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An Efficient Generator Voltages Control Method for Improvement of Voltage-Reactive States in Transmission Network

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Abstract: This paper presents an efficient generator voltage control method for improvement of voltage-reactive states in transmission networks. This method enables fast and sufficiently accurate definition of generator voltages to realize the favorable voltage-reactive states. In peak load state, this generator voltage control is made to improve the economic operation, e.g. to reduce the active and reactive power losses or to enlarge the reactive reserve of generators. In minimum load state, this voltage control is made to reduce the generator under-excitation states, or to make the favorable redistribution of those under-excitation states. The verification of method proposed is made in context of steady-state and dynamic simulation models, on the examples of realized and perspective states of Serbian transmission network, in own wide environment.

Keywords: Electric power systems, computer program, generator voltage control, voltage-reactive states, transmission network.

1 Introduction

AN IMPORTANT problem in modern (EPS) is the provision of the necessary level of operational security. In recent years, the increased practical interest to these issues has been shown and corresponding new challenges appeared, mainly due to increased loading of EPS's, combined with a process of deregulation in electric power market and restructuring of the power utilities. In this context, the voltage-reactive power problem plays an essential significant role. References [1,2] are only few from the long list of recent published work in this very important area.

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Also, the processes mentioned above, are very important and topical for all countries in Southeast Europe, as well as for Serbia and its electric power industry, in accordance with:

- Reconnection of the Second UCTE synchronous zone with the main part of the UCTE grid, whichwas successfully made in 10 October 2004.
- Establishment of Regional Electricity Market in Southeast Europe, according to the Memorandum of Understanding [3].
- Obligation to satisfy the requirements, standards and criterions of UCTE, in area, among many other, of Voltage Control and Reactive Power Management [4].

In context of many activities of evaluation the before mentioned new relevant aspects, is the operational study [5], which is made by Nikola Tesla Institute for Serbian TSO (Transmission System Operator-"Elektromreža Srbije"). From a large number of characteristic results, is established a fact about the great influence of adequate choice of generator voltages on established voltage-reactive states of Serbian transmission network, in own wide environment.

Thus, the basic objective of this paper is to presents a simple method for improvement of voltage-reactive states in transmission networks by generator voltages control. This method enables fast and sufficiently accurate definition of generator voltages to realize the favorable voltage-reactive states. In peak load states, this generator voltages control is made to improve the economic operation, e.g. to reduce the active and reactive power losses or to enlarge the reactive reserve of generators. In minimum load states, this voltage control is made to reduce the generator under-excitation states, or to make the favorable redistribution of those under-excitation states.

The verification of method proposed is made in context of steady-state and dynamic simulation models, on the example of realized and perspective states of Serbian transmission network, in own wide environment.

2 Formulation of Method

In formulation of this method, the start point is the steady-state of electric power interconnection under consideration, represented by the node admittance matrix $\underline{Y}$ and known vector of all voltage phases $\underline{V}$ (the bar under the letter signifies a phasors or complex quantity). This interconnection consists of total number (set) of all nodes N. In this set, NGI is the number of the generator nodes in EPS of interest (e.g. in EPS, where the generator voltages control is made). Next, all admittances of consumers and admittances of generators, which are not located in EPS of interest, where added to the corresponding diagonal element of node admittance matrix $\underline{Y}$, which are calculated on based of known actual values of active and reactive power and magnitude of voltage. Then, the Gaussian elimination of all this nodes (N- NGI) is made.

In those new conditions after elimination (extremely reduced number of nodes, equal to the number of generators in EPS of interest - NGI), the connection between the vector of injected current $\underline{I}_G$ and vector of generator voltage $\underline{V}_G$ in EPS of interest, take the form

$$\underline{I}_G = \underline{Y}_G \underline{V}_G, \tag{1}$$

where $\underline{Y}_G$ is the square NGI is dimensional node admittance matrix which is obtained after elimination of all consumers nodes and generators nodes, which are not located in EPS of interest.

