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LOAD FLOW CALCULATION AND ANALYSIS

Load flow calculation and analysis in DAKAR complex is carried out using the method of compensational electromotance (optimization of Jacobi matrix conditioning, per-node Newton linearization). Electric condition is well balanced during every iteration, which is the characteristic feature of this method. Convergence monitoring is performed and if the condition does not exist, the closest found condition is recorded. The method gives a possibily to calculate normal, marginal and postemergency conditions both with or without frequency alteration, also when the power system is composed of several subsystems each with different frequency value. DAKAR features of the possibility of recording the highest estimated limits of generators reactive power. In the process of load flow calculation the highest limit is calculated taking into account the generator parameters specified in the current node, the number of generators, the voltage of a given node and the actual load of generators with active power.

1. INTRODUCTION

Methods formalization of power system conditions analysis most effectively is based on graph theory, matrix and vector algebra. Using graphs we represent the configuration of an electrical network, matrices are used for the analytic record of graphs structure and of power system parameters, and multi-dimensional vectors – to record coordinates of the condition. Using this mathematical apparatus, the equation of power system state in the different methods of analysis we present in the form of vector equations with full formalization of their formation, which is essential condition for automation of relevant calculations on a PC.

During solving the tasks of load flow analysis, equations of power system state, in general, are non-linear, so formalized methods of power system analysis are usually applied with the use of numerical methods for solving finite equations (such as equations of power system state in case of recording them in amplitude or in effective values of condition coordinates).

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For linearization of non-linear systems it is used a method of compensational electromotance [1], that provides control of the matrix conditioning of nodal admittances and is effective for the analysis of marginal or loading conditions.

2. METHOD OF COMPENSATIONAL ELECTROMOTANCE FOR LOAD FLOW ANALYSIS

This method uses the concept of active node. What is an electrical network node, where load or (and) generation power is set by static characteristics, or a low-voltage node of the transformer branches with complex transformation ratio, as well as HVDC. During calculation in active nodes we insert compensational electromotance. Generator or load power can be provided by an appropriate admittances, which on the basis of a compensation principle are set by certain admittance $\underline{y}_{ci}$, at which is applied compensational electromotance $\dot{E}_{ci}$ (fig. 1). This electromotance is changed to provide in the i-th node reference power:

$$\dot{S}_{i\,ref} = \dot{S}_{Li}(\dot{V}_i, f) - \dot{S}_{Gi}(\dot{V}_i, f), \tag{1}$$

where $\dot{S}_{Li}(\dot{V}_i, f)$, $\dot{S}_{Gi}(\dot{V}_i, f)$ – generator or load power of the *i*-th node, which is determined by static characteristics of voltage $\dot{V}_i$ and frequency f.

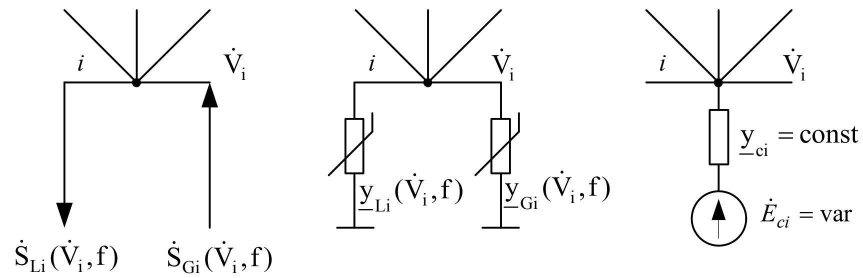

Fig. 1. Graphical explanation method of compensational electromotance

Admittances $\underline{y}_{ci}$ are included in diagonal matrix elements of the nodal admittance and improve its conditioning. Compensational electromotance $\dot{E}_{ci}$ that is multiplied by these admittances, form a current vector of active nodes, what is on the right side of equation (1). Model (1), converted in such way, can be written in a vector form:

$$\underline{\mathbf{Y}}_N \vec{\dot{U}}_N = -\underline{\mathbf{Y}}_c \vec{\dot{E}}_c, \tag{2}$$

where appropriate components are formed with regard to $\underline{y}_{ci}$ and $\dot{E}_{ci}$.

