Asymmetrical Load-Flow Solution by Fast Decoupled Method in Sequence Domain

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Abstract – **In this paper a very fast method for asymmetrical load-flow solution in sequence domain is presented. The proposed method is based on the standard Fast Decoupled method for symmetrical load-flow solution applied on the positive- sequence circuit, enhanced with two systems of linear equations which represent negative- and zero-sequence circuits. Few recently published procedures are used to establish this method in sequence domain. The real power system is analyzed by proposed method and the results are compared with results obtained by standard Fast decoupled method in phase domain.**

Keywords – **Asymmetrical load-flow, sequence domain, Fast Decoupled method.**

I. Introduction

Two very important studies for the power systems are load-flow and faulted states analysis. The steady state symmetrical load-flow studies (SLF) are performed in the more efficient and comfortable sequence domain instead of in the phase domain. Symmetrical states are good approximations of usual states of three-phase power systems. But actually, because of the presence of long unbalanced (untransposed) lines, asymmetrical or single-phase loads (as induction furnaces and traction motors etc.), asymmetrical states in power systems are occurred. These states cause: negative-sequence currents at generator terminals rise heating in their rotors; malfunctions of protective relays; zero-sequence currents increase greatly the effect of inductive coupling between parallel transmission lines; higher power system loss, etc.

For more precise analysis of three-phase power system asymmetrical states, the asymmetrical load-flow (ALF) analysis is required. ALF calculations are also required to study the effects of various phase arrangements of transmission lines, single pole switchings, etc.

The solution of ALF problem was successfully performed using methods in phase domain (Newton-Raphson and Fast decoupled procedures) [1-3]. But unfortunately, there are mutual couplings between phases and 6x6 node-admittance matrices which describe the generators, transformers and lines are not sparse. This fact implies increasing of both: memory for problem storage and CPU time for problem solution in the phase domain. Therefore, there was a question: are the methods in sequence domain more efficient against the methods in phase domain?

Long time the sequence domain was avoided in the ALF methods because of: presence of phase shifts of the three-phase transformers (ideal transformers with complex turns ratios in their sequence circuits); mutually couplings among sequence circuits for unbalanced lines and asymmetrical phase loads which cannot be specified in the sequence domain. Recently published procedures as: new scaling concept [4], unbalanced line decoupled model in sequence domain [5], [6], enhanced bus classification and synthesizing procedure [7], [11] and asymmetrical phase loads model specified in the sequence domain [6], [10] enabled to establish a few new methods for ALF calculations in sequence domain. The Reduced admittance matrix method [8] and fast method [9] in sequence domain are more efficient than any method in phase domain.

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II. New Approach for Power System Elements Modeling

The most important step of the ALF methods establishing in sequence domain is power system elements modeling. These models should have such properties that the entire power system can be modeled with three decoupled positive-, negative- and zero-sequence circuits.

The synchronous generator is balanced element of the power system. In the sequence domain it can be presented with three decoupled sequence circuits. Each sequence circuit is represented with corresponding impedance ($\underline{z}_G^d$ for positive-, $\underline{z}_G^i$ for negative- and $\underline{z}_G^o$ for zero-sequence). If the generator is grounded the $\underline{z}_{nG}$ represents the generator grounding impedance. With the sequence admittances obtained from the sequence impedances, the 6x6 node-admittance matrix representing the synchronous generator in the sequence domain is formed [10].

Balanced transmission overhead lines can be presented with three lumped-π decoupled sequence circuits. Each circuit consists series admittance between line ends and two equal shunt admittances at the line ends. Consequently, 6x6 node-admittance matrix for the line model will be sparse. If the unbalanced lines are considered in sequence domain there are inductive and capacitive couplings among positive-, negative- and zero-sequence circuits. These couplings are expressed by mutually non-zero admittances in the 6x6 node-admittance matrix for the line model which is not sparse. In this case the line model cannot be presented with lumped-π decoupled sequence circuits. But decoupling procedure explained in [5], enables to express the couplings by compensation current sources instead of mutually admittances. The current controlled sources in series and shunt branches of each sequence lumped-π circuit include the coupling influences from the other sequences. Now, the unbalanced line model can be presented with three decoupled sequence lumped-π circuits, with sparse 6x6 node-admittance matrix.

