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Voltage-Reactive States on Interconnected Lines According to the Generator Voltages Control in Real-Time

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Abstract: This papers presents the possibility effects of application in real-time an advanced method for fast and sufficiently accurate definition of generator voltages to realize the favorable voltage-reactive states of electric power interconnection. The application in real-time will be realized by use the results of state estimation, which is the part of the new SCADA/EMS system in NDC Elektromreža Srbije. The special part of method developed is the possibility to make the direct connection between the values of generator voltages and voltage-reactive states on interconnected lines. The verification of method proposed is made, on the examples of perspective states of Serbian transmission network, in own wide environment.

Keywords: Control, generator voltage, voltage-reactive states, interconnected lines, real- time, state estimator, Serbian transmission network.

1 Introduction

An important problem in modern Electric Power Systems (EPS's) 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.

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:

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- Reconnection of the Second UCTE synchronous zone with the main part of the UCTE grid, which was successfully made in 10 October 2004 [1].
- Establishment of Regional Electricity Market in Southeast Europe, according to the Memorandum of Understanding [2].
- Obligation to satisfy the requirements, standards and criterions of UCTE, in area, among many another's, of Voltage Control and Reactive Power Management [3].

In context of many activities of evaluation the before mentioned new relevant aspects, is the operational study [4], which is made by Nikola Tesla Institute for Serbian TSO (Transmission System Operator)-Elektromreža Srbije. From a large number of characteristic results obtained, is established a fact about the great influence of adequate choice of generator voltages on established voltage-reactive states of Serbian transmission network.

Reference [5] shows the development and practical application of a simple method for improvement of voltage-reactive states in transmission networks by generator voltages control. The verification of this method was 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.

The conditions and possibilities of application this method in real-time are exposed in [6]. The application in real- time in future will be realized by use the results of state estimation, which is the part of the new SCADA/EMS system in NDC (National Dispatching Center) Elektromreža Srbije. The first practical experiences of the possibility of the application in real-time, has been established also on the model of real interconnection, in which participates the EPS of Serbia.

The basic objective of this paper is to presents some advantages of method before mentioned. Those advantages are primarly apply to monitoring and control the reactive power flow on interconnected lines, according to forming the direct connection between the values of generator voltages and voltage-reactive states on interconnected lines. Also, in those advantages belongs the evaluation of series favourable technical effects after the generator voltages control.

The evaluation and verification of method proposed are made in context of steady-state simulation models, on the examples of perspective states of Serbian transmission network, in own wide environment.

2 Formulation of Advanced Method

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. 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. This fact is be clearly demonstrated in context of dynamic verification of proposed method [5].

The developemenet and practical application of initial version of method for improvement of voltage-reactive states in transmission networks by generator voltages control are exposed in [5].

For steady-state of electric power interconnection (which consists of total number (set) of all nodes N), it was necessary to find out a good practical measure of sensitivity change of reactive power of all generators in EPS of interest, caused by change of voltage on selected generators. For this purpose, the following linearized matrix equation is formulated, which gives a good practical measure of before mentioned sensitivity

$$\Delta Q_G = \frac{\partial Q_G}{\partial V_G}\Delta V_G \tag{1}$$

where ΔV_G is N_{CH}-dimensional vector of generator voltage change and ΔQ_G is dimensional vector of injected active power changes, caused by generator voltage changes.

The $\partial Q_G/\partial V_G$ is the square N_{CH}-dimensional voltage-reactive power sensitivity matrix, with the following elements

$$\frac{\partial Q_{G_i}}{\partial V_{G_i}} = 2V_{G_i}Y_{G_i}\cos\mu_{G_{ii}} - \sum_{\substack{j=1\\ j\neq i}}^{N_{CH}} V_{G_j}Y_{G_{ij}}\cos(\delta_{ij}-\mu_{G_{ij}}), \quad i=1,2,\ldots,N_{CH} \tag{2}$$

$$\frac{\partial Q_{G_i}}{\partial V_{G_j}} = -V_{G_i}Y_{G_{ij}}\cos(\delta_{ij}-\mu_{G_{ij}}), \quad i=1,2,\ldots,N_{CH} \quad j\neq i \tag{3}$$

where $Y_{G_{ij}}$, $\mu_{G_{ij}}$ are magnitude and complementary phase angle of the admittance and $\delta_{ij}=\delta_i-\delta_1$ are angle difference between voltage module of nodes “i” and “j”.

