Impact of the ULTC on the Dynamic Voltage Collapse of an Electric Power System with Large Scale of Wind Generation

R. M. Monteiro Pereira
IPC/Instituto Superior Engenharia de Coimbra, Portugal
rmfm@isec.pt

C. M. Machado Ferreira
IPC/Instituto Superior Engenharia de Coimbra and INESC Coimbra, Portugal
cmacfer@isec.pt

F. P. Maciel Barbosa
Faculdade Engenharia da Universidade do Porto and INESC TEC Porto, Portugal
fmb@fe.up.pt

***Abstract*-Voltage stability is predominantly a load stability phenomenon and solutions to voltage stability can be found by control of the load as seen from the bulk power network. A delay of the load restoration gives time for other corrective actions. The load restoration may be delayed and/or limited by certain countermeasures, such as blocking of Under Load Tap Changers (ULTC). In this paper it was studied the impact of the ULTC on the dynamic voltage collapse of an electric power system with large scale of wind generation. It is used the Cigré Electric Power Network with 32 bus and three wind farms equipped with wind turbines including pitch control coupled with a Fixed Speed Induction Generator (FSIG) and a shunt capacitor bank. The automatic voltage regulators (AVR) of the generating units and the turbine speed governors were modelled. Different load models were used and the ULTC were taken into account. Several significant disturbances were simulated in the test power network, such as the increase of the wind speed, the tripping of an overhead transmission line and three-phase short-circuits. The simulation results were obtained using the EUROSTAG software package. Finally, some conclusions that provide a better understanding of the ULTC effect on the dynamic voltage stability in a system with a large amount of wind power generation are pointed out.**

***Index Terms*--Load model, Under load tap changers, Voltage collapse, Wind farm, Wind generation.**

I. INTRODUCTION

The voltage collapse normally involves large disturbances. The most important evidences of voltage collapse are unacceptable voltage profiles, heavy reactive power flows in transmission lines, insufficient reactive support and heavily loaded systems [1]. The consequences of a voltage collapse often require long system restoration, while large groups of customers are left without supply for extended periods of time. The practical importance of dynamic voltage stability analysis is the help in designing and selecting countermeasures in order to avoid voltage collapse and enhance system stability. Corrective schemes that mitigate voltage collapse problems need to use the symptoms to diagnose the approach of the collapse in time to initiate corrective actions, such as load shedding and blocking of tap changers [2].

ULTC are a contributing element to voltage instability although it is also a possible solution for this problem. ULTC restore customer voltage profiles following contingencies and thereby increase load on a weakened system. If ULTC can be blocked so that customer voltages remain low, or are not fully restored, following a voltage disturbance, the load relief provided may help avoid collapse or reduce the investment in reactive sources to avoid voltage collapse [3]. The simplest method to eliminate the ULTC as a contributor to voltage collapse is to block the control's automatic raise operation during any period, where voltage collapse appears to be of concern [4]. However, this action may result in a period of low voltage profile on the affected loads. The effect of the reduced supply voltages on power quality to customers in the whole service area must be weighed against the possible alternative of complete disconnection of some customers in a smaller area [5].

The benefit of limiting ULTC response to voltage disturbances depends on load characteristics. Constant power loads are independent of voltage, while for the more frequent case, the real power loads have some voltage dependency. Limiting ULTC response to voltage stability problems at least slows the restoration of load, and where the load is permanently sensitive to voltage, provides a long term reduction in load. Nevertheless, the ULTC can be used to reduce the severity of the voltage collapse, if appropriate control measures are implemented [6].

II. ULTC MODEL

An under load tap changer controller is a device designed to change the taps on an ULTC transformer. The ULTC is an important power network voltage regulation device that automatically adjusts its transformation ratio in order to keep the load side voltage profile within an acceptable range. The regulator of the tap changer usually tries to minimize the number, or frequency, of tap changes in order to prolong the life of the tap changer [7].

A. Automatic voltage or active flow regulation

The node voltage or the transformer active flow in the positive sequence to be changed with any compounding necessary is compared with a voltage set point or flow V_C. When the voltage difference is outside a pre-defined insensitivity zone, the tap change is delayed for a time T_1. If after the tap change, the voltage or flow difference is still outside the defined dead band, change of a new tap is delayed for time $T_{INT} < T_1$. Voltage regulation may be remote, flow regulation is always local [8].

