factors is known. However, also a basically different approach is possible, which can be used relatively widely. This approach adopts a hypothesis according to which the probability distribution function of the influencing factors is not known. It is obvious it is thus no longer possible to formulate optimization tasks in the form of expressions (1.4.) or (1.7.); neither can the corresponding risk criteria be calculated. Giving up the use of probability distribution functions, the possibility is retained to calculate profit R at known values X, structures Σ and parameters Π and the method of adopting "scenarios" is used. The indeterminate parameters X are replaced by determinedvalues $X_j$ , which have been selected in such way as to encompass the whole range of the existence of the parameters X. For all $X_j$ the (profit) loss $R_j$ ($X_j$, Σ, Π) is calculated and the results are returned to the decision-maker. A problem arises: how is the scenario to be selected? For solving the problem, game theory methods and criteria are used [6]: Minimax, Hurwitz, Laplace etc.

### *1.7. Reliability theory criteria*

The well-developed and widely used reliability theory is dedicated to the capacbility of technical systems to retain the defined parameters and functions at the set conditions and modes for investigation [8]. This capability can be described by a number of particular, or complex, criteria. One of the basic concepts of the theory is dedicated to failures of elements; characterization of failures is often performed by means of failure probability values in the set time period. For calculating failure probabilities, two basic approaches are used:

1. The analytical approach. It has been proven that many technical systems, in terms of reliability, can be reflected by diagrams, which consist of a series of individual elements, parallel or mixed

connections. For particular tasks that are, however, widespread in practice, it can be assumed that failures of elements can be described by the exponential law of reliability. In this case, knowing the probabilities of element failures, we succeed in an analytical calculation of the probability of a failure of the whole system.

2. Simulations. For complicated systems, the analytical approach is not applicable and numerical methods, including the Monte-Carlo method, need to be used.

# 2. RISK MANAGEMENT METHODS, ALGORITHMS, MODELS AND TOOLS

## *2.1. The structure of the risk management algorithm*

The first stage of the power system management process includes (this stage is characteristic of any technical system operating in real time) the observation and prognosis of the condition of the object and the influencing environmental factors. As a result, a power system model seen on Figure 2.1 is created. Experiments with the model make it possible to assess the size of risk, to make decisions regarding the possible control actions and their consequences.

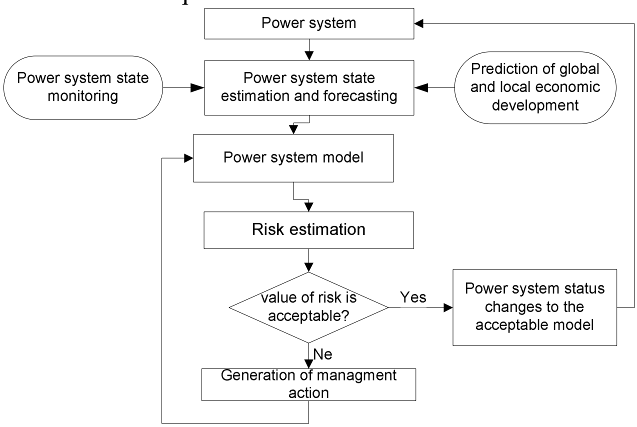


Figure 2.1. The generalized risk management algorithm

Control actions, methods for their selection and tools for their implementation depend strongly on the speed at which changes in the operating conditions of the power system take place. Based on the speed of processes, it is usual to divide the management task into three parts:

- Strategic planning;
- Operative planning and process management;
- Process management in the course of emergencies.

### *2.2. Types of power system models*

The complicated nature of the processes of the power system's operation and the importance of the task of their control has become the basis for the development of numerous models. A classification of models applicable for the evaluation of dynamic stability is provided in Figure 2.2.

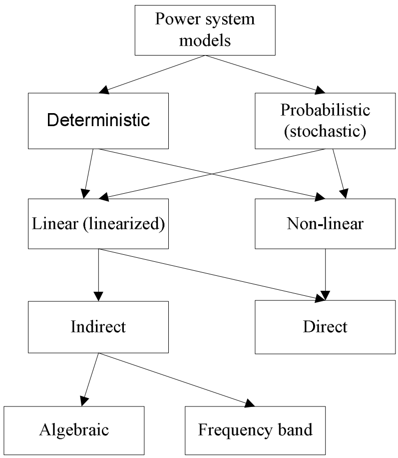


Figure 2.2. Classification of power system models

For many years, for assessing the stability of power systems, deterministic positions and linearized models of power systems were used. Indirect methods were used, which allow to avoid the need to solve differential equations of a high degree of complexity in stability assessment tasks.

### *2.3. Stochastic, non-linear models*

Let us assume that the initial state of the power system is known and stationary and the amount of generated energy coincides with the amount of consumed energy. The topology of the system is also known. At the time moment t=0, simulation of system processes is initiated. The planning time $t_{pl}$ is set for the mode; over that time, a series of events may or may not happen, the list and probability rates of which are known. Events that influence the power system may result in loss of stability, division of the system into parts, in which the produced and consumed energy is no longer in a state of equilibrium. The load is disconnected. Economic or other losses emerge. The aim of the simulation is to determine the mathematical expectation of the utility function by using (1.8.). Considering the large number of stochastic factors, it can be said that the integral (1.8.) has to be calculated by the Monte-Carlo method.

