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PROCEDURE FOR CHOICE OF POWER AND PLACEMENT LOCATION OF CONTROLLED SHUNT REACTORS IN HIGH VOLTAGE ELECTRIC NETWORKS OF POWER SYSTEMS

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Abstract- In relation to 330-500kV electric networks in foreign countries in the 80s-90s of the last century, the scientific direction associated with the use of controlled shunt reactors (CSR) was intensively developed. However, today there are no generalized technical requirements for the choice of power and placement location, which must meet the CSR. Scientific and methodological justification for the choice of power and placement locations of CSR in 330 kV networks for the compensation of charging power of PTL, increase of their capacity, as well as to ensure the required level of reliability of power systems are given in the paper.

Keywords: Power System, High-Voltage Electric Network of Power Grid, Controlled Shunt Reactor, Charging Power, Natural Power, Charging Power of Power Transmission Line.

I. INTRODUCTION

One of the ways to ensure the reliability of power supply to consumers is to increase the capacity of power transmission lines and the availability of power reserves. An effective solution of this problem is the use of PTL with the correct choice of the CSR placement location and the selection of their settings, which will provide greater "flexibility" of the transmission system and can be used in the FACTS concept [1]. Market economy conditions assume full use of capacity of power transmission lines, entrusting the solution of a problem of stabilization to the auxiliary power devices providing its predetermined or permissible parameters. Today a number of ways to solve this problem have been proposed and more than 30 CSRs have been installed in networks of different voltage classes [2]. However, with the increase of the unit power of electrical equipment of power supply systems, the requirements for the settings of regulators change, and, therefore, new restrictions appear for the modes of PTL operation.

However, today there are no generalized technical requirements to be met by linear controlled reactors, and, most important, the procedures for the feasibility study for the use of controlled shunt reactors are not developed and the criteria for the choice of their placement locations in power systems are not defined. For the choice of CSR placement location, it is necessary to conduct large-scale studies on the physical and mathematical model of the complete scheme of the network with the implementation of steady-state modes system. In this regard, the development of procedure and the formation of criteria for the choice of CSR placement locations in high-voltage networks are highly topical. It will make possible to estimate the feasibility of the application of the controlled transversal reactive power compensation device on one or another substation according to quantitative parameters of system.

The economic analyses have shown that additional energy losses are at such a high level that despite the availability of expensive equipment, the SR installation is self-supporting for a period of less than 5 years [2]. In most power systems, there is still the problem of elimination of the surplus reactive power generated in the minimum load modes. The main reason for this redundancy is that the charging power in 330 kV lines is higher than the reactive power loss in them, and this can cause the voltage level increase to a level dangerous for the line insulation.

Scientific and methodological justification for the choice of power and placement locations of CSR in 330 kV networks for the compensation of charging power of PTL, increase of their capacity, as well as to ensure the required level of reliability of power systems in whole are given in the paper. The object of the study the 330 kV high-voltage electric network of the Azerbaijan power system is selected.

II. THE CSR SELECTION PROCEDURE FOR HIGH VOLTAGE POWER SUPPLY NETWORK

In order to determine the powers of SR, installed in the priority nodes identified in the power system, it is necessary to know the values of reactive power flows that may be included in them. The total charging power of lines with different voltages can be determined from the following expression:

$$Q_{d,\Sigma} = \sum_{i=1}^{n} U_i^2 b_{0,i} \sum_{j=1}^{m} l_j = \sum_{i=1}^{n} q_{0,i} \sum_{j=1}^{m} l_j \qquad (1)$$

or considering only one node

$$Q_{d_i,\Sigma} = U^2 b_0 \sum_{j=1}^{m} l_j = q_0 \sum_{j=1}^{m} l_j \ , \quad i=\overline{1,\, n} \tag{2}$$

where, b_0 is capacitive susceptance of 1 km of line; q_0 is charging power of 1 km of line; U_i i-node voltage; and l_j is j-line length.

