VOLTAGE/REACTIVE SECURITY ENHANCEMENT IN POWER SYSTEMS WITH PILOT-NODE SECONDARY VOLTAGE CONTROL

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Abstract: This paper deals with the voltage/reactive aspects of steady-state security in power systems with the pilot-node secondary voltage control. In addition to the voltage/reactive security analysis, the main attention is paid to the corrective control actions, that should be implemented when voltage/reactive power security limits are violated. The corrective readjustment of pilot-node set-point voltages is chosen as the principal control action for the remedy of such insecure system states. The whole problem is formulated via a linear programming optimization model, where the minimization of pilot-node set-point voltage deviations, subject to operation constraints, is sought for. The optimization model is defined in the incremental form, and it is based on the extended load flow model, appropriately adopted for systems employing the pilot-node secondary voltage control. It was shown that the proposed model can be efficiently solved, and that it is suitable for the real-time application. The complete methodology was verified on several test examples, as well as on the eastern part of the high-voltage power system of former Yugoslavia.

Keywords: Voltage/reactive power stability and control; Pilot-node secondary voltage control; Security enhancement.

1. INTRODUCTION

The control of voltages, reactive generations, consumptions and flows (usually called voltage/reactive power control), represents one of the most accentuated problems in the operation of modern power systems. The most of researches in recent years were oriented toward the automation of the overall system voltage/reactive power control. The goals of this control were accomplished by developing various multi-level hierarchical control concepts. These concepts usually utilize a good natural three-level decomposition of the voltage/reactive power control problem into the primary, secondary and tertiary controls. While the primary control is a local, fully automatic control being in successful operation for decades, the introduction of general system-wide automatic secondary and tertiary control concepts is still a great challenge in front of power system control engineers. From this point of view, the development of the three-level voltage control concept, recently realized in France and Italy |1,2|, is particularly important, since its second level is a fully automatic secondary voltage control, superimposed to the first level - the primary voltage control. The initial development stage of this control represents the pilot-node (or decentralized) secondary voltage control applied in systems consisting of several mutually independent, compact zones |1|. It is the decoupled control of pilot-node voltages in individual control zones with the aid of common output signals from secondary voltage regulators. These signals are sent to all regulating units with the aim to provide the uniform distribution of relative reactive generations within a zone, while maintaining the desired voltage at the zone pilot-node.

The methods and procedures for the steady-state voltage/reactive security analysis developed so far, take into account the effects of the primary voltage control only. Their common feature is the use of two individual steps: 1) Contingency selection; and 2) Contingency analysis. In the contingency selection step, a fast screening method is applied to select the most dangerous contingencies and to rank them according to their severities. In the contingency analysis, detailed AC power flow studies are applied only to the set of potentially critical cases, selected in the first step. When some of these contingencies cause voltage/reactive power problems, the corrective control should be implemented, with the objective to cancel the violation of operation constraints and to increase voltage/reactive security margins. This problem appears still too complex to be efficiently solved in the real-time, so that the present operation policy utilizes somewhat different approach |3|. Various operation base-states are cyclically solved (for example every 15 min.) with the aid of a real-time optimum power flow model, where the voltage/reactive power limits are appropriately modified. The aim of these modifications is to enable the relaxation of voltage problems in case of the most critical contingencies. It should be pointed out that all these methods use the standard load flow model that takes into account the effects of the primary voltage control only. No attempts were made to incorporate the secondary voltage control in these algorithms, since no general secondary voltage control concept was established so-far.

In this paper, the voltage/reactive security analysis of power systems with the pilot-node secondary voltage control is extended with the proposed corrective control stage. The investigation, resulting to the voltage/reactive security enhancement method, is the direct continuation of recently published results in Ref. |4|, dealing exclusively with the voltage/reactive security analysis. Thus, the proposed corrective control stage is superimposed to the contingency selection and analysis steps, completing the procedure for the study of voltage/reactive security problems. The contingency selection and analysis steps are based on the extended load flow model with common output signals from secondary voltage regulators taken as unknown variables, and on the newly proposed voltage/reactive power performance index (PI) |4|. Then, the proposed corrective control stage is applied to each critical contingency from the previously determined set. In systems with the pilot-node secondary voltage control, the principal corrective control measure is the resetting of pilot-node set-point voltages, enabling the overall modification of voltage profiles in zones hit by disturbances. The solution of this corrective control problem is made by using the linear programming optimization model. The objective function is defined as the minimization of pilot-node voltage deviations from the corresponding set-point values, while the operation constraints are specified in the incremental form, via the extended load flow model. The solution of the model is efficiently obtained by using a single dual simplex iteration and it is superimposed to the base-state. The above problem formulation enables the real-time application of the proposed corrective control model as the last stage, after the voltage/reactive security analysis. Finally, the verification of the proposed methodology is done on several test examples, as well as on the real high-voltage power system of the eastern part of former Yugoslavia.

