Electromagnetic Torque Transient Control System of a Generic DFIG Wind Turbine Model

A. Lorenzo-Bonache, R. Villena-Ruiz, A. Honrubia-Escribano, E. Gómez-Lázaro, *Senior Member, IEEE*

***Abstract*—The Standard IEC 61400-27-1 intends to cover the current needs of power system operators regarding transient stability analysis of power systems. It provides generic wind turbine models adaptable to any vendor topology and simulation software, simple enough to work under RMS simulation. These models are developed under certain assumptions, trying to strike a balance between simplicity and accuracy. In these terms, depending on the flexibility or stability of the real topology, some behaviors or magnitudes may be dismissed, aiming to decrease the complexity of the model. Nevertheless, this is not the case for IEC Type 3 wind turbine model, which tries to emulate the behavior of magnitudes which are not usually relevant for stakeholders, such as aerodynamic response or electromagnetic torque.**

This work focuses on the ability of emulating the electromagnetic torque response under voltage dip conditions, illustrating its transient control possibilities in a generic Type 3 wind turbine model. The decrease of this magnitude, due to the voltage drop during the fault, as well as its recovery, can be defined in detail thanks to the complex control model. Hence, this paper may result of interest for those stakeholders involved in the development and adjustment of generic wind turbine models.

***Keywords*—Generic model, IEC 61400-27-1, DFIG, Type 3, Electromagnetic Torque, Transient Control**

I. Introduction

Generic wind turbine (WT) models developed by the International Electrotechnical Commission (IEC) intend to cover the needs of power system operators in the field of transient stability analysis [1]. The IEC 61400-27-1 "Electrical simulation models - Wind turbines" [2] proposes simplified WT models which allow to conduct these analysis as accurately as possible, but without the complexity of EMT models [3]. They are defined by a limited number of parameters, implementable in any simulation software and publicly available. Their simplicity allows them to be adjusted to any real WT model without the need of specific manufacturer parameters or software, which are usually confidential [4]. Furthermore, high computational resources are not needed (i.e., simulations are usually conducted with time steps from 1 to 5 ms) [5]. Nevertheless, this simplicity involves certain limitations and assumptions. As an example, nowadays, only positive sequence models are developed, and hence, only balance three-phase voltage dips can be emulated [6].

This work was supported by the "Ministerio de Economía y Competitividad" and European Union FEDER, which supported this work under project ENE2016-78214-C2-1-R. A. Lorenzo-Bonache, R. Villena-Ruiz, A. Honrubia-Escribano and E. Gómez-Lázaro are with the Renewable Energy Research Institute and DIEEAC-EDII-AB. Universidad de Castilla-La Mancha, 02071 Albacete, Spain (email: alberto.lorenzo@uclm.es; raquel.villena@uclm.es; andres.honrubia@uclm.es; emilio.gomez@uclm.es

Paper submitted to the International Conference on Power Systems Transients (IPST2019) in Perpignan, France June 17-20, 2019.

