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Wind farms in AGC: Modelling, simulation and validation

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Abstract
Wind farms are increasingly interested in participating in the secondary frequency control, especially in power systems where AGC is organized by regulation zones comprising generation units of different technologies. In order to estimate the wind farms behaviour and overall impact on automatic generation control (AGC), a reasonably simple wind farm model is needed. First-order and second-order linear models of wind farms are proposed in the literature in AGC-related studies. However, these simple models neglect key dynamic features for AGC integration of wind farms, such as artificial ramp limitations, dead bands, communication delays and start-up delays caused by turbine orientation. This paper presents a still simple wind farm model, however representing all relevant dynamics and availability constraints at power system control level. Applying an illustrative case study, model parameters are tuned and validated by means of field measurements, recorded during a response trail run of a real wind farm of 30 MW installed power operating within the Spanish power system.

1 | INTRODUCTION

Secondary frequency control restores system frequency to its scheduled value (once the primary frequency control has acted) and maintains the interchange power between control areas at the scheduled values through the automatic generation control (AGC) [1]. Traditional AGC systems control thermal power and hydropower plants based on a control signal denominated ACE, which indicates the required power modification to balance persisting power (interchange) and frequency deviations. Transients of secondary frequency control are in the time-scale of minutes [1].

However, with the ongoing increase of wind power, conventional power plants are bit by bit ruled out of operation [2] and the difficult to predict power provision of wind power is making system regulation increasingly challenging and ultimately more costly for all participants [3]. In order to counteract this development various transmission system operators (TSO) are delegating some regulation responsibility onto wind farms (WF) by imposing requirements to be capable of power tracking and frequency regulation [4].

In recent years, wind generator and supervisory WF controls have been elaborated which successfully enable power set point tracking [5, 6]. Moreover, control methods and strategies to further improve the regulation potential of wind power farms have been designed. These strategies comprise additional predictive control methods [7, 8], reserve provision [9], or intelligent communication between wind engines [10]. Such control strategies have also been implemented in the context of secondary AGC regulation systems, in order to facilitate the regulation task of wind power plants for the regulator in place [2]. Furthermore, demonstrative research projects have corroborated the ability of WFs to provide secondary frequency regulation [11, 12, 13]. However, no WF model is included in the description of the research projects.

To accurately estimate the WFs behaviour and its overall impact on the collective AGC regulation, a reasonable WF model is required which captures the principal dynamics and availability constrains relevant for AGC. Several works can be found in the literature on the modelling of WFs [14, 15]. WF models are usually aggregated models of individual wind generators. Further, there is a trade-off between model complexity and model performance. This is especially important when analysing large power systems, where the benefits of detailed models fade out and in addition increase simulation time. In the context of secondary frequency control, implemented through an AGC system that transmits set point commands at a sampling time of various seconds, essentially mid-term regulation dynamics such as power ramping, control delays, dead band, and offset characteristics are of interest [16], whereas short-term dynamics related to detailed modelling of wind generator components play a minor role. However, existing models of WFs, participating in secondary frequency control, are either simple linear models or very detailed models. Whereas detailed models catch short-term dynamics well, they are less suitable for long-term simulations with time horizons of several hours. Further, very detailed models are often difficult to adjust. Simple linear models by contrast neglect key dynamic issues for AGC integration of WFs, such as WF control delays, artificial ramp rate limits and communication and start-up delays [17–19].

To this end, this paper proposes as simple but still accurate model to reflect the real behaviour of WFs in AGC operation. Precise representation of real WF dynamics is very valuable to design and enable AGC regulators to place adequate regulation commands in wind frequency regulation support. The model follows a grey-box approach and approximates the linear dynamics of the WF through a generic second-order model. Moreover, it includes relevant non-linearities such as ramp limitations within the WF controller, maximum and minimum power limits and operation-dependent delays. The WF model is to be included in already existing models of one or several AGC areas to allow improved evaluation of the impact of WF inclusion in AGC and better design and tuning of AGC regulators. As an illustrative case study, a response trail run of 80 min duration of a real WF of 30 MW installed power was performed, in which regulation commands sent every 4 s (Spanish AGC is operated with cycles every 4 s [20, 21]). In contrast to references [11] and [13], the aim of such trail run is not demonstrating frequency support capabilities, but rather the understanding of relevant wind dynamics for AGC studies. The actual response of the WF during the run clearly shows that ramp rate limits and delays should not be neglected. The parameters of the proposed model are first tuned using as training set of 40 min of data. Subsequently additional 40 min of collected data is used as a validation set to prove the correct behaviour of the model. Finally, the proposed model is compared to basic first-order and second-order models to highlight gained improvements in WF representation.

The rest of the paper is structured as follows: In Section 2, relevant WF dynamics and models suitable for AGC studies are reviewed. Additionally, a test set of field measurements, recorded during a response trail run of a real WF of 30 MW is presented and analysed. In Section 3, the proposed WF model is presented and parametrized. Section 4 shows an illustrative case study using a different data set to validate and rate the elaborated model against basic first- and second-order WF models. Finally, Section 5 concludes the paper.