### *2.4. The Monte-Carlo method as a tool for calculating the risk indicators*

The algorithm consists of the following main blocks:

- Setting the initial state of the power system. Two basic alternatives can be used. The first alternative is based on the use of SCADA data(topology, power consumption, generating capacity, power flows). According to the second alternative, the state of the power system is set by the person who performs the calculation of the operating mode by using specific software. This person checks the permissibility of risks for exact operating modes.
- Forecasting a future state of the power system for an exact time interval. At this stage, all elements are to be considered undamaged, and the forecast operating mode is allowable in terms of absence of overloads and ensures static stability (otherwise measures are planned for preventing the inadmissible mode).
- A generator that simulates the failure of the elements of the power system. Short circuits and disconnections of the main elements of the power system are simulated. The statistic data of the power system are used.
- Dynamic models describing the processes in the power system triggered off by the disconnection of elements. This model is used for testing the consequences of disconnection, considering the impossibility of power supply.
- Risk assessment. The probability of the development of emergency situations and the costs of undelivered power are considered (it is assumed that the costs are known).

It has to be noted that to assess the risks caused by large-scale emergencies, it is necessary to consider even rarely occurring cases. In this case, the number of trials according to the Monte-Carlo method may be very large (100 000 or more).

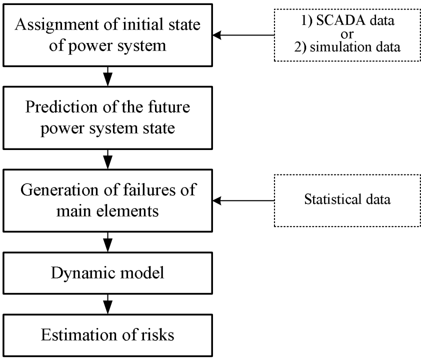


Figure 2.3. The algorithm for calculating risk indicators

# 3. RELAY PROTECTION AND AUTOMATION MODELS AND THEIR VALIDATION

## *3.1. Synthesis and use of relay protection and emergency automation models*

By summarizing the information laid out in Chapter 1, the following can be said:

1. Relay protection and emergency automation (RAPA) significantly influence the operation of power systems; if simulation of the power system's operation is planned, it is necessary to simulate the operation of not only primary devices but also secondary ones (i.e. RAPA). Consequently, corresponding models are needed.
2. In terms of number, RAPA devices can be regarded as the most widespread element of power systems. Consequently, by simulating the operation of a large power system, it is necessary to reckon with the need to use a large number of RAPA models. Even the relatively small Latvian power system contains thousands of RAPA devices.

Equipment of many generations is operated in power systems, from electromechanical relays, to microprocessor terminals. Consequently, models of all types of equipment are needed. Microprocessor terminals operate on the basis of digital signal processing algorithms; this type of algorithms can also be used for describing the operation of analog devices including electromechanical relays; therefore, our further discussion will only concern this type of devices.

Notwithstanding the large number of RAPA devices, their structure remains practically unchanged and corresponds to Figure 3.1.

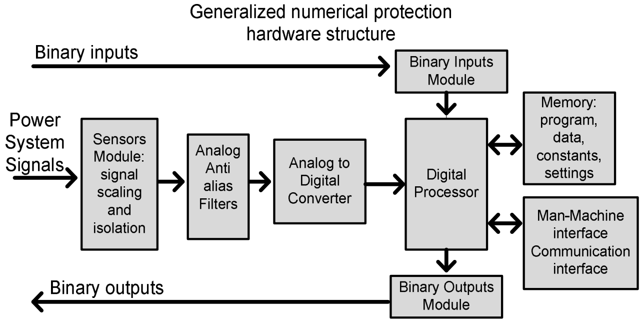


Figure 3.1. The structure of RAPA devices

### *3.2. The main requirements for RAPA models*

The main requirements are as follows:

- The response of RAPA models to input signals required for each of the discussed devices, has to correspond to the reaction of the real-life device to the input signal, which emerges at the set parameters of the power system mode.
- As a software product, the model needs to be easily integrateable in the software systems that are used in the power system process simulation;
- If the parameters of the power system influence the reaction of a device and vice versa, then the model of the device and of the power system have to be joined in a closed cycle;
- In the simulation of the behaviour of the power system and various types of protection, it is necessary to provide for interaction between different models;

### *3.3. Model validation methodology*

In order to solve the problem of model validation, it is necessary to develop a criterion for determining the compliance of models. Let us now formulate the requirements for RAPA devices:

1. Fast actuation requirements at conditions when actuation is desirable;
2. Non-actuation when actuation is not desirable (no short circuit and other cases of normal operating conditions).

The conformity of a certain device to requirements can be expressed by the efficiency criterion, which is formulated in the form of two probabilities:

- Failure probability in cases when actuation is needed – Par;
- Actuation probability at conditions when actuation is not desirable (superfluous actuation) – Pnr,

As a supplementary condition, the following can be used:

- The mathematical expectation of the actuation time – M(Tr).

