# Comparison of Standard Wind Turbine Models with Vendor Models for Power System Stability Analysis

## Preprint

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# Comparison of standard wind turbine models with vendor models for power system stability analysis

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***Abstract*—The IEC 61400-27-1 was published in February 2015. This International Standard deals with the development of generic terms and parameters to specify the electrical characteristics of wind turbines. Generic models of very complex technological systems, such as wind turbines, are thus defined based on the four common configurations available in the market. Due to its recent publication, the comparison of the response of the generic models with specific vendor models plays a key role to ensure the widespread use of this Standard. This paper compares the behaviour of a specific *Gamesa* dynamic wind turbine model with the corresponding generic IEC Type III wind turbine model response when the wind turbine is subjected to a three-phase voltage dip. This Type III model represents the Doubly-Fed Induction Generator (DFIG) wind turbine, which is not only one of the most commonly sold and installed technologies in the current market, but also a complex variable speed operation implementation. In fact, active and reactive power transients are observed during both fault and post-fault periods due to the voltage reduction. Hence, the boundaries of the generic models associated with transient events that cannot be represented exactly are discussed in this work.**

***Keywords*—DFIG; IEC 61400-27; power system stability; standard model; voltage dip**

## I. INTRODUCTION

Renewable energy sources (RES) have experienced a fast growth in recent years. Wind power was the leading source of new electricity generating capacity in Europe, the United States and Canada in 2015, and the second largest in China [1]. By the end of 2015, there were about 433 GW of wind power spinning around the globe and annual installations crossed the 60 GW mark for the first time in history [2]. The previous record was set in 2014 when almost 52 GW of new capacity was installed globally. Asia, which is leading the market for wind power for the last years, installed 34 GW in 2015 —31 GW of which were located in China—, summing up to 176 GW in total. Europe is in the second spot with around 14 GW installed in 2015 —148 GW total cumulative—, where almost half of all new installations added in the EU were located in Germany. North America is closing the gap with Europe, in third place, with 11 GW installed in 2015 —89 GW total cumulative—. Fig. 1 shows the total top ten cumulative wind capacity installed by the end of 2015, where it is observed that China and USA represent more than half of the current capacity installed in the world.

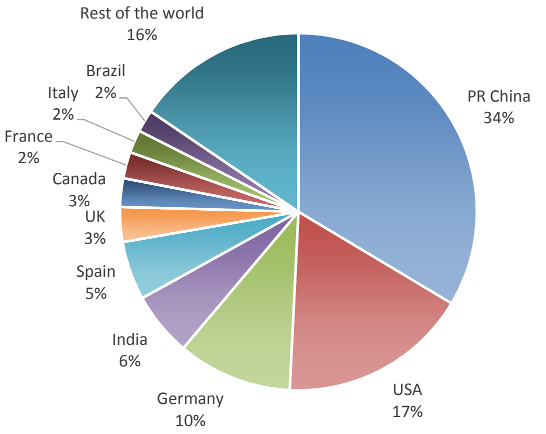

Fig. 1. Total cumulative wind capacity installed in a global basis by the end of 2015, in %.

Not only the wind capacity installed but also the contribution of wind power to the electricity demand coverage may be referred to as the second key performance indicator. The current wind capacity installed in the EU is enough to cover 11.4% of the EU's total electricity consumption in 2015 [3], which presents a considerable increase from the 6.3% value observed in 2011. In Denmark, where a new record was set in 2015 by meeting more than 40% of the electric demand with wind-generated electricity [1], wind power is contributing to demand coverage with more than 30% since 2012. In Spain, wind power was the first contribution to demand coverage among all other energy sources in 2013, covering around 21% of the electricity demand, which is similar to the rates obtained in 2014 and 2015 [4]. In this line, wind power covered about 24% of the electricity consumption in Portugal in the period between 2013 and 2015, rising 4% compared to 2012.

As a consequence of this increasing wind penetration in power systems, the development and validation of wind turbine dynamic models is a fundamental task to ensure the quality of power system stability simulations [5]. Although wind turbine manufacturers have developed their particular wind turbine dynamic models for stability analysis, some relevant concerns have been raised, such as confidentiality issues [6] and implementations done in a specific simulation software [7]. Under this framework, the International Electrotechnical Commission (IEC) and the Western Electricity Coordinating Council (WECC), have been working during the last years to define generic wind turbine dynamic models for power system stability analysis. This collaboration has resulted in the publication of IEC 61400-27-1 in February 2015 [8]. 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 parameterised to reasonably emulate the dynamic behaviour of a wide range of equipment while not directly representing any actual wind turbine control [9]–[11].

