Application of static thyristor compensators to increase the reliability of distribution networks

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Abstract. Currently, the use of FACTS devices for voltage regulation and optimal control of electric power system modes is widely used. Controlled FACTS devices, based on power electronics, allow obtaining the desired characteristic of not only power transmission, but also a dedicated part of the electrical system. The paper presents the results of a study of the operating modes of a real distribution network, taking into account the installation of a static thyristor compensator (STC), in order to increase its operating reliability. The efficiency of distribution networks in and the area of existence of modes significantly depend on the installation location and the law of power control of compensating devices. To solve this problem, a systems approach based on graph theory methods is proposed. The conditions for stabilizing nodal voltages to reduce total active power losses in the electrical network are studied. The ranges of change in the required powers with the corresponding STC control laws are determined to ensure a minimum of total power loss in the network
Key words: distribution electric network, reactive power, voltage, topology, graph theory.

Introduction

Changes occurring in the electric networks of power systems show that the increase in reactive power consumption significantly exceeds the increase in active power consumption [1,2]. Increasing the output of reactive power by generators for the purpose of delivering it to the consumer is impractical. Therefore, the most appropriate is reactive power compensation (RPC) at the places of energy conversion, including at the places of connection of objects of electricity consumption (EE). Considering that in high-voltage electric networks, active power losses are the greatest compared to losses in lower-voltage networks (in percentage terms, significantly lower!). Therefore, the placement of RPC technical means in higher-voltage networks increases the energy efficiency of electric networks [3,4].

In recent years, static compensators (SCC) of reactive power, which are part of FACTS (Flexible Alternative Current Transmission Systems - flexible AC transmission systems) of technology, which includes a set of technical and information means of automatic control of parameters of power transmission lines. Shunt reactors and capacitors (hereinafter referred to as static capacitor banks - BSC or capacitor units - KU) are the main reactive elements of the STC. These elements can be used both individually and jointly. Shunt reactors can be regulated using power electronics (thyristor valves, etc.) or by changing the saturation of the magnetic core of the reactor, and capacitor banks can be either permanently connected or step-regulated using switching equipment or power electronics [5,6].

The choice of one or another type of STC and the locations of their installation are determined by the specific configuration of the electrical network, the balance of electrical load capacities, the equipment installed in the network and its capabilities for voltage regulation, as well as the technical and economic indicators of specific types of STC [7,8].

This study is devoted to improving the operational reliability of a 110 kV distribution electrical network using a STC.

Brief information about reactive power compensation

In industrially developed countries, as well as in the CIS countries, much attention is paid to reactive power compensation using SC. In particular, in France, Sweden, Germany, the capacity of the BSC is 35 percent of the active peak power, in the USA and Japan - about 70 percent. In some energy companies in the USA, the capacity of the installed compensating devices is 100 percent of the generator capacity [6-8].

The global practice of solving problems of the power factor control system shows the effective use for these purposes of the normative method, in accordance with which the values of the power factor (PF) are standardized on buses of certain voltage classes.

The optimal value of the reactive power factor $tg\varphi$depending on the nominal network voltage in the

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maximum load mode in the USA, Japan and most European countries is maintained at the level of 0.2-0.4, which corresponds to $cos\varphi = 0{,}98 - 0{,}9$.In recent years, in many US power systems, distribution electric networks in the maximum load mode operate with $tg\varphi = 0$ [9,10].

If the voltage regulation is carried out by a static compensator, then the required reactive power in the node under consideration is determined by using the standard value of the power factor. In this case, the value $Q = P \cdot tg\varphi$determines the upper limit of the network voltage regulation range provided by the static compensator. If we assume that in power supply networks with a voltage of up to 220 kV inclusive, the determining factors are load power losses and EE, which are mainly inversely proportional to the square of the voltage level, then in such networks it is advantageous to maintain a higher voltage level (up to the technical limit). During hours of minimum loads in a node with a static compensator, reactive power can be generated in the network, which leads to a significant increase in voltage. Regulation of the static compensator power in the specified ranges leads to the provision of permissible voltage modes at the point of its connection [11].

