Authors:

Andrés Honrubia-Escribano, Francisco Jiménez-Buendía, Emilio Gómez-Lázaro, Jens Fortmann

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Abstract:

Considerable efforts are currently being made by several international working groups focused on the development of generic, also known as simplified or standard, wind turbine models for power system stability studies. In this sense, the first edition of International Electrotechnical Commission (IEC) 61400-27-1, which defines generic dynamic simulation models for wind turbines, was published in February 2015. Nevertheless, the correlations of the IEC generic models with respect to specific wind turbine manufacturer models are required by the wind power industry to validate the accuracy and corresponding usability of these standard models. The present work conducts the validation of the two topologies of variable speed wind turbines that present not only the largest market share, but also the most technological advances. Specifically, the doubly-fed induction machine and the full-scale converter (FSC) topology are modeled based on the IEC 61400-27-1 guidelines. The models are simulated for a wide range of voltage dips with different characteristics and wind turbine operating conditions. The simulated response of the IEC generic model is compared to the corresponding simplified model of a wind turbine manufacturer, showing a good correlation in most cases. Validation error sources are analyzed in detail, as well. In addition, this paper reviews in detail the previous work done in this field. Results suggest that wind turbine manufacturers are able to adjust the IEC generic models to represent the behavior of their specific wind turbines for power system stability analysis.

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Article

Validation of Generic Models for Variable Speed Operation Wind Turbines Following the Recent Guidelines Issued by IEC 61400-27

Andrés Honrubia-Escribano [1,*], Francisco Jiménez-Buendía [2], Emilio Gómez-Lázaro [1] and Jens Fortmann [3]

1. Renewable Energy Research Institute and DIEEAC-EDII-AB, Universidad de Castilla-La Mancha, 02071 Albacete, Spain; emilio.gomez@uclm.es
2. Gamesa Innovation and Technology, 31621 Sarriguren, Spain; fjimenez@gamesacorp.com
3. Hochschule für Technik und Wirtschaft (HTW) Berlin—University of Applied Sciences, 12459 Berlin, Germany; Jens.Fortmann@HTW-Berlin.de

* Correspondence: andres.honrubia@uclm.es; Tel.: +34-967-599-200 (ext. 8216)

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Abstract: Considerable efforts are currently being made by several international working groups focused on the development of generic, also known as simplified or standard, wind turbine models for power system stability studies. In this sense, the first edition of International Electrotechnical Commission (IEC) 61400-27-1, which defines generic dynamic simulation models for wind turbines, was published in February 2015. Nevertheless, the correlations of the IEC generic models with respect to specific wind turbine manufacturer models are required by the wind power industry to validate the accuracy and corresponding usability of these standard models. The present work conducts the validation of the two topologies of variable speed wind turbines that present not only the largest market share, but also the most technological advances. Specifically, the doubly-fed induction machine and the full-scale converter (FSC) topology are modeled based on the IEC 61400-27-1 guidelines. The models are simulated for a wide range of voltage dips with different characteristics and wind turbine operating conditions. The simulated response of the IEC generic model is compared to the corresponding simplified model of a wind turbine manufacturer, showing a good correlation in most cases. Validation error sources are analyzed in detail, as well. In addition, this paper reviews in detail the previous work done in this field. Results suggest that wind turbine manufacturers are able to adjust the IEC generic models to represent the behavior of their specific wind turbines for power system stability analysis.

Keywords: doubly-fed induction machine (DFIG); full-scale converter (FSC); generic model; IEC 61400-27; model validation; power system stability; standard model

1. Introduction

A new record of wind power capacity installed in a single year was reached in 2015, adding 63 GW in a single year. More than 40% of the total renewable power capacity installed in 2015 came from wind [1]. At the end of 2015, the number of countries with more than 1 GW installed capacity was equal to 26. In this sense, the wind power capacity currently installed in the European Union (EU) is able to produce 315 TWh of electricity in an average wind year, which is enough to cover 11.4% of the EU's total electricity consumption in 2015. In several countries, wind power covers a high share of the electricity consumption. For example, in Denmark, wind energy has contributed to demand coverage with more than 30% from 2012 [2], rising up to 42% in 2015. Wind power in Spain represented the first contribution to demand coverage among all other energy sources during 2013, representing an average electricity demand coverage around 20% in the period 2012–2015 [3]. Wind capacity in Uruguay supplied 19.5% of its electricity demand in 2015 [1], and Germany is also able to cover 12% of the electricity demand with wind energy.

This rapid growth in both the installed wind capacity and the wind energy coverage has to be integrated into the power systems. For this purpose, transient stability analysis is commonly done by transmission system operators (TSOs), distribution system operators (DSOs), wind turbine manufacturers, power system software developers and technical consultants [4–23]. Dynamic models of wind power generation, which are mostly load-flow and dynamic root mean square (RMS) models [24–26], are required for these network stability studies to simulate the behavior of wind turbines in power systems. However, there is a lack of universally standardized and validated wind generator models, which is in contrast to conventional synchronous machine-based generators [13]. In fact, almost all wind turbine manufacturers have developed electro-magnetic transient (EMT)-type models, commonly referred as detailed models [12], which are able to reproduce the electrical and mechanical response of the wind turbine with the highest accuracy [15–17]. Though these detailed models were initially used for system planning and generator interconnection studies [27], they are not recommended for large-scale grid integration studies because of several reasons [10], such as the considerable amount of input parameters to characterize each wind turbine type [28] (for example, a typical General Electric gas turbine has on the order of 4000 state variables in the detailed design model, whereas planning models typically have on the order of four state variables [29]), increased computational time cost [17], confidentiality issues [7,22] and complex maintenance, and they are commonly implemented in the specific simulation software used by the wind turbine manufacturer [6]. Therefore, these detailed implementations are currently required by some TSOs only under some specific network conditions. In contrast, simplified models of wind turbines are commonly asked from wind turbine manufacturers by TSOs and DSOs for transient stability studies [30,31]. To deal with these concerns, working groups from the International Electrotechnical Commission (IEC) and the Western Electricity Coordinating Council (WECC) have been actively working during the last few years to define generic wind turbine dynamic models [32–39], which are intended for typical transient stability simulations spanning 10–30 s [14,34], where wind speed is assumed to be a constant. The term generic, also commonly known as standard or simplified, refers to a model that is standard, public and not specific to any vendor so that it can be parameterized to reasonably emulate the dynamic behavior of a wide range of equipment while not directly representing any actual wind turbine control [15,40]. Several transient and dynamic events, such as switching of power lines, loss of generation or loads and balanced faults, though these fault types are rare [41–43], represent the most interesting scenario for some TSOs [26] and are the main focus of these standard models [44,45]. Since simulation time steps for stability studies are in the order of a few ms, the converter switching dynamics, µs range, as well as other higher frequency harmonics are omitted in these simulation models [25]. In addition, some capabilities of current wind turbines, such as virtual inertia support, are out of the scope of these generic implementations.

The first meeting of the IEC 61400-27 working group was held in October 2009, and it was initially agreed to distinguish between two parts: Part 1 focused on wind turbine models and validation procedures, whereas Part 2 would present an extension of Part 1, but focused on wind power plant models. In this sense, the definition of the validation procedures was the main issue of the meetings held during 2010. The development of the generic wind turbine models was the main objective of the IEC group during 2011, and as a consequence, the first Committee Draft (CD) of Part 1 was submitted at the end of 2011. The IEC 61400-27-1 Committee Draft for Voting (CDV) version was circulated at the end of 2013 and the Final Draft International Standard (FDIS) in mid-2014, and it was finally published in February 2015 [46]. However, once Part 1 was published, it was found that Part 2 would include duplications from Part 1, and due to the similar scope, this situation could pose serious concerns related to the updates of each part. Therefore, it was decided to create a new edition of IEC 61400-27-1 in order to include the models related to both wind turbines and wind power plants in Part 1, while 27-2 would deal with the validation procedures. Based on this new structure and according to the working group meeting held in March 2016, both 27-1 Ed. 2.0 and 27-2 Ed. 1.0 are currently being prepared in parallel, and the CDV version is expected in mid-2017, while the FDIS is planned for the beginning of 2018. Several submodels of Part 1 are reviewed in [14,21], and a comprehensive review of the evolution and changes experienced by these generic models is presented in [23].

A simulation model is just a representation of reality focused on emulating the behavior of a real device under a specific event, such as a power system fault. In general, generator dynamic modeling requires some simplifications to observe the relevant characteristics of the model within a specified frequency, voltage range or time interval of interest [27]. Therefore, the response of simulation models needs to be compared against real experiments, as well as previous validated models for its worldwide acceptance. In the special case of the dynamic wind turbine models defined in IEC 61400-27-1, due to its recent development and publication, validations with respect to particular manufacturer models are urgently required by the wind power industry.

Under this framework, the aim of the present paper is to validate the two wind turbine topologies that hold the largest market share across the world, i.e., the doubly-fed induction machine (DFIG) and the full-scale converter (FSC) topology. In addition, these specific wind turbine topologies are the focus of the validation because they provide the most complex behavior due to the advanced power electronics implemented. On the one hand, the IEC 61400-27-1 generic models have been modeled in the MATLAB® software tool (MathWorks, Natick, MA, USA). Furthermore, the response of these standard models is compared to the simplified models' response of a wind turbine manufacturer. The simulations are conducted under a wide range of voltage dips with different characteristics and wind turbine load conditions. Not only the test cases defined by IEC 61400-21, but also several additional simulation scenarios are considered to identify possible modeling errors. The differences between the model responses are highlighted, aiming at providing an improved usability of the generic models. In addition, this paper also reviews previous contributions related to the validation of dynamic wind turbine generic models and performs a detailed model validation approach based on the IEC 61400-27 guidelines. In this sense and motivated by the recent development of this IEC standard, a reduced number of works may be found in the scientific literature presenting comparisons between IEC generic models and manufacturer models. However, a comprehensive model validation of different wind turbine topologies subjected to a wide range of power system disturbances is required to promote the widespread use of these standard models.

