STATCOM to improve the Voltage Stability of an Electric Power System using Trajectory Sensitivity Analysis

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Abstract- **The voltage stability security is a very important and relevant issue in the modern power networks. The voltage instability can drive the system to a blackout. One of the methodologies to deal with this problem is analysing the trajectory sensitivity of the system. The STATCOM is an important hardware that is used to improve the voltage stability of an electric power network. The main objective of this paper is to analyse the results of different studies that were realized in a power system with wind farms. The wind farms were modelled considering that the wind turbines were equipped with pitch control coupled with a Permanent Magnet Synchronous Generator. The EUROSTAG program was used to obtain the simulation results. The Matlab software package was used for the post-processing module developed.**

Index Terms-- **Electric power network, STATCOM, Trajectory sensitivity analysis, Voltage instability.**

I. INTRODUCTION

The voltage instability is nowadays of great concern for the systems operators as it is one of the main reasons of the electric network failures [1]. The voltage collapse is considered as a dynamic phenomenon, so one of the methods used to study this phenomenon is by the trajectory analyse of the system variables.

One of the main reasons for the voltage instability in a system is the deterioration of the operating conditions along the time, for example due to a rapid load raise or the occurrence of severe events, like line contingencies. Control actions in reactive compensation devices and in transformer tap changers should be carried out to avoid the voltage collapse of the system [2].

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 in voltage stability studies. Traditionally, the voltage stability studies were limited to the power flow based static methods, but today we know that only the dynamic stability studies permit to assess the system evolution in instability conditions [3].

Preventive and emergency control measures can be defined using the trajectory sensitivities analysis methodology. From its nominal trajectory is not possible to identify completely the behaviour of a dynamic system, reason why trajectory sensitivities are used to provide an insight into the behaviour of a dynamic system [4]. The computational cost to evaluate the sensitivities and disturbances in the trajectories is reduced. Recent applications use the capabilities of trajectory sensitivities for the stability assessment of power systems, mainly for post mortem analysis [5], [6], [7].

According to published studies, the stability margin decreases when the trajectory sensitivities undergo larger excursions [4]. For unstable situations, trajectory sensitivities increase much more rapidly than the nominal system trajectory. A fast increase in trajectory sensitivities is linked with an underlying stability problem, reason why sensitivities can be effectively used as an early indicator of imminent instability problem [8], [9], [10].

The influence of Static Synchronous Compensators (STATCOM) in the voltage stability of an electric power network using trajectory sensitivity approach is studied and discussed in this paper. Different values of capacities of STATCOM were used to avoid voltage collapse. The EUROSTAG [11] program and post-processing module developed using the Matlab software package were used to obtain the all simulation results.

The EUROSTAG is a very user-friendly software that enables design of a new graphic model and, in this way, avoids the risk of human error inherent to the transcription of block diagrams into computer code. The software offers a series of interactive graphic aids for analysis and presentation of results [12], [13].

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. An interpolation technique to have a uniform time step in all simulations was used to obtain the trajectory sensitivity solutions. It was developed a post processing unit that allows displaying and analysing the trajectory sensitivity results. The post processing unit is designed to take advantages of advanced user interface features of the Matlab environment. This unit enhances the user ability to analyse a large amount of output data and to produce visually appealing graphic representations of the results.

The paper organization is the following:

- Section II is devoted to the formulation of the problem using dynamic voltage stability assessment combined with a trajectory sensitivity approach.
- Section III describes the model of the STATCOM device used in this research work.
- Section IV is presented the test power network used in this study.
- Section V shows the results obtained using the proposed methodology.
- Section VI, some conclusions that provide a valuable contribution to the understanding of the dynamic voltage stability assessment of an electric power network are pointed out.

II. FORMULATION OF THE PROBLEM

The trajectory sensitivity approach can provide valuable insights into the voltage stability assessment of a power network that otherwise would not be fully clear from its nominal trajectory [5]. This methodology is mainly based upon linearizing the system around a nominal trajectory rather than around an equilibrium point [7].

