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FEATURE OF OPTIMAL NETWORK RECONFIGURATION PROBLEM STATEMENT IN DISTRIBUTION SYSTEMS WITH LOCAL ENERGY SOURCES

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Purpose. Increasingly widespread integration of local sources of energy generation and storage, growth of electric vehicle charging stations in electrical distribution systems sharply reduce the efficiency of the traditionally used methods and technical means of the control of their modes. In particular, this concerns such a popular task as choosing the optimal places of the normally open points in the circuits of distribution networks with objective to minimize loss of electrical energy. Methodology. The selected normally open point remained unchanged for quite a long time. However, the above features of modern distribution systems cause serious changes in the traditional structure of distribution networks and their modes of operation, which will become less stable and more unpredictable. As a result, under the influence of random factors, load flows of various durations are appeared in the networks, and in many cases will differ significantly from the mode (load flow) for which the optimal normally open points were determined. Compared to the traditional distribution network reconfiguration approach, a novel dynamic reconfiguration is proposed for a system with a high penetration of renewable energy sources or high level of load heterogeneity. The decision to change the location of the open point of the network is made when the positive effect of the additional reduction in energy losses exceeds the damage from the increased use of the switching resource of the circuit breakers and reduction in their life cycle. Findings. A special algorithm is proposed to make such a decision, taking into consideration technical as well as economical aspects of the problem. Originality. In this regard, this paper discusses the possibility, feasibility and efficiency of selective use of the so-called 'soft open points' technologies, which allow independent optimal control of active and reactive power flows for minimization of electrical energy losses. Practical value. Power electronic devices as a 'soft open points' have been proposed to combine the benefit of distribution networks operations both radial and closed modes. This solution is especially useful in the case of frequent and short-term changes in network modes. A new algorithm to speed up of independent modeling the active power and reactive power flows in feeders with to-way power supply is discussed. Conclusions. A general approach to the control of the corresponding power electronic equipment is proposed to ensure optimal load flow in the distribution feeder in real time. References 14, figures 4.

Key words: distribution networks, distributed generation, network reconfiguration, energy losses, soft open points.

INTRODUCTION. The integration of distributed generation (DG) has a significant impact on the distribution network (DN). In a traditional DN, power flows in a one-way from the substations (slack bus) to the load side; meanwhile, a DG may change power flow in multiple directions from points with local generation sources inside the DN, in accordance with the level of the voltage.

With increasing penetration of distributed resources, especially renewable (such as photovoltaic panels and wind turbines), in medium voltage electrical networks new challenges such as hardly predicted and even reverse power flow, voltage excursion, equipment overloads, harmonic distortion are increasingly prominent. At the same time the grouse of such consumers as electrified heat and electric vehicles, may significantly increase the peak demand of DN. Moreover, it is necessary to take into consideration the uncertainties in consumption and local power generation.

All this makes it difficult to maintain the optimal distribution networks modes, focusing on traditional technical means and methods (for example, by realizing network reconfiguration or on-load tap changers of transformers in a standard way). At the same time, the choosing the optimal configuration of loop distribution networks has been and remains one of the most effective actions to minimize power losses and to provide the necessary voltage levels.

In almost all countries, electrical DNs were designed and operated as open circuits, which made it possible to use less expensive systems of their relay protection and automation. Such solutions provide quick isolation of damaged elements and restoration of power supply, simplified the control of the network modes. Therefore, for many decades, the choice of optimal location of normally open points has been considered as one of the most popular and effective problems of optimizing the modes of distribution networks, mainly built according to the loop scheme [1–6].

To achieve a better performance of the DNs operation and to reduce the overall cost, other solutions, for example, such as soft open points (SOPs) have to be used. A SOP is a new type of power electronic equipment which mainly consists of two back-to-back voltage source converters (VSCs) and can replace the traditional tie switch in most cases installed in normally open point [7].

The conventional DNs are usually operated in open loop. As a power electronic device, SOP can accurately and rapidly control the active and reactive power of the two connected feeders and in such a way to combine the advantages of both a radial and loop (mesh)-operated network. So, the deployment of SOPs makes possible to continue using networks with an open topology simulating their operation in a closed mode.

The main topologies of SOPs as multi-functional power electronic devices include back-to-back voltage source converters, multi-terminal voltage source converters, SOP integrated with energy storage system (ES) and some other. Fig. 1 illustrates the single line representation of the distribution network with various basic forms of SOP application.