2 | DYNAMICS AND OPERATION OF WIND FARMS IN SECONDARY REGULATION

In this section, key dynamics of WFs relevant for secondary frequency control are summarized. First, a single wind turbine configuration is reviewed for active power control (APC) in Section 2.1. Dynamics related to the APC are most relevant. Second, models of WFs for AGC operation are reviewed in Section 2.2. These WF models aggregate wind turbine generators (WTGs). Lastly, in Section 2.3 field measurements of a real Spanish WF of 30 MW will be used to showcase that features such as artificial ramp constraints, dead bands, communications and start-up delays should not be omitted in AGC WF modelling.

2.1 | Wind generator dynamics relevant for secondary regulation at power system control level

A WF controller supervises and controls wind generators in a WF [22]. The WF controller receives active power set points of the AGC when under secondary regulation. This is illustrated in Figure 1a, which shows the interaction between the WF controller and a hierarchical AGC as the one in Spain, where the system operator computes the power set point updates for secondary regulation. The WF controller, containing a PI controller, further distributes the set points among the WTGs. In the absence of very different wind speeds [23], it is reasonable to assume that the collective response dynamic of the WF is similar to that of a single WTG. Each individual WTG model basically consists of four main components: the wind turbine, the generator, the converter, and the control and protection system. Figure 1b shows the topology of a full-converter permanent magnet WTG, whilst Figure 1c illustrates its control scheme (see, e.g. [22]). If WTG does not implement deloaded operation through rotor speed control (RSC), WTG can decrease its power output below the maximum power point (MPP) and subsequently increase it through the pitch angle control (PAC). Whereas the grid-side converter usually controls the reactive power and dc-link voltage, the generator-side converter controls direct axis stator current and the generator speed according to the maximum power point tracking (MPPT). In the time horizon of secondary frequency regulation, the dynamics of the wind generator, the dc-link and the grid-side converter controls (current and dc-link voltage control loops—CC and VC) can be neglected, since associated response times are an order of magnitude below the AGC sampling time [24]. The APC including MPPT might however affect secondary frequency regulation.

APC objectives can basically be divided into the following two objectives [22]: (i) maximizing energy extraction from wind, if the wind speed is lower than the nominal speed, and

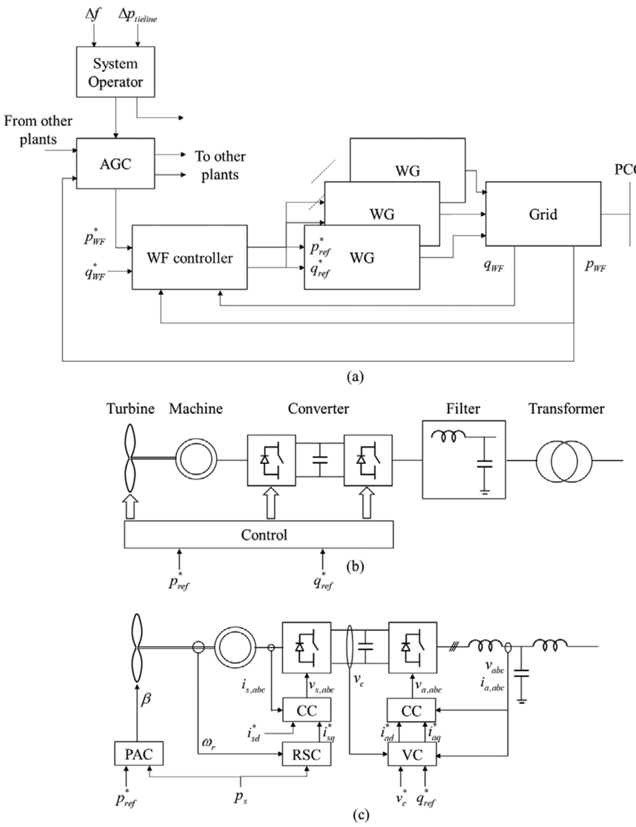

FIGURE 1 Wind farms in AGC: (a) overall AGC control scheme, (b) topology of a full-converter permanent magnet wind generator and (c) its control scheme. CC, current control; VC, dc-link voltage control; RSC, rotor speed control; and PAC, pitch angle control

(ii) limiting the power output to nominal power, if wind speed is higher than the nominal speed. Objective (i) can be achieved by constantly adjusting the rotor speed in function of the generated power (RSC), while the pitch angle is maintained at its optimum point, corresponding to around zero degrees [23]. Objective (ii) is achieved by adjusting the pitch angle (PAC). Under secondary frequency regulation, the objective might not necessarily be the extraction of the maximum amount of energy but to follow of the power set point received by the WF control (e.g. the AGC). Both controls are executed simultaneously, limiting the active power output according to the desired power command, whilst maintaining MPPT at increased pitch angle [6, 25].

