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Initialization of Steady-State Security Analyses of Electric Power Interconnections

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Abstract: The basic objective of this paper is to present the relevant methodological and practical aspects of two efficient procedures for initialization of steady-state security analyses of electric power interconnection. The first procedure gives the load-flow solution for known initial generators scheduling and the second one gives the load-flow solution in conditions of bilateral or multilateral exchange programs realization. Those procedures are fully consistent with the specially developed procedure for steady-state security analysis, which is based on successive solutions of load-flow in characteristic post-dynamic quasi-stationary states, occurring after the considered disturbances. The efficiency of proposed procedures is demonstrated on the example of real electric power interconnection in the Balkan area.

Keywords: Steady-state, security analyses, initialization, load-flow solution, electric power interconnection.

1 Introduction

An important problem in modern Electric Power Systems (EPSs) is to provide the necessary level of operational security [1]. In the cases of single or multiple disturbances it is required for the power system to remain inside previously defined tolerance limits. In recent years, the increased practical interest to this problem and corresponding new challenges are essentially due to increased loading of EPSs, combined with a process of deregulation in electric power market and restructuring of the power utilities. As the practical importance of obtaining the necessary level of electric power system security is a well-known fact, the author will proceed directly to presenting the main objective of the paper.

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This paper deals with the steady-state security analysis of power system, which is one of the most important parts of existing Energy Management System (EMS). In this context, the special attention is paid to the initialization of those analysis, e.g. to the solving of the load-flow problem in initial steady-states. One of the important practical questions is how to make initialization of this analysis? In modern EMS, the most popular approach to the steady-state security analysis is based on well known fast decoupled load-flow method [2], with single iteration fast contingency selection. Also, this method is used for initial load-flow solution, e.g. the initialization and steady-state security analyses are based on same conventional model and solution technique. However, the question is how to make efficient initialization of those analyses, which are based on unconventional load-flow models? Evidently, in this case, the desired efficiency is not reached by conventional model for ”self starting”, because the next calculations in context of future steady-state security analyses are based on unconventional load-flow model.

The basic objective of this paper is to present the relevant methodological and practical aspects of two efficient procedures for initialization of EPS's steady-state security analyses, e.g. the procedures of solving the initial load-flows problem, which preceding these analyses. The first procedure enables the load-flow solution for given initial generators scheduling in interconnection considered. The second procedure gives the load-flow solution in conditions of realization of a set bilateral or multilateral exchange programs between EPS's. Those procedures are fully consistent with the specially developed methodology for steady-state security analyses [3,4]. This methodology is based on unconventional load-flow models, in which the power system frequency is a relevant variable. In this context, steady-state security analysis are based on successive solutions of the unconventional load-flow, by specially developed fast decoupled method for a set of characteristics post-dynamic quasi-stationary states of the power systems (states resulting from primary voltage and frequency control, states after the action of automatic secondary control of frequency and tie-line power and states after the corresponding possible dispatch activities, if necessary). Such developed procedures' characteristics enable complete autonomy and uniformity of security analyses, the unification of corresponding computer program, as well as their successive execution, which have a great practical importance.

The efficiency of proposed improved methodology is demonstrated on example of existing electric power interconnection in the Balkans, formed by EPS's of ex Yugoslavia, Romania, Bulgaria, Former Yugoslav Republic of Macedonia, Greece and Albania (ex second UCTE synchronous zone). The results obtained for the so called ”base case” (”zero” exchange program between EPSs), as well as for a set of multilateral and bilateral exchange programs, at first, show a very good, fast, and reliable convergence characteristics of procedure developed and also show their great flexibility in cases of creation of important exchange programs between EPS's considered.

2 Unconventional Load-Flow Models

For the state resulting from primary voltage and frequency control, the following balance equations hold [3, 4]:

$$\Delta P_i = P_{G0i} - k_{pi}\Delta f - P_i = 0, \quad i \in NG \tag{1}$$

$$\Delta Q_i = Q_{G0i} + Q_{0i}\frac{V_{G0i} - V_{Gi}}{s_{Vi}V_{G0i}} - Q_i = 0, \quad i \in NSV \tag{2}$$

$$\Delta P_i = P_{Li}(V_i, f) - P_i = 0, \quad i \in NL \tag{3}$$

$$\Delta Q_i = Q_{Li}(V_i, f) - Q_i = 0, \quad i \in NL \tag{4}$$

which satisfy the following constraints:

$$P_{Gmin\,i} \leq P_{Gi} \leq P_{Gmax\,i}, \quad i \in MG \tag{5}$$

$$Q_{Gmin\,i} \leq Q_{Gi} \leq Q_{Gmax\,i}, \quad i \in MG \tag{6}$$

where N is total number (set) of all nodes of the interconnected power system, NG is total number (set) of generator nodes ($NG \in N$), NSV is number (set) of generators with static voltage-reactive power characteristic ($NSV \in NG$) and NL is number (set) of load nodes ($NL \in N$; $NL = N - NG$). P_{G0i} is active power of the i-th generator in the initial steady-state, k_{pi} is primary frequency control constant of i-th generator, $\Delta f = f - f_0$ is deviation of the quasi-stationary value of frequency f from its initial value f_0, k_{si}^j-the participation factor of the i-th regulation generator in the AGC control of j-th interconnected area, Q_{GOi}, V_{0i} are reactive power and voltage at the ends of i-th generator in the initial steady-state, s_{Vi} is droop of the static voltage-reactive power characteristic of the i-th generator, P_i, Q_i are injected active and reactive powers and $P_L(V_i, f)$, $Q_L(V_i, f)$ are load active and reactive powers at node i, as a complex function of the voltage at its end and the quasi-stationary value of the frequency.