For RAPA models, similar criteria can be used, accordingly Pmar, Pmnr и M(Tmr)). The degree of compliance of a model can be expressed by means of parameter differences:

$$Da = Par - Pmar,$$
$$Dn = Pnr - Pmnr, \qquad (3.1)$$
$$M(DT) = M(Tr) - M(Tmr)$$

It can be seen that in the case of small differences (3.1) the corresponding model will ensure the required accuracy of process simulation. In a probabilistic problem formulation, it means that with a high degree of probability, the processes will be simulated accurately. Insignificant differences are such differences that are encompassed within the range of accuracy of determination of the selected criteria Par, Pnr and M(Tr). In this way, for validating the model, it is necessary to calculate the probability of failure or superfluous actuation of a real-life device and its model, as well as the differences of the actuation time mathematical expectations and criteria (3.1.).

### *3.4. Implementation of the validation procedure*

A model validation methodology based on the evaluation of the probability values can be implemented by using the Monte-Carlo method. In this case, it is necessary to foresee the transmission of identical test signals both to a software model and a real-life device. Moreover, it is sufficient to observe the reaction of a real-life device and model, which makes it possible to calculate the probabilities (3.1). The value of the differences in the calculated probability rates of the real-life device and the model determines the suitability of a model and the answer to the question if the model is valid. The model validation process is shown on Figure 3.2.

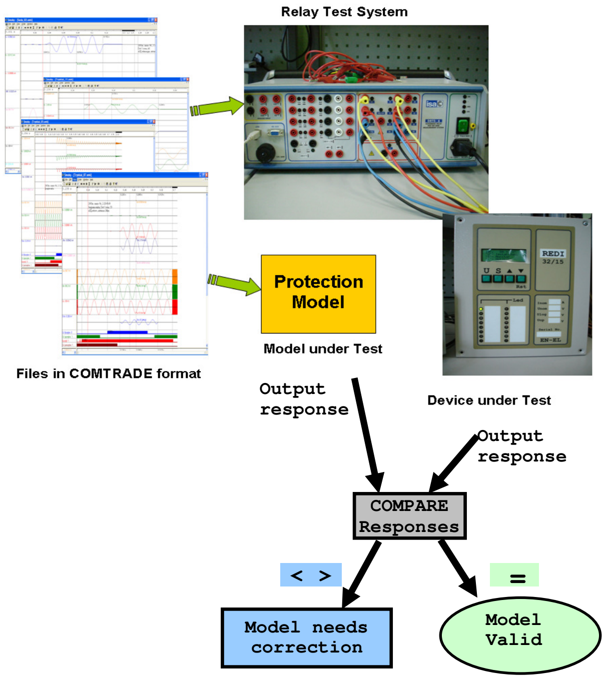

Figure 3.2. Model validation process

The sources of the test signals (the analog current and voltage signals; binary signals), the use of which makes it possible to evaluate the efficiency of the RAPA model, may be as follows:

- A software model for the protected facility or power system part that has been created by means of corresponding software (EMTP, EUROSTAG) and makes it possible to generate test signals for the protected object at various operating conditions, including emergency situations [3]. The advantage of the use of the software model is the absence of limitations when performing simulation at changeable conditions.
- As test signals, real-life data recorded during the operation of the power system (oscillographs). The source of such signals can be the digital devices for recording emergency processes and RAPA devices, which have a process recording function. Unfortunately, compared to the possible number of simulation cases, the number of oscillographs is limited. On the other hand, the use of recorded test signals makes it possible to modify the operation of a real-life

device at real-life conditions and discover deficiencies that cannot be discovered by means of simulation. Test signals have to be depicted in digital format (for testing the model) and in the form of real-life currents and voltages (for testing the device). For all the above-mentioned sources, test signals are depicted in the form of their digital equivalents. The conversion function of a signal that is depicted as an unchangeable value of a digital equivalent, can be applied by means of any state-of-the-art relay test system (FREJA 300 or ISA-DRTS). The initial digital data need to be depicted in the form of data files in COMTRADE format. The existence of a unified COMTRADE standard makes it possible to create a library of test signals, which may include both files created as a result of the simulation of a software model, and the real-life oscillographs obtained in the transition process.

### *3.5. Distance Protection Algorithm for Power Transmission Lines based on Monte-Carlo method*

Distance protection is one of the most widely used methods to protect transmission lines. The fundamental principle of distance relaying is based on the local measurements of voltages and currents where the relay responds to the calculated impedance value between the relay terminal and the fault location in the transmission network.

The increase of the efficiency of the protection operation is possible utilizing the adaptive approach  For example, the adaptive protection depending on the parameters of the monitored process can change the boundaries of the protection zones.

As an example, the first zone protection operation is investigated for the most frequent fault type: the single phase to ground. Particularly, it becomes realistic to exchange the deterministic approach by the more advantageous probabilistic one that requires real-time implementation of the Monte-Carlo method.