Due to the recent publication of the IEC 61400-27-1, very few works are found in the scientific literature presenting comparisons between generic IEC models and manufacturer models. Nevertheless, these generic models recently published must be properly compared with specific vendor models to validate the accuracy of the generic approaches, which is the main aim of the present paper. Specifically, the response of a generic IEC Type III —i.e. doubly-fed induction generator (DFIG)— wind turbine model is compared with the simplified wind turbine model response of the manufacturer *Gamesa*. In fact, *Gamesa* is one of the market leaders in the EU as regards assets owned. This specific DFIG configuration is the focus of the current work since the most advanced power electronics are implemented and, as a consequence, the most complex behaviour is provided. Both, the generic IEC Type III model and the simplified DFIG *Gamesa* model, have been implemented and simulated in the MATLAB® software tool. A simulation scenario is conducted where both wind turbine models are subjected to a three-phase voltage dip. The differences between the model responses are highlighted, aiming at providing an improved usability of the generic models defined in the IEC 61400-27-1.

After this introduction, the paper is structured as follows: Section II defines the main features of the Type III wind turbine model topology. Then, Section III provides a detailed description of the simulation and validation methodology implemented in the present work. Results are included in Section IV. Finally, Section V collects the conclusions of the paper.

## II. GENERIC TYPE III SIMULATION MODEL

Power system stability analysis are performed typically by grid operators as well as other technical consultants in order to evaluate the behaviour of wind turbines when subjected to different types of grid disturbances [12]–[21]. For this purpose, dynamic RMS models [22], which represent simplified versions of complex detailed models, also known as EMT-type models, are commonly requested by grid codes [23], [24]. To deal with this concern, working groups from the IEC and the WECC, have defined generic wind turbine dynamic, models [25]–[28], which are intended for transient stability simulations [17], [25]. After the publication of the IEC 61400-27-1 in February 2015 [8], four standard wind turbine types have been defined to cover the different wind turbines topologies present in the market:

- Type I: directly grid connected asynchronous generator with fixed rotor resistance.
- Type II: variable rotor resistance induction generator.
- Type III: doubly-fed induction generator (DFIG).
- Type IV: generator connected to the grid through a full scale power converter (FSC).

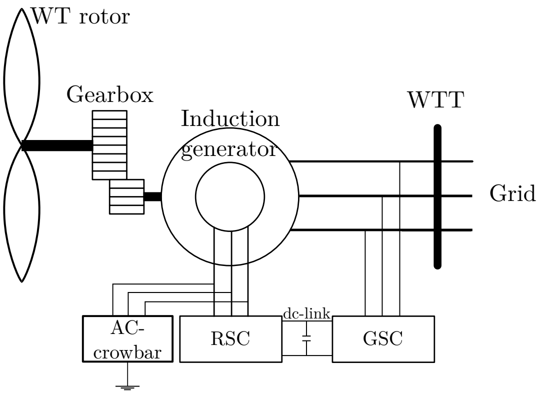

Fig. 2. Configuration and main elements of a Type IIIB wind turbine.

A Type III wind turbine topology is considered in the present work due to not only its dominance in the current market but also the most relevant technological advances found. The DFIG design is composed of a wound rotor induction generator with a back-to-back frequency converter connected between the rotor terminals and the network, as shown in Fig. 2. The stator is directly coupled to the grid. This configuration has gained attention in the last years because it allows for a variable rotor speed operation between -40% and +30% of synchronous speed [13], [29]. In addition, since the converter handles only the slip power, its power rating can be only a fraction of the rated power of the wind turbine, typically in the range of 15–30% [30]. The frequency converter is composed of two independent controlled voltage source converters —rotor-side, RSC, and grid-side, GSC—, which are connected through a common dc-link. The RSC is normally used to control the rotational speed and the reactive power exchange with the grid via its stator terminals while the GSC is adopted to regulate the dc-link voltage [6], [30].

