Practical Experiences in Developing and Using a Wind Turbine Model based on IEC 61400-27-1

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***Abstract*—With a growing penetration of wind turbines in many power systems around the world, a need has arisen to accurately reflect their behaviour for stability simulations. To reduce the complexity of such simulations, generic models have been developed that can be used by grid operators. IEC standard 61400-27-1 proposes a set of such models. However, these models lack certain features, such as Delta Control, Active Power Reduction with Overfrequency or Emulated Inertia, which might play an important role in the future. This papers shows how existing IEC models can be extended by incorporating the aforementioned features in the type 3 IEC model. Subsequently, the enhanced IEC model is compared with two manufacturer models and, with an appropriate parametrization, similar behavior can be achieved.**

I. Introduction

The goal of the EU-funded project Migrate[1] (Massive Integration of Power Electronic Devices) is to conduct dynamic simulations of large grids with a high share of power electronic devices. As such, also dynamic simulation models of inverter coupled wind turbines (WTs), i.e. type 3 and 4 WTs, are required. In the course of the project, a number of dynamic simulations are to be carried out, such as fault-ride-through (FRT) events, reference value steps, and under- and overfrequency events. Therefore, the Migrate project has contracted Energynautics to develop a set of generic wind turbine models. This paper describes the development work and the experience gained.

To reflect the dynamic behavior of wind turbines, WT models based on IEC standard 61400-27-1 [1] can be used, which proposes generic simulation models for different types of WTs. However, several important features of future wind turbines are missing in the standard. To meet the requirements, the IEC models had to be modified and expanded with additional features, such as emulated inertia, power reduction with overfrequency, and more.

This paper describes the development and usage of the IEC-based WT-models which were developed in DIgSILENT PowerFactory. First, IEC standard 61400-27-1 is shortly introduced. Next, the necessary modifications and extensions are described and it is explained how they are incorporated into the control frame of the IEC model. Finally, simulation results of the models are presented and compared with results from two manufacturer models, highlighting lessons learned while adapting the model.

[1]For more information see: https://www.h2020-migrate.eu/

II. IEC Standard 61400-27-1

The main purpose of IEC standard 61400-27-1 [1] is to introduce generic wind turbine models, which can be used by grid operators in stability studies. Using these generic models, the need for manufacturer models is eliminated, which usually require large amounts of input data due to their high level of detail.

The standard was first published in 2015. It specifies generic RMS simulation models for WTs that can be used in all kinds of dynamic simulations. Models for each type of WT (1 to 4) are specified. The models refer to the WT terminals and are described in a modular way, so that they can be expanded easily.

In this project, generic models of type 3 (WT with doubly-fed induction generator (DFIG) and small converter) and type 4 (WT coupled through a full-scale converter) were developed. The type 4 model of the IEC standard is highly simplified compared to the type 3 model. These simplifications make it difficult to add the required additional features (see section III). Therefore, the structure of type 3 model from the standard was used as the basis for both developed models, type 3 and 4. According to the standard, it is explicitly allowed to use the type 3 model to represent a type 4 WT. Hence, only the IEC model for type 3 WTs is described in this paper.

The overall structure of the type 3 model is shown in fig. 1. The inputs of the model are reference values for active power (p_{WTref}) and reactive power or voltage (x_{WTref}), respectively, and can be provided e.g. by an external wind power plant controller. The outputs of the model are the currents injected by the WT at its terminal. The main part of the model is the "Control" block which includes separate controllers for active and reactive power as well as a pitch angle controller and limitations for currents and reactive power. The "Mechanical" part of the model is implemented as a two-mass-oscillator. Generator and inverter are represented by the "Generator system" block. Depending on the WT type, different submodels are used for this block (e.g. according to [2] for type 3 generator without crowbar). The "Electrical equipment" block includes breakers and the transformer. The breakers open, when they get triggered by the "Grid protection".