For this EPS transformed, the generator injected apparent power will be

$$\underline{S}_{Gi} = \underline{V}_{Gi} \underline{I}^*_{Gi}, \qquad i = 1, 2, \ldots, NGI. \tag{2}$$

According to (1) and (2), the node-injected active and reactive powers have the following well-known form

$$P_{Gi} = V_{Gi}^2 Y_{Gii} \sin \mu_{Gii} + \sum_{\substack{j=1 \\ j \neq i}}^{N_{Gi}} V_{Gi} V_{Gj} Y_{Gij} \sin (\delta_{ij} - \mu_{Gij}) \tag{3}$$

$$Q_{Gi} = V_{Gi}^2 Y_{Gii} \cos \mu_{Gii} - \sum_{\substack{j=1 \\ j \neq 1}}^{N_{G_i}} V_{Gi} V_{Gj} Y_{Gij} \cos (\delta_{ij} - \mu_{Gij}), \quad i = 1, 2, \ldots, NGI, \tag{4}$$

where Y'_{Gij} and μ_{Gij} are magnitude and complementary phase angle of the admittance Y'_{Gij} respectively; $\delta_{ij} = \delta_i - \delta_j$ is angle difference between voltage module of nodes i and j.

Now, for steady-state considered, it was necessary to find out a good practical measure of sensitivity change of active and reactive power of all generators in EPS of interest, caused by change of voltage on selected generators. For this purpose, the following linearized matrix equations are formulated, which give a good practical measure of before mentioned sensitivity

$$\Delta P_G = \frac{\partial P_G}{\partial V_G} \Delta V_G \tag{5}$$

$$\Delta Q_G = \frac{\partial Q_G}{\partial V_G} \Delta V_G \tag{6}$$

where ΔVG and NGI are dimensional vector of generator voltage change; ΔPG and NGI are dimensional vector of injected active power changes, caused by generator voltage changes; ΔQG and NGI are dimensional vector of injected active power changes, caused by generator voltage changes; $\partial P_G/\partial V_G$ is the square NGI - dimensional active power sensitivity matrix, with the following elements:

$$\frac{\partial P_{Gi}}{\partial V_{Gi}} = 2V_{Gi}Y_{Gii}\sin\mu_{Gii} + \sum_{\substack{j=1\\ j\neq i}}^{N_G} V_{Gj}Y_{Gij}\sin(\delta_{ij}-\mu_{Gij}), \quad i=1,2,\ldots,N_{GI} \tag{7}$$

$$\frac{\partial P_{Gi}}{\partial V_{Gj}} = V_{Gi}Y_{Gij}\sin(\delta_{ij}-\mu_{Gij}), \quad j=1,2,\ldots,N_{GI}, j\neq i, \tag{8}$$

where $\partial Q_G/\partial V_G$ is the square N_{GI} - dimensional reactive power sensitivity matrix, with the following elements:

$$\frac{\partial Q_{Gi}}{\partial V_{Gj}} = 2V_{Gi}Y_{Gii}\cos\mu_{Gii} - \sum_{\substack{j=1\\ j\neq i}}^{N_G} V_{Gj}Y_{Gij}\cos(\delta_{ij}-\mu_{Gij}), \quad i=1,2,\ldots,N_{GI} \tag{9}$$

$$\frac{\partial Q_{Gi}}{\partial V_{Gj}} = -V_{Gi}Y_{Gij}\cos(\delta_{ij}-\mu_{Gij}), \quad j=1,2,\ldots,N_{GI}, j\neq i \tag{10}$$

Thus, applying the matrix equations (5) and (6), after specification the voltages change of selected generator (definition of the corresponding elements of vector ΔV_G), the corresponding changes of active ΔP_G and reactive Q_G powers are obtained.

Generally or theoretically speaking, it is evidently, according from the fact that the sensitivity matrices $\partial P_G/\partial V_G$ and $\partial Q_G/\partial V_G$ are full matrices, that the change of only one generator voltage will cause the changes of active and reactive powers in all generators. Naturally, in practical sense, those changes will be significant, if this voltage change is made in relevant generator.