It should be noted that the traditional method can determine the approximate ranges of the power of the control unit in the network nodes using the standard values of the power factor, which is insufficient under the conditions of using FACTS devices .

In this work, a new technology for determining the power of a compensating device is implemented based on a topological method from the standpoint of synthesis of voltage modes.

Calculations of the power of compensating devices.

Calculations of the powers of compensating devices can be obtained on the basis of a topological model of the formation of steady-state modes. After replacing the setting currents $\dot{\underline{J}}$with powers, the equation of the steady-state mode is written as follows [12,13]:

$$\dot{U} = U_0 + C^T Z_B C \overline{U_D^{-1}} \bar{S} \tag{1}$$

where $C$is a rectangular complex matrix of current distribution coefficients; $Z_B$is a diagonal matrix of branch resistances; U_D – diagonal matrix of nodal conjugate voltages; $\bar{S}$– column vector of conjugate powers of nodal loads and generators, T −transposition sign

The complex power $i$of the -th node , taking into account the powers of the transverse branches, is determined as:

$$\dot{S}_i = P_i + jQ_i + (g_i + j \cdot (b_L - b_C))_i |U_i|^2 \tag{2}$$

Where$j -$ imaginary unit , P_i, Q_i −active and reactive power $i$of the -th node; g_i, b_L, b_C −active, inductive, capacitive conductivity $i$of the -th node; U_i −modulus of complex voltage $i$of the -th node.

All components of the right-hand side of equation (1), except for the sought node voltages, are constant values for a given electrical network circuit. It is known that modern compensation devices equipped with controlled power electronics allow stabilizing the voltage of an arbitrary node regardless of the electrical system mode. Consequently, the desired voltage values on the buses of an arbitrary network node can be considered a given value. Then, the problem is reduced to determining the power of compensating devices, for example, STC, installed to provide the desired node voltages.

The values of the required powers of the compensating devices are determined by the equation [14,15] :

$$\dot{U}_ж = U_0 + C_d^T Z_B C_d \overline{U_D^{-1}} \left(\bar{S} - j\overline{Q_k}\right) \tag{3}$$

where is $\dot{U}_ж$ −the complex value of voltage, and at certain nodes the voltage modulus must take the desired value; Q_k −reactive power of compensating devices at the same nodes (3).

$$\begin{cases} |U_{жk}| \cos\delta_k = U_0 - \sum |Z_{kj}| \dfrac{|S_j| \cos(\delta_j - \phi_j + \psi_{kj}) + Q_{Kj} \sin(\delta_j + \psi_{kj})}{|U_{жj}|} \\ |U_{жk}| \sin\delta_k - \sum |Z_{kj}| \dfrac{|S_j| \sin(\delta_j - \phi_j + \psi_{kj}) + Q_{Kj} \cos(\delta_j + \psi_{kj})}{|U_{жj}|} \end{cases}$$

where $Z = C^T Z_B C -$ symmetric matrix of nodal resistances, δ_k −phase of nodal voltage,
φ_k −phase of conjugate complex of nodal load,
$\psi_{k,j} = \arg(Z_{k,j})$ −phase of element of matrix of nodal resistances.

Improving the operational reliability and energy efficiency of a real 110 kV distribution network using the FACTS device

The initial data of the system under study are presented in Table 1, and the calculation scheme is shown in Fig. 1.

In the maximum load mode, all consumers have a standard power factor $cos\varphi = 0{,}92 \div 0{,}93$. Calculations were carried out based on the topological model of the formation of steady-state mode parameters (1). The study of the maximum mode without the use of the control unit showed that at the voltage of the power supply center (PC) $U_0 = 121$кВ, in all distribution substations, standard values are provided on the low-voltage buses, taking into account the action of the OLTC installed on the transformers. The total losses of active power are equal to $\Delta P_\Sigma = 6{,}431$ МВт,which is 9.9% of the active power entering the network, $P_{\text{act}} = 64{,}978$ МВт,which are presented in Table 2.

