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A Tool to Group and Coordinate Preventive Controls Actions on the Context of Voltage Stability Assessment

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Abstract— **A new methodology for grouping and adjusting the most effective controls actions to prevent voltage instability in electrical power systems with multiple critical contingencies is developed in this paper. This methodology is based on a sensitivity analysis of the maximum loadability point with respect to voltage controls and a parallel evolutionary algorithm. Considering not only the effectiveness of the control elements but also their availability, the methodology designs a set of controllers to eliminate all critical contingencies. The methodology was successfully tested in a reduced south-southeast Brazilian system with 107 buses and 171 lines.**

Introduction

The occurrence of recent blackouts, with large impact in the system, associated with voltage stability problems justifies the necessity of developing Voltage Stability Analysis (VSA) tools to assess the security of Electrical Power Systems (EPS), specially in large power systems, on real time.

The main aim of a VSA tool is the screening and ranking of a large number of contingencies and the selection of preventive and/or corrective controls. Contingencies are ranked according to severity, which is measured in terms of Voltage Stability Margin (VSM). In case of existence of critical contingencies, the system is considered insecure and preventive control actions have to be designed and implemented to turn them into non-critical ones.

Many methods were developed for preventive control selection in the context of voltage security analysis. A natural choice for the design of preventive control actions are the techniques based on optimization methods. In this approach, the VSM is treated as a constraint in the optimization problem [1], [2]. One problem of optimization approaches is that a large number of control variables are usually taken into account and many control actions have to be activated to achieve the optimal control. In order to avoid this problem, techniques to select the most effective control actions have been desired such that a small number of control variables, the most effective ones, are taken into account in the optimization phase.

Feng et al. [3], for example, presented a methodology that combines preventive and corrective control actions in stressed EPS. For cases in which the voltage stability margin is low, a sensitivity analysis of the margin identifies the most effective control actions and an optimization problem is solved to specify and coordinate them. For severe contingencies, when the power flow equation is not solvable, a strategy of parameterized control is employed to restore feasibility. In [4], for example, a single continuation power flow (CPFLOW) determines the maximum loadability point (the nose of the PV curve) for the base case and an analysis of sensitivity of the margin with respect to parameters is proposed. This sensitivity can be used to assess the impact of a control action in the voltage stability margin. In [5] a new mechanism of control is employed to mitigate voltage instability problems. This mechanism employs the CPFLOW, to determine the maximum loadability point, and the sensitivity of the stability margin with respect to controls. In [6], modal analysis [7], in the neighborhood of the maximum loadability point is explored to identify the best location for a static VAr compensation (SVC). In [8] a new methodology to supervise and redesign preventive control actions is developed aiming the mitigation of voltage instability. This methodology is based on multiple solutions of the load flow and sensitivity analysis.

Most of the techniques to select the best control actions are based on sensitivity analysis, in the neighborhood of the maximum loadability point. Our believe is that contingencies cause a large perturbation in the system and sensitivity analysis in the maximum loadability point of the base case may not reflect the impact of control actions when contingencies are taken into account. In [9], a fast method for sensitivity calculation, which does not require an accurate computation of the MLP, but relies on the estimation of the MLP via solution of two power flows [10], was developed. Evaluating the sensitivity of each control element, the controls are classified according to its sensitivity degree and the most effective controls are selected in order to enhance the VSM.

All these methods are capable of ranking the most effective controls for each individual contingency of the list, however they are not suitable to provide coordination of these controls when a large number of critical contingencies coexist.

In this context, in this paper a new methodology to group and

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coordinate the most effective preventive controls for all critical contingencies is proposed. To this end, the methodology employs the sensitivity analysis proposed in [9] to evaluate the sensitivity of the VSM with respect to the variation of a control parameter, a new method to group the preventive controls that are more efficient to eliminate the criticality of all critical contingencies simultaneously and a parallel evolutionary algorithm to adjust the actions values of the preventive controls of the group.