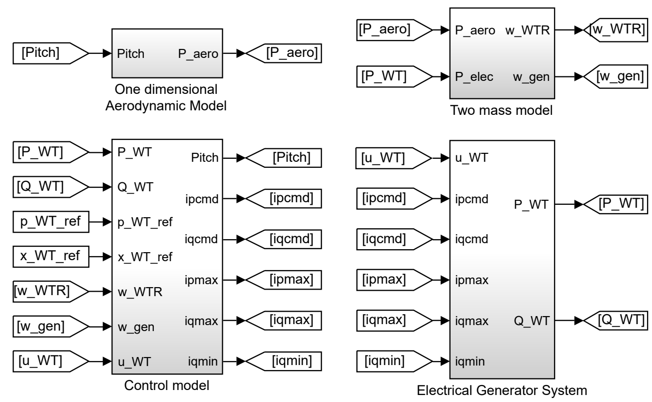

Fig. 1. General structure of a generic Type 3 WT defined by IEC 61400-27-1

The Standard IEC 61400-27-1 was published in 2015. It classifies all the existing WT models in four types, mainly according to the electrical generator. For this paper, authors focus in Type 3 WT, which represents a WT equipped with a doubly-fed induction generator (DFIG), in which the stator is directly connected to the grid, and the rotor is connected via a power converter converter (rated at 30-40 % of the nominal power of the WT) [7]. This topology is equipped with variable pitch blades as well. The flexibility provided by the power converter and the variable pitch, along with the relatively low cost of the power converter (e.g., a full-converter WT – Type 4 – needs a converter rated at nominal power, which involves larger costs), have made this topology the most widespread in current power systems [8]. The modular structure of a Type 3 generic model defined by IEC 61400-27-1 is shown in Fig. 1. Furthermore, the systems included into the 'Control model' are depicted in Fig. 2. The control model provides the active and reactive command currents ($ipcmd$ and $iqcmd$, respectively), which are the main inputs to the electrical generator system. For the case of Type 3, the electrical generator system is based on the simplification of a real DFIG [9], [10], including the crowbar protection system [11] and grid coordination. Control model works according to the active and reactive power references (p_WT_ref and x_WT_ref, respectively), which can be commanded by the wind farm model or manually set.

The relevance of this topology nowadays is reflected in the generic model defined by the Standard. It includes the most complex systems to control its behavior during a voltage dip. To see the big picture of this fact, the generic Type 3 WT model is defined by more than 400 blocks and 100 parameters.

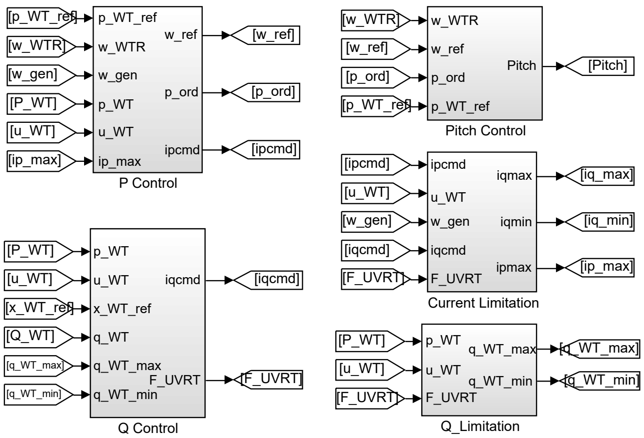

Fig. 2. Control systems included the 'Control model'

In comparison, the generic Type 4 WT model is defined by, approximately, 250 blocks and 55 parameters. The higher flexibility and stability provided by the full-converter of the Type 4 involves the dismissing of aerodynamic parts and most of the active power control systems [12].

This work focuses in the analysis of the electromagnetic torque transient control systems. The electromagnetic torque cannot be maintained by the WT during a voltage dip, due to the decrease of voltage magnitude [13]. Nevertheless, other model topologies (e.g., IEC's generic Type 4 model) or even DFIG model from other guidelines (e.g., WECC's "Second Generation of Wind Turbine Models" [14]) neglect the variation of electromagnetic torque [15]. Indeed, generic WT models are defined to provide an accurate response in the WT terminals (i.e., internal variables do not have to be necessarily emulated). Thus, for these simpler models the electromagnetic torque is kept constant (pre-fault value) during and after the fault [16]. In contrast, the IEC Type 3 active power control includes a complex electromagnetic torque system which intends to emulate, as accurately as possible, the behavior of this magnitude during and after the fault [17]. The Type 3 WT model has been developed in the simulation software MATLAB/Simulink. Authors validated its behavior in previous works [18], [19]. A three-phase voltage dip measured in a real wind farm is used to test the different behaviors of the system. To test the flexibility of control, the most important parameters which define the behavior of this system are modified within a certain range. The main contributions of this paper are: i) Provide a comprehensive description of the operation of the electromagnetic torque control system of the IEC Type 3 WT model, and ii) showing the impact of varying its main parameters in the response of the system when it faces a voltage dip. This study focuses for the first time in analyzing electromagnetic torque which, at first, may be seen as a secondary magnitude in the behavior of generic models, but in fact, it deeply influences to active current and power response. Thus, this work may result of interest to those stakeholders involved in the modeling and validation of generic DFIG WT models.