Also, in opposite problem definition, the corresponding linearized matrix equations are formulated:

$$\Delta V_G = \left(\frac{\partial P_G}{\partial V_G}\right)^{-1}\Delta P_G \tag{11}$$

$$\Delta V_G = \left(\frac{\partial Q_G}{\partial V_G}\right)^{-1}\Delta Q_G \tag{12}$$

which give a good practical measure of sensitivity of necessary change of all generator voltages, for wished correction of active or reactive power on selected generators.

Thus, applying the matrix equations (11) or (12), after specification the wished correction of active (definition the corresponding elements of vector ΔP_G), or reactive (definition the corresponding elements of vector ΔQ_G) powers of selected generators, the necessary correction of generator voltage ΔV_G are obtained.

The main objective of this paper is the voltage-reactive power problem, e. g. the subject of primarily interest are the processes in so called $Q-V$ contour. In other words, the practical application of matrix equations (6) and (12), of order NGI, is main preoccupation of this paper.

Per instant, in peak load state, is desirable to define such generator voltages profile, which will be enable the convenient reactive power (in respect to the available possibilities), of generators, which are nearest to the bigger consumer centers. This new generator voltage profile will to improve the economic operation, e.g. to reduce the active and reactive power losses or to enlarge the reactive reserve of generators. Also, in minimum load state, is desirable to define such generator voltage profile, which will be enable to reduce the generator under-excitation states, or to make the favorable redistribution of those under-excitation states to generators, which are most convenient for this purpose.

However, the processes in so called $P-\delta$ contour are not neglected. Those processes are not dominating, but exist, in very small intensity, after the generator voltage changes, according to matrix equations (5) and (11). This fact will be clearly demonstrated in context of dynamic verification of proposed method (see next Figure 3).

3 Computer Program *VOLTCONT*

On the basis of the approach presented before, a modularly organized computer program named *VOLTCONT VOLTagesCONTrol*) is developed, using *Visual Fortran Professional Edition 6.0.0.*. This computer program enables to analyze the interconnection with 10000 nodes, 30000 lines, 2000 generators and 4000 transformers. User can load input data from UCTE format exchange files or PTI raw format files, using import/export utility.

This computer program consists of the following relevant parts (which differ o the usually approach)

- Two procedures for initialization of steady-state security analyses, e.g. the procedures for solving the initial load-flows problem, which preceding these analysis [6]. 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 in interconnection considered;

- These procedures are fully consistent with the specially developed method for the following steady-state security analysis [7];
- The limits of generator reactive power, as opposed to the usual approaches, are not constant, a priory defined quantities, but rather corresponding functions of relevant generator parameters and state variables [8].

Also, this computer program enables the following:

- For the initial steady-state solved, the Gaussian elimination of (N- NGI) nodes is made;
- Calculation the elements of active and reactive power sensitivity matrices;
- Calculation the elements of active and reactive power inverse sensitivity matrices (LU factorization);
- Application the matrix equations (5) and (6), for new generator voltages profile;
- Application the matrix equations (11) and (12) for new values of generator active and reactive powers;
- For new values of generator voltages, solving the new load-flows problem in whole interconnection, before elimination of (N- NGI) nodes;
- For new steady-state of interconnection considered, calculation the change of all relevant variables and quantities, according to the initial steady-state;
- Calculation the difference between values of generator active and reactive powers, which are obtained from the application of linearized matrix equations and from the load-flow solution in condition of whole interconnection (stricter steady-state approach). This calculation enables the verification of method proposed in context of steady-state simulation models.

4 Verification of Proposed Method

The characteristics and possibilities of proposed method (e.g. computer program *VOLTCONT*), have been established during the work on the operational study, which is made by Nikola Tesla Institute for Serbian TSO [5]. The main preoccupation of this investigation was the solution of voltage-reactive problem in Serbian transmission network, in own wide environment.

