Influence of Load Shedding in the Voltage Stability of an Electric Power System using Trajectory Sensitivity Analysis

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Abstract- **Trajectory sensitivity analysis can provide valuable insights into the security of an electric power system. There is a strong correlation relating the system stability and the corresponding trajectory sensitivity. In this paper it is analyzed the influence of load shedding in the voltage stability of an electric power system using trajectory sensitivity analysis. It is recognized that voltage instability and collapse have led to major system failures. The emergency load shedding is one of the most important methods to preserve the system stability. In this study different values of load shedding were used to avoid voltage collapse. The automatic voltage regulators of the generating units and the turbine speed governors were modelled. Different load models were used and the under load tap changers were also taken into account. The simulation results were obtained using EUROSTAG program and post-processing module developed using the Matlab software package.**

Index Terms-- **Electric power network, Trajectory sensitivity analysis, voltage stability.**

I. INTRODUCTION

Dynamic voltage stability has become one of the most important issues in the power industry. It is generally recognized that voltage collapse is a dynamic phenomenon. However, due to the complex nature of the problem and the multiplicity of factors that contribute to voltage collapse, in the past, a large portion of the voltage stability studies were limited to the power flow based static methods [1]. In voltage stability studies the importance of the dynamic behaviour of voltage collapse is obvious and the need to relate the static methods with the dynamic methods for voltage stability analysis is usually required [2].

Voltage instability usually arises from a gradual deterioration in system operating conditions due to a rapid load raise or if a severe contingency occurs. In order to avoid voltage collapse a set of control actions in reactive compensation devices and in transformer tap changers should be carried out. Moreover, load shedding techniques may also be used successfully to overcome the instability problem [3].

It is generally recognized that load representation is an important element in stability studies since it affects power system dynamic performance [4], [5]. Load model should realistically represent the aggregate load behaviour of all type of individual components. As a consequence, load modelling received significant attention over the past decades [6].

The shedding of loads with low power factors will usually be the most effective strategy to withstand system voltage [7], [8]. Loads that depend on power factor compensation using capacitor banks are also interesting to be shed. During abnormal low voltage levels, they become low power factor loads, since the capacitor banks supply less reactive power. Also, loads with a large component of induction motors, such as industrial loads and air conditioning, are appropriate for fast load shedding under this strategy, since asynchronous devices can contribute drastically to the voltage collapse phenomena [9].

It has been observed and can be mathematically justified, that as the stability margin decreases the trajectory sensitivities undergo larger excursions [10]. For unstable situations, trajectory sensitivities increase much more rapidly than the nominal system trajectory. A fast increase in trajectory sensitivities can be linked with an underlying stability problem. Consequently, sensitivities can be used as an early indicator of imminent instability [11].

Trajectory sensitivities have a potential for both preventive and emergency control. Trajectory sensitivities provide an insight into the behaviour of a dynamic system, which would not be otherwise obvious only from its nominal trajectory [12]. An impact of initial conditions and/or parameters on the system trajectory can be analysed [13]. Moreover, the computational cost to evaluate the sensitivities and perturbed trajectories is minimum. These capabilities of trajectory sensitivities have been used so mainly for post mortem analysis [14]. More recent applications have included stability assessment of power systems [15].

In this paper it is analysed the influence of load shedding in the voltage stability of an electric power system using trajectory sensitivity analysis. The emergency load shedding is one of the most important methods to preserve the system stability. In this study different values of load shedding were used to avoid voltage collapse. The simulation results were obtained using EUROSTAG [16] program and post-processing module developed using the Matlab software package.

This paper is organized as follows. In Section II it is described succinctly the applied software package. Section III is devoted to the formulation of the problem using dynamic voltage stability assessment combined with a trajectory sensitivity approach. In section IV it is presented the BPA test power network and two cases that were analysed. Section V shows the results obtained using the proposed methodology. Finally, in section VI, some conclusions that provide a valuable contribution to the understanding of the dynamic voltage stability assessment of a power system are pointed out.