This paper is structured as follows: section reviews the algorithms used to estimate the MLP of each contingency and to rank the most effective preventive controls; section presents the proposed method methodology to determine a global group of preventive controls based on the selection of the most effective ones for all the critical contingencies; section presents the proposed method to determine the optimal values of the preventive controls actions in the selected group; the proposed tools is applied to a reduced model of the south-souteast Brazilian systems and the results is presented in section ; andthe paper is finished with some concluding remarks in section

Problem Formulation

After screening a large number of credible contingencies, a VSA tool offers a list of critical contingencies. In the context of voltage stability, a contingency is considered critical if its voltage stability margin, measured as the difference of load power between the MLP and the current operating condition, is lower than a certain threshold. System operators usually define acceptable voltage stability margins for planning studies and operation. The National System Operator in Brazil - ONS, for example, establishes that 7% is the limit for study of expansions, reinforcements and planning of the operation.

Estimating the maximum loadability point (λ_{max})

In the proposed methodology in this paper, the screening step is carried out via the Look-Ahead Method [10]. Basically, the Look-Ahead method employs two power flow solutions to estimate λ_{max}. Consider x_1 and x_2 two power flow solutions, for two different levels of load λ_1 and λ_2, respectively. The maximum loadability point estimate is made with the most sensitive bus, called voltage pilot bus (V_i), that is the bus that presents the largest relative voltage variation.

The λV curve of the pilot bus is used to estimate the load margin of the EPS. This estimate is obtained by fitting a quadratic curve to the λV curve, modelled by the following equation:

$$\lambda = \alpha + \beta V_p + \gamma V_p^2 \tag{1}$$

in which, α, β and γ are parameters to be determined. Given the load levels λ_1 and λ_2, the state vectors x_1 and x_2, the operating points for load levels λ_1 and λ_2 that are obtained via solution of power flow equations, one obtains two equations:

$$\begin{aligned} \lambda_1 &= \alpha + \beta V_{p,1} + \gamma V_{p,1}^2 \\ \lambda_2 &= \alpha + \beta V_{p,2} + \gamma V_{p,2}^2 \end{aligned} \tag{2}$$

A third equation is obtained by differentiating the second onde with respect to λ_2. Using these 3 equations, the following system of equations calculate the parameterss α, β and γ:

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & V_{p,1} & V_{p,1}^2 \\ 1 & V_{p,2} & V_{p,2}^2 \\ 0 & \frac{dV_{p,2}}{d\lambda_2} & 2\frac{dV_{p,2}}{d\lambda_2}V_{p,2} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \tag{3}$$

Using the values of α, β and γ, an estimate of the maximum load λ_{max} that the EPS can supply before the ocurrence of a voltage collapse is obtained via equation (4).

$$\lambda_{max} = \alpha - \frac{\beta^2}{4\gamma} \tag{4}$$

For more details about the Look-Ahead method, see reference [10].

Sensitivity Analysis for Preventive Control Ranking

Given the list of critical contingencies, the problem consists of designing preventive control to eliminate these criticalities. The design of preventive control is divided in two phases. In the first phase, a list of the most effective controls is determined and, in the second phase, these selected controls are adjusted to bring the VSM to acceptable levels.

In the process of selecting the most effective controls, three main aspects have to be considered: (i) the effectiveness of each control element in improving the margin, (ii) the availability of each control and (iii) the cost of choosing each control action.

The effectiveness of each control can be computed via sensitivity analysis of the VSM with respect to the control variable. Let λ be a real variable that parametrizes the load and generation increasing and define λ_{max} as the maximum loadability of the system. The sensitivity of the MLP with respect to a control variable u_c is given by the derivative $d\lambda_{max}/du_c$.

Let $u_c \in \mathcal{R}$ represent the c-th control. In order to consider the availability of the control element, a parametrization is chosen such that $u_c = 0$ represents the actual value of the control while $u_c = 1$ corresponds to its maximum value.