After this short Introduction, the paper is structured as follows. Section 2 introduces the main characteristics of the DFIG and FSC wind turbine topologies. After that, Section 3 provides an overview of generic wind turbine model validation approaches and summarizes the main contributions found in the scientific review conducted. Then, Section 4 provides a detailed description of the simulation and validation methodology implemented in the present work, whose results are included in Section 5. Finally, Section 6 collects the conclusions of the paper.

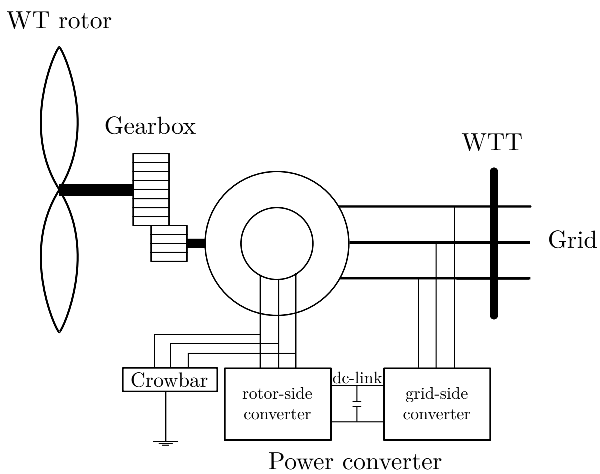
2. Generic Type III and Type IV Wind Turbine Models

Basically, there are two operation possibilities for wind turbines: fixed speed and variable speed. Fixed speed operation implies that the rotational speed of the rotor is constant and determined by the network frequency regardless of the wind speed, whereas under variable speed operation the rotational speed of the rotor is adjusted according to the incoming wind speed, which is possible due to the use of an AC/DC/AC bi-directional power converter [47]. Because of the advantages of variable speed wind turbines, such as an increased energy capture, improved power quality and reduced mechanical stresses [48], these wind turbine topologies are the most commonly sold and installed technologies in the current market [37]. In this sense, to cover most of the wind turbines topologies available in the market, four standard wind turbine types have been defined at the IEC level: (a) Type I, which stands for a directly grid-connected asynchronous generator with fixed rotor resistance; (b) Type II, which is similar to Type I, but equipped with a variable rotor resistance; (c) Type III, which represents the DIFG configuration; and (d) Type IV, which is connected to the grid through an FSC. As may be deduced, Type I and Type II are fixed speed operation wind turbines, while variable speed operation is represented by Type III and Type IV. Due to the dominance of variable speed operation wind turbines in the current market, these wind turbine types are considered in the present work. Furthermore, the simplified modeling of the asynchronous generators implemented in Type I and Type II wind turbines is quite well documented in the scientific literature and has already been implemented in most simulation tools for power system stability investigations. Therefore, the main focus from a model validation perspective is on Type III and Type IV, whose main characteristics are described as follows.

2.1. Type III Wind Turbine Model

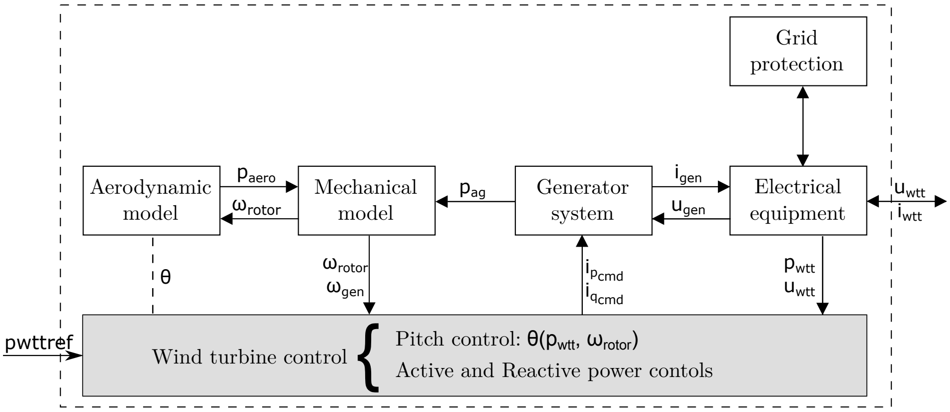
A DFIG wind turbine is composed of a wound rotor induction generator where the frequency converter is connected between the rotor terminals and the grid, whereas the stator is directly coupled to the grid. This configuration allows a rotational speed operation between −40% and +30% of synchronous speed [4,48]. The power converter is composed of two independent controlled voltage source converters connected to a common DC-link. The rotor-side converter is normally employed to control the rotational speed and reactive power exchange with the grid via its stator terminals [49], while the grid-side converter is adopted to regulate the DC-link voltage and the reactive power exchange with the grid [47].

Recent grid codes require grid-connected wind turbines to remain connected to the power system under certain network disturbances, which is commonly known as the fault ride-through (FRT) requirements [50]. When a voltage drop, resulting from a fault, for example, occurs at the DFIG terminals, high currents will appear in the rotor [5,11]. Therefore, the implementation of a DC-chopper and/or an AC-crowbar are the solutions typically used by manufacturers in order to protect the rotor against over-currents and over-voltages caused by voltage drops [20,49]. Actually, ABB (Turgi, Switzerland) designs use a crowbar on their commercial Type III wind turbines, which is basically a resistance connected in series with the rotor circuit [30]. As a result, IEC 61400-27-1 has defined two versions of Type III generator models: Type IIIA, which stands for a wind turbine design without a crowbar; and Type IIIB, which represents a wind turbine equipped with a crowbar. The present work is focused on the validation of a Type IIIB model because this wind turbine type represents a relevant share in the current market [51], and it has some extra modeling complexities specifically related to the crowbar operation that need to be further analyzed. Figure 1 shows the typical configuration of a Type IIIB wind turbine, whose main electrical and mechanical components are included in Figure 1a, and the block diagram of the corresponding simulation model is in Figure 1b.



(a)

Figure 1. *Cont.*

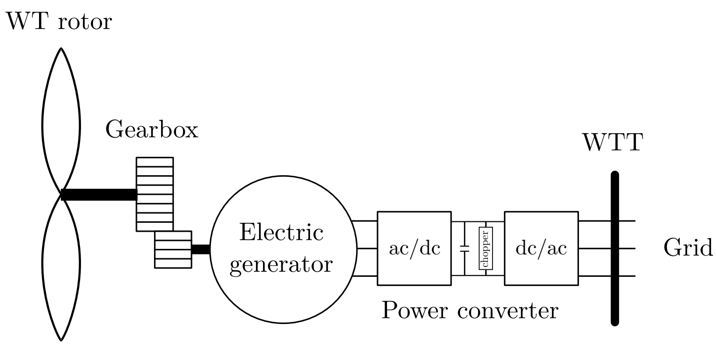


(b)

Figure 1. Configuration of a Type IIIB wind turbine. (**a**) Main elements; and (**b**) corresponding model block diagram. WT: wind turbine; and WTT: wind turbine terminals.

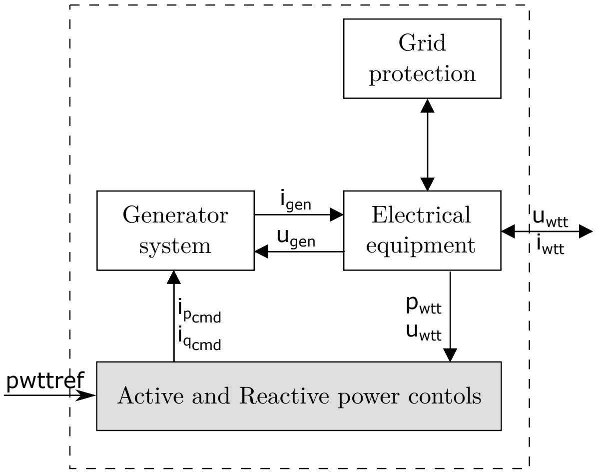
2.2. Type IV Wind Turbine Model

The generator used in this variable speed wind turbine topology may be either an induction or a synchronous machine; Siemens Wind Power Type IV wind turbines are commonly equipped with induction generators [25]. Some Type IV wind turbines use direct drive synchronous generators without a gearbox. Their common characteristic is that the total generated power is processed through the power converter [6]. This converter is responsible for providing an active and reactive power control over a wide range of generator speeds. Precisely, two versions of Type IV generic models have been defined at the IEC level depending on the power converter configuration implemented by the manufacturer for FRT purposes [34–36]: Type IVA, which stands for wind turbines equipped with choppers on the DC-link (these can normally be modeled neglecting the aerodynamic and mechanical components of the wind turbine); and Type IVB, which represents wind turbines without a chopper; as a consequence, post-fault power oscillations are injected because of torsional oscillations, so an additional two-mass mechanical model is thus needed [36]. In the present work, a generic model of a Type IVA wind turbine is modeled and validated with the simplified model of the manufacturer because Type IV wind turbines equipped with choppers are both more commonly used to meet grid code requirements and present a complex response due to the chopper implementation. Figure 2 shows the typical components of this Type IVA configuration together with the corresponding simulation model.



(a)

Figure 2. *Cont.*



(b)

Figure 2. Configuration of a Type IVA wind turbine. (**a**) Main elements; and (**b**) corresponding model block diagram.

