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Finding of the rational approach at the decision of a compensation in high-voltage networks

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Abstract: **The aim of the present work is to find a computational model, sufficiently simplified for practical use which determines the sensitivity of the complex high-voltage electrical networks when switching compensatory powers. We show how this model can be used as a basis for creating practical criteria for a one-valued choice in the two situations. First, switching the compensatory power does not lead to leaving the permissible range of voltage. In this case the power which minimizes the power losses is used. Second, the compensatory power is switched in order to return the voltage to the permissible range. Then that compensatory medium is chosen which is sensitive enough in addition to causing the minimal increase in electrical power losses.**

I. INTRODUCTION

Compensatory devices operating in high-voltage electrical networks (HV), such as reactors, capacitors batteries, synchronous and static compensators, generators exciting systems and others, for steady states management of voltage, usually there are two situations:

1) The nodal compensatory power switch (also increase/decrease) does not lead to the voltage output from legitimate range. In this case it is necessary to use the compensator as the mean to decrease the network loss.

2) In case when voltage is outside the permissible area, to switch, it is necessary to select that compensatory device to which the network mode is sufficiently sensitive with minimal increase in losses. Apart of network loss it is necessary to consider auxiliary loss in the compensatory device (ventilators, pumps and other).

Our object is to identify a simple reasonable practical criterion for the analysis of possible options for rational compensation. An issue of determining the sensitivity of voltage and compensating the loss of a single power, using a simplified computational model based on the linear transformation circuit network is considered here.

A. *The voltage sensitivity in the compensation*

The voltage sensitivity (h) when connected to the unit nodal reactive power can be defined as the ratio of the change [1]:

$$h = \frac{\Delta U}{\Delta Q} \quad \left[\frac{kV}{MVar}\right], \tag{1}$$

or in relative units and in percentage for the voltage:

$$h_{r.u.} = \frac{\Delta U}{U \cdot \Delta Q} \cdot 100\% \;, \left[\frac{\%}{MVar}\right]$$

In general, the parameter h can be defined for all other nodes, entering the "zone of compensation". Considering the sensitivity of nodal voltage relative to the impact of reactive power management regime of the voltage in normal and disaster conditions can be easily and quickly planned and carried out. When the voltage is in the admissible domain, the parameter h becomes very important for the techno-economic analysis and optimization of the regime. In the alternative situation where the voltage is out of range, this parameter helps to determined which of all the compensatory capacity after the switch will have the greatest impact for the introduction (or even approximating) the voltage in the permissible area. This is particularly important for the transition to repair schemes, in accidents or sudden changes in the regime with subsequent complex operational switching.

Theoretically, the sensitivity of h depends on all factors relevant to the treatment system, but also on the network configuration. The method of determination of h systematic daily observations of operational practices is unacceptable. Our idea is to use the fact that h is weakly depended on the distribution of active power, but mainly depends on network configuration and the voltage at the node where the compensation is processed. Let's suppose that, using the radial node model (Fig.1) for the balance of reactive currents in the node k, after its voltage changing of ΔU_k, which is evoked by inclusion of compensating susceptibility b_k, let's put it according to the Kirchhoff's First law:

$$(U_k + \Delta U_k) \cdot b_k + \Delta U_k \cdot \sum_{j=0}^{n} b_{kj} = 0\,, \tag{2}$$

where with the help of b_{kj} we denote susceptibility branches between node k and node j with almost the same (reference) voltage. By doing that, we assume that the balance of currents in the node k existed prior to switching, and (2) applies only to changes in currents, when saving the values of reference voltages.

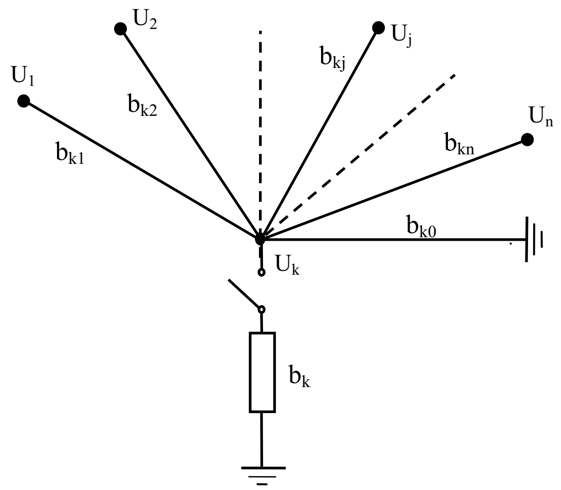

Fig. 1 The radial (star) equivalent circuit for determining the sensitivity of the voltage in the node k with the inclusion of compensatory conductivity b_k and the n reference nodes with constant voltage