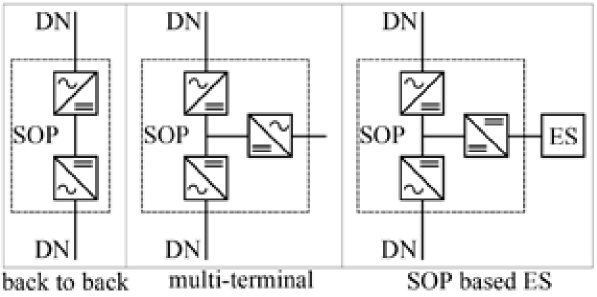

Fig. 1. Forms of SOP application

In any case SOPs can provide fast active and reactive power flow control, which can bring benefits under normal operation of DN: balance in optimal way the power loads between connected feeders and thereby to reduce the overall power and energy losses, improve the voltage profile, to eliminate network overload, to mitigate the three-phase unbalance by the ability to rapidly regulate the three-phase active and reactive power, to enhance DG hosting capacity. When a fault occurs, SOPs can detect it and isolate the fault area resulting in the reliability improvement.

Quantifying the benefits of SOPs is important tool for their implementation, for example, it can be used as objective functions in the optimization problems for the optimal control of SOPs in distribution networks. There are various suggestions to quantify of SOP benefits.

For example, in [8] the apparent power flow is used to represent the line utilization index (FLB – feeder load balancing)

$$FLB = \sum_{n=1}^{N} \left(\frac{S_n}{S_{n,\,r}} \right)^2 ,$$

where S_n is the apparent power flow in branch n;

$S_{n,r}$ is the rated capacity of this branch;

N is the total number of branches.

Voltage profile index (VPI) reflects the degree of dispersion of all bus voltages from the nominal values and is used as a measure of the voltage improvement

$$VPI = \sum_{k=1}^{K} \left(\left| U_i -_r U \right| \right)^2 ,$$

where U_k, U_r are the real and nominal voltage magnitudes at bus k, K is the total number of buses.

In [9], the three-phase balancing indices are given as follows

$$f^U = \sum_{i=\Phi}^{N} \sum_{=a}^{c} \left| U_{\ddot{o},i} - \frac{1}{3}\left(U_{a,i} + U_{b,i} + U_{c,i} \right) \right|$$

or $$f^I = \sum_{\ddot{o}=\grave{a}}^{\tilde{n}} \left| I_{\ddot{o},0} - \frac{1}{3}\left(I_{a,0} + I_{b,0} + I_{c,0} \right) \right|,$$

where f^U and f^I are the index of the voltage unbalance of the network and the current unbalance of the substation;

$U_{\varphi,i}$ is the complex voltage on phase φ ($\varphi = a, b, c$);

$I_{\varphi,0}$ corresponds to the complex current on phase φ of the busbar i of substation.

At the same time power (energy) losses reduction is the key benefits brought by using the SOPs in distribution networks.

Due to the nonlinearity of power losses equations and SOP constraints in the optimization models, the optimal control of SOPs is nonlinear problem. Various methods of nonlinear programming [10] as well as metaheuristic algorithms [11] have been used for its solving.

However, in all such researches, the issues of uncertainty of distributed energy resources and loads were not considered. To account for this factor the chance-constrained programming embedded nonlinear optimization model formulated for SOP control was proposed in [12]. A large number of scenarios are required to fully characterize the uncertain power output of renewable resources that makes this model computationally difficult.

Usually, the control of SOPs requires sufficient measurements of the DN modes of operations through fast and reliable communication means. In many researches the historical or forecasted power loads and local generation are used as well.

To eliminate the influence of the factor of information uncertainty on the decision-making process, to simplify the implementation of the optimization problem and taking into account the information support that modern distribution systems must comply with, the following approach can be proposed to control the operation of SOPs in real time with objective to minimize electrical energy losses.

It is necessary to manage of the SOP operation in a way to form the optimal modes in the DN from the standpoint to minimize power losses at any period of time that as the result allows one to reduce the total electrical energy losses. It is well known, that operation of loop networks in closed mode in most cases leads to minimum power losses. So, the main idea of using SOP in distribution networks is to keep of the load flow of the network (in the general case, separately in active and reactive power) as close as possible to that which would be formed in the same circuit in the case of its operation in closed mode.

Thus, in the process of control we have to determine the amount of active power that must be transmitted through the SOP from one part of the circuit to another, as well as the value of the reactive power generated or absorbed from the SOP, depending on the current node loads and the output power of local energy sources that are subject for permanent monitoring.

Here the problem arises of the quick modeling the mode of distribution feeder with two-way power supply. The classical approach to its solution [13] in a distribution feeder equipped with a SOP is not convenient enough, since lack of connection between load flows in sections and alterations of nodes loads and/or of local energy sources output power. In this regard, to determine the load flow, it is proposed approach based on the principle of superposition.