Calculations were made with a decrease in the voltage of the central control unit in order to determine the permissible modes for the voltage of the distribution network. The calculations established that the permissible mode for the voltage in the network is ensured with a decrease in the voltage of the base node to 117 kV inclusive.

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Table 1. Initial data of the network calculation scheme

Node data					Branch data					
No.	Load powers				No.	start	con	R, Ohm	X, Ohm	b , mkSm (capacity+, ind-)
	Min. mode		Max mode							
	P, MW	Q,MVar	P, MW	Q,MVar						
1	0.02	0,1	0.02	0,1	1	B	1	4.95	10.5	134.9
2	0.02	0,1	0.02	0,1	2	1	2	7.92	16.8	215.9
3	0.042	0.224	0.042	0.224	3	2	3	1,485	3.15	40.48
4	0.02	0,1	0.02	0,1	4	3	4	2.59	4.44	13,785
5	0.02	0,1	0.02	0,1	5	4	5	11,118	24,211	75.15
6	0.028	0.14	0.028	0.14	6	5	6	6,225	10,675	33,135
7	0.038	0.22	0.038	0.22	7	6	7	7.47	12.81	39,765
8	0.028	0.151	0.028	0.151	8	7	8	14.94	25.62	79.55
9	0,011	0.076	0,011	0.076	9	8	9	18.36	26.04	78.35
10	2,419	1,814	6,048	4,536	10	3	9	18.36	26.04	78.35
11	2,419	1,814	6,048	4,536	11	1	10	8	110.2	0
12	3,072	2,304	7.68	11.52	12	2	11	8	110.2	0
13	2,419	1,814	6,048	4,536	13	3	12	2,2	43.24	0
14	2,419	1,814	6,048	4,536	14	4	13	8	110.2	0
15	3.84	2.88	9.6	7.2	15	5	14	8	110.2	0
16	0	0	0	0	16	6	15	3.95	69.45	0
17	1.92	1.44	4.8	3.6	17	7	16	2,515	71,085	0
18	1.92	1.44	4.8	3.6	18	16	17	2,515	0	0
19	0	0	0	0	19	16	18	2,515	41.33	0
20	1.21	0.907	3,024	2,268	20	8	19	4.83	112.83	0
21	1.21	0.907	3,024	2,268	21	19	20	4.83	0	0
22	0.48	0.36	1,2	0.9	22	19	21	4.83	65.6	0
B	0	0	0	0	23	9	22	42.6	508.2	0