2. PILOT-NODE SECONDARY VOLTAGE CONTROL

The basic principle of the pilot-node secondary voltage control is the division of the transmission network into distinct, non-overlapping compact zones and the decoupled, decentralized control in each of them. The secondary voltage control is performed by controlling the voltage in one particular point of the zone, referred to as the pilot-node, by using the sufficient amount of controllable reactive power distributed to selected generating units (called "regulating units") within the zone. The control of the pilot-node voltage is realized by forming the common output signal from the secondary voltage regulator, whose input is the zone pilot-node voltage deviation. This signal is used for the modification of the reference inputs of automatic voltage regulators on all zone regulating units in a way, that they operate with the same portion of the maximum reactive power outputs. These steady-state reactive outputs change according to the formula

$$Q_i = Q_i^o + N_\ell \cdot \Delta Q_i^{REG} \; ; \quad i \in \alpha_{G\ell} \; ; \quad \ell=1,2,\ldots,L \; , \qquad (1)$$

where

Q_i^o is the base-state reactive output of all regulating units connected to node i,

N_ℓ is the steady-state value of the common output signal from the zone secondary regulator $N_\ell(t \to \infty)$ which is from now on called the "uniform reactive generation level",

ΔQ_i^{REG} is the reactive regulating range of all units connected to node i,

$\alpha_{G\ell}$ is the set of node indices with connected regulating units in zone ℓ,

L is the total number of zones.

The uniform reactive loading of all generators in a zone enables the elimination of large reactive power circulations between individual units within a zone, and prevents the excessive reactive loading of primary regulating units which are electrically close to the location of a disturbance. Consequently, this feature of the secondary voltage control generally provides the uniform reactive margins on regulating generators and higher level of systems security |5|.

In case of a disturbance, the secondary voltage control acts to return the pilot-node voltage to its set-point value, providing a "good" voltage profile in the whole zone. All regulating units within a zone participate in the compensation of a voltage/reactive power disturbance and follow nearly linear relationship between voltage changes and additional reactive generations. Thus, voltage deviations of all nodes within a zone are proportional to the corresponding uniform reactive generation level. This idea was exploited in Ref. |4| for the definition of a new voltage/reactive power PI, and it would be also used in the fourth section of this paper to specify the voltage/reactive power corrective control problem in the form suitable for the application of the linear programming model.

3. VOLTAGE/REACTIVE SECURITY ANALYSIS

As it was already mentioned, the voltage/reactive security analysis of power systems with the pilot-node secondary voltage control consists of two principal steps, namely:

1. Contingency selection.
2. Contingency analysis.

Within the contingency selection step, contingencies are ranked according to the severity of disturbances, by using the proposed voltage/reactive power PI. The set of potentially critical contingencies is examined next, with the aid of the extended load flow model |4|. These two models are briefly elaborated in the sequel.

3.1. Extended load flow model

The pilot-node secondary voltage control described in the previous section is essentially the voltage control by remote regulating generators. Mathematical modeling of this control in load-flow calculations is based on the error-feedback adjustments of control variables outside the [B"] matrix within the fast decoupled load flow (FDLF) solution procedure |6|. When using this procedure for on-line calculations, certain shortcomings appear due to the need to solve the second auxiliary (1Q) half iteration, after each FDLF full iteration |7|. This was the reason why the extended load flow model was developed |4|. This model encompasses effects of the pilot-node secondary voltage control by means of the automatic adjustments approach within the [B"] matrix. The unknown uniform reactive generation levels (N_ℓ; $\ell=1,2,\ldots,L$) are introduced into the load flow model as state variables, enabling the direct assessment of the secondary voltage control action after the first full FDLF iteration. The extended load flow model is then derived from the standard model, by taking into account the reactive power balance equations (1) at all regulating generator nodes, and by substituting the prespecified voltages at all pilot-nodes with the corresponding uniform reactive generation levels (N_ℓ; $\ell=1,2,\ldots,L$). Assuming that node No. 1 is the slack-node, the vector of unknown variables in the extended load flow model is

$$x^T = (\theta_2,\ V_2,\ \theta_3,\ V_3,\ldots,\ \theta_j,\ N_\ell,\ldots,\ \theta_n,\ V_n) \; , \qquad (2)$$

where

j is the index of the pilot-node in zone ℓ,

n is the total number of nodes,

θ_i, V_i are the voltage phasor angle and magnitude at node i, respectively.

The extended load flow model is solved by using the FDLF method. In case when only the first iteration of the FDLF is dealt with, the uniform reactive generation levels (N_ℓ; $\ell=1,2,\ldots,L$) are the only variables that should be calculated, by using the sparse vector technique |8|. This is obvious from the definition of the new voltage/reactive power PI, described in the next subsection.

3.2. New voltage/reactive power performance index

When all regulating units in one zone generate the same relative reactive outputs, the standard voltage/reactive power PI can be modified by substituting individual reactive generations with uniform reactive generation levels (N_ℓ; $\ell=1,2,\ldots,L$) |4|. This voltage/reactive power PI is calculated after the first iteration of the FDLF, when no reactive limits testing is included yet. It implies that the pilot-node voltages are always returned to their set-point values, even when it is necessary to produce (or absorb) reactive powers on generating units greater then their limit generations. However, since the strong correlation between voltage changes and the uniform reactive generation levels exists, the selection of potentially critical contingencies can be performed by using the latter quantities only. Thus, it was possible to define a new, simplified voltage/reactive power PI based on the weighting average of deviations of the uniform reactive generation levels with respect to certain threshold values, bellow which no violation of voltage constraints exists. Its form is

$$PI_N = \sum_{\ell \in \alpha_N^{LIM}} w_\ell \cdot |N_\ell - N_\ell^{LIM}| \; , \qquad (3)$$

where

α_N^{LIM} is the set of indices of all zones, where absolute values of the uniform reactive generation levels N_ℓ are greater or equal to the threshold value,

w_ℓ is the weighting factor, attributed to the uniform reactive generation level of zone ℓ,

N_ℓ^{LIM} is the threshold value of the uniform reactive generation level in zone ℓ bellow which all node voltage changes are within specified tolerances.