The rest of the paper is structured as follows. After this introduction, Section II depicts the behavior of the different parts of the electromagnetic control system. Then, Section III shows the different tests which have been conducted to test the adaptability of the system to the behavior of a real WT. Finally, Section IV shows the conclusions of the paper.

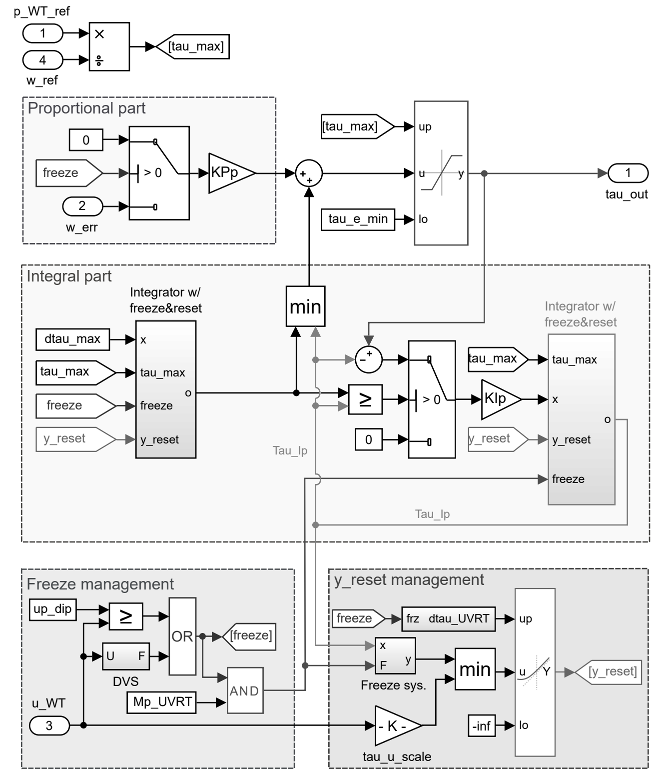

Fig. 3. Electromagnetic torque control system.

II. Electromagnetic torque control system

The electromagnetic torque control system of the generic Type 3 WT model defined in the IEC 61400-27-1 is included in the active power control system (*P Control* – Fig. 2) and is shown in Fig. 3. The inputs to this system are:

- p_WT_ref: Active power reference of the WT. Defines the active power that the WT should inject to the grid. Can be manually set or provided by a wind farm control system. For this work, it is set as $1\ pu$.
- u_WT: Voltage magnitude measured in the WT terminals. For this work, authors use the voltage profile of a voltage dip measured in a real wind farm.
- w_ref: Generator speed reference. This speed reference is defined by the characteristic *Torque-speed* curve of the WT [20]. This curve defines the speed at which the WT should be rotating when it is providing a certain electromagnetic torque. For the IEC model, this speed is provided by the active power control system via a lookup table.
- w_err: Speed error. Is the result of subtracting the speed reference to the actual generator speed.

The electromagnetic torque system defined in the IEC 61400-27-1 have been subdivided in different parts in order to clarify its behavior (Fig. 3). The output of the system is calculated as the sum of a proportional and an integral part. The sum is saturated with the value tau_max, which represents the electromagnetic torque reference (calculated as p_WT_ref/w_ref). The following sections depict the operation of these parts.

