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Post-emergency reconfiguration of a distribution network as a method for restoring power supply to consumers

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Abstract. The work is aimed at solving the problem of using reconfiguration and additional reactive power sources to restore power to consumers of the medium-voltage distribution network in the case of emergency disconnections of connections by bus section circuit breakers. The reconfiguration problem for a 118-node test distribution network is solved using a high-speed algorithm involving the construction of a maximum spanning tree on a network graph as the basis for determining information about the composition of branches and chords of independent circuits necessary to restore power following disconnection. To ensure acceptable voltage levels following power restoration, additional reactive power sources determined using singular Jacobian matrix analysis methods are installed in the sensor nodes of the network. For the test circuit, the modes for single disconnections of individual sectional switches, including in dead-end sections, are analysed. By optimally reconfiguring the network in the normal mode, it is possible to reduce voltage deviations from 13% to 7%. For the modes caused by disconnections of individual bus section circuit breakers that lead to unacceptable voltage deviations, the set-down locations and reactive power of additional sources are selected. In the most severe of the considered disconnection scenarios, the installation of additional sources provided a reduction in voltage deviations from 18 to 8%. Thus, the methods proposed by the authors make it possible to restore the test network mode following emergency disconnections and ensure that the voltages in the network nodes are maintained within acceptable limits, both in normal and in post-emergency modes.

Keywords: distribution network, resilience, reconfiguration, supply restoration

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ЭНЕРГЕТИКА

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Послеаварийная реконфигурация распределительной сети как способ восстановления электроснабжения потребителей

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Резюме. Цель – проведение исследований, направленных на решение проблемы использования реконфигурации и дополнительных источников реактивной мощности для восстановления питания потребителей распределительной сети среднего напряжения при аварийных отключениях связей с секционными выключателями. Проблема реконфигурации для 118-узловой тестовой распределительной сети решается с использованием быстродействующего алгоритма, заключающегося в построении на графе сети максимального покрывающего дерева и определения на его основе информации о составе ветвей и хордах независимых контуров, необходимой для восстановления питания после отключения связей. Для обеспечения допустимых уровней напряжений после восстановления питания производится установка дополнительных источников реактивной мощности в сенсорных узлах сети, определяемых методами сингулярного анализа матрицы Якоби. Для тестовой схемы проанализированы режимы при единичных отключениях отдельных секционных выключателей, в том числе и в тупиковых секциях. Показано, что оптимальная реконфигурация сети в нормальном режиме позволила уменьшить отклонения напряжений с 13 до 7%. Для режимов, вызванных отключениями отдельных секционных выключателей, которые приводят к недопустимым отклонениям напряжения, выбраны места размещения и реактивные мощности дополнительных источников. В наиболее тяжелом из рассмотренных сценариев отключения связей установка дополнительных источников обеспечила снижение отклонений напряжений с 18 до 8%. Таким образом, предлагаемые авторами методы позволяют восстановить режим тестовой сети после аварийных отключений связей и обеспечить поддержание напряжений в узлах сети в допустимых пределах, как в нормальном, так и в послеаварийном режимах.

Ключевые слова: распределительная сеть, отказоустойчивость, реконфигурация, восстановление электроснабжения

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INTRODUCTION

A distribution network represents an important link in an electric power system for connecting power sources to end consumers. One of its most significant functions is the ability to restore operating conditions during emergency disconnections of individual branches and multiples thereof. Three major approaches to enhancing resilience are: strengthening distribution poles in critical lines [1]; network reconfiguration [2]; penetration of distributed energy resources [3]. When solving the problem of power supply restoration, it is necessary to factor in the operational and technical limitations associated with the need to maintain the radial configuration of the network, with feasible feeder sections currents and nodal voltages levels [4].

The methods used to restore power supply to consumers can be conditionally divided into three groups: those based on graph theory, those relying on artificial intelligence technologies, and those using expert systems [4].

RECONFIGURATION ALGORITHM USING THE MAXIMUM SPANNING TREE METHOD

Numerous reconfiguration algorithms, reconfiguration criteria and constraints have been developed. Among the various reconfiguration criteria, heuristic optimization algorithms are most commonly used. These include genetic algorithms [5, 6], tabu search algorithms [7], ant colony algorithms [8, 9], harmony search algorithms [10] and particle swarm optimization algorithms [11]. However, the complexity of present-day heuristic algorithms hinders their real-time application, especially when applied to large systems.

