Analysis of the Active and Reactive Power Transient Responses of a Generic Type 3 Wind Turbine Model

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Abstract—**Wind power capacity is considerably growing around the world. Based on such growth and the variable nature of renewable resources, it is necessary to conduct transient stability analyses to plan and maintain network operation, ensuring the integration of not only new installed wind farms, but also of all renewable energy plants. Focusing on the wind industry, Transmission System Operators (TSOs) and Distribution System Operators (DSOs) are two of the main entities interested in these types of analyses, such as the simulation of dynamic wind turbine models which are able to faithfully represent the behavior of actual wind turbines operating nowadays, without the need to work with complex wind turbine models belonging to private companies. The International Electrotechnical Commission (IEC), through the IEC 61400-27-1 standard, is the organization responsible for the development of the generic wind turbine models, which cover the four main topologies of actual wind turbines installed. This paper addresses the implementation and simulation of the generic Type 3 wind turbine model, i.e., the doubly-fed induction generator wind turbine, which is the most technologically advanced and widely installed type of wind turbine. The generic Type 3 wind turbine model will furthermore be studied under both normal and fault conditions, and its transient responses in terms of active and reactive power will be discussed in detail.**

Keywords—**Transient stability analysis, dynamic simulation, DFIG, generic type 3 model, IEC 61400-27-1.**

I. Introduction

IN the European Union, 11.6% of the electricity demand was covered by wind energy in 2017. Moreover, nearly 60,000 MW were installed globally in that same year [1]. Also during 2017, a large number of new onshore and offshore wind power plants were installed all over the world. There is, therefore, no question that wind energy, together with the rest of renewable energy sources (RES), is becoming increasingly important as non-renewable energy sources get scarcer. Nevertheless, the fluctuating and uncertain nature of the RES implies that the control and operation of the network must be carefully planned. In particular, wind energy positions itself as one of the most promising RES worldwide, with a total installed capacity exceeding 539,000 MW. This is the point at which the standard IEC 61400-27-1, first released in February 2015, took a direct responsibility. It developed four generic wind turbine (WT) models [2], covering the four main topologies of WTs available in the market: (i) Type 1 WT, which consists of an asynchronous generator directly connected to the grid, with no power converter; (ii) Type 2 WT, consisting of an asynchronous generator equipped with a variable rotor resistance; (iii) Type 3 WT, that uses a Doubly-Fed Induction Generator (DFIG), where the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter [3], [4]; (iv) and Type 4, which is connected to the grid through a full-scale power converter [5], [6]. They are all intended to simulate in an accurate manner the behavior of actual WTs when they are connected to the grid. For that reason, several transient analyses are conducted throughout the development of this research work, always attempting to analyse in a reasoned way the responses obtained, and focusing on the transient periods appearing during the simulation. The generic Type 3 WT model studied is tested under three voltage dips of different magnitude and duration (two at full load conditions and one at partial load conditions), the effects of which are explained in terms of active and reactive power injection into the grid. The WT model is also analyzed under normal conditions, where the active and reactive power setpoint is changed by the user. The paper also undertakes a brief review of how each dynamic model within the generic Type 3 WT works, listing their main input and output signals, and showing the general structure of some of them. Summarizing, the main objective of the present work is to analyse the transient periods that appear when submitting the generic WT to critical situations such as voltage dips. Moreover, although a complete validation procedure has not been applied in this case, results show the good performance of the model, behaving as expected, especially if compared to model's responses presented in works such as [7]. Stakeholders related to the wind power industry, such as wind turbine manufacturers, wind power plant owners or transmission and distribution system operators, as well as research institutes, may gain competitive advantages through these types of studies.

The paper is structured as follows: Section II includes a brief description of the software used to implement the generic Type 3 WT model, furthermore showing a graphical representation of some of the dynamic control models and explaining how they all operate. Section III addresses the types of simulations conducted, while Section IV presents the results obtained.

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Lastly, Section IV summarizes the main conclusions.

II. Generic Type 3 WT model in accordance with standard IEC 61400-27-1

Based on the current need of TSOs and DOs, with the objective of gathering the features of the huge number of different WTs belonging to manufacturers, Standard IEC 61400-27-1 developed four generic WT dynamic models which represent the four typologies existing nowadays, as stated in Section I. Thus, since Type 3 WT, i.e., the doubly-fed induction generator WT, is the most complex one and the most widespread across countries, it has been implemented and simulated in one of the most powerful software tools related to the simulation of power systems: DIgSILENT PowerFactory (PF) [8]. IEC 61400-27-1 guidelines have therefore been followed, although some modelling adaptations were required.