The real interconnection is observed, which consists of the EPSs of Serbia (SRB), Hungary (H), Croatia (HR), Bosnia and Herzegovina (BiH), Montenegro (MNE), Romania (RO), Bulgaria (BG), Macedonia (MK), Greece (GR) and Albania (AL). All 400 kV and 220 kV networks of SRB (including 110 kV network), MNE, H, HR, BiH, RO, BG, MK were modeled, as well as the complete 220 kV network of AL. The EPS of GR was represented by a corresponding equivalent at the 400 kV and 150 kV levels, with the exception of the Northern part, which was modeled in detail. As illustration, Figure 1 shows the block diagram of examined interconnection, with the active and reactive power flows (MW/Mar) and voltages (kV) on interconnection lines, for peak-load conditions for years 2006. (1100 nodes (120 generators and 1413 elements)) are modeled).

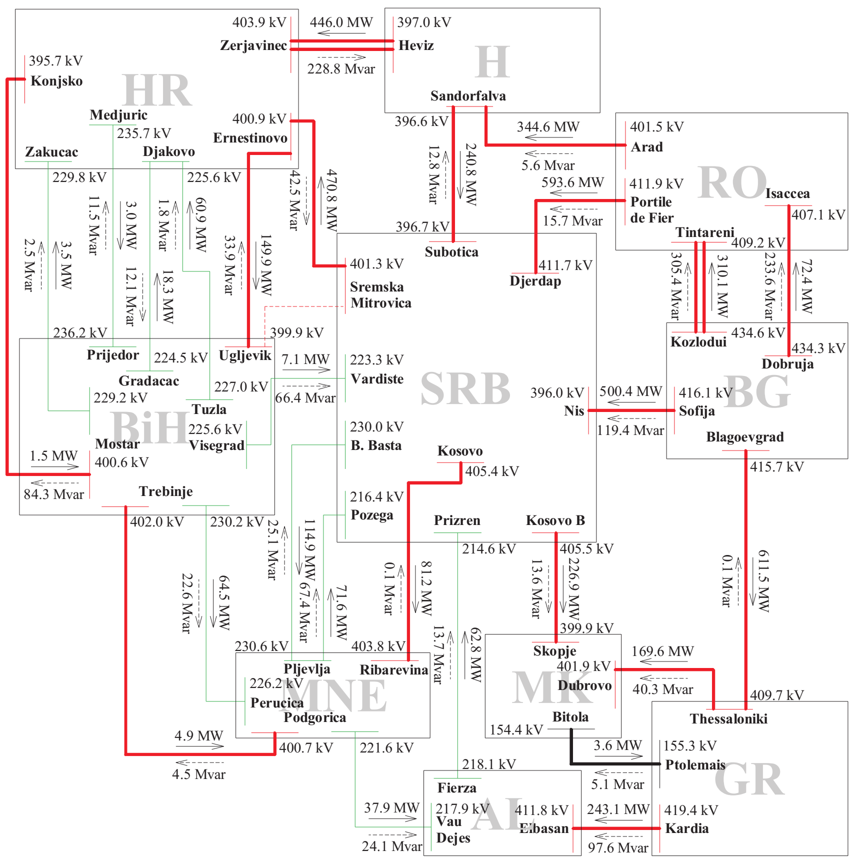

Fig. 1. Active and reactive power flows and voltages on interconnecting lines of interconnection considered.

In this approach the peak load and minimum load states for years 2005. and 2006. as well as the expected states for years 2010. and 2015. are analyzed. The security analysis are performed for single and multiple contingencies, e.g. for outages of large generators in EPS of Serbia. Also, the different generator scheduling and exchange programs in interconnection considered are analyzed. All analysis are made with strictly respect to the before mentioned actual document [4].

The results obtained highlights that the main reason for introducing the new 40 Mvar compensation (along already introduced 200 + 200 + 80 Mvar) is to improve the economic operation, e.g. to reduce the active and reactive power losses, or to enlarge the reactive reserve of generators in EPS of Serbia. Further improvements of voltage-reactive state are found in application of secondary voltage control (a significant segment of the hierarchical voltage control in power system), which, in present state of Serbian transmission network, is made ”handy”.