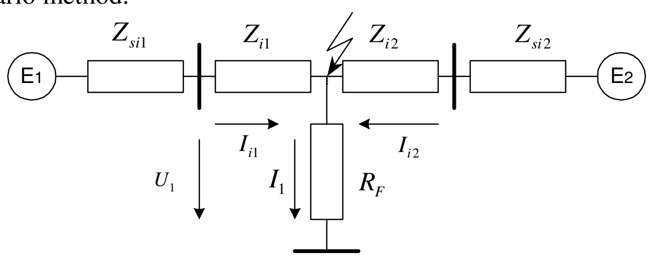


Figure 3.3. One-line diagram of the transmission system equivalent for the single line to ground fault conditions.

Summarizing the stated above equations, one can declare that the distance to the fault $L_F$ and $R_F$ are linked to the measured phasors of the currents $I$ and voltages $U$ and unknown equivalent impedances $Z_{si2}$ of the remote transmission line end system by relation of the following form:

$$L_F = \Phi(I, U, Z_{si2}) \tag{3.2}$$

where Φ is for some procedure of the distance $L_F$ and $R_F$ calculation. The procedure employs the measurement results of the controlled currents and voltages and information of the impedance $Z_{si2}$ values.

To determine distribution density g($L_{Fest}$) of the $L_{Fest}$ on the base of (3.2), it is necessary to know the distribution relative density function $g(I,U, Z_{si2}/I_{est},U_{est})$, - the density of the current, voltage and impedance distribution under obtained measurement result $I_{est}$, $U_{est}$. For this purpose, significant number of trials should be performed, and consequently, notable processing time will be needed.

However, more effective procedure could be obtained, using the linearization method, taking into account the physical nature of the measured values and relatively small values of measurement errors, and supposing that measurements errors are additive with the zero value of mathematical expectation, it can be stated that:

$$\begin{aligned} &E[\Phi(I,U,Z_{si2})] \cong E[\Phi(I_{est},U_{est},Z_{si2})] \\ &\sigma[\Phi(I,U,Z_{si2})] \cong \sigma[\Phi(I_{est}+\Delta I,U_{est}+\Delta U,Z_{si2})] \end{aligned} \tag{3.3}$$

where $E(\ldots)$ is the mathematical expectation and $\sigma(\ldots)$ is the standard deviation.

Statement (3.3) is strictly true for linear functions. In considered non-linear case, it is deemed permissible for practical applications. On the other hand it becomes possible to employ more efficient procedure for Monte-Carlo method application.

The algorithm for estimation of the mathematical expectation $E[L_F]$, $E[R_F]$ and standard deviation $\sigma[L_F]$, $\sigma[R_F]$, values based on the Monte-Carlo simulations are shown in Figure 3.4.

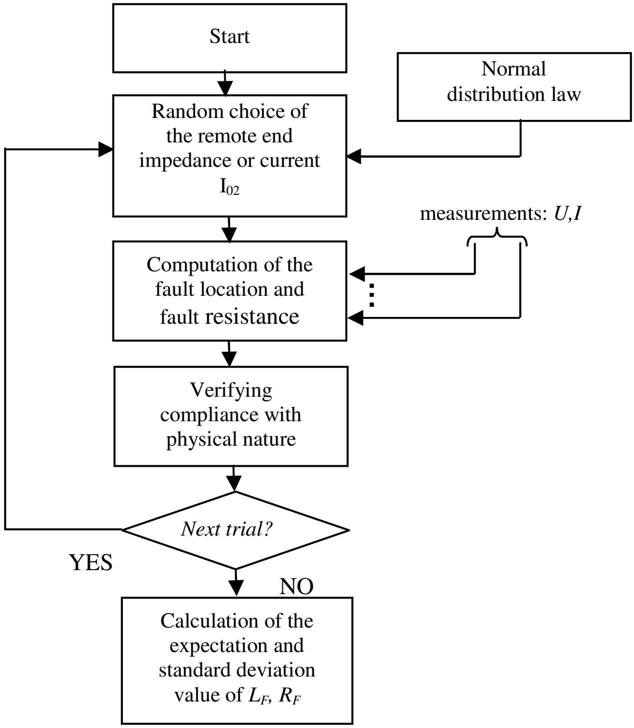


Figure 3.4. Algorithm for the distance to fault and fault resistance estimation.

# 4. EXAMPLES OF SIMULATION OF LOSS OF STABILITY PROCESSES IN POWER SYSTEMS

## *4.1. Simulation of the operation of out-of-step elimination automation*

The goal of the operation of out-of-step elimination automation (OOS) is to find unstable energy flows and to divide the power system network into pre-determined areas, for the case if an excessive phase angle diference appears between the generators of the power system. In order to perform this task, OOS needs to differentiate the energy fluctuations that go over to the out-of-step mode, from processes that do not lead to the disruption of stability and other kinds of disturbances, first and foremost, short circuit.

Several OOS algorithms can be used:

- Monitoring of the changes in the resistance that is to be measured at the place where the relay is installed. The energy fluctuations are characterized by a slow movement of the resistance over the resistance plane. The rate of resistance change is usually determined by the amount of sliding between equal sources of the system. In practice, the implementation of this concept is achieved by measurements of the resistance movement in the monitored line.