In general, implementing the generic Type 3 WT model on any relevant simulation software implies knowing how that software works when conducting transient stability analyses, i.e, when conducting dynamic simulations. As contributions related to the implementation and simulation of generic WT models in MATLAB are numerous in the scientific literature, PF has been the software used to carry out the present study, of which currently there is a lack of research studies related to the simulation of generic DFIG WTs. Indeed, innovation of this work is based on the importance of using a specialized electrical engineering software tool to implement and simulate an IEC-developed WT model which, in the rest of works related to this topic, has only been studied using multidisciplinary software tools such as MATLAB/Simulink. The use of a specialized software such as DIgSILENT-PowerFactory will allow the conduction of highly complex power systems involving both wind power generation and conventional power generation to be carried out, extending the use and scope of application of standard IEC 61400-27-1. Moreover, this powerful software is usually used by TSOs and DSOs to conduct the technical complex studies which they required, while software tools such as MATLAB Simulink are rather used by research institutions and universities.

Fig. 1 presents the general structure of the generic Type 3 WT model according to [9]. Note that the generator control model is divided into four sub-models representing the controls of active power, reactive power, current limitation and reactive power limitation. Before explaining the dynamic models' behavior, it must be pointed out that PF is unable to work only with control models. In other words, a network model to which the control models are connected must be indispensable defined. Hence, as the generic Type 3 WT model is only composed of dynamic control models (even the generator system is composed of dynamic blocks), the electrical device used to interconnect the WT to the grid is an AC current source. The network model is shown in Fig. 2.

For further information regarding the implementation of dynamic power systems in PF using DSL, see [10].

The following sub-sections are thus aimed at explaining the general behavior of the dynamic control models which are part of the WT [11].

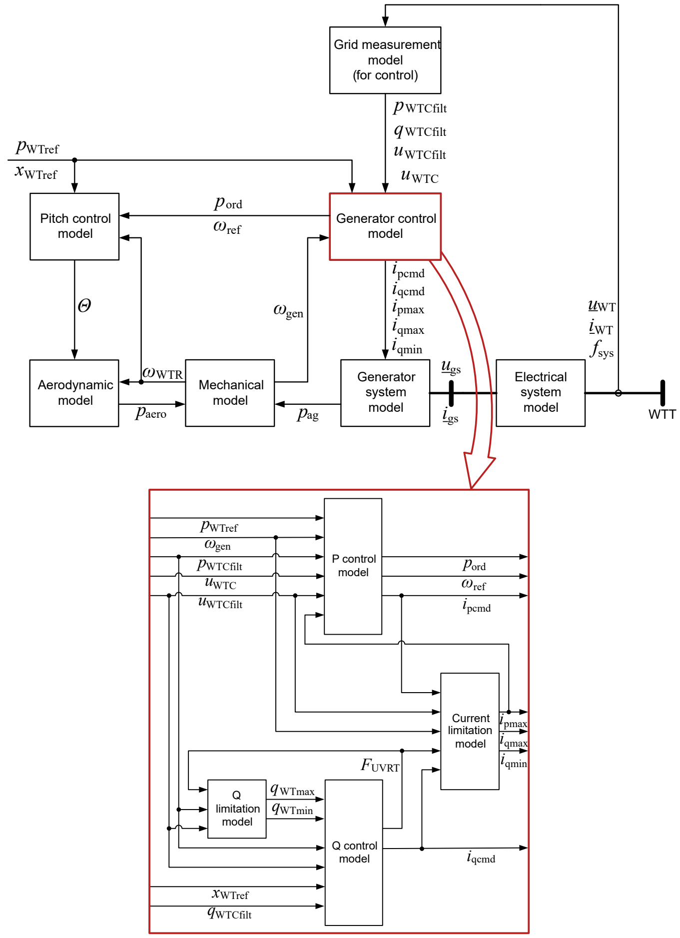


Fig. 1: General structure of generic Type 3 WT. Source: [9]

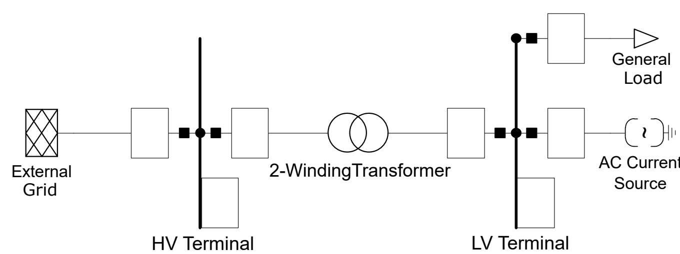


Fig. 2: Test network implemented in PF.

