The Connection Studies for 1200 MW Wind Power Integration in Portugal

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Abstract— **During the last years Portugal has been facing a massive increase of renewable energy power plants in the Electric Power system, mainly driven by the wind power connected. The wind power represents for the country a key opportunity to invest in one energy source that is naturally available and at the same time represents a reduction on the dependency of foreign energy imports and carbon dioxide emissions.**

In the year 2005, the Portuguese government released one Public Tender process for the installation, in a first phase, of 1200MW of wind energy. Within the Tender requirements was included one Annex with the minimum Electrical capabilities to be provided by the Wind Turbines/ Wind Farms[2]. Some of the requirements were starting to appear in the most advanced grid codes in Europe (as Germany and Spain), such as:

- **the Fault Ride Through capability (with reactive current injection)**
- **the Power Factor regulation capability,**

both of them related to the Wind Farm's Point of Connection.

This process joined ENERCON as the main technology supplier, INESC Porto as the research institute with the background and knowledge for modeling and simulation in PSS®E of the wind farms grid and REN/EDP-Distribuição as the system operators of the national grid and the ones with the operational knowledge needed to identify critical scenarios for the study.

The partnership ENERCON-INESC Porto together with the contribution and feedback from the REN and ENEOP technical direction was a very fruitful experience for our institutions. The working procedure, with simulations done for key operating scenarios, led to interesting results.

Index Terms— ***Grid Codes, Wind Power, FRT, Voltage Control, Reactive Power Capability***

I. Nomenclature

DGEG – Direcção Geral de Energia e Geologia
FRT – Fault Ride Through
GDA – Grid Data Acquisition
PoC – Point of Connection of the Wind Farm
QUM2 – ENERCON FRT mode with Reactive current injection
RES – Renewable Energy Sources
RPCC – Reactive Power Capability Curve
WEC – Wind Energy Converter
WF – Wind Farm
ZPM – ENERCON FRT mode "Zero Power Mode"

II. Introduction

In July 2005, the Portuguese Government launched a Public Tender to provide interconnection rights for new wind farms for a maximum of 1500 MVA / 1800 MW [(1)], divided by 2 lots: Lot A – 1000 MVA / 1200 MW and Lot B – 500 MVA / 600 MW, under the following general conditions:

- An industrial cluster, integrating experienced technological and production players, should be created for each lot, assuring investment, employment and technology transfer to Portugal. These clusters should supply the wind energy converters, electrical equipment and civil works for the wind farms to be build and also wind energy converters for exportation;
- New solutions should be developed to exploit the wind resource more efficiently and more compliant with electrical system management, namely: wind farms compliant with new grid codes, dispatch centre for on-line remote control, forecasting models and energy storage solutions;
- A new regulated tariff for energy payment around 20 to 25% lower than the granted tariff for the ~3500 MW interconnection rights provided before 2005.

ENEOP - Eólicas de Portugal, a consortium composed by ENERCON (with 29 associated companies) and by 4 top-tier wind farm Portuguese promoters (EDP Renováveis, Generg, Finerge and TP [(2)]) won the Lot A (1200 MW) which Contract was signed on 27th October 2006.

Since then, during 2007-2008, 7 new factories have been built and 12 factories upgraded. The wind farms erection begun on July 2008 and the first wind energy converter have begun operation on March 2009. On September 2012, 860 MW are in operation and more 100 MW under erection. For that, ~1500 M€ have been invested and ~1500 direct and ~5500 indirect jobs have been created.

ENEOP expects to complete the 1200 MW during 2014.

The following notes apply to this section:

(1) The values in MVA are the global limits of power to be injected into the Grid by each Lot and the values in MW are the global limits of the rated power to be erected on the wind farms of each Lot. A 20% over equipment was considered for both Lots A and B.
200 MW more were provided later by public auction in lots not greater than 50 MW.
The new 2000 MW in total provided will lead the wind capacity in Portugal to ~5500 MW.

(2) Finerge and TP, at the time from Endesa Group, are now integrated on ENEL Green Power

III. The Portuguese Transmission System and the Grid Requirements

Considering the Portuguese goals for Renewable Energy Sources (RES) by 2020 and the wind contribution to those goals (5300 MW) the Tender for 1200 MW of wind generation launched in 2005 represented an important milestone in the contribution to those goals. Also, from the network security point of view, those were the first generators that had to be compliant with dedicated technical requirements for operation in disturbed and in steady-state situations.