II. APPLIED SOFTWARE

The time-domain simulations provide a realistic picture about voltage collapse phenomena. In this paper the simulations were carried out using the professional grade time domain simulation software package EUROSTAG, developed by Electricité de France (EDF) and Tractebel Energy Engineering [17].

Whatever the type of disturbances observed (with the exception of electromagnetic transients) and the size of the system, EUROSTAG simulates the behaviour of the power system until it returns to its steady state. However, this complete simulation does not lead to any downgrading in the accuracy of calculations.

In effect, the algorithm used in EUROSTAG carries out an automatic control of the simulation considering the accuracy criteria laid down by the user. It is thus possible throughout the simulation to maintain a full model of the system and to show up the inter-relation of dynamic phenomena (apart from electromagnetic transients).

The EUROSTAG software is also very user-friendly. It enables design of new graphic models and in this way avoids the risk of human error inherent in the transcription of block diagrams into computer code. With regard to interpretation of results, it offers a series of interactive graphic aids for results analysis and presentation [18].

The results were exported into Matlab software package, since it is not possible to impose the same time step in two distinct time domain simulations. The trajectory sensitivity solutions were produced using an interpolation technique in order to have a uniform time step in all simulations. It was developed a post processing unit that allows displaying and analyzing the trajectory sensitivity results. The post processing unit is designed to take advantages of the advanced user interface features of the Matlab environment. This unit enhances the user ability to analyze a large amount of output data and to produce visually appealing graphic representations of the results.

III. FORMULATION OF THE PROBLEM

Trajectory sensitivity analysis can provide valuable insights into the security of an electric power systems that otherwise would not be clear from its nominal trajectory [10]. This approach is based upon linearizing the system around a nominal trajectory rather than around an equilibrium point [12].

Analysis of electric power system dynamics requires a computationally efficient non-restrictive model formulation capable of capturing the full range of events. The systems dynamics can be modelled, taking into account their hybrid nature –combination of continuous and discrete dynamics - as a set of differential algebraic (DA) equations [12]:

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \tag{1}$$

$$0 = \begin{cases} g^{-}(\underline{x}, y) & s(\underline{x}, y) < 0 \\ g^{+}(\underline{x}, y) & s(\underline{x}, y) > 0 \end{cases} \tag{2}$$

with the vectors

$$\underline{x} = \begin{bmatrix} x \\ \lambda \end{bmatrix} \text{ and } \underline{f} = \begin{bmatrix} f \\ 0 \end{bmatrix} \tag{3}$$

where x are the dynamic state variables, y are the algebraic variables and λ are the system parameters. A switching occurs when $s(\underline{x}, y) = 0$. The initial conditions are given by:

$$\underline{x}(t_0) = \underline{x}_0 \text{ and } y(t_0) = y_0 \tag{4}$$

Trajectory sensitivity analysis studies the variations of the system variables with respect to the small variations in initial conditions and parameters [12]. If the discontinuities are not taken into account, the system dynamics evolve according to the DA system:

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \tag{5}$$

$$0 = g(\underline{x}, y) \tag{6}$$

The flows of the system can be defined as:

$$\phi(\underline{x}_0, t) = \begin{bmatrix} \phi_{\underline{x}}(\underline{x}_0, t) \\ \phi_y(\underline{x}_0, t) \end{bmatrix} = \begin{bmatrix} \underline{x}(t) \\ y(t) \end{bmatrix} \tag{7}$$

Differentiating equations (5) and (6) with respect to the initial conditions and parameters yields:

$$\dot{\underline{x}}_{\underline{x}_0} = \underline{f}_{\underline{x}}(t)\,\underline{x}_{\underline{x}_0} + \underline{f}_y(t)\,y_{\underline{x}_0} \tag{8}$$

$$0 = g_{\underline{x}}(t)\,\underline{x}_{\underline{x}_0} + g_y(t)\,y_{\underline{x}_0} \tag{9}$$

where $\underline{f}_{\underline{x}}$, $\underline{f}_y$, $g_{\underline{x}}$ and g_y are time varying matrices and are evaluated along the system trajectories; $\underline{x}_{\underline{x}_0}(t)$ and $y_{\underline{x}_0}(t)$ are the trajectory sensitivities.