It should be noted that in this case, as opposed to the usual approaches, the upper ($P_{Gmax\,i}$, $Q_{Gmax\,i}$) and lower ($P_{Gmin\,i}$, $Q_{Gmin\,i}$) limits of active and reactive power generation are not constant, a priori defined quantities, but rather corresponding functions of relevant state variables [5].

In the case of the post-dynamic quasi-stationary state, occurring due to the automatic secondary control of frequency and tie-line power, the balance equations of the form (1) still hold, but only for generators which are not participating in the secondary control, as well as (2) - (4). Here, two following new equations are added (limits (5) and (6) still hold):

$$\Delta P_i = P_{G0i} - k_{pi}\Delta f + k_{si}^{i} REG_j - P_i = 0, \quad i \in NAGC_j,\ j \in M \tag{7}$$

$$\Delta ACE_j = P_{Tj} - P_{T0j} + B_j \Delta f = 0, \quad j \in M \tag{8}$$

where M is number (set) of power systems in synchronous parallel operation, $NAGC_j$ is number (set) of generators which participate in the secondary frequency control and tie-line power (or automatic generator control) in j-th power system, i.e. area ($NAGC_j \in NG;\ j\imath M$), ΔACE_j is static area control error of the j-th interconnected area ($j \in M$), PT_j, P_{T0j} are actual and scheduled total tie-line power of j-th interconnected area, B_j is the bias factor on the automatic generator control (or secondary control constant) of j-th area and REG_j is amount of regulation power of j-th area necessary for elimination the own static control error ΔACE_j. The effects of the automatic secondary frequency and tie-line power control, together with (7), result in (8), which gives the static area control error of all the EPSs in the interconnection, i.e. of all the control areas.

3 Procedure for Solving the Unconventional Load-Flow Models

The first step in the development of the solution method is the application of the Newton-Rhapson method [6], on the balance equation (1) - (4). Then, inspired by [2], in the formation of the Jacobian matrix, the similarly justified assumptions and simplifications resulting from the ”physical” nature of the problem are introduced. Thus, we obtained the following two decoupled systems of equations (naturally, only during one iteration), which are solved successively, in accordance with the iteration indices k and l [3, 4]:

$$\begin{bmatrix} \Delta \boldsymbol{P}/\boldsymbol{V} \\ \Delta \boldsymbol{P}_r/\boldsymbol{V}_r \end{bmatrix}^k = [\boldsymbol{H}' \quad \boldsymbol{F}'] \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta(\Delta f) \end{bmatrix}^{k+1} \tag{9}$$

$$\Delta \boldsymbol{Q}/\boldsymbol{V}^l = \boldsymbol{L}' \Delta \boldsymbol{V}^{l+1} \tag{10}$$

where $\boldsymbol{\theta}$ is the angle vector of dimension $N-1$, $\boldsymbol{V}$ is voltage magnitude vector of dimension $NSV + NL$, and r denotes the reference node. The scalar $\Delta P_r/V_r$ represents the power mismatch (divided by the magnitude of the voltage) of an arbitrary reference node, which has an *a priori* defined phase angle (usually set at zero).

The elements of the coefficient sub-matrices H', F' and L' have the following constant values, for a given network topology [3, 4]:

$$
\begin{aligned}
&H'_{ii} = V_n B_{ii}, \quad i \in (N/r) \\
&H'_{ij} = V_n B_{ij}, \quad i \in N; j \in (N/r) \\
&F'_i = \begin{cases} k_{pi}/V_n, & i \in NL \\ 0, & i \in NL \end{cases} \\
&L'_{ii} = \begin{cases} Q_{G0i}/(s_{Vi}V_{G0i}^2) + B_{ii}, & i \in NSV \\ B_{ii}, & i \in NL \end{cases} \\
&L'_{ij} = B_{ij}, \quad i, j \in (NSV \cup NL)
\end{aligned}
\tag{11}
$$

were B_{ij} is susceptance of the element $i - j$ and V_n denotes the rated value of voltage.

The system of equations (9) and (10) remain valid for the state of the system after the action of the automatic secondary frequency and tie-line power control [3,4]. In this case, the vector of active power mismatch $\Delta \boldsymbol{P}/\boldsymbol{V}$ contains the coordinates which pertain the regulating power stations, according to relation (7), while the necessary magnitude of mismatch, that is, the static area controls error, is determined separately, during the successive iterative solution of the systems (9) and (10), using (8).

Therefore, this simplification practically reduces to an additional decoupling, while the justification for this results from the physical nature of the problem under consideration. Namely, the automatic secondary frequency and tie-line power control (if all the conditions for its normal operation are fulfilled) is performed slowly and continuously, and most important, under conditions of relatively small changes of relevant state variables resulting in compensation of unavoidable error in the realization of the programmed generator scheduling.

It should be pointed out that the tolerance for the condition $\Delta ACE_j = 0$ $(j \in M)$ is in direct correlation with the actual capabilities (imperfections) of the existing systems for the automatic secondary frequency and tie-line power control.

4 Procedures for Solving the Initial Load-Flow

In this section of paper the determinations of procedures for solving the initial load-flow will be made, which are based on no conventional load-flow models (equations (1), (2), (3), (4), (7)and (8), and their solution techniques (decoupled equations (9) and (10)).