Another problem to establish new methods for ALF calculation in sequence domain was transformer model. The three-phase transformer with complex turn ratio can be treated as a balanced element and its model can be presented with the three decoupled sequence circuits. But the problem of complex turn ratio still exists because ideal transformers with complex turns ratios disturb the symmetry and the simplicity of deriving power system node-admittance matrices in the sequence domain. Transferring the values from the absolute to the relative value domain by the standard PU system doesn't solve the problem of phase shifting. Application of the "New scaling concept" definitely eliminates these problems. The result of scaling the absolute in relative values with this concept is transformer model represented with three decoupled sequence circuits in which only the transformer (and grounding) impedances exist. The phase shifts are eliminated from the sequence circuits and transformer 6x6 node-admittance matrix is simple and sparse [10], [11].

The load model in phase domain is given by specified load active and reactive powers for each phase. If the complex voltages from the load buses *k* are on disposal, the injected complex currents for each phase can be calculated. With known complex currents in phase domain and inverse transformation matrix [11], injected complex currents in node *k* in any sequence circuit can be obtained very easy. From the sequence complex voltages and currents, the sequence complex powers can be calculated. Thus, the load model in sequence domain can be presented through injected complex currents or injected complex powers in node *k* of any sequence circuit. The widely explanation of power system elements modeling in sequence domain can be find in [10].

Consequently, all necessary conditions for all (balanced and unbalanced) power system elements representation with decoupled sequence circuits are achieved. Thus, the entire power system can be modeled with three decoupled positive-, negative- and zero-sequence circuits.

III. New Bus Classification and Synthesizing Procedure

The classifications of buses applied in all ALF methods in phase or sequence domain for example as proposed in [1-3], [5], [6] were taken directly from classical SLF problem statements. They consist of three types of buses: "load busbars", "generator busbars" and a "slack (or swing) busbar; or: "PQ bus", "PV bus" and "θV (slack) bus". Their definitions were generalized for the purpose of the ALF problem statement. But these definitions are not performed in a full accordance with the nature of the ALF problem, because they do not enable a correct treatment of Q limits enforcement at PV buses.

In the new classification there are $P_\Sigma V$ type buses in which the value of three-phase injected active power (P_Σ) and the control law of the automatic voltage regulator (AVR) are specified. The θV bus (slack bus) is a bus in which the angle of a voltage and the control law of the generator AVR are specified. To provide a correct treatment of reactive power limits enforcement at the generators (at $P_\Sigma V$ buses), a new type of buses called $P_\Sigma Q_\Sigma$ are introduced. In this type of buses values of the three-phase injected active and reactive powers (sums of phase powers P_Σ and Q_Σ) are specified. All three types of buses mentioned above are suppressed in the high voltage buses of their corresponding step-up transformers. The last PQ type of buses is a standard type of buses in which values of three pairs of phase injected active and reactive powers are specified. More detailed explanation for the different types of buses is given in [7], [9].

The general representation of the sequence circuits for a generator and its step-up transformer are shown on Fig. 1. The bus presented in this figure denoted as *g*, can be of θV , $P_\Sigma V$ or $P_\Sigma Q_\Sigma$ type.

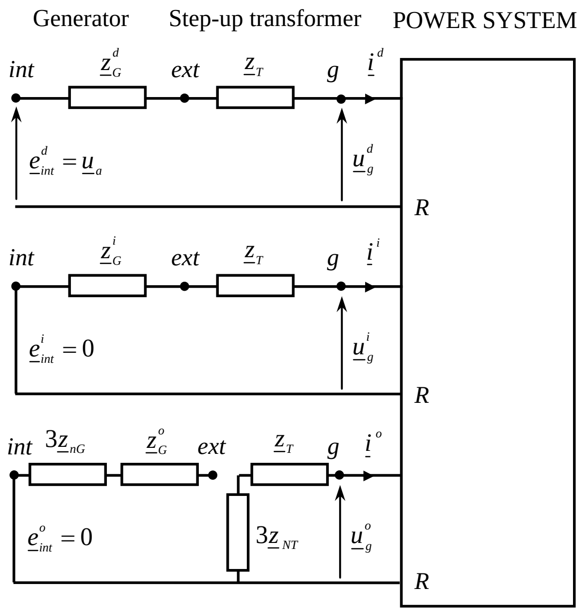

Fig. 1. Scaled sequence circuits of synchronous generator and step-up transformer.