The algorithm used in the present paper is based on graph theory [12–14]. The reconfiguration of a distribution network generally involves opening normally closed sectional bus section circuit brekers and closing normally open line switches. At the beginning of the first step of the algorithm, all line switches are assumed to be closed. At each iteration of the first stage, the number of which is equal to the number of independent circuits, the power flow is calculated, the maximum spanning tree is constructed (the weights of its branches represented by the magnitudes of currents flowing through them), and the chord with the minimum current is opened. The optimal composition of the line switches will provide the minimum currents in the spanning tree chords.

At the second stage of reconfiguration, each of the chords opened at the first stage is sequentially closed and to determine the set of branches of the circuit associated with the chord. After sequentially opening the branches of this set, the power flow is calculated and the total losses determined. The chord whose opening corresponds to the minimum losses, is optimal. Thus, the minimum value of power losses in the distribution network is ensured.

RECONFIGURATION OF THE TEST DISTRIBUTION NETWORK

For illustrative purposes, let us reconfigure a distribution network consisting of 118 nodes, 132 branches, and 15 line switches (Fig. 1). The total power loads are 22 709.7 kW and 17 041.1 kVAR. The parameters of the equivalent circuit elements and the load are taken from [15].

The optimal composition of line switches corresponding to the chords of the new spanning tree is determined using the fast-acting steady-state calculation program SDO-7. The

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composition of the line switches and their corresponding independent circuits of the original and optimal schemes is given in Table 1.

Assuming the voltage at the power node S1 equal to 11 kV, we compare power losses in the network for its three states: initial, with closed line switches, and after reconfiguration. An analysis of the steady state showed that for the original network, the losses amounted to 1 298.54 kW; for the closed network – 819.67 kW; for the network following reconfiguration – 887.48 kW. Thus, a power loss value close to the minimum losses in a closed network was achieved.

The minimization of power losses additionally affected the value of nodal voltage in the network. Taken as the nominal voltage of the power source, the deviation of the nodal voltage from the voltage value reaches 13% (9.57 kV) for the initial network configuration, significantly exceeding the standard values. After determining the optimal composition of line switches, the deviations of the nodal voltage do not exceed 7% (10.23 kV).

A further increase in the voltage levels in the network can be achieved, for example, by increasing the voltage of the power source, connecting additional active and (or) reactive power sources, managing the demand of load-controlled consumers, or by combining these measures.

RESTORATION OF OPERATING CONDITIONS AFTER AN EMERGENCY DISCONNECTION OF TIE LINES

The main purpose of reconfiguration in case of emergency shutdown of the bus section circuit breaker is to restore power supply to the maximum number of consumers by closing the line switch. Since the same branch of the spanning tree can be included in several circuits, the operating conditions in the case of an emergency tripping of the bus section circuit breaker can be restored by switching on any of the line switches connected with these circuits.