For any active node there is available power:

$$\dot{S}_i = \underline{y}_{ci}\dot{V}_{Ni}(\dot{E}_{ci} - \dot{V}_{Ni})\,. \tag{3}$$

Load flow analysis by compensational electromotance method is reduced to finding such compkoensational electromotance $\dot{E}_{ci}$, in which in active nodes power and voltage are equal to reference values accordingly $\dot{S}_{i\,ref}$ or $P_{i\,ref}$ and $V_{i\,ref}$, so that is

$$\dot{S}_i = \dot{S}_{i\,ref} \text{ or } P_i = P_{i\,ref} \text{ and } \left|\dot{V}_i\right| = \left|\dot{V}_{i\,ref}\right|. \tag{4}$$

Iterative process is constructed so that changing of $E_{ci}^{(k)}$ for each *i*-th active node in each *k*-th iteration approach available power $\dot{S}_i^{(k)}$ to the reference value $\dot{S}_{i\,ref}^{(k)}$. Calculated condition at each iteration is balanced, so all nodes are satisfied by laws of balance and incompletion of iterative process is determined by mismatch of available and reference active nodes power.

1.1. Static characteristics of load and generator for voltage and frequency

Static load characteristics on voltage are set by polynomial of second degree, and on frequency – dependent linear proportion to frequency deviation. General view of these characteristics is:

a) if the node voltage is more than critical V_{cr}:

$$P_{L\,ref} = P_{norm}\left(a_0 + a_1\left(\frac{V}{V_{norm}}\right) + a_2\left(\frac{V}{V_{norm}}\right)^2 + a_f\left(\frac{f - f_0}{f_{nom}}\right)\right) \tag{5}$$

$$Q_{L\,ref} = Q_{norm}\left(b_0 + b_1\left(\frac{V}{V_{norm}}\right) + b_2\left(\frac{V}{V_{norm}}\right)^2 + b_f\left(\frac{f - f_0}{f_{nom}}\right)\right); \tag{6}$$

b) if the node voltage is less than critical V_{cr}:

$$P_{L\,ref} = P_{norm}\left(a_{cr}\left(\frac{V}{V_{norm}}\right)^2 + a_f\left(\frac{f - f_0}{f_{nom}}\right)\right) \tag{7}$$

$$Q_{L\,ref} = Q_{norm}\left(b_{cr}\left(\frac{V}{V_{norm}}\right)^2 + b_f\left(\frac{f - f_0}{f_{nom}}\right)\right), \tag{8}$$

where P_{norm}, Q_{norm} - measured load power of normal operating condition; V_{norm} - normal operating condition voltage, when load was measured; f_{nom} - frequency rating of power system; f_0 - frequency, in which was the load power measured (the frequency of pre-balanced condition); V, f - actual (estimated) values of the node voltage and frequency; $P_{L\,ref}, Q_{L\,ref}$ - reference values of active and reactive loads; a_0, a_1, a_2, a_f - coefficients that determine the static characteristics of active load for voltage and frequency; b_0, b_1, b_2, b_f - similar coefficients for the reactive load; V_{cr} - a critical voltage (when occurs pull-out of induction motors); a_{cr}, b_{cr} - coefficients, which determine the jump-change load in case $V = V_{cr}$.

During the design and perspective calculations rated voltage of relevant electrical networks degree is accepted like V_{norm}. In case of operational conditions calculation voltage, in which was measured load power, is used as V_{norm}.

In case when coefficients a_{cr} and b_{cr} are equal to zero, their value is determined from the condition of static characteristics continuity when $V = V_{cr}$. Condition with less critical node voltage cannot physically exists. If condition was calculated with static characteristic $P = const$ and $Q = const$, it is neccesary to repeat the calculation with actual static characteristics. In case of their absence we should repeat the calculation using typical static characteristics.

Considering the existence of voltage control devices in the network, most of the conditions should be calculated with using the static characteristics $P = const$ and $Q = const$. Post-accident and repair conditions are exceptions. During such calculations in some areas may occurs deep voltage decrease.

Algorithm consideration of power dependence on voltage may be next. Make calculation of normal load flow with static characteristics $P = const$ and $Q = const$. Calculated voltage is used as a nominal (measured) for static characteristics during next calculations. Set real or typical static characteristics and make calculations with their consideration. Re-calculation of normal condition should not lead to changes in the power balance and voltage levels.

