Real-Time Transient Simulation and Studies of Offshore Wind Turbines

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Abstract—The real-time models of offshore wind turbine generators complied with industry standards are presented in this paper. The developed models provide essential capabilities for future electromagnetic transient controls and testing offshore wind farms, such as low-voltage ride-through, active/reactive power support, transient current limiting. Furthermore, the proposed models provide an additional capability of controlling negative sequence current, which meets the future requirements for protecting wind farm systems. This paper presents average-value and detailed switching real-time models in the Opal-RT real-time simulator. The efficacy of the proposed real-time models in terms of computational efficiency is demonstrated by comparing them with the non-real-time models. Extensive case studies are performed to demonstrate the control functions of the proposed models, such as dynamic-wind condition, power curtailment, low-voltage and fault ride-through, negative sequence current control, etc. The wind turbine model validation against the generic model presented by the Western Electricity Coordinating Council (WECC) is conducted to show their compliance with industry standards utilized by WECC. A real-time model of a 450 MW offshore wind farm is developed to show the feasibility of large-scale wind farm modeling.

Index Terms—Negative sequence current injection, offshore wind turbine, permanent magnet synchronous generators, turbine model validation.

I. INTRODUCTION

OFFSHORE wind energy systems have received considerable attention recently due to the need for decarbonization in conjunction with their potential to generate more wind power [1]. The rapid development of the direct-drive multi-megawatt turbines leads offshore wind systems to be a cost-competitive solution [2]. Since transporting offshore wind turbine parts through ships and barges reduces some logistical challenges that land-based wind turbines encounter, such as narrow roadways or tunnels, manufacturers can build larger turbines capable of producing more electricity [3]. In addition, the advanced direct-drive wind turbine system addresses the problem of gearbox failure, which results in the growing usage of high-power wind turbine generators. Existing 13 MW [4], 14 MW [5] and 15 MW [6] wind turbines are designed for offshore wind applications. With increased developer experience and industry maturity, offshore wind projects are getting larger. Offshore wind turbine modeling complied with industry standards plays an essential role in de-risking offshore wind projects. The majority of existing wind turbine models have been developed without considering industry standards. Therefore, they are not suitable for practical studies of offshore wind farms. The wind turbine models that are aligned with industry standards have been discussed in a few studies [7], [8], [9], [10]; however, these models require extensive computations when a large number of wind turbine generators (WTG) is considered.

Power system operators such as transmission or distribution system operators need a universal, standardized, and validated WTG to perform transient stability analysis. The generic WTG models were presented by international working groups such as the Western Electricity Coordinating Council (WECC) and International Electrotechnical Commission (IEC) [11], [12], [13], [14]. These generic models can represent the behavior of any vendor’s WTG model. The technical report [15] presented the validation of the WECC generic WTG models against the field-measured data from actual Type-4 WTGs of Siemens 3.6 MW, ABB 2.5 MW, and Vestas 3.075 MW. They can produce sufficiently accurate results without requiring a large number of parameters [16]. WECC and IEC models are simple aggregated WTG models, which lack detailed converter controllers such as torque control, DC voltage control, or inner current control, etc. WECC model aims at minimizing the number of turbine parameters while the IEC one focuses on improving the accurate responses [17]. These generic models are essential for dynamic studies of large-scale wind farm systems since they are simplified and do not require significant computation. However, with the uses of power converters integrated with wind turbine generators such as Types 3 and 4, these generic models might fail to represent the harmonic and control interaction among WTGs since the current control loops of power converters are omitted. The study on harmonic instability of large-scale wind farms would be more challenging [18] and it requires the...
development of WTG models that not only are in accordance with the standards but also can represent harmonic interactions. Numerous studies have introduced electromagnetic transient (EMT) models for offline simulation tools like PSCAD/EMTDC, MATLAB/Simulink, EMTP, etc. These models are suitable for investigations of a single wind turbine or small-scale wind farm system as they suffer computational burdens. They have not been tested in real-time and are relatively slow when running in offline simulations [19]. In [7], [20], generic EMT models of WTG Type 4 were presented, which were validated against the field tests and grid codes. A 5-MW WTG model was presented in [8], which provides the low-voltage ride-through capability to meet the U.S. grid code. The limitation of these models is the lack of the ability to control negative sequence current as they were developed with positive sequence, which can lead to incorrect operation of the protection system under unbalanced conditions. Furthermore, under unbalanced conditions, the oscillation at second-order harmonic in DC voltage and active power is caused by the presence of negative sequence voltage [21]. In [22], modeling of 1.5-MW wind turbine generators has been presented, which has the ability to control negative sequence current during imbalanced faults. Both averaged-value (AVG) and detailed switching (DSW) models were studied; however, these models were not tested in real-time simulators. Furthermore, the dynamic response of the DSW model was not well-represented by the AVG model. The measurement of CPU usage in [22] indicated that the AVG and DSW models required 144.7 s and 28.8 s for a 1 s simulation time, respectively. Therefore, there is a need to investigate an efficient model for real-time simulations.