In the initial version of method [5], $N_{CH}=N_{GI}$, where N_{GI} was the number of the generator nodes in EPS of interest (e.g. in EPS, where the generator voltages control is made). The corresponding sensitivity matrix is obtained after Gaussian elimination of all consumers nodes and generators nodes, which are not located in EPS of interest in electric power interconnection under consideration (elimination of $N-N_{GI}$ nodes).

In the advanced version of this method, which is the main subject of this paper, the order of matrix equation (1) is extended for observed interconnected lines (N_{IL}, e.g. this order now is $N_{CH}=N_{GI}+N_{IL}$. Thus, this now order of matrix equation of form (1) is obtained after Gaussian elimination of all consumers nodes, excepts the boundary nodes in EPS of interest and elimination of all generators nodes, which are not located in EPS of interest (elimination of $N-(N_{GI}+N_{IL})$ nodes).

In those new conditions, after elimination, exists extremely reduced number of nodes, equal to N_{GI}, or equal to $N_{GI}+N_{ID}$. Thus, applying the matrix equation (1), after specification the voltages change of selected generator (definition of the corresponding elements of vector ΔV_G), the corresponding changes of reactive powers of generators and interconnected lines are obtained. (calculation the elements of vector ΔQ_G).

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

In opposite problem definition, in context of proposed advanced method, the corresponding linearized matrix equation, of order $N_{GI}+N_{ID}$ is formulated

$$\Delta V_G = \left(\frac{\partial Q_G}{\partial V_G}\right)^{-1} \Delta Q_G \tag{4}$$

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

Thus, applying the matrix equation (4) after specification the wished correction of reactive powers of selected generators, and/or selected interconnected lines. (definition the corresponding elements of vector ΔQ_G), the necessary correction of generator voltage ΔV_G are obtained.

3 Computer program VOLTCONT

On the basis of the approach presented before, a modularly organized computer program named VOLTCONT (VOLTages CONTrol) is developed, using Visual Fortran Professional Edition 6.0.0. and Microsoft Visual Basic 5.0. 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 to the usually approach):

- Two procedures for initialization of steady-state security analysis, e.g. the procedures for solving the initial load-flows problem, which preceding these analysis [7, 8]. 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 8;
- The limits of generator reactive power, as opposed to the usual approaches, are not constant, a priori defined quantities, but rather corresponding functions of relevant generator parameters and state variables [9].

Also, this computer program enables the following:

- For the initial steady-state solved, the Gaussian elimination of $(N - N_{CH})$ 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 equation (1) , for new generator voltages profile;
- Application the matrix equation (4) for new wished correction of reactive powers of generator and/or interconnected reactive powers;
- For new values of generator voltages, solving the new load-flows problem in whole interconnection, before elimination of (N- NCH) 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, and reactive power flows on tie-lines, 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 Practical Application of Proposed Method

The characteristics and possibilities of advanced method proposed (e.g. computer program VOLTCONT), have been established on example of real electric power interconnection, 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, Fig. 1 shows the block diagram of examined interconnection (which has 1110 nodes), with the active and reactive power flows (MW/Mvar) on interconnected lines and voltages on boundary nodes of Serbian EPS, for expected peak-load conditions for years 2015.