For generating nodes static characteristics of active power dependence on frequency may be next:

$$P_{G\,ref} = (\mu_\Sigma - k_D (f - f_0)/f_{nom}) P_{G\,nom} \tag{9}$$

$$\mu_T = P_{G0}/P_{G\,nom} - (f - f_0)/(f_{nom}\sigma_s) \tag{10}$$

$$\mu_\Sigma = \mu_{min}\text{, when } \mu_T < \mu_{min}; \tag{11}$$

$$\mu_\Sigma = \mu_T\text{, when } \mu_{min} < \mu_T < \mu_{max}; \tag{12}$$

$$\mu_\Sigma = \mu_{max}\text{, when } \mu_T > \mu_{max}, \tag{13}$$

where $P_{G\,ref}$ – reference generator active power; $P_{G\,nom}$ – nominal generator active power; P_{G0} - generator active power, that is defined by frequency setting; μ_T - calculated control valves opening of turbine (distributor); μ_Σ - similar amount in accordance with limitations on control valves opening; μ_{min}, μ_{max} - allowable control valves openings, that determine minimum and maximum generator power; k_D - factor, that consider static auxiliary load characteristics of generators on frequency; σ_s - frequency droop of speed turbine regulator.

1.2. Consideration of generator overloads limitations on stator and rotor currents

Each node condition is completely characterized by four variables: active and reactive power P, Q, which are generated by generator or consumed by load; absolute voltage value V and its phase relative to some axis. From equations, that describe the balance of network, we can find two of these four variables. The other two should be determined based on the equation of generator or load state.

During normal operation of the generator when the rotor and stator currents are within allowable values, any AER supports almost constant voltage on buses of generating or higher voltages. Small frequency droop on voltage is provided not only by large amplifying factors of voltage deviation (which, however, are limited by the terms of oscillating stability) but also by current compensation. Therefore, absolute voltage value at certain buses, depending on how regulator is tuned, can be considered constant and equal to reference value. The second reference value is an active generator power.

So, in the case of normal generator work, its model includes only two reference values: P and V. The values of Q and θ are determined during solution of the network equations.

It is known that power system state changing may lead to generator overload on rotor and (or) stator current, and that there are cases, when limitations on stator and rotor current should be considered in load flow calculations. In practice, consideration of limitations on stator or rotor current usually is tended to the limit:

$$Q < Q_{max}. \quad (14)$$

If such limitation is broken, we will set P and $Q = Q_{max}$ in generating nodes. Then the values Q and θ, that will be determined by load flow calculation, become unknown.

Since stator and rotor current or electromotance depend on the reactive power, then limit of stator or rotor current and limit of maximum reactive power are almost equivalent. If in the limitation condition, when $Q = Q_{max}$, generator voltage remains close to pre-set one and if Q_{max} is calculated (during the preparation of output data) correctly, then consideration of the limitations for reactive power won't lead to errors.

But in cases, where generator voltage may be essentially reduced due to the limitations, the situation becomes more complicated.

Let's identify connection of Q_{max}, which limits allowable reactive power value, with the rest parameters and coordinates.

1. Reactive power from allowable stator current condition is equal to

$$Q_{max} = S_{nom} \sqrt{k_I^2 \left(\frac{V}{V_{nom}} \right)^2 - k_{gen}^2 \cos^2 \varphi_{nom}} , \qquad (15)$$

where k_{gen} - load generator factor; k_I - long duration allowable stator current; V - estimated voltage; $S_{nom}, V_{nom}, \cos\varphi_{nom}$ - nominal values of total power, voltage and power factor.

2. Reactive power from allowable rotor current condition is equal to

$$Q_{max} = \left(\sqrt{k_E^2 E_{qnom}^2 \cdot V^2 - P^2 \cdot x_d^2} - V^2 \right) / x_d , \qquad (16)$$

where k_E – allowable multiplicity of excitation current or of electromotance E_q (usually is taken $k_I = k_E = 1.1$).

So we should consider stronger limitation while setting Q_{max}. In some cases stronger is stator current limitation, and in others – the rotor one.

Nominal value $E_{q\,ref}$ may be calculated in accordance with this expression

$$E_{q\,nom} = \frac{U_{nom}^4 + Q_{nom} U_{nom}^2 (x_d + x_q) + S_{nom}^2 x_d x_q}{U_{nom} \sqrt{U_{nom}^2 + 2Q_{nom} U_{nom}^2 x_q + S_{nom}^2 x_q^2}} . \qquad (17)$$

While the load flow calculation it is regularly checked the reactive power limit fulfillment in generating nodes. Mean time between checking is following: after 15 iterations, if the calculation is carried out from zero initial conditions; after 5 iterations since the previous checking; after reaching reference accuracy.