Dynamics of the controls depend on their tuning. In reference [26] it is mentioned that variable speed wind turbines can increase their power output significantly faster than conventional power plants. This seems to be especially true for CC, CV, and RSC controls. The latter imposes appropriate torque references that translate very fast into power variations. PAC however exhibits slower dynamics. Response and settling times between 03–09 and 08–38 s, respectively, have been tested in reference [27]. Reference [22] exemplarily shows the response of a 660 kW wind generator to a change in the power set point of approximately 0.5 pu. Generator power reaches the new power set point, with some overshoot, after approximately 10 s. However, non-linearities in the control such as ramp

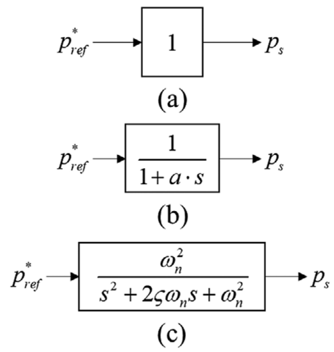

FIGURE 2 Wind farm models for AGC studies: (a) instantaneous response model, (b) first-order model, (c) second-order model

limitations of set point variations might further affect the overall response.

In reference [28] a maximum limit of power variation between 0.18 and 1.5 pu/min (relative to the nominal power) is stated. Reference [22] illustrates a power ramp for wind engines of approximately 0.05 pu/s, equivalent to 3 pu/min. Reference [29] indicates, that wind generators can provide power ramps of 0.4 pu/s, equivalent to, 24 pu/min. From the above it can be concluded that wind generators hold a considerably high ramping speed, especially compared to thermal generation (the maximum ramps can be in the order of 10 MW/min), allowing them to react quickly to new power set points. However, despite holding a very fast power ramping capacity, it is important to point out, that in AGC operation, it might be advantageous to impose artificial ramp limitations for wind generators, inferior than their actual ramping limitations, in order to avoid turbine degradation or to harmonize the wind engines behaviour with that of a conventional plant.

2.2 | Review of wind farm models for AGC

From Section 2.1, it can be concluded that the principal dynamics of wind generators affecting AGC are those related to the APC. Figure 2 summarizes the linear simplified models of WFs traditionally proposed in AGC-related studies. Basically, they correspond to instantaneous response models (Figure 2a), first-order linear models (Figure 2b) and second-order linear models (Figure 2c). Second-order models typically approximate APC control loops.

Reference [15] applies modal analysis and balanced truncation to obtain low-order equivalent models of DFIG. Selective modal analysis has been used in [18] to derive linear first-order and third-order models. A second-order model is presented in reference [30]. A first-order model has been used in [17] for stability assessment of long-term frequency dynamics involving AGC, where the first-order model approximates the fast dynamics of the DFIG and its control. In reference [31], wind generators have been modelled as a controllable negative load, that is, power variations due to primary frequency controls apply nearly instantaneously. However, if operating at MPP, active pitch angle power control, as indicated in Figure 1, does

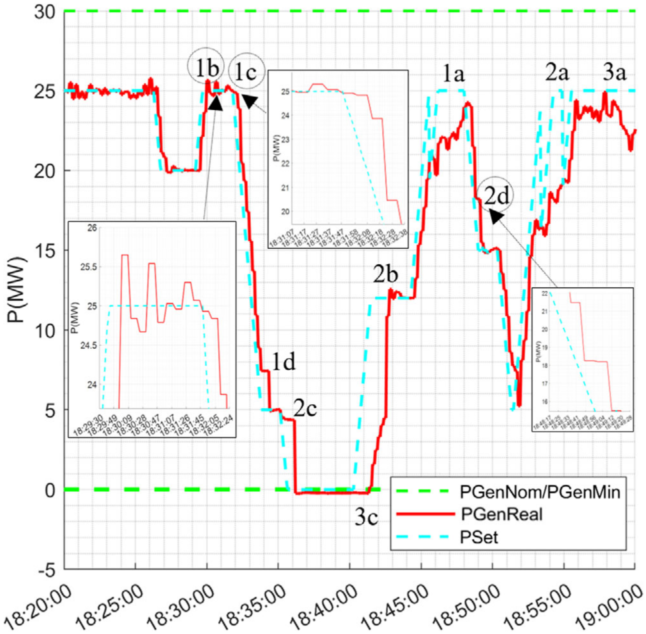

FIGURE 3 Wind farm response trail run

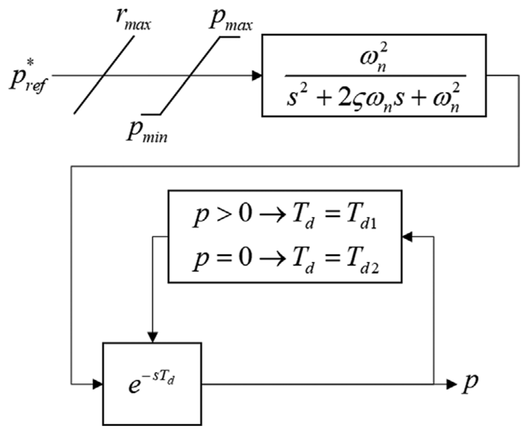

FIGURE 4 Wind farm model for AGC studies

not apply instantaneously. In reference [23], an aggregate first-order model has been proposed with individually included wind speeds. All the described models typically consider aggregate individual wind generator dynamics, whilst neglecting WF control dynamics which might include additional ramp limits and other non-linearities.