Usually, in practice the voltage control and the active power control are associated with the high voltage transformer bus *g*. The generator internal bus voltage, as well as the voltage drops on the generator and transformer impedances are not of interest simultaneously with values of other power system quantities. Thus, the equivalent impedance in the positive- sequence circuit can be omitted and equivalent impedances in the negative- and zero-sequence circuits can be suppressed in the transmission network as it is shown on the Fig. 2. The procedure which enable to exclude the external and internal generator buses and associate the bus properties to the high voltage buses in their corresponding step-up transformers is called synthesizing procedure. Also suppression of the negative- and zero-sequence impedances in the power system is part of this procedure. This suppression enables zero-valued injected currents and powers in the corresponding negative and zero-sequence nodes *g*. Therefore, the injected currents and powers are different from zero only at the positive-sequence node.

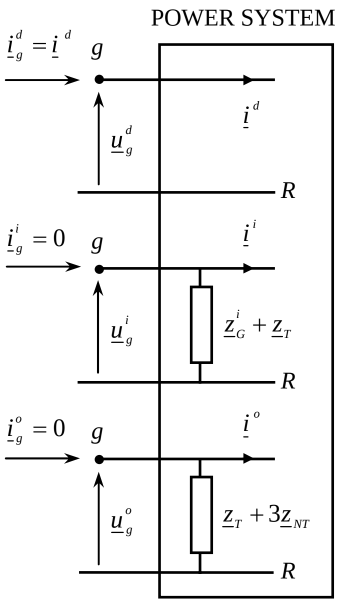

Fig. 2. Sequence circuits of a generator and its step-up transformer represented after synthesizing procedure.

Now, the issue of shortage of four equations corresponding to each $P_\Sigma V$, θV and $P_\Sigma Q_\Sigma$ bus in the sequence domain can be solved [7]. One more benefit of the synthesizing procedure is power system buses reduction. Thus, the power system with N_G generators and total number of buses n can be treated as a system with $r = n - 2N_G$ buses or 3r nodes.

IV. Fast Decoupled method definition

Taking into account all above mentioned procedures, entire power system can be presented with positive-, negative- and zero-sequence scaled, decoupled and node-reduced circuits. In accordance with these facts, the system of three linear nodal-voltage equations represents the base ALF model in sequence domain:

$$\mathbf{Y}^d_{r\times r}\mathbf{U}^d_r = \mathbf{I}^d_{rc}\,, \tag{1}$$

$$\mathbf{Y}^i_{r\times r}\mathbf{U}^i_r = \mathbf{I}^i_{rc}\,, \tag{2}$$

$$\mathbf{Y}^o_{r\times r}\mathbf{U}^o_r = \mathbf{I}^o_{rc}\,, \tag{3}$$

where $\mathbf{Y}^d_{r\times r}$, $\mathbf{Y}^i_{r\times r}$, $\mathbf{Y}^o_{r\times r}$ are node-admittance; $\mathbf{U}^d_r$, $\mathbf{U}^i_r$ and $\mathbf{U}^o_r$ are node-voltage matrices for positive-, negative- and zero-sequence decoupled circuits respectively. The matrices of node injected complex currents, corrected by compensation currents (as result of circuits decoupling) are denoted as $\mathbf{I}^d_{rc}$, $\mathbf{I}^i_{rc}$ and $\mathbf{I}^o_{rc}$. At first Eq. (1) can be conjugate and than multiply from the left by a diagonal matrix containing the complex positive-sequence voltages. As the result of this procedure, a new nonlinear system of equations representing the power system positive-sequence is obtained:

$$\mathbf{U}^d_{r,dij}\left(\mathbf{Y}^d_{r\times r}\right)^*\left(\mathbf{U}^d_r\right)^* = \mathbf{S}^d_{rc}\,. \tag{4}$$

In Eq. (4), matrix $\mathbf{S}^d_{rc}$ represents complex, compensated injected powers in the positive sequence circuit nodes [11].