A. Freeze management

This part provides the freeze states which define the moments in which the system is operating under fault or post-fault conditions. While the voltage magnitude is lower than a threshold (up_dip), the output *freeze* takes the value of 1. As explained in the following sections, this involves that the output of the different parts is modified from the steady-state value, working in fault condition. Furthermore, for severe faults ($u\_WT \leq 0.1\, pu$) the system can be frozen for a certain additional post-fault period, defined by the time t_{DVS}. Finally, the parameter Mp_UVRT allows to control the active power control mode: reactive power control (0) or voltage control (1).

B. y_reset management

The value y_reset is the output of the integral part during the freeze period. This value is calculated as the minimum between two possibilities:

- A value proportional to the voltage magnitude, calculated by multiplying $u\_WT \cdot tau\_u\_scale$. Varying tau_u_scale allows controlling the torque value during the fault.
- The pre-fault value of Tau_ip (Fig. 3), which, under normal conditions, is the steady-state torque. This steady-state torque is kept constant during the fault.

Basically, y_reset is calculated via the proportional voltage relationship, except in those cases in which the WT is injecting torque lower than this value (i.e., the WT cannot inject during the fault a torque larger than the steady-state one).

Furthermore, this part allows controlling the rising rate of y_reset during the fault. This fact is important when the voltage profile shows a spike at the beginning of the fault (as it is the case of this work). If the upper rate limit ($dtau\_UVRT$) is set to 0 during the fault, y_reset takes a low value when the spike occurs, which cannot be recovered once the spike ends. Adjusting the value $dtau\_UVRT$ allows controlling the response during the fault when these transient behaviors occur.

C. Proportional part

The behavior of the proportional part of the controller is based on a conventional proportional controller. The input is w_err, which is multiplied by the proportional gain KPp. During the *freeze* period, this part takes the value of 0. Hence, this system does not have any influence during the fault. Nevertheless, once it is cleared, w_err takes a positive value (the WT accelerates during the fault due to the lack of electromagnetic torque to counter the mechanical wind torque). Thus, the bigger KPp, the faster the electromagnetic torque reaches the steady-state value.

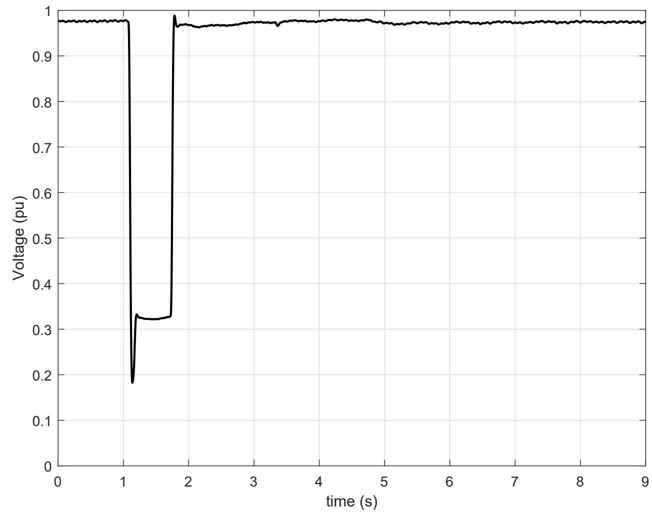

Fig. 4. Three-phase voltage dip voltage profile.

D. Integral part

During steady-state, the integral part value is the nominal torque, which coincides with the reference torque (tau_max). When the fault takes place, the output takes the value y_reset (Section II-B). Finally, when the freeze state ends, the integral part is calculated as the minimum value between two different responses:

- Beginning from the value y_reset, the value increases as a ramp with constant rate $dtau\_max$. This value can be defined either because of limitations of the WT or due to limitations imposed by a grid code.
- The output of an integral controller (Tau_ip), the reference of which is the output of the torque system (tau_out). If this value is higher than the value of the ramp defined by $dtau\_max$, an anti wind-up system actuates. Thus, the adjustment of KIp allows controlling the rise behavior of tau_out itself, which behaves, in fact, as a first order system.

