Optimization of power flow through facts in electrical networks

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Abstract. A mathematical model is presented for optimizing power flows in an electric network with a flexible controlled alternating current power transmission device - FACTS. The range of questions on the problem of optimizing the power flow in electric networks with one of the FACTS devices, the SVC static power factor compensator, has been expanded and investigated. The Lagrange function for the SVC device is proposed, which serves as the basis for obtaining a linearized equation and determining the optimum of the objective function. The method and algorithm of the optimization problem in the electric power system containing devices of the FACTS technology have been synthesized. The mathematical model allows for flexible and reliable optimization of the electrical power system. Flexibility is explained by the universality of the model, and reliability is explained by the high convergence rate of the Newton method used.

1. Introduction

The aim of the study is to develop mathematical models that describe intelligent FACTS technology. The objective of the study is a mathematical model and an algorithm for calculating the flows of electric power and optimizing the modes of energy systems. The object of study is the electric power system with its characteristics and parameters. The operation of power plants in a mode with active power exceeding the nominal value and reaching a maximum value in the limit according to the thermal stability of the line wires in the general case leads to a change in the mode of the system for reactive power and requires the installation of additional lateral compensation devices generating or consuming reactive power. The installation of compensating devices on power lines and load nodes is widely used to improve voltage modes, increase transmission system capacity, and increase the reserves of static and dynamic stability. As these devices, static unregulated devices (capacitor banks), adjustable synchronous compensators are used, and static thyristor regulated sources of reactive power are FACTS (Flexible AC Transmission Systems) devices. The latter is characterized by high speed and, as a result, can significantly affect not only the steady-state modes of the system, but also the conditions of its static and dynamic stability. The most important goal in optimizing the modes is to ensure that the calculated mode satisfies technical constraints in terms of reliability and quality of electricity. Modules of generator voltage and load, active and reactive power of generators, currents, and power flows in lines, etc. must satisfy technical limitations. The article synthesizes the method and algorithm of the optimization problem in an electric power system containing devices of the FACTS technology [1, 2, 5].
2. Methods

Typically, the task of optimizing the power flow is expressed as a nonlinear programming problem having a target function in the form of nonlinear programming, having a target function in the form of a nonlinear equation with constraints, which, in turn, are represented as a set of nonlinear or linear equations and inequalities. This problem can also be called the problem of conditional optimization [3, 4, 9].

The task of optimizing the power flow for the steady-state mode of EPS can be represented as the following general formula for global minimization:

\[
\min_{h(x)=0} f(x) = \min \{ f(x) \colon h(x) = 0, \ g(x) \leq 0 \}
\]

or in another form:

\[
f(x) \rightarrow \min,
\]

\[
h_j(x) = 0, \quad j = 1, 2, \ldots, r,
\]

\[
g_j(x) \leq 0, \quad k = 1, 2, \ldots, m,
\]

\[
x = [x_1, x_2, \ldots, x_n]^T \in \chi \subseteq R^n
\]

where \( R^n \) denotes an n-dimensional real space, and \( \chi \) is a subset of \( R^n \).

In other words, in the general case, it is required to minimize the vector function \( f(x) \) from the vector argument \( x \) (to find the optimum), provided that the strict equality \( h(x) = 0 \) is ensured (the constraint in the form of equality holds). In what follows, we will assume that \( f(x) \) is a twice differentiable function.

In expression (1) under the conditions of the EPS, \( x \) is a vector of variable functions and is usually called the state vector of the EPS. The function \( f(x) \) is called the objective function to be optimized. The function \( h(x) \) represents the power flow equation, and \( g(x) \) describes the constraints imposed on the state vector \( x \).

Vector \( x \), as a rule, is divided into two subvectors:

\[
x = \left( \begin{array}{c}
x_1 \\
x_2
\end{array} \right)
\]

where \( x_1 \) is a subvector containing controlled (dependent) variables; \( x_2 \) subvector containing control variables (controls).

Control variables \( x_2 \) include active power generation, taps, and phase angles in transformers with switched branches and with transverse voltage regulation, voltage values on generator buses, etc. Controls are usually taken as continuous values. Dependent variables \( x_1 \) can take any values within the given limits. Examples of dependent variables are phase angles of voltage on all loaded buses, excluding unloaded voltage values on all tires on loaded tires, reactive power on all generating buses, active power generation costs, and active and reactive power flows in power lines and transformers, including losses.