During this checking, nodes, in which limits on reactive power are not fulfilled, are transferred to the conditional working out mode of reactive power limits. Means that, if this node voltage on next iterations is set at reference level, it will be again transferred to the condition of working out reference voltage. There may be few changes of generating nodes condition (in the Dakar base version – 5).

Value Q_{max} doesn't remain constant for considering of stator or rotor current limitations. If generator parameters are set for generating node, then Q_{max} is calculated with regard to (з врахуванням) stator or rotor current limitation. For further calculations we accept stronger limitation. The developed algorithm doesn't require external loop for calculations refinement. Additional time spending is very small, only for Q_{max} calculation.

2. SPECIFICS OF LOAD FLOW ANALYSIS WITH VARIABLE FREQUENCY

There is a notion of balanced node in power system models of load flow analysis with fixed frequency. It is known that not less than one power source should be set by its voltage (as an electromotance source) or by electromotance with certain complex resistance. The condition of this δ-th node in network calculated model depends on condition of other network nodes. From the physical point of view balanced node is required to active power output to ensure its balance and to maintain steady value of frequency. In addition, this node is required to reactive power output for providing its balance and for maintenance of required voltage level.

But in the real power system such node doesn't exist, therefore putting it in the estimated model may lead to inadequate calculation conditions or to inability of obtaining the condition at all.

Consideration of variable frequency allows to get rid of this disadvantage and to consider all nodes as equal in the sense of working out necessary power in them. This is especially important during calculations of post-accident conditions, whose existence is possible only for frequencies different from nominal [2].

2.1. The method of compensational electromotance for load flow calculation with variable frequency

One of the advantages of this method is that at each iteration electric network condition is balanced (in all nodes and circuits the Kirchhoff's laws are satisfied). So in the network equation we put in a frequency as an independent variable. Now balanced node performs other functions and is called major node. It gives the necessary reactive power for providing a reference voltage level. The active power in this node is calculated in the same way as in any other generation node.

Based on simple calculations we define the predicted frequency deviation for the *k*-th iteration.

$$\Delta f^{(k)} = \frac{\left(\Delta P_\delta^{(k)} - \sum_{i=1}^{m} \Delta P_i^{(k)}\right)}{\left(\frac{\partial P_{ref\,\delta}(V,f)}{\partial f}\right)^{(k)} - \sum_{i=1}^{m}\left(\frac{\partial P_{ref\,i}(V,f)}{\partial f}\right)^{(k)} \Big/ \left(\frac{\partial P_{ref\,\Sigma}(V,f)}{\partial P_{ref\,\delta}}\right)^{(k)}}, \qquad (18)$$

where ΔP_δ and ΔP_i are difference between the calculated and reference power in major and *i*-th nodes; $\partial P_{ref\,\delta}(V,f)/\partial f$, $\partial P_{ref\,i}(V,f)/\partial f$ – partial derivatives of major and *i*-th nodes power on frequency; $\partial P_{ref\,\Sigma}(V,f)/\partial P_{ref\,\delta}$ – partial derivative of total power for reference power of major node, which determines the degree of change in total active power of *i*-th nodes from changes of major node power.

In practice, frequency value is defined in the beginning of iterative process. All further calculation process is reduced to achieve reference accuracy of working out the power and voltage for already known frequency.

This feature allows you to consider functioning of emergency control system, that are related to frequency change, without waiting for the full condition working out and thereby to reduce significantly the total time of calculation. Considering that the method of compensational electromotance is multistep and thereby less critical to condition parameter limitation, so stabilizing functioning of frequency to iterative process character are shown more than while using the Newton-Raphson methods. Putting the frequency as a variable, at the beginning of iterative process makes the estimated condition less difficult than a similar condition with fixed frequency. In this way not only the total number of iterations decreases, but also significantly increases the reliability of obtaining calculation result, especially for post-accident conditions.

3. CONCLUSIONS

These presented methods and models of load flow analysis in the Dakar complex [3, 4] provide: calculation of normal, repair and post-accident load flows with constant and variable frequency; detailed analysis of calculation results for the balance of power, power loss; consideration of static characteristics of load power dependency on voltage and frequency; consideration of active power corona losses, depending on voltage and weather conditions; automatic choice of tapped transformers' position to provide a consumer with a desired level of voltage; loading of normal and repair conditions; load flow calculation during electromechanical transients' analysis; calculation of long-term quasi-established transients; load flow calculation with HVDC; consideration of automatic devices action during load flow analysis.

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