2.3 | Field measurements of a real 30 MW Spanish wind farm

This subsection presents field measurements of a 30 MW Spanish WF which will be used to identify key components of their response dynamic. The WF consists of 15 wind generators (6 Gamesa G80/2000 and 9 Gamesa G87/2000 WTGs), of 2 MW capacity each. Figure 3 shows the set point command, the resulting power generation and the upper and lower power limits of the WF for 40 min of the conducted trail run. Figure 3 allows extracting valuable information on WF response dynamics under AGC, also with respect to the models commonly used (e.g. see Figure 2).

As can be seen in Figure 3 the WF is able to follow the power assignments fairly well, whenever the demanded power set point does not surpass the current power limit imposed by the prevailing wind conditions (MPP). Illustrative examples of occasions where the set point has exceeded the current MPP of the WF, can be found at position 1a—3a. Moreover, as already identified in the previous section, one can occasionally recognize a relatively quick second-order response dynamic, characterized by a certain overshot before reaching the set point (cf. 1b and 2b). Oscillations at 1b last for about 60 s, which reflect WF controller and WG APC interactions coupled with wind speed variations. Additionally, when a new power set point is assigned a certain initial response delay can be detected (cf. positions 1c and 2c), which plausibly result from overall WF control delays. As can be seen in Figure 3, at position 3c, such delays can even be significantly longer, when the WF is turned off before receiving a new start-up command. In this case, the additional response time can easily be associated to the necessary start-up and/or turbine orientation processes. Finally, it is shown, that the power response often comprises certain stagnations before reaching the assigned power set point (cf. 1d and 2d). The origin of such stagnations is not fully clear but it is most likely related to the implementation of the WF control. The variation in the up ramp between 3c and 2b seems to be the result of the sequence of start-up of individual WTGs. Some of the identified non-linearities have been highlighted to improve their visibility.

3 | PROPOSED AGC WIND FARM MODEL

This section presents the proposed WF model for AGC operation. It aims to adequately represent the dynamics of a WF relevant within the time frame of AGC regulation, which follows a sampling time between 1 and 5 s, and a response time typically in the range from 30 s to 5 min. The model is based on the response characteristics of wind generators and on the identified operation dynamics and constraints from WF field measurements as presented in Section 2. The idea of our paper is not to model each physical characteristic of the WF and WTGs but it rather follows a "grey-box" approach in which know physical characteristics of single wind turbines as well as overall observed WF behaviour (due to unknown control dynamics) are connected for model designing.

Figure 4 shows the block diagram of the proposed WF model in the continuous time domain. First, the model includes an overall maximum ramping speed $r_{\max}$ in order to approximate the detected power response stagnations. Second, the model considers the upper power limit imposed by the MPP, $P_{\max}$. Please note that limit $P_{\max}$ does not necessarily correspond to the nominal installed power of the WF, but instead needs to be adjusted to the current MPP to maintain the model's accuracy when the power set point surpasses the MPP. Since start-up delays can be significant, shutdown of wind turbines is at times not desired or permitted. Consequently, a minimum power limit $P_{\min}$ is introduced to account for this possibility. A generic linear second-order model (defined by parameters ω_n and damping ς) is used to reflect the aggregated linear dynamics of the APC of the WF including WF controller and APC of WTGs. The second-order model parameters do not represent a particular control loop (e.g. the PAC) and thus lack a direct physical correspondence. The objective of the second-order model is rather to represent the overall response of the WF. Note that the final parametrization of the second-order model depends on the particular WF, its control and further aspects like prevailing conditions (wind speed fluctuations) and set point variation. Finally, to represent the general control delays at the moment of power assignment, a response delay of T_{d1} is added to the model. T_{d1} represents communication delays as well as delays due to signal processing, computation and different sampling rates of the AGC and the WF control. Additionally, a second delay T_{d2} is modelled, which characterizes the WF start-up process, so that it is only activated after a total WF shutdown ($P_{WP} < 0.05$ MW) (cf. Figure 4). T_{d2} primarily depends on the orientation of the WTGs in regard to the current wind direction at start-up as well as on the particular WTG start-up sequence. Such delay could be reduced by either avoiding a total WF shutdown whenever possible or by maintaining proper wind turbine orientation in wind direction during shutdown. It should be noted that $P_{\max}$ and $P_{\min}$ are known input data, while the rest ($r_{\max}$, ω_n, ς, T_{d1} and T_{d2}) are unknown parameters to be tuned using data of real operation. Since AGC simulations are discrete simulations with a sampling time according to the AGC signal the proposed transfer function must be converted to the z transform

