The Use of Thyristor-Based Static VAR Compensators to Enhance Distribution System Security

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***Abstract* — Nowadays, FACTS devices are commonly used for voltage regulation and optimal control of operating parameters of power systems. Controllable FACTS devices relying on power electronics can be used to obtain the required characteristic curve not only for power transmission lines, but also for a specific part of the electrical system. This paper reports the results of a study on operating conditions of a real-world distribution system that has a static thyristor-based VAR compensator (SVC) installed to enhance its security. The efficiency of distribution systems and available ranges of their operating conditions largely depend on the placement of compensation devices and the rules governing their capacity. We propose a consistent approach based on graph theory methods to address this issue. The approach involves examining the conditions for nodal voltage stabilization to reduce the total active power loss in the electrical network. The ranges of variation in SVC capacity are identified and appropriate SVC control rules required to ensure the lowest possible total power loss in the network are established.**

***Index Terms* — Power distribution system, reactive power, voltage, topology, graph theory.**

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I. Introduction

The changes that occur in electrical networks of power systems indicate that the growth in reactive power consumption significantly outpaces the rise in active power consumption [1, 2]. Increasing the generators' output of reactive power to meet the demand of the consumer is not a viable solution. Therefore, reactive power compensation is most appropriate at the places of energy conversion, including the points for connection of electric power consumption facilities. Given that active power loss is the highest in high-voltage electrical networks compared to that in lower voltage networks (in percentage terms, it is way lower), the placement of reactive power compensators in higher voltage networks contributes to energy efficiency of power grids [3, 4].

Recent years have seen widespread adoption of static VAR compensators (SVC), which are part of the family of FACTS (Flexible Alternating Current Transmission Systems) devices that cover a range of technical and information means of automatic control of power line parameters. Shunt reactors and capacitors (in what follows, referred to as static capacitor banks (SCBs) and capacitor units (CUs)) are the main reactive components of SVC. These components can be used individually or together. Shunt reactors can be controlled by using power electronics (thyristor valves, etc.) or by changing the saturation of the reactor magnetic core, while capacitor banks can be either permanently connected or step-regulated using switching devices or power electronics [5, 6].

The choice of a specific type of SVCs and their placement depends on the configuration of a given electrical network, the power balance of electrical loads, the equipment installed in the network and its voltage control capabilities, as well as technical and economic performance of specific types of SVCs [7,8].

This study seeks to enhance the security of 110 kV distribution systems using SVCs.

II. Background on Reactive Power Compensation

Industrialized countries, as well as CIS countries, put much effort into reactive power compensation using static compensators. In particular, in France, Sweden, and Germany, SCB capacity is 35% of active peak power, and in the United States and Japan it is about 70%. In some power utilities in the United States, the capacity of installed compensation devices amounts to 100 percent of the generators' capacity [6–8].

The internationally established practice of addressing reactive power compensation issues demonstrates the effectiveness of the techniques grounded in standardized values. According to them, the power factor (PF) is normalized to standard-compliant values on busbars of certain voltage classes.

The optimal value of the reactive power factor $\mathrm{tg}\,\varphi$ depending on the rated voltage of the network operating under the maximum load flow is maintained at the level of 0.2–0.4 in the USA, Japan, and most European countries, which corresponds to $\cos\varphi = 0.98 - 0.9$. In recent years, many power distribution systems in the United States has been operating under the maximum loads with $\mathrm{tg}\,\varphi = 0$ [9, 10].

If voltage is controlled by a static compensator, the required reactive power at a given node is determined by relying on the standardized power factor value. In this case, the value $Q = P\,\mathrm{tg}\,\varphi$ establishes the maximum limit of the controlled range of network voltage provided by the reactive power compensation device. Assuming that the load loss of power and electricity are mainly inversely proportional to the square of the voltage level, it becomes critical to maintain a higher voltage level (up to the technical limit) in supply networks operating at voltages of up to 220 kV. This approach proves beneficial in such networks. During the hours of minimum loads at the node with an SVC, there is a possibility of reactive power flowing into the network, resulting in a significant increase in voltage. Control of SVC capacity within specified limits ensures an acceptable voltage profile at the point of its connection [11].

It is worth noting that the conventional technique determines approximate ranges of capacitor unit capacity at network nodes by relying on standardized values of the power factor, which proves inadequate when FACTS devices are used.

This study implements a novel topology-based technique for calculating the capacity of a compensation device, focusing on voltage profile synthesis.