The integral part will finally reach the steady-state value, correcting the rotational speed error.

III. Results

This section depicts the effects of varying the parameters included in the control system in the response of the electromagnetic torque when a fault occurs. Fig. 4 shows the measured profile of the voltage dip used in this work to test the different features of the electromagnetic torque control system.

First, Fig. 5 shows the effect of varying the proportional relationship between the voltage and the electromagnetic torque during the fault (tau_u_scale). For this case, the parameter $dtau\_UVRT$ is set to infinite. It is shown how the electromagnetic torque value during the fault is modified, proportionally to the voltage level. The adjustment of this parameter results crucial, since it influences not only the value during the fault, but also the value from which the torque starts rising, and consequently, the rising time.

Fig. 6 shows the effect of limiting the rising rate of electromagnetic torque during the fault ($dtau\_UVRT$). As

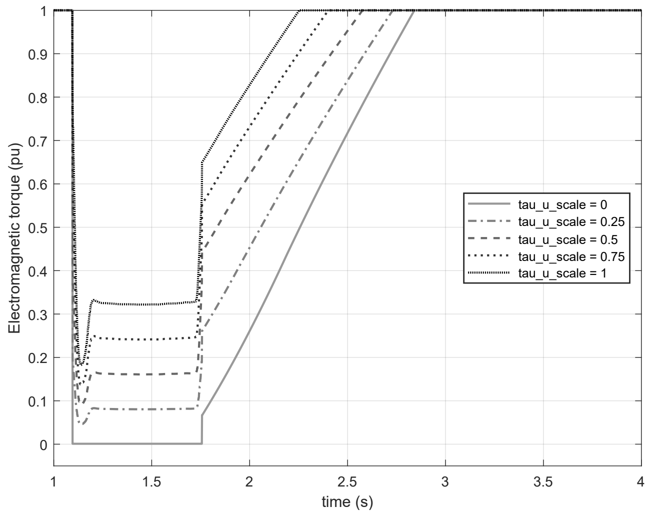

Fig. 5. Effect of varying tau_u_scale in electromagnetic torque.

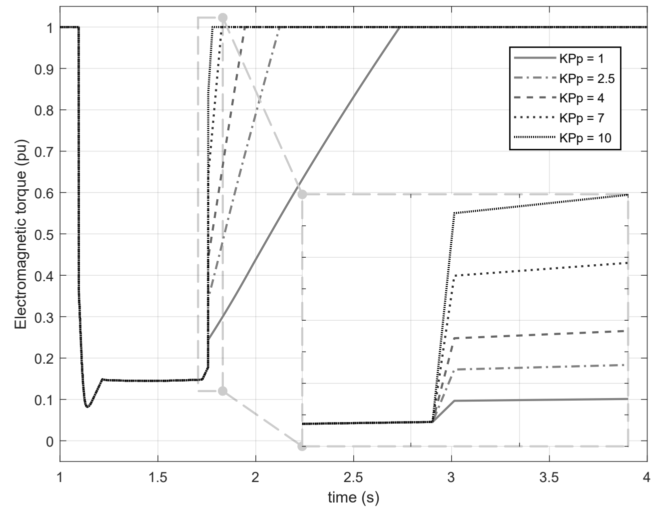

Fig. 7. Effect of varying KPp in electromagnetic torque.