Initial trajectory sensitivities can be computed from:

$$\underline{x}_{\underline{x}_0}(t) = \mathbf{I} \tag{10}$$

$$y_{\underline{x}_0}(t_0) = -\left[g_y(t_0)\right]^{-1} g_{\underline{x}}(t_0) \tag{11}$$

where $\mathbf{I}$ is the identity matrix. It is assumed that $g_y(t_0)$ is non-singular along the trajectories.

The trajectory sensitivities can be obtained by solving equations (8) and (9) simultaneously with (5) and (6) using (4), (10) and (11) as the initial conditions. The sensitivities can also be evaluated using a Taylor series expansion of the system flows (7).

If the trajectory sensitivities are known, the sensitivity of the system dynamic behaviour to small changes in the initial conditions and parameters can be evaluated from the following relation:

$$\Delta\phi(\underline{x}_0,t)=\begin{bmatrix}\Delta\underline{x}(t)\\ \Delta y(t)\end{bmatrix}=\begin{bmatrix}\underline{x}_{\underline{x}_0}(t)\\ y_{\underline{x}_0}(t)\end{bmatrix}\Delta\underline{x}_0 \qquad (12)$$

Trajectory sensitivities can be obtained as a by-product of implicit numerical integration techniques and require a little additional computational effort [19].

IV. ELECTRIC POWER SYSTEM

In Fig. 1 it is shown the BPA test power network that was used in this study. The simulations were carried out considering the network data presented in [8], [20]. It was simulated the tripping of one of the five 500 kV overhead transmission lines between busbars 6 and 7 at the time equal to 20 seconds. The operating point assumed in this study corresponds to a 6855 MW and 1046 MVAr load level.

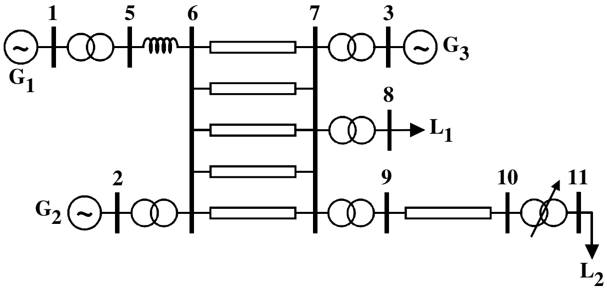

Fig. 1. BPA test power network single line diagram.

Two scenarios were analysed. In the first one (case I) the loads were assumed as constant impedance in busbar 11 and constant power in busbar 8. The second situation (case II) the load model in busbar 11 is similar to the previous one while in busbar 8 the load demand corresponds to 50 % of constant power and 50 % of induction motors. In both situations the Under Load Tap Changers (ULTC) regulation effect of the transformer connected between busbars 10 and 11 was taken into account considering a time delay and a deadband. Time delays for ULTC operations are assumed to be 30 seconds for the first tap movement and 5 seconds for subsequent tap movements and the load shedding was performed at the time equal to 110 seconds.

In every scenario it was analysed the overall system voltage stability. Generator G1 is considered as an infinite busbar, G2 and G3 are modelled in detail. The automatic voltage regulators of the generating units and the turbine speed governors were considered.

V. RESULTS

For a better understanding of the simulation results this section is organized as follows: part A is devoted to case I and part B shows the solutions produced in case II. In order to compare the results obtained by the developed formulation with the solutions produced with the time-domain simulation scheme it is presented the voltage variation curves and reactive power generation of G2 and G3 for the same scenarios.

A. Case I

The study of the trajectory sensitivity analysis was performed considering four values of load shedding at busbar 11 at the time equal to 110 seconds: 3.0 %, 3.5 %, 4.0 % and 4.5 %. Fig. 2 presents the voltage trajectory sensitivities in busbar 11 produced by the post-processing unit.