A. Aerodynamic Model

The input signals are the pitch angle (θ) and the wind speed (p_{init}), while the output signal is the aerodynamic power (p_{aero}). This model is implemented as a one-dimensional model [9], [12]. It provides the *Mechanical Model* with (p_{aero}) to make the active power injection equal to the active power reference (p_{WTref}), which is a value set by the user. It can also be stated that the higher the value of the pitch angle, the lower the value of the aerodynamic power.

B. Pitch Control Model

The wind turbine rotor rotational speed (ω_{WTR}) and the reference rotational speed (ω_{ref}), as well as the power order

(p_{ord}) and the active power reference (p_{WTref}), are the input signals to the *Pitch Control Model*, while θ is the output signal. This model rectifies the error between p_{ord} and p_{WTref}, and between ω_{WTR} and ω_{ref}, through the calculation of the pitch angle θ required. The position angle of the WT blades is thus adjusted to reach the active power value set, i.e., p_{WTref}.

C. Mechanical Model

The *Mechanical Model* is a two-mass model which has two sides: the low-speed and the high-speed side. The wind turbine rotor inertia, the drive train stiffness coefficient or the drive train damping coefficient are some of the parameters needed to implement the model. The input signals are p_{aero} and the active power measured in the wind turbine terminals (WTTs) once it is filtered ($p_{WTCfilt}$). The output signals are ω_{WTR} and the generator rotational speed (ω_{gen}). Fig. 3 shows the *Mechanical Model* implemented in PF using DSL.

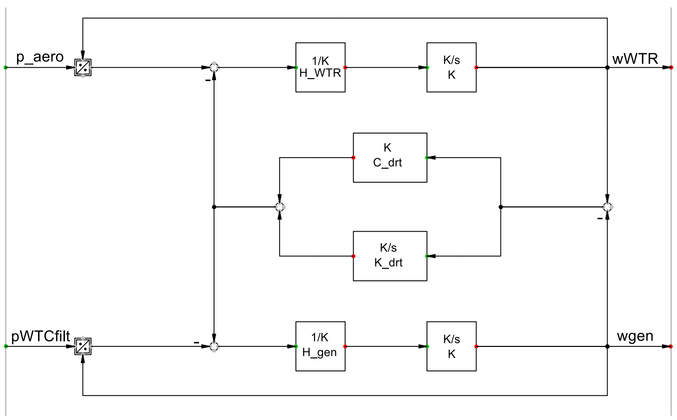


Fig. 3: Two-mass mechanical model implemented in PF.

D. P Control Model

The *Torque PI* is a sub-model incorporated within the *P Control Model*. It calculates the torque value (τ_{out}) needed to rectify the difference between both ω_{gen} and ω_{ref}. The power order p_{ord}, one of the output signals from the *P Control Model*, is in turn calculated using τ_{out}, the measured voltage ($u_{WTCfilt}$), the maximum active current (i_{pmax}, provided by the *Current Limitation Model*), and ω_{gen}. p_{ord} is the input signal to the *Pitch Control Model*. The active current command (i_{pcmd}) is also an output signal from the *P Control Model*, and it serves as an input to the *Generator System Model*.

E. Q Control Model

The *Q Control Model* is able to operate following five different control modes [13]. When operating under the reactive power control mode, a reference value (x_{WTref}, which, in this case, represents the reactive power injection setpoint), must be defined by the user. The model will thus calculate the reactive current command (i_{qcmd}), which is the parameter used to control the injection of reactive power at the WTTs. The under voltage ride through flag signal ($FUVRT$), which varies depending on the operation stage of the WT (normal, fault or post-fault operation), also influences the value of i_{qcmd}.

