Flexible Power Distribution Networks: New Opportunities and Applications

Konstantin Suslov[1][a], Ilia Shushpanov[1][b], Nadezhda Buryanina[2][c] and Pavel Ilyushin[3][d]
[1]*Irkutsk National Research Technical University, Irkutsk, Russia*
[2]*Chukotka branch of North-Eastern Federal University, Anadyr, Russia*
[3]*Petersburg Power Engineering Institute of Professional Development, Saint-Petersburg, Russia*

Keywords: Power Distribution Network, Reliability, Survivability, Relay Protection and Automated Systems, Adaptive Setting, Overhead Power Line, Microprocessor Measuring Device, Information Communication Network, Flexibility.

Abstract: Today, electricity companies worldwide use digital devices. Their use is commonplace in the grid, whether it is electricity generation, transmission or distribution. Power distribution networks are the most widespread but are the least digitalized because they have to deal with the problems related to the collection of necessary information, the adaptation methods, failures to identify some emergencies and their effect, and the insufficient number of reliability assessment methods. These networks were not important for energy companies and they did not pay attention to them. Nowadays, however, there is a need to pay special attention to these networks. Insufficient attention to them has led to delay in their digitalization and today there are some issues to work on. For example, improper placement of devices leads to a lack of complete and reliable information, which is the reason why relay protection and automatic systems in distribution electrical networks do not provide selectivity. An algorithm is proposed to site measuring devices so that information is collected most effectively. The proper installation of the devices will allow adjusting the operating parameters of the relay protection and automatic systems depending on changes in external weather conditions and fluctuations in power consumption in the network. It will also help to determine the best network topology. The paper proposes a technique for distribution network control, which takes into account the type of failure in case of emergency in real time, and a method to locate measuring devices and establish an information and communication network.

1 INTRODUCTION

Recently, it has been possible to use high-tech intelligent devices that are capable of implementing the most modern and effective algorithms for the operation of relay protection and determining the fault location of power lines. The use of microprocessor devices allows controlling energy systems, as well as electrical energy distribution systems. By adopting standard IEC 61850 relay protection and emergency control (RPEC) receiving more information not only on measuring instruments and sensors, but also on other RPEC devices. Such devices are able to work with a wide information base, and therefore the problem of developing new relay protection algorithms is becoming increasingly more relevant. At present, relay microprocessor-based protection systems must be intelligent and able to adapt and learn. Sometimes, the operation of the RPEC devices may function incorrectly if their settings do not reflect the real state of the monitored overhead power line (OPL). It is important to specify the OPL parameters to accurately determine the settings of relay protection using simulation models. Therefore, the development of a relay protection system with adaptive response setting depending on

[a] https://orcid.org/0000-0003-0484-2857
[b] https://orcid.org/0000-0001-7121-7651
[c] https://orcid.org/0000-0001-8806-1817
[d] https://orcid.org/0000-0002-5183-3040

Suslov, K., Shushpanov, I., Buryanina, N. and Ilyushin, P.
Flexible Power Distribution Networks: New Opportunities and Applications.
DOI: 10.5220/0009393300570064
In *Proceedings of the 9th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2020)*, pages 57-64
ISBN: 978-989-758-418-3

changes in external conditions in distribution overhead power transmission lines a relevant task. This is extremely important for the distribution network survivability.

2 CURRENT STATE OF THE PROBLEM

Analysis of the operating modes of power distribution networks is one of those tasks that are important in the design and operation of electrical systems. In this case, the analysis of the steady state of the electrical system has a significant role.

The radial configuration is typically used for medium and low voltage power distribution networks. For example, urban networks can be either loopback or ring. But under normal conditions, due to technological features, they work as radial.

A feature of the classical radial electric network is the assumption that it receives power from only one point, which is called the source node. And under these conditions, there is a unidirectional flow in any state of the network.

Analysis of the operation modes of radial electric networks is much simpler. If you give the activity of the power distribution network, then the radial structure can both be preserved and broken. In such a scenario, when power distribution networks operate as non-radial, it is very difficult to analyze operating modes and requires special attention.