The analysis of an electric power network security dynamics requires a computationally efficient, practical, non-restrictive, model formulation capable of capturing the full range of events. The systems dynamics can be analysed, taking into account the hybrid nature – combination of continuous and discrete dynamics – as a set of differential algebraic equations [6], [7]:

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

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

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: dynamic state variables, y : algebraic variables, λ : system parameters.

A switching occurs when $s(\underline{x}, y) = 0$. The initial conditions are given by:

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

The influence of small variations in the initial conditions and parameters can be assessed using the trajectory sensitivity approach in order to study the evolution of system variables [7]. If discontinuities are disregarded, the system dynamic variations are described by the differential algebraic equations:

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

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

The system flows can be obtained from:

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

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

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

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

with $\underline{f}_{\underline{x}}$, $\underline{f}_y$, $g_{\underline{x}}$, g_y: time varying matrices, evaluated along the system trajectories; $\underline{x}_{\underline{x}_0}(t)$, $y_{\underline{x}_0}(t)$: trajectory sensitivities. Trajectory sensitivities initial conditions can be computed from:

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

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

The term $g_y(t_0)$ is assumed to be nonsingular along the trajectories. The trajectory sensitivities are obtained solving (8) and (9) simultaneously, with (5) and (6) considering the relations (4), (10) and (11) as the initial conditions. A Taylor series expansion of the system flows (7) allows to evaluate the system sensitivities.

The system dynamic behaviour sensitivity due to small changes of the initial conditions can be numerically evaluated applying the following relation:

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

One of the great advantages of using trajectory sensitivities is that it can be obtained as a by-product of implicit numerical integration techniques and only requires a small additional computational effort [14].

III. STATCOM DEVICE DESCRIPTION

After a permanent fault occurred on a structure in the network (line, transformer) protective devices disconnect the structure in question in order to eliminate rapidly the fault. The loss of the faulty structure leads to a weakening of the network that generally results in a voltage drop at the load terminals in the zone affected by the fault [15]. The phenomenon is particularly visible on networks with low short-circuit power and a high proportion of industrial loads. A risk of localised drop in voltage then occurs. In this situation the STATCOM must maintain the voltage when the fault has been eliminated to eliminate the risk and enable the loads to be satisfactorily powered by injecting active energy and reactive energy simultaneously.

STATCOM measures the value of the voltage at the medium voltage or high voltage connection bus and modifies the reactive power supply to maintain the voltage at a given set point. When the voltage is lower than the rated voltage, STATCOM injects reactive power into the network. It absorbs reactive power when the voltage at the medium voltage or high voltage connection bus is greater than the rated voltage [12]. Figure 1 presents the STATCOM scheme that was used in this study.

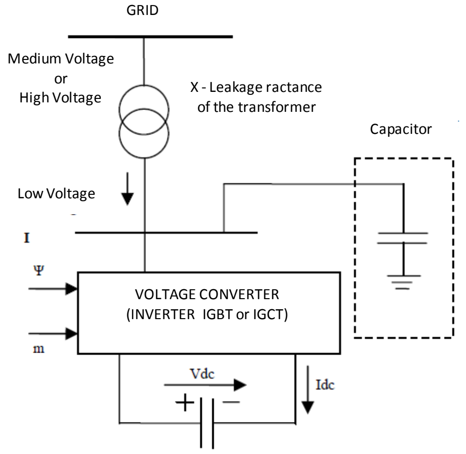

Figure 1. STATCOM scheme [12].

Power injections begin 20 ms after the fault. This time includes the time needed to detect the fault and check, over a given period (between 16 and 20 ms depending on the frequency of the network), that a fault has indeed occurred and that it is not simple an inaccurate measurement.