In this paper, we use a methodology inspired in the Look-Ahead method to compute the sensitivity of VSM with respect to control variables. The sensitivity analysis proposed in [9] estimates the changes of the MLP with respect to changes in the control parameter u_c. Actually, the sensitivity of the maximum loadability point estimate (λ_{max}), obtained via Look-Ahead, is calculated for each control element u_c by the following equation:

$$\frac{d\lambda_{max}}{du_c} = \frac{\partial \alpha}{\partial u_c} - \frac{\beta}{2\gamma}\frac{\partial \beta}{\partial u_c} + \frac{\beta^2}{4\gamma^2}\frac{\partial \gamma}{\partial u_c} \quad (5)$$

The control actions are ranked according to this sensitivity level and those that are most effective are employed to eliminate the criticality of a critical contingencies set.

For more details about the sensitivity analysis, see reference [9].

Selecting the Best Preventive Controls

The methodology proposed in [9] determines the most effective controls to eliminate the criticality of a single contingency. However, a voltage control may be effective for more than one contingency. Thus, we can determine a set of preventive controls to eliminate the criticality of all contingencies simultaneously. In this scenario, this work proposes a new methodology to determine a global group of preventive controls based on the selection of the most effective ones for all the critical contingencies.

To this end, the sensitivities of the MLP with respect to a control u_c for each contingency i are calculated. For each contingency, a list $\mathcal{S}_i$ containing these sensitivities is obtained. In this step, the methodology proposed in [9] was used to obtain the list $\mathcal{S}_i$. However, it is noteworthy that other methods of sensitivity analysis may be applied for this purpose.

After obtaining the list $\mathcal{S}_i$, it becomes necessary to determine the group of the most effective preventive controls to be applied to eliminate the criticality of all the selected contingencies. This is performed evaluating the efficacy degree of each control u_c (CEI_c – Control Efficacy Index) with respect to all the selected contingencies and mapping the ones which are effective.

Let $\mathcal{S}_i^n$ a normalization of the sensitivity list $\mathcal{S}_i$ given by

$$\mathcal{S}_i^n = \mathcal{S}_i / max(\mathcal{S}_i) \quad (6)$$

where S_i is the vector of sensitivities of the MLP with respect to the controls for contingency i and $max(\mathcal{S}_i)$ is the maximum sensitivity entry in S_i, i.e., the most effective control for the contingency.

Given a control u_c, the CEI_c represents the effectiveness of this control in eliminating the criticality of all selected contingencies. This index is given by the sum of $\mathcal{S}_{ic}^n$ with respect to all the selected contingencies,

$$CEI_c = \sum_{i=1}^{NCT} \mathcal{S}_{ic}^n. \quad (7)$$

where NCT is the number of selected contingencies and $\mathcal{S}_{ic}^n$ is the normalized sensitivity of the c-th control. Thus, this index is computed for each control u_c and a vector CEI is obtained, i.e., CEI is composed by the CEI_c of all controls.

The aforementioned index indicates only the efficacy of a certain control with respect to all the selected contingencies. However, this index does not indicate the contingencies in which the respective controllers are effective. This information is important to know the contingencies whose criticality is mitigated by a certain control and guide the proposed method to select the effective controls. To obtain this information, a mapping of the contingencies in which the control u_c is effective is proposed in this paper. This mapping is a relation matrix $\mathbf{R}$ which is obtained via the evaluation of the normalized sensitivities $\mathcal{S}_{ic}^n$ with respect to a $threshold$. Each element of the matrix $\mathbf{R}$ is computed as follows

$$\mathbf{R}_{ic} = \begin{cases} 1, & \text{if } \mathcal{S}_{ic}^n \geq (\mathcal{S}_i^{n*} - threshold) \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

where $\mathcal{S}_i^{n^*}$ is the most effective control, i represents the i-th contingency and c represents the c-th preventive control. In (8), the value 1 in $\mathbf{R}_{ic}$ is assigned to all controls u_c that have $\mathcal{S}_{ic}^n$ greater than or equal to the difference between $\mathcal{S}_i^{n^*}$ and the $threshold$, this ensures that only the effective controls for contingency i will be selected.