The PI_N (3) is used to select and rank potentially critical contingencies in systems employing the pilot-node secondary voltage control.

4. VOLTAGE/REACTIVE SECURITY ENHANCEMENT

The set of critical voltage/reactive power contingencies is determined within the contingency selection and analysis steps. The question of voltage/reactive security enhancement should be now raised, since the system has reached a so-called "normal insecure" state |9|. In such a case, security objective dominates over the economic one, and "appropriate" corrective control measures need to be implemented in order to return the analyzed base-state to the "normal secure" mode |9|. This can be achieved by translating the critical contingencies into non-critical ones. In systems with the pilot-node secondary voltage control, the principal corrective control action represents the resetting of pilot-node set-point voltages. This control action should be performed for each critical contingency, in order to obtain pilot-node set-point changes that enable the satisfaction of all imposed operation constraints. To solve this corrective control problem, the linear programming model for resetting pilot-node set-points is proposed. The details of this model, its solution algorithm and the discussion of the implementation are given in following subsections.

4.1. Linear programming model for resetting pilot-node set-points

As it was already mentioned, in power systems with the pilot-node secondary voltage control the strong correlation between voltage changes and the uniform reactive generation levels exists. For this reason, the linearization of the voltage/reactive power control loop seems much more appropriate, than in systems with the primary voltage control only. In addition, the corrective resetting of pilot-node set-point voltages represents a supplementary step that should be "added" to the previously calculated operation base-state. Thus, the problem of voltage/reactive power security enhancement can be stated in the linear incremental form, and its solution should be superimposed to the pre-contingency base-state. This principle leads toward the linear programming formulation of the problem of corrective readjustments of pilot-node set-point voltages. The essential idea behind the proposed corrective control model is to apply the minimum of control actions, in order to eliminate the violation of security constraints. In this way, the adopted objective function is the minimization of pilot-node set-point voltage deviations, subject to constraints imposed on bus voltages and reactive generations. Since the system consists of several independent compact zones, the whole problem can be decomposed into the corresponding number of subproblems, each of them dealing with one zone, i.e.:

$$\left.\begin{aligned} &\min\ z_\ell = \Delta V_j\ ; \\ \text{s/to:}\quad &B''_\ell \cdot \Delta V_\ell - (k_\ell \,/\, V^o_\ell)\cdot N_\ell = \Delta Q_\ell \,/\, V^o_\ell\ ; \\ &V^{MIN}_\ell \le \Delta V_\ell + V^o_\ell \le V^{MAX}_\ell\ ; \\ &N^{MIN}_\ell \le N_\ell \le N^{MAX}_\ell\ , \end{aligned}\right\}\ \ell=1,2,\ldots,L; \tag{4}$$

where

ΔV_j is the set-point voltage deviation of the pilot-node in zone ℓ with respect to the base-state value determined by the tertiary voltage control (for instance, the output from the optimal power flow model),

B''_ℓ is the node susceptance matrix of zone ℓ reflecting the contingency under consideration,

ΔV_ℓ, V^o_ℓ are the vectors of node voltage deviations and corresponding base-state values in zone ℓ (including the pilot-node), respectively (superscripts (^{MIN}) and (^{MAX}) denote lower and upper limit values),

k_ℓ is the vector of reactive regulating ranges describing the allocation of the uniform reactive generation level to all regulating units in zone ℓ (equation (1)),

N_ℓ is the uniform reactive generation level in zone ℓ (superscripts (^{MIN}) and (^{MAX}) denote its limit values),

ΔQ_ℓ is the vector of reactive mismatches in zone ℓ.

In the linear programming model (4), it is supposed that the base-state value of the uniform reactive generation level is $N^o_\ell=0$. This model will give correct results (i.e. minimum correction of the control variable) only when the pilot-node set-point voltage deviation is positive. This is the case when low voltages at demand nodes need to be canceled by raising the pilot-node set-point voltage. When the elimination of high voltages at generator nodes is required by lowering the pilot-node set-point voltage, it is necessary to change the sign of the objective function of the model (4), or equivalently, to solve the following problem:

$$\left.\begin{aligned} &\max\ z_\ell = \Delta V_j\ ; \\ \text{s/to:}\quad &B''_\ell \cdot \Delta V_\ell - (k_\ell \,/\, V^o_\ell)\cdot N_\ell = \Delta Q_\ell \,/\, V^o_\ell\ ; \\ &V^{MIN}_\ell \le \Delta V_\ell + V^o_\ell \le V^{MAX}_\ell\ ; \\ &N^{MIN}_\ell \le N_\ell \le N^{MAX}_\ell\ . \end{aligned}\right\}\ \ell=1,2,\ldots,L; \tag{5}$$