The main goal of solving the problem of optimizing the power flow is to determine the magnitude of the control and controlled variables of the state of the system that globally minimizes the value of the objective function. Target selection should be based on a thorough analysis of EPS. Costs for the production of electricity - this is the total consumption of fuel equivalent BT at EPS stations. This flow rate can be represented by a second-order nonlinear function

\[
B_T = \sum_{k=1}^{n_c} B_k(P_{gk})
\]
where $B_k$ is the equivalent fuel consumption at the $k$-th station; 

$p_{gk}$ - active power generated by the $k$-th station; 

$n_c$ is the number of stations in the EPS, including stations with unloaded generators.

More precisely, 

$$B_k(p_{gk}) = \sigma_k + \tau_k p_{gk} + \alpha_k (p_{gk})^2$$  \hspace{1cm} (2)

where $\sigma_k, \tau_k, \alpha_k$ are the cost coefficients for the $k$-th station.

The first step to solving the problem of optimizing the power flow in the EPS is to determine the network topology and its parameters. This forms a set of fixed parameters of the power flow optimization problem. The equations of power fluxes for the equivalent circuit of the EPS, including generation, load, and power lines (Fig. 1), can be written taking into account the relationship between the control and dependent variables:

$$P_k(U, \delta) + p_{hk} - p_{gk} = 0 \quad (3)$$

$$Q_k(U, \delta) + q_{hk} - q_{gk} = 0 \quad (4)$$

where $P_k(U, \delta)$ and $Q_k(U, \delta)$ are the active and reactive power on the bus $k$, respectively; $p_{hk}$ and $q_{hk}$ are the load corresponding to active and reactive power on bus $k$; $p_{gk}$, $q_{gk}$ are the active and reactive power, respectively, generated by the $k$-th station; $U$ is the nodal voltage module; $\delta$ is the phase angle.

![Figure 1. EES equivalent circuit](image)

In (3), (4), the dependence of the active and reactive powers (controlled variable state of the EPS) on the voltage modulus and phase angle (control) is explicitly indicated. It is known that all physical variables have upper and lower limits of change (limitation). Therefore, these restrictions must be satisfied in the optimal mode. All quantities that must be within acceptable limits are called controlled quantities.

Power flow optimization by Newton’s method. In the problem of power flow optimization with equality constraints, the Lagrange function can be written as

$$L(x, \lambda) = B_T + \sum_{k=1}^{n_y} \lambda_{pk}(P_k(U, \delta) + p_{hk} - p_{gk}) + \sum_{k=1}^{n_y} \lambda_{qk}(Q_k(U, \delta) + q_{hk} - q_{gk})$$  \hspace{1cm} (5)

where $B_T$ is the objective function; $\lambda_{pk}$ and $\lambda_{qk}$ are the Lagrange multipliers for the equations of active and reactive powers, respectively.

The solution of the global minimization problem (5) using the Newton method, according to can be effectively obtained using the following system of linearized equations [1, 4, 5, 7]:

$$M^{(i)} \left[ \frac{\Delta x}{\Delta \lambda} \right]^{(i)} = \left[ \frac{\partial x}{\partial \lambda} \right]^{(i)}$$  \hspace{1cm} (6)

or in even shorter form

$$M \Delta z = -\varphi$$  \hspace{1cm} (7)
Matrices and vectors are indicated here:

\[ M = \begin{pmatrix} H & J^T \\ J & 0 \end{pmatrix} \] (8)

\[ \Delta z = \begin{pmatrix} \Delta x \\ \Delta \lambda \end{pmatrix} \] (9)

\[ \varphi = \begin{pmatrix} \nabla L_x \\ \nabla L_\lambda \end{pmatrix} = \begin{pmatrix} \Delta x \\ \Delta \lambda \end{pmatrix} \] (10)

\[ \Delta x = \begin{pmatrix} \Delta P_p \\ \Delta \delta \\ \Delta U \end{pmatrix}, \quad \nabla x = \begin{pmatrix} \nabla P_p L_x \\ \nabla \delta L_x \\ \nabla U L_x \end{pmatrix} = \begin{pmatrix} \Delta P_p \\ \Delta \delta \\ \Delta U \end{pmatrix} \] (11)

\[ \Delta \lambda = \begin{pmatrix} \Delta \lambda_p \\ \Delta \lambda_q \end{pmatrix}, \quad \nabla \lambda = \begin{pmatrix} \nabla \lambda_p L_x \\ \nabla \lambda_q L_x \end{pmatrix} = \begin{pmatrix} \Delta \lambda_p \\ \Delta \lambda_q \end{pmatrix} \] (12)