In those conditions, the application of method proposed (e.g. computer program *VOLTCONT*) has and will have a great practical importance. From a large number of interesting results of its application, some are presented in Tables 1, 2 (for peak load state for year 2006) and 3 (for minimum load state for year 2015). Table 1 gives the results (application of matrix equation (6)) after the simultaneous changes of generator voltage in TPP N. Tesla A 1, 2, 3, 4, 5 and 6 and TPP N. Tesla B1 and B2, from initial 1.00 Vn to 1.05 Vn (Vn denotes the generator rated voltage). The order of sensitivity matrix $\partial Q_G/\partial V_G$ was 29, equal to the number of generators in EPS of Serbia. This order is obtained after elimination of 1071 nodes in interconnection considered (the initial number of node, as before mentioned, was 1100).

Table 1. The results of proposed method, stricter steady-state and stricter dynamic approaches, after generator volt-age changes in TPP N. Tesla A and B.

No	Power plant	Q_{GO} (Mvar)	Q_{GU} (Mvar)	Q_G (Mvar)	Q_{GD} (Mvar)	Q_G (%)	Q_{GD} (%)
1	TPP N. Tesla B 1, 2	280.0	473.1	475.8	472.4	−0.570	0.148
2	TPP N. Tesla A 1, 2	163.9	244.8	239.3	238.8	2.287	2.513
3	TPP N. Tesla A 3, 4	210.6	312.1	304.2	311.2	2.589	0.289
4	TPP N. Tesla A 5, 6	162.6	277.0	278.6	275.0	−0.592	0.727

The quantity QGO (Mvar) denotes the values of generator reactive powers in initial steady-state and quantity QGU (Mvar), denotes the new values of generator reactive powers, which are obtained, applying the matrix equation (6), according the above mentioned simultaneous changes of generator voltage. The values of reactive power QG (Mvar) is obtained from the load-flow solution in condition of whole interconnection, for mentioned new values of generator voltages. The values QGD (Mvar), is obtained from dynamic simulation model (application of computer program *PRIMCONT* [9]). This calculation enables the verification of method proposed in context of dynamic simulation models (stricter dynamic approach).

This computer program continuously monitors the transient processes of duration last up to 30 s, occurring after the characteristic disturbances. It covers the period of short-term dynamic processes, as well as the period of uniformity of generators movements (i.e. the period of unique power system frequency) and restoration of their voltages. The transition from one type of dynamic to another is performed automatically, when certain predefined criteria are met (the new fulfillment of the condition of uniform rotor movement of synchronous machines and reinstatement of their voltages).

From a large number of interesting results of dynamic simulation, some are presented in Figure 2, 3, 4, 5, 6 and 7, which give the dynamic change of relevant quantities (reactive power, active power, voltage, electrical angle, EMF E_{fq} and EMF E_q) of selected generators, after above mentioned generator voltage changes in TPP N. Tesla A and B. The quantity ΔQ_G (in %) is the error of proposed method, compared with to the steady-state approach and quantity ΔQ_{GD} (in %) is the error, compared with to the dynamic approach.

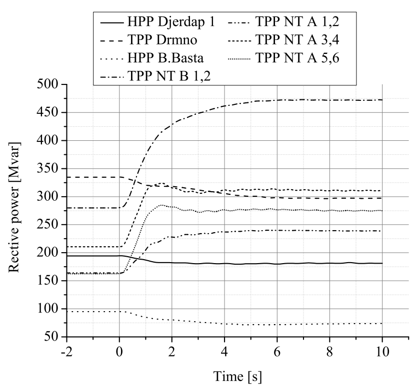

Fig. 2. The dynamic change of reactive power of selected generators, after generator voltage changes in TPP N. Tesla A and B.