In addition to the injection of active and/or reactive power, the STATCOM control command, manages the connection and disconnection of the capacitor. The supply of reactive power from the capacitor, although essential in the event of a fault, becomes superfluous when the voltage regains an acceptable value. If the capacitor remains connected under these circumstances, the reactive power supply increases the voltage that forces the STATCOM to absorb the excess reactive power. This situation presents several drawbacks, particularly if it sends strong currents through the STATCOM that may result in losses, heating and wear of the components (this operating mode is rare, however, possible). Connecting the capacitor to the network only when required implies that the STATCOM neither supplies nor absorbs reactive power in fault-free mode. Management of the connection and disconnection of the capacitor, associated with the STATCOM, is given in detail in Figure 2.

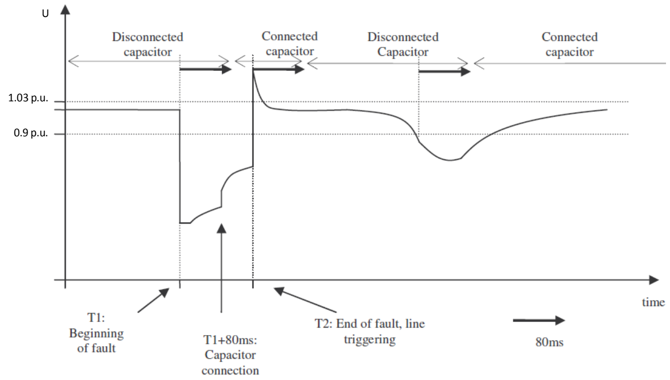

Figure 2. Management of the capacitor of the STATCOM [12].

The control command of the STATCOM controls the connection and disconnection of the associated capacitor. To simplify matters, the voltage on the medium voltage or high voltage network, referred as U, is expressed in per-unit (p.u.), i.e. standardized in relation to the associated rated voltage (1 p.u. = U_n).

T1: beginning of fault.

T1+20 ms: beginning of STATCOM participation, order to connect the capacitor.

T1+80 ms: effective connection of the capacitor (time 60 ms depending on the circuit breaker technology) after the fault has been eliminated and hysteresis cycle occurs. The capacitor connects if the voltage drops below 0.9 p.u. and disconnects if the voltage at the medium voltage or high voltage connection node of STACOM returns to above 1.03 p.u. Each connection or disconnection takes 80 ms, between exceeding the threshold and the effective connection or disconnection: 20 ms to ensure the voltage remains above the threshold and 60 ms to perform the operation.

T2: end of fault (opening of the line), the voltage exceeds 1.03 p.u.

T2+20 ms: the STATCOM order to disconnect the capacitor.

T2+80 ms: disconnection of the capacitor.

T3: voltage drops below 0.9 p.u.

T3+20 ms: the STATCOM order to connect the capacitor.

T3+80 ms: connection of the capacitor.

IV. TEST POWER NETORK

In Figure 3, it is shown the single line diagram of the electric power network that was used in this study. The simulations were carried out considering the network data presented in [13], [16].

Generator G2 is considered as an infinite bus. The Automatic Voltage Regulators (AVR) and OvereXcitacion Limiter (OXL) of the generating units and the turbine speed governors were taken into account. The Load Tap Changers (LTC) actions of the power transformer between buses N3 and N4 (380/150 kV) are represented considering a time delay and a dead-band. Time delays for LTC operations were assumed to be 30 s for the first tap movement and 5 s for subsequent tap movements.

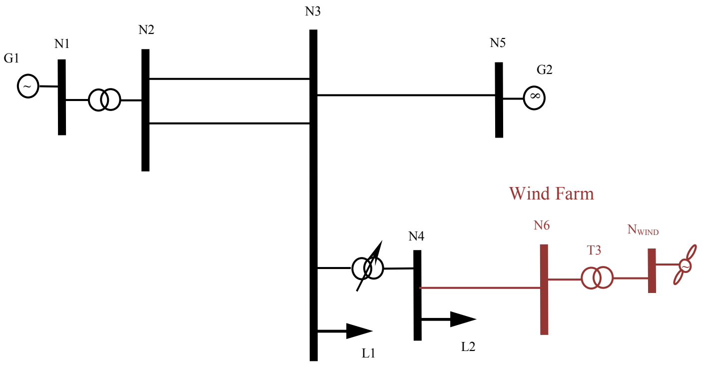

Figure 3. Single line diagram of the power network.