4.1 Initial load-flow in conditions of given initial generators scheduling

In conditions of given initial generators scheduling, all active generator powers are known (except for chosen reference generator, i.e. slack bus). Then, in balance equation (1), the part $k_{pi}\Delta f$ doesnt participate, except for reference (or slack) generator. Next, according to the fact that all generator voltages are known, the all balance equations of form (2), also, dont participate. Next, by corresponding choice of the coefficients in equations for load active $P_{Li}(V_i, f)$ and $Q_{Li}(V_i, f)$ reactive power, their constant, in advance known values, are insured, which is an usual approach in analyses of initial steady-state. Thus, for this type of initial steady-state of electric power interconnection considered, the balance equations of the form (1) still hold (but without the part $k_{pi}\Delta f$ for all generators, except for reference), as well as the balance equations (3) and (4) (with given constant values of load active and reactive powers), which satisfy the constraints (5) and (6).

The way of forming the balance equations of forms (1), (3) and (4) heads to their solution technique, e.g. the manner of forming the decoupled systems of equations which are similarly with the forms of equations (9) and (10). The system of equations (10) will have also the order N, (but, now in sub-matrix F' exists only control constant k_{pr} of slack generator), and system of equations (10) is reduced to the order NL. In the case of application of Stott-Alsac approach [2] in forming sub-matrices $\boldsymbol{H}'$ and $\boldsymbol{L}'$, the systems equation (9) and (10), having in mind previous, will be transformed into the following form:

$$\begin{bmatrix} \Delta\boldsymbol{P}/\boldsymbol{V} \\ \Delta P_r/V_r \end{bmatrix}^k = \begin{bmatrix} \boldsymbol{B}' & \boldsymbol{0} \\ \boldsymbol{B}'_r & f' \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta(\Delta f) \end{bmatrix}^{k+1} \tag{12}$$

$$\Delta\boldsymbol{Q}/\boldsymbol{V}^l = \boldsymbol{B}''\Delta\boldsymbol{V}^{l+1} \tag{13}$$

It is evident, that the form of equations (12) and (13) presented, in cases of solving angle vector $\boldsymbol{\theta}$ (of dimension $N-1$) and voltage vector $\boldsymbol{V}$ (of dimension NL), is fully identical with the form of procedure [2], and also, as it will be shown, has fully identity about essence. In this way, with successive iterative solution of two decoupled systems of equations (12) and (13) (also, only during one iteration), considering the constraints (5) and (6), the following unknown variables are obtained: angle vector $\boldsymbol{\theta}$, of dimension $N-1$, scalar Δf is deviation of the ”quasi-stationary value of frequency” from its initial value, voltage magnitude vector in load nodes $\boldsymbol{V}$, of dimension NL.

Therefore, the newly formed decoupled equations (12) and (13) are the mathematical base of the fast decoupled procedure for solving the load-flow problem in initial stationary states, in conditions of given initial generators scheduling and their voltage. In context of this approach, some explanations about significance and function of variable Δf should be given. At first, it is evident that this variable doesnt have the physical sense, e.g. in reality, this variable doesnt represent the real deviation of the quasi-stationary value of frequency from its initial value (for this reason quotations signs are used). Apparently, this variable is an artificial variable, which is associated only to the slack node, in which the angle value is fixed in advanced (usually set at zero value). The final value of this variable is obtained after the end of iterative procedure of solving the equations (12) and (13). This value determines (together with the selected value of control constant k_{pr}) amount of correction $(-k_{pr}\Delta f)$ of initial value of active power of slack generator $\boldsymbol{P}_{G0r}$. This final value will fully "close" active power balance in initial steady-state considered (also, including "covers" of the active power losses ΔP_g). Or, at the end of iterative procedure, the following equality is valid:

$$\sum_{\substack{i=1\\ i\neq r}}^{NG} P_{G0i} + P_{G0r} - k_{pr}\Delta f = \sum_{i=NG+1}^{N} P_{Li} + \Delta P_g \tag{14}$$

As it will be shown in subsection 6.1 of this paper, the procedure developed, which is based on equations (12) and (13), has identical converegence characteristics like a procedure [2], independently to the choice of: slack node, value of its initial active power P_{G0r} and value of its control constant k_{pr}.

4.2 Load-flow in conditions of given bilateral or multilateral exchange programs

The problem of existance of exchange programs (bilateral or multilateral), between EPSs in interconnection considered, is successfully solved in reference [7]. This reference presents the basic segments (unconventional load-flow model and the simplified fast decoupled procedure at its method of solution) of methodology intended for a more accurate evaluation of the relevant technical effects resulting from relatively significant (both in magnitude and transmission path length) power transfer in electric power interconnection. The more accurate evaluation is evidenced in the possibility of taking into consideration the action and effects of primary voltage and frequency control, a more accurate modelling of generator reactive power limits and the sufficiently accurate representation of operation of existing systems for the automatic secondary frequency and tie-line power control.

This methodology is fully based on unconventional load-flow model (equations (1), (2), (3), (4), (7) and (8)) and their solution technique (two decoupled systems of equations (9) and (10), only during one iteration, which are solved successively). Before applying this methodology, it is necessary to solve load-flow in initial quasi-stationary steady-state case (so-called "base case") in manner which is explained in previous section (4.1) of this paper. Next, the exchange programs (bilateral and/or multilateral) between EPSs in interconnection considered are defined (all scheduled total tie-line powers PRP are defined), which will be superposed on the ”base case”, which is before established. For this purpose, the corresponding generators are selected, as well as the necessary corrections of their active power injections are demanded, according to the realization which the exchange programs demanded. By application of the decoupled equations (9) and (10), load-flow after the action of primary frequency control is solved. This control is cosed by the realization the new generators scheduling.