The blocks and signals marked in red and bold are not part of IEC standard 61400-27-1, but were added or modified for this particular project. The aerodynamic model was replaced by a more detailed one and some additional features to

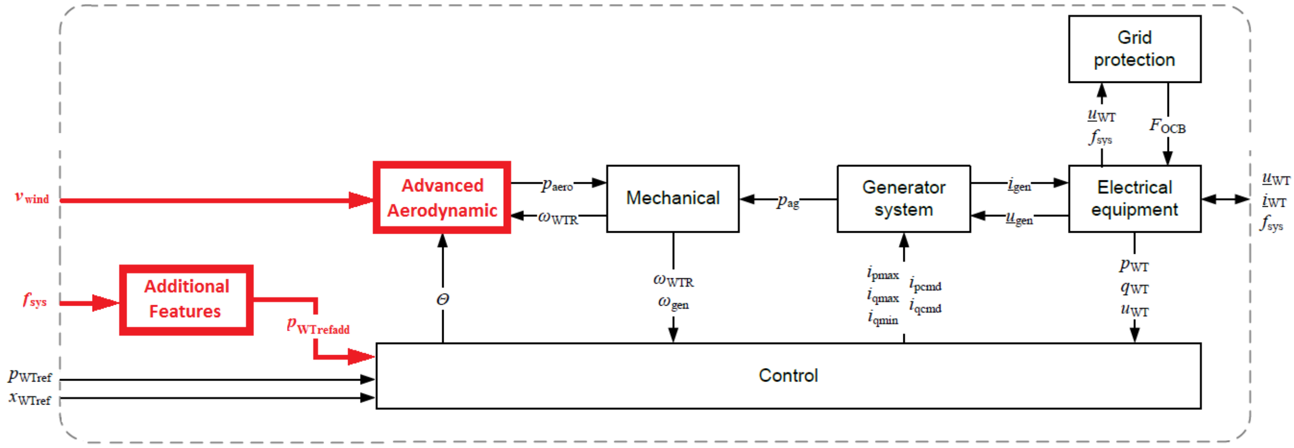


Fig. 1. Modified IEC control structure of type 3 WT, new or modified blocks or signals are marked in red and bold

control active power depending on grid frequency were included (see section III).

By adjusting the parameters of the WT model and selecting the appropriate control mode, arbitrary wind turbines can be represented. Usually, wind turbine manufacturers are able to provide parameters to represent their WTs with the IEC model.

III. Additional Features

The model proposed by the IEC standard, which is described in the previous chapter, is a relatively simple and yet detailed way to represent a wind turbine's behavior in dynamic simulations. However, considering that WTs are more and more required to provide grid services and contribute to frequency stability, additional features were included in the IEC model.

These features are developed on the basis of publicly available literature. Below, the main extensions and changes to the original IEC model are listed:

- **Emulated Inertia** according to [3] increases the active power above the available power for a short time period during an underfrequency event;
- **Delta Control** according to [4] operates the WT with an output power below the available power. It adapts the power in both directions depending on the frequency;
- **Active power reduction with overfrequency (APROF)** according to [5] reduces the output power linearly if the frequency exceeds a certain threshold;
- **Wind speed as input**: The wind speed can be entered time-dependently by the user. It is the main input to the model and determines the available power;
- **Aerodynamic model**: The simplified aerodynamic model is replaced by an advanced aerodynamic model including Cp curves. The advanced aerodynamic model uses wind speed, rotor speed and pitch angle as input to calculate the mechanical power. The user can choose between three different options for the calculation of Cp curves [6] [7] [8].

The additional features can be activated or deactivated by the user. In this chapter, only the first two features, which include completely new functions and have a significant influence on the behavior of the WT, are introduced in detail. They have in common that they adapt the output power to frequency deviations, by sending an offset to the active power reference value of the active power controller and/or the pitch angle controller, respectively. Inside these control blocks small adjustmens have to be made to incorporate the additional signal $p_{WTrefadd}$.

By expanding the control structure and replacing the aerodynamic model it was shown that modifications and extensions of the IEC model are generally possible. It would also be possible to modificate other elements, such as the generator system, or to add even further additional blocks. If future versions of the standard propose new blocks, the old ones can be replaced easily.

The following sections and figures explain how two of the features that were added here were implemented in detail. The parameters, that are used by the the additional features, depend on user preferences or the relevant grid code.