Let $\mathcal{G}$ be the group of preventive controls to eliminate the criticalities of the selected contingencies. The proposed strategy in this paper to determine this group is based on the selection of the controls with highest CEI_c with respect to each critical contingency. The selection is made sequentially, initiating from those controls that are the most effective. The criterion to stop the inclusion of more control to $\mathcal{G}$ is based in two conditions: i) the application of the controls in the group $\mathcal{G}$ implies in a MLP greater than or equal to $\lambda_{threshold}$; ii) the strategy has evaluated all the controls in the EPS and the criterion i) was not satisfied. The steps to determine this group is presented in the Algorithm 1.

In Algorithm 1, for each contingency i the proposed strategy verifies if the control u_c can be inserted in group $\mathcal{G}$. This is accomplished selecting the controls with highest CEI and checking if these controls are really effective, via matrix $\mathbf{R}$, to increase the MLP of the contingency in analysis. For each selected control, the value of their sensitivity is added with the MLP of all the selected contingencies. This strategy performs an approximation of how much the selected control can improve the MLP. Thus, this algorithm stops when the criterion i) or ii) are satisfied.

Algorithm 1 Selecting the best preventive controls

```
G ← ∅;
for i ← 1, 2, ..., NCT do
    aux ← CEI;
    while stop criterion is not satisfied do
        c ← get index of maximum value in aux;
        aux_c ← −1;
        if R_ic = 1 then
            λ_max ← λ_max + S_ic;
            if u_c ∉ G then
                G ← G ∪ u_c;
            end if
        end if
    end while
end for
```

Adjusting the Preventive Controls Actions

Evolutionary Algorithms are search and optimization methods based on the evolution mechanisms of the living beings [11]. There are several types of algorithms that can be classified as EAs, the most common of them being the Genetic Algorithms [12] and their corresponding variants ([13] is an example).

Generally, genetic-type EAs work in the following way [12]: an initial population of chromosomes is generated, where each chromosome represents a possible solution for the problem. This population is evaluated and each chromosome receives a fitness value (according to the objective function), which represents the quality of its solution for the problem. In general, the most able chromosomes are selected for the next generation and the less able chromosomes are discarded.

The selection method must prioritize chromosomes with higher fitness value, but with no damage to genetic diversity of the population. After the selection, a part of the chromosomes can be subject to modifications through crossover and mutation operators, generating offspring. It is necessary to specify mutation and crossover rates that will define the probability of chromosomes to receive such operations [11]. This process is repeated until a satisfactory solution is found or some stopping criterion is reached.

There are some important aspects to consider in the search with EAs to get a good performance and to adequately cover the region of interest within the search space. One of these aspects is the codification of the chromosome because, in general, each chromosome encodes a solution for the problem and must be written in terms of the decision variables of the objective function [11], [12]. Other important aspects are population size, genetic operators of crossover and mutation and their respective rates [11], [12]. In our method, we propose an encoding for the chromosomes so that each gene represents one of the control u_c. Fig. 1 illustrates an example of the proposed encoding for the chromosomes for any population i.

u_{i1}	u_{i2}	u_{i3}	...	u_{iNC}

Fig. 1. Chromossome Representation.

First, an initial population is generated randomly considering the max and min limits of each preventive control. The individuals for the mating pool are selected based on the tournament selection scheme [11]. Three candidates are selected at random from the population and the best individual based on the objective function is placed in the mating pool. The tournament selection is done repeatedly until the mating pool gets filled.

After that, it is necessary to define the crossover operator to match the characteristics of individuals. Initially, two chromosomes P_1 and P_2 are selected (these are considered as the parent chromosomes). Then one of the preventive controls encoded in P_1 and P_2 is selected, and its respective parameters are switched between them, thus generating two new offspring chromosomes F_1 and F_2. Thus, through this combination is expected to obtain ideal values for parameters each control. Fig.2 illustrates an example of crossover application for the proposed method.