In this case, initially, we find the load flow without taking into account the difference in voltages in the busbars of substations, using the superposition principle for pre-calculated partial power flows from each of the substations to any of the network nodes. At the next stage, to this power flow is added the power flow caused by the difference of voltages on the busbars.

FIRST ALGORITHM OF LOAD FLOW MODELING

Let us consider how partial power flows from substations to individual network nodes can be determined. For this purpose, we use a simplified feeder with two-way power supply (Fig. 2).

Represent original feeder as two equivalent ones (Fig. 3).

The voltages at nodes 2 and 3 can be calculated both from the voltage U_1 and from the voltage U_4. Without taking into account power losses, for each of the above equivalents (Fig. 3) we can write

The voltages at nodes 2 and 3 can be calculated both from the voltage U_1 and from the voltage U_4. Without taking into account power losses, for each of the above equivalents (Fig. 3) we can write

$$\underline{U}_3=\underline{U}_1-\Delta\underline{U}_{1,3}=\underline{U}_4-\Delta\underline{U}_{3,4}, \tag{1}$$

$$\underline{U}_2=\underline{U}_1-\Delta\underline{U}_{1,2}=\underline{U}_4-\Delta\underline{U}_{2,4}. \tag{2}$$

For the real part of (1) and (2) we have

$$\begin{aligned}&U_1-\frac{P_{1,3}(R_{1,2}+R_{2,3})+Q_{1,3}(X_{1,2}+X_{2,3})}{U_{e1}}=\\&=U_4-\frac{P_{4,3}R_{3,4}+Q_{4,3}X_{3,4}}{U_{e4}},\end{aligned} \tag{3}$$

$$\begin{aligned}&U_1-\frac{P_{1,2}R_{1,2}+Q_{1,2}X_{1,2}}{U_{e1}}=U_4-\\&-\frac{P_{4,2}(R_{2,3}+R_{3,4})+Q_{4,2}(X_{2,3}+X_{3,4})}{U_{e4}},\end{aligned} \tag{4}$$

for the imaginary part of the same equations

$$\begin{aligned}&U_1-\frac{P_{1,3}(X_{1,2}+X_{2,3})-Q_{1,3}(R_{1,2}+R_{2,3})}{U_{e1}}=\\&=U_4-\frac{P_{4,3}X_{3,4}-Q_{4,3}R_{3,4}}{U_{e4}},\end{aligned} \tag{5}$$

$$\begin{aligned}&U_1-\frac{P_{1,2}X_{1,2}-Q_{1,2}R_{1,2}}{U_{e1}}=U_4-\\&-\frac{P_{4,2}(X_{2,3}+X_{3,4})-Q_{4,2}(R_{2,3}+R_{3,4})}{U_{e4}},\end{aligned} \tag{6}$$

where $P_{1,3}$, $Q_{1,3}$, $P_{1,2}$, $Q_{1,2}$ are the partial powers coming from the substation 1 to nodes 3 and 2, respectively;

$P_{4,3}$, $Q_{4,3}$, $P_{4,2}$, $Q_{4,2}$ are the partial powers coming from the substation 4 to nodes 3 and 2, respectively;

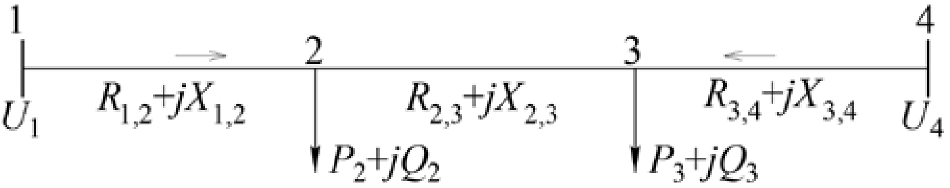

Fig. 2. Simplified two-way closed distribution network

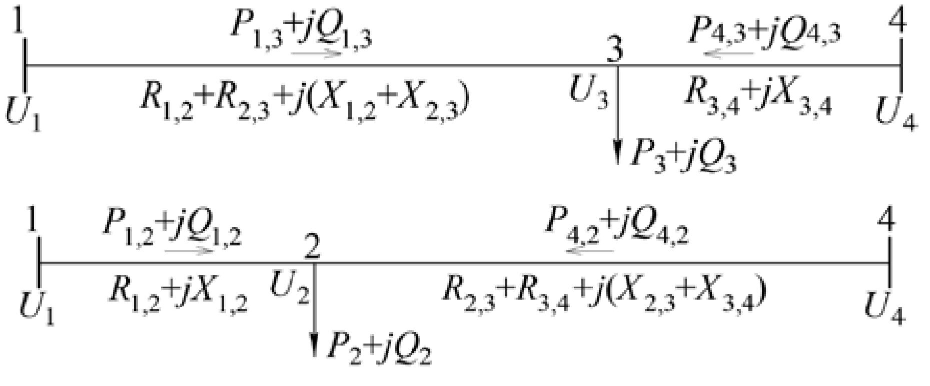

Fig. 3. Equivalents of two-way closed distribution network

U_{e1}, U_{e4} are the equivalent voltages that may be defined, for example, as $U_{e1}=\frac{U_1+U_n}{2}$ and $U_{e4}=\frac{U_4+U_n}{2}$, U_n is the rated voltage.