A. *Emulated Inertia*

Emulated Inertia gets activated, when the frequency drops below a certain adjustable threshold. As a consequence, output power is linearly increased with decreasing frequency up to an adjustable maximum value. This output power is increased even when there is no additional wind power available. This means the additional power must be drawn from the rotating mass of the wind turbine rotor which decreases the rotor speed and leads to a suboptimal operating point. Emulated Inertia lasts until the frequency returns to its normal frequency range or until the user-defined maximal allowed duration was reached. After this, the wind turbine needs energy to accelerate the rotor back to optimal speed. During this recovery phase the output power is below maximal available power.

Fig. 2 shows the behavior of the model with activated Emulated Inertia. In this simulation, a load step occurred after 50 seconds. As a result, the frequency decreases. When it passes the threshold of 49.75 Hz (0.995 p.u.), additional power from the WT is released. The rotor loses speed during that time, which is subsequently restored when the need for Emulated Inertia ceases or the maximal allowed time (set to 5 seconds) is exceeded, which is the case for the example below. It can be seen that the output power is reduced during the recovery phase. In this case, the influence

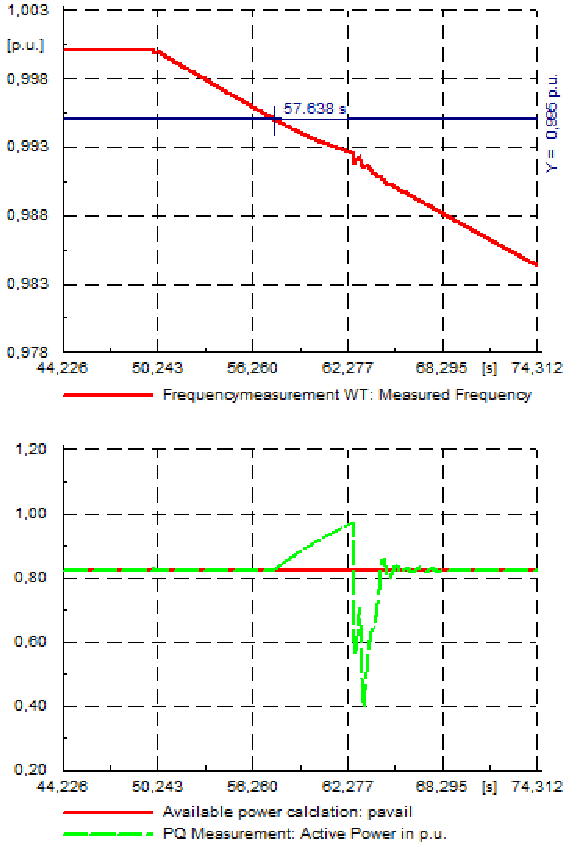


Fig. 2. Reaction of the WT to Underfrequency with activated Emulated Inertia

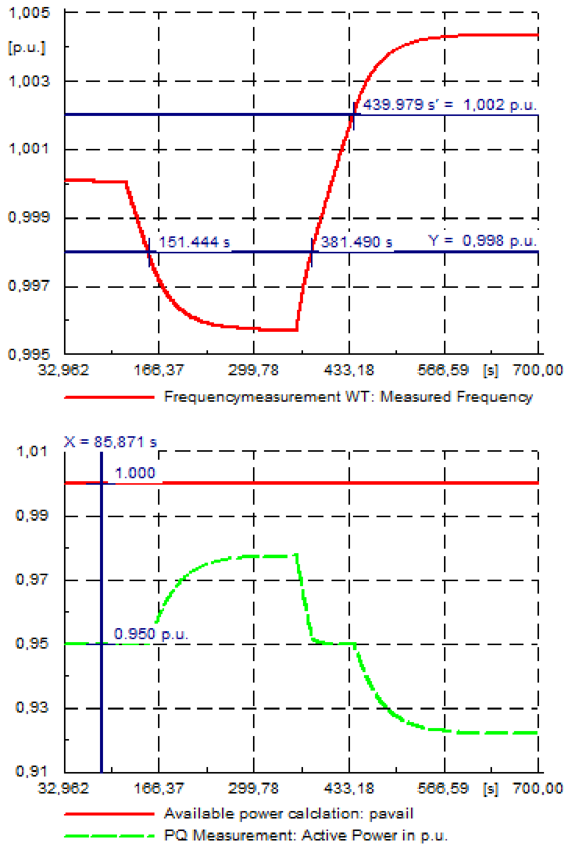


Fig. 3. Reaction of the WT to frequency deviations with activated Delta Control

on the frequency is very small. However, this depends on the inertia of the grid and the power and number of participating wind turbines.