The direction of violated voltage constraints is known from the contingency analysis step. Then, it is possible to identify which model ((4) or (5)) should be used for each particular critical contingency. It should be pointed out, that when both lower and upper voltage limits are violated in the same zone, the pilot-node secondary voltage control can not compensate for opposite effects of the corresponding contingency. In both optimization models (4) and (5), the variables (ΔV_ℓ and N_ℓ) can take negative values, and it is necessary to transform these models. With this feature, the final formulation of the corrective control problem is as follows:

$$\begin{aligned} &\min\ (\max)\ z_\ell = \Delta V'_j\ ; \\ &\text{s/to:} \\ &B''_\ell \cdot \Delta V'_\ell - (k_\ell/V^o_\ell)\cdot N'_\ell = \Delta Q_\ell/V^o_\ell - B''_\ell \cdot \Delta V^{MIN}_\ell + (k_\ell/V^o_\ell)\cdot N^{MIN}_\ell\ ; \\ &0 \le \Delta V'_\ell \le \Delta V^{MAX}_\ell - \Delta V^{MIN}_\ell\ ; \\ &0 \le N'_\ell \le N^{MAX}_\ell - N^{MIN}_\ell\ ; \qquad \ell=1,2,\ldots,L\ , \end{aligned} \tag{6}$$

where superscript (') denotes transformed variables.

It is interesting to discuss the incremental form of models (4) and (5). If the specification of quantities is done in accordance with the definitions given above, the linearization is performed around the base-state point, because the vector V^o_ℓ corresponds to the base-state node voltages. In optimization models (4) and (5), this implies that non-linearities due to the considered contingency and the change of the pilot-node set-point voltage are approximated with the linear model. However, it is possible to improve the accuracy of models (4) and (5), since they are run after the contingency analysis step. Then, the incremental forms (4) and (5) can be obtained by linearizing the extended load flow model around the contingency solution point. In this case, vector V^o_ℓ corresponds to node voltages after the contingency, vector ΔQ_ℓ is calculated with these voltages (it is a zero vector), and the limit values of uniform reactive generation levels N^{MIN}_ℓ and N^{MAX}_ℓ should be transformed in accordance with the calculated post-contingency values of uniform reactive generation levels N_ℓ. Thus, only the increment of the pilot-node set-point voltage is expressed with the aid of the linearized model.

The above optimization model (6) should be applied to each zone ℓ having voltage problems, and for each critical contingency from the previously specified set. Thus, it is of prime importance to solve the model efficiently, since the whole procedure is run in the real-time. It can be shown that it is possible to apply for this purpose the dual simplex algorithm with bounded variables |10|. In this case, only one non-basic variable exists, indicating that the optimum solution (if any) can be achieved in a **single** dual simplex iteration. If the "optimum" solution is primary feasible, voltage problems in the considered zone ℓ are eliminated. The algorithm of the solution procedure is given in the sequel.

4.2. Solution of the linear programming model

The complete algorithm for the solution of the linear programming model (6) consists of eight sequential steps. It should be pointed out that the most of calculation results are already available from the contingency selection and analysis steps. The principal steps of the algorithm are as follows:

1. Calculate deviations of voltage phasor angles

$(\Delta\theta_\ell)$, by using the first half (1P) FDLF iteration. When analyzing a branch outage, use the midcompensation technique (branch oriented modification) |11| to reflect the contingency. No additional calculations are necessary in this step, since all results of interest are at the hand after the contingency selection step.

2. Calculate the vector of zone reactive power mismatches ΔQ_ℓ, by using the deviations of voltage phasor angles $(\Delta\theta_\ell)$. This step is already executed during the contingency selection step, so that all necessary results are available.

3. Specify the vector **w** that represents the column of the susceptance matrix B''_ℓ corresponding to the pilot-node, as follows:

$$\mathbf{w}^T = [B''_{1j}, B''_{2j}, \ldots, B''_{jj}, \ldots, B''_{nj}] \ . \tag{7}$$

If a branch connected to the pilot-node is subject to the outage, modify the vector **w** appropriately.

4. Establish dual feasibility conditions by setting the pilot-node set-point voltage deviation equal, either to its minimum value $(\Delta V_j = \Delta V_j^{MIN})$ in case of the minimization model (4), or to the maximum value $(\Delta V_j = \Delta V_j^{MAX})$ if the maximization formulation (5) is in the process. Calculate the rest of basic variables (i.e. the dual feasible basic solution), by solving the following set of equations:

$$\underbrace{\begin{bmatrix} B''_{11} & B''_{12} & \cdots & -k_1/V^o_1 & \cdots & B''_{1n} \\ B''_{21} & B''_{22} & \cdots & -k_2/V^o_2 & \cdots & B''_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ B''_{n1} & B''_{n2} & \cdots & -k_n/V^o_n & \cdots & B''_{nn} \end{bmatrix}}_{B^o_\ell} \cdot \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ N_\ell \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \Delta Q_1/V^o_1 \\ \Delta Q_2/V^o_2 \\ \vdots \\ \Delta Q_j/V^o_j \\ \vdots \\ \Delta Q_n/V^o_n \end{bmatrix} - \Delta V_j^{LIM} \cdot \mathbf{w} \tag{8}$$

At the right hand-side of the equation (8), ΔV_j^{LIM} is equal to ΔV_j^{MIN} in case of the model (4), while it is ΔV_j^{MAX} when the model (5) is used. Since the desired direction of the pilot-node set-point voltage change is known in advance, it is very convenient to set

$$\begin{aligned} \Delta V_j^{MIN} &= 0 \ ; \qquad \text{(for model (4))} \ ; \\ \Delta V_j^{MAX} &= 0 \ ; \qquad \text{(for model (5))} \ . \end{aligned} \tag{9}$$

In this case, there is no need for any additional calculations, since the solution of the equation (8) is already available after the first full FDLF iteration in the contingency analysis step. If the outage of a branch is analyzed, apply the midcompensation technique (node oriented modification) |11|, to modify the solution vector.