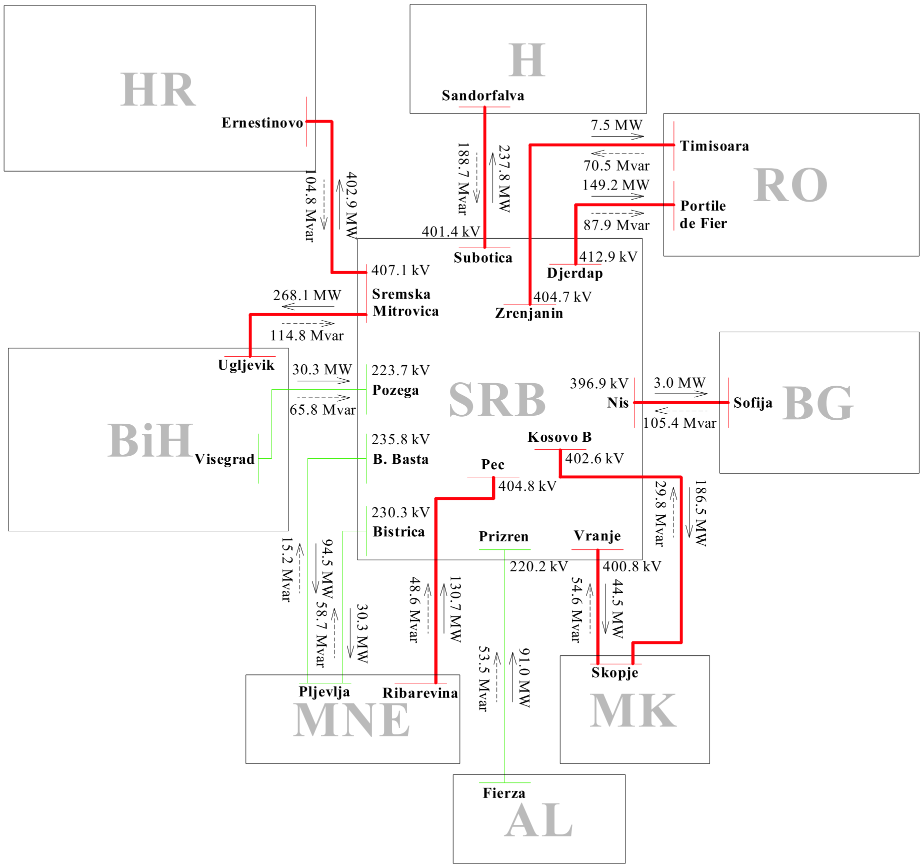

Fig. 1. The active and reactive power flows on interconnected lines and voltages on boundary nodes of Serbian EPS.

To apply the method proposed, in condition of whole interconnection considered, it was necessary to made the Gaussian elimination of 1066 nodes (90 generator nodes and 976 so called ”consumer” nod (the initial number of nodes, as before mentioned, was 1110). Thus, the problem will be reduced on 44 (32+12) nodes (NGI+NIL). Thus, the number 44, is equal to the number of generators (32) and interconnected lines in operation (12) in Serbian EPS. In this case, for successful application of method, it will be need to know all necessary data (topology, voltages, active and reactive power injections), not only for Serbian EPS, but also for all neighbor EPS.

However, if the results of state estimation will be used, for successful application of method, it will be necessary to know the data for only 443 nodes (the total number of nodes in Serbian EPS, which includes the boundary nodes). In those conditions, the elimination of the only 399 nodes will be necessary. The problem will be also reduced on 44 nodes (equal to the number of generators and tie-lines, which are in operation in Serbian EPS. Therefore, for successful application of method in conditions of expected peak-load conditions of Serbian EPS for years 2015., will be necessary to know, along the state vector and topology of Serbian EPS, also to know voltage-reactive state on interconnected lines 400 kV i 220 kV, which are presented on Fig 1.

Table 1 will be serve a good illustration, in context of evaluation and verification of this proposed advanced method. This table gives the selected relevant off-diagonal elements of sensitivity matrix $\partial QG/\partial VG$, which correspond to the considered expected peak-load conditions for years 2015. It should be noted, that for the each of different state considered, the new formming of sensitivity matrix is necessary.

Table 1. The selected off diagonal elements of sensitivity matrix $\partial QG/\partial VG$.

	Interconnected line				
Power plant	Ugljevik-Sremska Mitrovica	Ernestinovo-Sremska Mitrovica	Sandorfalva-Subotica	Sofija-Niš	Portile de Fier-Đerdap
TPP Kolubara B1,2	−2.907	−2.097	−1.722	−1.705	−1.586
TPP N. Tesla B1,2	−7.849	−5.662	−4.597	−0.761	−1.996
TPP N. Tesla B3	−3.913	−2.821	−2.280	−0.378	−0.999
TPP N. Tesla A5,6	−4.227	−3.049	−2.504	−0.519	−1.355
TPP Drmno	−1.278	−0.922	−1.020	−0.290	−11.588
HPP Đerdap	−0.046	−0.033	−0.035	−0.433	−166.759

Those elements give the direct connection between change of the reactive power flows (Mvar) on interconnected lines presented, for 1% change of voltages in presented relevant generators in Serbian EPS. It should be specialy noted, that those elements of sensitivity matrix have identical values in the case of modeling whole interconnection considered (elimination of 1066 nodes) and in the case when the results of state estimation are used (elimination of only 399 nodes). This fact is the results or consequence of existing topology structure of interconnection considred. In elimination process, with keeping in both cases the boundary nodes, which correspond to the tie-lines in EPS of interest, the problem is reduced to the 44 nodes (number of generators nodes in EPS of interest + number of boundary nodes).