- Monitoring of voltage fluctuations in the monitored line. When the centre of the energy fluctuations is situated on the monitored line, then the centre of the voltage fluctuations can be calculated knowing the local voltage and the angle between voltage and line current. The voltage value at the centre of the fluctuations varies from zero (if the angle between two sources is 180 degrees) to the maximum value (if the angle between two sources is 0 degrees.
- Monitoring of the phase angle differences between the generator voltages. The voltages are simulated by using the voltage and current of the monitored line, as well as the equivalent resistances of the system from the location of the device to the generators;
- Using synchronous voltage measurements. Synchronous measurements of voltages, which can be performed by means of the global positioning system (GPS), make it possible to calculate the angle between the voltages and to make an assessment as to the existence of the energy fluctuations process.

Further, let us look at the operating principle of an OOS for monitoring the angle φ between two simulated voltages U1 and U2 [9, 10]. For simulating these voltages, a circuit of two units is used, which is an equivalent of a real-life system (Figure 4.1.). The voltages U1 and U2 are simulated in accordance with the following system of equations:

$$\left.\begin{aligned} \underline{U}_1 &= k_1 \cdot \underline{U} + \underline{Z}_{K1} \cdot \underline{I} \\ \underline{U}_2 &= k_2 \cdot \underline{U} + \underline{Z}_{K2} \cdot \underline{I} \end{aligned}\right\} \qquad (4.1.)$$

where: U – voltage in the monitored power line;
I – the current in the power line;
k1, k2, $\underline{Z}_{K1}$ and $\underline{Z}_{K2}$ are settings that are selected depending on the parameters of the corresponding transmission line and the equivalent parameters of the power system.

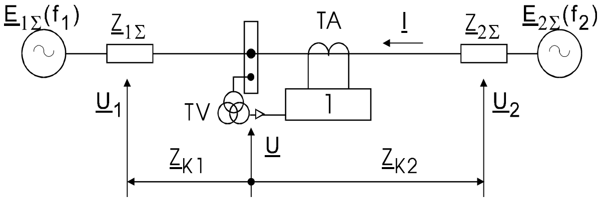

Figure 4.1. The equivalent circuit of the power system

In case of out-of-step operation in the power system, the angle δ between equivalent electromagnetic forces $\underline{E}_{1\Sigma}$ and $\underline{E}_{2\Sigma}$ increased to 180°, and in the electric centre of the fluctuations, the voltage is equal to zero. If the simulated voltages U1 and U2 are situated at the same end as seen from the centre of the fluctuations, the angle $\varphi$ does not exceed 90°. On the other hand, if U1 and U2 are situated at opposite ends from the centre of the fluctuations, then the angle $\varphi$ reaches 180° (Figure 4.2.).

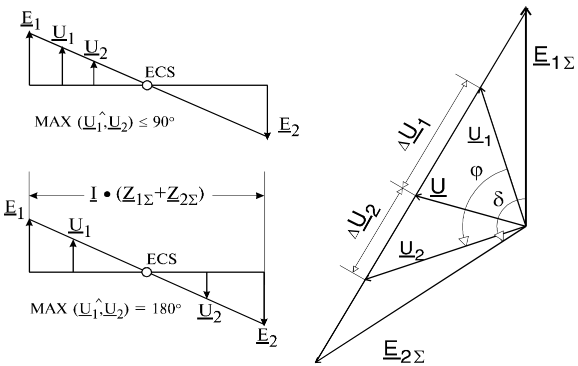

Figure 4.2. The operation diagrams of an AGNA device

The protection is functioning, if the following requirements are fulfilled:

1. The angle φ has reached its limit value;
2. The angle is changing at a sufficiently high rate (dφ/dt);
3. The currents and voltages are symmetrical.

$$\left.\begin{aligned} &\varphi_1 < \varphi = \arg\left(\frac{\underline{U}_1}{\underline{U}_2}\right) < \pi \\ &C_1 > d\varphi/dt > C_2 \end{aligned}\right\} \qquad (4.2)$$

The model of the discussed AGNA device is based on the monitoring of the direct voltage vector, by calculating the difference of the voltage phase angle φ by the formula (4.2.). The EUROSTAG software was used for simulating the asynchronous operation process of the power system. The processes were simulated by using simplified power system diagrams recommended by IEEE for testing tasks: a system of three generators and eight power busbars, as well as a more complicated example of IEEE 39 power busbar power system.

Various modes of power systems (short circuit on the transmission lines, unauthorized disconnection of the load/ generation, disconnection of lines, load changes) were simulated by using the EUROSTAG [1] software.

## 5. DISTRIBUTED ENERGY RESOURCES AND THE STABILITY OF THE POWER SYSTEM

### *5.1. A future power system with a large number of sources of distributed generation*

The wish to increase the efficiency of primary sources of energy, diminish the energy losses in the networks and ensure the sustainable development of the power industry has brought about interest in research dedicated to the opportunities of wide use of dissipated generation in power systems.