B. Delta Control

Delta Control means that output power of the wind turbine is constantly below maximal available power (e.g. five percent). For this purpose, the available power is estimated by measuring wind speed. This does not only allow reduction of output power during overfrequency but also enables the WT to permanently increase output power during underfrequency events. The drawback of this method is that the available power is not fully utilized, due to the intentionally reduced operating point.

Fig. 3 shows the behavior of the WT with Delta Control during an under- and a subsequent overfrequency event. First, the WT dispatches an output power of 0.95 p.u., although 1 p.u. is available. After 120 s the load is increased and eventually decreased after 360 s, corresponding with a drop/increase in frequency, respectively. As soon as the frequency deviates more than 0.002 p.u. (100 mHz) from the reference value of 50 Hz the WT output power is increased or decreased, by adjusting the pitch angle to control the rotor frequency. When the frequency returns to the allowed interval, the output power returns to the initial value of 5 % below available power.

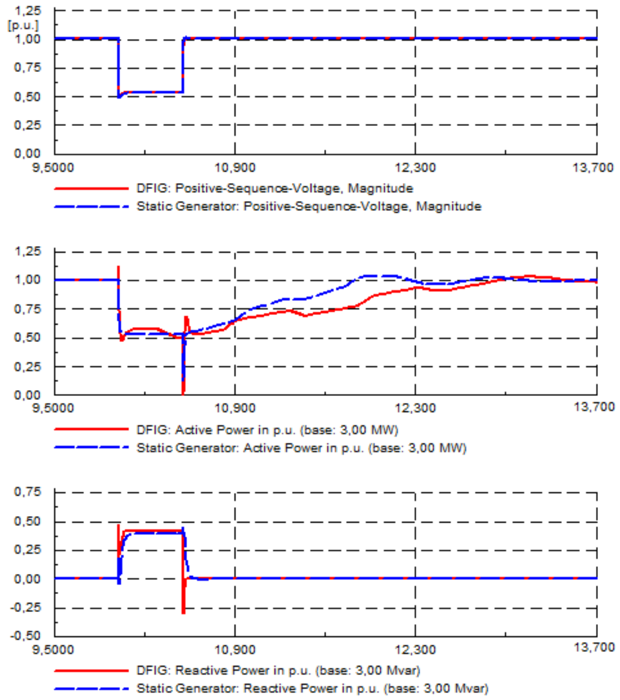
IV. Simulation Results and Verification

After developing the models, they were verified by comparing the simulation results with simulation results of manufacturer models. Each type of WT (3 and 4) was compared to a manufacturer model. To set up the generic model similar to the manufacturer models, the IEC parameters were needed. Two manufacturers provided their models as well as their parameters for the IEC model.