The notion of active power distribution network is considered in (Voropai (a), 2013, Mokryani, 2017, Xie, 2018, Ghadi, 2019, etc.) on the basis of existing concepts (McDonald, 2008, Celli, 2012). It is necessary to clarify and detail it as follows. The activity of the power supply system implies the use of automatic devices to control configuration and parameters of the system with the view to rationally (optimally) meet the requirements for economic effectiveness of normal, maintenance, post-emergency and other, reliability of power supply to consumers. The control actions can be implemented by disconnectors (Begovic, 2013).

In our opinion, the activity of power supply systems is understood to mean their ability to automatically self-recover the circuit and maintain the required values of the mode parameters by the action of the corresponding control systems for distributed generation units and reconfiguration of power distribution network (Suslov, 2015, Shushpanov, 2019).

The model of the power distribution network control is based on the reliability model (Voropai (b), 2013). Formalization of the problem of choosing a rational configuration of power supply system is presented in (Svezhentseva, 2012). Mathematical models and methods of the complex optimization of the power supply system structure and parameters, considering, in particular, the distributed generation, are mainly addressed in the publications by researchers (Khator, 1997, Georgilakis, 2015, Conte, 2019, Ehsan, 2019, Ilyushin, 2019, etc.).

It is very important to consider the security of the power supply system. The security of the power supply system as well as the security of the entire electric power system is understood as an ability of the system to maintain an acceptable state in case of changes in operating conditions, component failures, and sudden disturbances (Reliability Concepts, 1985).

Methods for estimating the security of the power supply system are presented in a great number of publications (Balu, 1992, Marceau, 1997, Endrenyi, 1978, Jiyan, 2009, Billinton, 1996,etc.). Earlier the object of these methods was a passive power distribution network, which electricity was supplied to the power supply system from power supply points in the main network of the electric power system. Use of modern multifunction switching devices, development of protection and automatic systems, and the necessity to coordinate their operation have significantly altered the response of the distribution electric network to the changes in operating conditions, failures of components, and sudden disturbances owing to the automatic measures (reconfiguration of the network) and thus have made the flexible network. In a sense, the power distribution network becomes capable of self-healing, i.e., capable of automatically restoring power supply to consumers to the maximum in minimum time (Nepomnyashchy, 2011).

The considered feature of activity of the power distribution network should be taken into account in the security model of the flexible distribution network.

3 MODEL OF THE FLEXIBLE POWER DISTRIBUTION NETWORK CONTROL

The basis is taken the traditional model of the power distribution network reliability. This model has the following basic principles. (Shushpanov, 2019):

• As initial reliability indicators for each main component of power systems (lines, transformers, etc.), the parameters of the failure flowλ rate and the restoration rate of the component μ. are used.

• Based on them, on the assumption that the failure (restoration) flow has the Markov property, that is λ= const and μ = const, the well-known formulas are used to determine the probability of failure, the failure rate and the component restoration time.

• Based on the indicated indices of network components, the average failure rate, average failure duration and average system availability ratio are calculated.

• Failures of protection devices and circuit breakers, are taken into account indirectly in the values of the failure flow parameters and the restoration rates of the main components.

In the study of flexible active distribution systems, we propose to use the following methodology for research. The flow chart of the algorithm for analyzing the reliability of flexible power distribution networks is represented in Fig. 1.

As an example, let consider the power distribution network. Based on this scheme, it is possible to demonstrate how reliability factors in relation to an active distribution network are taken into account in the model.