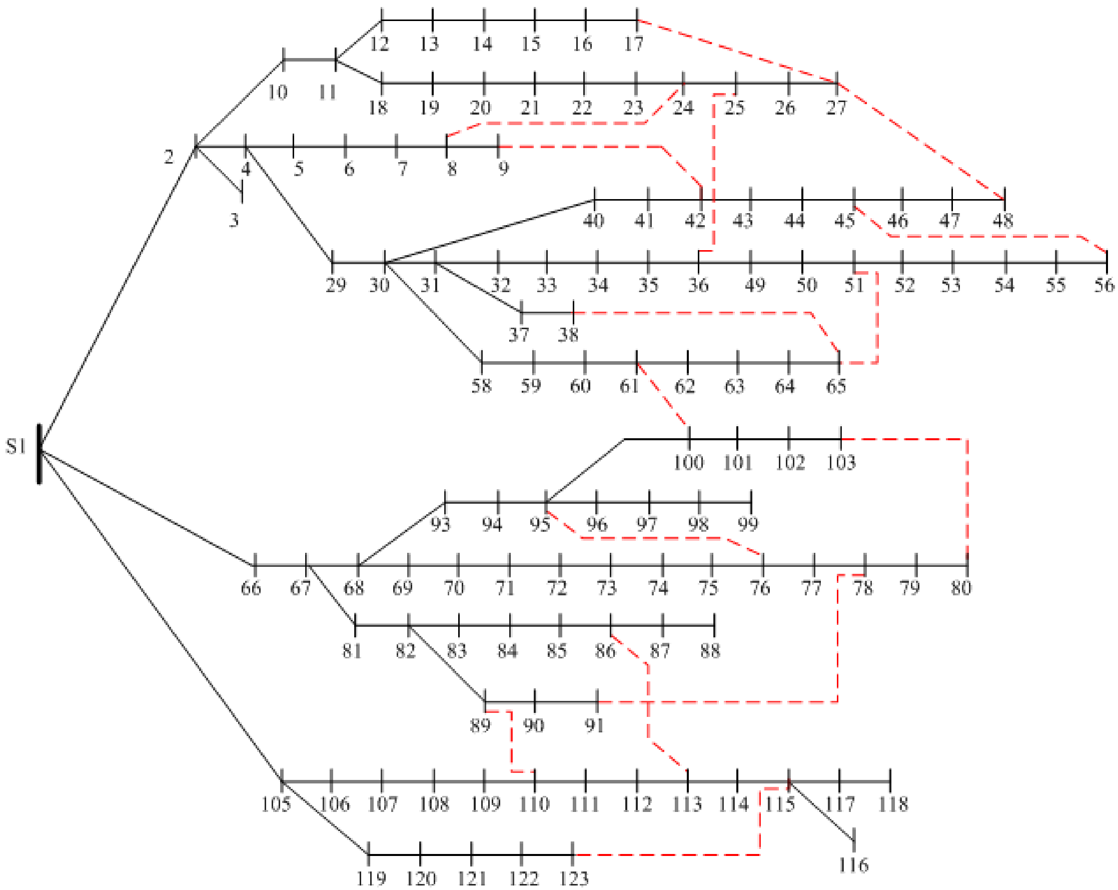

Fig. 1. Initial scheme of the distribution network
Рис. 1. Исходная схема распределительной сети

Table 1. Composition of independent circuits of initial and optimal schemes
Таблица 1. Состав независимых контуров исходной и оптимальной схемы

No.	**Initial scheme**		**Optimal scheme**	
	Chord	Independent circuit	Chord	Independent circuit
1	8–24	**8**-7-6-5-4-2-10-11-18-19-20-21-22-23-**24**	23–24	**23**-22-21-20-19-18-11-10-2-4-5-6-7-8-**24**
2	9–42	**9**-8-7-6-5-4-29-30-40-41-**42**	35–36	**35**-34-33-32-31-30-29-4-5-6-7-8-24-25-**36**
3	17–27	**17**-16-15-14-13-12-11-18-19-20-21-22-23-24-25-26-**27**	17–27	**17**-16-15-14-13-12-10-2-4-5-6-7-8-24-25-26-**27**
4	25–36	**25**-24-23-22-21-20-19-18-11-10-2-4-29-30-31-32-33-34-35-**36**	41–42	**41**-40-30-29-4-5-6-7-8-9-**42**
5	27–48	**27**-26-25-24-23-22-21-20-19-18-11-10-2-4-29-30-40-41-42-43-44-45-46-47-**48**	44–45	**44**-43-42-9-8-24-25-26-27-48-47-46-**45**
6	38–65	**38**-37-31-30-58-59-60-61-62-63-64-**65**	50–51	**50**-49-36-25-24-8-7-6-5-4-29-30-31-37-38-65-**51**
7	45–56	**45**-44-43-42-41-40-30-31-32-33-34-35-36-49-50-51-52-53-54-55-**56**	53–54	**53**-52-51-65-38-37-31-30-29-4-5-6-7-8-24-25-26-27-48-47-46-45-56-55-**54**
8	51–65	**51**-50-49-36-35-34-33-32-31-30-58-60-61-62-63-64-**65**	64–65	**64**-63-62-61-60-59-58-30-31-37-38-**65**
9	61–100	**61**-60-59-58-30-29-4-2-S1-66-67-68-93-94-95-**100**	61–100	**61**-60-59-58-30-29-4-2-S1-66-67-68-93-94-95-**100**
10	76–95	**76**-75-74-73-72-71-70-69-68-93-94-**95**	74–75	**74**-73-72-71-70-69-68-93-94-95-76-**75**
11	78–91	**78**-77-76-75-74-73-72-71-70-69-68-67-81-82-89-90-**91**	76–77	**76**-95-94-93-68-67-81-82-89-90-91-78-**77**
12	80–103	**80**-79-78-77-76-75-74-73-72-71-70-69-68-93-94-95-100-101-102-**103**	79–80	**79**-78-91-90-89-82-81-67-68-93-94-95-100-101-102-103-**80**
13	86–113	**86**-85-84-83-82-81-67-66- S1-105-106-107-108-109-110-111-112-**113**	85–86	**85**-84-83-82-81-67-66-S1-105-106-107-108-109-110-111-112-113-**86**
14	89–110	**89**-82-81-67-66-S1-105-106-107-108-109-**110**	89–110	**89**-82-81-67-66-S1-105-106-107-108-109-**110**
15	115–123	**115**-114-113-112-111-110-109-108-107-106-105-119-120-121-122-**123**	114–115	**114**-113-112-111-110-109-108-107-106-105-119-120-121-122-123-**115**