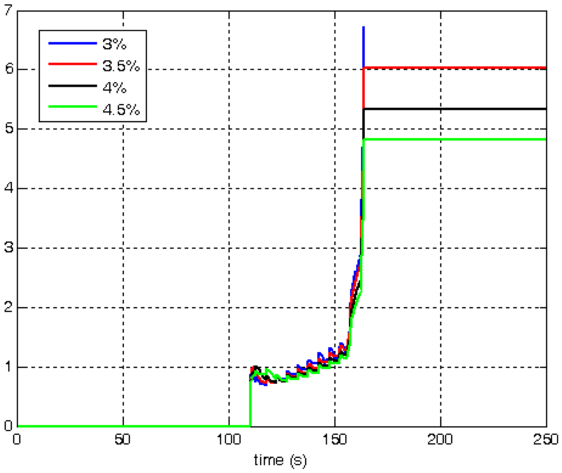

Fig. 2. Voltage trajectory sensitivities in busbar N11.

In Fig. 3 it is shown the voltage variation in busbar 11 for the different load shedding schemes. The simulation results were obtained using the EUROSTAG.

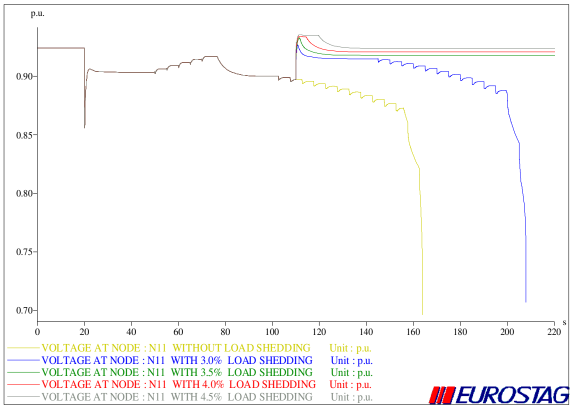

Fig. 3. Voltage variation in busbar 11.

In this case, from the sensitivity analysis presented in Fig. 2 it is shown that only for a load shedding of 3.0 % the system will experience a voltage collapse. A load shedding of 4.5 % allows restoring the voltage to its pre-fault value. The same conclusion can be extracted from Fig. 3, since the time domain results are in accordance with the solutions produced by the sensitivity analysis.

Fig. 4 and 6 present the reactive power generation trajectory sensitivities of G2 and G3 for the load shedding applied in the busbar 11, respectively. These curves were produced by the post-processing unit.

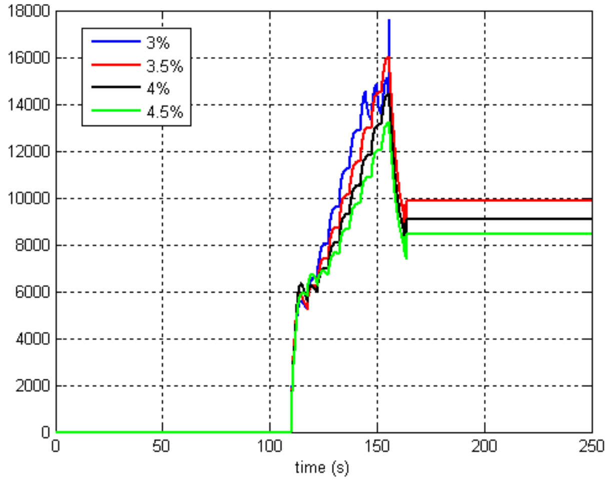

Fig. 4. Reactive power generation trajectory sensitivities of G2.