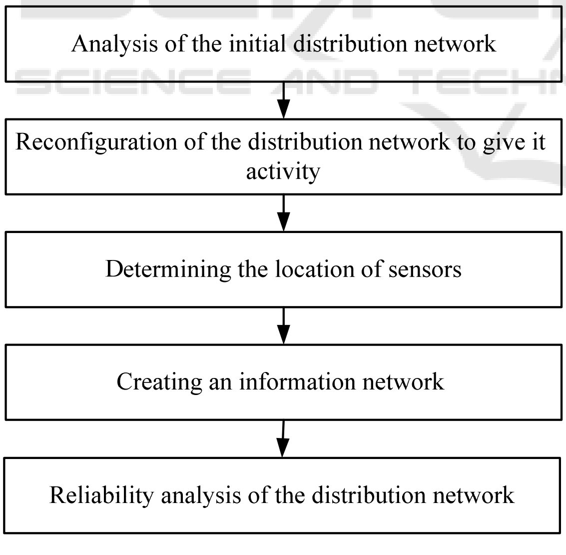

Figure 1: Flow chart of the algorithm for analysing the reliability of flexible distribution networks.

Fig. 2 represents initial scheme of the power distribution network. Distribution network voltage is 10 kV This network powered by two different sources - C1 and C2. Voltage of tis sources is 110 kV. The distribution network supplies power to 15 busses

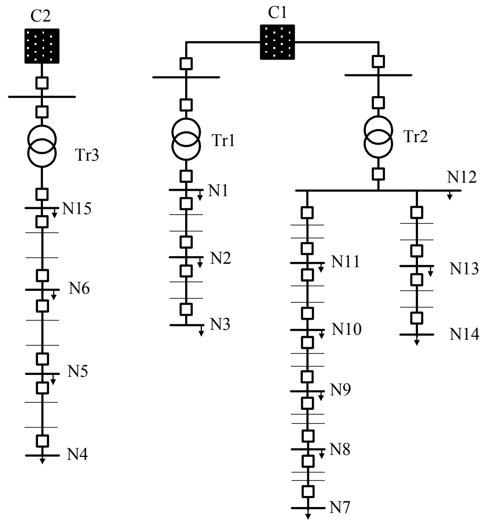

Figure 2: Initial scheme of the power distribution network.

indicated as N1-N15 in the Figure. Transformers, transmission lines, and load feeders are connected to the scheme by circuit breakers.

The goal of this concept is to reconstruct the network with its transfer to “active power distribution network” from “passive power distribution network” using additional switching devices (in the figure, these lines are marked with an X). In this case, new nodes appear in the power distribution network.

The reconstructed scheme of power distribution network with operating areas is shown in Fig. 3. It should be noted that this distribution network in normal mode operate as a radial one. Under normal mode, redundant lines are disconnected.

In this research we use the concept of an “Operating area” (Voropai (a), 2013, Shushpanov, 2019). Using this concept makes the power distribution network controllable and flexible. When we using this concept, all relay protection devices installed directly on the circuit breakers are combined into one common system and exchange data with each other. This position corresponds to standard IEC 61850.

The need to introduce operating zones is caused by the logics of the switching devices operation. The operating zones are formed on the basis of network structure and represent a set of components that are grouped according to the functions determined by the principles of switching devices operation. It should also be noted that operating areas are formed on the basis of the structure and topology of the power distribution network.

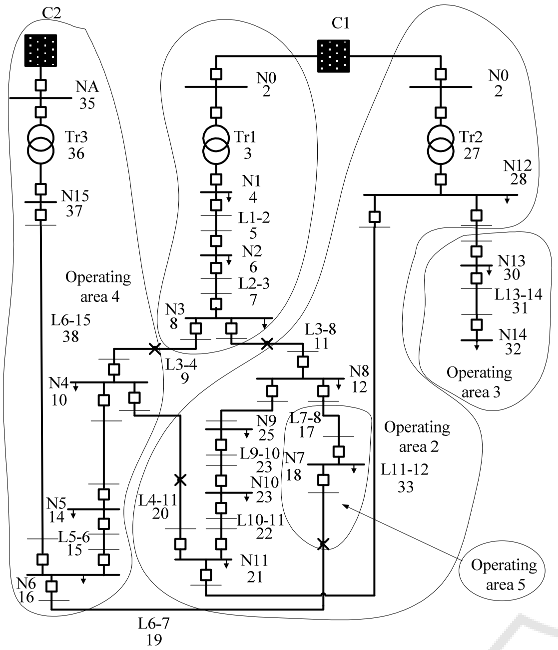

Figure 3: Reconfigured distribution network with operating areas.