3. Need for the Validation of Generic Wind Turbine Models

Model validation is a key requirement if a wind turbine model is to be used with confidence in power system stability studies. The validation of a wind turbine model is intended to ensure that for each event, especially during severe transient disturbances [7,13], the dynamic response generated by the wind turbine model matches, to the extent possible, the benchmark dynamic response [52].

Basically, two types of model validation are identified according to the validation benchmark source [27]: validating the dynamic model against measured data, either from on-site field tests or laboratory experiments [53], or validating the software model against a vendor verified model. Each validation type presents different characteristics. The main drawbacks related to the first option are the inaccuracy in measurements and the difficulties in getting field data of wind turbines operating at varying conditions; whereas the access to the specific manufacturer model is usually limited by a non-disclosure agreement in the second alternative. A reasonable approach to overcome these concerns is outlined in [52], consisting of using real event records for the validation of a detailed EMT wind turbine model firstly, and in a second step, this validated EMT model is applied in simulations for the validation of a simplified RMS model for power system stability. Some authors emphasize that since the goal of generic modeling is to replace vendor-specific models, validation against vendor-specific models is both sufficient [54] and the easiest and least expensive validation method [13]. Actually, detailed manufacturer models have been historically accepted to develop and validate simplified models [4,9]. Specifically, when the first generation of WECC generic dynamic wind turbine models was published in 2010 [55,56], vendor detailed models were considered the only benchmark available for validation due to the lack of real measurements [17,32].

In addition, from the IEC 61400-27 working group perspective [33,34], two validation approaches are defined according to the input to the simulation model: the full grid simulation approach, where both the wind turbine system and the equivalent power system and the interface between the wind turbine and the grid are modeled; and the playback approach, where only the wind turbine system is modeled and one of the measured signals, typically voltage, is played-back into the simulation model while the responses of the other quantities, typically active and reactive current, are used for validation purposes. Since the grid model is not considered in the playback approach, additional uncertainties are not included, and the differences between simulation results are thus reduced. In this sense, these two simulation methodologies are compared under a power factor change event in [22], where it is observed that the full grid simulation approach is able to capture only the non-oscillatory behavior, while the playback approach can capture the impact of the oscillatory grid voltage. Therefore, the playback validation method is recommended by IEC guidelines for assessing the model accuracy [34], and it will be followed in the present work for validation purposes. Once the measurements and the simulations, or the generic model simulations and the manufacturer model simulations depending on the validation benchmark source used, have been performed, a methodology to compare the results is essential to quantify the deviation between them [24,33]. In this line, for power system stability simulations, equipment models usually have bandwidths in the range of 0.1 Hz–10 Hz [7,57]. Therefore, the resulting signals have to be filtered with a 15-Hz low pass filter before they are compared [34]. Furthermore, it is also necessary to adjust the same time step between the validation benchmark sources, i.e., downsampling or downscaling the data. To sum up, Figure 3 describes the validation methodology followed by IEC 61400-27, which is implemented in the present work (more details in Section 4). On the left side of this figure are shown the input measurements and tests to be conducted according to IEC 61400-21 [58]. It should be noted that the IEC 61400-27 validation procedure does not define specific test and measurement procedures because these are based on the tests specified in IEC 61400-21. Positive sequence values of active and reactive current components, i_p and i_q, must be calculated using the fundamental positive sequence voltage and current phasors. In this sense, six methods to estimate reactive power are evaluated in [59], where several reasons are provided to promote the use of the positive sequence of the fundamental method.

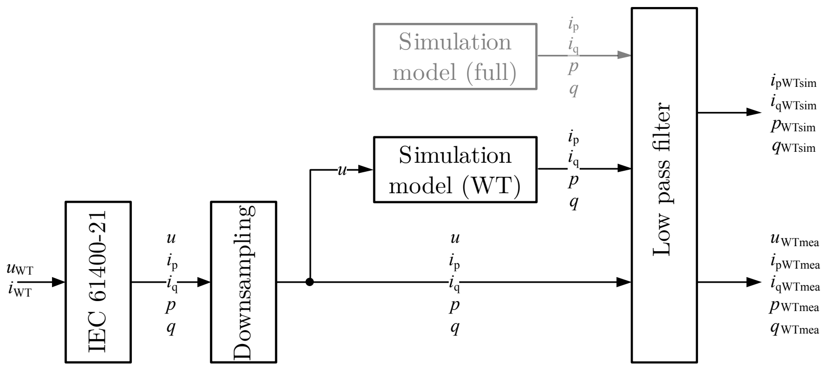


Figure 3. Methodology to compare simulation results for validation purposes according to the IEC 61400-27 guidelines: full grid simulation (in grey) and playback approaches.

With regard to power quality and from a grid code perspective, voltage dips are the most relevant concerns. A voltage dip is described as a decrease in RMS voltage between 90% and 10% of the rated voltage, with a duration between 0.5 cycles and 1 min [60]. Voltage dips are commonly characterized by two parameters [41–43]: residual voltage, also known as dip magnitude and defined by the minimum RMS value measured, and dip duration, the time during which RMS values in any phase are within the voltage range previously defined. In order to characterize the model accuracy for the simulation of voltage dips, three adjacent windows are defined according to IEC 61400-27 [34,61]: a pre-fault, a fault and a post-fault window. The fault window starts when the short circuit occurs in one of the phases for the first time and ends when the fault is cleared in one of the phases for the first time. The pre-fault and post-fault windows are adjacent to the fault window, with durations equal to 1000 ms and 5000 ms, respectively. In each window, three characteristic parameters must be calculated: the mean error, x_{ME}, the mean absolute error, x_{MAE}, and the maximum absolute error, x_{MXE}. In order not to consider transient errors, this x_{MXE} is used to quantify the maximum absolute errors in the quasi-steady state calculation windows following the transient periods in the beginning of the fault window (140 ms transient delay not considered) and the post-fault window (500 ms transient delay not considered). It should be noted that the errors in the pre-fault window are not quantifying the quality of the model, but rather the external condition prior to the test. Therefore, as the present work implements the playback validation approach, the errors associated with the pre-fault window are not considered.

Due to the recent development and publication of IEC 61400-27-1, a very reduced number of contributions are found in the scientific literature focused on evaluating the correlation between generic wind turbine models and manufacturer models. A Type III wind turbine model implemented in Siemens-PTI PSS®E commercial software (Siemens AG, Munich, Germany) for stability studies by the Canadian TSO Hydro-Quebec (Montreal, QC, Canada) is validated with a detailed model developed in MATLAB®/SimPowerSystems™ (MathWorks, Natick, MA, USA) in [9], and a good correlation is observed. However, only three simulation scenarios are used for validation. In addition, the same DFIG RMS model developed by Hydro-Quebec is compared with the generic model included in the library of Siemens-PTI PSS®E, and an insufficient correlation is specifically noted with regard to the reactive power response. Two generic wind turbine models—a 1.5-MW Type III and a 2.5-MW Type IV—are implemented for the latest wind turbines from the manufacturer GE Energy in the GE PSLF dynamic simulation program (GE Energy Consulting, Schenectady, NY, USA) and compared to the corresponding detailed models in [10]. The correlation results for one voltage event with a dip magnitude equal to 0.2 pu and a 150-ms duration shows that the generic model matches the detailed model representation of GE Energy wind turbines. GE Energy RMS models are also used to validate a Type III and a Type IV wind turbine topology implemented in the Power System Toolbox, which is a MATLAB®-based package, in [18]. In this line, the wind turbine manufacturer Siemens Wind Power has developed and validated generic dynamic simulation models for the 2.3-MW and 3.6-MW Type IV wind turbines through the DIgSILENT PowerFactory software platform (DIgSILENT GmbH, Gomaringen, Germany) for power system stability analysis [25,26]. Three reduced models for a 1.5-MW direct-drive Type IV wind turbine are validated by comparing the dynamical response with the wind turbine full order models developed in PSCAD™ (Manitoba HVDC Research Centre, Winnipeg, MB, Canada) under one voltage dip simulation in [62]. Furthermore, a few validations of generic models against detailed manufacturer models are included in the report where the WECC first generation of generic models are described [32,55,56], although the number of simulations is quite reduced, being limited to one simulation per wind turbine manufacturer. In this sense, WECC generic models were mainly focused on representing the behavior of wind turbines installed in the USA and, thus, fulfilling U.S. grid code requirements [37]. It should be remarked that there are significantly varying views around the world related to model validation; some regions, such as Europe, focus on a detailed analytical approach to model validation, which is attempting to identify a quantitative measure of model accuracy, while others, such as the USA, take a more qualitative approach relying on engineering judgment [15,52]. A few recent contributions deal with generic IEC 61400-27-1 model implementations and validations. Specifically, a generic IEC Type IIIB model is validated against a detailed model implemented in PSCAD™/EMTDC™ in [19]; but only one voltage dip event is considered for validation purposes, and there is no comparison to a particular manufacturer wind turbine model response. Some other works have implemented different generic IEC wind turbine topologies, but no validation with manufacturer models or field measurements is conducted. For example, Type I, Type IIIA and Type IVB generic IEC wind turbine topologies are implemented in several software tools in [16,21,28,44], the need for a validation being highlighted. In fact, the same author conducts the validation of this Type I wind turbine in [17,45] against one voltage dip event using the playback approach.

From this scientific review, it is worth noting the difficulties associated with the widespread use of the IEC generic models due to not only the reduced number of correlations provided by manufacturer models, but also the low number of simulation scenarios considered in each validation. This paper provides the validation of the two wind turbine topologies with the largest market share—Type IIIB and Type IVA—based on the specific models of a wind turbine manufacturer. Furthermore, an additional contribution of this work consists of the implementation of the validation methodology proposed in the IEC 61400-27, which is detailed in Section 4 together with the characteristics of the 45 different test cases simulated.