III. Capacity Calculations of Compensation Devices

Capacities of compensation devices can be calculated based on the topological model of steady states. Substituting reference currents with capacities, the steady-state equation is written as follows [12, 13]:

$$\dot{U} = U_0 + C^{\mathrm{T}} Z_B C \hat{U}_D^{-1} \hat{S}\,, \tag{1}$$

where C is the rectangular complex matrix of current distribution coefficients; Z_B is the diagonal matrix of branch impedances; U_D is the diagonal matrix of nodal conjugate voltages; $\hat{S}$ is the column vector of conjugate powers of nodal loads and generators, T is the transposition sign.

The complex power of the i-th node, given the powers of the transverse branches, is defined as:

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

where j is the imaginary unit, P_i, Q_i are active and reactive powers of the i-th node, respectively; g_i, b_L, b_C are the conductance, inductive susceptance, and capacitive susceptance of the i-th node, respectively; U_i is the complex voltage magnitude of the i-th node.

All components of the right-hand side of equation (1), except for the node voltages, which are the quantities to be determined, are constant values for a given diagram of the electrical network. It is known that modern compensation devices equipped with controllable power electronics stabilize the voltage at an arbitrary node regardless of operating conditions of the power system. Consequently, the values of the required voltage at the busbars of an arbitrary network node can be considered a given quantity. Then, the problem is reduced to determining the capacity of compensation devices, such as SVC, installed to provide the required nodal voltages.

The values of required capacities of compensation devices are determined using the equation [14]:

$$\dot{U}_{reg} = U_0 + C_d^{\mathrm{T}} Z_B C_d \hat{U}_D^{-1}\left(\hat{S} - jQ_k\right), \tag{3}$$

where $\dot{U}_{reg}$ is the complex voltage value, with the voltage magnitude taking the required value at certain nodes; Q_k

is the reactive power of compensation devices at the same nodes.

The component-wise form of equation (3) written for the real and imaginary parts is as follows:

$$\begin{cases} \left|U_{reqk}\right|\cos\delta_k = U_0 - \\ -\sum\left|Z_{kj}\right|\dfrac{\left|S_j\right|\cos\left(\delta_j-\varphi_j+\psi_{kj}\right)+Q_{Kj}\sin\left(\delta_j+\psi_{kj}\right)}{\left|U_{req\,j}\right|}, \\ \left|U_{reqk}\right|\sin\delta_k = \\ = \sum\left|Z_{kj}\right|\dfrac{\left|S_j\right|\sin\left(\delta_j-\varphi_j+\psi_{kj}\right)+Q_{Kj}\cos\left(\delta_j+\psi_{kj}\right)}{\left|U_{req\,j}\right|}, \end{cases} \quad (4)$$

where $Z = C^{\mathrm{T}} Z_B C$ is the symmetric matrix of nodal resistance, δ_k is the phase of the nodal voltage, φ_k is the phase of the conjugate complex of the nodal load, and $\psi_{k,j} = \arg\left(Z_{k,j}\right)$ is the phase of the entry of the nodal impedance matrix.

IV. Enhancement of Security and Energy Efficiency of a Real-World 110 kV Distribution Network Through the Integration of a FACTS Device

Table 1 summarizes the input data on the investigated system and Fig. 1 shows its calculated scheme.

During maximum load operation, all consumers have a standardized power factor $\cos\varphi = 0.92 \div 0.93$. The calculations were based on a topological model that defined steady-state parameters (1). The study of the maximum load operation without CUs showed that when the voltage at the main substation (MS) is $U_0 = 121$ kW, all distribution substations have standard-compliant values

TABLE 1. Input Data on the Calculated Scheme of the Network

Node data					Branch data					
No.	Load power: Min. load operation *P*, MW	Load power: Min. load operation *Q*, MVAr	Load power: Max. load operation *P*, MW	Load power: Max. load operation *Q*, MVAr	No.	start	end	*R*, Ohm	*X*, Ohm	*b*, µSm (cap+, ind-)
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