Applying the Taylor’s procedure, the nonlinear system of equations given by matrix Eq. (4), can be transformed in the new linear system of equations. This new system is consisted of equations for differences between the injected specified and calculated powers $-\Delta\mathbf{S}^d_{kor}$ in the power system positive-sequence circuit nodes, represented by the Jacobian $\mathbf{J}^d$ (for this sequence circuit) and unknown differences of voltage magnitudes and angles given by the matrix $\Delta\mathbf{X}^d$:

$$\mathbf{J}^d\Delta\mathbf{X}^d = \Delta\mathbf{S}^d_{kor}\,. \tag{5}$$

or in the well known form with sub-matrices:

$$\begin{bmatrix}\mathbf{H}^d & \mathbf{N}^d\\ \mathbf{M}^d & \mathbf{L}^d\end{bmatrix}\begin{bmatrix}\Delta\theta^d\\ \Delta\mathbf{U}^d/\mathbf{U}^d\end{bmatrix} = \begin{bmatrix}\Delta\mathbf{P}^d_{kor}\\ \Delta\mathbf{Q}^d_{kor}\end{bmatrix}. \tag{6}$$

Actually, the matrix Eq. (6) has the same form as the equations which represents the symmetrical Newton-Raphson load-flow model [12]. The elements of the sub-matrices $\mathbf{H}^d$, $\mathbf{N}^d$, $\mathbf{M}^d$ and $\mathbf{L}^d$ in iteration h, can be calculated as:

$$H^{d(h)}_{ki} = \left.\frac{\partial P_k}{\partial\theta_i}\right|^{d(h)} = U^{d(h)}_k U^{d(h)}_i\left(G^d_{ki}\sin\theta^{d(h)}_{ki} - B^d_{ki}\cos\theta^{d(h)}_{ki}\right), \tag{7}$$

$$N^{d(h)}_{ki} = U^{d(h)}_i\left.\frac{\partial P_k}{\partial U_i}\right|^{d(h)} = U^{d(h)}_k U^{d(h)}_i\left(G^d_{ki}\cos\theta^{d(h)}_{ki} + B^d_{ki}\sin\theta^{d(h)}_{ki}\right), \tag{8}$$

$$M^{d(h)}_{ki} = \left.\frac{\partial Q_k}{\partial\theta_i}\right|^{d(h)} = -U^{d(h)}_k U^{d(h)}_i\left(G^d_{ki}\cos\theta^{d(h)}_{ki} + B^d_{ki}\sin\theta^{d(h)}_{ki}\right), \tag{9}$$

$$L^{d(h)}_{ki} = U^{d(h)}_i\left.\frac{\partial Q_k}{\partial U_i}\right|^{d(h)} = U^{d(h)}_k U^{d(h)}_i\left(G^d_{ki}\sin\theta^{d(h)}_{ki} - B^d_{ki}\cos\theta^{d(h)}_{ki}\right), \tag{10}$$

$$H^{d(h)}_{kk} = \left.\frac{\partial P_k}{\partial\theta_k}\right|^{d(h)} = -Q^{d(h)}_k - B^d_{kk}\left(U^{d(h)}_k\right)^2, \tag{11}$$

$$N^{d(h)}_{kk} = U^{d(h)}_k\left.\frac{\partial P_k}{\partial U_k}\right|^{d(h)} = P^{d(h)}_k + G^d_{kk}\left(U^{d(h)}_k\right)^2, \tag{12}$$

$$M^{d(h)}_{kk} = \left.\frac{\partial Q_k}{\partial\theta_k}\right|^{d(h)} = P^{d(h)}_k - G^d_{kk}\left(U^{d(h)}_k\right)^2, \tag{13}$$

$$L^{d(h)}_{kk} = U^{d(h)}_k\left.\frac{\partial Q_k}{\partial U_k}\right|^{d(h)} = Q^{d(h)}_k - B^d_{kk}\left(U^{d(h)}_k\right)^2. \tag{15}$$