When a Type III wind turbine is subjected to a voltage dip, high currents and voltages will appear in the RSC [14], [31]–[33], which are commonly limited by the use of a DC-chopper and/or an AC-crowbar. In this regard, two different Type III generator models have been defined in the IEC 61400-27-1: Type IIIA, which stands for a DFIG design without crowbar; and Type IIIB, which represents the DFIG with crowbar, as shown in Fig. 2. The present work has modelled and validated the generic IEC Type IIIB model because this wind turbine type represents a relevant share in the current market and it has some extra modelling complexities specially related to the crowbar operation that need to be further analysed. The detailed IEC generic Type IIIB model structure is found in [8].

## III. DESCRIPTION OF THE VALIDATION METHODOLOGY

A simulation model is a mere representation of a real equipment. The main aim of simulation models is to emulate the behaviour of the real equipment when subjected to a disturbance, such as a power system fault. Several simplifications are implemented on generator dynamic modelling

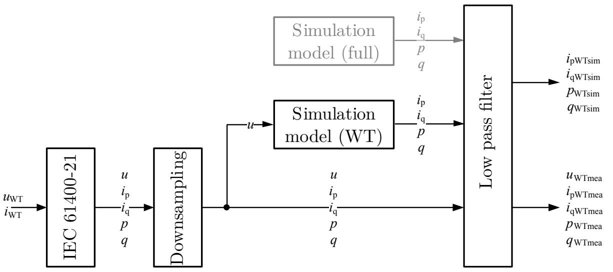

Fig. 3. Validation methodology approaches according to IEC 61400-27 guidelines: playback VS full grid simulation (in grey).

to characterize the response of the model within a specified frequency, voltage range, or time interval of interest [34]. This simplification has a considerable cost with respect to accuracy. In this sense, simulation models response needs to be compared with real experiments as well as previous validated models. The use of real events data to validate a detailed EMT wind turbine model in a first step and then this validated EMT model is used to validate a simplified RMS model for power system stability is proposed in [5]. Due to the recent development and publication of the IEC 61400-27-1 generic models, there is a need to validate them with respect to particular vendor models. In this line, one common validation procedure is defined in the German FGW TR4 [35], whose main characteristics are discussed in [36] together with the validation guidelines recently issued by the IEC 61400 working group. In [36] it is finally recommended to take advantage of the benefits provided by the recent IEC validation procedure, which is thus the validation methodology followed in the present work.

Two validation types depending on the input to the simulation model have been defined in the IEC 61400-27 working group [23], [25], [37], as shown in Fig. 3:

- Playback: the specific wind turbine Type is modelled and voltage signal, $u$, is played-back as input to the simulation model. The response of the other signals, such as currents and power —$i_p$, $i_q$, $p$, $q$—, are used for validation purposes.
- Full grid simulation: both the specific wind turbine Type and the equivalent grid and the interface between the wind turbine and the network are modelled.

The playback validation approach is recommended by IEC guidelines [25], and it will be followed in the present work. Once the generic IEC model simulations and the corresponding vendor model simulations have been performed, the resulting signals are filtered by a 15 Hz low pass filter, as shown in the right side of Fig. 3. In fact, bandwidths between 0.1 Hz and 10 Hz are typical for equipment models commonly used for power system stability simulations [38], [39]. In order to estimate the model accuracy based on the resulting simulated signals, three adjacent time windows are considered:

- Pre-fault window: duration equal to 1 s before voltage dip start.
- Fault window: starting when the fault occurs in one of the phases and ending when the fault is cleared in one of the phases for the first time.
- Post-fault window: duration equal to 5 s after voltage dip clearance.

Three validation performance indicators are estimated in every time window based on the error calculated for each resulting signal (1): the mean error (2), the mean absolute error (3) and the maximum absolute error (4). A transient period of 140 ms and 500 ms is given in the fault and post-fault windows, respectively, for the $x_{MXE}$ estimation.

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

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

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

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

The methodology described above has been applied to validate the model under one three-phase voltage dip simulation scenario. With regard to the voltage dip characteristics, voltage dip magnitude and duration are equal to 0.50 pu and 500 ms, respectively. In fact, although this fault type is not the most common [40], [41], it may present one of the worst scenarios for renewable energy power plants. Furthermore, the wind turbine is assumed to operate under a full load condition where active power delivery, $p$, is equal to 1.0 pu and wind speed is equal to 1.1 pu. The vendor simplified DFIG model was executed at a rate of 1 ms while the simulation time step of the generic IEC Type IIIB model is equal to 5 ms. Finally, the results comparison between both models is done at a rate of 10 ms. The model simulation and validation procedure conducted in this work has been implemented in MATLAB® software tool. In a first phase, the *Gamesa* simplified model is simulated and the output voltage is used in a second step as input for the generic IEC model —playback validation type—.