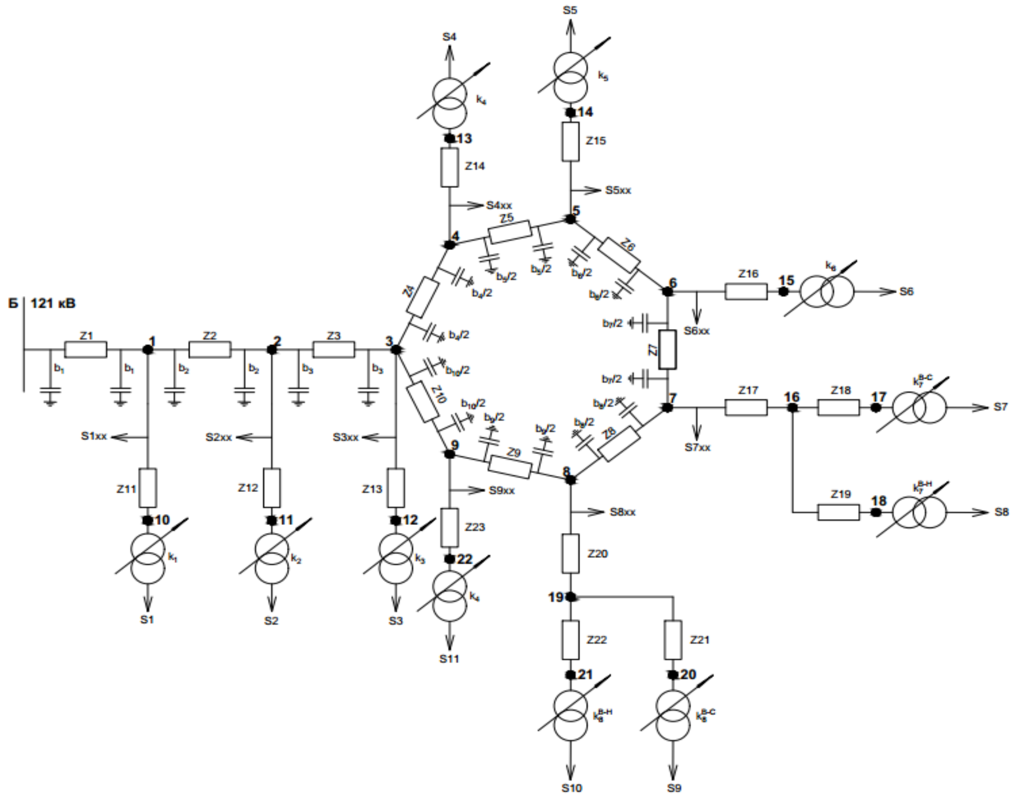

Fig. 1. Calculated scheme of the network.

on the low-voltage busbars, given the action of on-load tap-changers installed on transformers. Table 2 presents the total active power loss equal to $\Delta P_{\Sigma} = 6.431$ MW, or 9.9% of the active power supplied to the network, $P_{source} = 64.978$ MW.

The calculations were performed for a reduced voltage of the main substation in order to determine the permissible voltage profile in the distribution network. The results indicated that the permissible voltage profile in the network is ensured when the voltage of the base node is reduced down to 117 kV.

Lowering the main substation voltage leads to an increase in total active power loss, which is not feasible. Elevated voltage in the network facilitates additional active power loss due to the transmission of reactive power into the network. Therefore, reduction in active power loss in the network ensuring security presupposes the use of FACTS devices, which has both theoretical and practical implications.

The third and seventh nodes of the closed-loop network were selected for experimental analysis of SVC installation.

The scenario of a CU installed at the third node, stabilizing voltage level within the limits of the permissible voltage profile, involved calculating the reactive power of the CU and total active power loss in the network. Table 3 summarizes the results of the calculations and Fig. 2

TABLE 2. Changes in Power Loss as a Function of the Main Substation Voltage

U_0, kW	121	120	119	118	117	116	115
P_{source}, MW	64.978	65.73	66.509	67.317	68.156	69.031	69.945
P_{load}, MW	58.547	58.547	58.547	58.547	58.547	58.547	58.547
ΔP_{Σ}, MW	6.431	7.183	7.962	8.77	9.609	10.484	11.398
ΔP_{Σ}, %	9.90	10.93	11.97	13.03	14.10	15.19	16.30

TABLE 3. Power Loss Changes Given the Compensation at the Third Node

U_3 , kW	120	119	118	**117**	116	115	114	113
P_{source} , MW	70.376	70.245	70.148	**70.086**	70.059	70.067	70.110	70.188
P_{load} , MW	58.547	58.547	58.547	**58.547**	58.547	58.547	58.547	58.547
ΔP_{Σ} , MW	5.911	5.818	5.758	**5.732**	5.741	5.784	5.86	5.971
ΔP_{Σ} , %	10.10	9.94	9.83	**9.79**	9.81	9.88	10.01	10.20
Q_k , MVAr	67.78	63.99	60.29	**56.66**	53.12	49.65	46.27	42.97