Consider the principles of operation and the principles of switching in the presented operating areas of the distribution network. This principlies based on papers (Voropai (a), 2013Shushpanov, 2019).

Operating Area No.1. (Fig.3) In that case, if the transformer Tr1 fails, the backup line L3-4 (component No.9) is switched on in this operating area. In this case, a change in the power point and reconfiguration of the power distribution network occurs. For example, another case is possible. A short circuit occurs on line L1-2 (component No.5) ,. In this case, it is disabled by overcurrent protection. Then the redundant line L3-4 is automatically switched and this provides power to consumers connected to the buses N2 (component No.6) and N3 (component No.8). In the same way, if a short circuit occurs in the line L2-3 and it is disabled by the overcurrent protection, the automatic connection of the redundant L3-4 line provides power to consumers connected to the bus N3. In an emergency event and loss of power on the bus N3, an additional redundant line L3-4 is not connected. In this case, when the L2-3 line is disconnected, power to consumers connected to the N1 and N2 buses can be provided from source C1 using the line L 3-4.

Operating Area No. 2. In this area, reconfiguration is performed in the same way: in case of an accident, line L3-8 is automatically turned on, in which power is supplied to consumers connected to busses N8 (component No.12)., N9 (component No.25)., N10 (component No.23)., and N11(component No.21). In the case that bus N8 fails, the backup line L3-8 (component No.11). is not switched on but power supply to the other consumers is provided by the main source C1.

Operating Area No. 3. In this area, the power distribution network is not reconfigurable, since there is no technical possibility due to the radial structure of the network.

Operating Area No. 4. In this work area, automatic switching occurs similarly to control in operating areas No. 1 and No. 2. In case of failures in this zone, the redundant line L4-11 (component No.20) is used.

Operating Area No. 5. In this area, the power distribution network is reconfigured similarly to the previous zones considered. In this case, automatic switching on of the line L6-7 (component No.19) is used.

This methodology allows for the control of the overcurrent protection in the lines and the undervoltage protection at the power buses in active power distribution networks. Thus, the presented methodology makes it possible to make the power distribution network flexible, as well as increase the reliability.

4 A MODEL OF PLACEMENT OF SENSORS IN THE POWER DISTRIBUTION NETWORK

Traditionally, power distribution networks have a rather low level of automation. This networks are often equipped with switching devices that can only be controlled manually. If one adds control drives to the disconnectors, it will be possible to control them remotely, the price of disconnectors increases. For these disconnectors the need to create a control system. In the above text, a method of the power distribution network control based on flexibility was proposed. This method can also be applied to the network with disconnectors. However, then the question arises for the relay protection devices, how to determine certain failures and emergency situations. Installation of sophisticated microprocessor-based protection devices will cost too much, however a solution to this problem is the option of creating an information communication network with sensors (Shushpanov, 2019).

Traditionally, sensors are used for power distribution networks to obtain information about the current state of the network. There are many studies on this issue (Krajnak, 2000, Grilo, 2010, Suslov, 2011, Gavrilov, 2019, Bulatov, 2017, etc.). In this case, the sensors are used to give flexibility to the power distribution network in post-emergency situations. As such devices we used IKI-Overhead fault indicators intended for detection of faults on overhead power distributions lines. These indicators transmit information using GSM and easily fit into the IEC 60870 standard. Indicators are installed directly on the wires without additional mounting devices. According to the control model of the power distribution network, all switching devices are integrated into one information-switching network with a common control center. Information from IKI indicators is transmitted to this center. Figure 4 shows the network, in which the sites for installation of these indicators are shown by circles (Shushpanov, 2019). These devices can determine the following parameters: short circuit, single-phase fault to ground, overhead line break, and maximum load of the overhead line.