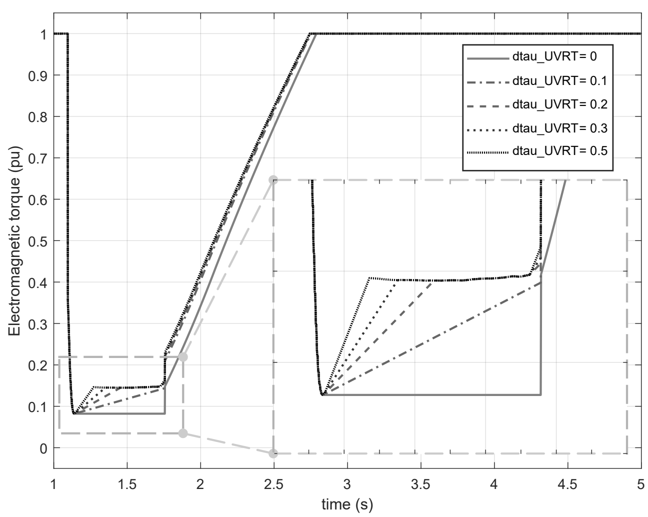

Fig. 6. Effect of varying $dtau\_UVRT$.

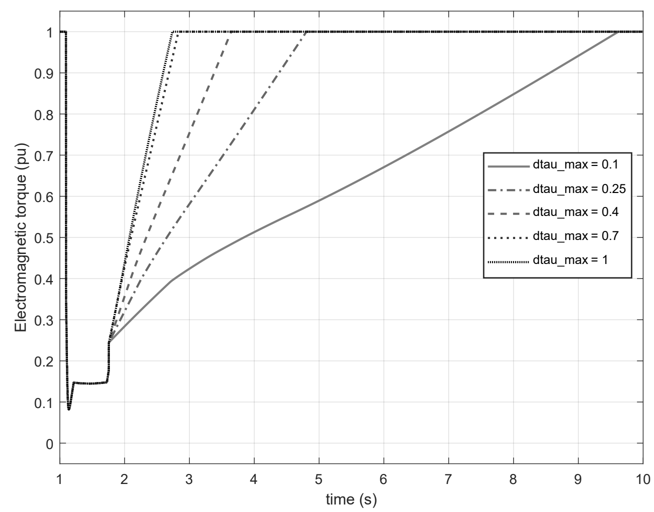

Fig. 8. Effect of varying $dtau\_max$ in electromagnetic torque.

shown in Fig. 4, the voltage dip shows a large spike when the fault occurs. If the rising rate is limited (i.e., $dtau\_UVRT = 0$), the value y_reset is set proportionally to the lowest voltage value and it cannot rise after the spike. Then, as $dtau\_UVRT$ takes bigger values, the electromagnetic torque is able to follow the voltage profile. Hence, this value should be adjusted depending on the behavior of the real WT regarding this transient period.

The effect of variating the proportional constant (KPp) is shown in Fig. 7. The proportional part of the controller is neglected during the fault. Then, the rotational speed error is used as input to recover steady-state. Since the WT accelerates during the fault due to the lack of electromagnetic torque, the rotational speed error is positive once the fault ends. Thus, the output of the proportional part increases suddenly when the fault is cleared. As shown in the zoom of Fig. 7, the bigger KPp is, the faster increases the value of electromagnetic torque just after the fault. This fact have its consequence in the rate at which electromagnetic torque recovers the steady-state value as well.

Regarding the behavior of the integral part, Fig. 8 shows the consequences of varying the maximum rising rate of electromagnetic torque ($dtau\_max$). The integral constant (KIp) is set to a large value, guaranteeing that the output of the integral part is the constant rate ramp (see Section II-D). The effect of modifying this variable is visible: it defines the rate at which the electromagnetic torque rises once the fault is cleared, starting from the point defined by KPp. The value of this parameter depends either on the characteristics of the WT or on the limitations imposed by a grid code.

Finally, Fig. 9 shows the effect of varying the integral constant of the system (KIp). The input to the integral controller is the electromagnetic torque itself. Thus, adjusting KIp allows controlling the settling time of the system, the limitation of which is imposed by the parameter $dtau\_max$.