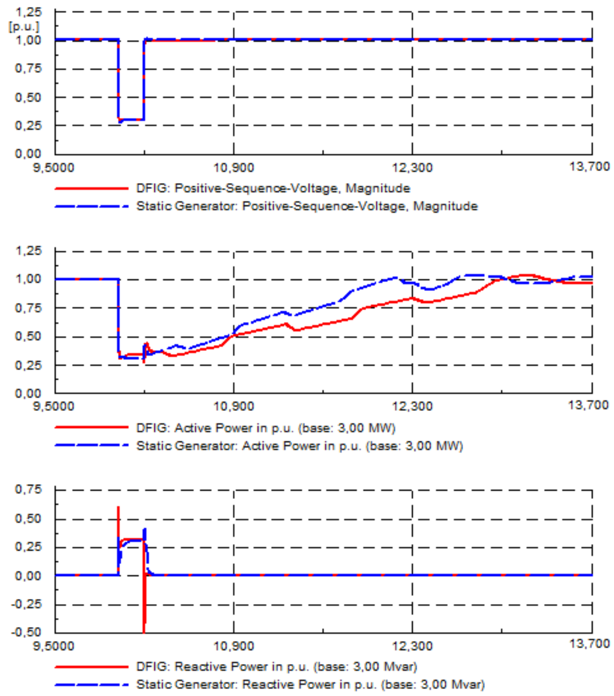
Since the developed type 4 model varies slightly (especially in the P control block) from the IEC type 4 model, not all necessary parameters were available by the manufacturer. Therefore, some assumptions were made. The parameters were chosen in such way that the resulting control structure was as similar as possible to the IEC type 4 model.

To compare the models, the parametrized IEC-based model as well as the manufacturer model were inserted in a simple test grid. In each test, both models had exactly the same conditions. Then, the models were compared by applying three different symmetrical short circuits and reference value steps for active and reactive power. The simulations were conducted according to IEC standard 61400-21 [9]. During all these simulations, any additional features were deactivated in both models and the wind speed was set to be constant. This means the type 3 generic model was exactly the same as the IEC model. Type 4 was like type 3 IEC model, but with a type 4 generator system.

Fig. 4 shows the simulation results of two different FRTs for both type 3 IEC-based model and type 3 manufacturer model. It can be seen that both models behave roughly similiar. The active power oscillates with the same frequency, but it has slightly different ramp rates when recovering from the FRT. This leads to a maximum deviation of approximately



(a)

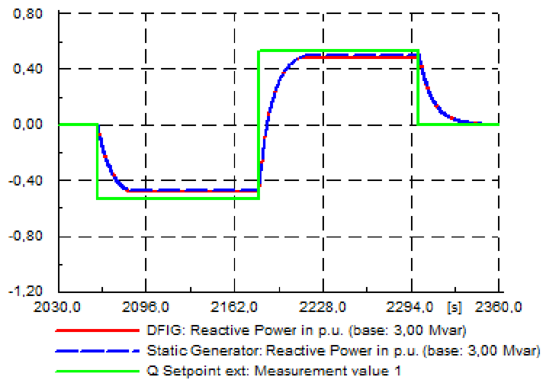


(b)

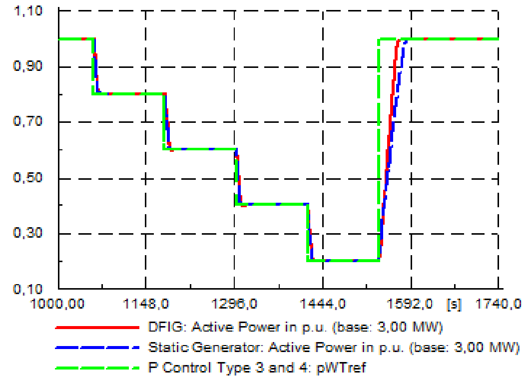
Fig. 4. FRT simulations with Type 3 generic model (blue dashed line) and manufacturer model (red solid line), (a): 50 % residual voltage, (b): 25 % residual voltage

20 % of the active power, when reaching nominal power. Regarding reactive power, a good match can be observed during both FRTs.

Fig. 5 shows the simulation results of different reference value steps for both type 3 IEC-based model and type 3 manufacturer model. During these simulations all other quantities were kept constant. It can be seen that the generic model



(a)