- The voltage V in the positive sequence on the changed node, is calculated by the formula:

$$V = \sqrt{|U|^2 + R^2 |I|^2 + 2|U||R||I|\cos\varphi} \qquad (1)$$

where:

$U = U_R + jU_I$ − Voltage in the positive sequence on controlled node;

$I = I_R + jI_I$ − Current in the positive sequence flowing through the transformer;

$\varphi = \text{arctg}(I_I / I_R) - \text{arctg}(U_I / U_R)$ − Phase differences between current and voltage in the positive sequence;

R − compounding factor, compounding is allowed only for 2 winding transformer when the changed voltage is either at sending node or at receiving node. Otherwise, compounding is not taken into account, especially for the 3 winding transformers.

- The flow in the positive sequence is calculated at a given end of the transformer (option available only for two-winding transformers).
  The voltage or flow difference $DV = V - V_C$ should be between $\pm E_1$.
  If it is no, the following process is applied:
  1. When the difference DV is under threshold $-E_1$ or over threshold $+E_1$, a counter C_1 is set.
  2. If the voltage or flow difference after being under $-E_1$ rises to a value of over $-E_2$ or if the voltage or flow difference after being over $+E_1$ drops back to a value under $+E_2$, counter C_1 is cleared $(E_2 < E_1)$.
  3. If counter C_1 remains set for T_1 seconds, there is:
     - transmission of an order to reduce or increase a transformer tap on the basis of the value of *ISENS*. This tap change is performed within the temporal margin *"Margin"* (remembering that if *t* is the event order issue time, it is actually performed between times *t* and *t* + *Margin*);
     - tap changer is disabled for T_{INT} seconds.
  4. When the disable time is reached, the controller tests the voltage again:
     - if the voltage or flow difference is still under $-E_2$ or over $+E_2$, the counter C_1 is still set and the controller issues a new order to change a transformer tap. The change is effective at T_{INT} seconds after the previous one;
     - if the voltage or flow difference becomes over $-E_2$ or under $+E_2$, the counter C_1 is unset and the operating cycle recommences at point 1.

The transformer ratio variation direction with respect to the tap change direction must be specified by the user in order to obtain a stable control:

- *ISENS* = 1 if the regulated voltage or flow increases;
- *ISENS* = −1 if the regulated voltage or flow is reduced.

The temporal margin *"Margin"* is used to synchronize the events produced by several automatic devices of this type.

B. *Automatic blocking on voltage criterion*

If the voltage V at the controlled node drops below a given value V_1, a counter C_3 is set. When the voltage increases over a value V_2 where $(V_2 > V_1)$, this C_3 counter is instantly cleared. If C_3 remains set for T_{V1} seconds, an "under load tap changer blocking" order blocks the under load tap changer after T_{DEL} seconds (transmission time modelling). The blocking is always on the active tap. Fig. 1 presents the diagram of automatic blocking on voltage criterion [8].

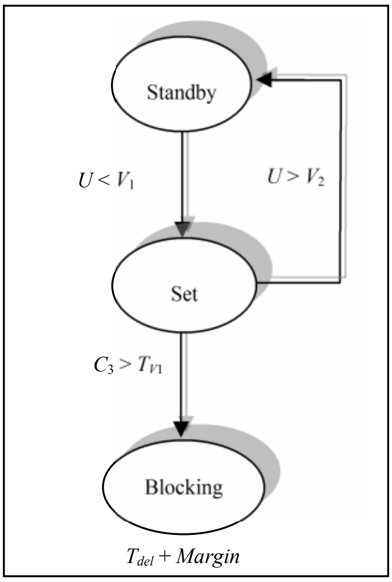

Fig. 1. Diagram of automatic blocking on voltage criterion.

III. Case Studies

In fig. 2, it is shown the modified Cigré Electric Power Network with 32 buses that was used in this study [9], [10]. The external system is simulated by means of three 380 kV infinite buses (N12, N15 and N16). Connected at this voltage level there are two important power stations, N1 and N10 (M1 and M2 with a rated power of 2000 MVA and M6 with 5000 MVA). The total power generated at the 380 kV is 7000 MVA.

Three wind farms with 318 MVA each are connected respectively at buses N101, N103 and N105. The total generation at 150 kV level is 954 MVA (wind farm 1, wind farm 2, wind farm 3). Approximately 12% of the energy produced are from wind turbines.

The total load of the system is 5000 MW and is mainly located at the sub transmission level (70 kV). The 70 kV loads are a mix of induction motor loads, constant impedance loads and compensation capacitors. The other loads were modelled as constant impedance type. The generators were modelled in detail.