Additionally, taking into account that

$S_3 = S_{1,3} + S_{4,3}$ and $S_2 = S_{1,2} + S_{4,2}$,

after simple transformations, for the real part (3) and (4) we obtain, respectively

$$U_1-\frac{P_{1,3}R_{1,3}}{U_{e1}}-\frac{Q_{1,3}X_{1,3}}{U_{e1}}=U_4-\frac{P_{4,3}R_{3,4}}{U_{e4}}-\frac{Q_{4,3}X_{3,4}}{U_{e4}}$$

$$\text{and } U_1-\frac{P_{1,2}R_{1,2}}{U_{e1}}-\frac{Q_{1,2}X_{1,2}}{U_{e1}}=U_4-\frac{P_{4,2}R_{2,4}}{U_{e4}}-\frac{Q_{4,2}X_{2,4}}{U_{e4}},$$

where $R_{1,2}$, $X_{1,2}$, $R_{1,3}$, $X_{1,3}$ are the resistances from substation 1 to load nodes 2 and 3, respectively;

$R_{2,4}$, $X_{2,4}$, $R_{3,4}$, $X_{3,4}$ are the resistances from the substation 4 to load nodes 2 and 3, respectively.

By implementation of the superposition principle and taking into account that in case under consideration $P_{1,3} = P_3$, $Q_{1,3} = Q_3$, $P_{4,3} = P_3$, $Q_{4,3} = Q_3$, $P_{1,2} = P_2$, $Q_{1,2} = Q_2$, $P_{4,2} = P_2$, $Q_{4,2} = Q_2$, we will obtain for the real part

$$U_1-\frac{P_3R_{1,2}+P_3R_{2,3}+Q_3X_{1,2}+Q_3X_{2,3}}{U_{e1}}-$$

$$-\frac{P_2R_{1,2}+Q_2X_{1,2}}{U_{e1}}=U_4-\frac{P_3R_{3,4}+Q_3X_{3,4}}{U_{e4}}-$$

$$-\frac{P_2R_{2,3}+P_2R_{3,4}+Q_2X_{2,3}+Q_2X_{3,4}}{U_{e4}}$$

$$\text{or } U_1-\frac{(P_3+P_2)R_{1,2}+P_3R_{2,3}+(Q_3+Q_2)X_{1,2}+Q_3X_{2,3}}{U_{e1}}=$$

$$=U_4-\frac{(P_2+P_3)R_{3,4}+P_2R_{2,3}+(Q_2+Q_3)X_{3,4}+Q_2X_{2,3}}{U_{e4}}.$$

Similar analysis can be made for the imaginary part of expressions (5) and (6). This allows one to form for the circuits (Fig. 2) the following conditions to fine of partial power flows, assuming at this stage that the voltages on the substations are the same ($U_1 = U_4$)

$$-\frac{P_{1,3}R_{1,3}}{U_{e1}}-\frac{Q_{1,3}X_{1,3}}{U_{e1}}+\frac{P_{4,3}R_{3,4}}{U_{e4}}+\frac{Q_{4,3}X_{3,4}}{U_{e4}}=0,$$

$$-\frac{P_{1,3}X_{1,3}}{U_{e1}}+\frac{Q_{1,3}R_{1,3}}{U_{e1}}+\frac{P_{4,3}X_{3,4}}{U_{e4}}-\frac{Q_{4,3}R_{3,4}}{U_{e4}}=0,$$

$$P_{1,3}+P_{4,3}=P_3,\quad Q_{1,3}+Q_{4,3}=Q_3,$$

$$\text{and } -\frac{P_{1,2}R_{1,2}}{U_{e1}}-\frac{Q_{1,2}X_{1,2}}{U_{e1}}+\frac{P_{4,2}R_{2,4}}{U_{e4}}+\frac{Q_{4,2}X_{2,4}}{U_{e4}}=0,$$

$$-\frac{P_{1,2}X_{1,2}}{U_{e1}}+\frac{Q_{1,2}R_{1,2}}{U_{e1}}+\frac{P_{4,2}X_{2,4}}{U_{e4}}-\frac{Q_{4,2}R_{2,4}}{U_{e4}}=0,$$

$$P_{1,2} + P_{4,2} = P_2,\ Q_{1,2} + Q_{4,2} = Q_2.$$

Partial power flows from the substations to each of the network nodes ($P_{1,2}$, $Q_{1,2}$, $P_{4,2}$, $Q_{4,2}$, $P_{1,3}$, $Q_{1,3}$, $P_{4,3}$, $Q_{4,3}$) can be determined in the process of solving the above systems of equations.