4 | ILLUSTRATIVE CASE STUDY

As illustrative case study, a real WF of 30 MW installed power operating within the Spanish power systems is represented by the proposed model in Section 3. A response trail run of 80 min of duration was run, recording set point command and resulting power generation every 4 s. It should be noted that, since AGC simulations for the case study are discrete simulations with a sampling time according to the AGC signal (4 s) the transfer function of the model must be converted to the z transform. As stated before, parameter $P_{\max}$ is initially set to the nominal power of 30 MW, but is curtailed when the power set point surpasses MPP; parameter $P_{\min}$ is set to 0 allowing a complete WF shutdown.

The first 40 min of data is used as training set to tune the model parameters (Section 4.1). After tuning the model, the second 40 min of data is saved to be used as test set to validate correct behaviour of the model (Section 4.2). In Section 4.3, the proposed model is compared with simple first-order and second-order linear models in order to highlight the improved representation of the model proposed in the paper. Finally, a sensitivity analysis of the utilized second-order model is performed by varying its parameters from their optimal value in order to demonstrate their influence on the accuracy of the total WF model (Section 4.4).

TABLE 1 Optimal wind farm model parameters

Parameter	Opt. Values
ω_n [rad/s]	3.6748
Σ	34.1799
$r_{\max}$ [MW/s]	10
T_{d1} [s]	8
T_{d2} [s]	88

4.1 | Tuning of wind farm model parameters

The parameters $r_{\max}$, ω_n, ς, T_{d1} and T_{d2} of the proposed model need to be tuned by using real operation data. The tuning basically consists in adjusting these model parameters such that the simulated response coincides as much as possible with the measured response.

The adopted tuning procedure includes the following aspects: (i) acquisition of operational data, if possible, with differing wind speeds. Such data includes in particular the real power output of the WF, the WF power set point and an estimation of the total MPP of the WF. To obtain such WF MPP, each WTG computes and shares its potential MPP with the WF control, which calculates the total MPP by aggregating all individual MPPs. Please note that the collection of individual MPPs should be reasonably synchronized. Also note that a reasonable sampling rate similar or higher than the one of the AGC (1–5 s) is required; (ii) data pre-treatment. Time periods where the power set point is above the MPP of the WF and/or with atypical behaviour should be excluded; (iii) division of trail run data into training and test set. Both, training and testing/validation should be sufficiently rich in AGC-related dynamics. The more data available, the more robust the tuning; (iv) application of an optimization method to optimally tune the model parameters by minimizing the error between the simulated and measured responses. Here, such error is quantified by the sum of the stand ard deviation (SD) and maximum deviation (MD) of the simulated response with respect to the measured response. Optimal values for the mentioned model parameters can be obtained using a non-linear optimization method. A genetic algorithm with default options for selection, crossover and mutation has been used here (see [32]), although other algorithms could be used instead. The flow chart in Figure 5 illustrates the tuning process. Table 1 shows the solution from the optimization process of the model parameters. Please note that the obtained parameters may differ depending on the individual WF characteristics such as its size, layout and specific WTG control. Consequently, individual tuning may be required according to the above outlined tuning process. Furthermore, as mentioned above, training data which represents differing wind speeds is beneficial for optimal model tuning.