5. Compare the vector of basic variables calculated in the previous step, with corresponding lower and upper limits. If they are inside prespecified limits, the problem is solved and the optimum solution is either the minimum deviation of the pilot-node set-point voltage (in case of the model (4)), or the corresponding maximum value (if the model (5) is used). In the opposite case, find the greatest absolute violation of the lower/upper limit (variable N_ℓ always remains in the basis of the linear programming model). Let the corresponding variable be ΔV_m. Store the index of the variable (m) and the violated limit value.

6. Solve the following equation:

$$(B^o_\ell) \cdot \mathbf{x}_j = \mathbf{w} \ , \tag{10}$$

and select the m-th element of the solution vector $\mathbf{x}_j$ (which is called "pivot" element x_{mj}). Modify the vector $\mathbf{x}_j$ in the same way as in the step No. 4., if a branch outage is analyzed. If it is supposed that the m-th variable was either beneath the lower limit (in case of the model (4)), or above the upper limit (in case of the model (5)), the "pivot" element should be negative. Continue with the next step, if the above condition is satisfied. If not, the problem has no feasible solution. In both cases, one additional forward/backward substitution is necessary in this step.

7. Find the new basic solution, by exchanging the non-basic ΔV_j and the basic ΔV_m. This is done by using the "product form of inverse" technique |12|, where the solution vector $\mathbf{x}_j = [x_{1j}\ x_{2j}\ \ldots\ x_{mj}\ \ldots\ x_{nj}]^T$ from equation (10) is substituted into the relation

$$\begin{array}{c} \\ \\ m \rightarrow \\ \\ \end{array} \begin{bmatrix} (\Delta V_1)^1 \\ (\Delta V_2)^1 \\ \vdots \\ (\Delta V_j)^1 \\ \vdots \\ (\Delta V_n)^1 \end{bmatrix} = \begin{bmatrix} \Delta V_1 - (x_{1j}/x_{mj}) \cdot (\Delta V_m - \Delta V_m^{LIM}) \\ \Delta V_2 - (x_{2j}/x_{mj}) \cdot (\Delta V_m - \Delta V_m^{LIM}) \\ \vdots \\ (\Delta V_m - \Delta V_m^{LIM})/x_{mj} \\ \vdots \\ \Delta V_n - (x_{nj}/x_{mj}) \cdot (\Delta V_m - \Delta V_m^{LIM}) \end{bmatrix} . \tag{11}$$

In the equation (11), ΔV_m^{LIM} denotes the lower (in case of the model (4)), or upper (in case of the model (5)) limit value of the "worst" basic variable.

8. Test the newly calculated basic variables against the lower and upper limits. If all constraints are satisfied, the optimum value of the pilot-node set-point is

$$V_j^{OPT} = \begin{cases} V^o_j + (\Delta V_j)^1 + \Delta V_j^{MIN} & \text{(for model (4))} \ ; \\ V^o_j + (\Delta V_j)^1 + \Delta V_j^{MAX} & \text{(for model (5))} \ , \end{cases} \tag{12}$$

where V^o_j denotes pre-contingency pilot-node set-point value. On the contrary, it is not possible to cancel voltage problems in zone ℓ by resetting its pilot-node set-point voltage only, so that other corrective measures should be applied.

Finally, it can be summarized that for the calculation of the proposed corrective control model, very little additional time is required. One forward/backward substitution (step No. 6.), and n multiplications (step No. 7.) are only needed per each considered zone and the contingency case.

4.3. Connection of the voltage/reactive security analysis and corrective control stages

The proposed corrective control model (4) or (5) should be added to the contingency analysis step. If the linearization around the base-state point is used, the solution of the first full FDLF iteration need to be stored for each analyzed potentially critical contingency, and the corrective control model should be applied immediately after the severity of the contingency has been proven. However, the whole procedure can be even accelerated, if the pilot-node set-point voltage deviation is the only variable calculated from the corrective control model. In this case, the step No. 6. of the above algorithm consists of one **fast** forward/backward substitution, while the steps No. 7. (except for the pilot-node set-point voltage deviation) and No. 8. can be omitted. It is also possible to merge the contingency analysis and the corrective control into one single stage. Then, the corrective control model is run after the first full FDLF iteration during the solution of the analyzed contingency, and the FDLF procedure is continued until its final convergence, with the corrected pilot-node set-point voltage. These computation schemes can significantly contribute to the efficiency of the proposed methodology.

5. TEST RESULTS

The verification of the proposed voltage/reactive security enhancement procedure was done on several test examples, and on the real high-voltage power system of eastern part of former Yugoslavia. A nine node power network is used in this paper as a test system (Fig. 1).