The reconfiguration algorithm used in the study can be used to identify the section with line switches that provide minimal power losses in the network, as well determining the lists of bus section circuit breakers whose power supply (when any of them is tripped) can be restored by closing the line switch. The selection of the optimal option for restoring power supply to consumers follows the criterion of power loss minimization, which, as a rule, ensures minimal voltage deviations. If the voltage deviations exceed the feasible limits, then a decision on additional measures is made to ensure their previously determined feasible values.

The studies carried out in [16–20] show that the sensor nodes at which the response of voltage magnitudes and phases to external disturbances will be maximum, can be determined by the maximum components of the right singular vector corresponding to the minimum singular value of the Jacobian matrix. The response of voltage magnitudes of sensor nodes to disturbances can be decreased by installing active and reactive power sources at them. An indicator of network reinforcement with the introduction of additional sources at sensor nodes is an increase in the minimum singular value of the Jacobian

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matrix, which characterizes the improvement in its conditionality consisting in a the decrease in the influence of changes in active and reactive nodal powers on changes in voltage magnitudes and phases. Let us analyze the accidents associated with the disconnection of bus section circuit breakers connecting nodes 4–29, 29–30, 30–31, 51–52, 81–82, and 105–106. These disconnections are considered as outages leading to significant voltage drops that require network modernization.

Table 2 contains data on modeling the tripping of sectional switches, including disconnected sections; the number of circuits that include the disconnected section; possible options for power supply restoration; the chord whose closure corresponds to the minimum power loss; the node number having the minimum values of voltage and power losses in the network after closing the line switch.

Disconnection of Section 4–29. As seen in Tables 1 and 2, this section comprises part of five circuits. The best option for power supply restoration is to close chord 41–42. However, at the same time, the voltage drop observed at some nodes is unacceptable (up to 8.801 kV at node 53). To ensure acceptable voltage levels at load nodes, only the connection of additional reactive power sources was analyzed. The graph in Fig. 2 depicts the sensor nodes that are most sensitive to external impacts and which correspond to the maximum components of the right singular vector associated with the minimum singular value of the Jacobian matrix. Since groups of sensor nodes form sequentially located load nodes, the most sensitive nodes that belong to different sections of the radial network and are the farthest from the power source are selected to accommodate additional reactive power sources. In the case of this emergency shutdown, these are the nodes numbered 35, 53 and 64, the capacities of the reactive power sources installed at them are 1658 kVAR, 3430.42 kVAR, and 1958.76 kVAR, respectively.

The feasible voltage level at the network nodes ensured by performing this measure demonstrated by the graph in Fig. 3. The minimum voltage value in this case is 10.22 kV at node 60; the power loss value decreased to 1480.8 kW.

Disconnection of sections 29–30, 30–31, 51–52, 81–82, and 105–106. The analysis of power supply restoration with the indicated sections disconnected is performed similarly to that in the study on the disconnection of section 4–29. The calculation results are given in Table 3.

Disconnection of dead-end sections. In addition, the reconfiguration algorithm is used us to identify dead-end sections, whose disconnection will lead to a lack of power for the consumer during their repair. For the network under study, such sections are those with load nodes 3, 87, 88, 96, 97, 98, 99, 116, 117, and 118. The decision on the need to install backup power sources for these consumers should be based on the information about their power supply categories.