4. Methodology

A detailed validation methodology is required to estimate the accuracy of simulation models. The main aspects of the validation procedures included in both the German FGW TR4 (DIgSILENT Gmbh) [63] and the IEC 61400-27 are discussed in [53], where it is finally recommended to adopt the recent IEC validation procedure into the German procedure to benefit from the improvements made. The present section details the validation methodology followed in the present work, which is based on the IEC 61400-27 guidelines. In order to develop a comprehensive model validation, a wide range of different simulation scenarios associated with power quality disturbances has been considered using the two wind turbine topologies that hold the largest market share: DFIG and FSC topologies. Specifically, voltage dip magnitude and duration, as well as several wind turbine load conditions have been taken into account for validation purposes based not only on the test cases defined by 61400-21 [58], which are required by the IEC 61400-27 guidelines, but also on some additional simulation scenarios considered. In this line, five test cases are carried out in the present work with regard to the voltage dip parameters involved in the simulations, as follows:

- 1% dip magnitude and 140-ms duration (test case not required by IEC 61400-21);
- 20% dip magnitude and 200-ms duration;
- 50% dip magnitude and 500-ms duration;
- 75% dip magnitude and 500-ms duration (test case not required by IEC 61400-21);
- 85% dip magnitude and 500-ms duration.

For each couple of voltage dip parameters, each test case is repeated five times to take into account different load conditions. Specifically, active power delivery has been considered equal to 20%, 40%, 80% and 100% of wind turbine capacity. In addition, in the 100% active power simulation test, two scenarios for wind speed have been considered for the Type IIIB model simulation: 1.1 per unit wind speed and 1.8 per unit wind speed. Therefore, the total number of simulations performed is equal to 25 for the DFIG wind turbine model and 20 for the FSC. It should be noted that some of the tests carried out are not required by IEC 61400-21 [58]. Specifically, with regard to the load condition, only three tests for the wind turbine operating between 10% and 30% of rated power and three tests for the wind turbine operating over 90% rated power are required according to this standard. However, several additional test cases have been included in the present work in order to find out possible modeling errors, as is discussed in the results provided in Section 5.

In the present work, the manufacturer simplified models were executed at a rate of 1 ms while the IEC standard models were executed at a rate of 5 ms; as noted in Section 1, generic models use integration time steps in the order of 1 ms–10 ms [37], which is in accordance with the typical time step used for RMS simulations, and thus, some TSOs state in their grid codes that wind turbine models must be able to run with integration time steps larger than 5 ms or 10 ms [9]. Each simulation has a duration equal to 10 s, which is in line with common transient stability simulations [14,34], and the voltage dip is generated after 1000 ms from the simulation start. Finally, the comparison between the results offered by the two simulation sources—the generic IEC 61400-27-1 model and simplified manufacturer model—was done at a rate of 10 ms. To sum up, the simulation and validation methodology conducted in the present work are based on the execution of an automated procedure designed in the MATLAB® software tool, which comprises the following steps:

(1) Choose a couple of voltage dip parameters;
(2) Choose a wind turbine load condition;
(3) Conduct the simulation of the manufacturer simplified model with the specific parameters defined at Steps 1 and 2;
(4) Save the main magnitudes of the manufacturer model simulation, such as voltage, current, power, speed and/or torque;

(5) Modify the wind turbine load condition and conduct the next simulation scenario by repeating Steps 2–4 until all simulations are performed for the couple of voltage dip parameters defined in Step 1;
(6) Modify voltage dip parameters and repeat Steps 2–5. Therefore, once Step 6 is concluded, all of the simulation scenarios associated with the simplified manufacturer wind turbine model have been conducted;
(7) Repeat Steps 1–6 using the generic IEC model implemented based on IEC 61400-27-1 [46]. Model parameters used for simulation are included in Appendix A. An additional input to this IEC model is the voltage profile, which is added from the voltage obtained in the simulation of the manufacturer model carried out at Step 4. It should be noted that all of the test cases have been simulated firstly in the manufacturer simplified model, and then its voltage output is used as input for the generic IEC model simulation. This is done in order to simulate the IEC models in playback mode as explained in Section 3 and represented in Figure 3. Hence, once Step 7 is concluded, all of the simulation scenarios considered for the IEC generic wind turbine model have been conducted.
(8) Results comparison: Each similar test case is loaded, and the sample rate is adjusted to 10 ms for both the manufacturer and IEC simulation results. Then, the output signals are filtered as defined in IEC by means of the implementation of a 15-Hz Butterworth filter, as previously explained in Section 3. After the low pass filter, the filtered simulation signals to be validated—active power and reactive current—have the same constant time step, and the simulation error time series in each voltage dip window, $x_{error}(n)$, where x stands for the variable to be validated and n the index of the time series vector in each window, between the manufacturer model simulated response and the IEC model response is thus calculated, Equation (1). Several sources of errors may be expected, mainly caused by active power oscillations after voltage dips (only in Type III model simulations), transient periods (crowbar activation, inrush currents, magnetic saturations), complex control logics and reactive current injection. These error sources are further analyzed in Section 5 depending on the results obtained;

$$x_{error}(n) = x_{vendor}(n) - x_{IEC}(n) \tag{1}$$

(9) Results validation: From the error time series calculated at Step 8, the validation coefficients—mean error, x_{ME}, mean absolute error, x_{MAE}, and maximum absolute error, x_{MXE}—are estimated for each test case according to Equations (2)–(4), respectively, where N is the total number of samples in each time window. According to IEC 61400-27, errors between 3% and 5% are considered as valid for representing a good match between simulation results. Nevertheless, in the present work, these errors have been analyzed, as well, in order to avoid minor modeling errors.

$$x_{ME} = \frac{\sum_{n=1}^{N} x_{error}(n)}{N} \tag{2}$$

$$x_{MAE} = \frac{\sum_{n=1}^{N} |x_{error}(n)|}{N} \tag{3}$$

$$x_{MXE} = max\left(|x_{error}(n)|\right) \tag{4}$$

5. Results

Positive sequence values of active power, p, and reactive current, i_q, are analyzed in the present section for each simulated test case previously described in Section 4. In fact, the reactive power error is similar to the reactive current error. However, as power is voltage dependent, during voltage dips, the errors will be lesser, or they even can be negligible. Due to length limitations, some simulation scenarios are ignored if they are similar to a previous test.

For every figure, blue color is used to represent the generic IEC model signal, whereas red stands for the simplified manufacturer model signal; both simulated, filtered and interpolated at a rate of 10 ms, as commented on in Section 4. The following input variables are considered in each simulation scenario:

- p: active power delivery, i.e., wind turbine load condition, in pu.
- u: voltage dip magnitude, in pu.
- t: voltage dip duration, in ms.
- w_s: wind speed, in pu (only in Type IIIB test cases when $p = 1.0$ pu).

Results are presented according to both the wind turbine type considered and the operation condition of the wind turbine (partial load operation and full load operation).

5.1. Type IIIB Wind Turbine Results

First of all, the tests required by IEC 61400-21 are presented, and the validation errors are calculated based on the validation methodology developed in Section 4, which is based on the guidelines issued by the recent IEC 61400-27.

5.1.1. Partial Load Simulation Scenarios

Three simulation scenarios under one wind turbine operation condition when active power delivery is equal to 0.20 pu are included in Figures 4–6. These simulation scenarios correspond to three different couple of voltage dip parameters: 0.20 pu and 200 ms, 0.50 pu and 500 ms and 0.85 pu and 500 ms, respectively. Furthermore, Table 1 presents the validation errors obtained according to the voltage dip test case and the corresponding time window. It should be remarked that this partial load condition presents a critical scenario for the operation of a Type III wind turbine because it is related to the sub-synchronous operation of the induction generator.

Table 1. Validation results for the Type IIIB wind turbine, in %. Partial load simulation scenario: $p =$ 0.20 pu. ME: mean error; MAE: mean absolute error; and MXE: maximum absolute error.

Error	$u = 0.20$ pu and $t = 200$ ms				$u = 0.50$ pu and $t = 500$ ms				$u = 0.85$ pu and $t = 500$ ms			
	Fault		Post-Fault		Fault		Post-Fault		Fault		Post-Fault	
	p	i_q	p	i_q	p	i_q	p	i_q	p	i_q	p	i_q
ME	−0.06	−3.39	3.91	1.23	−0.18	−2.89	0.02	0.44	0.15	−2.77	0.02	−0.08
MAE	4.29	1.20	6.01	1.63	2.09	1.74	0.08	0.97	0.45	4.63	0.03	0.45
MXE	—	—	21.92	0.55	2.48	1.93	0.29	0.46	0.49	4.71	0.03	0.46