## IV. RESULTS

Based on the validation procedure described in Section III, positive sequence values of active power, $p$, reactive power, $q$, active current, $i_p$, and reactive current, $i_q$, are shown in Figs. 4, 5, 6 and 7, respectively, for the three-phase voltage dip simulation scenario considered in this work. At every figure, blue colour is used to represent the generic IEC model response, while red is used for the representation of the simplified *Gamesa* model signal —both simulated, filtered and interpolated at a rate of 10 ms, as commented in Section III—. Table I shows the values of the validation errors obtained according to the voltage dip time window and Figure 8 presents a graphical representation of this table for a better understanding. The first finding from these results is that the errors found in the pre-fault window are negligible, which is due to the playback validation type considered.

With regard to the active power and active current simulation results, Fig. 4 and 6, respectively, it is observed the considerable reduction of the capability to deliver active power during the fault period. Both simulation signals — the generic IEC model in blue and the *Gamesa* model in

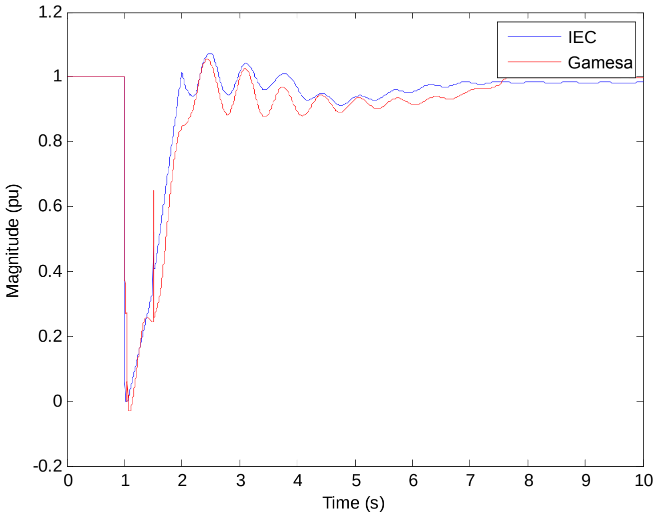

Fig. 4. Positive sequence active power, $p$.

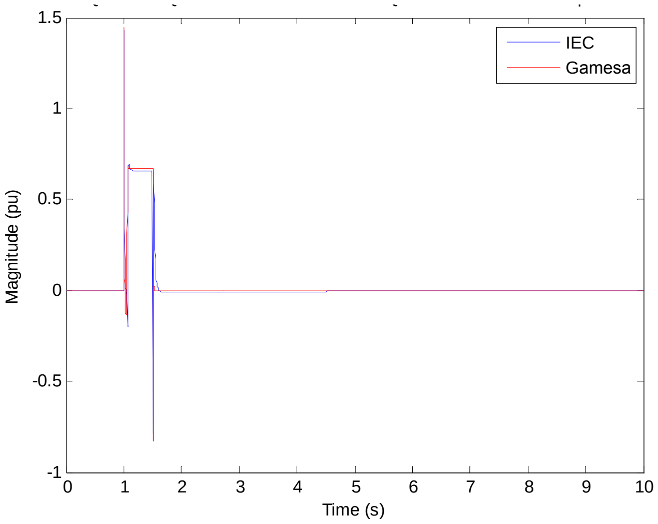

Fig. 5. Positive sequence reactive power, $q$.

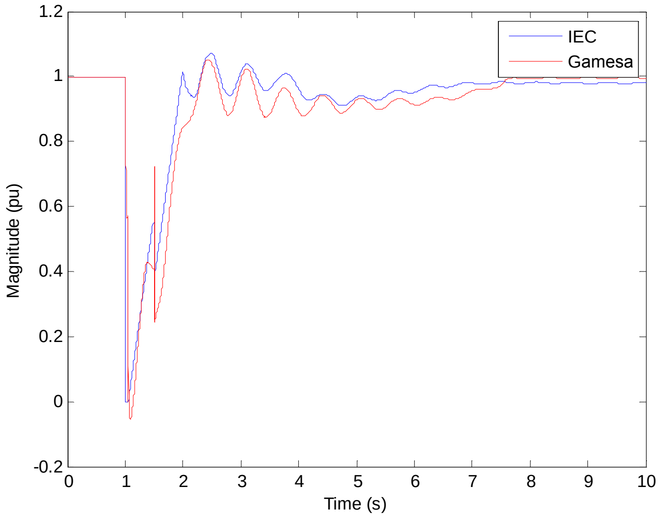

Fig. 6. Positive sequence active current, $i_p$.