Thus, with the adjustment of these 5 parameters, the response of electromagnetic torque during and after the fault can be controlled in a very flexible manner. The parameter tau_u_scale allows fitting the value during the fault, and with the adjustment of $dtau\_UVRT$ the behavior facing a voltage

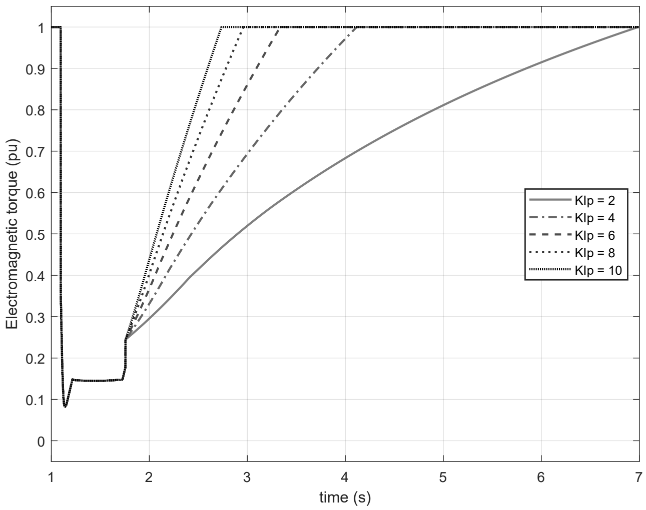

Fig. 9. Effect of varying KIp in electromagnetic torque.

spike can be modeled as well. The rise of electromagnetic torque can be controlled in detail. The proportional constant allows controlling the point from which the torque rises, and with the adjustment of $dtau\_max$ and KIp, the rise response can be fully fitted.

IV. Conclusions

The assumptions and limitations of generic WT models result in different approaches in their development. The magnitudes which should be properly emulated for stakeholders are usually the active and reactive currents and powers. This involves that magnitudes such as the rotational speed or the electromagnetic torque are usually dismissed. As an example of this, the IEC generic model of a full-scale WT completely neglects both of them due to the stability provided by the full-power converter. By contrast, the generic model of a DFIG WT (Type 3) tries to fully emulate these responses. The electromagnetic torque control system, included within the active power control system intends to emulate the decrease of this magnitude when a voltage dip occurs. This paper shows the different features included in this system.

A comprehensive analysis of the operation of the electromagnetic torque control system facing a voltage dip was conducted. Moreover, in order to test the abilities of this system, authors used the voltage profile of a real voltage dip measured in a wind farm to conduct several simulations in which the values of the main parameters of this system are varied in a certain range. The electromagnetic torque response is able to adapt its magnitude when facing voltage dips during and after the fault. Furthermore, the behavior facing transient periods, such as spikes in the voltage profile, can be emulated. These features allow Type 3 generic model to provide accurate results when modeling these grids perturbations. It is worth noting that, despite the study of electromagnetic torque is usually dismissed in the literature regarding generic models, its fine adjustment allows to control important magnitudes, such as active current or power. This paper may be of interest for those stakeholders who need to understand the operation of a generic Type 3 WT model, as well as for those who need to adjust the response of a generic model to that of a real WT.

References

[1] P. Sørensen, "Introduction to IEC 61400-27. Electrical simulation models for wind power generation," *EERA Workshop on Generic electric models for wind power*, 2012.

[2] *IEC 61400-27-1. Electrical simulation models - Wind turbines*, International Electrotechnical Commission Std., Rev. Edition 1, February 2015.

[3] A. Honrubia Escribano, E. Gomez-Lazaro, J. Fortmann, P. Sørensen, and S. Martín-Martínez, "Generic dynamic wind turbine models for power system stability analysis: A comprehensive review," *Renewable & Sustainable Energy Reviews*, vol. (In Press), 2017.

[4] S. Seman, "Need for confidentiality. A converter manufacturer's view," *1st Wind Integration Symposium*, p. 30pp, 2011.

[5] J. Fortmann, S. Engelhardt, J. Kretschmann, C. Feltes, and I. Erlich, "New generic model of DFG-Based wind turbines for rms-type simulation," *IEEE Transactions on Energy Conversion*, vol. 29, no. 1, pp. 110–118, 2014.