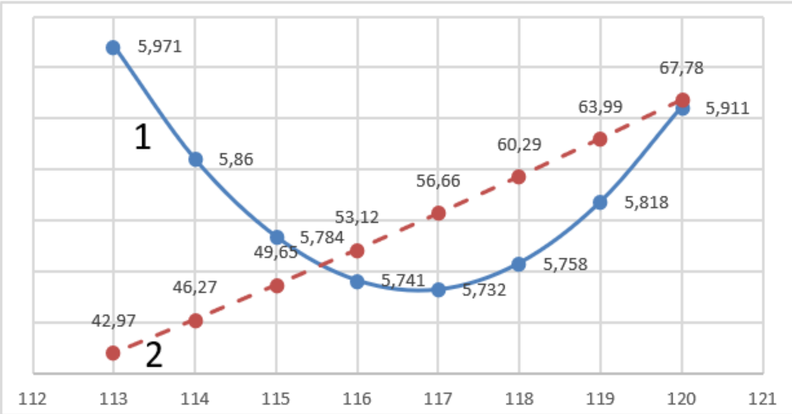

Fig. 2. Graphs of changes in the total active power loss (1) and the capacity of the compensation device (2).

demonstrates them.

The study has shown that the operating parameters exhibiting the lowest active power loss in the network are achieved with stabilization of voltage at the third node at the level of 117 kV, given the CU capacity of 56.661 MVAr. At the same time, the total active power loss in the network decreases and becomes equal to 5.732 MW, which is 8.92% of the active power supplied to the network (64.279 MW).

When the CU is installed at the seventh node, the optimum parameters of power system operation are achieved by voltage stabilization at 111 kV, with a CU

TABLE 4. Power Loss Changes Given the Compensation at the Seventh Node

U_7 , kW	114	113	112	**111**	110	109	108
P_{source} , MW	69.834	69.772	69.729	**69.704**	69.699	69.714	69.746
P_{load} , MW	58.547	58.547	58.547	**58.547**	58.547	58.547	58.547
ΔP_{Σ} , MW	5.659	5.611	5.581	**5.57**	5.578	5.605	5.65
ΔP_{Σ} , %	8.10	8.04	8.00	**7.99**	8.00	8.04	8.10
Q_k , MVAr	40.41	38.56	36.75	**34.98**	33.25	31.55	29.90

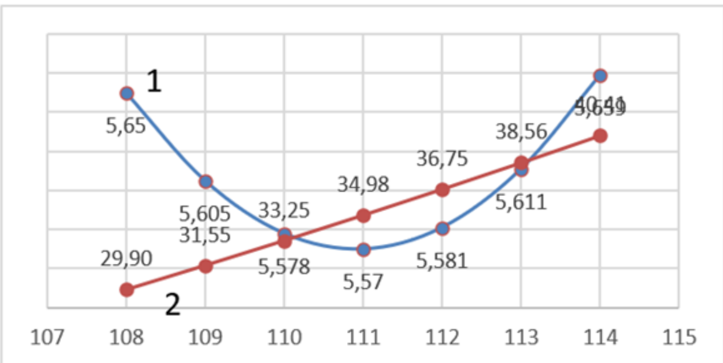

Fig. 3. Graphs of changes in the total active power loss (1) and the capacity of the compensation device (2).

TABLE 5. Changes in Power Loss Given the Compensation at the Third and Seventh Nodes

$U_3 = U_7$, kW	119	118	117	**116**	115	114	113	112
P_{source} , MW	63.92	63.841	63.795	**63.782**	63.801	63.854	63.939	64.057
P_{load} , MW	58.547	58.547	58.547	**58.547**	58.547	58.547	58.547	58.547
ΔP_{Σ} , MW	5.373	5.294	5.248	**5.235**	5.254	5.307	5.392	5.51
ΔP_{Σ} , %	8.41	8.29	8.23	**8.21**	8.23	8.31	8.43	8.60
$Q_{k,3}$, MVAr	27.18	23.29	19.48	**15.74**	12.08	8.49	4.97	1.53
$Q_{k,7}$, MVAr	35.01	35.13	35.25	**35.37**	35.49	35.62	35.75	35.88

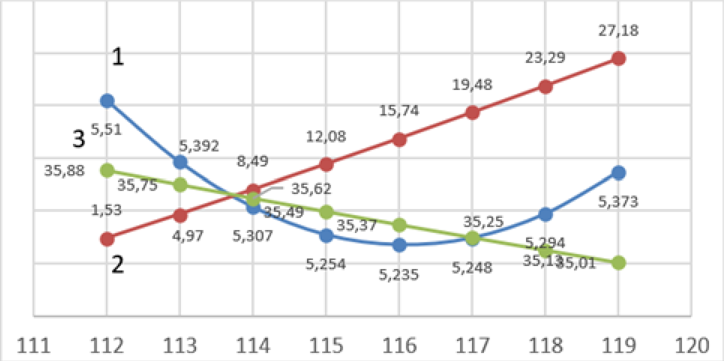

Fig. 4. Graphs of changes in total active power loss (1), capacity of the compensation device at node 3 (2), capacity of the compensation device at node 7 (3).