Summarizing the results obtained and introducing the certain indices,

$$\alpha_{A,k}=\frac{\sum_{i=1}^{k}R_i}{U_{eA}},\ \beta_{A,k}=\frac{\sum_{i=1}^{k}X_i}{U_{eA}},\ \alpha_{B,k}=\frac{\sum_{i=k}^{n-1}R_i}{U_{eB}},$$

$$\beta_{B,k}=\frac{\sum_{i=k}^{n-1}X_i}{U_{eB}},$$

for arbitrary network circuit (Fig. 4)

we obtain the following systems of equations

$$-\alpha_{A,k}P_{A,k}-\beta_{A,k}Q_{A,k}+\alpha_{B,k}P_{B,k}+\beta_{B,k}Q_{B,k}=0,$$

$$-\beta_{A,k}P_{A,k}+\alpha_{A,k}Q_{A,k}+\beta_{B,k}P_{B,k}-\alpha_{B,k}Q_{B,k}=0,$$

$$P_{A,k}+P_{B,k}=P_k,\ Q_{A,k}+Q_{B,k}=Q_k,\ k=1,\ldots,n-1,$$

where k is the number of load node; n is quantity of feeder sections.

In the process of solving these systems of equations, partial flows of power to each network nodes are determined

$$P_i^{/}=\sum_{j=i}^{n-1}P_{A,j}-\sum_{j=1}^{i-1}P_{B,j},\ Q_i^{/}=\sum_{j=i}^{n-1}Q_{A,j}-\sum_{j=1}^{i-1}Q_{B,j}. \quad (7)$$

The resulting load flow in each section of the feeder (Fig. 4) is calculated using the principle of superposition, so far, without taking into account different voltages on substations.

A similar approach to modeling the mode of a feeder with two-way power supply can also be implemented based on the following considerations.

SECOND ALGORITHM OF LOAD FLOW MODELING

Regarding the networks shown in Fig. 2 and 3, without taking into account power losses, according to [13] can be obtained

$$\underline{S}_{1,3}=\frac{\underline{S}_3\overset{*}{Z}_{3,4}}{\overset{*}{Z}_{\Sigma}},\ \underline{S}_{1,3}-\underline{S}_3=-\frac{\underline{S}_3\left(\overset{*}{Z}_{1,2}+\overset{*}{Z}_{2,3}\right)}{\overset{*}{Z}_{\Sigma}},$$

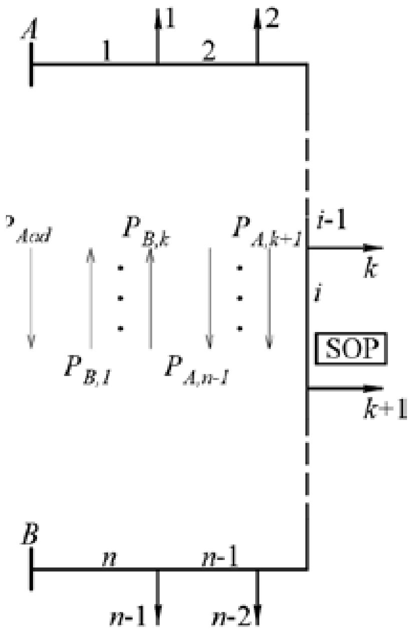

Fig. 4. Determination of the load flow in the feeder on the basis of superposition method

$$\underline{S}_{1,2}=\frac{\underline{S}_2\left(\overset{*}{Z}_{2,3}+\overset{*}{Z}_{3,4}\right)}{\overset{*}{Z}_\Sigma},\quad \underline{S}_{1,2}-\underline{S}_2=-\frac{\underline{S}_2\overset{*}{Z}_{1,2}}{\overset{*}{Z}_\Sigma},$$

$$\underline{S}_{4,3}=\frac{\underline{S}_3\left(\overset{*}{Z}_{1,2}+\overset{*}{Z}_{2,3}\right)}{\overset{*}{Z}_\Sigma},\quad \underline{S}_{4,3}-\underline{S}_3=-\frac{\underline{S}_3\overset{*}{Z}_{3,4}}{\overset{*}{Z}_\Sigma},$$

$$\underline{S}_{4,2}=\frac{\underline{S}_2\overset{*}{Z}_{1,2}}{\overset{*}{Z}_\Sigma},\quad \underline{S}_{4,2}-\underline{S}_2=-\frac{\underline{S}_2\left(\overset{*}{Z}_{2,3}+\overset{*}{Z}_{3,4}\right)}{\overset{*}{Z}_\Sigma}.$$