Reactor powers can be determined by the below formula [5, 6]:

$$Q_r = P_{nat} \cdot \lambda \cdot \left(1 - \frac{P}{P_{nat}}\right) \cdot l \tag{3}$$

where, λ is wavelength is determined as follows:

$$\lambda = \frac{\omega}{v} = \frac{314}{3\times10^5} = 1.05\times10^{-3}\,\frac{\text{rad}}{\text{km}}$$

where, P_{nat} is natural power of line; P is power transmitted from line; ω is angular velocity; and v is velocity of electromagnetics wave propagation. The 330 kV PTL natural power is $P_{nat} = 360$ MVt [4-6].

Reactor power is selected from $P = P_{nat}$ condition, in this case

$$Q_r = P_{nat} \cdot \lambda \cdot l \tag{4}$$

For this purpose, the following formula can be used [7]:

$$Q_r = P_{nat} \cdot \tan\lambda \tag{5}$$

On the basis of the above method, the problem of determining the charging powers for 330 kV nodes of the Azerbaijan power system and the nominal powers of shunt reactors is considered (Figure 1). The power system consists of 14 Nos. nodes with 330 kV voltage. The nodes have intersystem and backbone nature. For example, let's consider the 330 kV Goranboy intrasystem node. So, the 330 kV Goranboy node connects 1st Goranboy 330 kV (2×ACO-300, 56.3 km), 2nd Goranboy 330 kV (2×ACO-300, 84.2 km), 3rd Goranboy 330 kV (2×ACO-300, 165.8 km), 5th Mingechevir 330 kV (2×ACO-300, 33.8 km) and 6th Mingechevir 330 kV (2×ACO-300, 33.3 km) overhead lines.

In order to determine the SR power, the charging powers of the lines for each node are calculated. Charging power falling on 1 km of 2×ACO-300 type 330 kV PTL is $q_0 = 0.41$MVAr/km [4]. This will be obtained by means of calculation:

$$q_0 = U^2 b_0 = 330^2 \times 3.4\times10^{-6} \approx 0.37\ \text{MVAr/km}$$

III. PROCEDURE FOR PLACEMENT OF SHUNT REACTORS IN 330 KV NODES OF POWER GRID

A special procedure can be used for the reactor placement in the power system. The essence of the procedure is as follows. SR placement on all 330 kV substations, including open 330 kV SG of power plant, is possible in principle. However, for known reasons it is impossible to implement. In order to determine the criteria for selection of the most efficient SR installation locations, it is necessary to analyze their impact on two important indicators of the power system mode. It is known that such indicators are the quantities of absolute and relative reduction of voltage levels at various points of the network before and after the installation of reactors. Calculations should be carried out for the most severe minimum load conditions, so that the voltage levels at the observed points of the network reach the maximum possible value. It is clear that in this mode the reactor power should be maximal. Therefore, during the comparative calculations, the SR power is assumed to be equal to the reactor rated power for all nodes.

As a result of SR installation at separate substations, there will be various impacts on the average voltage level in 330 kV nodes of the power system and the total loss level in networks. Obviously, the SR installation at any substation will lower the voltage level both at this station (most of all) and at other substations. Therefore, the average under voltage can be accepted as main technical efficiency indicator of reactor installation. Another important indicator is power loss reduction in networks.

It should be noted that during the installation of a single SR, in contrast to the voltage, the power loss can both increase and decrease. In other words, the power loss reduction factor can be both positive and negative. Taking into account the above-mentioned, as a special technical efficiency indicator of the reactor installation, the mean absolute δU_{or}, mean relative $\delta\bar{U}_{or}$ voltage reduction and, accordingly, the absolute δP_{Σ} and relative $\delta\bar{P}_{\Sigma}$ total power loss reduction can be accepted. These quantities can be determined by performing multivariate calculations with the alternate SR placement at different substations. In addition to the above, for a comprehensive assessment of the technical and economic efficiency of the SR application, the resulting efficiency indicator $E_{ef,\Sigma}$ was proposed, which is expressed as follows [2]:

$$E_{ef,\Sigma} = \delta\bar{U}_{or} \cdot \delta\bar{P}_{\Sigma} \tag{6}$$

It is possible to advance an idea of comparative efficiency of the SR installation at different points of the network in accordance with the value of this indicator. It should be noted that in the case when the SR placement has the same effect on the average voltage level (it always reduces), the reactor loss level is double affected. Thus, in this case the loss may both increase (beneficial effect) and decrease (useless effect).