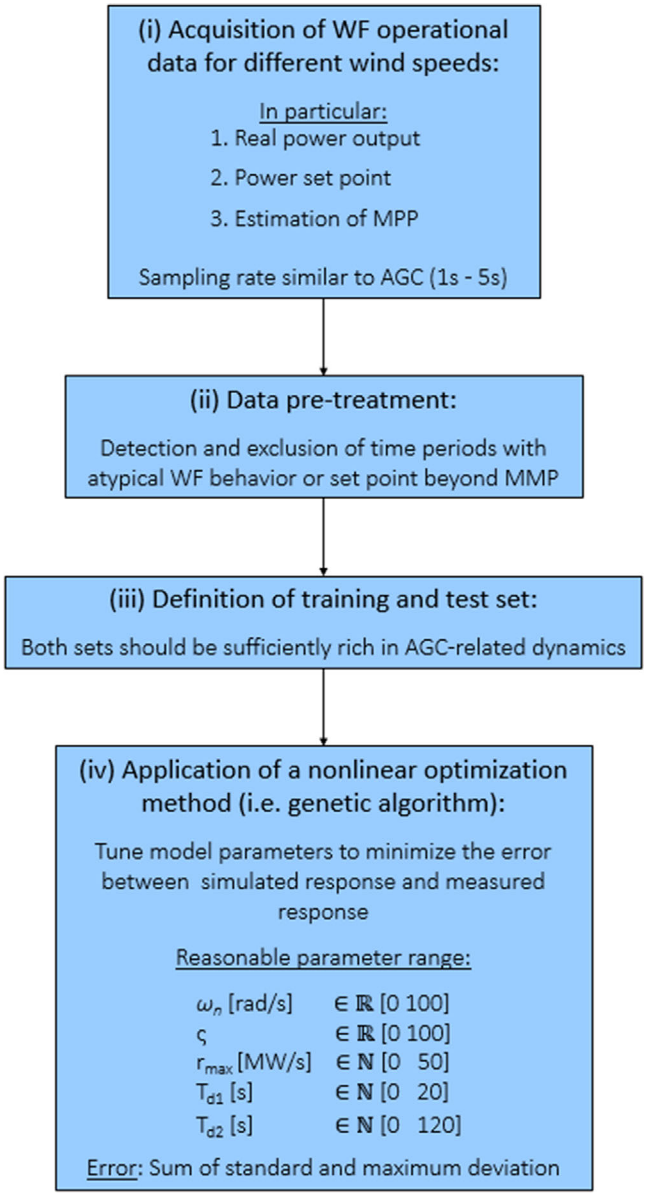

FIGURE 5 Model parameter tuning process

Our model has been trained in wind speeds which allowed WF MPPT between 15 and 25 MW and tested in wind speeds which correspond to WF MPPT between 10 and 15 MW. Figure 6 illustrates the set point command (PSet), real power generation (PGenReal) and simulated power generation (PGenSim) of the adjusted model applying the training set data used in parameter tuning. Simulated response locates quite close to real response, since parameters of the model have been optimized to minimize this distance.

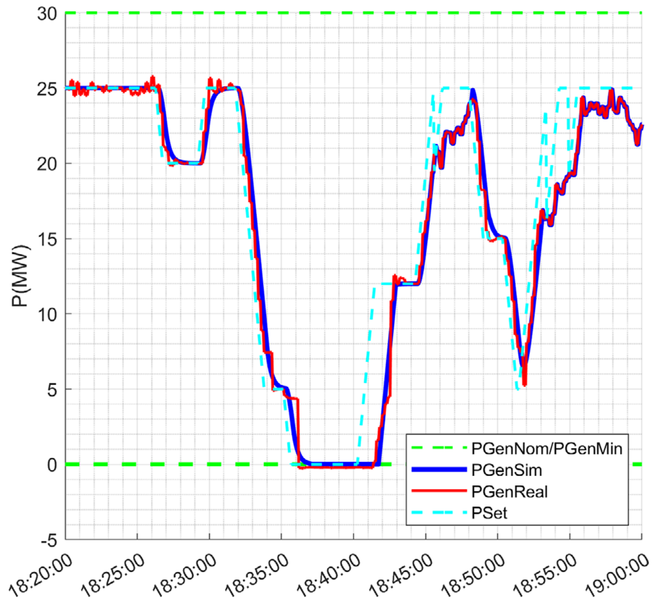

FIGURE 6 Real power generation versus simulated power generation (training data set)

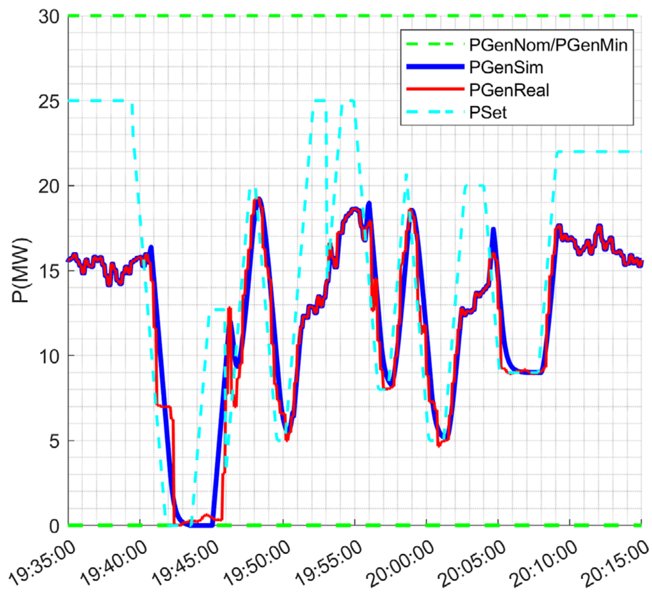

FIGURE 7 Real power generation versus Simulated power generation (validation data set)

4.2 | Wind farm model validation

In order to validate the correct behaviour of the proposed model in the context of secondary AGC regulation, in this subsection the second 40 min of data set of the response trail run is used to validate the model and its power response. Figure 7 shows the comparison of real and simulated power generation for the validation data set. It seems that the proposed model is able to reproduce the real power output quite well. A strong similarity of the real and simulated active power response can be appreciated both in situations of great and small set point variation as well as in the case of complete WF shutdown.