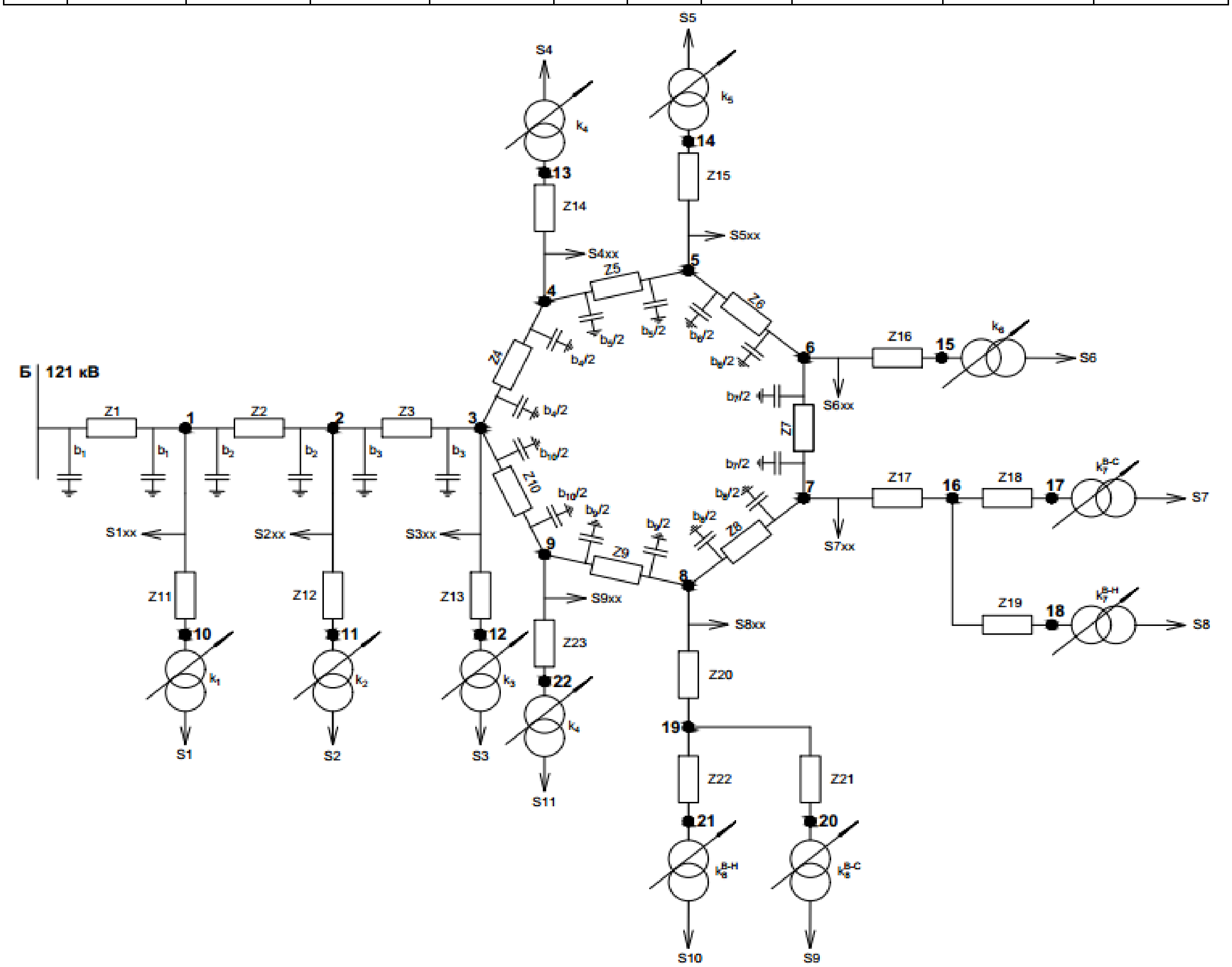

Fig 1. Network calculation scheme

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Table 2. Changes in power loss depending on power centre voltage

U_0	P_{act}	P_{load}	ΔP_Σ	ΔP_Σ
kV	MW	MW	MW	%
121	64,98	58,55	6,43	9,90
120	65,73	58,55	7,18	10,90
119	66,51	58,55	7,96	11,90
118	67,32	58,55	8,77	13,00
117	68,16	58,55	9,61	14,10
116	69,03	58,55	10,48	15,20
115	69,94	58,55	11,4	16,30

Reducing the voltage of the CPU leads to an increase in the total losses of active power, which is not advisable. Increased voltage in the network creates a condition for the occurrence of additional losses of active power due to the transfer of reactive power in the network. Therefore, to reduce the losses of active power in the network while ensuring operational reliability, it is envisaged to use FACTS devices, which is of great importance both theoretically and practically.

For the experimental analysis during the installation of the STC, the third and seventh nodes of the closed network were selected.

When installing the control unit in the third node with stabilization of the voltage level in the region of permissible voltage modes, the reactive power of the control unit and the total losses of active power in the network were determined.