The AVR of the generating units and the turbine speed governors were taken into account in the study. The 380/150 kV transformers have remote controlled taps. The 150/70 kV distribution transformers are fitted with automatic tap-changers regulating on the low voltage side. In this study the out-of-step and under voltage relays protecting the generating units were modelled.

The three wind farms are connected to the grid by a three winding transformer 150/0.69/0.69 kV. In this study simulations the wind farms are represented as an aggregated equivalent model. the three wind farms were modelled considering that the wind turbines were equipped with pitch control coupled with a Fixed Speed Induction Generator (FSIG) and a shunt capacitor bank.

The FSIG consists of a squirrel cage induction machine where the blades of the turbine are coupled directly to the induction generator through a gearbox. The stator of the generator is connected to the electric power grid while the rotor is short-circuited. The speed of the turbine rotor is changed with a gearbox. The squirrel cage induction generator uses the reactive power for generating the magnetizing current. It is excited by the grid and consumes reactive power. For this reasons in this case, shunt capacitors bank are connected at the terminals of induction generators to provide the reactive power.

Two scenarios were analysed. In the first one (case I) the seven distribution transformers (150/70 kV) are equipped with automatic tap-changers regulating on the low voltage side and are represented considering a time delay and a deadband. Time delays for ULTC operations are assumed to be 30 seconds (T_1) for the first tap movement and 5 seconds (T_{INT}) for subsequent tap movements. In the second situation (case II) the controller of the seven distribution transformers (150/70 kV) are blocked automatically if the voltage remains lower than 0.95 p.u. (V_1) for at least 60 seconds (T_{VI}). The automatic blocking system operates with a transmission delay of 1.0 second (T_{DEL}). In the two cases the following events were simulated:

- an increase of the wind speed from 7 to 25 m/s, from 20 seconds to 90 seconds;
- a contingency occurs at the 100 seconds and M2 trips;
- a three-phase fault occurs in the bus N101 at 300 seconds;
- at 300.2 seconds the three-phase short-circuit is remove;
- the tripping of the 380 kV overhead transmission line between buses N3 and N16 at 400 seconds.

IV. Results

For a better understanding of the obtained simulation results, this section is organized as follows: part A is devoted to case I, part B is dedicated to case II and in part C some of the results obtained in the previous cases were compared in order to show the influence of the ULTC on the dynamic voltage stability of the system.