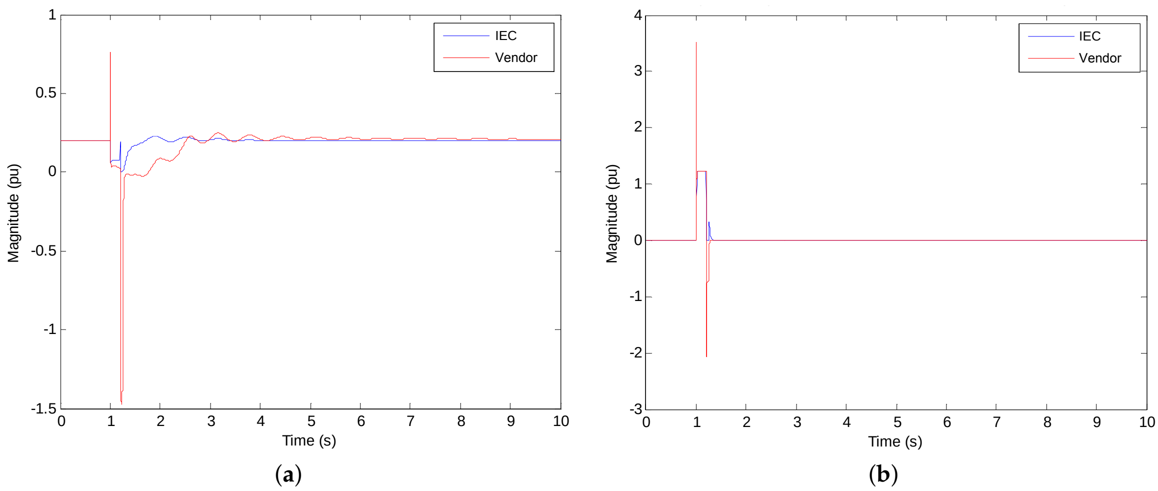
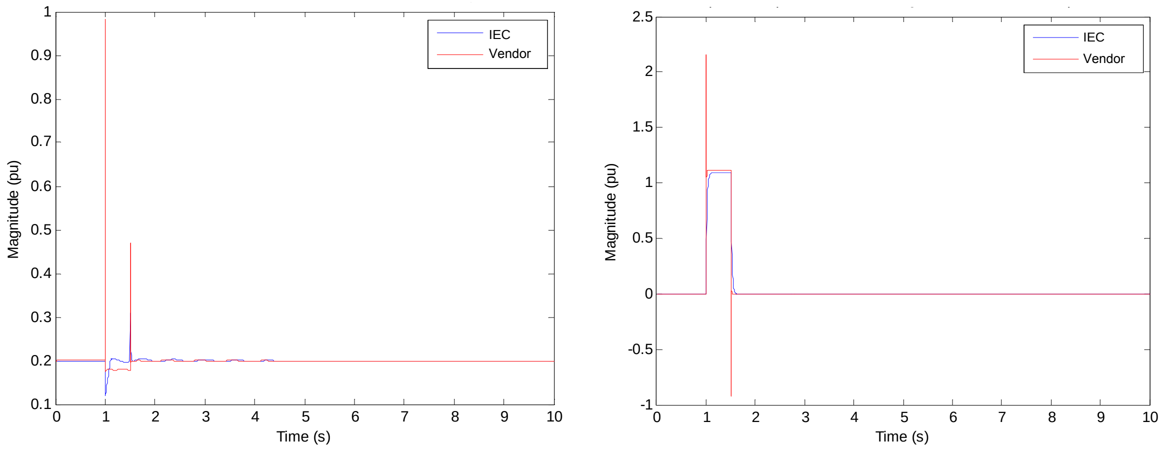
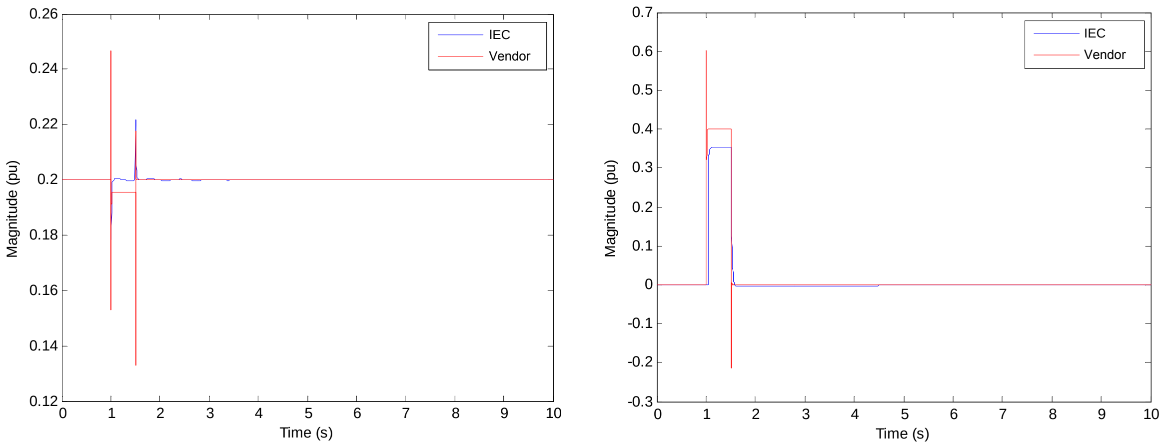


Figure 4. Type IIIB results. Simulation scenario: $p = 0.20$ pu, $u = 0.20$ pu, $t = 200$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.



(**a**) (**b**)

Figure 5. Type IIIB results. Simulation scenario: $p = 0.20$ pu, $u = 0.50$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.



(**a**) (**b**)

Figure 6. Type IIIB results. Simulation scenario: $p = 0.20$ pu, $u = 0.85$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.

Under the most severe voltage dip scenario, Figure 4, the largest validation errors are obtained, as summarized in Table 1. With regard to the reactive current, the differences between the IEC generic model and manufacturer simplified model are moderate: the largest error is found out during the fault period, where $i_{q_{ME_{fault}}} = -3.39\%$. Nevertheless, the active power presents higher error values, specifically during the post-fault response where the maximum absolute error increases up to $p_{MXE_{post-fault}} = 21.92\%$. These errors are mainly due to differences in crowbar modeling between the IEC generic model and the vendor simplified model. When the wind turbine is operating at partial load and a severe voltage dip appears, the crowbar is activated, and a consumption of active power is observed (in red, Figure 4). However, this behavior cannot be accurately represented by the IEC generic model (in blue). In this sense, the implementation of the crowbar as an FRT solution for wind turbines is associated with active and reactive power transients after fault inception and fault clearance, as was pointed out by the authors in [30,39]. For this reason, several interesting discussions about the crowbar modeling have been held in the IEC 61400-27 working group, whose results are detailed in [23].

On the other hand, in the second simulation scenario, which is shown in Figure 5, very small differences after both voltage dip and voltage recovery are found in both active power and reactive current: both p and i_q errors are below 3% and 1% at the fault window and post-fault window, respectively, as observed in Table 1. Hence, these errors can be neglected. In this specific test case, no crowbar operation is observed.

In the last simulation scenario (less severe voltage dip), Figure 6, a very good fit is obtained for the active power response: error below 0.5% at every time window as collected in Table 1. Again, no crowbar operation is observed. However, in this test case the reactive current errors obtained during the fault describe the most substantial differences: $i_{q_{MAE_{fault}}} = 4.63\%$ and $i_{q_{MXE_{fault}}} = 4.71\%$. Though this error is still acceptable for validation purposes, it is because the reactive current cannot be properly represented between 0.75 pu and 0.90 pu rated voltage. Therefore, the delivered reactive current is different between both model responses during the fault period. If the reactive current reference is limited to zero during this specific simulation, the reactive current curve can be limited to match the reactive injection curve.

5.1.2. Full Load Simulation Scenarios

Two couples of voltage dip parameters considered—0.20 pu and 200 ms and 0.85 pu and 500 ms—are shown in Figures 7 and 8, respectively, under one wind turbine operation condition equal to 1.0 pu and wind speed equal to 1.1 pu. The results with dip magnitude equal to 0.50 pu and a 500-ms duration are not shown due to the almost identical response in comparison with the 0.20 pu and 200 ms dip parameters test. However, Table 2 collects the validation errors calculated in these three test cases.

Table 2. Validation results for Type IIIB wind turbine, in %. Full load simulation scenario: $p = 1.0$ pu, $w_s = 1.1$.

Error	$u = 0.20$ pu and $t = 200$ ms				$u = 0.50$ pu and $t = 500$ ms				$u = 0.85$ pu and $t = 500$ ms			
	Fault		Post-Fault		Fault		Post-Fault		Fault		Post-Fault	
	p	i_q	p	i_q	p	i_q	p	i_q	p	i_q	p	i_q
ME	0.39	−3.87	2.31	0.76	−0.13	−1.56	4.77	0.12	−0.32	−2.78	1.02	−0.40
MAE	2.69	1.21	3.07	1.87	2.86	1.63	4.77	1.29	0.25	4.67	1.04	0.76
MXE	—	—	8.16	1.06	7.07	1.71	16.31	1.05	0.63	4.75	1.33	1.00

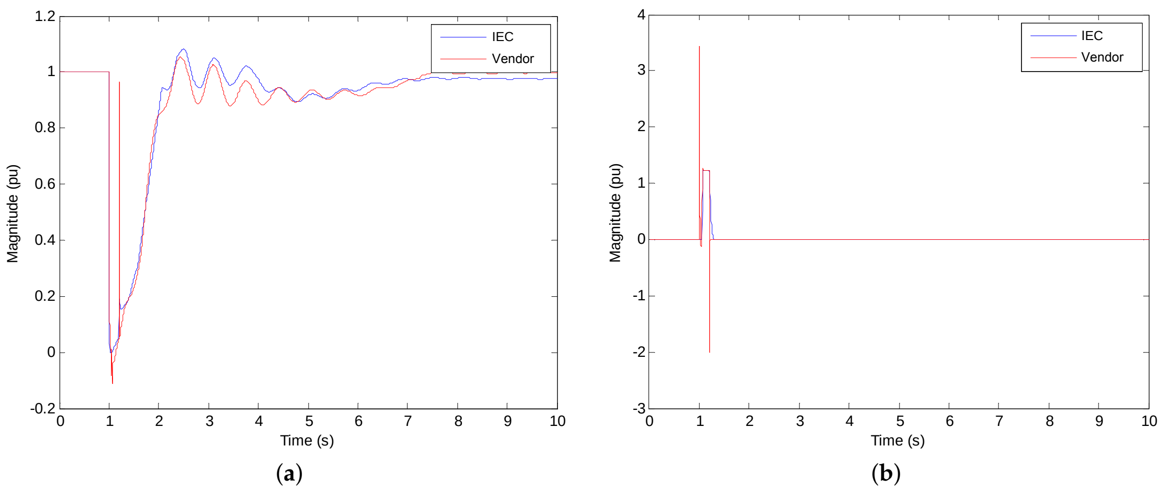


Figure 7. Type IIIB results. Simulation scenario: $p = 1.0$ pu, $u = 0.20$ pu, $t = 200$ ms, $w_s = 1.1$. (**a**) Active power, p; and (**b**) reactive current, i_q.