The engineering and production of low-capacity generators using steam-gas technologies in combined heat and power mode, wind or solar power, fuel cells, is developing very rapidly. Power sources of this kind can fully or almost fully meet the growing power supply requirements. Using alternative power sources and placing them near consumers may diminish the currents and capacities that are transmitted over high-voltage and super-high voltage networks, thus saving on capital investments for the development and operation of networks, repayment of power losses and maintenance of the reliability level.

This section reflects the results obtained by studying future power systems, which contain a considerable number of distributed energy resources (DER). The main assignment and question of the present study is maintained: how the DER influence the stability of power systems and the possibility of large-scale emergencies.

One more question, which is being asked recently: is it possible to continue the operation of DER after unforeseen splitting of the system and is it possible to perform autoreclosing to the high voltage line after its operation has been restored? In order to answer these questions, this chapter uses an approach that is different from the other approaches [2].

The following questions are sought to be answered:

1. How will the introduction of DER influence the stability of the transmission network?

2. What should the simulation methods be like?

3. How are the technical requirements changed for a distribution power unit with DER?

For this purpose, we are proposing that industrial software be used, which simulates electromechanical transient processes in systems containing both traditional and DER generators and are complemented with the following:

- a unit (procedure), which automatically foresees the potential further states of the future power system, including load flows, equipment with a dynamic description and events;
- a unit (procedure), which determines whether in terms of angle stability the conditions of the power system are acceptable or unacceptable.

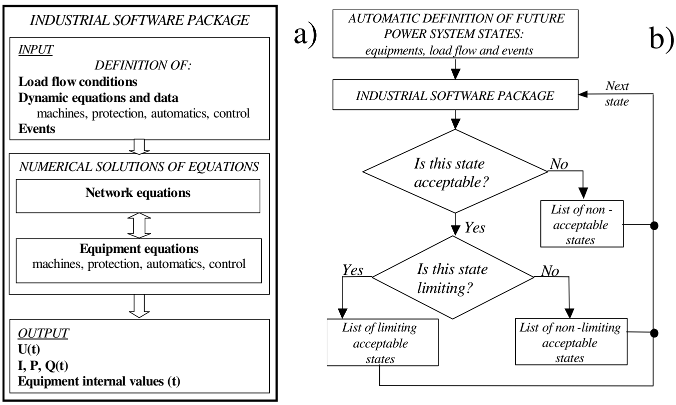


Figure 5.1. a) Transition simulation stages by using industrial software packages; b) Expanded units for assessing the dynamic limitations of the future power system

### *5.2. Classification of the conditions of the future power system*

The classification of acceptable or unacceptable conditions of the future power system is based on the evaluation of the sufficiency of the stability reserves of the transmission power network. As the criterion for sufficiency, the permissible (critical) short circuit disconnection time (the critical cleaning time or CCT) is adopted.

CCT is set as the maximum duration of a fault, which does not result in loss of synchronism of one or more generators [9].

The minimum value of CCT is limited by the action time of the relay protection and the speed of the power circuit breakers.

Permissible conditions are such conditions at which the value of CCT exceeds the CCT limitation. Non-permissible conditions are such ones at which CCT is lower than the CCT limitation value. The application of DER cannot be higher than that which requires the use of relay protections and power circuit breakers with maximum speed of action (see Figure 5.2).

The above-described algorithm was used to explore the power system of the Baltic countries (Estonia, Latvia and Lithuania) with the connected parts of Northwestern Russia and Belarus.

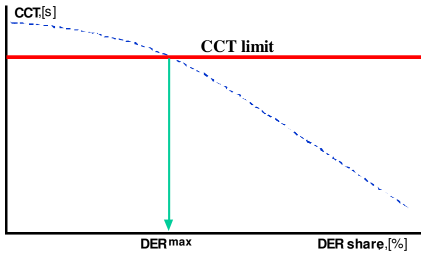

Figure 5.2. The maximum possible use of DER

### *5.3. The selected results*

**Description of the model**

The electric power networks of Estonia, Latvia, Lithuania, as well as their neighbours – Russia and Belarus – form an electric ring, which consists of 330 and 750 kV lines [10]. In the discussed integrated power system, the 750 kV network is not closed into a loop.

In this system, the most dangerous disturbance in terms of stability is a sudden interruption of the 750 kV line connecting the Leningrad substation and the Kalinin nuclear power plant (NPP).

If the 750 kV line is disconnected, then the electric power that used to flow over that power line before the emergency condition, will be immediately distributed among many other elements of the network, including lines with lower voltages. The 330 kV electrical network does not have a sufficiently high level of stability as to transmit considerably increased current values (as compared to the current value at pre-emergency conditions). In this way, an emergency disconnection of elements of the 750 kV network may result in loss of the stability of the 330 kV network.

For Monte-Carlo simulation, a list of the 110 kV units was prepared, to which it is possible to connect power networks with DER. The possible junctions with distribution power networks containing DER were placed in Estonia, Latvia, Lithuania, Belarus, and in Pskov Oblast (Russia), all in all approximately 130 junctions.

**The results of the simulation**

The interaction of transient processes in transmission and distribution networks may influence the stability of the transmission system both in a positive and in a negative way. Stoppage of DER generators may cause an increase or a decrease in the flow of electrical power in the transmission line, therefore, stabilization or destabilization of the system ensues.