In this case we have the following

$$P_{1,2}+jQ_{1,2}=\left(1-\frac{R_{1,2}-jX_{1,2}}{R_\Sigma-jX_\Sigma}\right)\left(P_2+jQ_2\right),$$

$$P_{1,3}+jQ_{1,3}=\left(1-\frac{\left(R_{1,2}+R_{2,3}\right)-j\left(X_{1,2}+X_{2,3}\right)}{R_\Sigma-jX_\Sigma}\right)\left(P_3+jQ_3\right),$$

$$P_{4,2}+jQ_{4,2}=\left(1-\frac{\left(R_{2,3}+R_{3,4}\right)-j\left(X_{2,3}+X_{3,4}\right)}{R_\Sigma-jX_\Sigma}\right)\left(P_2+jQ_2\right),$$

$$P_{4,3}+jQ_{4,3}=\left(1-\frac{R_{3,4}-jX_{3,4}}{R_\Sigma-jX_\Sigma}\right)\left(P_3+jQ_3\right). \quad (8)$$

Taking into account that

$$\frac{R_{ij}-jX_{ij}}{R_\Sigma-jX_\Sigma}=\frac{R_{ij}R_\Sigma+X_{ij}X_\Sigma}{R_\Sigma^2+X_\Sigma^2}+j\frac{R_{ij}X_\Sigma-X_{ij}R_\Sigma}{R_\Sigma^2+X_\Sigma^2}$$

and introducing the following indices

$$\alpha_{ij}=\frac{R_{ij}R_\Sigma+X_{ij}X_\Sigma}{R_\Sigma^2+X_\Sigma^2},\ \beta_{ij}=\frac{R_{ij}X_\Sigma-X_{ij}R_\Sigma}{R_\Sigma^2+X_\Sigma^2},$$

we will obtain

$$P_{1,2}+jQ_{1,2}=\left(1-\alpha_{1,2}-j\beta_{1,2}\right)\left(P_2+jQ_2\right)=$$
$$=\left[\left(1-\alpha_{1,2}\right)P_2+\beta_{1,2}Q_2\right]+j\left[\left(1-\alpha_{1,2}\right)Q_2-\beta_{1,2}P_2\right],$$

$$P_{1,3}+jQ_{1,3}=\left(1-\alpha_{1,3}-j\beta_{1,3}\right)\left(P_3+jQ_3\right)=$$
$$=\left[\left(1-\alpha_{1,3}\right)P_3+\beta_{1,3}Q_3\right]+j\left[\left(1-\alpha_{1,3}\right)Q_3-\beta_{1,3}P_3\right],$$

$$P_{4,2}+jQ_{4,2}=\left(1-\alpha_{4,2}-j\beta_{4,2}\right)\left(P_2+jQ_2\right)=$$
$$=\left[\left(1-\alpha_{4,2}\right)P_2+\beta_{4,2}Q_2\right]+j\left[\left(1-\alpha_{4,2}\right)Q_2-\beta_{4,2}P_2\right],$$

$$P_{4,3}+jQ_{4,3}=\left(1-\alpha_{4,3}-j\beta_{4,3}\right)\left(P_3+jQ_3\right)=$$
$$=\left[\left(1-\alpha_{4,3}\right)P_3+\beta_{4,3}Q_3\right]+j\left[\left(1-\alpha_{4,3}\right)Q_3-\beta_{4,3}P_3\right].$$

By generalizing the given above results, in particular for the network shown in Fig. 4, we get

$$P_{Ak}=\left(1-\alpha_{Ak}\right)P_k+\beta_{Ak}Q_k, \quad (9)$$

$$Q_{Ak}=\left(1-\alpha_{Ak}\right)Q_k-\beta_{Ak}P_k, \quad (10)$$

$$P_{Bk}=\left(1-\alpha_{Bk}\right)P_k+\beta_{Bk}Q_k, \quad (11)$$

$$Q_{Bk}=\left(1-\alpha_{Bk}\right)Q_k-\beta_{Bk}P_k,\ k=1,\dots,n-1, \quad (12)$$

where $\alpha_{Aj}=\dfrac{R_\Sigma\sum\limits_{j=1}^{k}R_j+X_\Sigma\sum\limits_{j=1}^{k}X_j}{R_\Sigma^2+X_\Sigma^2}$, (13)