Obviously, in this case, the comparison and alternation of substations according to the $E_{ef,\Sigma}$ indicator gives meaning to its positive values. In other words, certain places for the SR installation should be selected among the nodes with the $E_{ef,\Sigma} > 0$ condition. In addition, other factors should be taken into account, especially periods of commissioning of substations, the availability of place for SR installation, possibility of electric connecting diagram and reactive power flow from neighboring power systems.

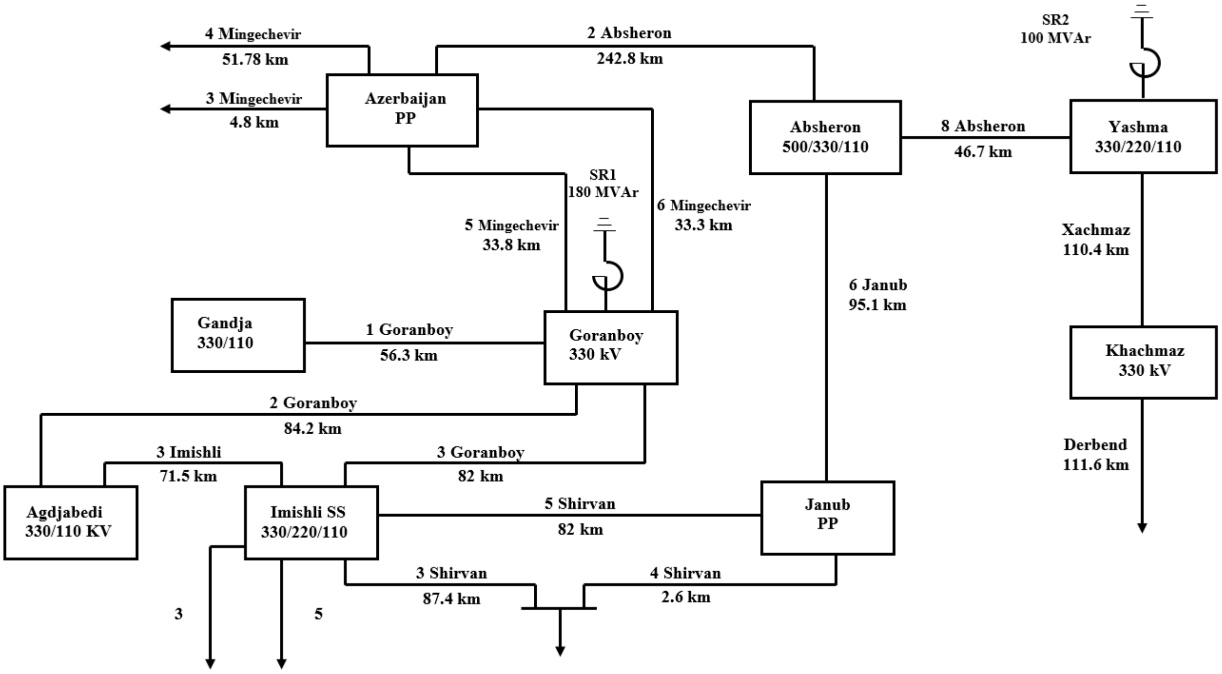

Figure 1. Structural connection diagram of 330 kV nodes of power

The values of the special and resultant efficiency indicators indicated for the 330 kV nodes of the power system under consideration (initial loss of 15.2 MW) are given in Table 1. The nodes are arranged in a sequence of decreasing values of $E_{ef,\Sigma}$ indicator.