Taking into consideration the present integration of wind generation in the generation portfolio in Portugal (4300 MW) the technical requirements that were established in the tender together with the requirements stated in the Portuguese Transmission Grid Code published in 2010, represent an extremely important contribution to the security of the network. The full implementation of this measures gives an indispensable contribute to the grid security.

In this paragraph it will be presented a short description of the main characteristics of the Portuguese system in terms of the consumption and generation as well as the technical requirements that were established in the Tender for the wind generators.

A. *Description of the system*

In 2011 the maximum demand in the Portuguese electrical system was 9 192 MW (24th January at 19:45 pm) and the total energy demand supplied by the public network was 50.5 TWh.

This 50.5 TWh value represents the aggregation of the liquid production that was injected in the public network from the production centers, both conventional and RES, and also from the international exchange, subtracting the demand from hydro pumping.

Fig. 1 presents the disaggregation, of the 50.5 TWh of total consumption in 2011, by the different generation sources.

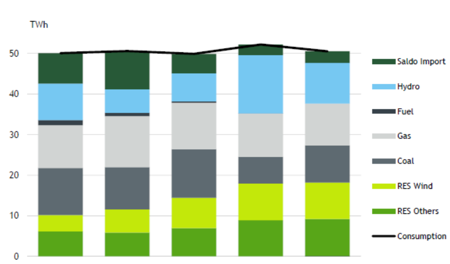

Fig. 1 Satisfaction of annual demand from source type [1].

RES with 18.2 TWh had a contribution of approximately 36% for the demand satisfaction. Considering this RES contribution around 50% (9.0 TWh) is from wind energy, being the remaining 50% from, thermal (43%), hydro (6%) and PV (1%).

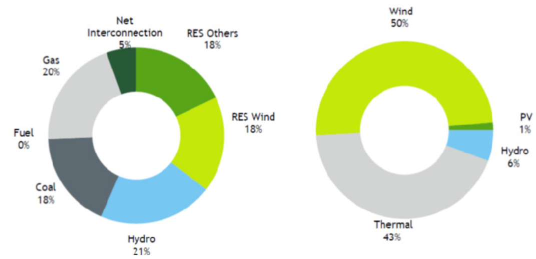

Fig. 2 Energy emission from source type. General and RES [1].

B. *The 1200MW Tender requirements*

The Tender required that the wind parks to be installed shall have the following minimum requirements

1) *Fault Ride Through capability*

According to this proposal, Wind Energy Converters (WECs) should remain connected to the grid during faults when voltage is above the curve depicted in Fig. 3. Additionally should not consume active or reactive power during fault and voltage recovery. After fault clearance, active power should recover with a rate of at least 5% of the rated power per second.

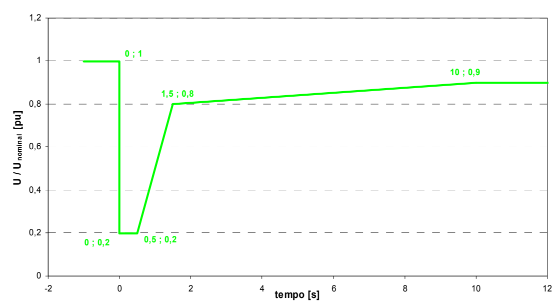

Fig. 3 Fault Ride Through Capability [2].

2) *Reactive current injection during the fault*

Wind Farm must supply reactive current during voltage dips (Fig. 4), providing support to network voltage.

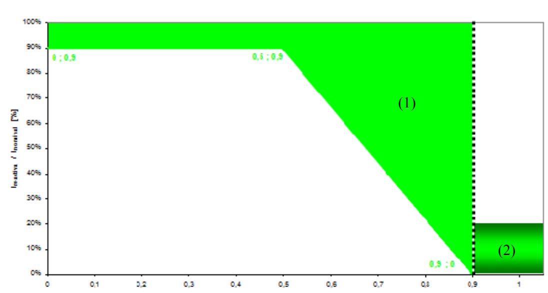

Fig. 4 Reactive curve supply by the Wind Farms during voltage dips [2].

Ipre-fault - Injected Current in the network by the Wind Farm in the instant immediately before the voltage dip occurrence.

Ireactive - Reactive Current (value of the reactive component of the current) injected in the network by the Wind Farm.

The following notes apply to Fig. 4:

(1) Zone corresponding to fault and recovery operation. In the sequence of a fault that originates voltage dips higher than 10 %, the Wind Farm must respect minimum reactive support curve with a maximum delay of 40 ms after voltage dip detection.