The block matrix \( M \) (8) contains partial derivatives of the Lagrange function \( L(x, \lambda) \) to the state variables \( x \) and the Lagrange multiplier \( \lambda \) and therefore consists of four blocks. The matrix \( H \) is the Hessian matrix, i.e. matrix of second derivatives of the objective function. Matrix \( J \) denotes the Jacobian of the objective function.

The block matrix \( M \) is symmetric and in its lower right corner contains the zero matrix \( O \). This is indeed so, since, due to the independence of the Lagrange multipliers, the identity

\[ \frac{\partial^2 L(x, \lambda)}{\partial \lambda_i \partial \lambda_k} \bigg|_{i \neq k} = 0 \]

The symbol \( \nabla \) in (10-12), as above, denotes the operation of calculating the gradient of a vector function (for brevity, we will use the notation given in the right-hand sides of (10-12). The Lagrange multipliers describe the additional costs of active \( \lambda_p \) and reactive \( \lambda_q \) powers, respectively. The vector \( \Delta z \) (9) is a vector of correction terms According to (11), the vector of state variables \( \Delta x \) includes generated active powers, nodal stresses, and phase shift angles, respectively.

The elements \( \Psi (g(x, \lambda)) \) associated with inequality constraints are not included at the beginning of the iterative solution using Newton. According to the Kuhn-Tucker condition, these constraints are introduced into the linearized system of equations (7) only after they enter Thus, the Hessian and Jacobi matrices have the following form:

\[ H = \frac{\partial^2 L(x, \lambda)}{\partial x^2} = \frac{\partial^2 f(x)}{\partial x^2} + \left( \frac{\partial^2 h(x)}{\partial x^2} \right)^T \lambda \] (13)

\[ J = \frac{\partial^2 L(x, \lambda)}{\partial x \partial \lambda} = \frac{\partial h(x)}{\partial x} \] (14)

The main and most important feature of matrices (13), (14) is the fact that they all have the same sparse structure as the matrix of nodal full conductivities.

In the general case, the fulfillment of the global optimum condition (5) for the pair \( (x^{opt}, \lambda^{opt}) \) can be checked by evaluating the positive definiteness of the matrix \( M \). The positive definiteness of the symmetric matrix \( M \) (8) means that all its eigenvalues are strictly positive real numbers.

However, when solving the optimization problem for large electric power systems, this method of verification from the point of view of required computing costs is quite expensive. Other methods are controlling the vanishing of the gradient vector (10), as well as establishing the fact that the Lagrange...
multipliers for inequalities change sign (which, as noted above, should not occur, since in this case, it changes to the opposite direction of the gradient vectors).

Before starting the process of solving the problem of optimizing the power flux, for all state variables and the Lagrange multiplier, initial approximations must be specified. To ensure an acceptable rate of convergence, the initial values in practice are selected taking into account engineering estimates. So, the values of nodal stresses should be set close to the value of 1 pu, and the phase angles for all tires should be within 0°. This provides suitable conditions for initializing the iterative process. As experience suggests, in solving most problems, the actual deviation from the unit voltage value and the zero value of the phase angles in the normal EES mode is not too significant, more precisely [4, 6]:

\[ 0.95 \leq U_k \leq 1.05 \]
\[ -10^0 \leq \delta_k \leq 10^0 \]

\( k \) is the number of the network node.