Table 1. Efficiency indicator values for the 330 kV nodes of power grid

Node No.	Node name	Voltage, kV		Total loss in network, MW	Total loss absolute and relative reduction		Mean absolute and relative voltage reduction		Efficiency index, E_{ef}
		Bus voltage before SR connection	Average voltage after SR connection		MW	%	kV	%	
39	Absheron 330	344.38	334.23	14.5	0.7	4.61	3.60	1.07	4.912
201	Janub PP	346.53	334.66	14.6	0.6	3.94	3.17	0.94	3.701
101	Yashma 330	342.18	333.96	14.9	0.3	1.97	3.87	1.15	2.261
601	Min HPP	339.44	335.55	14.7	0.5	3.29	2.41	0.71	2.349
651	Az PP 330	339.23	335.55	14.7	0.5	3.29	2.28	0.68	2.219
400	Goranboy SG	338.76	334.91	14.9	0.3	1.97	2.92	0.86	1.704
333	Agdjabedi 330	342.64	333.78	15.0	0.2	1.32	4.05	1.19	1.577
280	Imishli 330	344.27	333.86	15.0	0.2	1.32	3.97	1.18	1.548
801	Khachmaz 330	343.43	333,99	15.0	0.2	1.32	3.84	1.14	1.497
411	Shamkir HPP	331.01	336,13	15.4	-0.2	-1.32	1.70	0.50	-0.663
401	Gandja 330	329.82	335,79	15.5	-0.3	-1.97	2.04	0.60	-1.190
456	Samukh 330	328.74	335,98	15.6	-0.4	-2.63	1.85	0.55	-1.443
457	GAZ 330	328.28	335,89	15.8	-0.6	-3.95	1.94	0.58	-2.269
502	Akstafa 330	330.89	335.25	15.9	-0.7	-4.61	2.58	0.76	-3.516

As can be seen from the table, the $E_{ef,\Sigma}$ quantity value is positive only for the considered nodes 14-9, and the reactor installation locations should be selected between the nodes just with this value $E_{ef,\Sigma} > 0$. In this case, in addition to the condition $E_{ef,\Sigma} > 0$, as noted above, other factors should be taken into account (the periods of commissioning of substations, the availability of places for the SR installation, the technical possibility for the electric schematic diagram of switchgear, etc.).

Therefore, taking into account the above factors, the 330 kV Yashma and SG 330 kV Goranboy nodes are accepted as priority nodes. Thus, for both nodes the condition $E_{ef,\Sigma} > 0$ is met and in addition, due to the possibility of connection at the 330 kV Yashma SS to the reactor bus, and at the SG Goranboy 330 kV to the free node of one circuit of a 3/2 circuit, as well as due to the availability of appropriate places for the placement of reactors, the schemes become effective and reliable. In addition, the calculations performed for the case of connecting reactors in the Yashma 330 kV and SG Goranboy 330 kV nodes (100 and 180 MVAr respectively) have showed that an appropriate efficiency indicator in this case was $E_{ef,\Sigma} = 5.422$. As another option, in the case of SR connection to the Absheron 330 kV and Agdjabedi 330 kV nodes, the value of this indicator becomes $E_{ef,\Sigma} = 7.127$. This shows the efficiency index increase in comparison with the different cases under consideration.

As can be seen from Table 1, to connect the reactor in the future, 330 kV bus of Janub ES, 330 kV nodes of Agdjabedi and Imishly can be considered as the third priority node. Additional research works should be carried out for this purpose.

IV. RESULTS OF REGIME CALCULATIONS ACCORDING TO NORMAL SCHEME WITH PLACEMENT OF COMPENSATING SCHEMES IN POWER SYSTEM

In order to determine the voltage levels in the nodes of the power system, regime calculations should be carried out for the maximum and minimum load conditions of the power system. Some typical voltage profiles of 330 and 500 kV load nodes on the basis of calculations performed for the maximum and minimum modes on real perspective diagram of the power system in MUSTANG-95 format (taking into account Baku-3 220/110/10 kV, Sulutepe (Goba) 330(220)/110/10 kV and Agsheher 220/110/10 kV substations) are represented in Figure 2. The voltages are expressed in relative units $\left(U_{r.u.}=\dfrac{U}{U_{nom}}\right)$.