Let us explain a single radial circuit model acquisition. We suppose that all the network settings are given the same level of voltage or relative units, so there are no ideal transformers. To simplify we neglect positive conductance, as a convenience to conditionally accept that inductive conductivity is positive but capacitive is negative. Supporting nodes numbered $1,2,..., j,...n$ are those nodes that restrict certain parts of the original network with a central node k, over which the impact of compensation are produced at the node k is not covered. Practically this is generator nodes with a voltage regulation or sufficient remote electric, powerful, well-developed nodes in the system (big substations), which, because of remoteness do not feel the impact of compensation undertaken. Obviously, in any electrical system, you can always make the area near the compensatory node with the same properties. Next to the scheme obtained we have to exclude all the non-regulated voltage loading nodes. Nodes with other not investigated the sensitivity of compensating capacity are joined to them. Presenting a load of load nodes by a shunts (conductivities on the ground), they can be excluded from the scheme of a linear transformation of the original description (the matrix of nodal conductivity) by Jordan. At this the influence of loads on the evaluation of the sensitivity will be automatically replaced by the equivalent conductivity b_{k0} (Fig.1).

Unknown ΔU_k can easily be identified from (2):

$$\Delta U_k = -U_k \cdot \frac{b_k}{b_k + \sum_{j=0}^{n} b_{kj}} = -U_k \cdot \frac{b_k}{b_{kk}}, \tag{3}$$

where b_{kk} is obviously the own conductivity of node k after its switching.

It can be proved quite accurately, that this "practical" approach and the formulas of type (3) lead to the maximum possible error app. 2%. This assessment was confirmed by comparing the formula (3) with the results of program PSLF (General Electric) in the case of the Bulgarian electrical system, where they do not have long lines.

We were able to determine the sensitivity of the system for compensation only on the basis of the network configuration (topology) – change of voltage is directly proportional to the conductivity of compensating power b_k and inversely proportional to its node conductivity b_{kk}. The following conclusions are made from here:

1) The sensitivity of voltage to compensation decreases with the increase of the adherence. The nodes remote enough with a large number of divergent-line almost become insensitive; they can be taken as reference nodes.

2) Affiliation with the domain capacitive conductivity (capacitors, lines at idle) improve the sensitivity because of the opposite sign of their b_{kj}, that leads to the reduction of b_{kk}.

3) Changing the coefficient of transformation, reflecting the given transformer's conductivity, has a greater impact when the transformer (autotransformer) is directly connected to the node k and even more, when the number of connections in this node is not enough. In other cases, changes in the coefficients of transformation can be neglected.

4) The availability of long lines (they have relatively more capacity and lower susceptance) helps to improve the sensitivity. The same result is available if the parts of the lines in the considered area are deactivated.

5) The presence of closely located node with automatic voltage regulation is represents an addition a new reference node, and consequently the increase in the number of lines in the equivalent scheme (Fig.1) that conducts to decrease in sensitivity of node to compensation.

According to the principle of imposing we will write down the nodal equations of the distribution of setting compensatory current J_k in matrix form:

$$|Y| \cdot |\Delta U| = |J|, \tag{4}$$

Where the vector $|J|$ contains only 1 non-zero element that sets the current of compensating power J_k :

$$J_k = -U_k \cdot b_k, \tag{5}$$

Vector ΔU_k contains unknown changes of voltages of all nodes in the scheme when the compensating power is switched on. Determined ΔU from (4):

$$|\Delta U| = |Y|^{-1} \cdot |J| = |Z| \cdot |J|, \tag{6}$$

Here the matrix Z is the matrix of nodal resistance.

In the case of disconnection of compensating power will be the same, but it is necessary to take the opposite sign of the master current, but from their own nodal conduction b_{kk} in Y matrix must be subtracted b_k. Upon receipt of ΔU for all nodes in the allocated area, the sensitivity in relative units for each node can be determined:

$$\left|\Delta U\right|_{pu} = \frac{|Z| \cdot |J|}{U_k}, \tag{7}$$

Receptions of use of the formula (7) for all possible schemes in the normal mode for the purpose of management of modes of voltage are considered in [1].

On the basis of (7) was established created the software product "Q-sens". The calculation is computed by the method of Gauss, and the results firstly were compared with the results of the program PSLF, and then were checked and have proved to be true at the practice in territorial dispatching management ТДУ „Изток", Bulgaria.

The sensitivity of voltage h as a differential value can be used only in at very small change in reactive power. Its use in the real sources of reactive power demands it's preaveraging or taking into account the size of a total power of a source. This corresponds to the case where the real power of compensator takes the role of unit power.

B. The sensitivity of active losses in the network, with compensation

The losses of active power P_{loss} can be expressed as a Hermitian quadratic form of complex nodal voltages. Then its sensitivity f with the compensation will have a linear form:

$$f = \frac{\Delta P_{loss}}{\Delta Q_k} = \left(\frac{\Delta P_{loss}}{\Delta U_k}\right) \cdot \left(\frac{\Delta U_k}{\Delta Q_k}\right) = h \cdot \left(\frac{\Delta P_{loss}}{\Delta U_k}\right), \tag{8}$$

This linear form should not be changed when at linear transformation of the scheme that is at the exception of nodes. This fact allows us to determine the losses of using the equivalent radial scheme (Fig.1). This approach is fully corresponds with to the РЕИ Dimo models at the determining the losses in complex networks [2].