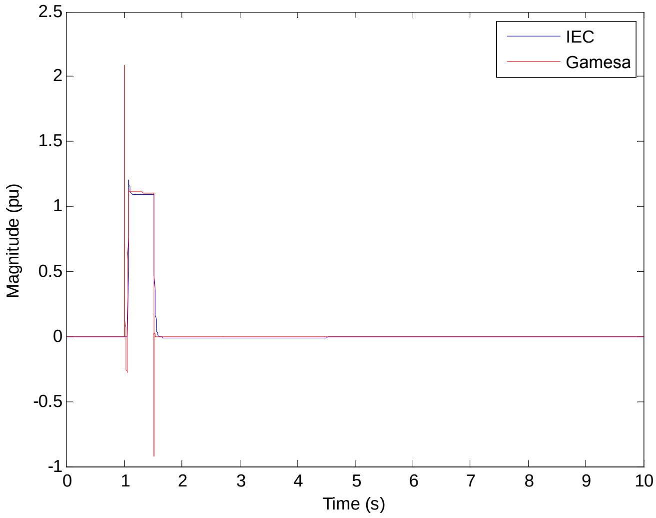

Fig. 7. Positive sequence reactive current, $i_q$.

TABLE I
VALIDATION ERRORS CALCULATED, IN %.

| Variable | fault | | | post-fault | | |
|---|---|---|---|---|---|---|
| | **ME** | **MAE** | **MXE** | **ME** | **MAE** | **MXE** |
| $\boldsymbol{p}$ | -0.13 | 2.86 | 7.07 | 4.77 | 4.77 | 16.31 |
| $\boldsymbol{q}$ | -0.32 | 0.99 | 1.03 | -0.21 | 0.97 | 1.06 |
| $\boldsymbol{i_p}$ | -1.11 | 4.99 | 12.20 | 4.81 | 4.81 | 16.44 |
| $\boldsymbol{i_q}$ | -1.56 | 1.63 | 1.71 | 0.12 | 1.29 | 1.05 |

red— show a good correlation. Specifically, during the fault period, mean error and mean absolute error of both variables, $p$ and $i_p$, are lower than 5%, Table I. Although these errors are low, it is noted the considerably larger error values obtained in the $i_p$ than in the $p$. In fact, as power depends on voltage, the errors related to power will be lesser than the errors related to current during the voltage dip. However, the maximum absolute error during fault presents a larger value: $p_{MXE} = 7.07\%$ and $i_{p_{MXE}} = 12.20\%$. Although during the post-fault window larger error values than during fault are found, the same oscillation frequency is observed and the oscillation amplitude is quite similar as well. This situation is due to the difficulties in modelling active power oscillations after fault clearance. During this post-fault window it is observed that $p_{ME} = p_{MAE}$ and $i_{p_{ME}} = i_{p_{MAE}}$, which is due to there absence of matching point between IEC and *Gamesa* signals.

With regard to the reactive power and reactive current simulation results, Fig. 5 and 7, it is highlighted the very good correlation obtained because every validation error are below 2%, as shown in Table I. Hence, these errors can be neglected. Again, as noted before for the active both power and current, reactive power errors are lower than the corresponding reactive current errors. During the post-fault window, it is observed that $i_{q_{MAE}} > i_{q_{MXE}}$, which is due to the assumption of the transient period not considered for the maximum absolute error calculation.