(2) Zone corresponding to normal operation (by entering this functioning zone the Wind Farm must return to operation according to reactive power production regulation)

3) *Reactive power capability at steady state*

The wind energy converters shall have the capability to adjust, if requested from the Network Operator, the injected reactive power to values within the range of tan φ [0; 0.2_{exp}], measured at the PoC..

IV. ENERCON WIND ENERGY CONVERTER

A. *ENERCON WEC concept*

The concept of the ENERCON WEC can be explained through Fig. 5. Basically, the wind moves the drive train that is directly connected to the generator. The AC variable frequency voltage at the generator terminals is converted to DC voltage through a rectifier. Then, a DC/AC power converter is necessary to feed the power into the grid at fixed frequency. In addition, a chopper resistance (dump load) is included in the DC link to consume the amount of active power which cannot be fed into the grid during a fault. Consequently, the torque of the generator does not change significantly and the rotating part of the ENERCON WEC can be considered as almost completely decoupled from the grid. Furthermore, there is a circuit-breaker to isolate the WEC from the grid and a step-up transformer to increase the WEC voltage level to the WF voltage level.

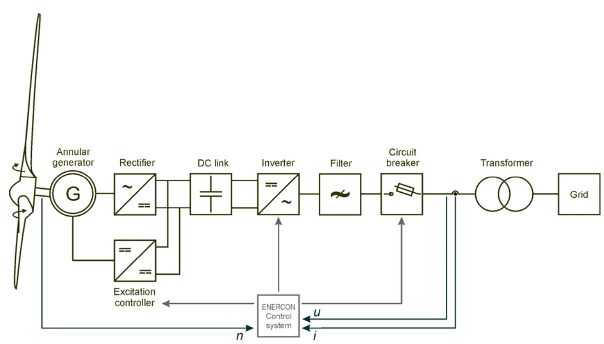

Fig. 5 Simplified electrical diagram of ENERCON WEC

B. *ENERCON WEC Features*

The flexible full-scale converter concept of the ENERCON WEC allows the use of advanced features to improve the grid integration and fulfill the Tender requirements in Portugal. The main features are FACTS properties and FRT capability.

1) *FACTS properties*

One of the main features of ENERCON WEC with FACTS properties is an extended reactive power diagram [3]. Reactive power is fully available on the active power operation range of 20% to 100% for standard configuration. For STATCOM option (not applicable in ENEOP projects) the reactive power is fully available over the all active power operation range, as presented in Fig. 6.

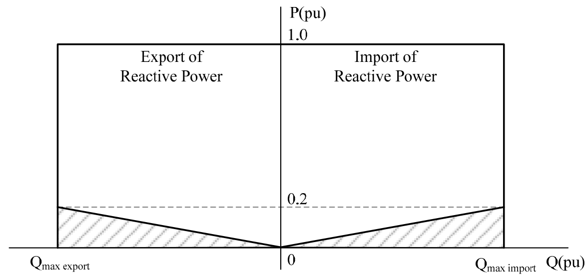

Fig. 6 Reactive power diagram of ENERCON WEC with FACTS capability: Diagram for standard and STATCOM configuration.

2) *Fault Ride Through capability*

The ENERCON WEC equipped with FRT capability is able to stay in operation during under- or overvoltage conditions for up to five seconds, as described in Fig. 7. In addition, the injection of active and reactive current into the grid can be independently controlled. This allows the control of reactive current based on the voltage dip at the WEC terminal as required by the Tender requirements.

The operation mode suggested for the Tender is the same as the FRT mode developed for Germany, named QUM2. The QUM2 operation is coordinated with Zero Power Mode (ZPM). The operation ranges of these two modes as well as the normal operation ranges are presented in Fig. 7.

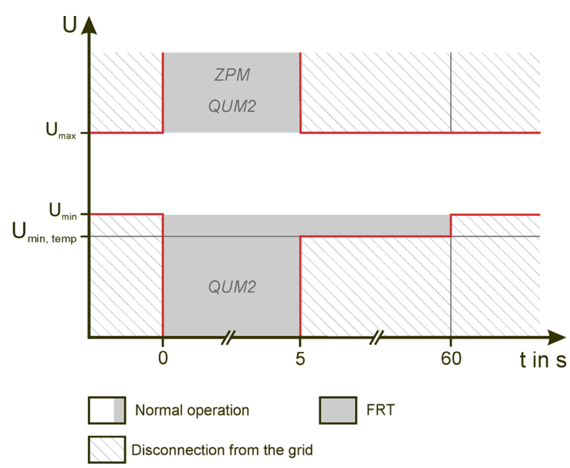

Fig. 7 FRT capability and QUM2 operation ranges

According to the Tender requirements presented in section III, after an undervoltage is detected, the reactive current is adjusted according to the terminal voltage, as shown in Fig. 8, for the QUM2 mode. The reactive current reference value in the QUM2 is set to