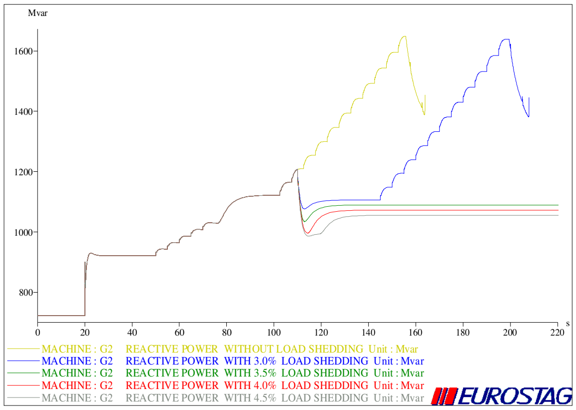

Fig. 5. Reactive power generation of G2.

Fig. 5 shows the reactive power generation of G2. The OvereXcitation Limiter (OXL) of G2 works only in two situations, without the load shedding and when 3.0 % of load shedding was applied. When there is no load shedding, the OXL acts more rapidly (150 s) than with 3.0 % load shedding (190 s). In both situations the OXL also contributes to the voltage instability in the system.

Fig. 7 presents the reactive power generation of G3. The OXL of G3 works in all situations, since this device works before the load shedding occurs.

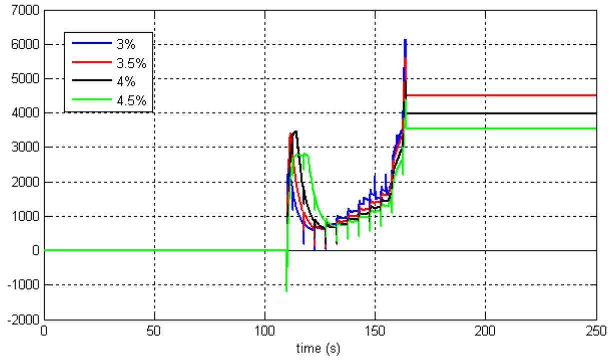

Fig. 6. Reactive power generation trajectory sensitivities of G3.

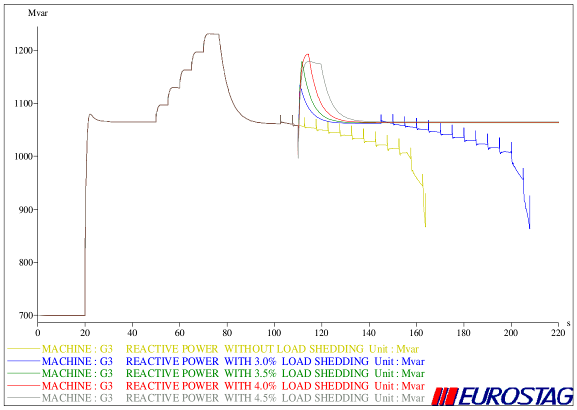

Fig. 7. Reactive power generation of G3.

B. Case II

The study of the trajectory sensitivity analysis was performed considering four values for the load shedding applied to the busbar 11: 3.0 %, 3.5 %, 4.0 % and 4.5 %. Fig. 8 presents the voltage trajectory sensitivities in busbar 11 produced by the post-processing unit.

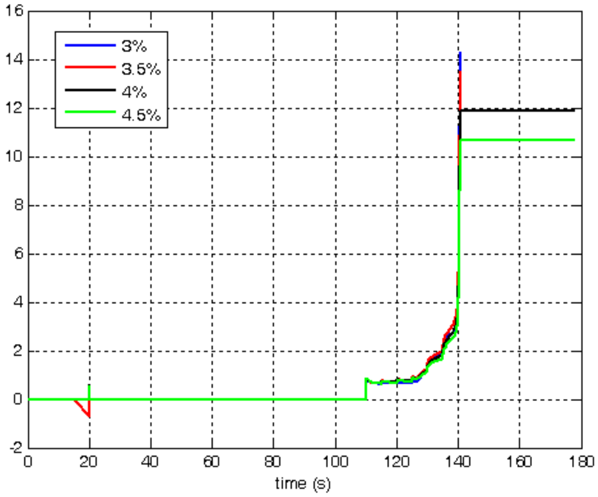

Fig. 8. Voltage trajectory sensitivities in busbar 11.