In this study, the operating point assumed corresponds to a load level of 1710 MW and 845 Mvar. In bus N3 it is assumed a load level of 710 MW and 545 Mvar whereas in bus N4 the active power load is 1000 MW and reactive power load is 300 Mvar. In bus N4 the load was assumed as constant impedance and in bus N3 was assumed as constant power. The wind farm is connected at bus N6 by a transformer T3 150/0.69 kV.

Table I presents the parameters of the STATCOM model used in this study with values of 1.5%, 3%, 10%, 20%, 40% and 60%.

TABLE I. PARAMETERS OF THE STATCOM MODEL.

Parameters		**Values**					
		1,5 %	3 %	10 %	20 %	40 %	60 %
BNON	Additional capacitor (p.u.)	0.015	0,03	0,1	0,2	0,4	0,6
C	Internal capacitor (p.u.)	0,000054	0,000054	0,000054	0,000054	0,000054	0,000054
CAPAD	Use of additional capacitor (1: used; -1 out of order)	1	1	1	1	1	1
DECL	Coefficient to determine whether fault	0,98	0,98	0,98	0,98	0,98	0,98
IMAX	Rated power of the STATCOM (p.u.)	0.015	0,03	0,1	0,2	0,4	0,6
IPMAX	Maximum possible active power (p.u.)	0,037	0,037	0,037	0,037	0,037	0,037
ISMAX	Maximum coil current (p.u.)	0,0125	0,0125	0,0125	0,0125	0,0125	0,0125
ISMIN	Minimum coil current (p.u.)	0,00399	0,00399	0,00399	0,00399	0,00399	0,00399
ISREF	Recommended coil current (p.u.)	0,010226	0,010226	0,010226	0,010226	0,010226	0,010226
K	Inverter internal coefficient	0,225	0,225	0,225	0,225	0,225	0,225
K2	Active power error integrator coefficient	-200	-200	-200	-200	-200	-200
K3	Coefficient of the time constant on the DC voltage error	160	160	160	160	160	160
KOND	Inverter overload coefficient	2,3	2,3	2,3	2,3	2,3	2,3
KP	Coefficient of the error integrator on the network voltage	80	80	80	80	80	80
L	Coil inductance (p.u.)	347,22	347,22	347,22	347,22	347,22	347,22
PINIT	Initial active power setpoint (p.u)	0,037	0,037	0,037	0,037	0,037	0,037
RMAX	Max. limit of the DC voltage regulation (p.u.)	1	1	1	1	1	1
RMIN	Min. limit of the DC voltage regulation (p.u.)	-1	-1	-1	-1	-1	-1
SEUILB	Network voltage threshold under which reactive power is not injected (p.u)	0,1	0,1	0,1	0,1	0,1	0,1
VDCREF	DC voltage setpoint (p.u.)	6,25	6,25	6,25	6,25	6,25	6,25
XIND	Transformer short-circuit reactance (p.u.)	4	2	0,6	0,3	0,15	0,1

The wind farm has 80 wind turbines each with 2.0 MVA and is represented by an aggregated equivalent model. The wind farm was modelled considering that the wind turbines were equipped with pitch control coupled with a Permanent Magnet Synchronous Generator and STATCOM of 100 Mvar (correspond to 100%).

In this study the following events were simulated:

- an increase of the wind speed from 8.45 to 12.45 m/s, from 20 s to 40 s;
- the tripping of the 380 kV overhead transmission line between buses N3 and N5 at 50 s.

The study of the trajectory sensitivity analysis was performed considering six values of capacities of STATCOM applied in the bus N6 where is connected the wind farm: 1.5%, 3%, 10%, 20%, 40% and 60%.

V. RESULTS AND DISCUSSION

Figure 4 presents, the reactive power injection of the STATCOM in the bus N6, for the different percentage values of capacities of STATCOM. The simulation results were obtained using the EUROSTAG.