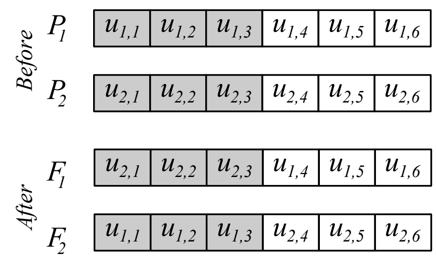

Fig. 2. The proposed crossover operation

In this work, all critical contingencies are analyzed simultaneously. Thus, each chromosome will be considered at all critical contingencies in parallel and the fitness value is obtained according to the lowest MLP provided by this chromosome among all the critical contingencies analyzed. To calculate the fitness value, the following objective function was used:

$$\begin{aligned} \text{max.} \quad & \text{min.}(\lambda_{max_1}, \lambda_{max_2}, \ldots, \lambda_{max_N}) \\ \text{s. t.} \quad & \\ & \lambda_{max_i} \text{ given by Look-Ahead}, \\ & u_c^{min} \le u_c \le u_c^{max} \end{aligned} \tag{9}$$

where λ_{max_i} represents the i-th critical contingency; N the number of critical contingencies; and u_c^{min} and u_c^{max} represent the minimum and maximum limits of the preventive control u_c, respectively.

In (9), the MLP is computed via the Look-Ahead method for each critical contingency i. This function finds the least MLP among all the critical contingencies. Thus, as the EA iterates, bigger values of this objective function are generated. It is important to remark that moving along the maximization of (9) corresponds to the maximization the least MLP.

For a large critical contingencies set, computing the fitness function of each solution requires a large computational effort. Therefore, to overcome this limitation, the proposed EA computes the fitness function uses an algorithm that employs parallel processing. Basically, the MLP is computed over a set of M solutions per core, where M is given by

$$M = \frac{NS}{NCORE} \quad (10)$$

in which NS is the number of solutions and $NCORE$ is the number of cores in the CPU. For example, if the CPU has 8 cores and the number of solutions is 16, 2 solutions will be computed in each core.

Simulations and Results

The proposed algorithm has been tested in a reduced south-southeast Brazilian system (test-system), this system is composed of 107 buses and 171 lines (see Fig. 3) [14]. For the voltage control, this system supports 20 shunt reactors, 13 shunt capacitors, 1 synchronous compensator and 1 static compensator. Only shunt capacitors (see Table I) were considered available for voltage control. It is noteworthy to mention that the shunt capacitor 4522 is being used in their maximum capacity, i.e., $u_{4522} = 1$ (100%). Consequently, this capacitor will not be available for control.

TABLE I
SHUNT CAPACITORS AVAILABLE FOR CONTROL.

Bus Control	Name	MVar	Availability
1210	Gravataí	400	100%
939	Blumenau	350	100%
959	Curitiba	100	50%
104	Cachoeira Paulista	300	100%
122	Ibiúna	300	50%
1504	Itajubá	300	100%
123	Campinas	300	100%
120	Poços de Caldas	300	100%
234	Samambaia	200	100%
4522	Rondonópolis	100	0%
4533	Coxipó	30	100%
4582	Sinop	30	100%
231	Rio Verde	100	100%

The contingencies were classified via Look-Ahead method and the critical ones were selected according to the guidelines for operation and planning adopted by ONS (National System Operator) [15], i.e. the critical contingencies are those whose VSM is lower than 7%, see Table II.

The algorithm proposed in [9] was employed to estimate the sensitivity of λ_{max_i} with respect to changes in the control parameter u_c for each contingency of Table II (See Table III). After obtaining these sensitivities, Algorithm 1 was employed to determine the group of the most effective preventive controls to eliminate the criticalities of the contingencies.

TABLE II
THE CRITICAL CONTINGENCIES.

i	Outage Line	λ_{max}	i	Outage Line	λ_{max}
1	(101-102)	1.0472	5	(225-231)	1.0308
2	(101-103)	1.0364	6	(231-4501)	1.0392
3	(140-138)	1.0642	7	(233-320)	1.0690
4	(140-138)	1.0606	8	(896-897)	1.0468

*i is the $i-$th contingency.

To this end, initially the CEI and the matrix **R** were obtained, as can be seen in Tables (IV) and (V), respectively. It is worth noting that, the control u_{4522} is equal to zero in CEI_{4522} and $\mathbf{R}_{i,u_{4522}}$, i.e., this control is already being used to its fullest and therefore has no available margin to operate.