The Lagrange function for EPS without loss can be expressed by the following formula:

\[ L = L_g(x, \lambda) = B_t + \lambda(P_n - \sum_{k=1}^{n_c} P_{gk}) \]  \hspace{1cm} (15)

A necessary condition for minimizing the costs of generating active power is, firstly, that the first derivative of the objective function concerning each variable is equal to zero:

\[ \frac{\partial L(x, \lambda)}{\partial P_{gk}} = \frac{d\theta_k}{dP_{gk}} - \lambda P_k = 0 \]  \hspace{1cm} (16)

and secondly, the balance between power generation and load must meet the condition

\[ \sum_{k=1}^{n_c} P_{gk} = P_n. \]  \hspace{1cm} (17)

Also, the constraints in the form of inequalities presented in for the Lagrange function (15) must be satisfied, taking into account the conditions defined above, has a relatively simple form:

\[
\begin{bmatrix}
  \frac{d^2 \theta_1}{dP_{r1}^2} & 0 & \cdots & 0 & -1 \\
  0 & \frac{d^2 \theta_2}{dP_{r2}^2} & \cdots & 0 & -1 \\
  \vdots & \vdots & \ddots & \vdots & \vdots \\
  0 & 0 & \cdots & \frac{d^2 \theta_{nc}}{dP_{rnc}^2} & -1 \\
  -1 & -1 & -1 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
  \Delta P_{r1}^{(i)} \\
  \Delta P_{r2}^{(i)} \\
  \vdots \\
  \Delta P_{rnc}^{(i)} \\
  \Delta \lambda
\end{bmatrix}
= -
\begin{bmatrix}
  \frac{\partial L}{\partial P_{r1}} \\
  \frac{\partial L}{\partial P_{r2}} \\
  \vdots \\
  \frac{\partial L}{\partial P_{rnc}} \\
  P_n - \sum_{k=1}^{n_c} P_{rK}
\end{bmatrix}
\]  \hspace{1cm} (18)

With the quadratic cost function (2) and the absence of a violation of restrictions, the optimal solution, in this case, is achieved in just one iteration. If, after the first iteration, the constraints are violated, then these constraints become active and the iterative process will continue. The square matrix in (18) has a simple form for calculating the matrix inverse to it.

3. Results and Discussions
Optimization of power flow in the electrical network with FACTS devices. We expand the range of questions under study in the problem of optimizing the power flow in electric networks with FACTS devices. In this case, we will consider one of the types of the FACTS device - the SVC static reactive power compensator and two varieties of the SVC mathematical model: the lead-angle model and the shunt reactive conductivity model. The state variables of the FACTS device are combined with the state variables of the EES (values of the node voltage of the network and phase angles) in a single reference system to find the optimal solution using the Newton method [AvtoResShVZienethttp://library.ziyonet.ru/book/download/107674].
The Lagrange function in the problem of optimizing the power flux with a FACTS device in the form of an SVC model expressed in the form of adjustable reactive conductivity $B(\beta)$, $\beta$ - where $\beta$ is the lead angle of the thyristors, can be written as

$$L(x, \lambda) = f(P_g) + \lambda^T h\left(P_g, U, \delta, B(\beta)\right),$$

where $f(P_g)$ is the objective function; $h\left(P_g, U, \delta, B(\beta)\right)$ are the equations of the power flow with the FACTS device; $x$ is the state vector; $\lambda$ is the vector of Lagrange multipliers for constraints in the form of equalities; $P$, $U$, $\delta$, $B(\beta)$ are the generation of active power, the value of voltages, phase angles of voltage and shunt reactance SVC, respectively. The restriction in the form of inequalities $g(P, U, \delta, B(\beta)) < 0$ is not indicated in expression (19) since it is added to $L(x, \lambda)$ only if it is activated, when the variables go beyond the limits of the constraints.

The reactance SVC $B(\beta)$ can be expressed either as equivalent reactance $B_{\text{SVC}}$ or reactance, which is an explicit function of the lead angle $\beta$. The presence of control from SVC can be represented in Newton’s method using the following Lagrange function:

$$L_{\text{SVC}}(x, \lambda) = \lambda_{qk} Q_k$$

where $L_{\text{SVC}}(x, \lambda) = \lambda_{qk} Q_k$, is the reactive power applied or absorbed by SVC on bus $k$; $\lambda_{qk}$ is the Lagrange multiplier for the $k$ bus associated with the reactive power balance equation. The variable $B(\beta)$ is either reactance $B_{\text{SVC}}$ or the lead angle of thyristor $\beta$, depending on the SVC model.

Representation of SVC in the power flow optimization algorithm using the Newton method requires that for each SVC connected to the network, the matrix $M$ (8) be expanded by one column and one row. Depending on the selected SVC model, either $B_{\text{SVC}}$ or $\beta$ will enter, as an additional state variable, into the structure of the equations of the power flux optimization problem.