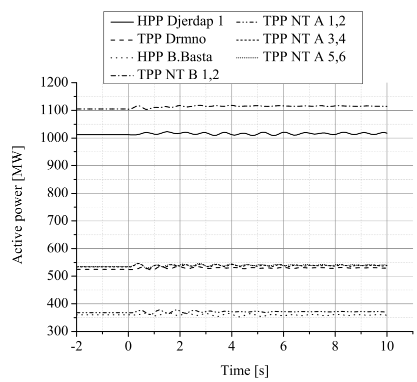

Fig. 3. The dynamic change of active power of selected generators, after generator voltage changes in TPP N. Tesla A and B.

Next Table 2, which is in continuity with Table 1, gives the results (application of matrix equation (12), also of order 29) after establishment the new generator voltages profile (from initial value VGO to new value VGN), for demand reactive power correction of selected generators (Q_{GU} -Q_{GO}). This new generator voltage profile is reduced the total active and reactive power losses for 1.2 MW and 15.6 Mvar and is enlarged the reactive reserve of generators in EPS of Serbia for 54.2 Mvar.

Also, the validity of proposed method is investigated in the case of minimum load state for the year 2015. Table 3 gives the results after the simultaneous changes of generator voltage in HPP Đerdap 1 (from initial value $V_{GO} = 1.000V_n$ to new value $V_{GN} = 0.980V_n$) and in TPP N. Tesla A1, A3, A5 and TPP N. Tesla B1 (from 0.975 V_n to 0.985 V_n). The quantity ΔV_G denotes the generator voltage changes

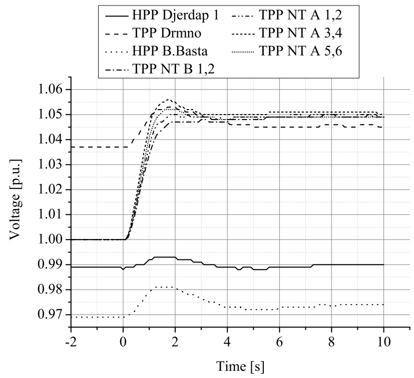

Fig. 4. The dynamic change of voltage of selected generators, after generator voltage changes in TPP N. Tesla A and B.

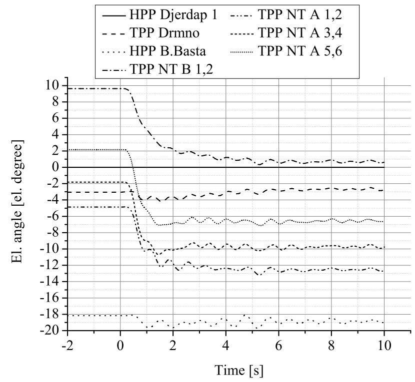

Fig. 5. The dynamic change of electrical angle of selected generators, after generator voltage changes in TPP N. Tesla A and B.

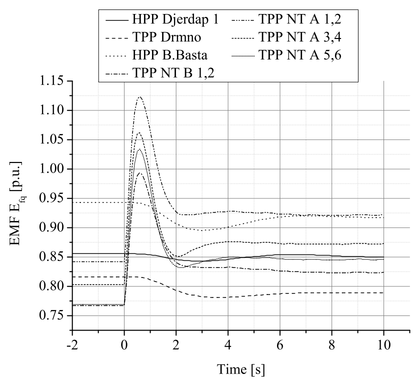

Fig. 6. The dynamic change of EMF Efq of selected generators, after generator voltage changes in TPP N. Tesla A and B.

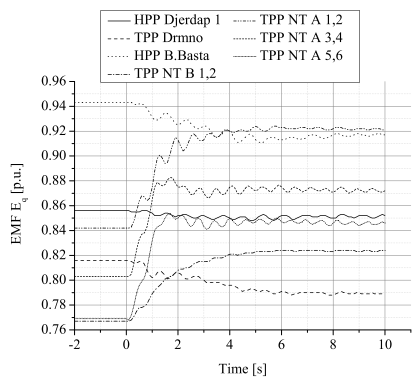

Fig. 7. The dynamic change of EMF Eq of selected generators, after generator voltage changes in TPP N. Tesla A and B.