$$\beta_{Aj}=\frac{R_\Sigma\sum\limits_{j=1}^{k}X_j-X_\Sigma\sum\limits_{j=1}^{k}R_j}{R_\Sigma^2+X_\Sigma^2}, \quad (14)$$

$$\beta_{Aj}=\frac{R_\Sigma\sum\limits_{j=1}^{k}X_j-X_\Sigma\sum\limits_{j=1}^{k}R_j}{R_\Sigma^2+X_\Sigma^2}, \quad (15)$$

$$\beta_{Bj}=\frac{R_\Sigma\sum\limits_{j=k+1}^{n-1}X_j+X_\Sigma\sum\limits_{j=k+1}^{n-1}R_j}{R_\Sigma^2+X_\Sigma^2}. \quad (16)$$

lying the superposition principle, on the bases of partial power flows (9) – (12) the load flow (P_i', i = 1, …, n–1) for the original network circuit (Fig. 4) can be determined similar to (7).

The final step in modeling the feeder mode, if it is necessary and expedient to take into account the difference in voltages on busbars of substations, is the adding on the obtained load flow (7) of the additional power ($\underline{S}_{ad}$), which, using the actual values of the busbars' voltages, is determined as follows

$$\underline{S}_{ad} = \frac{U_A - U_B}{\overset{*}{Z}_\Sigma} U_n .$$

Then

$$P_{adA} + jQ_{adA} = \frac{U_A - U_B}{R_\Sigma - jX_\Sigma} U_n = \frac{\left(U_A - U_B\right) R_\Sigma U_n}{R_\Sigma^2 + X_\Sigma^2} + $$

$$+ j\frac{\left(U_A - U_B\right) X_\Sigma U_n}{R_\Sigma^2 + X_\Sigma^2}.$$

The final load flow will be defined as follows (Fig. 4)

$$P_j = P_j^{/} + P_{adA} sign\left(P_j^{/}\right),\ Q_j = Q_j^{/} + Q_{adA} sign\left(Q_j^{/}\right).$$

ANALYSIS OF SOP OPERATION

In the process of implementing this control strategy at least the following constraints for the SOP operation have to be taken into account.

The capacity range of SOP

$$0 \le S_{i,j,t}^{SOP} \le S_{\max}^{SOP},\ t = 1,\ \ldots,\ T,$$

where $S_{i,j,t}^{SOP}$ is the capacity transmitted at instant *t* through the SOP installed at branch *i*, *j*.

The constrained of branch current

$$I_{i,j,t} \le I_{i,j,\max},\ t = 1,\ \ldots,\ T,$$

where $I_{i,j,\max}$ is the current upper limit of branch *i*, *j*.

The range of nodal voltage

$$U_{i,\min} \le U_{i,t} \le U_{i,\max},\ t = 1,\ \ldots,\ T,$$

where $U_{i,\ \min}$, $U_{i,\ \max}$ are the lower and upper limits of voltage magnitude at node *i*.

A main advantage of the proposed approaches is the ability to quickly determine changing in the active and reactive power flows in a certain section of the feeder in function from the alteration of any node load, the output power of local energy sources or state of energy storage systems.

Parameters (13) – (16) can be calculated in advance and they remain unchanged in the process of modeling the feeder mode regardless of the values of loads and output of local energy sources.

In the process of ongoing monitoring of the mode parameters of the feeder section adjacent to the SOP (Fig. 4), the existing load flow is compared with that which would be during the operation of this feeder in close mode (P_i), taking into account the current values of node loads and of distributed generation sources output power.

The resulting imbalance has to be compensated by changing the direction and magnitude of active power flows through the SOP, as well as by the volume of additional generation (or absorption) of reactive power, which is achieved by appropriate VSC control.

If the distribution feeder has a more complex structure, in particular, includes branches, several local energy sources, then the original circuit can be transformed in equivalent one.

The question of SOP optimal placement is of a great importance, because it effects on total costs associated with the implementation of the corresponding project. It is usually suggested to place SOP in a section with a minimum load, assuming the line is operated in closed mode. However, under conditions of heterogeneous loads and the use of distributed energy sources, such a solution is not stable. Therefore, in the [14] it was proposed to use the following index (betweenness index) for this purpose

$$K_{ij} = \sum_{m \in G} \sum_{n \in L} \min(S_m, S_n) \frac{P_{ij}(m,n)}{P(m,n)},$$

where $P_{ij}(m,n) = \dfrac{P_{i,j,m} P_{i,j,n}}{P_{ij}}$;

G is the set of all the distributed generators;

L is the set of all the nodes;

S_m is the apparent power output of generator *m*;

S_n is the apparent load of node *n*;

min(S_m, S_n) is the transmitted apparent power between generator *m* and node load *n*;

P(*m*, *n*) is the transmitted active power from generator *m* to node load *n*;

P_{ij}(*m*, *n*) is the part of *P*(*m*, *n*) in the line *i*, *j*;

$P_{i,j,m}$ is the active power of line *i*, *j* from generator *m*;

$P_{i,j,n}$ is the active power of line *i*, *j* flowing to node load *n*;

$P_{i,j}$ is the active power of line *i*, *j* from node *i* to node *j*.