Finally, introducing the equations (7) and (8) in next calculations, in way which is described before, the load-flow solution is made for quasi-stationary state after the action of automatic secondary frequency and tie-line power control, in context of accurate realization of demanded exchange programs. Therefore, the following order of operations, which are made successively in real operational practice in realization of given exchange programs, is fully respected:

- increase/decrease active powers of selected generators,
- action of primary voltage and frequency control, caused by appearance of active power imbalance, according to the change of total active power losses, caused by demanded correction of generator active powers and new load-flow in interconnection considered,
- action of automatic secondary control of frequency and tie-line power, in context of accurate realization the exchange programs demanded.

5 Global Concept of Improved Steady-State Security Analysis

Figure 1 presents the global concept of the proposed improved methodology (computer program STATIC). Using the flow in block 1, a set of states of interconnection considered are formed. Next, in block 2, load-flow solutions for given generators scheduling are performed. If different exchange programs are analyzed, in block 3, load-flow solution for a specific bilateral of multilateral exchange program will be performed.

The creation of the unified external network equivalent and adaptive buffer system selections, according to the procedure given in [8], are performed in block 4. In block 5, disturbance list is made. The computer program STATIC provides to the operator the way to define the list of characteristic disturbances, as well as the automatic performance of these functions (outages of all generators and all elements, which are loaded above the previously specified values).

The next block 6 performs the fast contingency selection, which is based on results from the single iteration of solving (9) and (10). For the potentially critical

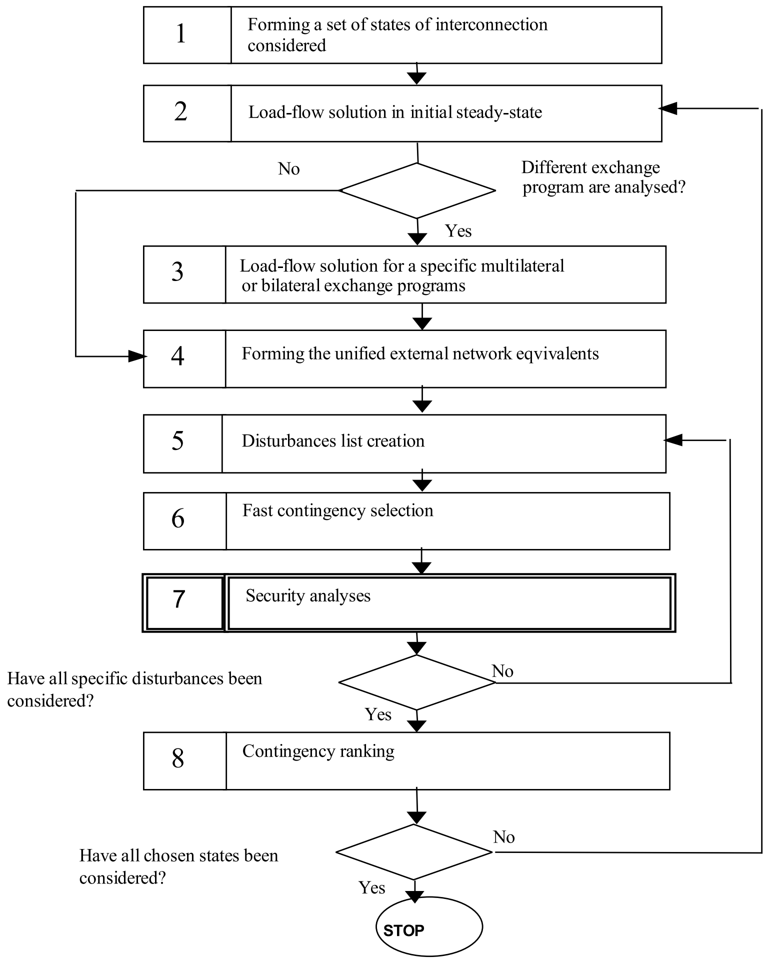

Fig. 1. Global flow diagram of improved steady-security analyses of power systems interconnection

contingency, the continuation of iterative solution of (9) and (10) is performed; e.g. the successive solutions of load-flow for an above-mentioned characteristic post-dynamic quasi-stationary state are made (block 7). Finally, in block 8, contingency ranking is made, according to the values of specially formed performance indices.

Thus, the following fundamental characteristic of the proposed methodology should be pointed out:

- the unified manner of initial load-flows solutions,
- fast contingency selection and solutions of all the necessary load-flows, by the presented simple unique fast decoupled procedure, with constant elements in the corresponding coefficient matrices,

- minimum number of modifications and additions depending on the character of initial and the post-dynamic quasi-stationary state of power system under consideration.