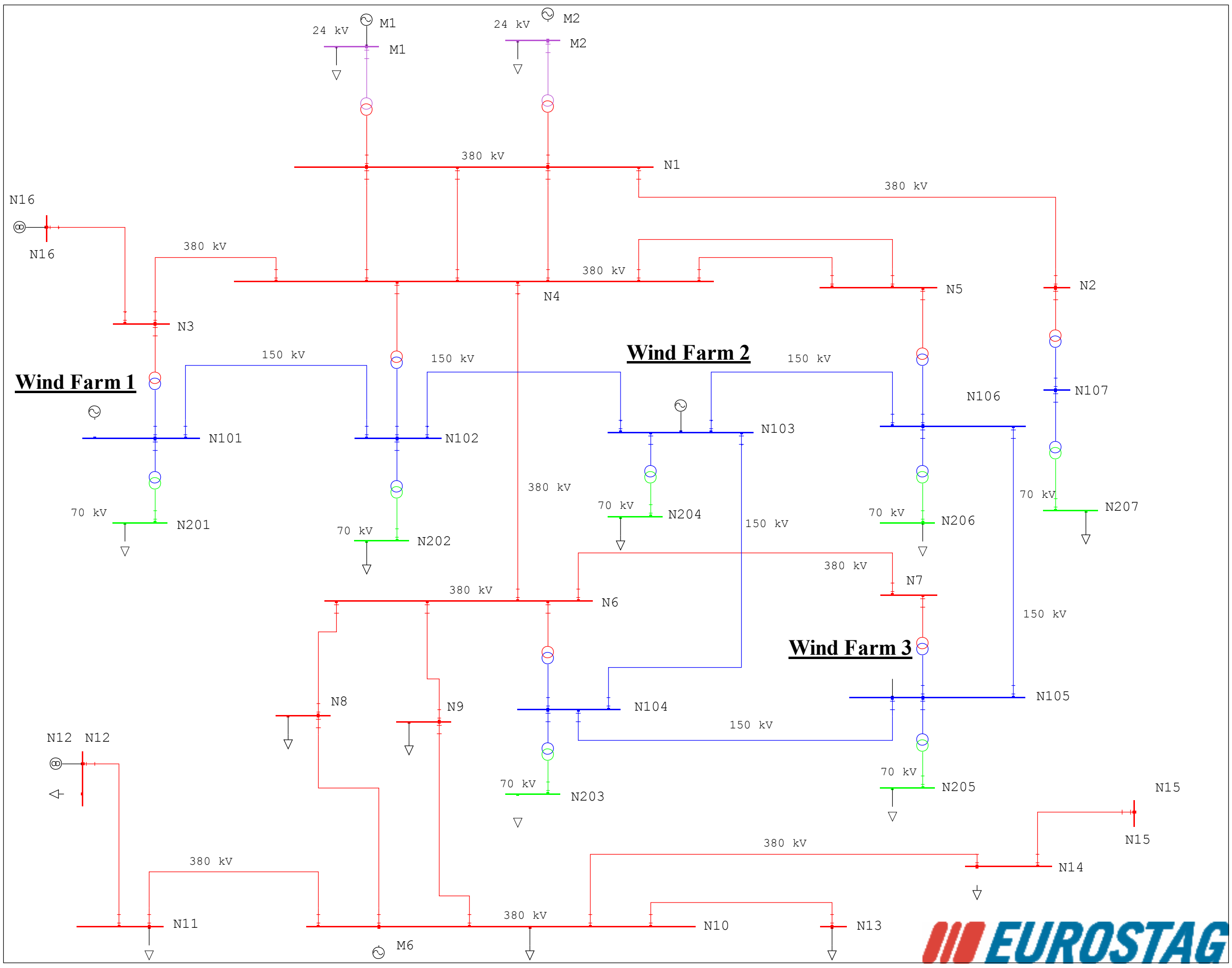

Fig. 2. Cigré test power network single line diagram [8], [9].

Part A- case I

In fig. 3 it is shown the field currents of M1, M2 and M6. After unit M2 tripping at 100 s, since M1 is closer to M2, it produces more reactive power. The OvereXcitation Limiter (OXL) of M1 operates and the field current changes to its maximum value of 3 p.u., at 117 seconds. The minimum voltage relay trips (approximately at 574 seconds) when the M1 terminal voltage decay abruptly.

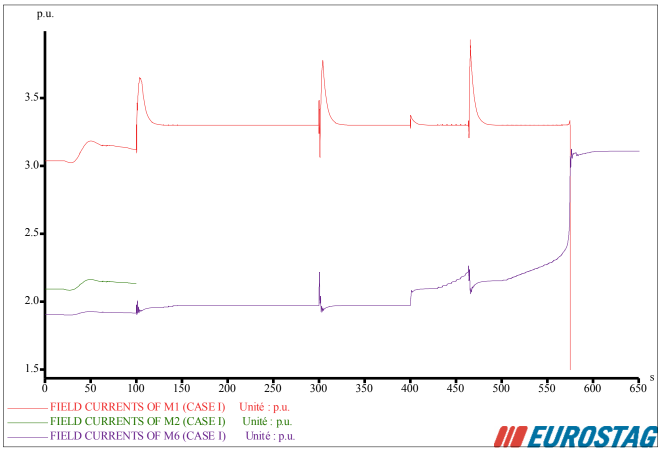

Fig. 3. Field currents of M1, M2 and M6.

Fig. 4 and fig. 5 present, respectively the reactive power injection of the shunt capacitor bank and reactive power consumed by the FSIG for the three wind farms.

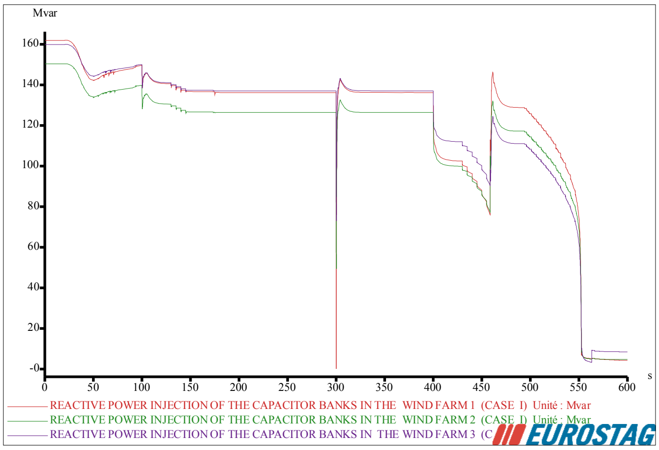

Fig. 4. Reactive power injection of the shunt capacitor bank.