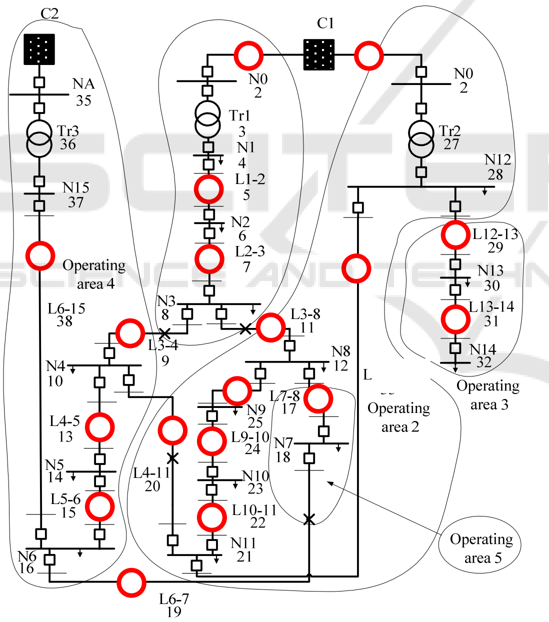

Figure 4: Power distribution network with places for installation of current and voltage sensors.

Thus, superimposing the control model of the power distribution network over the model of installation of the state monitoring sensors, we can say that the power distribution network is made flexible because monitoring of the network parameters makes it possible to redistribute the load, isolate the faulty section, and maintain power supply to the consumer (Shushpanov, 2019).

These sensors can transmit information to the control center. In the case of a massive outage due to strong winds, however, it is also necessary to check the information network for the ability to transmit all information over the information network.

Currently, various indicators are used that characterize different aspects of the reliability of electric power systems and power supply to consumers (Billinton, 1996): System average Interruption Frequency Index (SAIFI), customer average interruption frequency index (CAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), average system availability index (ASAI), etc.

A widespread index of power supply system security is risk. The risk is defined as the sum of the probabilities of the sequence of events on the value of effects resulting from each event, usually in the form of power shortage or undersupply of power (McCalley, 1999, Li, 2005). At the same time, the risk is also assessed the implementation of various measures to improve the operational reliability of the power supply system (Schwan, 2012, McDonald, 2006). In paper (Hua, 2008), a formula is given for an integral risk assessment taking into account all the factors considered.

If in the final post-emergency state as a result of the considered cascading failure the steady-state conditions are admissible, we estimate power shortage in the system and its probability. Based on the obtained information, we calculate the risks for the analyzed state of the power supply system.

In this case, the probabilities of the system states as a result of complex failures are determined using the known equation (Billinton, 1996):

$$p_k(D_k) = \sum_{i,j} \prod_i q_i \prod_{j \neq i} p_j \ , \tag{1}$$

where $p_k(D_k)$ probability of power shortage equal to D_k in the considered state k of the power supply system; p_j is the probability of failure-free operation of component j or its protection; q_i is the failure probability of component i or its protection; *i, j* are the numbers of power supply components.

The paper (Voropai (a), 2013) presents a methodology for risk assessment.

The conventional approach to the risk termination during the estimation of the power supply system security is represented by the equation (Billinton, 1996) :

$$R_k = \sum_k p_k(D_k) \cdot D_k \tag{2}$$

However, the equation (2) does not consider the severity of power shortage consequences for different categories of consumer loads. Taking into account the fact that security is estimated for a certain time point, at which a sudden power shortage may occur, we can determine the severity of consequences on the basis of specific losses caused by sudden power shortage $y_{int\,l}$. Modern estimates of $y_{int\,l}$ for different types of consumer loads can be assumed in accordance with paper (McDonald, 2006). Thus, the modified equation for risk determination during security estimation will have the following form:

$$R_{ky} = \sum_{k=1}^{K} p_k(D_k) \cdot \sum_{l=1}^{n} D_l y_{int\,l} \tag{3}$$

where n is the number of nodes in the scheme of the power supply system, K is number of states of the power supply system.

Obviously, the number of states K of the power supply system is determined by the total number of primary failures of the scheme components, i.e. lines, transformers, distributed generation sources. By correlating the risk assessments with specific components of the scheme, one can identify the network weaknesses in terms of security and based on this information make recommendations on the measures to increase it.