6 Practical Application of Procedures Proposed

The first practical experiences in the application of procedures proposed have been gained on an example of the synchronous parallel operation of the EPSs of ex Yugoslavia (EX YU), Romania (RO), Bulgaria (BG), Former Yugoslav Republic of Macedonia (FYROM), Greece (GR) and Albania (AL) (ex second UCTE synchronous zone). Figure 2 shows the block diagram of examined interconnection

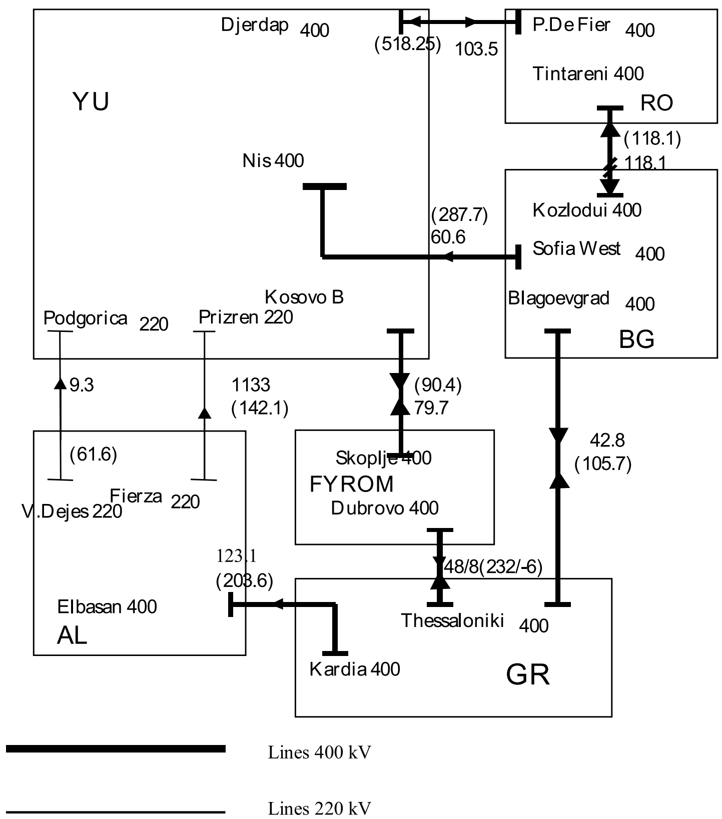

Fig. 2. Block diagram of Balkan electric power interconnection considered.

with the active power flows (MW) on interconnecting lines in two following cases:

1. without exchange programs between EPSs (”zero” exchange programs) e.g.

the active powers on interconnecting lines represent at the same time the so-called ring power flows;

2. the multilateral exchange programs: RO→EX YU, 400 MW, BG→EX YU, 300 MW and GR→EX YU, 400 MW (values given in parentheses).

6.1 Initial load-flow in conditions of given generators scheduling

Generally speaking, the most important practical aspects in promotion of new procedures are their convergence characteristics. Good illustrations of the convergence characteristics of developed iterative procedures (decoupled equations (12) and (13)) are presented in tables 1, 2, 3, 4 and 5. It should be pointed out that the iterative procedure in all cases considered, had a so-called "flat" start (1 p.u. voltage magnitude for all PQ nodes and zero value for all angles). Also, it should be noted that the tables 1, 2, 3 and 4 are addressed to the case, where the TPP Nikola Tesla B (TPP NT B) is the reference (slack) generator.

Table 1 gives the flow of iterative procedure of solving the equations (12) and (13), according to the maximum active (max$|\Delta P|$) and reactive (max$|\Delta Q|$) power mismatches, as well as according to the value of active power mismatch of slack generator (P_{G0r}). These mismatches are given for three initial values of active power of slack generator PG0r (0, 500 and 1000 MW) and for value of its primary frequency control constant 100 MW/Hz.

Table 1. The flow of iterative procedure of solving the equations (12) and (13).

Iteration number	Pr MW	$P_{G0r} - k_{pr}\Delta f$ (MW) 0	500	1000
0	18.0	0	500.0	1000.0
1	826.5	769.0	792.8	816.5
2	1159.1	1133.5	1134.6	1135.7
3	1145.6	1145.5	1145.5	1145.6
4	1148.9	1148.7	1148.7	1148.7
5	1149.0	1149.0	1149.0	1149.0

Table 2 gives active power changes of slack node (TPP NT B), during the iterative procedure (P_r - denotes active power injection; $P_{G0r} - k_{pr}\Delta f$ - specified power), together with three initial values of active power of slack generator P_{G0r} (0, 500 and 1000 MW), and value of its control constant k_{pr} 100 MW/Hz.

Table 3 gives the change of deviation of "quasi-stationary value of frequency" during the iterative procedure, for three initial active power values of reference generator PG0r (0, 500 and 1000 MW) and two values of their control constant k_{pr} (100 and 1000 MW/Hz).

Table 2. Active power changes of reference node during the iterative procedure of solving the equations (12) and (13).

Iteration number	Pr MW	$P_{G0r} - k_{pr}\Delta f$ (MW) 0	500	1000
0	18.0	0	500.0	1000.0
1	826.5	769.0	792.8	816.5
2	1159.1	1133.5	1134.6	1135.7
3	1145.6	1145.5	1145.5	1145.6
4	1148.9	1148.7	1148.7	1148.7
5	1149.0	1149.0	1149.0	1149.0

Table 3. The change of deviation of "quasi-stationary value of frequency", during the iterative procedure of solving the equations (12) and (13).

Iteration number	$\Delta(\Delta f)(k_{pr} = 100$ MW/Hz) Hz			$\Delta(\Delta f)(k_{pr} = 1000$ MW/Hz) Hz		
	0	500	1000	0	500	1000
1	-7.691	-2.928	1.835	-0.7691	-0.2928	0.1835
2	-3.644	-3.418	-3.192	-0.3644	-0.3418	-0.3192
3	-0.120	-0.109	-0.098	-0.0120	-0.0109	-0.0098
4	-0.032	-0.031	-0.0031	-0.0032	-0.0031	-0.0031
5	-0.003	-0.003	-0.003	-0.0003	-0.0003	-0.0003

The sensibility of iterative procedure (according to the changes of values $P_{G0r} - k_{pr}\Delta f$, $\Delta(\Delta f)$ and ΔP_r), to the initial active power P_{G0r} and control constant k_{pr} of slack, is shown in Table 4. The letter A corresponds to the case when $P_{G0r} = 0$ MW and $_{kpr} = 0.1$ MW/Hz, and letter B corresponds, to the case when $P_{G0r} = -500$ MW and $k_{pr} = 100$ MW/Hz.