(in %). The other quantities, given in this table, are explained before. According to this table, the new generator voltage profile is reduced the generator underexcitation states in TPP N. Tesla A and B, what have a great practical importance.

Thus, the quantities, given in Table 1, 2 and 3, show a good insight into the accuracy of proposed method, e.g. apart from its simplicity, this method is characterized bysufficiently accuracy. The maximum value of error was about 4 %, in context of steady-state and dynamic simulation models.

Table 2. The results of proposed method and stricter (steady-state) approach, after establishment the new generator voltages profile, for demand reactive power correction of selected generators.

No	Power plant	V_{GO} (p.u.)	V_{GN} (p.u.)	V_G (%)	Q_{GO} (Mvar)	Q_{GU} (Mvar)	Q_G (Mvar)	Q_G (%)
1	HPP Djerdap 1	0.989	1.001	1.3	165.3	215.3	225.0	-4.283
2	TPP Drmno	1.037	1.050	1.3	248.6	298.6	298.5	0.041
3	HPP B.Basta	0.969	1.000	3.1	70.2	120.2	121.3	-0.867
4	RHPP B.Basta	0.960	0.985	2.5	54.6	104.6	107.4	-2.643
5	TPP N. Tesla B 1, 2	1.050	1.039	-1.1	475.8	395.8	401.9	-1.518
6	TPP N. Tesla A 1, 2	1.050	1.038	-1.2	239.3	199.3	201.3	-0.968
7	TPP N. Tesla A 3, 4	1.050	1.039	-1.1	304.2	264.2	266.6	-0.898
8	TPP N. Tesla A 5, 6	1.050	1.040	-1.0	278.6	238.6	241.7	-1.275

Table 3. The results of proposed method, stricter steady-state and stricter dynamic approaches, after generator volt-age change in HPP Djerdap1 and TPP N. Tesla A and B

No	Power plant	V_{GO} (p.u.)	V_{GN} (p.u.)	V_G (%)	Q_{GO} (Mvar)	Q_{GU} (Mvar)	Q_G (Mvar)	Q_{GD} (Mvar)	Q_G (%)	Q_{GD} (%)
1	HPP Đerdap 1	1.000	0.980	−2.0	270.3	131.1	133.8	128.4	−1.948	2.103
2	TPP N. Tesla B1	0.975	0.985	1.0	−111.9	−84.0	−82.6	−83.4	1.712	0.719
3	TPP N. Tesla A1	0.975	0.985	1.0	−29.3	−19.0	−18.6	−19.6	2.350	3.061
4	TPP N. Tesla A3	0.975	0.985	1.0	−35.7	−23.0	−22.4	−22.9	2.314	0.437
5	TPP N. Tesla A5	0.975	0.985	1.0	−62.4	−44.0	−45.6	−45.9	1.899	4.139

5 Conclusions

This paper presents a possible way to form a simple and efficient generator voltages control method. The development of this method is inspired by known fact of great influence of adequate choice of generator voltages on established voltage-reactive states. The basic purpose of method is to realize the favorable voltage-reactive states in peak load and minimum load states. In peak load state, it is possible to define such generator voltages profile, which will be enable the convenient reactive power (in respect to the available possibilities), of generators, which are nearest to the bigger consumer centers. This new generator voltage profile willto improve the economic operation, e.g. to reduce the active and reactive power losses or to enlarge the reactive reserve of generators. Also, in minimum load state, it is possible to define such generator voltage profile, which will be enable to reduce the generator under-excitation states, or to make the favorable redistribution of those under-excitation states to generators, which are most convenient for this purpose.

Apart from its simplicity, the method is characterized bysufficiently accuracy (in context of steady-state and dynamic simulation models), which was demonstrated on the example of real electric power interconnection, which consists of the EPSs of Serbia, Montenegro, Hungary, Croatia, Bosnia and Herzegovina, Romania, Bulgaria, Macedonia, Greece and Albania.

Thus, the method (e.g. computer program *VOLTCONT*) presented, can be regarded as a useful addition to the software support of operational planning, as an integral part of EMS of Serbian TSO.

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