In positive cases, if DER are located mainly at the input side of the transmission coridor (Figure 5.3.a illustrates this case).

The negative effect of CCT decrease was found within other simulations conducted in the present study. Such situations emerge in two cases: if the DER are situated mainly on the outlet side of the transmision corridor, and if the DER are uniformly distributed over the whole system. Figure 5.3.b shows the effect of the above-mentioned decrease.

To explain the above-described phenomenon, it is necessary to consider the dynamic behaviour of DER synchronous generators after damages in the transmission line.

DER units, due to their low capacity, are equipped with rotors with low mechanical inertia and are very sensitive towards damages that have originated in transmission lines. There are two types of DER reactions that influence the values of CCT:

- Stopping the operation of DER, performed by their protection system, by reacting to repeated voltage drops (fluctuations) in high-voltage lines;
- Out-of-step operation of DER generators as a result of considerable and sudden changes in the operating conditions of transmission networks. In such case, the syncronization of the system can be maintained by the large generators, yet this mode is dangerous to the DER themselves. Considering this fact, all the simulations performed by the DER synchronous generators were equipped with protections, which prevent conditions characteristic of modes with out-of-step operation.

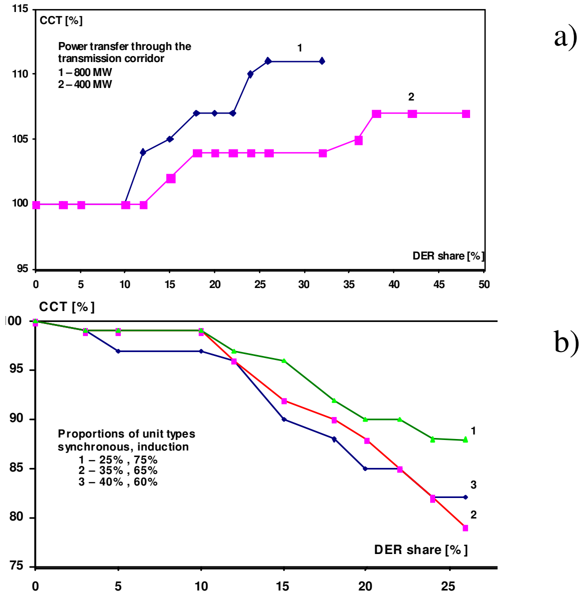


Figure 5.3. a) Conditions at which the CCT level increases, b) Conditions at which the CCT level diminishes

The boundary area of the acceptable states was determined at $IEA_{max}$ ≈ 25% from the total amount of energy to be generated by the future power system. This diminishes the value of CCT to 79% (with 100% return in production without DER). Figure 5.3 shows the clarified trends that differ from the above-mentioned percentages if the relation between synchronous and induction generators changes.

The boundary between an acceptable state and a non-acceptable one can be expanded by introducing one of these options:

- using fast-acting relays and power circuit breakers in transmission networks;
- application of new requirements in order to maintain the operation of DER at the conditions of decreased and increased voltage and frequency.

The latter option also ensures integration basis for the maintenance of the operation of transmission networks in island mode when the transmission and distribution networks are separated from each other.

## CONCLUSIONS

1. There is a wide variety of reasons why in power systems can happen and regularly happen large-scale accidents, which causes huge economic and social losses.
2. Risk management of power systems is a widely recognized task because of its importance yet has not been developed a uniformed and sufficiently substantiated methodology to solve it.
3. For a wide application, deterministic N-1 criterion has serious faults and imperfections. Its practical use creates situations in which is necessary to take subjective, poorly reasoned solutions. This criterion does not give chance to evaluate the behavior of the power system and operational automatics in cases of loss of stability.
4. Statistical-decision theory provides criteria of risk management –the mathematical expectation of function of advisability, which allows to describe optimization of power system management tasks in one-criterion statement, taking into account at the same time probability of adverse events, their consequences and the wish of the decision-maker to avoid big losses, even if they appear in very rare cases.
5. Approaches of reliability theory can be used for relief of calculating the tasks of determinate size of risks, with help of methods of this theory calculate the probability of adverse events as well.
6. Major difficulties are caused by evaluation of losses caused by accidents. Cost of undelivered energy cannot be the sole indicator of the risk management tasks. For description of loss assessment can be used rules of decision-making, verified in practice of projecting power objects.
7. Risk assessment is conjugated with sever difficulties caused by mathematic (large number of variables, complex structure and equations, need to calculate more current integrals) and information (existence of unspecified parameters, complexity of presentation of loss functions) indicators.
8. For risk assessment should be used a model of probabilistic power system and the Monte Carlo method.
9. Risk assessment requires primary (generators, transformers, lines, load,…) and secondary (relay protection, anti-accident automatic, …) modeling of power system.
10. Use of Monte Carlo method in tasks for risk assessment of power systems requires big expenses for calculation. To reduce them is possible to use specificity of the task and decline modeling of processes (normal mode) which are little informative.