$$I_{react,ref} = I_{b0} + \Delta I_b \tag{1}$$

where I_{b0} is the initial reactive current injected by the WEC. ΔI_b is an additional reactive current proportional to the voltage dip calculated as described in Fig. 8

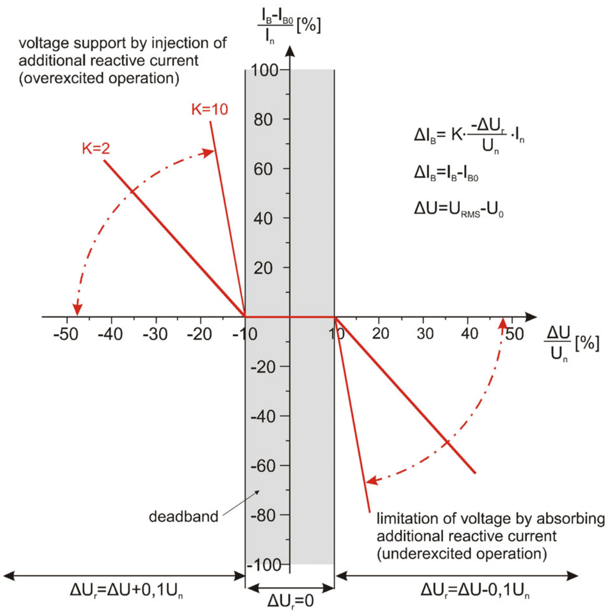

Fig. 8 QUM2 operation principle

In case of ZPM, after an under- or overvoltage is detected, the WEC blocks the injection of current to the grid i.e. there is no active and reactive current injection into the grid. The active and reactive current reference value is set to

$$I_{react,ref} = 0 \tag{2}$$

$$I_{act,ref} = 0 \tag{3}$$

After fault clearance is detected, the WEC starts to ramp up current to the pre-fault value with an adjustable time. To smooth the impact of WEC current injection during fault clearance and consequently avoid possible overvoltage, independent ramp up gradient can be adjusted for active and reactive power.

3) ENERCON Grid Data Acquisition

The ENERCON GDA is designed to continuously measure the voltage and the injected current at PoC - Point of Connection of the WF, through a measuring transformer.

The aim of the GDA is to permanently feed the ENERCON SCADA with the electrical values measured in the PoC. In this way a close-loop control between the WECs and the WF's PoC for the maximum Active Power and Power Factor of the WF is created (Fig. 9). This ensures that the required Active Power limitation and tan φ is verified at the PoC.

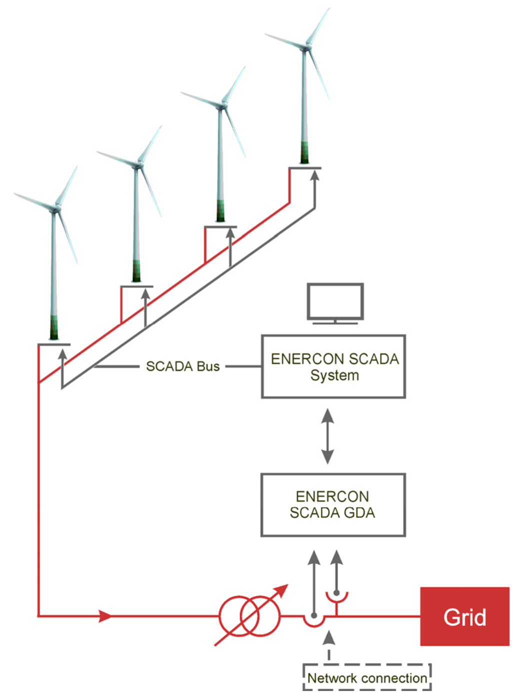

Fig. 9 ENERCON GDA system in a WF

C. ENERCON WEC model

The ExF2 model represents an ENERCON WEC, independent of WEC type (E-44, E-48, E-53, E-70, E-82, E-101 and E-126) and configuration (FD, FT and FTQ), for positive sequence phasor time domain simulations. The model was developed to simulate the performance of an ENERCON WEC in the context of transient stability studies with a time range up to 10 seconds. The maximum simulation step size is 10 milliseconds.