Figure 5 presents the calculation results of security risk indices for the initial scheme using the formula for risk determination when assessing the power supply system security taking into account specific damages caused by sudden power shortage of consumers and probabilities of the power shortage in the considered state of the power supply system.

In this case the failure probabilities of the primary components (transmission lines, transformers, buses), as well as circuit breakers and protection devices are assumed in accordance with (Voropai (a), 2013). The values of specific damages caused by power supply interruption as a function of the structure of consumers in the considered power supply system are applied according to (Voropai (b), 2013).

The diagram in Fig. 5 shows that the failures of buses 8, 10, 12, 14, transformers 34 and particularly 15 are dangerous from the security standpoint. The highest risk value at the failure of transformer 15 is conditioned by the fact that source C2 supplies power to more essential consumers than source C1, with the high values of specific damages. The zero risk values for components 7, 16, 17, 21 are explained by the absence of these backup transmission lines in the initial power supply system.

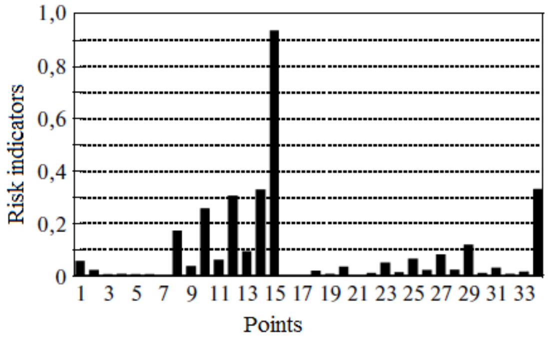

Figure 5: The diagram of risk indices for the initial scheme.

Figure 6 presents the estimates of security risk indices for the reconfigured power supply system scheme (Fig. 3) for the same initial data.

It is assumed that the disconnector operations on connection of the backup transmission lines are performed effectively and that their accuracy is high, though there is no concrete data as yet. It should be noted that the transmission line failure at its connection is practically improbable, the disconnectors failures due to connection of backup transmission lines will lead to the results identical for the initial scheme.

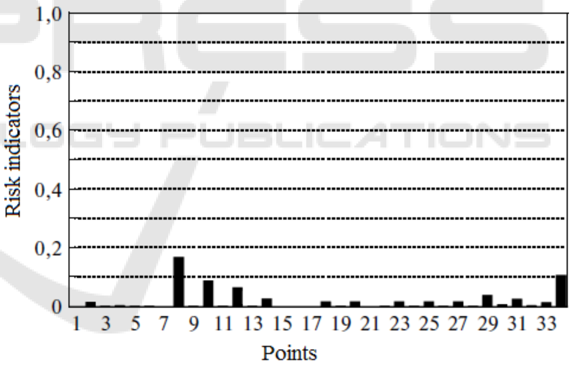

Figure 6: The diagram of risk indices for the power reconfigured network.

The diagram of the risk indices in Fig. 6 shows a high efficiency of the active (in the considered sense) power distribution network for the power supply system security improvement.

Further, system reliability indicators for the entire distribution network were calculated. The calculations were carried out taking into account the network operation mode and protection.

System average Interruption Frequency Index (SAIFI):

$$\omega = \frac{\sum_{i \in I}(\omega_i)}{I}, \tag{4}$$

where I - the number of nodes with loads in the system,

ω_i - failure rate in the i-th node, $i = \overline{1, I}$.

System average interruption duration index (SAIDI):

$$t_B = \frac{\sum_{i \in I}(t_{Bi})}{I} \quad , \qquad (5)$$

where t_{Bi} – power recovery time in the i-th node.

Average system availability index (ASAI):

$$k_r = \frac{\sum_{i \in I}(p_i)}{I} \quad , \qquad (6)$$

where p_i – probability of failure in the i-th node.

Calculations using sensors for the power distribution network and without using sensors were performed. The results are presented in Figure 7.