TABLE IV
CONTROL EFFICACY INDEX.

c	CEI	c	CEI
1210	1.8110	120	2.0181
939	1.9974	234	0.8179
959	0.8522	4522	0
104	4.3292	4533	0.5786
122	0.9061	4582	0.6542
1504	4.5036	231	3.0519
123	2.5024		

In Table V, the most effective controls for each contingency were selected via (8), these controls are represented by a number 1 in matrix **R**. In this example, a $threshold$ equal to 30% was chosen. This choice is based on an estimation of how much, in terms of percentage, each control is effective with respect to the most effective control.

Let 1.07 ($\lambda_{threshold}$) be the minimum value required for λ_{max}. Algorithm 1 was employed to determine the group of preventive controls that achieve this value. Using the proposed strategy, the group $\mathcal{G}$ of the most effective preventive controls is composed of u_{1504}, u_{104}, u_{123}, u_{231}, u_{939} and u_{1210}. The values of the preventive control actions in group $\mathcal{G}$ was determined via the proposed parallel EA (see section). The parameters utilized in the simulation were $NS = 16$ (Number of Solutions); $NCORE = 8$ (Number of Cores) and the objective was to determine an MLP greater or equal than 1.07 (7%). Table VI presents controls actions values obtained by the EA.

TABLE VI
CONTROL ACTION VALUES.

c	u_c
1504	0.25
104	1
123	0.5
231	0.5
939	1
1210	0.25

Using the value presented in Table VI, the MLP (λ_{max}) of

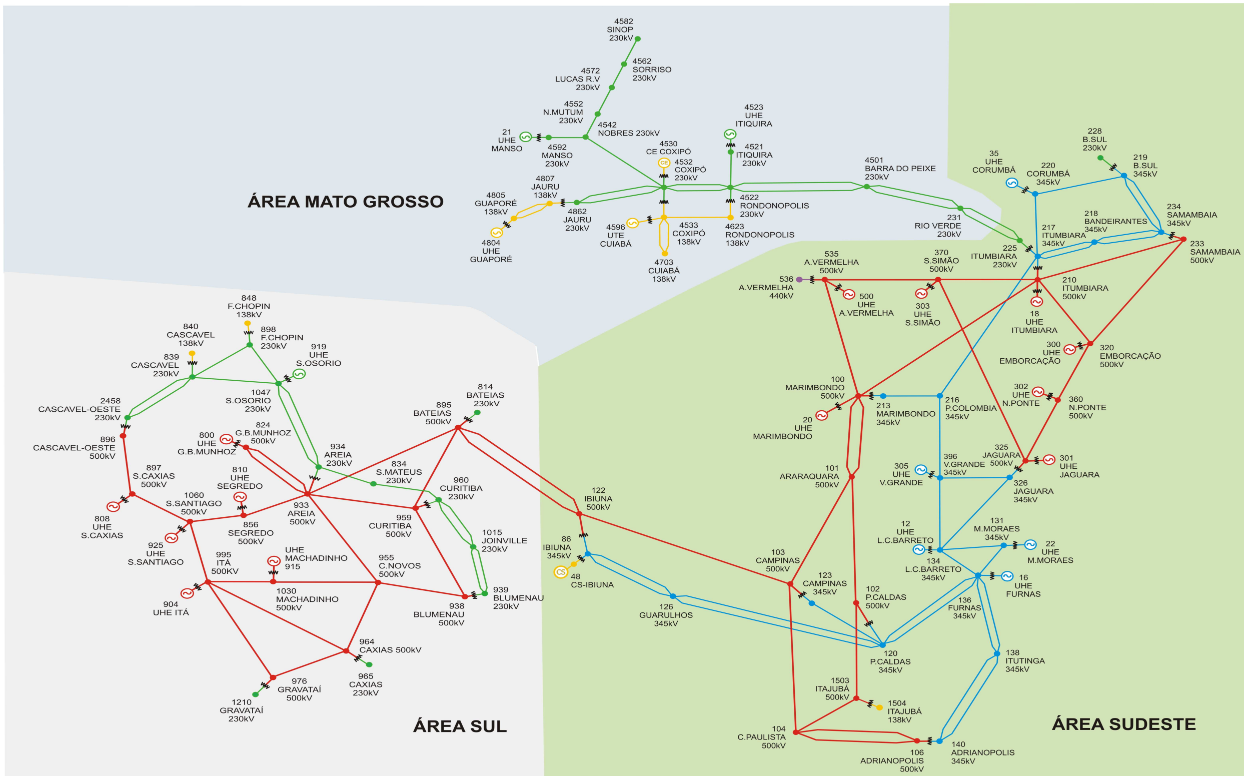

Fig. 3. Reduced south-southeast Brazilian system with 107 buses.