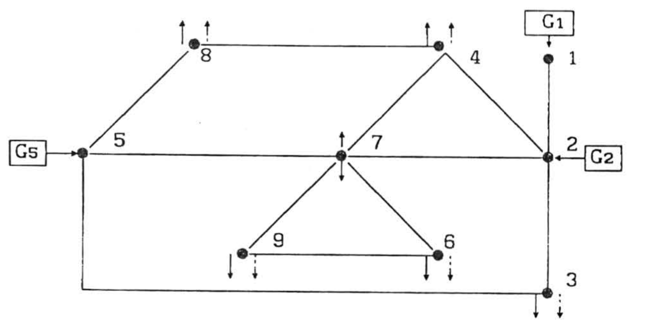

Fig. 1. - One-line diagram of the nine node test system

Data defining the system elements are given in Table I, and the corresponding base-state (prefault) quantities are listed in Table II. Node No. 1. is chosen as the slack node, while nodes Nos. 2. and 5. have regulating units participating in the secondary voltage control. All other nodes are demand nodes, and the node No. 7. is taken to be the zone pilot-node. Its set-point voltage in the base-state is set to 1.00 p.u. The lower and upper limits of all node voltages are chosen to be 0.95 p.u. and 1.05 p.u., respectively. Both reactive regulating ranges defining the allocation of the uniform reactive generation level to generators Nos. 2 and 5. were set to 1.00 p.u. The base-state value of the uniform reactive generation level was taken to be zero.

Table I - Normalized branch parameters describing the test system

BRANCH	g [p.u.]	b [p.u.]	$b^o/2$ [p.u.]
1 - 2	1.3214	-16.7378	0.4000
2 - 3	4.1294	-52.3056	0.1280
2 - 4	3.3035	-41.8445	0.2000
2 - 7	2.7529	-34.8704	0.2400
3 - 5	4.7193	-59.7778	0.1400
4 - 7	5.5058	-69.7408	0.1200
4 - 8	2.7529	-34.8704	0.2400
5 - 7	3.3035	-41.8445	0.2000
5 - 8	3.3035	-41.8445	0.2000
6 - 7	2.2023	-27.8963	0.4560
6 - 9	4.7193	-59.7778	0.1120
7 - 9	8.2588	-104.6112	0.0640

g - branch conductance, b - branch susceptance, b^o- branch shunt susceptance.

Table II - Node variables defining the base-state of the test system

NODE	P^o[p.u.]	Q^o[p.u.]	V^o[p.u.]	θ^o[deg]
1	0.031	-0.891	1.0000	60.0
2	6.900	1.081	1.0290	59.8
3	-1.000	-0.400	1.0275	59.5
4	-2.000	0.000	1.0117	55.7
5	8.000	1.481	1.0292	60.1
6	-3.000	-1.400	0.9755	50.9
7	-3.300	-1.000	1.0000	54.4
8	-2.500	-1.300	1.0065	56.3
9	-3.000	-1.000	0.9840	52.1

P^o- active injection, Q^o- reactive injection, V^o- voltage magnitude, θ^o- voltage phasor angle.

The contingency selection and analysis steps were performed by using the new voltage/reactive power PI and the extended load flow model. The values of the uniform reactive generation level marked as N_I in Table III, are calculated after the first full FDLF iteration and they are the basis of the contingency selection step (equation (3)). Then, the set of critical contingencies is determined, and three typical examples are given in columns marked as *P.C.* (Table III). When the branch 6-7 is outaged, the low voltage problems appear at the node No. 6. (sign (*) is used in Table III to stress such situations). Contrary, in case of the outage of the branch 2-7, the violation of the upper voltage limit at the node No. 2. exists. In the third case (outage of the branch 5-7), extremely high voltage appears at the node No. 5. (the problems exist at the node No. 3., as well). The proposed corrective control model is then applied, with the aim to relax the violation of voltage/reactive power operation limits. In the first and the second case, it was possible to obtain optimum pilot-node set-point voltage deviations that satisfy voltage/reactive power constraints. The new pilot-node set-point voltages are given in Table III, and they are marked as V_7^{OPT}. It was verified by repeated runs of the extended load flow model that no voltage problems in these two cases exist (columns marked as *P.C.C.*). The final values of the uniform reactive generation level (symbol N_F) are also given in Table III, and they are within the prespecified tolerance range. It should be noted that voltages at nodes No. 6. (outage of the branch 6-7) and No. 2. (outage of the branch 2-7) are equal to corresponding limit values (0.95 and 1.05, respectively) after the application of the corrective control model (since these variables are "pivoted" with the pilot-node set-point voltage). However, when the extended load flow model is run again, these values are slightly different, since the linearized incremental form of the corrective control model gives an approximate solution (i.e. the non-linearity of the load flow model is now encompassed). In case of the outage of the branch 5-7, the voltage change of the node No. 5. was exchanged with the pilot-node set-point voltage deviation. The obtained "optimum" pilot-node voltage $V_7^{"OPT"}$=0.9690 could not compensate for voltage problems, since the violation of the lower voltage limit at the node No. 6 existed. This was also verified by the repeated run of the extended load flow model (column *P.C.C.*), and it represents an example of the impossibility of the pilot-node secondary voltage control to eliminate big spans between individual node voltages.