F. Q Limitation Model

The reactive power limitation model or *Q Limitation Model*, shown in Fig. 4, provides the *Q Control Model* with the maximum and minimum reactive power values in the WTTs (q_{WTmax} and q_{WTmin}). These parameters depend on the filtered measured voltage ($u_{WTCfilt}$), $FUVRT$ and $p_{pWTCfilt}$.

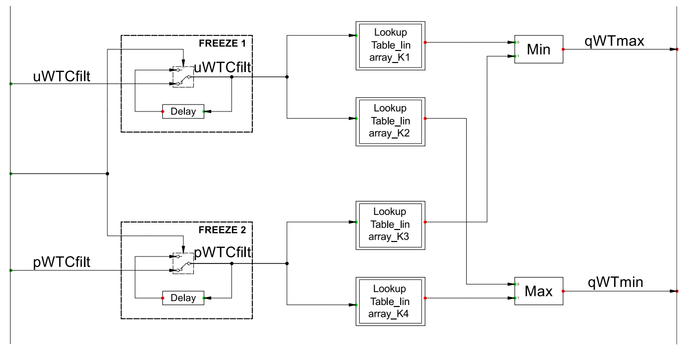


Fig. 4: Reactive power limitation model implemented in PF.

G. Current Limitation Model

The maximum and minimum limit values of reactive current are calculated by the *Current Limitation Model* (i_{qmax}, i_{qmin} and i_{pmax}), using the input signals $u_{WTCfilt}$, i_{pcmd}, i_{qcmd}, ω_{gen} and $FUVRT$.

H. Generator System

The most important sub-models within the *Generator System* are the crowbar system and the reference frame rotation. On one hand, when the measured voltage *u* is below a specific threshold, which usually involves the occurrence of a voltage dip, the active and reactive power commands coming from the *P Control Model* and the *Q Control Model* (i_{pcmd} and i_{qcmd}, respectively), are multiplied by zero. During this time, the generator behaves as a squirrel-cage induction generator. On the other hand, the current phase and the measured voltage phase are coordinated through the reference frame rotation. This sub-model provides the AC current source with the active and reactive current values, i_p and i_q. These values of current will ultimately make the active and reactive power values equal to the setpoints set by the user, i.e., equal to p_{WTref} and x_{WTref}, respectively.

I. Conversion System

Although this model is not defined in the IEC 61400-27-1, a user-defined *Conversion System* is required in PF to adapt the output signals from the *Generator System* to the input current signals of the AC current source.

J. Filter Model

This model filters the values of the active power, reactive power and voltage, all measured in the WTTs (*p*, *q* and *u*). The signals obtained are $p_{WTCfilt}$, $q_{WTCfilt}$ and $u_{WTCfilt}$.

III. Dynamic simulation

Once the test network and all the dynamic control models are implemented, the dynamic simulation starts. Simulations based on electromechanical transients are used. I.e., RMS simulations –which do not consider the electromagnetic transient dynamics–, are conducted [14], since these generic WT models are designed to be simulated only using these kind of simulations.

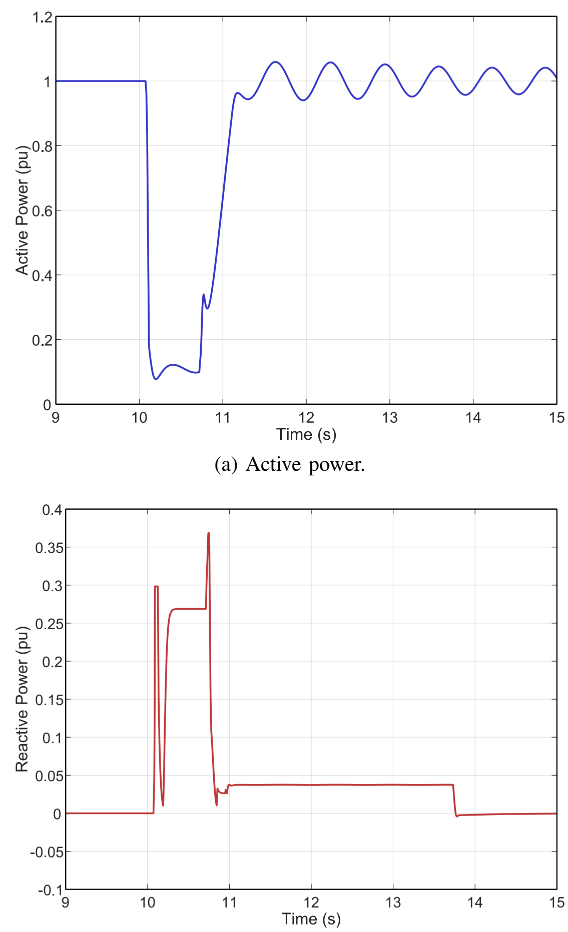
Before starting the dynamic analysis, a load flow calculation must be conducted, since this calculation will provide information on the steady state condition of the power system. The dynamic control models will thus be initialized on the basis of the known variables of the system. It is therefore very important, at this point, to manually set the initial conditions of all the input and output signals that are part of each control model, so that fictitious transients can be avoided (in some cases, the steady state condition might never be reached). Thus, the derivatives of all state variables in the dynamic sub-models must be set to zero -since the model is initialized to reach the steady-state conditions-, and then the rest of input and output signals are set based on the known variables within each model.