capacity of 34.978 MVAr, as can be seen in Fig. 3. The total active power loss in the network becomes equal to 5.57 MW, or 8.68% of the active power supplied to the network (64.117 MW).

Of the two options considered, Option 2 (CU installation at node 7) is more preferable. This option not only provides a significantly lower capacity of the CU but also achieves the greatest reduction in total active power loss in the network.

To further minimize active power loss in the distribution network, we considered the option of installing CUs simultaneously at the third and seventh nodes.

When the voltage is stabilized at 116 kV simultaneously at the two nodes (3 and 7), as can be seen in Fig. 4, active

TABLE 6. Power Loss Changes Given the Compensation at the Seventh Node

U_7 , kW	120	119.5	119	118.5	118	117.5	**117**	116.5	116
P_{source} , MW	24.35	24.33	24.31	24.29	24.28	24.27	**24.27**	24.27	24.28
P_{load} , MW	23.55	23.55	23.55	23.55	23.55	23.55	**23.55**	23.55	23.55
ΔP_{Σ} , MW	0.8	0.77	0.75	0.74	0.73	0.72	**0.715**	0.72	0.723
ΔP_{Σ} , %	3.28	3.18	3.1	3.03	2.99	2.95	**2.95**	2.95	2.97
Q_k , MVAr	14.06	13.09	12.12	11.17	10.23	9.30	**8.37**	7.46	6.55

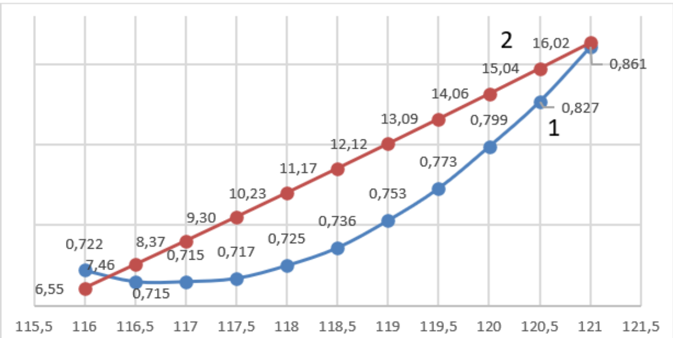

Fig. 5. Graphs of changes in the total active power loss (1) and capacity of the compensation device (2).

power loss in the network is reduced to 5.235 MW, which is 8.21% of the active power supplied by the main substation to the network (63.782 MW).

Based on the analysis of the calculations performed for the maximum load operation of the investigated network, we can state that the use of the static compensator as a device for stabilization of the required voltage level at the selected node notably enhances security and mitigates the total loss of active power while ensuring the voltage quality on the busbars of distribution substations.

The minimum load operation is also characterized by an increase in total active power loss in the network when the main substation voltage decreases. From the standpoint of reducing the total active power loss, it is necessary to stabilize the increased (technically permissible) voltage on the main substation busbars. The minimum value of total active power loss, which is equal to 0.902 MW, corresponds to the main substation voltage of 121 kV. When the main substation voltage is reduced, for example, down to 117 kV, the total active power loss increases to 1.001 MW. Table 6 shows the results of the minimum load operation with voltage stabilization at the seventh node.

The analysis of various operating conditions of the distribution system with an installed SVC revealed that the lowest value of active power loss is 0.715 MW (Fig. 5), or 2.95%, which is achieved when a compensation device is installed at node 7, with voltage stabilization at the level of 117 kV.

V. Conclusion

This study has demonstrated the effectiveness of using thyristor-based Static VAR Compensators (SVCs) as a means to enhance both the energy efficiency and operational reliability of 110 kV distribution networks. By employing a topology-based approach to determine optimal SVC placement and capacity, the analysis revealed that significant reductions in total active power losses can be achieved through voltage stabilization at selected nodes. The findings confirm that integrating FACTS devices into the distribution network not only ensures improved voltage profiles under varying load conditions but also contributes to the long-term security and stability of power supply. These insights can inform future strategies for optimizing reactive power compensation in complex electrical systems.

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