In this case, due to the induction motors connected to busbar 8 and in order to avoid voltage collapse the load shedding will be higher than in case I. Fig. 8 shows that for values of 3.0 % and 3.5 % of load shedding the system will face a voltage collapse situation. For the lowest sensitivity that corresponds to 4.5 % of load shedding the voltage will be closer to the pre-fault value.

In Fig. 9 it is shown the variation of the voltage in busbar 11 for the different values of load shedding. Fig. 10 and 12 present the reactive power generation trajectory sensitivities of G2 and G3 for different values of load shedding. These curves were obtained by the post-processing unit.

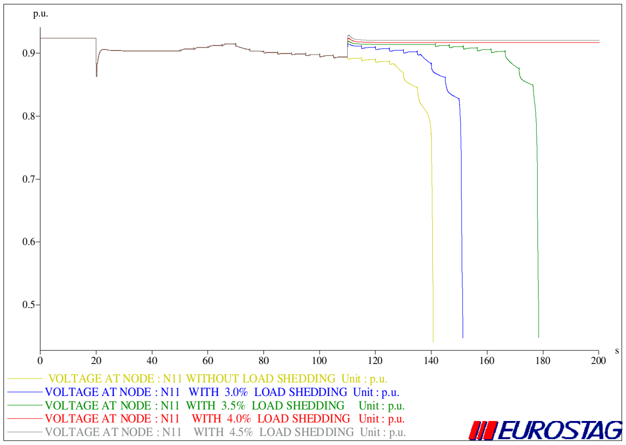

Fig. 9. Voltage variation in busbar 11.

In case I, without load shedding the system will experience a voltage collapse situation close to 165 s (Fig. 3), while in case II without load shedding the system will collapse near to 140 s (Fig. 9).

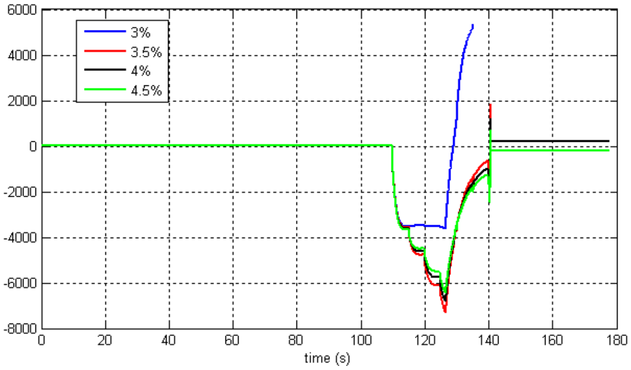

Fig. 10. Reactive power generation trajectory sensitivities of G2.

Fig. 11 shows the reactive power generation of G2. The OXL of G2 works limiting the production of reactive power. For values of 3.0 % and 3.5 % of load shedding the system will face a voltage collapse situation.

Fig. 13 presents the reactive power generation of G3. The OXL of G3 works in all situations, since this device works before the load shedding occurs.

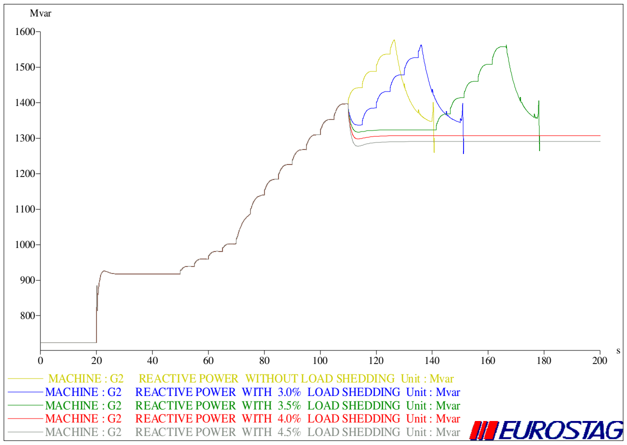

Fig. 11. Reactive power generation of G2.