Once the whole WT model has been correctly initialized, the transient periods on which this work is focused are the ones that appear in the figures related to the study cases listed in the following paragraph.

The generic Type 3 WT behavior is studied under both normal and fault conditions. On one hand, under fault conditions, there exist two main options to conduct a voltage dip: the playback approach, and the definition of a short-circuit in the WTTs. In the present work, three balanced three-phase short-circuits with different values of resistance and reactance are defined in the low voltage terminal, two at full load conditions and one at partial load conditions, thus causing the occurrence of three voltage dips of different magnitude and duration. Alternatively, it is also possible to connect an AC voltage source to conduct a voltage dip. In this case, the AC voltage source may be controlled through a data file containing a specific voltage dip information. This is the so-called playback approach, which enables the reproduction of voltage dips in a precise manner. This is a highly suitable method when validation tasks must be performed; i.e., when field and simulation measurements resulting from the same voltage dip must be compared. On the other hand, when analyzing the transient behavior of the WT under normal operation conditions, the active and reactive power setpoints are changed on several occasions over the simulation. The active power reference value, p_{WTref}, and the reactive power reference value, x_{WTref}, are changed on two and three occasions, respectively. The following section focuses on the results obtained once the above-mentioned operating conditions are simulated.

IV. Results

Four different WT operation conditions are analyzed in terms of active and reactive power behavior througout the current section. Fig. 5 and Fig. 6 show the WT responses when operating under full load conditions and voltage dips of u = 0.25 pu, t = 646 ms; and u = 0.50 pu, t = 957 ms, respectively. Fig. 7 presents the WT response when it operates under partial load conditions (0.23 pu), and a voltage dip of u = 0.20 pu, t = 644 ms. The last case, Fig. 8, shows the WT operating under normal conditions, in which the active power reference value p_{WTref} and the reactive power reference value x_{WTref} are varied during the simulation. p_{WTref} is changed at 15 s and 25 s, from an active power injection value of 1 pu to values of 0.6 pu and 0.4 pu, respectively. x_{WTref} varies three times, from 0 pu, to two different operating conditions of reactive power injection (0.1 pu at 15 s, and 0.3 pu at 20 s), and to a final operating condition of reactive power consumption with a value of -0.3 pu at 25 s. All these study cases help to provide interesting information about the transient periods appearing over the entire period of dynamic simulation.

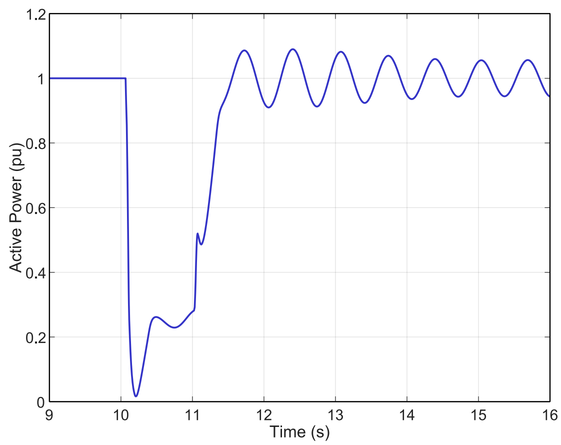


(a) Active power.