In those conditions, the elimination of all nodes in external EPS's have not influence to the obtained final values of elements of sensitivity matrix $\partial Q_G/\partial V_G$. Of course, above mentioned fact about identical values of elements, in both cases, is reached according to the hypothesis of reliable and efficient operation of state estimation, which will be enable, among others, the correct insight to the voltage-reactive state in boundary nodes (voltages phasor and active and reactive power injections).

At the some time, the quantites given in this table serve as good indication about quantification of the influence of voltage change of generators presented to the reactive power flow changes on selected interconnected lines. For example, if generator voltages in TPP N.Tesla B 1, 2 will be increased for 1%, the reactive power flow on tie-line 400 kV Ugljevik - S. Mitrovica will be reduced for 7.85 Mvar, the reactive power flow on tie-line 400 kV Ernestinovo - S. Mitrovica, will be reduced for 5.66 Mvar, e.c.t.

Next, in context of evaluation of this method, we are considered the case of the simultaneous changes of generator voltages in TPP Kolubara B1,2, TPP N.Tesla B1,2 and TPP N.Tesla B3, from initial values 1.00 V_n to 1.02 V_n (V_n denotes the generator rated voltage). Table 2 gives the effects of those voltages control, and results of comparison between simpler and stricter (steady-state) approach.

Table 2. The effects of generator voltages control in TPP Kolubara B, TPP N. Tesla B1,2 and TPP N. Tesla B3.

No.	Power plant or Interconnected line	Q_{G_0} (Mvar)	$Q_{G_K} = Q_{G_R}$ (Mvar)	Q_G (Mvar)	ΔQ_G (%)
1	TPP Kolubara B1,2	124.3	189.5	186.4	1.663
2	TPP N. Tesla B1,2	123.5	245.2	241.0	1.743
3	TPP N. Tesla B3	102.1	164.4	161.2	1.985
4	TPP N. Tesla A1,2	210.3	197.6	195.9	0.868
5	TPP N. Tesla A3,4	269.4	253.4	251.3	0.836
6	TPP N. Tesla A5,6	229.7	180.2	177.7	1.407
7	TPP Drmno	124.5	110.1	170.8	2.134
8	S. Mitroica-Ugljevik	−114.8	−85.5	−82.3	3.888
9	S. Mitroica-Ernestinovo	−104.8	−83.8	−81.4	2.948
10	Subotica-Sandorfalva	−188.7	−171.4	−167.9	2.085
11	Niš-Sofia	−105.4	−99.5	−98.5	1.015

In this table, the quantity Q_{G_O} denotes the values of reactive powers of selected generators and reactive power flows on also selected interconnected lines, in initial steady-state. The new values of generator reactive power and reactive power flows on interconnected lines have the mark Q_{G_K}. Those values are obtained by applaing the matrix equation (1), of order 44, in the case of modeling of whole interconnection considered (elimination of 1066 nodes).

The values of reactive power, for obtained new values of generators voltage have the mark Q_{G_R}. Those values are results of applaing the matrix equation (1), of order 44, using the results of state estimation (in this case, the elimination of only 399 nodes will be needed). Exists the indetical values between Q_{G_K} and Q_{G_R}), from the reasons above explain.

The quantity Q_G (Mvar) denotes the new values of reactive power, which are obtained from the load-flow solution in condition of whole interconnection, for mentioned new values of generator voltages. Finally, the quantity ΔQ_G (in %) is the error of proposed method, in condition of use the resultats of state estimation (ΔQ_G (%) = $(Q_{G_R} - Q_G) \times 100/Q_G$).

The effects of those voltage controls (the simultaneous changes of generator voltage in above mentioned TPP, from initial 1.00 V_n to 1.02 V_n) are, first, in increase of reactive powers at the generators, in which those controls are made, and, next, the coresponding reduce of reactive powers at the others generators in operation. At the same time, the total reactive power flows on Serbian interconnected lines will be reduced for 130.1 Mvar.

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 relevant part of this method is the possibility to monitoring and control the reactive power flows on interconnected lines. Apart from its simplicity, the method is characterized by sufficiently accuracy, which was demonstrated on the example of real electric power interconnection, which consists of the EPS's 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. The application in real- time in future will be realized by state estimation, which is the part of the new SCADA/EMS system in NDC Elektromreža Srbije

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