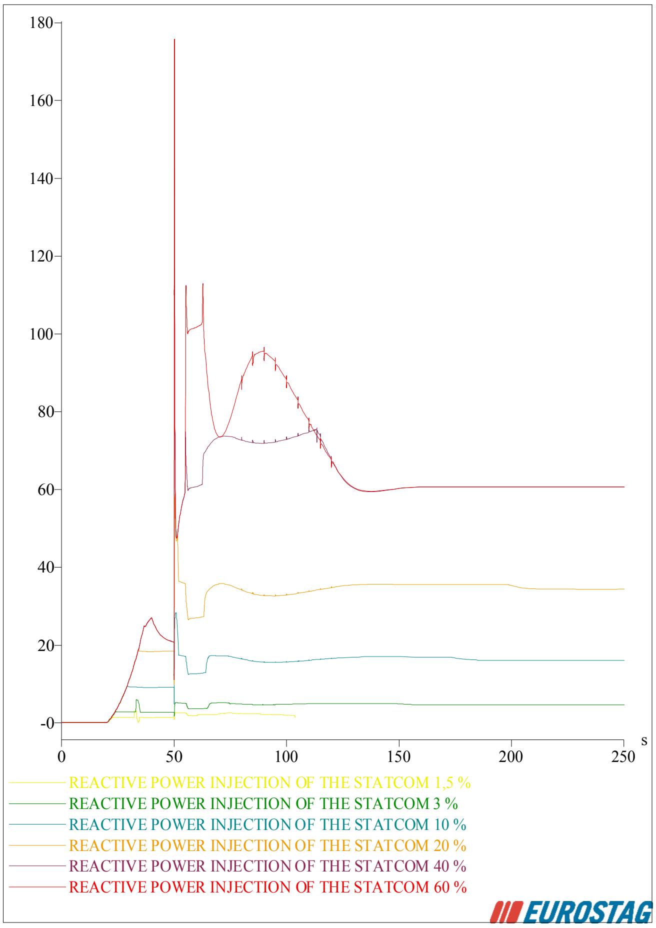

Figure 4. Reactive power injection of the STATCOM in bus N6.

The STATCOM is capable to supply reactive power even if the voltage at the bus is very low. With its reactive energy supply, the STATCOM stabilizes the voltage.

In Figure 5 it is shown the reactive power injection of the STATCOM and the variation the voltage in bus N6 where is connected the wind farm, for the different percentage values of STATCOM. The simulation results were obtained using the EUROSTAG.

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. An interpolation technique to have a uniform time step in all simulations was used to obtain the trajectory sensitivity solutions. It was developed a post processing unit that allows displaying and analysing the trajectory sensitivity results.

Figure 6 presents the voltage trajectory sensitivities for the different values of capacities of STATCOM produced by the post processing unit.