As we have accepted the assumption that the active flux-distribution in the area of compensation does not change, the change of losses at the compensation we can define only by changing the reactive currents:

$$\Delta P_{loss} = \sum_{j=1}^{n} \left(2 I_{kj} \cdot \Delta I_{kj} + \Delta I_{kj}^2\right) \cdot R_{kj}, \tag{9}$$

where the parameter R_{kj} is active resistance of the branches between the nodes k and j. Expressing I_{kj} trough reactive power of the branch Q_{kj} and U_k, and ΔI_{kj} trough $\Delta U_k \cdot b_{kj}$ receive:

$$\Delta P_{loss} = \Delta U_k^{pu} \sum \left(2 Q_{kj} b_{kj} + \Delta U_k^{pu} U_k^2 b_{kj}^2\right) \cdot R_{kj}$$

Let's divide the last expression into 2 parts, one of which (ΔP_2) does not depend from flux-distribution of reactive power:

$$\Delta P_1 = 2\Delta U_k^{pu} \sum Q_{kj} b_{kj}^2 R_{kj}, \; j = 1,...,n, \tag{10}$$

$$\Delta P_2 = 2\Delta U_k^{pu2} U_k^2 \sum b_{kj} R_{kj}, \; j = 1,...,n, \tag{11}$$

The total (complete) losses ΔP_Σ includes its own heat losses and energy consumption on cooling in the own compensating device ΔP_k. At jet sources with smooth management ΔP_k appears only at the time of inclusion.

Sensitivity of complete losses f on a single compensating power ΔQ is defined as:

$$f = \frac{\Delta P_\Sigma}{\Delta Q_k} = f_1 + f_2, \tag{12}$$

while f_1 depends on the regime, and f_2 is independent from the regime:

$$f_1 = \frac{\Delta P_1}{\Delta Q_k} = 2 h_{pu} \left(\Sigma Q_{kj} b_{kj} R_{kj}\right), \tag{13}$$

$$f_2 = const, \tag{14}$$

Note that the sign and value of f_1 are defined from the product at h_{pu} and ΣQ_{kj}, so that the optimality condition of the losses will depend from the previous regime.

Restrictions on the search for the optimal version are the restrictions in the search of an optimum variant of voltage. In the case when the voltage is out of the admissible range, the search for the optimal option should be made only among those compensators, which sensitivity on the h voltage is sufficient for entry into the allowable area. If this can not be comprehended, then must be chosen a compensating device, for which the product $h \cdot \Delta Q$ is largest, and thus pressure approach to one of the boundaries of the allowed range of the voltage change will be maximum while the increase of active losses in the network will be minimum.

On the basis of stated it is possible to suggest the following plan of switching of reactive power:

1) If the voltage U_k stays in acceptable range:

a) It is necessary to consistently switch on the compensating powers for which:

$$f < 0 \text{ and } \max_k\left(-f \cdot \Delta Q_k\right) - \Delta P_k\,, \tag{14}$$

b) It is necessary to consistently switch off the compensating powers for which:

$$f > 0 \text{ and } \max_k\left(f \cdot \Delta Q_k\right) - \Delta P_k\,, \tag{15}$$

2) If the voltage U_k is out of admissible range, it need to select a compensating device for which:

$$\mathrm{mod}(h) \cdot \Delta Q_k \Rightarrow \max\,, \tag{16}$$

and the sign of h need to be choose appropriately the direction of movement of the permissible area.

On the basis of gotten analytical expressions it is possible to make the following conclusions:

1) In homogenous networks $(R / x = cons)$ choice of an optimum variant can be made only on the value of f_2, that is only on permanent loss ΔP_2, because $f_1 = 0$. While the voltage remains in the acceptable range, in the beginning it need to switch off the devices with the largest own thermal losses and consumptions for cooling regardless of the sign h. Indeed, in homogeneous networks natural flux-distribution predetermines minimum losses and compensation in this sense is not very efficient.

2) In the optimal variant autotransformers directly connected to the compensatory node should be loaded more on reactive power than the lines divergent from the node, because the last the value $b_{kj} \cdot R_{kj}$ is bigger. Any breach of this condition is a sign of non-optimal flux-distribution on reactive power.

3) Switching of compensating capacities, can lead to rearranging the options in terms of their efficiency, because it changes the topology of the network and influences the determination of sensitivity of other sources. Therefore, at multi-process of optimization, it is necessary to review options which are deleted in the earlier phases after each step.

II. CONCLUSION

Introduced simple mathematical model make it easy allows two important characteristics of sources of reactive power – voltage sensitivity and loss sensitivity of active power in the network while changing the nodal reactive power.

The gotten simple characteristics of sensitivity can find application in the automated systems of dispatching management of the established regimes, and also for the needs of the analysis and designing of development of HV networks.

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