Table 3. Changes in power losses during compensation in the third node

U_3	P_{act}	P_{load}	ΔP_Σ	ΔP_Σ	Q_c
kV	MW	MW	MW	%	MVar
120	70,376	58,547	5,911	10,10	67,78
119	70,245	58,547	5,818	9,94	63,99
118	70,148	58,547	5,758	9,83	60,29
117	**70,086**	**58,547**	**5,732**	**9,79**	**56,66**
116	70,059	58,547	5,741	9,81	53,12
115	70,067	58,547	5,784	9,88	49,65
114	70,11	58,547	5,86	10,01	46,27
113	70,188	58,547	5,971	10,20	42,97

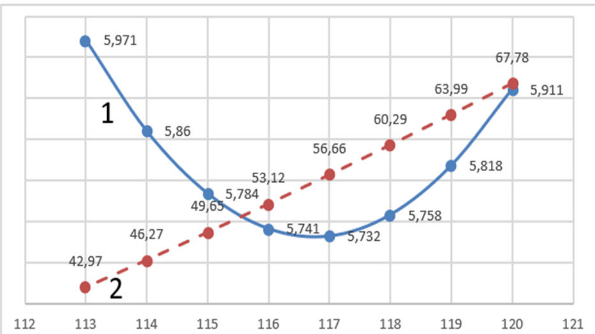

Fig. 2. Graphs of changes: 1 – total losses of active power, 2 – power of the compensating device.

The study showed that the appropriate mode for minimum active power losses in the network is ensured by stabilizing the voltage of the third node at 117 kV, with the power of the control unit equal to 56.661 MVAr . In this case, the total active power losses in the network are reduced and become equal to 5.732 MW, which is 8.92% of the active power entering the network (64.279 MW).

Table 4. Changes in power losses during compensation in the seventh node

U_7	P_{act}	P_{load}	ΔP_Σ	ΔP_Σ	Q_c
kV	MW	MW	MW	%	MVar
114	69,834	58,547	5,659	8,10	40,41
113	69,772	58,547	5,611	8,04	38,56
112	69,729	58,547	5,581	8,00	36,75
111	**69,704**	**58,547**	**5,57**	**7,99**	**34,98**
110	69,699	58,547	5,578	8,00	33,25
109	69,714	58,547	5,605	8,04	31,55
108	69,746	58,547	5,65	8,10	29,9

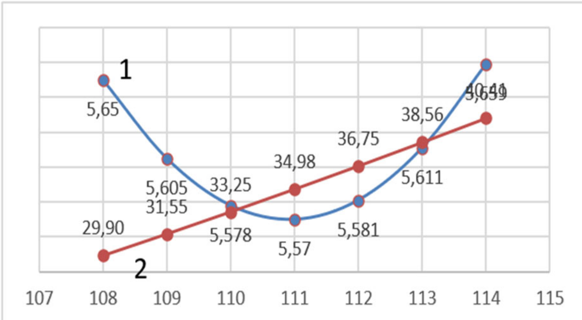

Fig. 3. Graphs of changes: 1 – total losses of active power, 2 – power of the compensating device.

When installing the control unit in the seventh node, the optimal mode occurs when the voltage stabilizes at 111 kV, with the control unit power of 34.978 MVAr . The total losses of active power in the network become equal to 5.57 MW, which will be 8.68% of the active power entering the network (64.117 MW).

Of the two options considered, preference is given to the second option, when the control unit is installed in node 7, since the power of the control unit is significantly lower and provides the greatest reduction in total active power losses in the network.

To further reduce active power losses in the distribution network, the option of installing the control unit simultaneously in the third and seventh nodes was considered.

When the voltage is stabilized at 116 kV, simultaneously in two nodes (3 and 5?), the active power losses in the network are reduced to 5.235 MW, which is 8.21% of the active power of the CPU supplied to the network (63.782 MW).