Table III - Typical examples of critical contingencies within the analyzed test system

	CONTINGENCY OF BRANCH					
	6 - 7		2 - 7		5 - 7	
	N_I=0.7757 V_7^{OPT}=1.00598 N_F=0.6890		N_I=1.0249 V_7^{OPT}=0.9916 N_F=0.7390		N_I=1.3765 $V_7^{"OPT"}$=0.9689 N_F=0.8140	
NODE	V [p.u.]		V [p.u.]		V [p.u.]	
	P.C.	*P.C.C.*	*P.C.*	*P.C.C.*	*P.C.*	*P.C.C.*
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	1.0387	1.0437	*1.0547	1.0483	1.0487	1.0227
3	1.0382	1.0437	1.0482	1.0405	*1.0632	1.0357
4	1.0167	1.0225	1.0205	1.0122	1.0235	0.9937
5	1.0407	1.0467	1.0457	1.0375	*1.0802	1.0512
6	*0.9425	0.9495	0.9755	0.9660	0.9755	*0.9430
7	1.0000	1.0060	1.0000	0.9916	1.0000	0.9689
8	1.0152	1.0212	1.0200	1.0112	1.0377	1.0077
9	0.9710	0.9772	0.9840	0.9747	0.9840	0.9520

P.C. - post-contingency values,
P.C.C. - post corrective control values.

The high-voltage transmission network of the eastern part of former Yugoslavia is used to verify the methodology under real-life circumstances (Figure 2.). Since this network does not employ the pilot-node secondary voltage control, its action was simulated by dividing the system into six weakly coupled control zones. The zones, corresponding pilot-nodes, and associated reactive regulating resources are given in Table IV. The quantities marked as V_J^o denote the base-state pilot-node set-point voltages.

In the considered high-voltage transmission system, the most dominant control zones belong to the power pool of Serbia. Various single contingencies within all listed control zones were considered, and major results are briefly summarized in Table V. The corrective control model was applied only to the zone where the contingency occurred. The limit values of all uniform reactive generation levels are taken to be N_ℓ^{LIM}=0.8; ℓ=1,2,...,6, and the contingencies are ranked according

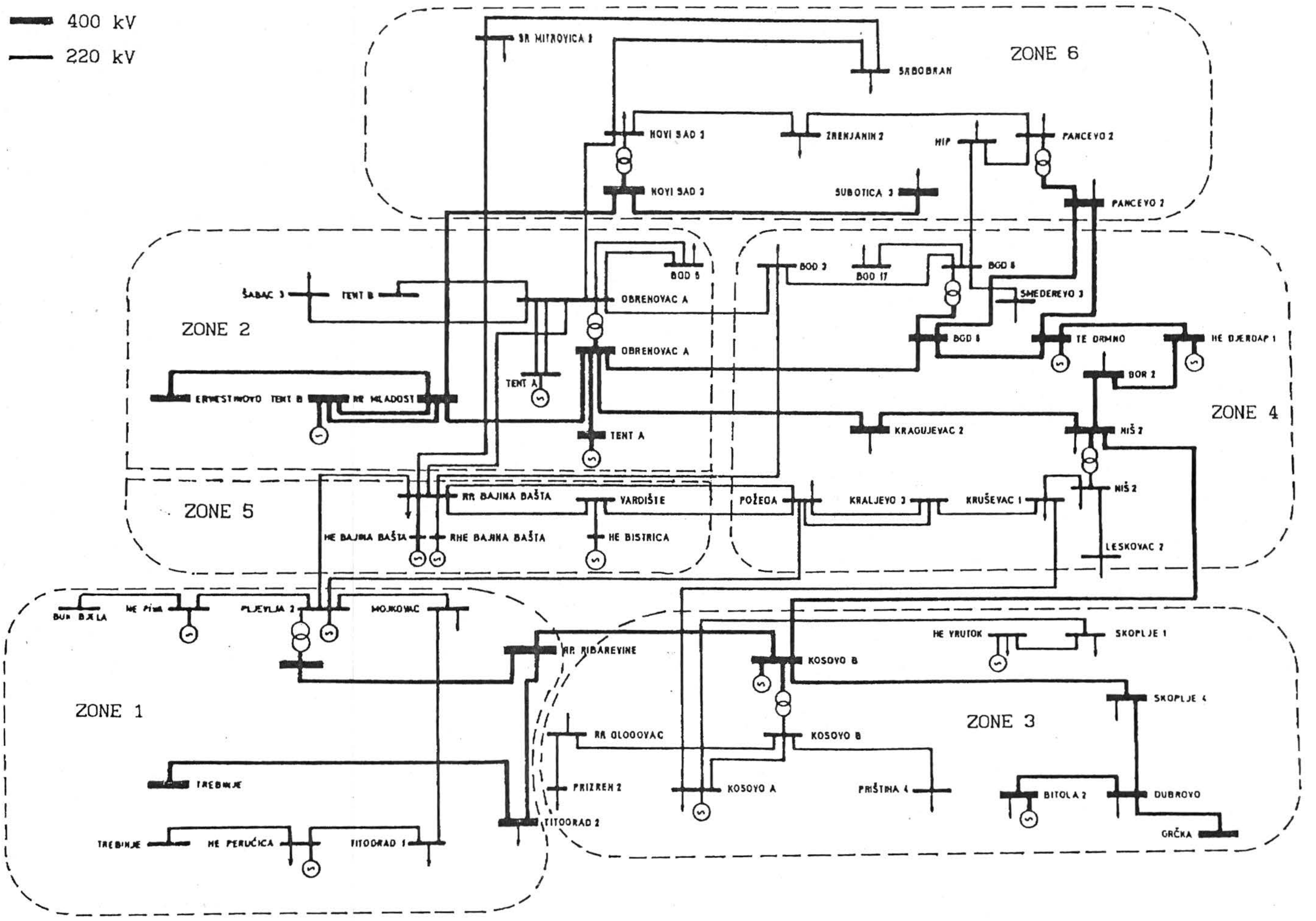

Fig. 2 - Eastern part of the high-voltage power system of former Yugoslavia divided into six control zones