11. For risk assessment should be used statistical dates about short circuits, equipment and system failures in power systems.
12. Algorithms of digital signal processing may be used for modeling analog equipment and that is why they are suitable for solving tasks of risks assessment.
13. Reaction detecting problems of RAPA equipment and consequently its models, can be divided into three parts:
    - Technical perfection that characterizes compliance of equipment for set targets under the conditions that it is in running order.
    - Safety that characterizes probability of equipment failure due to damage of elements.
    - Suitability for operating conditions which is characterized by probability of servicing personnel mishaps.
14. Modeling of technical perfection can be performed using models of different complexity. During modeling, can be used simplified input circuit models which characteristic curve due to technological advances are approaching to ideals.
15. To justify the use of models is required a methodology of validation of models. Validation of RAPA models may be performed by comparing the reaction of model and real equipment to the same input processes.
16. Even the most accurate RAPA technical perfection models do not reflect the safety and suitability of equipment for operating conditions.
17. Simulations of collapse of power systems can be performed using EUROSTAG software.
18. For calculations of collapsing processes is necessary to have models of automatics for preventing asynchronous run.
19. Simplified model of automatics for observing asynchronous run which does not use pre-calculated settings, gives accurate (from probabilistic approach view) results of calculations of collapsing processes of power system.
20. Use of alternative energy sources, placed next to consumers can reduce power and capacity, which is transmitted via high voltage or super-high voltage networks, thus saving capital investment for development and exploitation of networks, reimbursement of energy loss and maintenance of safety level.
21. Increasing the amount of distributed energy sources will increase their impact to stability in the overall size of power system. The impact can be positive and negative. In the common case will be necessary to use special automatic and limit power of dissipated sources.

22. Distribution network with IEA can have island regimes, provision of which reduces losses in cases of system collapses but their maintenance requires creation of special automatics.
23. For consolidation of islands in a single power system, can be used variety of approaches, one of which is close to the ones used during run of re-start of power system lines.

## BIBLIOGRAPHY


[1] Final Report on the August 14, 2003 Blackout in the United States and Canada. U.S.-Canada Power System Outage Task Force, April 2004/ Available at https://reports.energy.gov/

[2] Final report of System disturbance on 4 November 2006. UCTE, 2006. – 84 p./ Available at https://www.entsoe.eu/index.php?id=59

[3] Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy. UCTE, 2004. – 128 p./ Available at https://www.entsoe.eu/index.php?id=59

[4] Final report on the course of events of Power failure in Eastern Denmark and Southern Sweden on 23 September 2003. UCTE, 2003. – 24 p./ Available at http://www.energinet.dk/NR/rdonlyres/BC99F243-304D-4ADD-B769-46351A959C85/0/Powerfailurereportsept2003.pdf

[5] Makarov, Y.V. et al. Blackout Prevention in the United States, Europe, and Russia // Proceedings of the IEEE, Vol. 93, NO. 11, Nov. 2005. – p. 1942 – 1955

[6] M. DeGroot, "Optimal Statistical Decisions", McGraw-Hill Series in Probability and Statistics, 1970

[7] UCTE Operation handbook – Policy 3: Operational Security. UCTE, 2009/ Available at https://www.entsoe.eu/index.php?id=57

[8] W. Li, "Risk assessment of power systems: Models, methods, and applications" IEEE press series, 2005, 325 p

[9] Brian Stott, Ongun Alsac, Alcir J Monticelli. Security analysis and Optimization // Proceedings of IEEE. – Dec.1987. - vol.75, iss.12. – p.1633-1644

[10] Совалов С.А., Семенов В.А. Противоаварийное управление в энергосистемах. Москва: Энергоатомиздат, 1988. – 416 с.

[11] Task force on probabilistic aspects of reliability criteria, "Probabilistic security assessment for power system operations", IEEE PES General meeting Proc., vol.1, p.212-220, 2004

[12] IEEE PES CAMS, task force, “Initial review of methods for cascading failure analysis in electric power transmission systems”, IEEE PES General meeting Proc., Jul. 2004
[13] M.Groetaers dos Santos, M.T. Schilling, R. Billinton, “Bibliography on Power Systems Probabilistic Security Analysis 1968-2008”, The Berkeley Electronic Press: International Journal of Emerging Electric Power Systems, Vol.10, Iss. 3, Article 1, 2009
[14] I. Dobson, “Where is the edge for cascading failure?: challenges and opportunities for quantifying blackout risk”, IEEE PES General Meeting Proc., p.1-8, June 2007
[15] J. Barkans, D. Zalostiba, “Protection against Blackouts and Self-Restoration of Power Systems”, Riga, RTU Publishing House, 2009, p. 142
[16] CIGRE TF 38.03.12 (R. J. Marceau and J. Endrenyi, Chairmen), “Power system security assessment: A position paper,” Electra, no. 175, pp. 48-78, Dec. 1997
[17] EUROSTAG Release 4.2 Package Documentation, October 2002
[18] Bondarenko A., Gerikh V., Kreslins V. N-1 reliability criterion interpretation // Proceedings of CIGRE 2006, C2-106
[19] G.A. Korn and Th.M. Korn. Mathematical handbook for Scientists and Engineers: Definitions, Theorems and Formulas for reference and Review. Second, Enlargend and revised edition. McGraw-Hill Book Company, 1968.