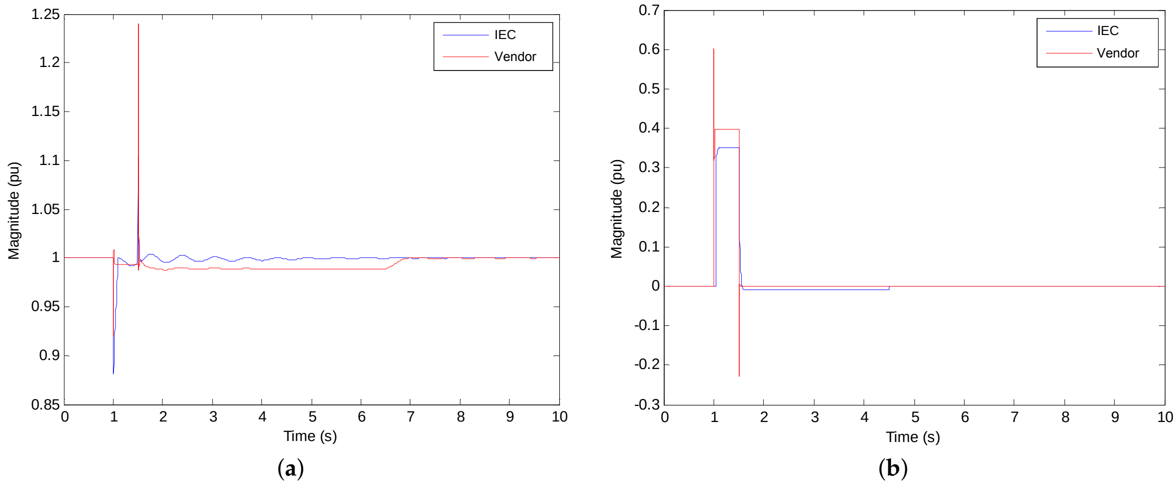


Figure 8. Type IIIB results. Simulation scenario: $p = 1.0$ pu, $u = 0.85$ pu, $t = 500$ ms, $w_s = 1.1$. (**a**) Active power, p; and (**b**) reactive current, i_q.

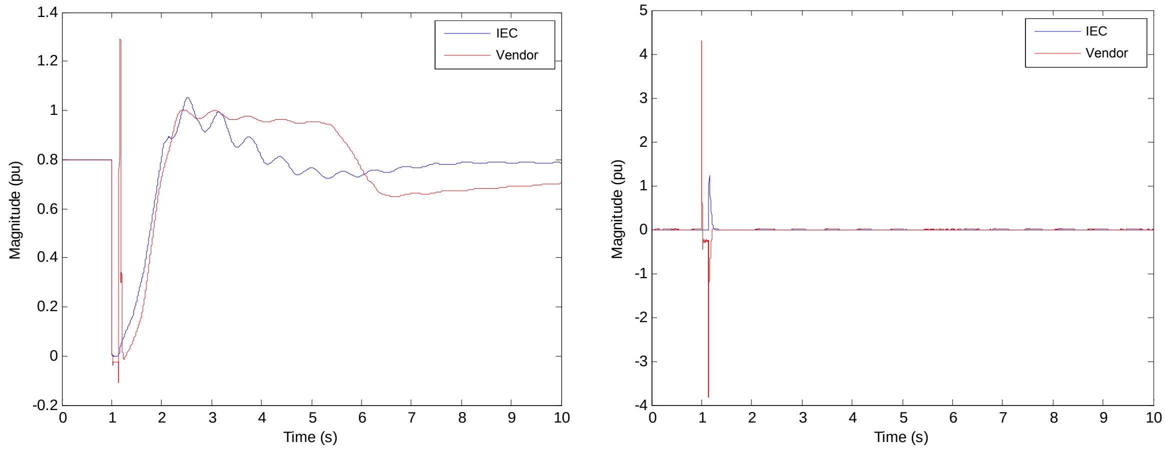
The mean errors obtained in the first full load scenario (most severe voltage dip), Figure 7, describe a good correlation, below 3%, between the different models at every time window. Nevertheless, both the mean absolute error and the maximum absolute error related to the active power after fault recovery are considerably larger: $p_{MAE_{post-fault}} = 3.07\%$ and $p_{MXE_{post-fault}} = 8.16\%$. A similar situation is found out for the full load test case with dip magnitude equal to 0.50 pu and a 500-ms duration, as is observed in Table 2. This is due to the difficulties in modeling active power oscillations after fault clearance. However, by the comparison of both signals—vendor model in red and IEC model in blue—the results are considered to be accurate enough because during this post-fault window, the same oscillation frequency is observed, and the oscillation amplitude is quite similar, as well.

Furthermore, with regard to the full load simulation scenario presented in Figure 8, every active power error is below 1.5%, and hence, these can be neglected. The reactive current errors obtained during fault are larger, but only two of them are over 3%: $i_{q_{MAE_{fault}}} = 4.67\%$ and $i_{q_{MXE_{fault}}} = 4.75\%$. As noted before in the partial load test case, although this error is acceptable, it is due to the difficulties in representing properly the reactive current between 0.75 pu and 0.90 pu rated voltage.

In addition to the tests required by IEC 61400-21, some further simulation scenarios are performed in the present work to identify any modeling concerns not previously identified. In case of the modeled and simulated Type IIIB wind turbine topology, the most conflictive extra scenario considered is found out under a 0.80 pu active power delivery and voltage dip magnitude equal to 0.01 pu and a 140-ms duration, as shown in Figure 9. From Figure 9a,it is observed that the active power presents a considerable difference in magnitude between both models during the post-fault recovery window: $p_{MXE_{post-fault}} = 22.09\%$. However, the reactive current represents a good fit, Figure 9b, because the larger error calculated is $i_{q_{MAE_{post-fault}}} = 3.13\%$.

As may be deduced from the results obtained by the wide range of simulations conducted on this Type IIIB wind turbine topology, an acceptable correlation between the IEC 61400-27-1 generic model and the simplified manufacturer model is found. Specifically, according to the test cases defined in IEC 61400-21, satisfactory validation results are obtained. Nevertheless, in some specific conditions, several error sources have been identified, which can be neglected in most of the cases.

Furthermore, large peaks are observed from Figures 4–9 at fault start and fault clearance in the manufacturer model response under some of the simulation scenarios conducted. This behavior is not described by the IEC generic simulation model. Therefore, it is worth mentioning the good numerical stability of these IEC generic models. In addition, as shown in the reactive current plots, a more progressive variation of the reactive current is observed in the IEC generic model, in contrast to a step response, which is directly related to the real behavior of the wind turbine.



(**a**) (**b**)

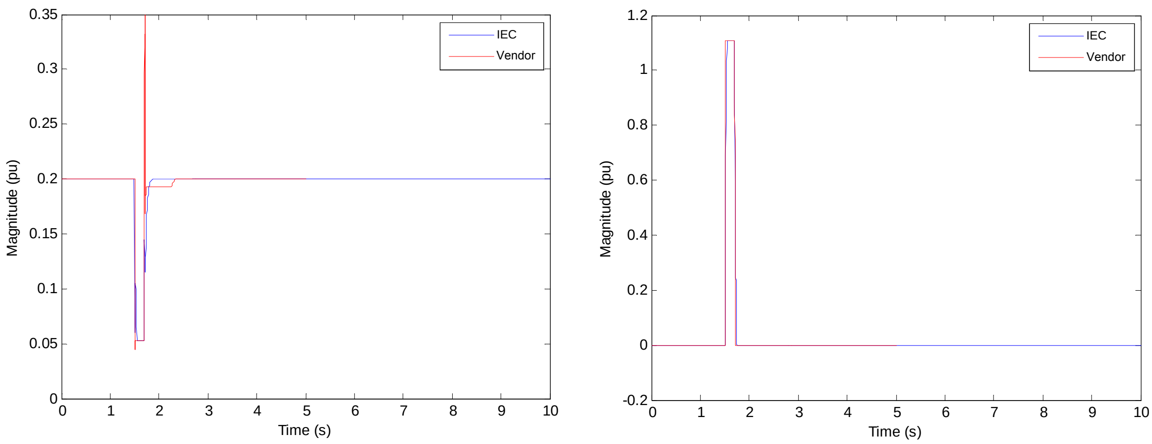
Figure 9. Type IIIB results. Simulation scenario: $p = 0.80$ pu, $u = 0.01$ pu, $t = 140$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.

5.2. Type IVA Wind Turbine Results

In a similar manner as previously analyzed for the Type IIIB wind turbine, the tests required by IEC 61400-21 are presented, and the validation errors are calculated in a first attempt for the partial load operation of the wind turbine and then for the full load operation.