The hub of an ENERCON WEC is directly connected to the rotor of the annular generator as shown in Fig. 5. The stator windings of the generator are connected to the grid through a full converter, which decouples the generator speed from the power system frequency. The control of the full converter dominates almost completely the dynamic performance at fundamental frequency for the time range typically addressed in transient stability studies. Consequently, as illustrated by Fig. 10, in the ExF2 model the ENERCON WEC is represented only by a controlled full converter model. The ExF2 model does not include a model of the aerodynamic system, pitch control, hub and generator.

The time range of transient stability studies is usually limited to 3 to 5 seconds following the disturbance, although it may extend to about ten seconds for very large systems [4]. For this time range, it is a reasonable approximation to assume that wind speed remains constant.

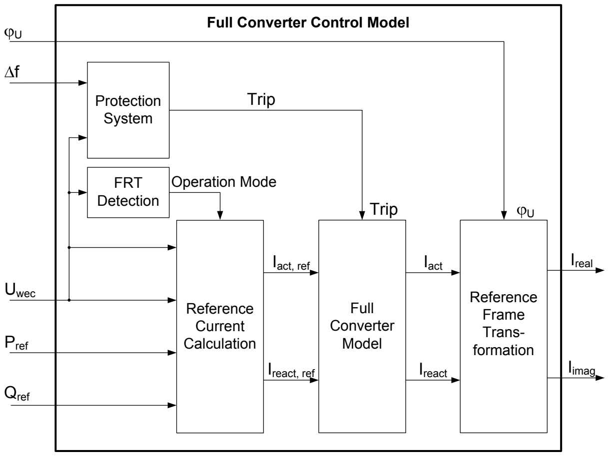

Fig. 10 Simplified ExF2 model structure

ENERCON WEC in Transmission Configuration are equipped with Fault Ride Through Capability (FRT) and are able to stay in operation during voltage dips or temporary overvoltage for up to five seconds. When a grid fault occurs, an ENERCON WEC in Transmission Configuration switches to FRT operation. The portion of active power that cannot be injected to the grid while operating in FRT-Mode is consumed by a controlled chopper resistance. Consequently, the generator speed does not change significantly and can be considered decoupled from the grid. Since the rotational speed can be considered constant before and during grid faults, the operating point of the pitch controller remains in steady-state. Due to the approximation of constant wind speed and constant rotational speed, the aerodynamic system, pitch control, hub and generator can be neglected in a model representing an ENERCON WEC for transient stability studies.

The Full Converter Control Model calculates the current to be injected to the grid in response to the power command values, the terminal voltage phasor and the operation mode (normal operation or FRT-Mode). It also includes a model of the voltage and frequency protection system. This model detects the terminal voltage and its frequency deviation relative to the system frequency. The WEC model is disconnected from the grid if voltage or frequency exceeds the protection settings for the specified delay times.

V. THE ALTO DOURO WIND FARM CASE STUDY

The Alto Douro WF has a total installed capacity of 204 MW divided in a set of 7 sub-WF (equipped with ENERCON E-82 FT WEC) that are interconnected through a private 60 kV grid. The rated capacity of each sub-WF is listed in Table I. The Alto Douro WF is then interconnected to the Portuguese transmission system at the 220 kV grid. The Alto Douro WF belongs to the 1200 MW Public Tender supported by the Portuguese Government.

The connection studies that are required for each WF aim the identification of the best suited parameters to be implemented in the individual WEC of each WF. Concerning the required studies, the Portuguese Transmission System Operator (REN) provided a PSS®E (Power System Simulator for Engineering) model of the Iberian generation and transmission system, as well as two representative operating scenarios (for peak and valley hours). In order to perform the studies described in this report, the Alto Douro Wind Farm was fully modelled in PSS®E Iberian generation and transmission system model, including the representation of the entire WF internal grid and all the WEC. In the peak hour scenario, the estimated generating capacity in the Portuguese grid is around 11.5 GW, from which 3.6 GW are provided by wind generation. In the valley hour scenario, the total estimated generating capacity in the Portuguese system corresponds to 4.9 GW, in which the wind generation and other generating units provide 2.9 GW. In this case, there is no power interchange between Portugal and Spain.