The larger index $K_{i,j}$ of a line is, the greater the total contribution of this line to the power transfer is in the distribution network. The major role of an SOP is to control the transfer power along the distribution lines. Therefore, proposed index is a good measurement for selecting SOP location.

CONCLUSIONS. Under the current trends of the widespread integration of local sources of energy generation and storage, growth of electric vehicle charging stations, changes in structure of electrical loads, the effectiveness of the traditionally used in electrical distribution systems methods and technical means for the control of modes of operation are sharply reduced due to frequent and difficult to predict modes alterations. At the same time, such a popular problem as the optimal reconfiguration of loop distribution networks has been and remains one of the most effective actions to minimize power losses and to provide the necessary voltage levels. However, under the current conditions, it is difficult to choose a normal opening point for a long time, at which a minimum of electrical energy losses would be ensured.

In this regard, a new approach was proposed to solve this problem using power electronics devices, in particular, consists of two back-to-back voltage source converters. This technical solution (SOPs) permits to keep of the network load flow (in the general case, separately in active and reactive power) as close as possible to that which would be formed in the same circuit in the case of its operation in closed mode, that ensures a minimum of power losses at any instant of time.

Taking into account, that in this case the network mode is controlled in real time, the paper proposes two approaches that allow one to speed up the process of calculating the change in the flow distribution in the network section, where the SOP is located, depending on the change in node loads and output parameters of local energy sources. Thus, the proposed approach makes it possible to ensure the efficient use of the SOP in order to minimize energy losses in the distribution network line.

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ОСОБЛИВОСТІ ПОСТАНОВКИ ЗАДАЧІ ОПТИМАЛЬНОЇ РЕКОНФІГУРАЦІЇ МЕРЕЖІ В СИСТЕМАХ РОЗПОДІЛУ З ЛОКАЛЬНИМИ ДЖЕРЕЛАМИ ЕНЕРГІЇ

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Все більш широка інтеграція локальних джерел генерації та систем накопичення енергії, зростання кількості зарядних станцій електромобілів у системах розподілу електричної енергії різко знижують ефективність традиційно використовуваних методів і технічних засобів керування їх режимами. Зокрема, це стосується такої популярної задачі, як вибір оптимального місця встановлення так званих «м'яких відкритих точок» (soft open points) у колах розподільних мереж із метою мінімізації втрат електричної енергії. Обрана нормально відкрита точка залишалася незмінною протягом досить тривалого часу. Проте зазначені вище особливості сучасних систем розподілу викликають серйозні зміни в традиційній структурі розподільних мереж і режимах їх роботи, які ставатимуть менш стабільними та більш непередбачуваними. У результаті під впливом випадкових факторів у мережах виникають потоки навантажень різної тривалості, які в багатьох випадках будуть суттєво відрізнятися від того режиму (навантажень), для якого були визначені оптимальні, так звані «м'які відкриті точки». У порівнянні із традиційним підходом до реконфігурації розподільної мережі пропонується нова динамічна реконфігурація для системи з високою проникаючою здатністю відновлюваних джерел енергії або високим рівнем неоднорідності навантаження. Рішення про зміну місця розташування відкритої точки мережі приймається, коли позитивний ефект від додаткового зниження втрат енергії перевищує збиток від збільшення використання комутаційного ресурсу вимикачів і скорочення їх терміну служби. Для прийняття такого рішення пропонується спеціальний алгоритм, який враховує як технічну, так і економічну сторони проблеми. У зв'язку з цим у роботі розглядається можливість, доцільність та ефективність вибіркового використання так званих технологій «м'яких відкритих точок», які дають можливість незалежно оптимально контролювати перетоки активної та реактивної потужностей для мінімізації втрат електроенергії. У роботі запропоновано загальний підхід до керування відповідним силовим електронним обладнанням для забезпечення оптимального навантаження та розподілу живлення в режимі реального часу.

Ключові слова: розподільні мережі, розосереджена генерація, реконфігурація мережі, втрати енергії, «м'які відкриті точки».