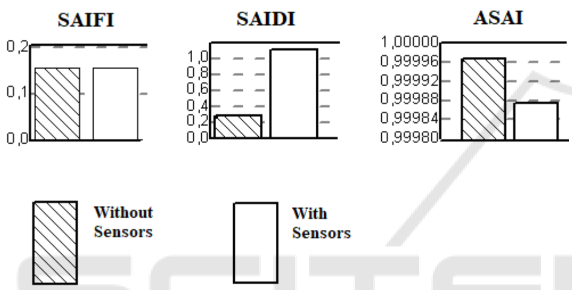

Figure 7: The diagram of system reliability indicators for the entire power distribution network

Calculation results shows a high efficiency of the use of sensors to give activity and flexibility to the power distribution network.

5 CONCLUSIONS

The correct location of the sensors is very important to give the network activity and its flexibility. It is also very important from the point of view of economic feasibility.

The use of new principles of operation in power distribution networks; the use of advanced multifunctional switching devices; the development of protection and automated control systems as well as the need to coordinate their work have led to a change in the principles of emergency control measures towards their automation for reconfiguring the power distribution network and making it flexible when responding to equipment failures and emergencies.

The paper presents distribution network control models that provide the flexibility of such networks and increase the reliability of energy supply.

To ensure maximum efficiency of the power distribution network, the authors proposed a technique for placing network status sensors in such a network.

A technique is developed to create an electrical complex of relay protection for power distribution system. The technique is based on the information communication technology of data transfer and exchange based on IEC 61850.

ACKNOWLEDGEMENTS

The study was carried out with the financial support of the Russian Foundation for Basic Research and the Subject of the Russian Federation - the Republic of Sakha (Yakutia) № 18-48-140 010.

REFERENCES

Voropai, N., Styczynski, Z., Shushpanov, I., Pham Trung Son, Suslov, K., Security model of active distribution electric networks. *Thermal Engineering Vol. 60, Issue 14, 2013, pp. 1024-1030*

Zeng, B., Wen, J., Shi, J., Zhang, J., Zhang, Y.,A multi-level approach to active distribution system planning for efficient renewable energy harvesting in a deregulated environment. *Energy, Volume 96, February 2016, pp. 614-624*

Mokryani, G., Hu, Y., Pillai, P., Rajamani, H.-S., Active distribution networks planning with high penetration of wind power. *Renewable Energy, Volume 104, April 2017, pp. 40-49*

Xie, M., Ji, X., Hu, X., Cheng, P., Liu, M., Autonomous optimized economic dispatch of active distribution system with multi-microgrids, *Energy, Volume 153, 15 June 2018, pp. 479-489*

Ghadi, M., Rajabi, A., Ghavidel, S., Azizivahed, A., Li, L., Zhang, J. From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors, *Applied Energy, Vol. 253, November 2019, pp. 113543*

McDonald, J., Adaptive intelligent power systems: Active distribution networks, *Energy Policy, Vol. 36, No. 6, 2008, pp. 4346-4351.*

Celli, G., Giani, E., Soma, G.G., Pilo, F., Planning of reliable active distribution systems, *44th Session CIGRE 2012, Paris, France.*

Begovic, M.M. (ed.), *Electrical Transmission Systems and Smart Grids: Selected Entries from the Encyclopedia of Sustainability Science and Technology,* Springer Science+Business Media New York 2013.

Voropai, N., Styczysnki, Z., Shushpanov, I., Suslov, K., Mathematical model and topological method for reliability calculation of distribution networks, In *2013 IEEE Grenoble Conference PowerTech, POWERTECH 2013.*

Suslov, K., Gerasimov, D., Solodusha, S. Smart grid: Algorithms for control of active-adaptive network components, In *2015 IEEE Eindhoven PowerTech, PowerTech 2015*

Shushpanov, I., Suslov, K., About Flexibility Problem of Distribution Electrical Network, In Proc. *2019 EPJ Web of Conferences 217, 01014*

Krajnak D. J., Faulted Circuit Indicators and System Reliability, *Rural Electric Power Conference, 2000*