TABLE I. CHARACTERIZATION OF THE ALTO DOURO WF

	Number of WEC	**Active Power (MW)**
Testos II	22	44
Serra da Nave	19	38
Serras de Armamar	13	26
Serras de Chavães	16	32
Sendim	18	36
Serras de Sampaio	9	18
Ranhados	5	10
TOTAL	**102**	**204**

A. *Simulation results*

This section presents a general overview about the main simulation conditions that are required in order to demonstrate that each WF fully complies with the requirements defined in the Tender.

B. *Reactive Power capability at the PoC*

Considering the WEC Reactive Power Capability Curve (RPCC), which is represent by the blue line in Fig. 11, it was possible to determine the wind farm RPCC at the 220 kV Point of Connection (PoC), which are also represented in Fig. 11 for both peak and valley hour scenarios when the WEC units are following the standard Q operation limits. The RPCC at the PoC was obtained by performing a computational routine developed in Python programming language for PSS®E software. For each point of the WEC reactive power capability curve, this computation routine allows the automatic calculation of the reactive power flow in the PoC. As it can be observed from the analysis of Fig. 11, when exploiting the WEC standard reactive power capabilities the planned WF reactive power range at PoC complies with the requirements defined by Public Tender (tan φ in the [0; 0.2] range). Additionally, it is also important to mention that the reactive power range offered by the WF promoter through the use of ENERCON WEC can be extended for tan φ in the [-0.2; 0.2] range.

C. *FRT behaviour*

In order to evaluate if the WF complies with the Fault Ride Through (FRT) requirements defined by the Portuguese Public Tender previously discussed, symmetrical short-circuits were simulated in a 220 kV busbar near the WF PoC (220 kV busbar of the Valdigem substation) both for peak and valley hours scenarios. A fault occurring in the Valdigem substation at 220 kV bus-bar is a severe case in what concerns system stability in the surrounding area. A fault duration of 250 ms was adopted (the time duration of 250 ms refers to a typical time for the operation of the second level of the protection systems). This fault duration time is typically used in studies concerning power systems transient stability, and in particular, in the studies required to evaluate the impact resulting from the integration of wind power in the Portuguese transmission network. It was also assumed each WEC is operating at the rated active power capacity and exporting maximum reactive of reactive power to the grid (WEC RPCC in Fig. 11). This operational condition represents a specific situation where the converters are exporting maximum reactive power to the grid.

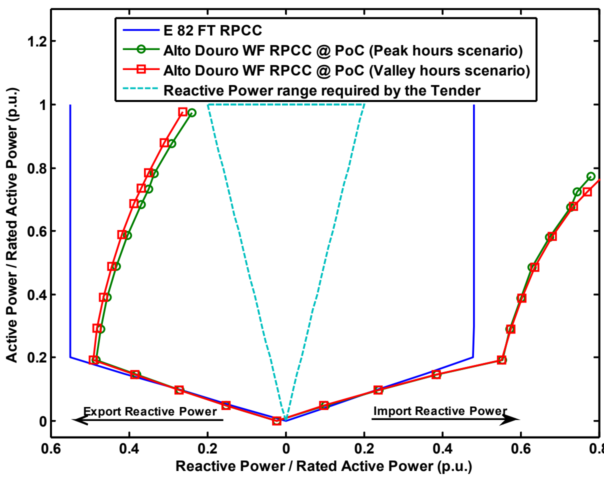

Fig. 11 Alto Douro Wind Farm RPCC at PoC (220 kV)

Fig. 12 and Fig. 13 depict the active and reactive power at the Alto Douro WF PoC and the corresponding terminal voltage for peak and valley hours scenarios. At t = 0.5 s, a symmetrical short-circuit with a clearing time of 250 ms (duration of the fault) is applied at the 220 kV busbar of the Valdigem substation. Due to the voltage drop at the WEC terminals, the power electronic converter detects the fault and activates the Under Voltage Ride Through (UVRT) control mode, which was previously selected to be the QUM2 (QU-Mode control). When the fault is eliminated, voltage returns to its nominal value and the WEC changes from QUM2 control to the normal operation mode. Simultaneously, WEC power output stabilizes in the same level it was prior to the fault occurrence. From the same results it is possible to conclude WEC stabilization following the fault is quite fast and no stability problems were identified.