It should be noted that the minimum load mode of the power system accepts the $0.3P_{\max}$ value ($P_{\max}$ is the maximum active load of the power system).

As can be seen from the figure, in the maximum load mode (P_y=5613.9 MW, Q_t=3355.2 MVAr) the voltage in 500 kV nodes varies within the (1.0-1.014)U_{nom} interval, in 330 kV nodes within the (0.972-0.999)U_{nom} interval, and in the minimum mode (P_y=1684.2 MW, Q_t=1006.6 MVAr) the voltage in 500 kV nodes varies within the (1.0-1.03)U_{nom} interval, in 330 kV nodes within the (0.996-1.05)U_{nom} interval (Table 2). Thus, the voltage in the maximum and minimum modes is within normal limits. In some nodes, the voltage is set to the upper limit.

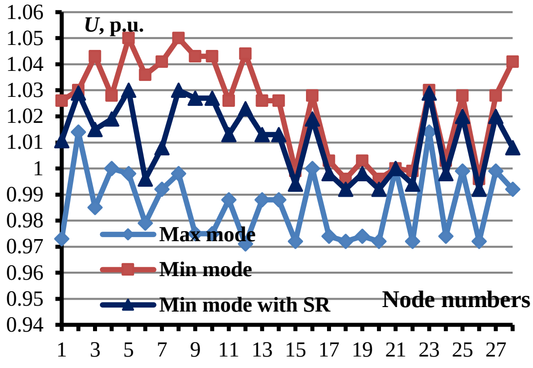

Figure 2. Voltage profiles on 330, 500 kV nodes for normal modes of power grid

Taking this into account, the calculation for the minimum mode was repeated when connecting shunt reactors with a capacity of 180 MVAr to the Goranboy-330 kV node and capacity of 100 MVAr to the Yashma-330 kV node. Apparently, in the case of connecting the reactors in the minimum mode, the voltage profiles improve and around the nominal value change in the range (0.992-1.03)U_{nom}.

The active power loss of the power system in the maximum mode is 96.6 MW, and in the minimum mode is 15.2 MW. After connection of the reactors, the loss in the minimum mode decreased to 14.7 MW (0.03%).

V. CHECK OF THE PROPOSED PROCEDURE IN CASE OF FAILURE OF POWER TRANSMISSION LINE OF HIGH VOLTAGE POWER SUPPLY NETWORK OF POWER SYSTEMS

The results of simulation of repair modes on the basis of N-1 and N-2 criteria were considered in order to clarify the maintenance of the regime reliability in case of sudden random cutoff of one or more elements of the power system in the minimum modes [8, 9].

For this purpose, the relevant regime calculations were carried out in the simulation of emergency conditions, taking into account the CSR impact in the cases of failure of some 330 kV power lines. The cases of cutoff of Absheron-1, Absheron-8, Agstafa-4, Goranboy-3, Shimal PP according to N-1 criterion, and Shimal PP and Absheron-1 according to N-2 criterion were considered.

Voltage profiles by nodes based on the results of calculation performed according to N-1 criterion are represented in the Figure 3.