Table 2. Options for power supply restoration when the bus section circuit breakers is tripped
Таблица 2. Варианты восстановления электроснабжения при отключении секционного выключателя

Disconnected section	The number of circuits	Possible replacements					Minimum voltage, kV – at nodes	Power losses, kW
4–29	5	35–36	**41–42**	50–51	53–54	61–100	8.801 - 53	1025.87
29–30	5	35–36	**41–42**	50–51	53–54	61–100	8.99 - 53	1683.34
30–31	4	35–36	**50–51**	53–54	64–65	–	9.125 - 35	1499.5
51–52	1	**53–54**	–	–	–	–	9.805 - 52	1052.08
81–82	4	76–77	79–80	85–86	**89–110**	–	9.636 - 77	1240.16
105–106	3	85–86	**89–110**	114–115	–	–	9.303 - 88	1542.24

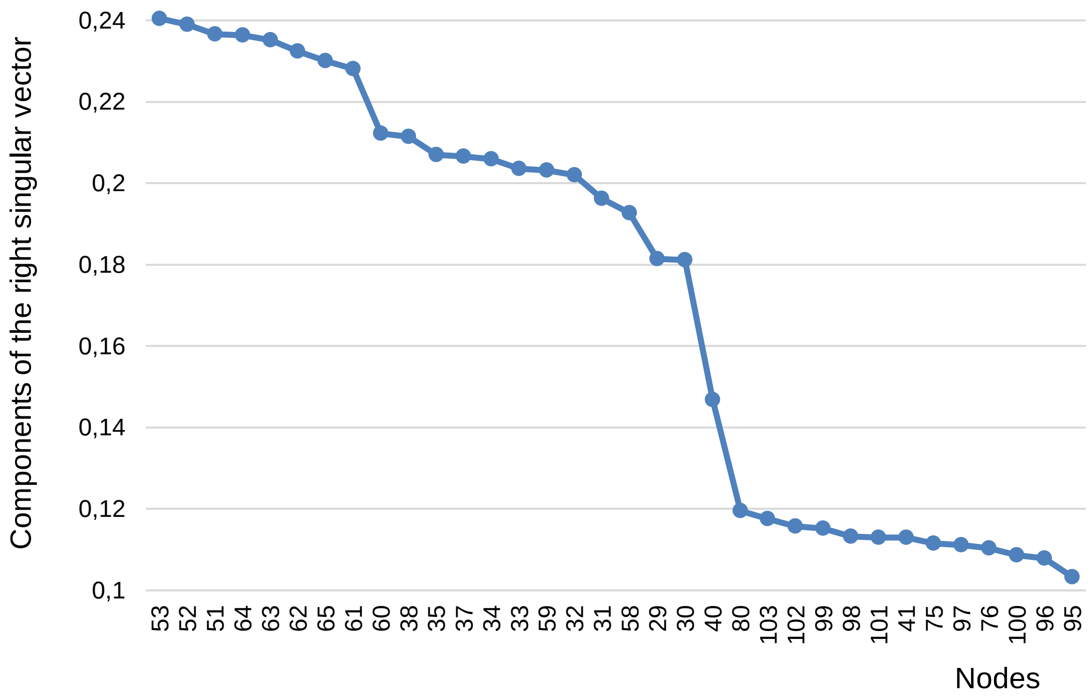

Fig. 2. Node sensitivity analysis for emergency disconnection of section 4–29
Рис. 2. Анализ сенсорности узлов для аварийного отключения секции 4–29