TABLE 2 First- and second-order model transfer functions and their optimal parameter values

Order	Generic transfer functinos	Opt. parameter values
First	$\frac{1}{1+as}$	$a = 49.9225$
Second	$\frac{\omega_n^2}{s^2+2\varsigma\omega_n s+\omega_n^2}$	$\omega_n = 3.7380$ $\xi = 93.3046$

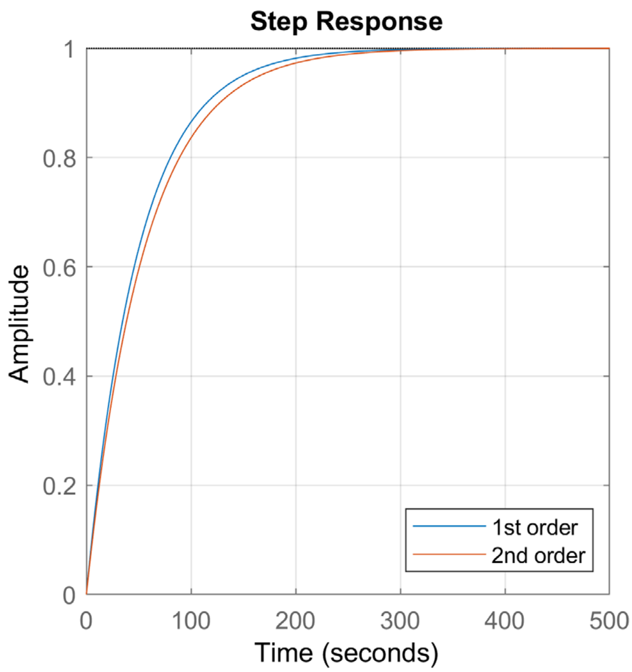

FIGURE 8 Step response comparison of transfer functions in Table 2

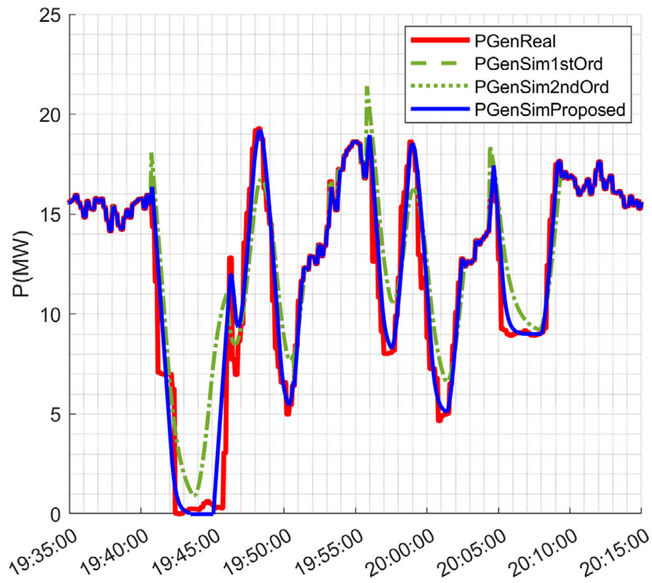

FIGURE 9 Comparison of wind farm models behaviour on validation data set

TABLE 3 Comparison of standard and maximum deviation of real versus simulated wind farm power response

Dev. in response diff. [MW] / Applied wind farm model	SD/MD Test set	SD/MD Validation set
First-order/second-order model	1.68 | 5.75	2.25 | 10.07
Proposed model	0.81 | 3.52	1.23 | 6.36

4.3 | Comparison with simple first-order and second-order linear models

In this subsection the proposed model is compared with a simple linear first-order model and a linear second-order model as suggested in related literature (cf. Section 2.2). To obtain the corresponding generic transfer functions the same test data set and genetic algorithm are utilized for optimal tuning of the model parameters. Table 2 shows the obtained optimal parameter values for each transfer function. It is noteworthy to indicate the optimal high damping value assigned to the second-order transfer function parameter ς. Such high damping will make the resulting response of a second-order transfer function resemble the response associated with a first-order transfer function.

In fact, a comparison of the corresponding responses to a 1 pu step set point command, shown in Figure 8, indicates that a multi-order response approximation seems unnecessary if no further response dynamics are considered.

Figure 9 visually contrasts the goodness of both models using the validation data set. It can be seen that the proposed model clearly outperforms the first- and second-order linear models (situated above each other). The deficiency of such simple representation of WFs becomes especially evident in the presence of WF shutdown events. In the attempt of approximating the corresponding response delays the first- and second-order models greatly lose accuracy regarding the modelling of the dynamic part of the WF behaviour.

Even though simple first- or second-order linear modelling might seem sufficiently accurate in the absence of such WF shutdowns, model's accuracy can once again highly decline if artificial ramp limitations are imposed (cf. Section 2.1). Therefore, a separate ramp modelling as well as response delay consideration are of high value. Table 3 quantifies first-order and proposed models' accuracy in standard and maximum deviation of the difference between real and simulated power response for both data sets.