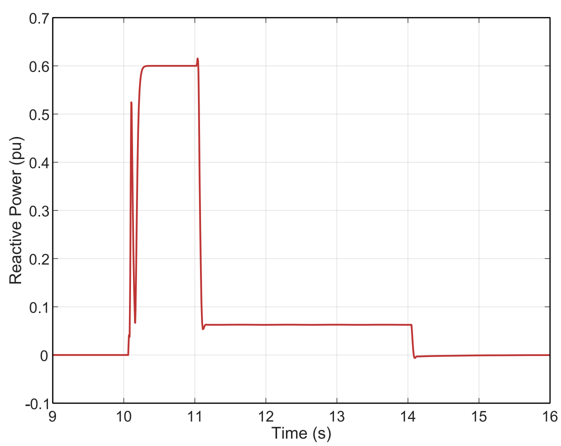
(b) Reactive power.

Fig. 5: Voltage dip 1: full load, u = 0.25 pu, t = 646 ms.

Having reached this point, different aspects need to be evaluated. First, as outlined in Section II-H, the crowbar system is activated when a certain voltage variation occurs. This limit value is set in the *Generator System* control model, and it is referred to as du. The crowbar system effects can be very clearly observed in Figs. 6 and 7 at the time the voltage dip occurs and when it is finally cleared. At those times, there exist a greater reduction of the active power injection, achieving values of almost zero (remember that the crowbar system, when activated, multiplies by zero the active and reactive current signals). However, as each manufacturer's crowbar model has its own particularities, many difficulties have arisen during the development of a generic crowbar model. This fact is also related to the inability of the generic WT model to reproduce the sub-synchronous behavior of actual WTs. It should, however, also be noted that the standard IEC 61400-27-1 is not designed to evaluate the accuracy of the WT behavior just at the time a dynamic event occurs [15], [7], but to reproduce with a certain accuracy the behavior of actual WTs during the rest of the simulation period.



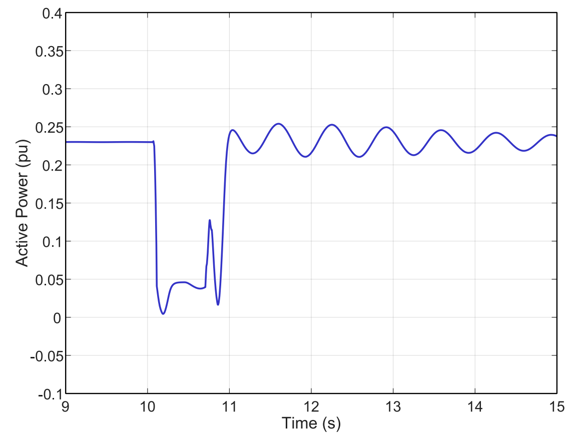
(a) Active power.



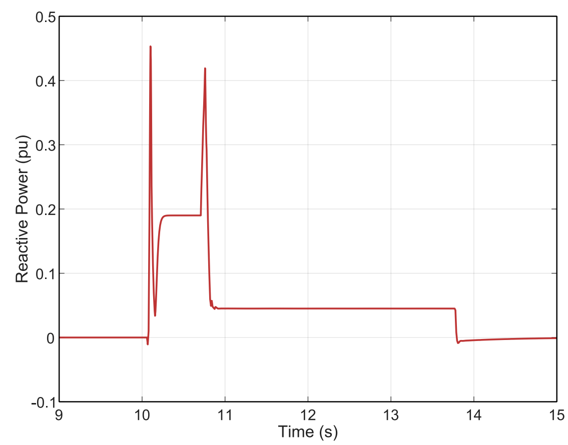
(b) Reactive power.

Fig. 6: Voltage dip 2: full load, u = 0.50 pu, t = 957 ms.

In the active power figures of the WT operating under fault conditions (Figs. 5a, 6a and 7a), after the voltage dip clearance, the amplitude and the phase shift of the responses depend on the setting of the two-mass mechanical model parameters (drive train stiffness and damping coefficients, and generator and WT rotor inertias). For example, the higher the drive train damping, the higher the damping of the active power general response. During this same simulation period (after the voltage dip clearance), there exist a post-fault reactive current injection that lengths a time period that may be set by the user, which has as consequence the injection of reactive power of a certain value (Figs. 5b, 6b and 7b). The output signal coming from the *Q Control Model* (i_{qcmd}, reactive current command, see Section II-E), corresponds therefore to this 'post-fault reactive current' during the post-fault time period set. Moreover, during the voltage dip, there is a reactive power injection aimed at stabilizing the voltage (for example, in the case of Fig. 6b, the reactive power reaches a value of 0.6 pu).