to the decreasing values of the new voltage/reactive power PI (the first column in Table V). The kind of voltage problems appearing at nodes within the considered zone is given in the second column, while the "optimum" corrections of pilot-node set-point voltages are presented in the third column. The final effects of the pilot-node set-points resetting are tested with the aid of the extended load flow model, and the results are summarized in the last column of Table V. It was confirmed again, that the violation of both lower and upper voltage limits can not be eliminated by the pilot-node secondary voltage control. In such cases, it is necessary to apply another, "more distributed" control concept.

Table IV - Specification of control zones, pilot-nodes and regulating resources of the analyzed Yugoslav power system

	CONTROL ZONE	PILOT-NODE (PILOT-NODE SET POINT VOLTAGE)	REGULATING NODES	REGULATING RANGE [MVAr]	
				PER UNIT	TOTAL
1	MONTENEGRO	SS RIBAREVINE (V^o_j=398 kV)	HP PIVA	± 15	± 60
			TP PLJEVLJA	± 15	
			HP PERUCICA	± 15	
			HP TREBIJNE	± 15	
2	SERBIA 1	SS OBRENOVAC A (V^o_j=404 kV)	TP NT A1	± 50	± 200
			TP NT A2	± 50	
			TP NT A3	± 50	
			TP NT B	± 50	
3	KOSOVO & MACEDONIA	TS KOSOVO B (V^o_j=403 kV)	TP KOSOVO A	± 75	± 150
			TP KOSOVO B	± 75	
4	SERBIA 2	TS BEOGRAD 8 (V^o_j=400 kV)	TP DRMNO	± 60	± 120
			HP DERDAP	± 60	
5	SERBIA 3	SS B.BASTA (V^o_j=225 kV)	HP BISTRICA	± 40	± 120
			PSHP B.BAST	± 40	
			HP B.BASTA	± 40	
6	VOJVODINA	TS N.SAD 3 (V^o_j=402 kV)	SC SRBOBRAN	± 30	± 90
			TP NOVI SAD	± 30	
			TP ZRENJAN.	± 30	

SS - substation, TP - thermal plant, HP - hydroplant PSHP - pumped storage hydroplant, SC -synchr. condenser.

Table V - The most critical contingencies within the power pool of former eastern Yugoslavia

No	CONTINGENCY OF	PI_N	VOLTAGE PROBLEMS	PILOT-NODE SET-POINT DEVIATION	PROBLEMS ELIMINATED
1	THE LINE 400 KV KOSOVO-RIBAREVI	6.00	HIGH/LOW	/	NO
2	THE LINE 400 KV MLADOST-N.SAD 3	4.40	LOW	+ 7.3 kV	YES
3	THE LINE 400 KV OBRENOV-KRAGUJE	1.40	HIGH/LOW	/	NO
4	THE 150 MVAR UNIT IN TP KOSO	1.16	LOW	+ 5.5 kV	YES
5	THE LINE 400 KV BEOGRAD8-PANC24	0.91	HIGH	- 4.6 kV	YES
6	THE 150 MVAR UNIT IN TP DRMN	0.72	LOW	+ 4.2 kV	YES
7	THE 50 MVAR UNIT IN SC SRBO	0.32	LOW	+ 2.6 kV	YES
8	THE 150 MVAR UNIT IN HP DERD	0.28	LOW	+ 3.2 kV	YES
9	THE LINE 400 KV BOR 2-NIS 4	0.26	HIGH	- 2.3 kV	YES
10	THE LINE 220 KV SRBOBR-N.SAD 3	0.16	LOW	+ 2.2 kV	YES

6. CONCLUSION

The purpose of this paper was to develop the methodology for the voltage/reactive security enhancement of power systems, employing the pilot-node secondary voltage control. It is fulfilled by extending the previously developed contingency selection and analysis steps with the proposed corrective control stage. After the set of critical contingencies violating the voltage/reactive power constraints is extracted, the attention is focused to the development of an efficient optimization model, that can be successively applied as a corrective control measure in the real-time. The resetting of pilot-node set-point voltages is chosen as the principal control action, and the whole problem is formulated within the frame of linear programming in the incremental form. It was found that the proposed optimization procedure can be successfully applied in real time situations, always when voltage problems, being the consequence of voltage/reactive power disturbances, exist. In this way, a simple and efficient corrective control model is proposed, representing a compromise solution between presently used optimum power flow models and practical needs in the real time environment. The importance of the developed model lies also in the possibility to get a good insight into the capabilities of the pilot-node secondary voltage control to compensate for voltage/reactive power disturbances.

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