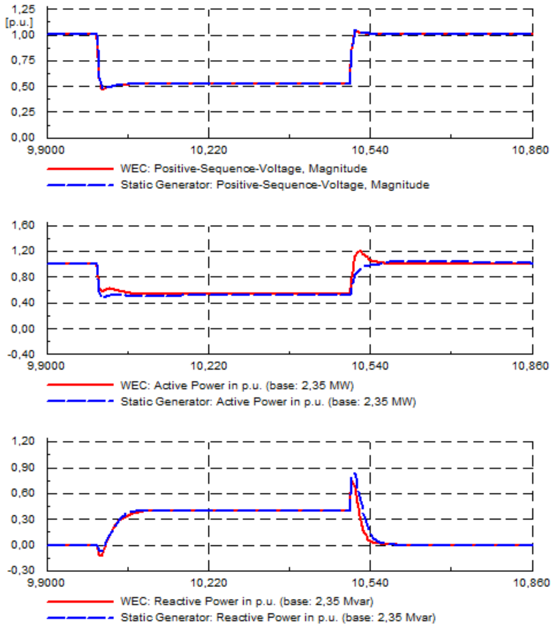
(b)

Fig. 5. Reference values steps with Type 3 generic model (blue dashed line) and manufacturer model (red solid line), (a): Reactive power (b): Active power, the simulations were conducted separately

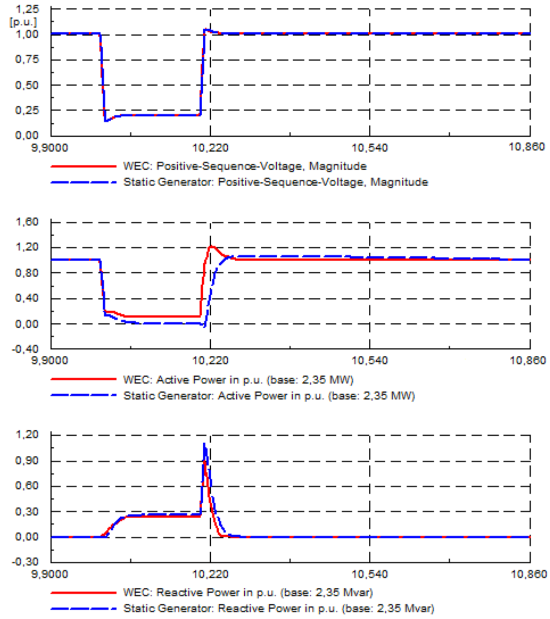
behaves similar to the manufacturer model in almost every reference value step. In the case of the Q reference value steps, almost no deviations between generic and manufacturer model can be observed. Also the steps for P reference value look similar to the manufacturer models results. Only during the final reference step, a slight difference can be noticed, when the power returns to 1 p.u.

The same simulations were conducted with the type 4 generic model using the type 3 controller structure (see fig. 6 and 7). For the FRT simulations, the deviations of active power are slightly bigger. Especially when returning to nominal voltage, there are big deviations for a short time period because the generic model has a slower reaction time and does not overshoot as much as the manufacturer model. Similar to the type 3 model comparison, the type 4 generic model simulates the reactive power very well.
Again, the reference value steps are replicated precisely by the type 4 generic model. Only the ramp rate, when returning to 1 p.u. active power shows a significant deviation. Reasons for the observed deviations in FRTs and reference value step simulations are:

- The developed models are generic models. Hence, they have probably a different controller structure than the manufacturer models. So, it is not possible to replicate the exact behavior for every case.
- The parameters set in the generic model come from manufacturers. They have determined those parameters

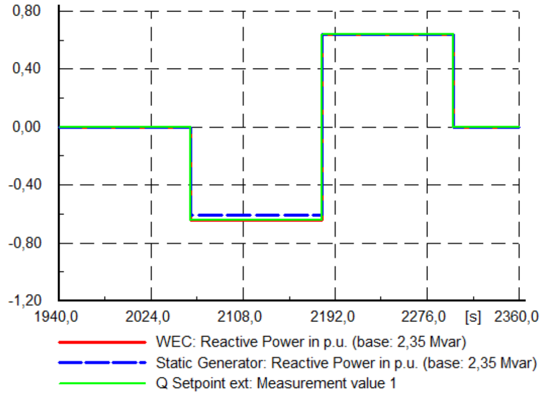


(a)