The FSIG wind turbine using a squirrel-cage induction generator, usually have the ability to withstand high currents during a voltage dip, due to its high thermal capacity. In this situation, the magnetization must be fast enough in order to prevent the overspeed protection tripping. These machines do not possess the ability to participate in voltage regulation, on the contrary, this type of machines consume reactive power, which can lead to a voltage collapse situation as shown in this case. The capacitors banks connected in parallel are not effective to prevent the voltage collapse, since the reactive power production diminishes with the terminals voltage decreasing.

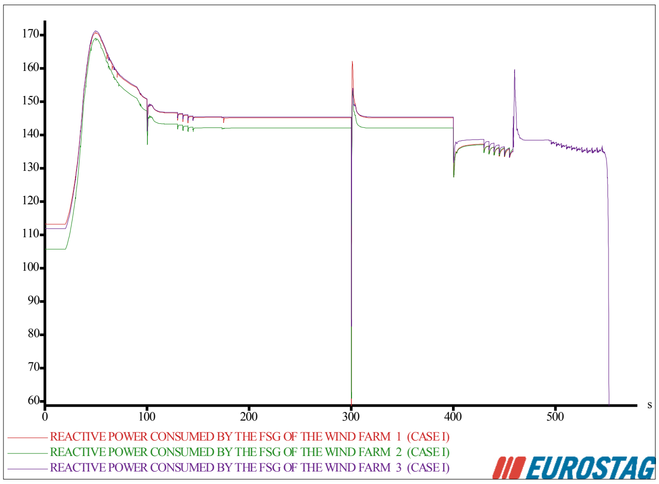

Fig. 5. Reactive power consumed by the FSIG for the three wind farms.

Fig. 6 presents the changes in the transformers taps of the seven distribution transformers (150/70 kV).

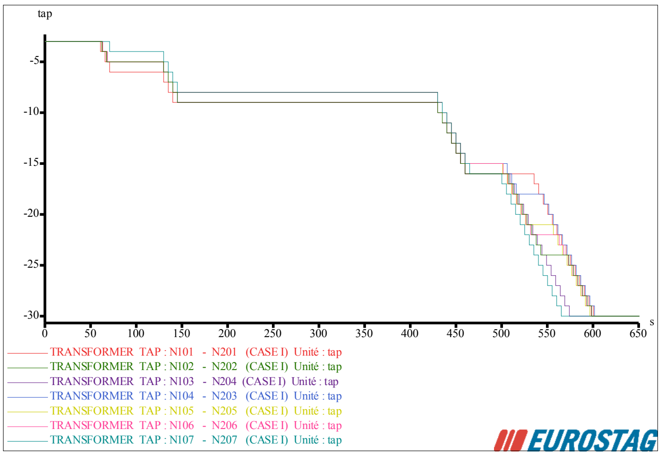

Fig. 6. ULTC position of the 7 (150/70 kV) distribution transformers.

Part B- case II

In fig. 7 it is shown the field currents of M1, M2 and M6. In this case, M1 remains in service, since the minimum voltage relay does not trip.

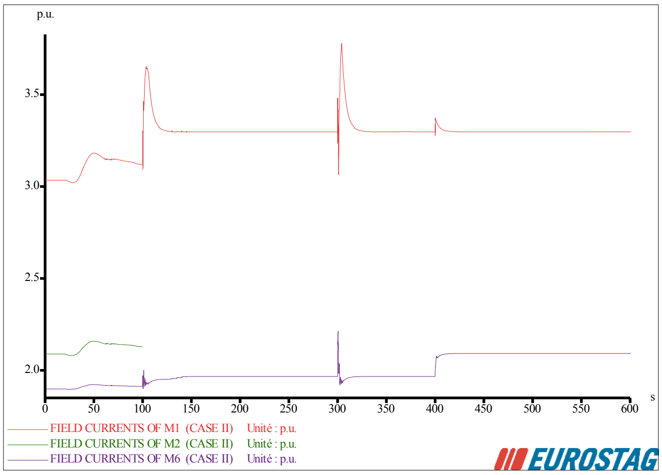

Fig. 7. Field currents of M1, M2 and M6.

Fig. 8 and fig. 9 present, respectively, the reactive power injection of the shunt capacitor bank and reactive power consumed by the FSIG for the wind farms.