Furthermore, large peaks are observed in red from Fig. 4 to 7 at fault inception ($t = 1.0\ s$) and fault clearance ($t = 1.5\ s$), which correspond with the vendor model

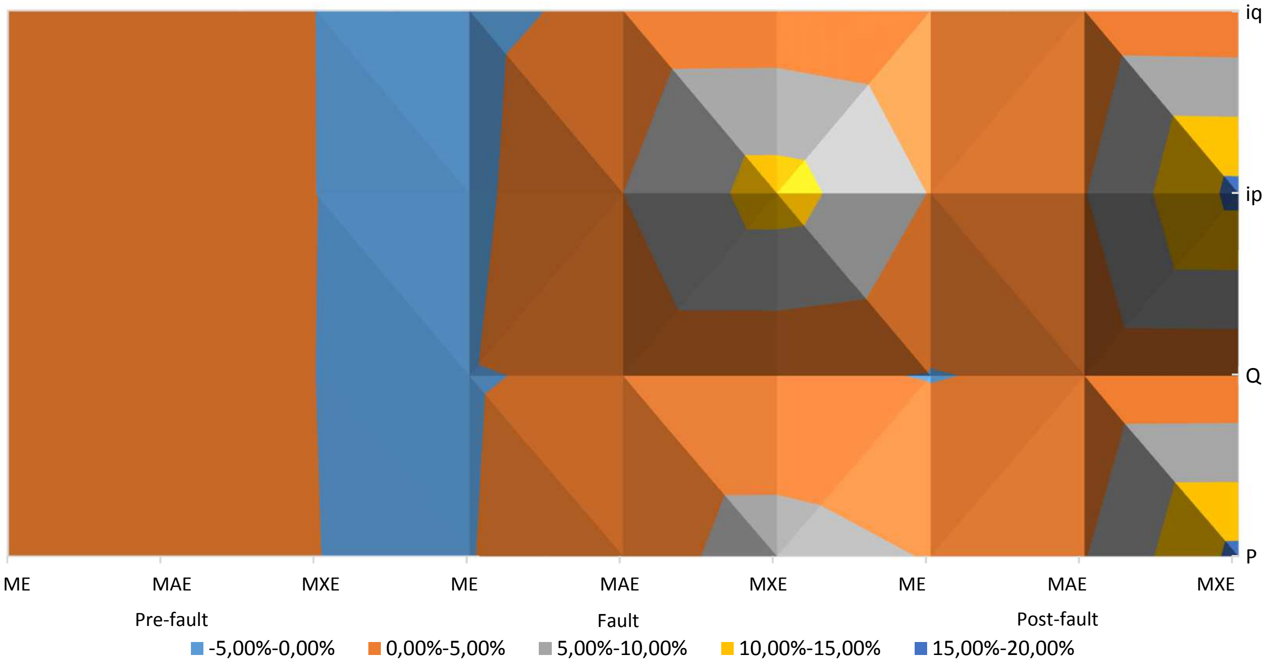

Fig. 8. Validation errors calculated for the four variables analysed (in vertical) depending on the voltage dip time window (in horizontal).

response. In contrast, this behaviour is not observed by the generic IEC simulation model response, in blue. Therefore, it is worth mentioning the good numerical stability of these IEC generic models. In addition, as shown in the reactive current and reactive power representations, Fig. 5 and 7, a more progressive variation of the red signal —generic IEC model— is observed than in the blue one —*Gamesa* model—, which implies a behaviour closely related to the field measured response of the wind turbine.

## V. CONCLUSIONS

RMS dynamic models of complex systems, such as wind turbines, are needed to perform network stability analysis and evaluate the effects of wind power generation on the power system performance. However, there was a lack of standard models —also known as generic or simplified— until the publication of the IEC 61400-27-1 in February 2015. Due to its recent publication, the comparison of the generic response with the wind turbine vendor models response has been recognised as a key task to promote the use of the International Standard. This paper has performed the validation of one of the wind turbine topologies that not only presents the largest market share but also is associated with several technological challenges, such as the crowbar operation, i.e. the Type IIIB system. In addition, the novel validation guidelines that are being developed under the IEC 61400-27-2 framework have been applied in the present work.

As it may be deduced from the results obtained, although an overall acceptable correlation between the generic IEC model and the simplified *Gamesa* model has been found, several concerns have been raised. Large maximum power errors have been identified. However, it is worth mentioning that the oscillation frequency is matched and even the amplitude is quite similar between both simulation data sources.

Furthermore, a suitable numerical stability has been observed in the generic IEC Type IIIB model response as well as a response quite related to the real behaviour that would be expected on field. Nevertheless, it should be highlighted that a larger number of simulation scenarios should be considered in the near future for a comprehensive validation. In addition, validations by using real measured data are expected to be done by wind turbine manufacturers in future works.

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