Grilo, A., Casaca, A., Nunes, M., Fortunato, C., Wireless Sensor Networks for the Protection of an Electrical Energy Distribution Infrastructure, In *International Conference CIP 2010, Springer, pp. 373-383,*

Suslov, K.V., Solonina, N.N., Smirnov, A.S., Smart Grid: A new way of receiving primary information on electric power system state, In *2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, ISGT Europe 2011*

Gavrilov, D., Gouzman, M., Luryi, S., Monitoring large-scale power distribution grids*, Solid-State Electronics Vol. 155,May 2019, pp. 57-64*

Bulatov, Y.N., Kryukov, A.V., Suslov, K.V., Multi-agent technologies for control of distributed generation plants in the isolated power systems, *Far East Journal of Electronics and Communications, Vol. 17(5), 2017, pp. 1197-1210*

Svezhentseva, O., Voropai, N., Optimization of supply source allocation in the problem of rational configuration of electricity supply system, In *2012 IEEE PES Innovative Smart Grid Technologies Conference Europe 2012, Berlin, Germany.*

Khator, S., Power distribution planning: A review of models and issues, *IEEE Transactions on Power Systems, Vol.12, No.4, 1997, pp. 1151-1159.*

Georgilakis, P., Hatziargyriou, N., A review of power distribution planning in the modern power systems era: Models, methods and future research, *Electric Power Systems Research, Vol.121, No.2, 2015, pp.89-100.*

Conte, F., D'Agostino, F., Silvestro, F., Operational constrained nonlinear modeling and identification of active distribution networks, *Electric Power Systems Research, Volume 168, March 2019, pp. 92-104*

Ehsan, A., Yang, Q., State-of-the-art techniques for modelling of uncertainties in active distribution network planning: A review, *Applied Energy, Volume 239, 1 April 2019, pp. 1509-1523*

Ilyushin, P., Suslov, K., Operation of automatic transfer switches in the networks with distributed generation, In *2019 IEEE Milan PowerTech, PowerTech 2019*

Reliability Concepts in Bulk Electric Power Systems (North American Electric Reliability Council, New York, 1985).

Balu N., Bertram T., Bose A., Brandwajn V., e.a., On-line power system security analysis, *Proceedings of the IEEE*, *Volume 80, No. 2, 1992, , pp. 682-699.*

Marceau R.J., Endrenyi J., Allan R., Alvarado F.L., e.a., Power system security assessment: A position paper, *Electra, 1997,No. 175, pp. 77-91.*

Endrenyi J., *Reliability modeling in electric power systems.*Yohn Wiley and Sons, 1978, 326 p.

Jiyan F., Borlase S., The evolution of distribution, *IEEE Power and Energy Magazine, 2009, Volume 7, No. 2, pp.37-43.*

Billinton, R. Allan, R., *Reliability Evaluation of Power Systems.* Plenum Press, New York, NY, 1996

McCalley, J.D., Vittal, V., Abi-Samra, N., An over view of risk based security assessment, *IEEE PES Summer Meeting, Edmonton, Canada, July 18-22, 1999.*

Li, W., *Risk assessment of power systems: Models, methods and applications*. N.Y.: John Wiley and Sons, 2005.

Schwan, M., Ettinger, A., Gunaltay, S., Probabilistic reliability assessment in distribution network master plan development and in distribution automation implementation, *CIGRE, 2012 Session, Paris, France, August 26-30, 2012, Rep. C4-203.*

McDonald, J.D.F., Pal, B.C. Representing the risk imposed by different strategies of distribution system operation. In *IEEE PES General Meeting, Montreal, Canada, 2006*

Hua X.-Y., Wan, Q.-L., Wang, L., Security assessment of power systems based on entropy weight-based gray relational method, *IEEE PES General Meeting, Pittsburgh, USA, July 20-24, 2008.*

Nepomnyashchy V.A., Economic and mathematical model of reliability in electric power systems and electric networks, *Elektrichestvo, 2011, No. 2, pp. 31-37 (in Russian).*