Because in the power systems X/R>>1 and differences between angles $\theta^{d(h)}_{ki} = \theta^{d(h)}_k - \theta^{d(h)}_i$ are very rare greater than 10^0, the next approximations can be taken into account:

$$G^d_{ki} << B^d_{ki};\ \cos(\theta^{d(h)}_k - \theta^{d(h)}_i) \approx 1;\ \sin(\theta^{d(h)}_k - \theta^{d(h)}_i) << 1\,. \tag{16}$$

These approximations applied in Eqs. (7) to (15), give zero-valued sub-matrices:

$$\mathbf{N}^d \approx \mathbf{0}\ \text{and}\ \mathbf{M}^d \approx \mathbf{0}\,. \tag{17}$$

Taking into account the above explanations, and Eqs. (2), (3), (6) and (17) the new developed Fast Decoupled method for ALF solution in sequence domain is defined as:

$$\mathbf{H}^d \cdot \mathbf{\Delta\theta}^d = \Delta\mathbf{P}^d_{kor}, \quad (18)$$

$$\mathbf{L}^d \cdot \mathbf{\Delta U}^d / \mathbf{U}^d = \Delta\mathbf{Q}^d_{kor}, \quad (19)$$

$$\mathbf{Y}^i_{r\times r}\mathbf{U}^i_r = \mathbf{I}^i_{rc}, \quad (20)$$

$$\mathbf{Y}^o_{r\times r}\mathbf{U}^o_r = \mathbf{I}^o_{rc}. \quad (21)$$

With the proposed method, the problem of ALF solution is considered as solution of SLF problem with standard Fast decoupled procedure (Eqs. (18) and (19)) [13] and solution of two supplementary systems of linear equations representatives of negative- and zero-sequence power system circuits Eqs. (20) and (21) respectively.

V. METHOD VERIFICATION

The Fast decoupled method is tested on the entire power system of the Republic of Macedonia consisting of 63 buses of 400, 220 and 110 kV voltage level, 53 lines, 5 interconecting transformers and 9 equivalent generators with step-up transformers. Eight states (variants) are considered. Each of the variants is solved with Fast decoupled three-phase load-flow method in phase domain (FD ALF-abc) [2] and proposed method in sequence domain (FD ALF-dio). The first state V1 is symmetrical. All other seven states are more or less asymmetrical. For the purpose to eliminate the influence of the computer type, the results are given in relative units. The base case is V1 solved with proposed Fast decoupled method in sequence domain. The results of total number of iterations and relative CPU time for each variant solution are given in Table I.

TABLE I.
RESULTS OF THE CALCULATIONS.

Number of iterations/CPU relative time								
M \ V	V1	V2	V3	V4	V5	V6	V7	V8
FD ALF-abc	7/ 8,2	7/ 8,2	57/ 11,54	9/ 8,34	8/ 8,24	10/ 8,36	7/ 8,16	7/ 8,25
FD ALF-dio	9/ 1,0	9/ 1,0	19/ 1,39	8/ 1,05	8/ 1,03	8/ 1,09	9/ 1,04	8/ 1,01
abc-r.time / dio-r.time	8,2	8,2	8,3	7,9	8,0	7,7	7,8	8,2

* **M**- method; **V**- variant.

From the results of the Table I it is obvious that proposed Fast decoupled method for ALF in sequence domain is very efficient, robust and much more faster than standard method for ALF in phase domain. Because the power system node-admittance matrix in sequence domain is sparse, the memory storage required for the proposed method is significantly smaller then the Fast decoupled method for ALF in phase domain.

VI. CONCLUSION

Recently published procedures as: enhanced bus classification, sequence circuits decoupling, new scaling concept, synthesizing procedure and approximations which are justified for the power systems enable new approach for ALF problem solution. In this paper the efficient very fast method based on the standard Fast decoupled method is established. The efficiency is achieved in memory requirements and CPU time for calculations. The form of the decoupled positive-sequence part of the presented ALF model is reduced to the form of the classical SLF problem. Thus, the standard SLF Fast decoupled procedure [13] is applied inside the ALF solution procedure. The negative- and zero-sequence parts of the presented ALF model are represented by two systems of linear equations and solved by Gauss's method.

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