D. *Reactive current injection analysis*

The reactive current injection capability during voltage drops is an important feature regarding the need of providing voltage support, which may avoid undervoltage tripping of other generating units. Although ENERCON WEC allows different FRT operational modes regarding the machine behaviour in terms of active and reactive current injection during the fault, the results presented in this section concerns the dynamic behaviour of the system in the case where the best-suited FRT operational mode to be installed in the Alto Douro WF is able to comply with the tender requirements (QUM2 mode). In general, this FRT operation modes allows WEC to inject reactive current proportionally to the voltage drop at its terminals, according to a pre-defined gain (k=1,9) that can be specified at WEC level.

Since the Tender requirements refer that the WF should respond injecting reactive current with a maximum time delay of 40 ms after fault detection at the PoC, simulation using ENERCON WEC model were performed in order to demonstrate this requirement. From the analysis of the performed simulations (Fig. 14), it is possible to conclude that the Alto Douro WF performs as required. As it can be observed in the same Fig. 14, the maximum reactive current being injected by the Alto Douro WF during the voltage drop is larger than the minimum required amount defined in by public Tender.

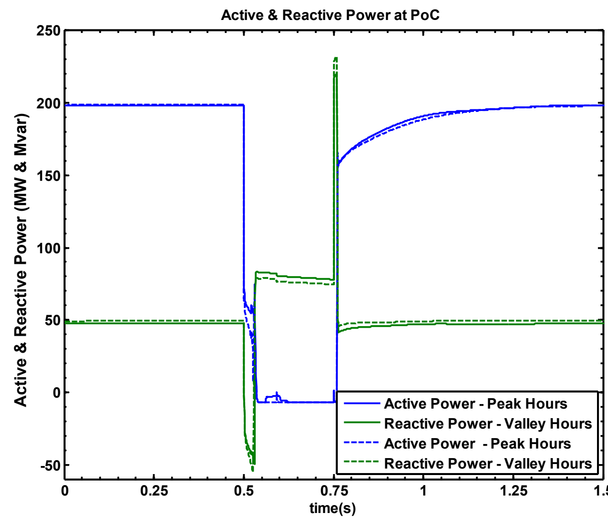

Fig. 12 Active and reactive power injection at the Alto Douro wind farm PoC for peak and valley hours.

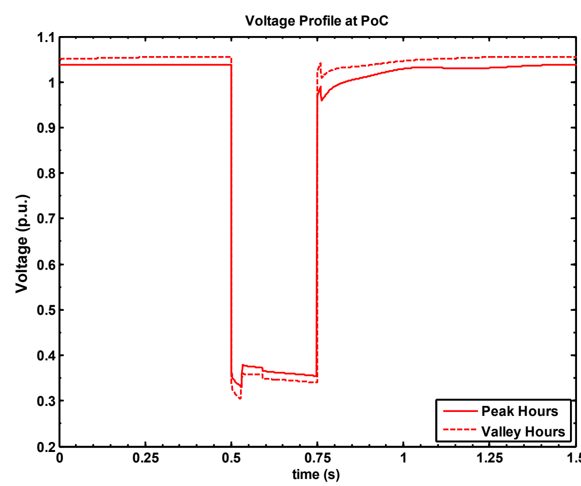

Fig. 13 Alto Douro wind farm PoC voltage for peak and valley hours scenarios

E. *Tele-protection system failure*

In order to validate the FRT performance of the Alto Douro WF in case of a tele-protection system failure in the 220 kV grid, which is also a critic condition regarding system stability, this condition was also simulated in a line connected to substation in the surrounding area of the WF

PoC. These conditions were simulated according to Fig. 15: a short-circuit with a time duration of 500 ms was simulated at the substation of Carrapatelo_aux bus-bar (extreme end of the 220 kV short line departing from the Valdigem substation). The breaker installed in the Carrapatelo bus-bar tripped at 150 ms after the fault occurrence (t_{fault} = 0.5s). However, and in order to simulate the failure in the tele-protection system, it is assumed that the fault continues to be supplied by the connection with Valdigem 220kV bus-bar, being only cleared 350 ms after opening the Carrapatelo breaker.

The results obtained from a simulation of the tele-protection failure illustrates that the Alto Douro WF performs as required by the Tender (Fig. 16). Additionally, it is important to mention that no stability issues, in terms of voltage profiles or in terms of active or reactive power injected in the transmission grid, are identified.