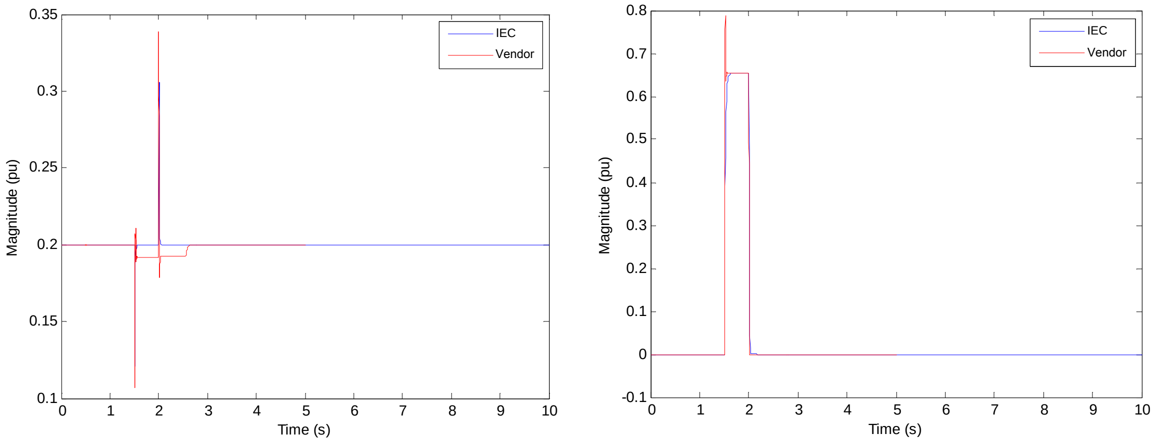
5.2.1. Partial Load Simulation Scenarios

Three simulation scenarios under one wind turbine operation condition equal to 0.20 pu, which correspond to three different couple of voltage dip parameters—0.20 pu and 200 ms, 0.50 pu and 500 ms and 0.85 pu and 500 ms—are included in Figures 10–12, respectively. In all of the test cases, a very similar response is observed between both models. In this sense, the calculated errors in every simulation scenario are below 1%.



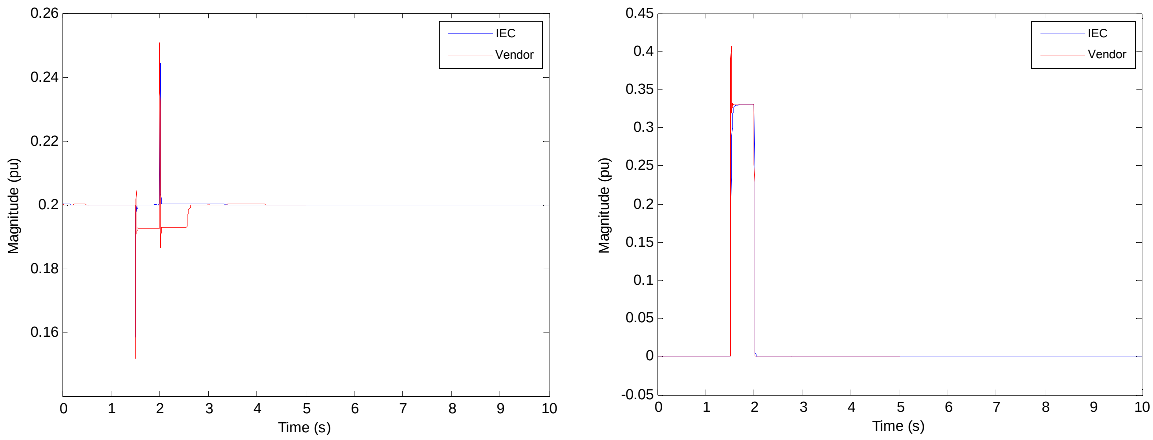
(**a**) (**b**)

Figure 10. Type IVA results. Simulation scenario: $p = 0.20$ pu, $u = 0.20$ pu, $t = 200$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.



(**a**) (**b**)

Figure 11. Type IVA results. Simulation scenario: $p = 0.20$ pu, $u = 0.50$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.



(**a**) (**b**)

Figure 12. Type IVA results. Simulation scenario: $p = 0.20$ pu, $u = 0.85$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.

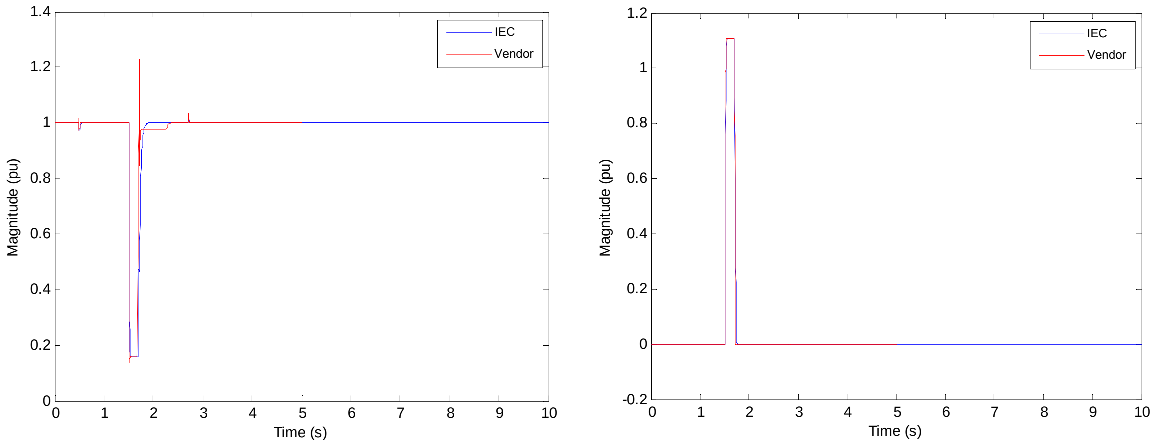
A very different behavior is noted in comparison with the Type IIIB wind turbine shown in Figures 4–6. Since the FSC topology is completely decoupled from the network, the oscillations are further dumped by the power converter.

5.2.2. Full Load Simulation Scenarios

The same three couples of voltage dip parameters considered for the partial load operation are analyzed under the full load operation of this FSC wind turbine topology. Each simulation scenario is collected in Figures 13–15, respectively. Both the active power and the reactive current errors obtained in the three test cases are quite similar. In the case of the reactive current error, it is negligible as the calculated value is below 1% in every window, which is in line with the active power error during fault, as well. However, the active power error has a larger value in the post-fault window only, $p_{MXE_{post-fault}} = 2.53\%$ for the first two simulation scenarios and $p_{MXE_{post-fault}} = 2.52\%$ for the last simulation with the less severe conditions. In any case, these errors are quite reduced, and they can thus be neglected.

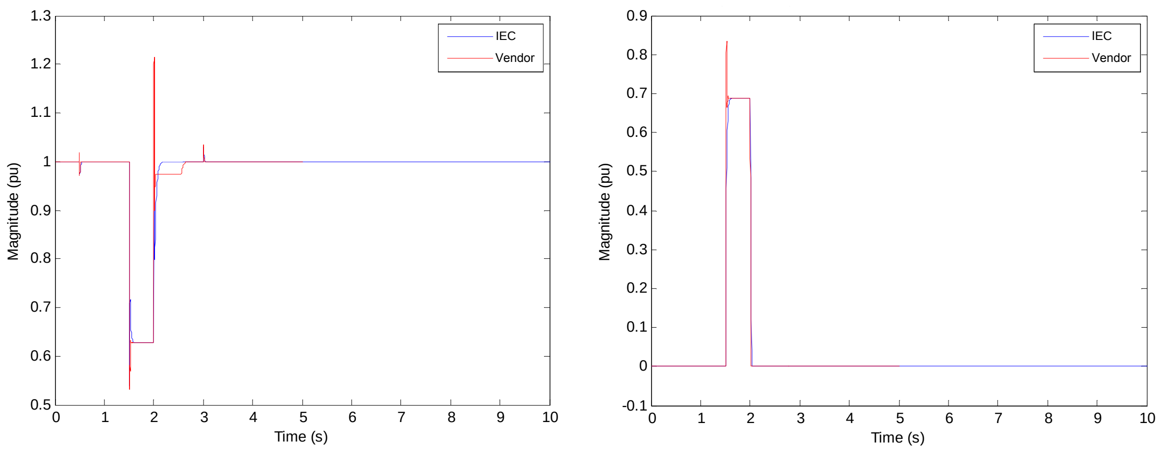
Although additional scenarios have been simulated in this Type IVA wind turbine model according to the test cases defined in Section 4, the errors obtained are below 1%, and the results are thus not included.

As may be deduced from the results obtained by the wide range of simulations conducted on this Type IVA wind turbine topology, quite reduced errors have been obtained between the IEC 61400-27-1 generic model and the simplified manufacturer model. This implies very good validation results in every simulation scenario considered for this FSC topology.



(**a**) (**b**)

Figure 13. Type IVA results. Simulation scenario: $p = 1.0$ pu, $u = 0.20$ pu, $t = 200$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.



(**a**) (**b**)

Figure 14. Type IVA results. Simulation scenario: $p = 1.0$ pu, $u = 0.50$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.