Table 4. Sensibility of iterative procedure to the initial value of active power and value of primary frequency control constant of slack generator.

Iteration number	$P_{Gor} - k_{pr}\Delta f$ MW		$\Delta(\Delta f)$ Hz		ΔP_r MW	
	A	B	A	B	A	B
0	0	-500.0	–	–	-18.0	-518.0
1	769.0	745.3	-769.0	-12.453	-57.5	-81.2
2	1133.5	1132.4	-3644.4	-3.870	-25.6	-26.7
3	1145.5	1145.4	-119.9	-0.131	-0.179	-0.232
4	1148.7	1148.7	-32.0	-0.032	-0.202	-0.205
5	1149.0	1149.0	-2.8	-0.003	-0.003	-0.003

Finally, Table 5 gives the sensitivity of iterative procedure to the choice of slack generator. All of slack generators selected have $P_{G0r} = 0$ MW and $k_{ept} =$

1000 MW/Hz. This table gives the total number of iterations necessary for the desired accuracy of 0.1 MW and 0.1 Mvar, finally values of slack generator active power P_r and finally value of "quasi-stationary value of frequency" f.

Table 5. The sensitivity of iterative procedure according to the choice of slack generator.

Slack generator	Total number of iterations	Pr MW	f Hz
TE NT B (EX YU)	5	1149.0	48.851
NE Kozlodui (BG)	5	1865.7	48.134
NE Cerna Voda (RO)	6	654.0	49.346
TE Agios Dimitros (GR)	5	1098.8	48.901
TE Bitola (MA)	6	288.9	49.711
HE Komani (AL)	6	329.7	49.670

In interpretation the results before presented, we will start from system of equations (12), but now, writing in the following, decoupled form:

$$\Delta \boldsymbol{P}/\boldsymbol{V}^k = \boldsymbol{B}'\Delta\theta^{k+1} \qquad 12a$$

$$\Delta P_r/V_r^k = B_r'\Delta\theta^{k+1} + F_2'\Delta(\Delta f)^{k+1} \qquad 12b$$

The system of equations (12a) shows that the unknown angle vector $\boldsymbol{\theta}$, of dimension $(N-1)$ are iterative calculated on identical way like in procedure Stott-Alsac [2]. Also, according to the system of equations (13) unknown voltage magnitude vector $\boldsymbol{V}$, of dimension NL, is calculated like a before mentioned procedure. From this exists the identical converegence characteristics procedure of determining vectors $\boldsymbol{\theta}$ and $\boldsymbol{V}$, using decoupled equations (12) and (13) and procedure given in [2]. These characteristics only depend to the choice of slack generator and fully independent to the its characteristics (initial active power P_{G0r} and regulation constant k_{pr}). Also, injection power of slack generator P_r is independent to the its characteristics.

On the other side, according to the equation (12b), the flow of iterative procedure of computation "quasi-stationary value of frequency" deviation depends also to the initial value of active power of slack generator P_{G0r} and its control constant k_{pr}. However, it is possible to see corresponding practical correlation, according to the equation (12b), writing now in the following way:

$$P_{G0r} - k_{pr}(f^k - f_0) = P_i^k + V_r B_r \Delta\theta^{k+1} + \frac{V_r}{V_n} k_{pr}(f^{k+1} - f^k)$$

Introducing the assumptions $V_r \simeq V_n$, this equation is transformed into following form:

$$P_{G0r} - k_{pr}(f^{k+1} - f_0) \simeq p_i^k + V_r B_r \Delta\theta^{k+1} \qquad 12c$$

Thus, for slack generator selected, the quantity $P_{GOr} - k_{pr}\Delta f^{k+1}$ practicaly has same values during iterative procedure, independently to the initial value of power P_{GOr} and control constant k_{pr} (according to the results given in tables 2 and 4). As a consequence, for selected initial value of slack generator active power P_{GOr}, the quantity $k_{pr}\Delta f^{k+1}$, also has the same value during iterative procedure, independently to the choice of control constant value k_{pr} (according to the results given in tables 3).

However, it should be specially noted, that the convergence characteristics of procedure developed are independent to the choice of initial value of power P_{GOr} and control constant k_{pr}, according to the results given in table 4, what is directly consequence of equation (12c). Now, only in question is the order of value of "quasi-stationary value of frequency", which doesnt have the physical sense of frequency, then, it is evidently that the "quasi-stationary value of frequency", is artificial variable.

Finally, the results given in table 5 show that the choice of slack generator practically doesnt have the influence to the very good and reliable convergence characteristics of procedure for solving the initial power-flow, which is based on equations (12) i (13). As shown before, the procedure developed has identical coveregence characteristics like a procedure given in [2].

6.2 Initial load-flow in conditions of given bilateral exchange programs

For the purpose of illustrating the possibility of procedure, which is based on unconventional load-flow model (the balance equations (1), (2), (3), (4), (7) and (8)) and solution technique (systems of decoupled equations (9) and (10)), the example of export of 600 MW from RO to GR is considered. The initial load-flow solution, for case of ”zero” exchange programs between the EPSs in interconnection under consideration, is made, according the procedure given in section 4.1 of this paper.