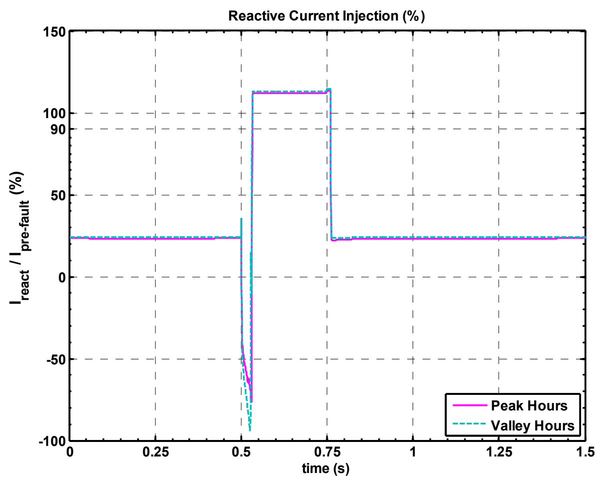

Fig. 14 Reactive current injection at the PoC during the fault

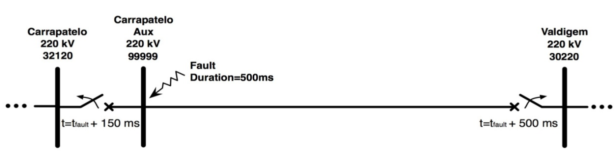

Fig. 15 Tele-protection system failure

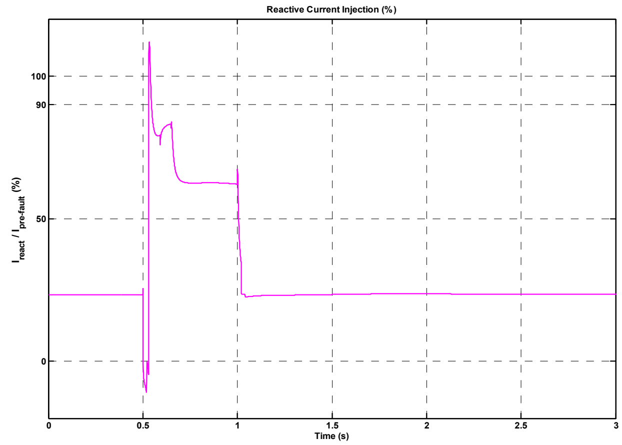

Fig. 16 Percentual reactive current injection at Alto Douro WF PoC for a teleprotection system failure

VI. CONCLUSIONS

The main target of this grid integration studies was to investigate electrotechnical issues concerning the wind farm in order to assess if the grid requirements defined by Portuguese Public Tender are fulfilled and at the same time to identify the most appropriate settings to be adopted for the WEC control system and WEC protections.

The study cases described in section VI – Simulation Results – considered two periods of the day (peak and valley hours) and for each of them, two scenarios were simulated: the first (steady-state operation) was intended to verify the WF reactive power capability such that, at the WF point of connection, the tan φ remains in the range of [-0.2; 0.2]; and the second (transient events) were intended to study the ENERCON QUM2 control of the WEC, and so to validate if the FRT requirements as well as the injection of the reactive current defined by Public Tender are ensured.

The results obtained from computational simulation, led us to the follow conclusions:

- The standard reactive power characteristics of the WECs are enough to comply the Tender requirement;
- As can be observed from the simulation results, the WECs present a very robust dynamic behaviour;
- The WEC, when operating in QUM2 control due to an undervoltage event, respond injecting reactive current after fault detection as a function of the WEC terminal voltage, thus optimizing the WEC response in order to reduce overvoltages in the moments subsequent to fault clearance. At the same time, QUM2 control allows the Alto Douro WF to be fully compliant with the requirement of Tender (even regarding the time delay between the conclusion of the fault detection stage and the reactive current injection from the WECs);
- The protection coordination between grid and WF substation should take into account the protection setting defined for the WECs and the modification to the technical guide approved by DGEG in order to ensure the Fault Ride Through conditions required by the Public Tender.

Is important to point out that the collaboration of REN with ENERCON and INESC-Porto on the studies discussed in this paper is a good example of how such discussions can create a Win-Win situation to the parties:

- For the System operator, as the entity in charge of keep safe and reliable the Portuguese grid, to better understand the WEC technology, its dynamic behavior and physical limits.
- For the WEC's manufacturer to assess the specific grid dynamics though, create and improve the controls of the WEC to reach the desired performance towards the grid.

Finally, refer that Alto Douro is just one interesting example of the several WFs studied for this Tender. The very diverse nature of the studied wind farms regarding total installed power, number of the wind turbines, distance of the wind turbines to the Point of Connection and connection to the transmission grid or distribution grid, represented some interesting challenges and a relevant added value to the ENEOP project.

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