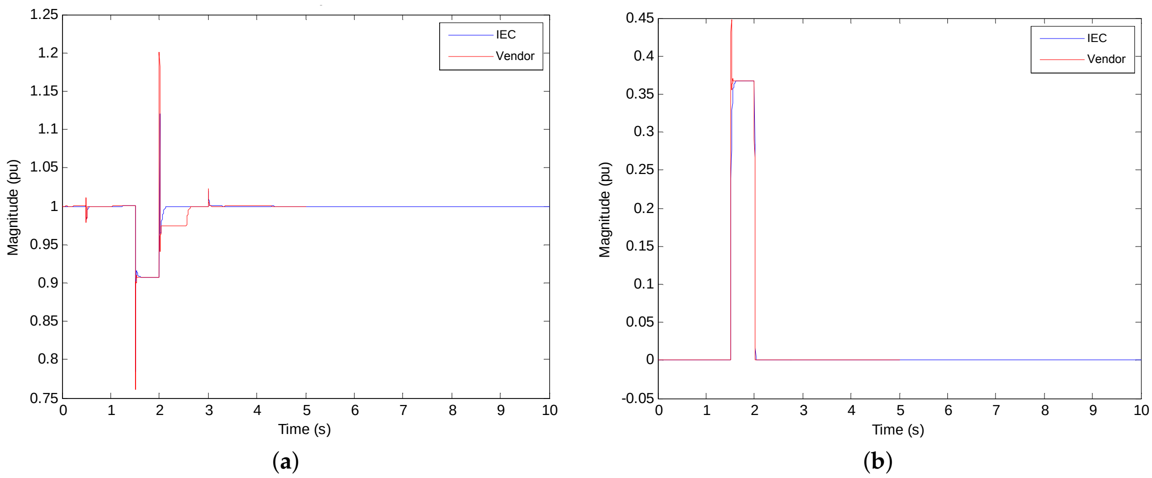


Figure 15. Type IVA results. Simulation scenario: $p = 1.0$ pu, $u = 0.85$ pu, $t = 500$ ms. (**a**) Active power, p; and (**b**) reactive current, i_q.

6. Conclusions

To evaluate the effects of wind power generation on the power system performance, RMS dynamic models of wind turbines are needed to conduct network stability analysis. Nevertheless, until the publication of the IEC 61400-27-1 in February 2015, there was a lack of standard models—i.e., generic or simplified—able to represent the behavior of wind turbines. Once published, further efforts focused on validating the response of the generic models in comparison to manufacturer models are required by the wind power industry. Since the generic models are simplifications of very complex systems, the validation with manufacturer models presents a key role to demonstrate the capabilities of these generic approaches. This paper has carried out the validation of two different variable speed operation wind turbine topologies based on the guidelines issued by IEC 61400-27. Specifically, Type IIIB and Type IVA wind turbine technologies have been modeled following IEC 61400-27-1 generic model specifications. Both systems have been subjected to a wide range of voltage disturbances, as well as several wind turbine operating conditions. In this sense, not only the test cases defined by IEC 61400-21 have been simulated, but also additional simulation scenarios have been considered to cover a wider scope and to identify possible modeling concerns. Furthermore, a novel validation approach has been implemented to compare the results from the IEC generic models and the wind turbine manufacturer simplified models. Based on the wide range of simulation scenarios considered and the validation methodology developed, relevant conclusions are deduced.

With regard to the behavior of the Type IIIB wind turbine models, the validation is acceptable, but several concerns have appeared under some specific conditions. The validation errors are analyzed depending on the error source, as follows:

- Power oscillations: In the IEC 61400-27-1 generic model, the power oscillation frequency is matched, and even the amplitude is near to matching against the manufacturer simplified model. Therefore, the modeling errors caused by this circumstance can be neglected. This error source affects specifically both the maximum absolute error, x_{MXE}, and the mean absolute error, x_{MAE}, during post-fault periods.
- Reactive curve injection: The reactive current injection curve cannot be perfectly matched using the IEC generic model. The main problem is the modeling of reactive current injected during voltage dips in the grid-side converter of the DFIG design. Using the best approximation, the reactive current is excessively limited between 0.75 pu and 0.90 pu rated voltage. This affects the reactive current error coefficients calculated during the fault window. However, these differences may be acceptable (below 5%).

- Complex control logics: The complex control logics cannot be emulated using the IEC generic model. The main differences are found when the wind turbine is operating at partial load and at rated generator speed. These conditions can be ignored as they are not included in the IEC validation procedure. However, if these conditions are required to be tested, a more detailed dynamic wind turbine model must be used.
- Transients: Some transients are not correctly modeled or they are modeled in a different way. For example, inrush current, magnetic saturation, crowbar activation, among others, are not modeled or they are modeled in a simpler way. This causes the transients to be different in comparison with field measurements or even compared against more detailed models. Since the IEC validation process defines the adjacent validation windows, in most cases, these transients are not evaluated, but if transient duration is large enough, then differences could be appreciable in the validation coefficients.

On the other hand, the validation performed with the Type IVA wind turbine model has provided very low error coefficients, which are mostly negligible. The deviations are mainly caused by differences in the reactive injection curve or due to unconsidered losses in the IEC generic model. As a consequence, a very good correlation between the IEC generic model and the vendor simplified model has been obtained for this Type IVA design. Therefore, this work has shown that wind turbine manufacturers are able to adjust the IEC generic models to represent the behavior of their specific wind turbines for power system stability analysis.

In addition, it should be noted that model validation is considerably influenced by site-specific factors, like turbine height, stiffness of the foundation, site-specific control parametrization, aging effects of the turbine and especially local wind turbulence and wind speed changes during faults that lead to considerably higher deviations between measurement and simulation. These effects are by far dominant compared to a further marginal increase of model accuracy that could be achieved by considerably more detailed models. If the effect of, e.g., drive train oscillations could be of relevance, it is strongly recommended to use a parameter variation (Monte Carlo simulations) to ensure grid stability for a wide range of possible turbine characteristics.

Furthermore, IEC generic models have performed with suitable numerical stability. A progressive variation of the modeled signals has been observed in these generic models, as well, which is directly related to the real behavior of the wind turbine. The contributions of this work are thus potentially interesting for stakeholders involved in the integration of wind energy into power systems, such as TSOs, DSOs, wind turbine manufacturers, software developers and technical consultants.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
CD	Committee draft
CDV	Committee draft for voting
DC	Direct current
DFIG	Doubly-fed induction generator

DSO	Distribution system operator
EMT	Electromagnetic transient
EU	European Union
FDIS	Final Draft International Standard
FRT	Fault ride-through
FSC	Full-scale converter
IEC	International Electrotechnical Commission
RMS	Root mean square
TSO	Transmission system operator
U.S.	United States
WECC	Western Electricity Coordinating Council
WT	Wind turbine
WTT	Wind turbine terminals

Appendix A

This Appendix contains the parameters needed by the models defined according to IEC 61400-27-1 [46], which are presented in alphabetical order. On the one hand, the following table details the parameters associated with the generic IEC Type IIIB model.

Table A1. Parameters for the generic IEC Type IIIB model.

Symbol	Submodel	Description	Value
di_{pmax}	Generator	Maximum active current ramp rate	1.3000
di_{pmin}	Generator	Maximum active current ramp rate	2.5000
dp_{max}	Active power control	Maximum WT power ramp rate	2.5000
i_{qpost}	Reactive power control	Post fault reactive current injection	0.0000
K_{qv}	Reactive power control	Voltage scaling factor for FRT current	−3.2238
M_{DFSLim}	Current limitation control	Limitation of Type III stator current	1
M_{qpri}	Current limitation control	Prioritization of reactive power control during FRT	1
M_{qG}	Reactive power control	Reactive power control mode	2
M_{qUVRT}	Reactive power control	FRT reactive power control mode	3
M_{WTcwp}	Generator	Crowbar control mode	1
r_{drop}	Reactive power control	Resistive component of voltage drop impedance	0.0071
$T_{CW}(du)$	Generator	Crowbar duration versus voltage variation table	0.06, −1.00 0.06, −0.21 0.00, −0.21 0.00, 1.00
T_{pfilt}	Power control	Time constant in power measurement filter	0.0200
T_{pord}	Active power control	Time constant in power order lag	0.0700
T_{qord}	Reactive power control	Time constant in reactive power order lag	0.0000
T_{ufilt}	Power control	Time constant in voltage measurement filter	0.0200
T_{wo}	Generator	Time constant for crowbar washout filter	0.0150
$T_{\omega filtp3}$	Active power control	Filter time constant for generator speed measurement	1.0000
$T_{\omega ref}$	Active power control	Time constant in speed reference filter	1,000,000
u_{db1}	Reactive power control	Voltage dead band lower limit	1.0000
u_{db2}	Reactive power control	Voltage dead band upper limit	1.0000
u_{DVS}	Active power control	Voltage limit for hold FRT status after deep voltage sags	0.0000
u_{max}	Reactive power control	Maximum voltage in voltage PI controller integral term	1.1000
u_{min}	Reactive power control	Minimum voltage in voltage PI controller integral term	0.9000
u_{qdip}	Reactive power control	Voltage threshold for FRT detection in q control	0.9000
x_{drop}	Reactive power control	Inductive component of voltage drop impedance	0.0805
ω_{offset}	Active power control	Offset to reference value that limits controller action	0.0000

Furthermore, the parameters related to the generic IEC Type IVA model are presented in the following table.

Table A2. Parameters for the generic IEC Type IVA model.

Symbol	Submodel	Description	Value
i_{qmin}	Reactive power control	Minimum reactive current injection	−1.0000
i_{qpost}	Reactive power control	Post fault reactive current injection	0.0000
K_{qv}	Reactive power control	Voltage scaling factor for FRT current	−2.0533
M_{DFSLim}	Current limitation control	Limitation of Type III stator current	0
M_{qpri}	Current limitation control	Prioritization of reactive power control during FRT	1
M_{qG}	Reactive power control	Reactive power control mode	2
M_{qUVRT}	Reactive power control	FRT reactive power control mode	3
T_{pfilt}	Power control	Time constant in power measurement filter	0.0200
T_{pord}	Active power control	Time constant in power order lag	0.0300
T_{post}	Reactive power control	Time period where post fault reactive power is injected	0.0000
T_{qord}	Reactive power control	Time constant in reactive power order lag	0.0000
T_{ufilt}	Power control	Time constant in voltage measurement filter	0.0200
u_{db1}	Reactive power control	Voltage dead band lower limit	1.0000
u_{db2}	Reactive power control	Voltage dead band upper limit	1.0000
u_{qdip}	Reactive power control	Voltage threshold for FRT detection in q control	0.9000

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