(a) Active power.



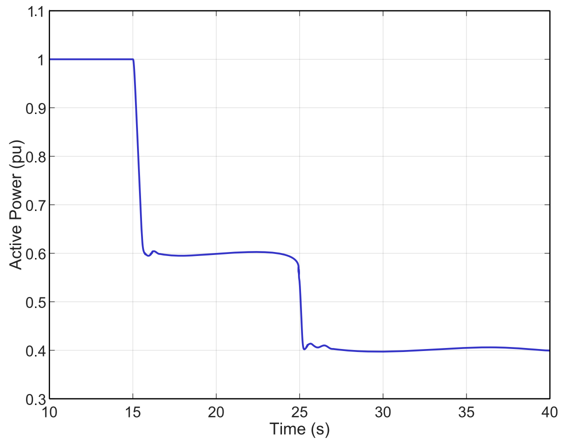
(b) Reactive power.

Fig. 7: Voltage dip 3: partial load (0.23 pu), u = 0.20 pu, t = 644 ms.

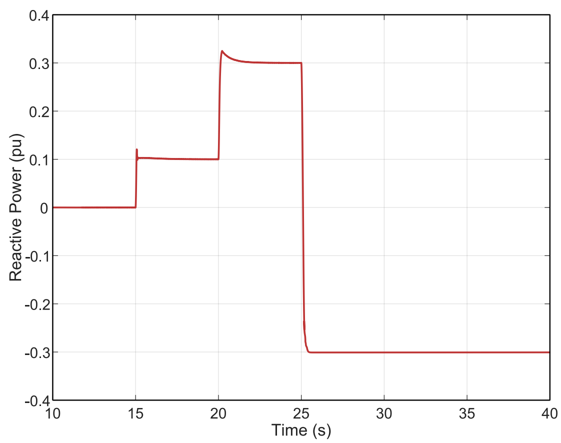
Finally, there is also the possibility of controlling the active and reactive power behavior under normal operating conditions by varying certain parameters (it should be remembered that when working with generic WT models, the wind speed is assumed to be constant during the simulation). Fig. 8a shows the active power response when changing the active power reference p_{WTref}, while Fig. 8b presents the reactive power behavior when varying the reactive power reference x_{WTref}. How quickly the active and reactive power adapt to the new setpoints largely depend on the controller parameters. It can be concluded that, in general, they reflect the good parameters setting carried out, since few oscillation periods appear at the moment the setpoints are changed.

V. Conclusions

Time-domain simulations are required by entities such as TSOs and DSOs, and also by all stakeholders related to the wind industry, to assess the dynamic performance of



(a) Active power.



(b) Reactive power.

Fig. 8: Transient responses to changes in active and reactive power setpoints.

power systems. The development of generic WT models by international standard IEC 61400-27-1 has resulted in a significant advantage in terms of having greater knowledge of the behavior of the network under different conditions. Moreover, since most of the dynamic simulation models of WTs are owned by private companies, and given their technical complexity, these generic or standard WT models allow the conduction of transient stability analyses in a straightforward and concise manner. Furthermore, they are able to reproduce the behavior of actual WTs operating under realistic conditions. However, there is still a long way to go in the improvement and validation of these generic WT models, notably in relation to the transient periods appearing at the beginning and end of a voltage dip, and also the analysis of the generic WT models' limitations. This paper is thus aimed at analysing the transient periods appearing during the dynamic simulation of the generic Type 3 WT under both normal and fault conditions. The effects of the crowbar system activation, as well as the effects of the two-mass mechanical model fitting may be clearly observed in most simulation cases. Moreover, results show the inability of the generic WT model to reproduce a sub-synchronous behavior where there is an active power consumption. This is mainly due, on one hand, to the difficulties associated with the development of a generic crowbar system and, on the other hand, to the non-inclusion in the standard IEC 61400-27-1 of all dynamics related to induction generator machines, as already explained in works such as [7]. Results are thus of interest to all stakeholders related to the wind industry which are, furthermore, interested in getting to know deeper the transient behavior of the most technologically advanced WT model, the generic Type 3 WT, i.e., the doubly-fed induction generator wind turbine.

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