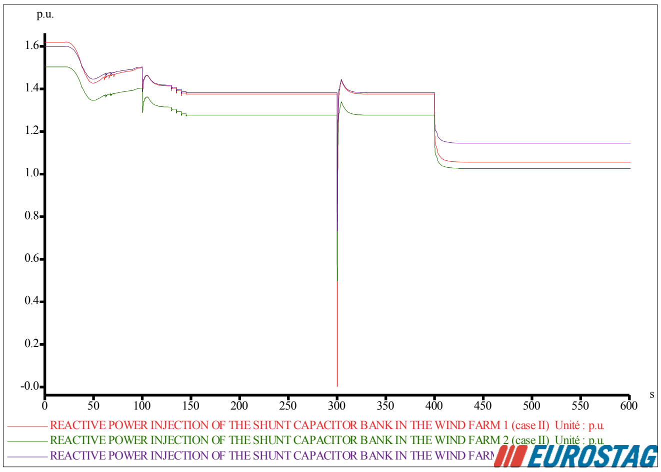

Fig. 8. Reactive power injection of the shunt capacitor bank.

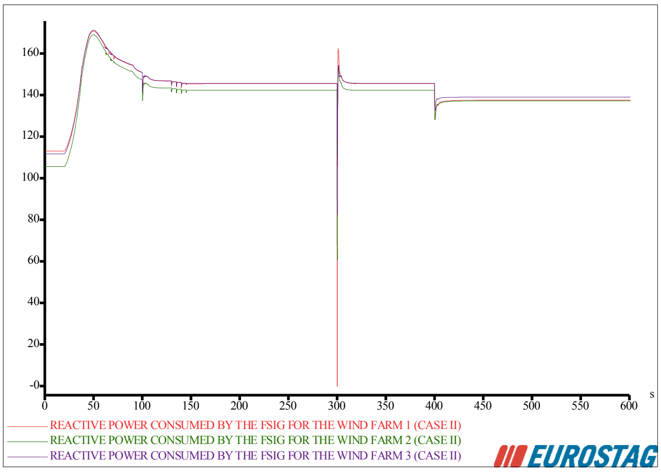

Fig. 9. Reactive power consumed by the FSIG for the three wind farms.

Fig. 10 presents the changes in the transformers taps of the seven distribution transformers (150/70 kV).

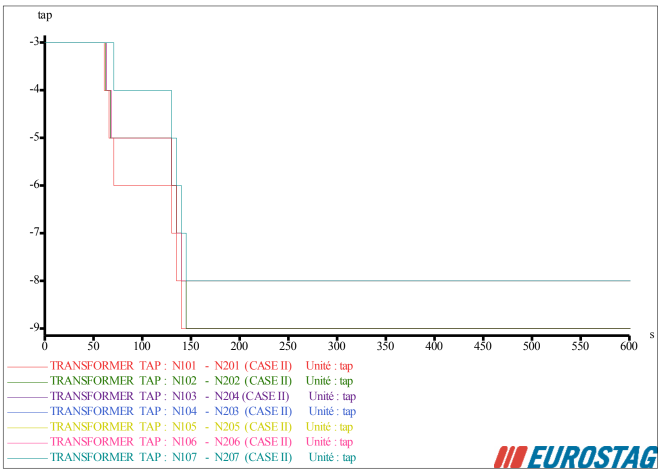

Fig. 10. ULTC position of the 7 (150/70 kV) distribution transformers.

Part C- case I and case II

For the voltage stability studies, the voltage variation in buses N105 and N205 were chosen to exemplify the system trajectory, since the voltages at the other buses have a similar behaviour. Figs. 11 and 12 present the voltage variation at bus N105 and N205 respectively, for case I and Case II.

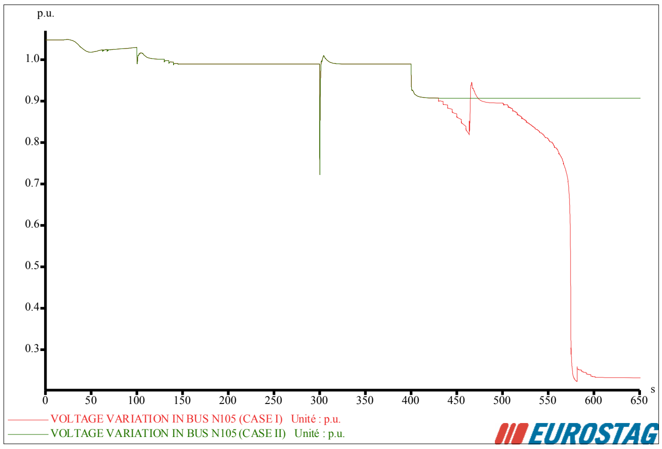

Fig. 11. Voltage variation in bus N105.