Application of the SVC model with an advancing angle of thyristors leads to a matrix iterated linearized equation:

$$\begin{pmatrix}
\frac{\partial^2 L}{\partial U_k^2} & \frac{\partial^2 L}{\partial U_k \partial \delta} & \frac{\partial^2 L}{\partial U_k \partial \beta} \\
\frac{\partial Q_k}{\partial U_k} & 0 & \frac{\partial Q_k}{\partial \delta} \\
\frac{\partial^2 L}{\partial \delta^2} & \frac{\partial^2 L}{\partial \delta \partial \beta} & \frac{\partial^2 L}{\partial \beta^2}
\end{pmatrix}^{(i)}
\begin{pmatrix}
\Delta U_k \\
\Delta Q_k \\
\Delta \beta
\end{pmatrix}^{(i)}
= -\begin{pmatrix}
\nabla U_k \\
\nabla Q_k \\
\nabla \beta
\end{pmatrix}^{(i)}.$$  

(21)

Where

$$\frac{\partial^2 Q_k}{\partial \beta^2} = \frac{4U_k \sin(2\beta)}{\pi X_L}, \quad \frac{\partial^2 Q_k}{\partial U_k \partial \beta} = \frac{4U_k (\sin(2\beta) - 1)}{\pi X_L}$$

The problem of power flow optimization with an alternative SVC model in the form of reactive conductivity $B_{\text{SVC}}$ leads to an iterated linearized system of equations of the form

$$\begin{pmatrix}
\frac{\partial^2 L}{\partial U_k^2} & \frac{\partial Q_k}{\partial U_k} & \frac{\partial^2 L}{\partial U_k \partial B_{\text{SVC}}} \\
\frac{\partial Q_k}{\partial U_k} & 0 & \frac{\partial Q_k}{\partial B_{\text{SVC}}} \\
\frac{\partial^2 L}{\partial B_{\text{SVC}}^2} & \frac{\partial Q_k}{\partial B_{\text{SVC}}} & 0
\end{pmatrix}^{(i)}
\begin{pmatrix}
\Delta U_k \\
\Delta Q_k \\
\Delta B_{\text{SVC}}
\end{pmatrix}^{(i)}
= -\begin{pmatrix}
\nabla U_k \\
\nabla Q_k \\
\nabla B_{\text{SVC}}
\end{pmatrix}^{(i)}.$$  

(22)

moreover
\[
\frac{\partial^2 Q_k}{\partial U_k^2} = -2B_{SVC} = - \frac{2}{X_C X_L} \left( X_L - \frac{X_C}{\pi} (2(\pi - \beta) \sin(2\beta)) \right)
\]

\[
\frac{\partial^2 Q_k}{\partial U_k \partial B_{SVC}} = -2U_k
\]

In studies of the problem of power flow optimization, it is usually assumed that the amplitude \( \Delta U_k \) lies in some predetermined limits (for example, 0.95–1.05 pu) \[8\].

However, when using the Newton method, one can set more stringent restrictions on the amplitude variation of this voltage. So, to fix the voltage on the bus \( k \) at a certain level, it is necessary in (21), (22) to add a sufficiently large “correcting” term to the derivative \( \frac{\partial^2 L}{\partial U_k^2} \), increasing this matrix element, and/or at the same time reduce the gradient \( \nabla U_k = \frac{\partial L}{\partial U_k} \).

Obviously, with an unlimited increase in the first diagonal element of the matrix \( M \) in (21), (22), due to the inverse matrix \( M^{-1} \), the change in \( \Delta U_k \) will tend to zero. The SVC can be initialized by choosing a lead angle corresponding to the equivalent resonant peak of reactance, which can be determined using the equation. The initial approximation of the Lagrange multiplier \( \lambda_{qk} \) in (20) can be set equal to zero. It is known that these initial approximations provide a rapidly converging iterative solution \[1\].

4. Conclusion

On the basis of optimization methods, the range of questions on the problem of power flow optimization in power grids with one of the types of FACTS device — the static reactive power compensator SVC — has been expanded. The proposed Lagrange function for SVC serves as the basis linearized equation for the search for the optimum can be modified for other known types of FACTS devices. Changes in the operating modes of the involved types of the FACTS devices are reflected in the structure of the task of optimizing the power flow.

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