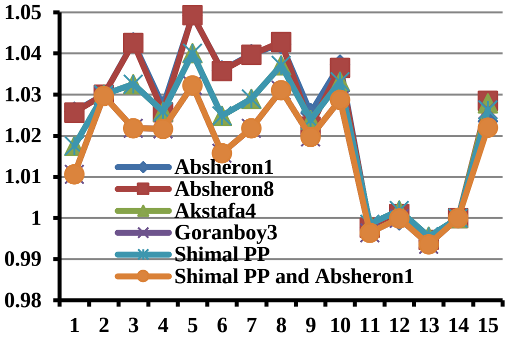

Figure 3. Voltage profiles for random cutoff cases

As can be seen from Figure 3, the voltage location in the nodes within the permissible limits during the calculation of model of emergency modes (random shutdown) of the power system based on the N-1 criterion should be noted. The voltage at some nodes, for example, the voltage at node 5 (Janub PP) is at the upper limit during the disconnection of the Absheron-8, Agstafa-4 and Goranboy-3 lines. The same conclusion can be made for the Imishli node. Taking this into account, in some considered emergency modes (disconnection of the Agstafa-4 and Goranboy-3 lines) the regime calculations were carried out for the case of connection of shunt reactors to identified nodes. The voltage profiles for the cases of cutoff of Akstafa-4 and Goranboy-3 lines are represented in the Figures 4 and 5, respectively.

As can be seen from Figures 4 and 5, in cases of CSR connection to both nodes, the voltage profiles relatively improve and are within the permissible limit.

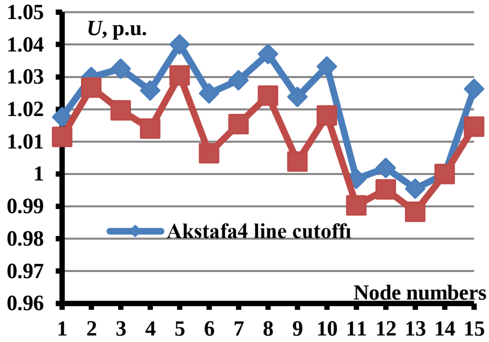

Figure 4. Voltage profiles for SR off and on cases for Agstafa-4 line cutoff case

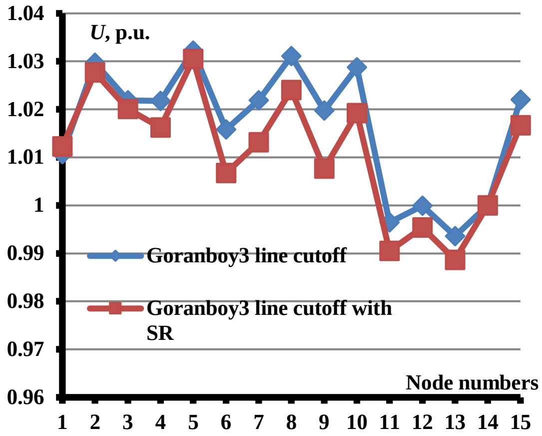

Figure 5. Voltage profiles for SR off and on cases for Goranboy-3 line cutoff case

VI. CONCLUSION

1. Based on the calculation of the charging power of high-voltage power supply network, the procedure for choice of power and placement location of controlled shunt reactors is proposed. It was found that in normal steady-state modes of the power system, despite the placement of 330 kV nodes mainly within the permissible voltage limits, in the minimum load conditions in some nodes, the voltage approaches the upper limit of 1.05 U_{nom} and in extreme cases can exceed this limit. For this reason, the CSR placement in some nodes is considered advisable.

2. In order to install the CSR, priority nodes of the power system were identified and justified. The CSR power was determined and the relevant regime calculations were carried out for their placement in two priority nodes of the power system. The obtained results confirmed the elimination of the surplus reactive power substantially in high-voltage networks of the power system in the minimum modes and, consequently, the voltage profile input at the nodes to the permissible limits. Application of the proposed procedure during reconstruction and design of power systems with long 330-500kV PTLs, allows for solving the problem of charging power compensation, voltage level stabilization and increase of PTL capacity.

3. The obtained results confirm the feasibility of CSR installation in the high-voltage power supply network of power systems and continuation in the future of studies for the consideration of uncertain factors affecting the accuracy of the proposed procedure.

4. The procedure for choice of power and placement location of CSR is proposed for adoption in 330 kV high-voltage power supply network of the Azerbaijan power system.

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BIOGRAPHY

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