There are works reported in the literature on the real-time WTG models. In [23], the Type-4 WTG is modeled in Typhoon HIL real-time simulator. However, this paper did not present detailed modeling of the wind turbine generators. The real-time WTG models in RTDS were presented in [24], [25], [26]. However, these studies did not evaluate the real-time computation to show the effectiveness of their real-time models. In [27], the real-time computation of the RTDS-based real-time WTG model was given. It was shown in this study that the proposed WTG model required more than five processors over eight available processors. Thus, this model is not applicable for large-scale system studies as it would require significant numbers of real-time processors. The real-time WTG models based on Opal-RT Technologies were presented in [28], [29], [30], [31]. However, these studies also either lack a detailed explanation of WTG modeling [28] or an evaluation of real-time capability [29], [30], [31].

In addition, these existing real-time WTG models have not complied with industry standards. These models also lack the negative sequence control capability. Existing detailed WTG models can be improved to be aligned with industry standards, but they are computationally intensive. With high-performance multi-core processors of real-time simulations such as Opal-RT and RTDS, existing WTG models can be modified to run in real-time simulators. However, those models still need further improvements to reduce computation time, making them insufficient for modeling large-scale wind farms. To address these research gaps, this paper proposes the real-time models of wind turbine generators for investigations of large-scale offshore wind farm systems. This paper is an extended version of our previous work published in [32]. More detailed modeling of the real-time wind turbine generators will be provided. Various comparison studies will be presented to show the advantages of the proposed models:

- A comparison between the proposed real-time and non-real-time models will be presented to show the feasibility and computational advantage of the proposed models.
- The proposed models will be validated against the WECC generic WTG models to demonstrate the compliance of the proposed models with the industry standards.
- A comparison with the typical WTG control will be conducted to show the advantage of the proposed models with advanced control function of negative sequence current injection.

Extensive case studies will be conducted to evaluate the performance of the proposed real-time models, such as dynamic performance under normal and abnormal conditions, including balanced and unbalanced faults, and dynamic performance of 450 MW offshore wind farm using the proposed models.

The following are the paper’s main contributions:

- The proposed real-time WTG models comply with the industry standards utilized by WECC. Thus, the proposed models meet the requirements of low-voltage ride-through, reactive and active power support, fault current limiting, etc. Compared to existing real-time models in [19], [26], [28], [31], the proposed models are optimized and applicable for practical studies.
- The real-time AVG and DSW models of wind turbine generators are presented in this paper. Compared to AVG model in [22], the proposed AVG model in this paper well captures dynamic responses of DSW model.

The remaining of this study is organized as follows: Section II presents a direct-drive PMSG wind generator modeling. The real-time AVG and DSW models of wind turbine generators are depicted in Section III. A comparison with the non-real-time models is conducted in this section. Section IV presents the validation of the proposed model against the WECC standard. The evaluations of the real-time models under abnormal and normal conditions are given in Section V. Section VI demonstrates the feasibility of the proposed real-time models for the study of a large-scale model of offshore winds. Finally, Section VII summaries the main findings of this study.

II. WIND TURBINE MODELING

Fig. 1 depicts the WTG configuration using direct-drive PMSG. The grid-side converter (GSC) regulates the reactive power and DC voltage, while the machine-side converter (MSC) regulates generator torque. The DC chopper protects the DC link during grid disturbances. The grid-side filters are used to reduce the switching harmonics caused by power converters. The step-up transformers are used to boost the turbine generator voltage to
the collector system levels. The following sections discuss three main controllers incorporated in the wind turbine generator: pitch angle controller, grid-side controller, and machine-side controller.

A. Wind-Turbine Aerodynamics

The wind turbine blades are used to capture the wind energy. The aerodynamic power extracted from wind is given by (1).

\[ P_m = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v_w^3, \]  

where \( \rho \) is the air density; \( R \) is the turbine rotor radius; \( C_p(\lambda, \beta) \) is the rotor power coefficient depending on tip-speed ratio \( \lambda \) and pitch angle \( \beta \); and \( v_w \) is the wind speed.

The tip-speed ratio (TSR) determines the fraction of available wind power extracted by the wind turbine rotor, which is calculated by (2).

\[ \lambda = \frac{\omega_r R}{v_w}, \]  

where \( \omega_r \) is the rotor angular speed.

Rotor power coefficient \( C_p \) represents the characteristic of the wind turbine, which is depended on the tip-speed ratio and the pitch angle, as given by (3).

\[ C_p(\lambda, \beta) = \sum_{i=0}^{4} \sum_{j=0}^{4} a_{ij} \lambda^i \beta^j, \]  

where coefficients \( a_{ij} \) is given in [33].

B. Mechanical System

A one-mass drive train model is used to model the mechanical system of the wind turbine generator, as the wind turbine is directly connected to the PMSG without a gearbox. The drive train model is expressed as follows:

\[ \frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_m), \]  

\[ \frac{d\theta_r}{dt} = \omega_r \]  

where \( J \) is the moment of inertia, \( T_e \) and \( T_m \) are the electrical and mechanical torques, \( \omega_r \) is the mechanical speed, and \( \theta_r \) is the rotor angular position.