Next, for the exchange program demanded (RO→GR 600 MW), the corrections of the generator active powers in EPSs RO and GR are made. The active power injection of NPP Cerna Voda (RO) is increased for 600 MW, and injection of TPP Agios Dimitros (GR) is decreased for the same quantity. After that, the procedure of solving the load-flow in state after the action of primary frequency control is started (according to the decoupled equations (9) and (10)), which iterative flow is given in Table 6. The quasi-stationary value of frequency (now, the frequency has a physical sense) in this new quasi-stationary state was 49.998 Hz. According to the results given in this table, very good and reliable convergence characteristics are shown.

Deviation of exchange programs $\Delta P_R(RO \rightarrow GR$, 600 MW) (the rest of EPSs has the ”zero” exchange program) and static area control error ACE, for the state

Table 6. Flow the iterative procedure of solving the state after the action of automatic secondary control of frequency and tie-line power during realization exchange program RO→GR 600 MW.

Iteration number	Max $\|\Delta P\|$ MW	Max $\|\Delta Q\|$ Mvar	$\Delta(\Delta f)$ Hz
0	659.9	105.3	–
1	28.8	4.2	−0.00014
2	1.4	0.250	−0.00161
3	0.056	0.125	−0.00022
4	0.016	0.105	−0.00003
5	0.014	0.063	0.00000

after the action primary frequency control, are given in Table 7.

Table 7. Deviation of exchange programs and static area control error for the state after the primary frequency control.

Control area	ΔP_R (MW)	ACE (MW)
Ex Yugoslavia	−10.1	6.6
Romania	19.0	13.7
Bulgaria	−8.0	−12.1
Macedonia	0.1	−0.2
Greece	0.6	−1.8
Albania	−1.5	−2.2

Thus, for realization of exchange programs demanded, the action of automatic secondary control of frequency and tie-line power was necessary (now, the balance equations (1) - (4), (7)and (8) are actual). The effects of this control are computed by the procedure, described in previous section 4.2. The characteristic quantities for this state are given in tables 8 and 9. Table 8 gives the total changes of generator active and reactive powers after the action of automatic secondary control, during realization of the exchange program RO→GR 600 MW. Table 9 gives the active and reactive power flows on relevant interconnected line in initial state and in state after the action of automatic secondary control of frequency and tie-line power, during realization of the same exchange program.

The results given in Table 7 and Table 8 shows the global aspects of power transit considered (600 MW from RO to GR). In the state after the action of primary frequency control, the static area control errors exists, as a consequence of the change of active power losses, according to the initial stationary state, without this transit. The sign and values of control area errors (see Table 7) are the real indication for changes of active power losses in each control areas. The final values of active power losses changes are given in Table 8, across to the total generator

Table 8. The total changes of generator active and reactive powers after the action of automatic secondary control of frequency and tie-line power during realization of the exchange program RO→GR 600 MW.

Control area	$\Sigma\Delta P_G$ (MW)	$\Sigma\Delta Q_G$ (Mvar)
Ex Yugoslavia	16.9	104.6
Romania	−13.4	−48.4
Bulgaria	12.0	101.0
Macedonia	0.2	11.1
Greece	2.0	31.4
Albania	2.3	18.5

Table 9. Power flows on relevant interconnected line in initial state and in state after realization of the exchange program RO→GR 600 MW.

Interconnected line	Initial state		State after the action of secondary control	
	P_{ij} MW	Q_{ij} Mvar	P_{ij} MW	Q_{ij} r Mvar
Đerdap (EX YU)–P.D.Fier (RO)	134.0	−97.2	−99.7	−123.7
Tintareni (RO)–Kozlodui (BG)	134.0	−150.7	500.3	−136.6
Niš (EX YU)–Sofija (BG)	−74.6	−129.7	−103.30	−125.4
Blagoevgrad (BG)– Thessaloniki (GR)	58.9	−19.1	396.7	−38.6
Kosovo (EX YU)–Skoplje (MA)	69.8	−51.3	249.4	−58.8
Dubrovo (MA)–Thessaloniki (GR)	69.7	−37.5	248.2	−51.8

active power changes $\Sigma\Delta P_G$ (only for generators, which participate in secondary control). The algebraic sum of changes of generator active powers gives the total change of active power losses in interconnection considered (in case considered, the total active power losses is increased for 18.0 MW). Also, the changes of total generator reactive power $\Sigma\Delta Q_G$ (see Table 8), caused by the large power transits considered, are very indicative. The results given in Table 9 are very indicative about explanation of the ”transmission path”. It will be seen, that the most amount of power transit ”goes across” EPS of Bulgaria (366.3 MW, e.g. 61% of power transit). The rest ”goes across” EPS of ex Yugoslavia (233.7 MW, e.g. 39%).

Naturally, developed procedure enables creation the set of other, also, very indicative quantities, addressed to considered power transit. In this way, on the example of real electric power interconnection in the Balkan area, the efficiency of proposed procedure, which is based on unconventional load-flow model, is demonstrated.

6.3 Initial load-flow in conditions of given multilateral exchange programs

Very good and reliable convergence characteristics of procedure proposed are established, also in conditions of set of multilateral exchange programs between EPSs in interconnection considered. It will be illustrated by next, very indicative example. In this example, after solution of initial state in conditions of given generators scheduling, which corresponds to the ”zero” exchange programs, the following multilateral exchange programs are considered: RO→EX YU, 400 MW, BG→EX YU, 300 MW, GR→EX YU, 400 MW. For realization of the exchange programs mentioned before, the next generators are selected: HPP Đerdap, TPP NT-A and TPP NT-B (EX YU); NPP Cerna Voda and TPP Mintia (RO); NPP Kozlodui (BG); TPP A.Dimitros and TPP Kardia (GR). The selected generators, in realization of the exchange programs mentioned before, are participating proportionally to their actual spinning reserve.