Table 5. Changes in power losses with compensation in the third and seventh nodes

U_7	P_{act}	P_{load}	ΔP_{Σ}	ΔP_{Σ}	$Q_{c,3}$	$Q_{c,7}$
kV	MW	MW	MW	%	MVar	MVar
119	63,92	58,55	5,37	8,41	40,41	35,01
118	63,84	58,55	5,29	8,29	38,56	35,13
117	63,79	58,55	5,25	8,23	36,75	35,25
116	**63,78**	**58,55**	**5,23**	**8,21**	**34,98**	35,37
115	63,80	58,55	5,25	8,23	33,25	35,49
114	63,85	58,55	5,31	8,31	31,55	35,62
113	63,94	58,55	5,39	8,43	29,9	35,75
112	64,05	58,55	5,51	8,60	1,53	35,88

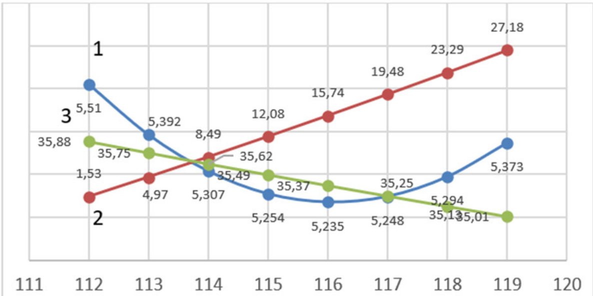

Fig. 4. Graphs of changes: 1 – total losses of active power, 2 – power of the compensating device in node 3, 3 – power of the compensating device in node 7.

From the analysis of the calculations performed for the maximum mode of the network under consideration, it can be stated that the use of a static compensator as a device for stabilizing the desired voltage level of the selected node significantly increases the operating reliability and reduces the total losses of active power while ensuring the quality of voltage on the busbars of distribution substations.

For the minimum load mode, an increase in the total active power losses in the network is also typical with a decrease in the CPU voltage. In terms of reducing the total active power losses, it is necessary to stabilize the increased (technically permissible) voltage on the CPU buses. The minimum value of the total active power losses, equal to 0.902 MW, corresponds to a CPU voltage of 121 kV. When the CPU voltage decreases, for example, to 117 kV, the total active power losses increase to 1.001 MW.

Table 6. Changes in power losses during compensation in the seventh node

U_7	P_{act}	P_{load}	ΔP_{Σ}	ΔP_{Σ}	Q_c
kV	MW	MW	MW	%	MVar
120	24,35	23,55	0,8	3,28	14,06
119,5	24,33	23,55	0,77	3,18	13,09
119	24,31	23,55	0,75	3,10	12,12
118,5	24,29	23,55	0,74	3,03	11,17
118	24,28	23,55	0,73	2,99	10,23
117,5	24,27	23,55	0,72	2,95	9,3
117	24,27	23,55	0,71	2,95	8,37
116,5	**24,27**	**23,55**	**0,72**	**2,95**	**7,46**
116	24,28	23,55	0,723	2,97	6,55

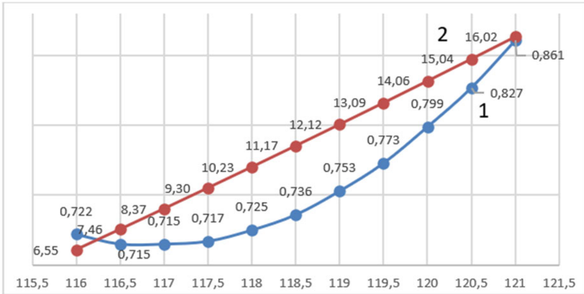

Fig. 5. Graphs of changes: 1 – total losses of active power, 2 – power of the compensating device.

The conducted analysis of the distribution network modes using the STC showed that the lowest value of active power losses is 0.715 MW, which corresponds to 2.946%, and is achieved by installing the control unit in node 7. At the same time, the voltage of this same node is maintained at 117 kV , with the voltage of the power center being 121 kV. When setting the voltage of the power center to 115 kV, the minimum value of power losses in the network is 0.833 MW. Therefore, in the minimum load mode, preference is also given to a higher CPU voltage level.

Conclusions

The use of the FACTS device for mode control significantly reduces technological losses of active power with an increase in the reliability of the distribution networks.

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