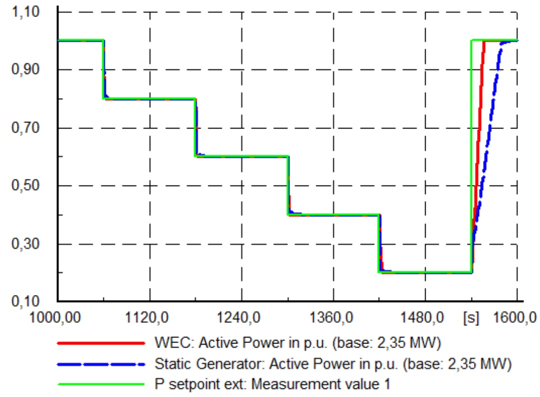


(b)

Fig. 6. FRT simulations with Type 4 generic model (blue dashed line) and manufacturer model (red solid line), (a): 50 % residual voltage, (b): 25 % residual voltage



(a)



(b)

Fig. 7. Reference values steps with Type 4 generic model (blue dashed line) and manufacturer model (red solid line), (a): Reactive power (b): Active power, the simulations were conducted separately

for the IEC model to replicate their wind turbine as well as possible. These parameters were mainly determined to simulate FRTs. They might not be the best solution for all the considered cases (especially P reference value steps) and there is still potential for improvement.

- The P controller of the type 4 model differs significantly from the controller in [1]. Hence, there were no parameters available from the manufacturers and some assumptions were made. It is possible that the chosen set of parameters is not the best solution for the considered wind turbine. Also the different structure of this block (see [1] for more information) probably leads to deviations.

The observations made here confirm the findings of [10], where the type 3 IEC model was compared to a manufacturer model of Gamesa. There, a similar yet not perfect behavior was observed during FRTs.

V. Experiences in Using the Models

The advantage of all generic models is their simplicity and their ease of use. Hence, the time for setting up grid models and running simulations is reduced. The drawback are less accurate results. The models described here as well as the IEC models offer a fast simulation time which facilitates simulations of large grids with many WTs in acceptable time. As shown before there are small deviations to manufacturer models. Nevertheless, the generic models are sufficient for assessing the general behavior and stability of a grid.

At the moment, the developed models are used in several dynamic simulations in the MIGRATE project. Users of the developed WT models apply them in large grid simulations. There, it is very important to use the correct parametrization for the models. With wrong parameters, any arbitrary behavior can be modeled. Usually manufacturers can provide IEC parameters for their wind turbines. As mentioned before, the IEC parameters for type 3 model can be used without changes for the generic model described here. For the developed type 4 model the IEC parameter have to be adjusted slightly, because the P control is different from the IEC model.

The parameters of the additional features can be adjusted by the user for his needs or as specified by the relevant grid code (e.g. ramp rate of APROF).

When parametrizing the WT models correctly a realistic representation of the modeled WTs can be achieved, as shown in the previous chapter. It is worth mentioning that the reactive power is simulated very well in all examined cases of both models, while the active power shows bigger deviations. This shows that the Q control block of [1] is very accurate (at least for the WTs tested here), while the P control block could be further improved.

However, both types of generic models offer an easy solution to implement different types of wind turbines in all kind of dynamic grid simulations. Especially, when enhanced reactions to frequency deviations or the behavior with varying wind speed shall be modeled, the developed models offer significant improvements compared to the IEC models. Since WTs are required to provide more and more grid services (e.g. ENTSO-E grid code RfG [11] requires APROF and enables TSOs to demand emulated inertia), it is advantageous to use the models developed in this paper in dynamic grid simulations. When these features are not needed, it is sufficient to use the unmodified IEC models.

VI. Conclusion

In this paper the development of generic models for type 3 and 4 wind turbines based on IEC standard 61400-27-1 was described. The IEC models were extended by several additional features which may be commonly required in future wind turbines. The functionality of a sample of these features (emulated inertia, delta control) has been shown in several simulations. Due to the modular structure of the IEC models, they can easily be expanded by additional control blocks. This was done by manipulating the reference value for active power which is sent to the control structure in dependency on the frequency.

It was also shown that the generic models show similar behavior to the manufacturer models which were examined here. Hence, it is possible to use the generic models developed here as well as the IEC models in all kinds of dynamic grid simulations. However, due to their generic character, these models should not be used when a high accuracy is needed.

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