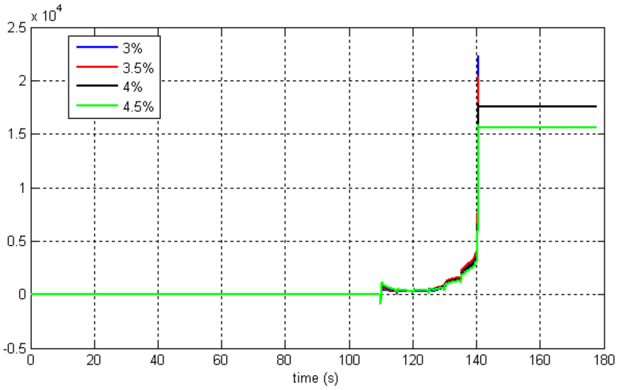

Fig. 12. Reactive power generation trajectory sensitivities of G3.

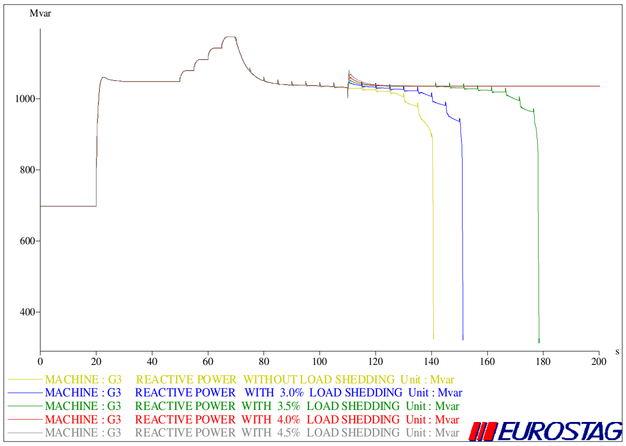

Fig. 13. Reactive power generation of G3.

In both cases, generator G3 is the one that produces more reactive power after the outage of one of the transmissions lines between busbars 6 and 7. This occurs due to the fact that G3 is closer to the loads. For this reason the OXL of the generator unit works, limiting the production of reactive power (77 s in case I and 70 s in case II). This occurs before the load shedding (110 s). When the OXL of G2 works the network collapses. The performance of the OXL will depend on the value of the load shedding, to values equal to or greater than 3.5 % for case I and values equal to or greater than 4.0 % in case II, the OXL of generator G2 does not work.

VI. CONCLUSIONS

This paper presents a study of the dynamic voltage stability of an electric power system using trajectory sensitivity analysis. Trajectory sensitivities were effectively obtained as a sub-product of simulating the nominal time-domain trajectory. These sensitivities offer a way of ranking the relative influence of system parameters.

In case I, the trajectory sensitivity analysis indicates that there is a collapse situation for load shedding of 3.0 % at busbar 11. For the other values of load shedding at busbar 11 the system remains stable. For the load shedding at busbar 11 of 3.5 % and 4.0 % the sensitivity values are higher than in the situation of 4.5 % of load shedding. This situation corresponds to the most stable scenario. The same conclusion can be drawn from observation of Fig. 3 where it is shown that the variation of the voltage on the busbar 11 for 4.5 % of load shedding is the most stable. In case II, trajectory sensitivity analysis proves that when the load shedding is 3.0 % and 3.5 % the system voltage collapses. However, only using a load shedding of 4.5 % (lower value of sensitivity) it is possible to restore the system stability closer to the initial voltage level.

From the results obtained it was proved that the developed technique is feasible and provides a deeper insight into the influence of parameters on system performance. The solutions obtained are in accordance with the results evaluated using the time domain simulation program. The accurate modeling of the OXL is an important factor in the simulation of voltage instability. The trajectory sensitivities of the system variables to different parameters can be used successfully to avoid the power system instability. Due to the output information supplied by the proposed approach it is possible to implement preventive control and corrective actions in order to avoid power system dynamic voltage instability.

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