TABLE III

SENSITIVITIES OF λ_{max_i} WITH RESPECT TO THE CONTROL PARAMETER u_c FOR ALL CRITICAL CONTINGENCIES.

i \ u_c	u_{1210}	u_{939}	u_{959}	u_{104}	u_{122}	u_{1504}	u_{123}	u_{120}	u_{234}	u_{4522}	u_{4533}	u_{4582}	u_{231}
1	0.1968	0.2461	0.1083	0.9826	0.1671	10.000	0.5441	0.4765	0.0182	0	0.0016	0.0012	0.0095
2	0.1942	0.2328	0.1022	0.8325	0.1533	10.000	0.4969	0.4196	0.0176	0	0.0011	0.0011	0.0091
3	0.1964	0.2362	0.1040	10.000	0.1639	0.9996	0.5245	0.4163	0.0236	0	0.0023	0.0023	0.0143
4	0.1940	0.2362	0.1040	10.000	0.1643	0.9981	0.5234	0.4152	0.0232	0	0.0023	0.0019	0.0139
5	0.0064	0.0090	0.0041	0.0286	0.0068	0.0286	0.0211	0.0169	0.1529	0	0.1544	0.1348	10.000
6	0.0093	0.0127	0.0059	0.0401	0.0093	0.0406	0.0293	0.0239	0.1804	0	0.2346	0.2649	10.000
7	0.0190	0.0243	0.0106	0.0799	0.0175	0.0815	0.0556	0.0450	0.3905	0	0.1810	0.2466	10.000
8	0.9949	10.000	0.4131	0.3655	0.2239	0.3552	0.3076	0.2046	0.0116	0	0.0013	0.0013	0.0051

*i is the $i-$th contingency and u_c is the $c-$th control.

TABLE V

MATRIX OF RELATION **R**.

i \ u_c	u_{1210}	u_{939}	u_{959}	u_{104}	u_{122}	u_{1504}	u_{123}	u_{120}	u_{234}	u_{4522}	u_{4533}	u_{4582}	u_{231}
1	0	0	0	1	0	1	1	1	0	0	0	0	0
2	0	0	0	1	0	1	1	1	0	0	0	0	0
3	0	0	0	1	0	1	1	1	0	0	0	0	0
4	0	0	0	1	0	1	1	1	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	1
6	0	0	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0	1	0	0	0	1
8	1	1	1	1	0	1	1	0	0	0	0	0	0

*i is the $i-$th contingency and u_c is the $c-$th control.

each contingency was evaluated via CPFLOW and the results are presented in Table VII.

Analyzing Table VII, it is possible to observe that the proposed tool to group and coordinate the preventive control actions eliminates all the selected critical contingencies by increasing the MLP to values bigger than 7%.

TABLE VII
MLP OF CONTINGENCIES WITH THE BEST PREVENTIVE CONTROLS.

i	Outage Line	λ_{max}	i	Outage Line	λ_{max}
1	(101-102)	1.1052	5	(225-231)	1.0969
2	(101-103)	1.0906	6	(231-4501)	1.0906
3	(140-138)	1.1041	7	(233-320)	1.0876
4	(140-138)	1.1042	8	(896-897)	1.1053

$*i$ is the $i-$th contingency in $\mathcal{C}$.