As can be seen, the proposed model demonstrates higher accuracy both visually and numerically.

4.4 | Sensitivity analysis of the second-order model

This last subsection illustrates the results of a sensitivity analysis of the parameters of the second-order model. The analysis

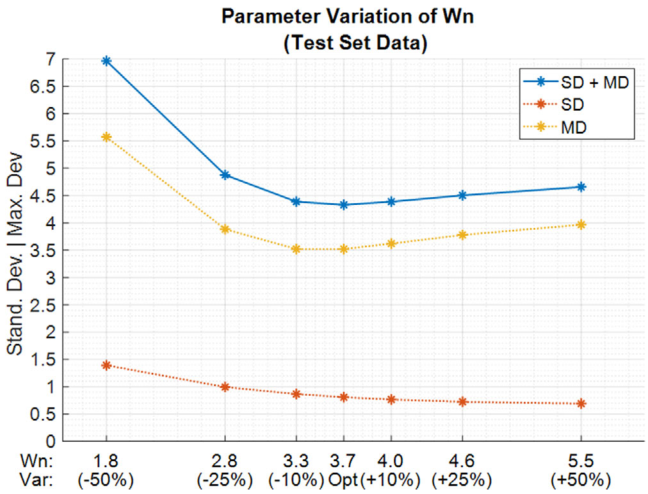

FIGURE 10 Sensitivity analysis of the second-order model in terms of standard and maximum deviation compared to the real power response. Parameter variation of ±10%, ±25% and ±50% of the parameter ω_n

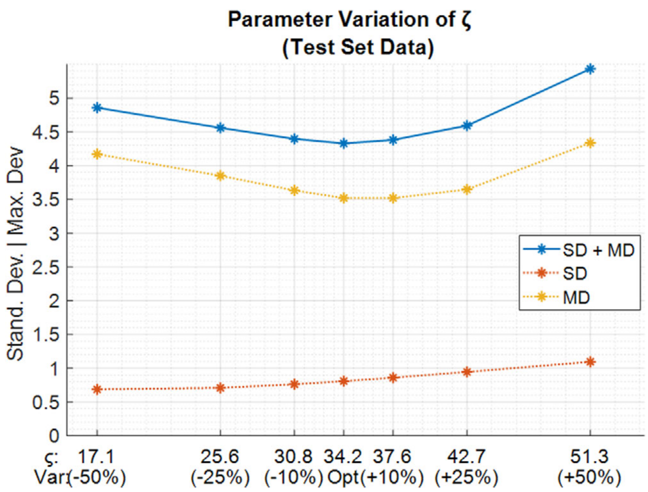

FIGURE 11 Sensitivity analysis of the second-order model in terms of standard and maximum deviation compared to the real power response. Parameter variation of ±10%, ±25% and ±50% of the parameter ς

has been performed by varying ω_n and ς by ±10%, ±25% and ±50% and evaluating the impact on the model's response deviation. Figures 10 and 11 separately show the impact of each parameter on the standard deviation (SD), the maximum deviation (MD) as well as on the sum of SD and MD, of the simulated response with respect to the measured response. The sum of SD and MD is the objective function used in the parameter turning process (cf. Section 4.1). Figure 10 illustrates that especially reducing the natural frequency ω_n (−25% and −50%) negatively affects the accuracy of the model in terms of both SD and MD.

On the other hand, increasing ω_n slightly improves SD but also worsens MD. Overall, minimizing the sum of SD and MD seems to be a suitable objective to keep both deviations within reasonable values. Regarding the damping parameter ς, Figure 11 shows that increasing ς has a negative impact on the total accuracy of the wind farm model. A decrease of ς shows some improvement in SD while worsening MD. Again, the sum of SD and MD as the objective function in the parameter optimization process yields a decent trade-off regarding both deviation types.

5 | CONCLUSION

With the ongoing expansion of renewable energies, WFs are attaining more regulation responsibilities. This paper has identified that typical WF modelling as proposed in related literature is insufficient to properly represent key dynamics of WFs operating in AGC regulation. Especially, artificial ramp constraints, set point delays and start-up delays caused by turbine orientation should not be omitted. A simple but still accurate enough model to represent such relevant dynamics is proposed for AGC WF integration. The model has been developed through literature research and adjusted and validated by means of an illustrative case example of 80 min AGC trail run. A comparison with hitherto existing simple first- or second-order models has shown improved accuracy especially in scenarios of total WF shutdowns. Ultimately, the identification of the mentioned WF dynamics offers highly valuable information to properly parameterize real AGC regulators, enabling feasible regulation command assignment to WFs participating in secondary frequency regulation. Future research will target model validation and refinements for additional wind farms, including different wind generation technologies. The model will also be used within advanced AGC studies of passive and active wind farm incorporation, where in case of the latter suitable control strategies of wind farms will be proposed and evaluated.

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