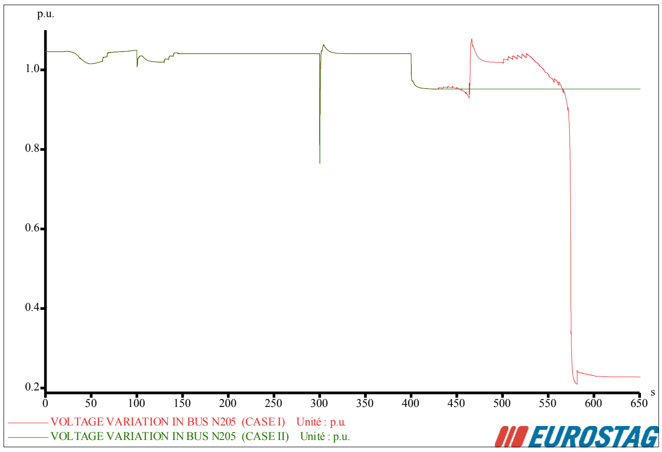

Fig. 12. Voltage variation in bus N205.

Fig. 13 and fig. 14 present, respectively, the variation of the active and reactive power load in bus N205.

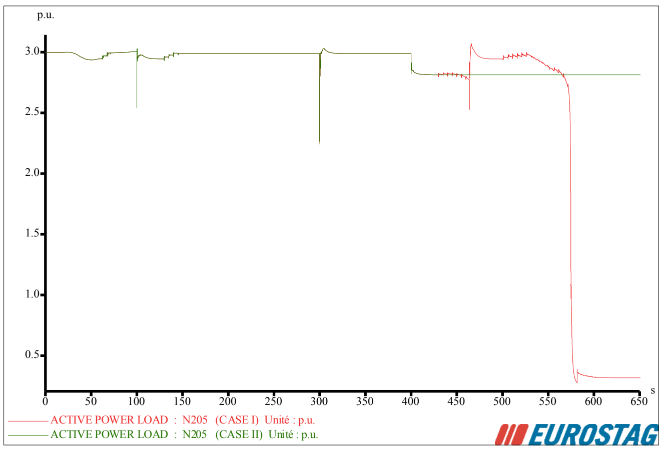

Fig. 13. Variation of the active power load in bus N205.

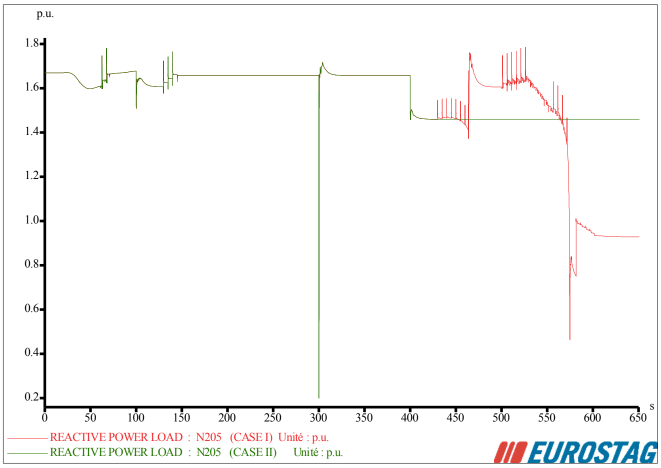

Fig. 14. Variation of the reactive power load in bus N205.

As it is shown in fig. 13 and 14 the fact that the ULTC is active (case I) and the voltage swell on bus N205 increases the active and reactive load power consumption. In case II the ULTC was blocked and the active and reactive load power consumption hold their values.

Fig. 15 presents the changes in the transformer taps, corresponding to the power device connected between buses N105 and N205.

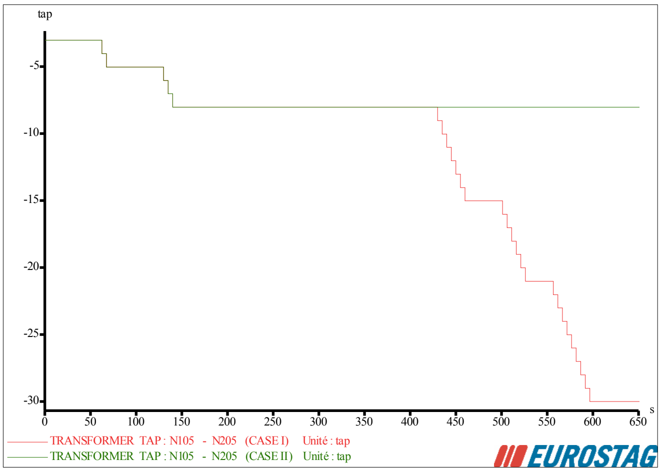

Fig. 15. ULTC position.