Conclusions

In this paper, a new tool to group and coordinate preventive controls actions to prevent the voltage instability in electrical power systems considering a set of critical contingencies. In the group step, we propose a new method to group the most effective preventive controls for a set of critical contingencies was proposed. This method is based on a sensitivity analysis proposed in [9] and a new method to group the preventive controls that are more efficient to eliminate the criticality of all critical contingencies simultaneously was developed. In the coordination step, we developed a new evolutionary algorithm (EA) to determine the values of the control actions in the group. This EA uses parallel programming to improve the computational effort nedeed to perform the MLP of all the critical contingencies.

Tests were conducted in the reduced version of the south-southeast Brazilian system with 107 buses and 171 lines. The control actions were well grouped in terms of their efficiency to increase the MLP for all the critical contingencies. This group was used as a start solution to determine the values of the selected controls via the proposed EA. Implementation of the control actions have shown that the criticality of that set is eliminated. It is noteworthy to mention that although the simulations were performed considering only the shunt capacitors, other control elements can be easily incorporated in the proposed methodology.

It is worth noting that the group of controls in the proposed methodology in this paper can guide the operator of the EPS to choose the minimum number of controls to eliminate the criticalities of the selected contingencies.

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References

[1] S. Granville, J. C. O. Mello, and A. C. G. Melo, "Application of interior point methods to power flow unsolvability," IEEE Power Systems, Trans on, vol. 11, pp. 1096–1103, 1996.

[2] M. Bedrinana, C. Castro, and D. Bedoya, "Maximization of voltage stability margin by optimal reactive compensation," in Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, july 2008, pp. 1 –7.

[3] Z. Feng, V. Ajjarapu, and D. J. Maratukulam, "A comprehensive approach for preventive and corretive control to mitigate voltage collapse," IEEE Transactions on Power Systems, vol. 3, no. 15, pp. 791–798, 2000.

[4] S. Greene, I. Dobson, and F. Alvarado, "Sensitivity of the loading margin to voltage collapse with respect to arbitrary parameters," Power Systems, IEEE Transactions on, vol. 12, no. 1, pp. 262–272, Feb 1997.

[5] J. Zhao, H.-D. Chiang, H. Li, and B. Zhang, "A novel preventive control approach for mitigating voltage collapse," in Power Engineering Society General Meeting, 2006. IEEE, 0-0 2006, p. 6 pp.

[6] B. Gao, G. K. Morison, and P. Kundur, "Toward the development of a systematic approach for voltage stability assessment of large-scale power systems," IEEE Transactions on Power Systems, vol. 11, pp. 1314–1324, 1996.

[7] ——, "Voltage stability evaluation using modal analysis," IEEE Transactions on Power Systems, vol. 7, pp. 1529–1542, 1992.

[8] T. Kumano, A. Yokoyama, and Y. Sekine, "Fast monitoring and optimal preventive control of voltage instability," Electrical Power and Energy Systems, vol. 1, pp. 117–125, 1994.

[9] M. Mansour, L. Alberto, and R. Ramos, "Look-ahead based method for selection of preventive control for voltage stability analysis," in Industrial Technology (ICIT), 2012 IEEE International Conference on, march 2012, pp. 469 –473.

[10] H.-D. Chiang, C.-S. Wang, and A. Flueck, "Look-ahead voltage and load margin contingency selection functions for large-scale power systems," Power Systems, IEEE Transactions on, vol. 12, no. 1, pp. 173–180, Feb 1997.

[11] A. Eiben and J. Smith, Introduction to Evolutionary Computing, ser. Natural Computing Series. Springer, 2008.

[12] D. Goldberg, Genetic algorithms in search, optimization, and machine learning, ser. Artificial Intelligence. Addison-Wesley, 1989.

[13] K. S. Tang, R. Yin, S. Kwong, K. T. Ng, and K. Man, "A theoretical development and analysis of jumping gene genetic algorithm," Industrial Informatics, IEEE Transactions on, vol. 7, no. 3, pp. 408 –418, aug. 2011.

[14] W. F. Alves, "Proposition of test-systems to power systems analysis," Niteroi, RJ, 2007. [Online]. Available: http://www.sistemas-teste.com.br/ (in Portuguese)

[15] ONS. (2011, nov) Submódulo 23.3: Diretrizes e critérios para estudos elétricos. [Online]. Available: http://www.ons.org.br/procedimentos/index.aspx