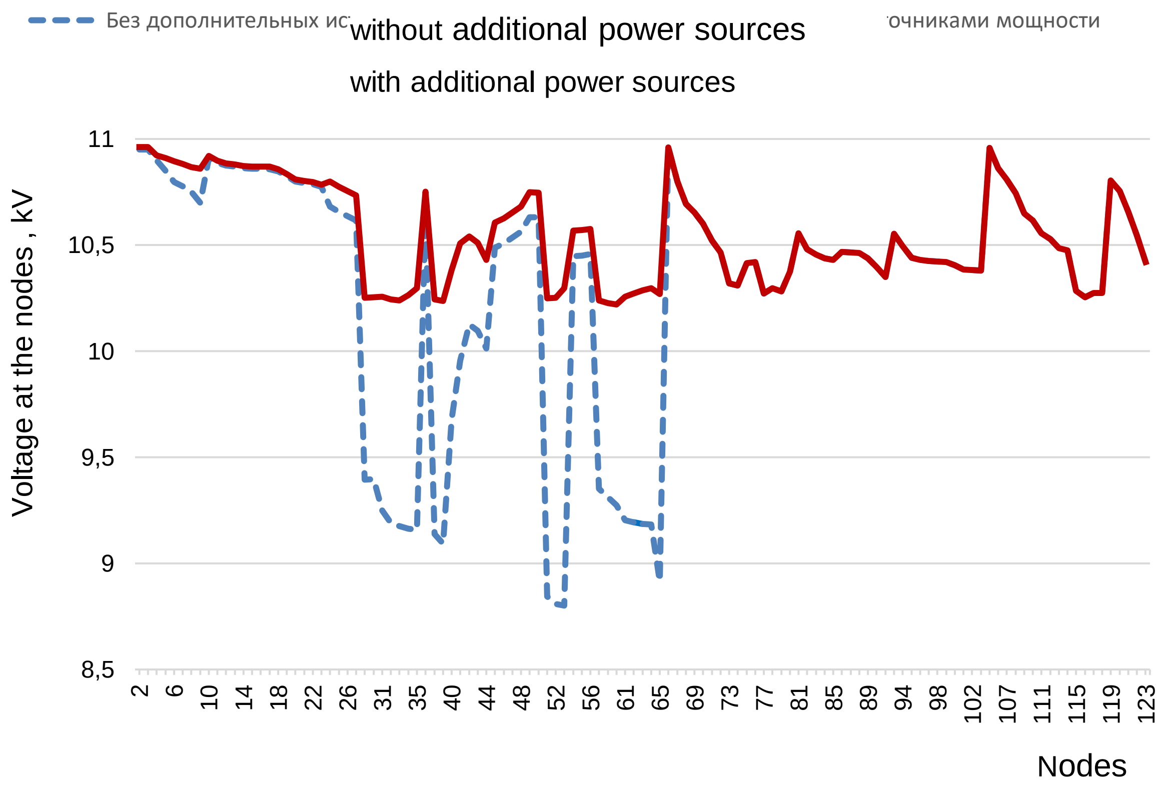

Fig. 3. Voltage level it network nodes for emergency shutdown of section 4–29
Рис. 3. Уровень напряжений в узлах сети для аварийного отключения секции 4–29

Table 3. Restoration of power supply when bus section circuit breakers are tripped
Таблица 3. Восстановление электроснабжения при отключении секционных выключателей

Disconnected section	Before installation of additional reactive power sources		Sensor nodes (in descending order of the magnitude of the right singular vector component)	Installation sites for additional reactive power sources	Capacity of additional reactive power sources, kVAR	After installation of additional reactive power sources	
	Minimum voltage, kV	Power losses, kV				Minimum voltage, kV	Power losses, kV
29–30	8.99	1 683.34	**53** 52 **64** 51 65 **35**	35 53 64	1 258.19 3 185.11 1 555.38	10.254	1306.5
30–31	9.125	1 499.5	**35** 34 33 32 31	35	4 792.82	10.208	1379.7
51–52	9.805	1 052.08	52 **53** 54 80 103 47	53	2 814.44	10.255	918.5
81–82	9.636	1 240.16	**79** 77 78 91 90	79 106	2 065.2 2 622.34	10.007	1062.7
105–106	9.303	1 542.24	**88** 87 114 113 112 **106**	88	3 090.93	10.219	1627.9

CONCLUSION

The presented numerical results confirm the applicability of the maximum spanning tree method for reducing power losses and levelling the voltage profile at the distribution network nodes under normal operating conditions. In emergency situations, the proposed method made it possible to restore power supply to the consumer by closing the corresponding line switch. For the most severe accidents, the singular analysis of the Jacobian matrix was employed to identify sensor nodes, at which the installation of additional reactive power sources ensured the feasible voltage values.

Further research will investigate the restoration of power supply to the consumer for the cases of simultaneous failure of several sections, as well as sections connected to a power source.

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