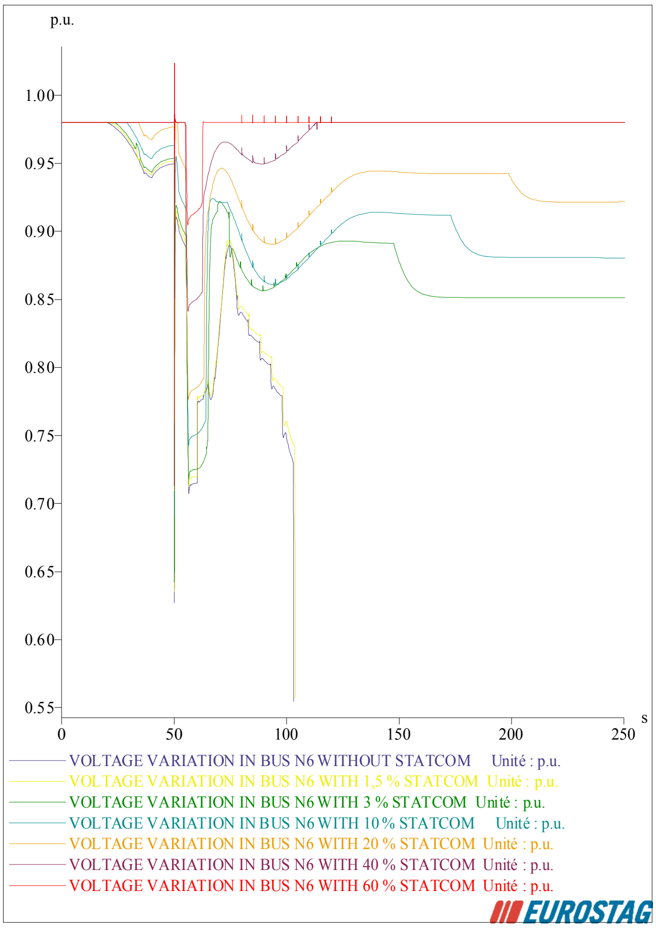

Figure 5. Voltage variation in bus N6.

As can be seen in Figures 5 and 6, the curves of 3%, 10%, 20%, 40% and 60% of STATCOM are curves that stabilize. However, the curves of 3% and 10% after stabilizing present values unacceptable for the system. The 1.5% curve corresponds to a situation of system voltage collapse (worst case scenario).

Figure 6 shows that the lower the amplitude of the sensitivity factor, the better the conditions with respect to the voltage stability. On the other hand, the critical or potential critical trajectory sensitivities undergo a jump allowing to detect voltage stability problems.

From the studies performed it is verified that all situations where the amplitude of the sensitivity factor is higher than 5 can be classified as not meeting the predefined values as acceptable for the voltage. This value can be considered as a threshold point of the system sensitivity analysis. The system stable situations tend to have a flat trajectory regardless the voltage variations.

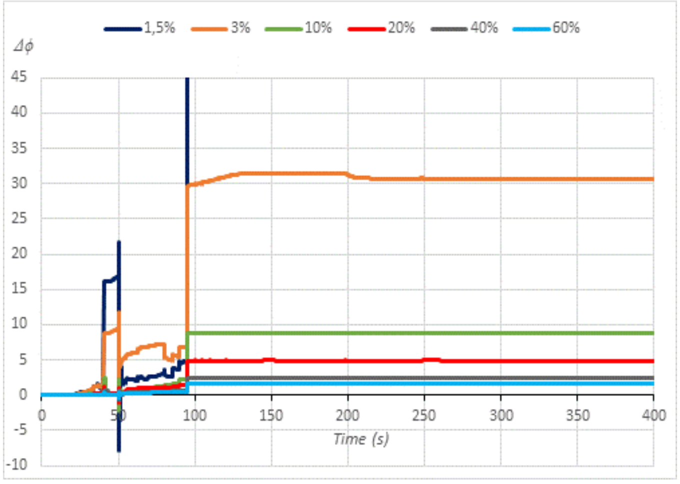

Figure 6. Voltage in bus N6 trajectory sensitivities.

VI. CONCLUSION

The main objective of the research work that is described in this paper was to analyse the effect of the STATCOM to increase the quality of the electric power system after the occurrence of severe contingencies and to show that the trajectory sensitivities of the system variables to different parameters can be used successfully to predict the power system instability.

The conductive idea of the investigation was to study the relation between the trajectory sensitivities and the system instability. The main conclusion of the work described is that the sensitivities are an efficient way to rank the relative system parameters for the system instability.

The results obtained in the test system used to validate the model, demonstrate that solutions are in a close agreement with the results obtained using the time domain simulation program.

Nowadays, the importance of wind farms is obviously so, in the test system used, a wind farm was considered. The wind farm was modelled considering that the wind turbines were equipped with pitch control coupled with a Permanent Magnet Synchronous Generator.

Of the work done, it is clear that is possible to predict the power system instability using the trajectory sensitivities of the system variables to different parameters. It is also possible to implement preventive control and corrective actions in order to avoid power system dynamic voltage instability using the output information obtained by the proposed approach.

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BIOGRAPHIES

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