[6] P. Pourbeik, J. J. Sánchez-Gasca, J. Senthil, J. Weber, A. Ellis, S. Williams, S. Seman, K. Bolton, N. Miller, R. J. Nelson, K. Nayebi, K. Clark, S. Tacke, and S. Lu, "Value and limitations of the positive sequence generic models of renewable energy systems," This is a brief white-paper prepared by an Adhoc group within the WECC Renewable Energy Modeling Task Force, December 2015.

[7] P. Sørensen, B. Andresen, J. Fortmann, and P. Pourbeik, "Modular structure of wind turbine models in IEC 61400-27-1," *IEEE Power and Energy Society General Meeting*, pp. 1–5, 2013.

[8] T. T. Cristina Vázquez Hernández and A. V. Pradas, "JRC Wind Energy Status Report 2016 Edition," Market, technology and regulatory aspects of wind energy. JRC Science for policy report, 2017.

[9] A. Lorenzo-Bonache, R. Villena-Ruiz, A.Honrubia-Escribano, and E. Gómez-Lázaro, "Comparison of a standard type 3B WT model with a commercial build-in model," *IEEE International Electric Machines & Drives Conference*, 2017.

[10] J. Fortmann, "Modeling of wind turbines with doubly fed generator system," Ph.D. dissertation, Department for Electrical Power Systems, University of Duisburg-Essen, 2014.

[11] M. B. C. Salles, K. Hameyer, J. R. Cardoso, A. P. Grilo, and C. Rahmann, "Crowbar system in doubly fed induction wind generators," *Energies*, vol. 3, pp. 738–753, 2010.

[12] A. Lorenzo-Bonache, A. Honrubia-Escribano, F. Jimenez, and E. Gomez-Lazaro, "Field validation of generic type 4 wind turbine models based on iec and wecc guidelines," *IEEE Transactions on Energy Conversion*, pp. 1–1, 2018.

[13] J. Smajo and D. Vukadinovic, "Electromagnetic torque analysis of a dfig for wind turbines," *WTOS*, vol. 7, no. 5, pp. 479–488, May 2008.

[14] WECC REMTF, "WECC second generation of wind turbine models," WECC, Tech. Rep., January 2014.

[15] Ömer Göksu, P. Sørensen, A. Morales, S. Weigel, J. Fortmann, and P. Pourbeik, "Compatibility of iec 61400-27-1 ed 1 and wecc 2nd generation wind turbine models," *15th Wind Integration Workshop*, 2016.

[16] A. Lorenzo-Bonache, A. Honrubia-Escribano, J. Fortmann, and E. Gómez-Lázaro, "Generic Type 3 WT models: comparison between IEC and WECC approaches," *IET Renewable Power Generation*, February 2019. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/iet-rpg.2018.6098

[17] J. Fortmann, "Generic aerodynamic model for simulation of variable speed wind turbines," *9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, p. 7pp, 2010.

[18] A. Lorenzo-Bonache, A. Honrubia-Escribano, F. Jiménez-Buendía, A. Molina-García, and E. Gómez-Lázaro, "Generic type 3 wind turbine model based on IEC 61400-27-1: Parameter analysis and transient response under voltage dips," *Energies*, vol. 10, no. 9, p. 23, 2017.

[19] A. Honrubia-Escribano, F. Jiménez-Buendía, E. Gómez-Lázaro, and J. Fortmann, "Field validation of a standard type 3 wind turbine model for power system stability, according to the requirements imposed by iec 61400-27-1," *IEEE Transactions on Energy Conversion*, vol. 33, no. 1, pp. 137–145, March 2018.

[20] E. A. Bossanyi, "The design of closed loop controllers for wind turbines," *Wind Energy*, vol. 3, pp. 149–163, 2000.