V. Conclusion

This paper presents a study of the impact of the ULTC on the dynamic voltage collapse of an electric power system with large scale of wind generation. In order to assess the power network voltage stability it was simulated severe contingencies in different locations.

The ULTC act on the ratios of distribution transformers to control the voltages at the load side. More precisely, each ULTC aims at keeping the load voltage inside a dead band around the nominal value. As a result, after grid faults, ULTC restore the power of the voltage dependent loads to their pre-contingency values. This behaviour is advantageous for customers under normal operating conditions, but when facing severe contingency the ULTC action may lead to voltage instability and voltage collapse.

In this study tap blocking is used as action aimed at counteracting long-term voltage instability in the presence of distribution loads modelled with a mix of induction motor loads and constant impedance loads (these loads are voltage sensitive). This control is an indirect way for reducing load through reduced distribution side voltage. Tap blocking is a softer form of load reduction than direct load shedding, since the reduction is distributed among all loads connected to the same substation.

The great advantage of this countermeasure the tap blocking is that can be easily implemented, nevertheless this measure could not be enough to guarantee the voltage stability. In certain cases the voltage can stabilize in very low values and lead to action of the minimum voltage protections. In some situations the load shedding is used as an additional countermeasure in order to mitigate the voltage collapse.

Acknowledgements

The first author would like to thank Program PROTEC (*Programa Especial de Apoio à Formação Avançada de Docentes do Ensino Superior Politécnico*), financial support to this research work through the Ph.D. grant nº SFRH/BD/49932/2009.

References

[1] L. Lin, N. Zhou and J. Zhu, "Analysis of voltage stability in a practical power system with wind power", Electric Power Components and Systems, vol. 38, no. 7, pp. 753-766, Jan. 2010.

[2] B. Otomega, L. Toma, C. Bulac and T. Cutsem, "Combined Control Actions to Counteract Long-Term Voltage Instability", U.P.B. Sci. Bull., Series C, Vol. 74, no. 1, 2012.

[3] IEEE Power System Relaying Committee, Substation Protection Subcommittee, Working Group K12, "Voltage Collapse Mitigation - Report to IEEE Power System Relaying Committee", Final version, December, 1996.

[4] F. Capitanescu, B. Otomega, H. Lefebvre, V. Sermanson and T. Cutsem, "Decentralized tap changer blocking and load shedding against voltage instability: prospective tests on the RTE system", International Journal of Electrical Power & Energy Systems, Elsevier Science, Vol. 31, no. 9, pp 570-576, October 2009.

[5] F. Capitanescu, B. Otomega, H. Lefebvre, V. Sermanson and T. Cutsem, "Prospects of an Improved System protection Scheme Against Voltage Instability in the RTE System", 16th Power System Computation Conference (PSCC 2008), July 2008.

[6] F. Dong, B. Chowdhury, M. Crow and L. Acar, "Impact of Load Tap Changing Transformers on Power Transfer Capability", Electric Power Components and Systems, Vol. 32, no 12, pp 1331-1346, 2004. [online] Available: http://dx.doi.org/10.1080/15325000490511545524, June 2010.

[7] J. Machowski, J. Bialek, J. Bumby, *Power System Dynamics: Stability and Control*, 2nd ed., Chichester, UK: Wiley, December 2008.

[8] Tractebel Energy Engineering and Réseau de Transport d´Electricité (RTE), Eurostag Software user's Manual and Release Notes, Eurostag Package Release 4.5, June 2010.

[9] M. Stubbe, et al., "Tools for simulating Long Term Dynamics", CIGRE Task Force 38.02.08, ELECTRA no. 163, pp. 150-166, December 1995.

[10] R. M. Monteiro Pereira, C. M. Machado Ferreira and F. P. Maciel Barbosa, "DFIG Performance Assessment during Low Voltage Ride through in the Dynamic Voltage Stability of an Electric Power System", 46th International Universities Power Engineering Conference, UPEC2011, South Westphalia University of Applied Sciences, Soest, Germany, 5th-8th September 2011.