After corrections of active powers of selected generators, with respects strictly to the exchange programs demanded, the procedure of solving the load-flow in state after the action of primary frequency control is started (applying systems of decoupled equations (9) and (10)).

Table 10 gives the flow of iterative procedure according to the maximum active ($\max|\Delta P|$) and reactive ($\max|\Delta Q|$) power mismatches and changes of deviation of quasi-stationary value of frequency ($\Delta(\Delta f)$). This iterative flow is given for two cases: A - iterative procedure starts on base of known initial state for ”base case” (”0” exchange programs) and B - iterative procedure starts with so-called ”flat” start (before mentioned). The results, given in this table, show very good, fast, and reliable convergence characteristics of procedure developed, especially if the procedure starts with known quantity from initial state (instead of the ”flat start”).

After that, the state after the action of automatic secondary control of frequency and tie-line power is calculated, using the procedure described before. For that, only a few iterations were necessary, which is not surprise, because the relatively small changes of relevant quantities are in question, according to the state, with corrections (automatic) of active power injections of selected generators, to satisfied the exchanges demanded. Thus, practically exists only relatively small compensation of difference between demanded and realized exchanges (of order several MW), caused by expected change of total active power losses, compared to the initial state.

Finally, Table 11 gives active power flows (MW) on interconnected lines in initial state and in state after realization of multilateral exchange programs considered (or in the state after the action of automatic secondary control of frequency and tie-line power). Also, in this table the differences in active power flows are given, which are caused by multilateral exchange programs considered. Those differences

Table 10. The flow of iterative procedure of solving the load-flow in state after the action of primary frequency control, in conditions of realization of the following multilaterally exchange programs: RO→EX YU, 400 MW, BG→EX YU, 300 MW and GR→EX YU, 400 MW.

Iteration number	$\max\lvert\Delta P\rvert$ [MW]		$\max\lvert\Delta Q\rvert$ [Mvar]		$\Delta(\Delta f)$ [Hz]	
	A	B	A	B	A	B
0	641.093	1.975.610	0.000	2.179.188	–	–
1	34.157	89.506	0.750	54.195	0.00027	0.03102
2	1.797	11.761	0.102	4.57	−0.00022	−0.02976
3	0.078	0.747	0.031	0.281	−0.00008	−0.00090
4	0.014	0.115	0.005	0.090	0.00000	−0.00034
5	0.000	0.018	0.000	0.031	0.00000	− 0.00003

in clear manner show the relevant transmission paths in realization of exchange programs RO→EX YU, 400 MW, BG→EX YU, 300 MW and GR→EX YU, 400 MW, e.g. in realization of import EPS EX YU in amount of 1100 MW. Thus, 56.5% of 1100 MW directly comes from RO, 20.6% from BG, 15.5% from MA and 7.4% directly from AL. The selected generators in EPSs of RO, BG and GR participate, in realization of this import, with 36%, 28% and 36%, respectively.

Table 11. Active power flows (MW) on interconnected lines in initial state and in state after realization of multilateral exchange programs considered.

Interconnected line	Initial state	State after realization of given exchange programs	Differences in active power flows
Đerdap (EX YU)–P.D.Fier (RO)	103.5	−518.2	−621.7
Niš (EX YU)–Sofija (BG)	−60.6	−287.7	−227.1
Kosovo (EX YU)–Skoplje (MA)	79.7	−90.4	−170.1
Prizren (EX YU)–Fierza (AL)	−113.3	−142.1	−28.8
Podgorica (EX YU)–V. Dejes (AL)	−9.3	−61.6	−52.3
Tintareni (RO)–Kozlodui (BG)	103.7	−118.1	−221.8
Blagoevgrad (RO)–Thessaloniki (GR)	42.8	−105.7	−148.5
Dubrovo (MA)– Thessaloniki (GR)	79.6	−90.4	−170.0
Kardia (GR)–Elbasan (AL)	123.1	203.6	80.5

7 Conclusions

The paper presents development and practical application of two efficient procedures for solving the load-flows in initial steady-state, which precede steady-state security analyses. The first procedure enables the load-flows solution for given initial generators scheduling in interconnection considered. The second procedure gives the load-flows solution in conditions of realization of a set bilateral or multilateral exchange programs between EPS's. Those procedures are fully consistent with the specially developed methodology for steady-state security analyses, which is based on unconventional load-flow models.

In this context, steady-state security analysis are based on successive solutions of the unconventional load-flow, by specially developed fast decoupled method for a set of characteristics post-dynamic quasi-stationary states of the power systems (states resulting from primary voltage and frequency control, states after the action of automatic secondary control of frequency and tie-line power and states after the corresponding possible dispatch activities, if necessary). Such characteristics of proposed procedures enable the unification of corresponding computer program, autonomy (”self starting”) and uniformity of steady-state security analysis, as well as their successive realization, which have a great practical importance.

The efficiency of procedures proposed is demonstrated on example of real power interconnection. The results obtained for the so called ”base case” (”zero” exchange program between EPSs), as well as for a set of multilateral and bilateral exchange programs, at first, show a very good, fast, and reliable convergence characteristics of procedure developed and also show their great flexibility in cases of creation of important exchange programs between EPS's considered.

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