C. Wind Turbine Characterization

The wind turbine generator operates in four primary operating regions (RG). In region 1, the WTG is idle since the wind speed is insufficient to produce electric power. In region 2, the WTG optimally regulates the generator torque to capture wind power maximally. In region 3, the pitch controller regulates the blade pitch angle as the wind speed is high enough to produce the rated power. The wind turbine generator is shut down in region 4 to protect the wind turbine generators from damage as the wind speed is too high. There is an additional Region 1.5 for the offshore wind turbines, which is utilized to avoid 3-period interference effects [34]. In Region 1.5, the wind speed is higher than the cut-in speed but lower than the wind speed that caused interference (\( v_{\text{inter}} \)). Fig. 2 shows regions 1.5, 2, and 3 of wind turbine operation.

D. Pitch Angle Controller

The pitch controller depicted in Fig. 3 regulates mechanical power captured from wind energy. In region 1.5, a lookup table is used to generate the pitch angle reference (\( \beta_{R1} \)). The proportional-integral (PI) regulator controls the pitch angle to manage the WTG power when the set-point power (\( P^* \)) is lower than \( P_{\text{rated}} \) or high wind speed. This PI regulator incorporates the limitation of both rate-of-change and magnitude to account for the mechanical dynamics of the turbine blades. In region 2, pitch angle reference is forced to zero.

E. Machine-Side Controller

Fig. 4 depicts the machine-side controller, which includes a torque control and a current control loop. The PI regulator compensates for the torque error, which is incorporated with the rated limiter to mitigate the transition effect between different
regions. The torque control loop produces the current reference \( i_{\text{opt}}^* \). The speed controller or optimal torque controller generates the torque reference based on the wind speed conditions. In region 1.5, the rotor speed is controlled at 0.6 pu, and the wind turbine generator begins to produce power. In region 2, a maximum power point tracking (MPPT) strategy is used to maximize the output power captured from wind energy. The MPPT control strategies and parameters vary with different vendors. The MPPT strategies can be categorized into two types: indirect and direct methods. The indirect methods, such as optimal torque control, tip speed ratio control, and power signal feedback, use the knowledge of the wind turbines to maximize the output wind power. The direct methods do not require prior knowledge of the wind turbines, such as hill climbing search and fuzzy logic control. In this paper, the MPPT strategy based on optimal torque control is used. The optimal torque given by (6) is used for maximizing the output power captured from wind energy, in which \( \lambda_{\text{opt}} \) is the optimal tip-speed ratio. In region 3, the generator torque is regulated by an additional rotor speed control to maintain rotor speed constantly at 1 pu.

\[
T_{\text{opt}} = k_{\text{opt}} \omega^2, \quad k_{\text{opt}} = 0.5 \rho R^2 C_p^{\text{max}} (R/\lambda_{\text{opt}})^3, \tag{6} \tag{7}
\]

**E. Grid-Side Controller**

The GSC controller regulates the voltage of the DC link and reactive power. The sudden drop in WTG’s terminal voltage results in a rapid rise in DC voltage when there is a fault on the grid side. The DC chopper based on hysterisis control is activated to protect the DC system. Under fault conditions, the DC voltage control loop is frozen, and the current loop controls the reactive and active currents injected into grids.

The GSC controller is designed based on asymmetrical components. The negative and positive components can be used to represent the unbalanced three-phase signals. By using (8), such components are transformed into the synchronous rotating frame [35].

\[
v_{\text{Gdq}}^* = \frac{2}{3} \left( v_{\text{Ga}} + a v_{\text{Gb}} + a^2 v_{\text{Gc}} \right), \tag{8}
\]

\[
v_{\text{Gdq}}^+ = \frac{2}{3} \left( v_{\text{Ga}} + av_{\text{Gb}} + a^2 v_{\text{Gc}} \right) e^{-j \omega t} + v_{\text{Gdq}}^* e^{j \omega t}, \tag{9}
\]

\[
v_{\text{Gdq}}^- = \frac{2}{3} \left( v_{\text{Ga}} + av_{\text{Gb}} + a^2 v_{\text{Gc}} \right) e^{j \omega t} + v_{\text{Gdq}}^* e^{-j \omega t}, \tag{10}
\]

where \( v_G \) is the output voltage; \( a = e^{j \pi/3} \); \( v_{\text{Gdq}}^+ \) and \( v_{\text{Gdq}}^- \) are the negative and positive \( d \)q components, respectively.

For the sequence currents, the negative \( i_{\text{Gdq}} \) and positive \( i_{\text{Gdq}}^* \) components are obtained in the same manner. Then, the complex power is obtained by using (11).

\[
S = p(t) + jq(t) = v_{\text{Gdq}}^* i_{\text{Gdq}}^*, \tag{11}
\]

\[
p(t) = P + P_{s2} \cos(2\omega t) + P_{s2} \sin(2\omega t), \tag{12}
\]

\[
q(t) = Q + Q_{s2} \cos(2\omega t) + Q_{s2} \sin(2\omega t), \tag{13}
\]

where

\[
P = \frac{3}{2} \left( v_{\text{Gd}}^* i_{\text{Gd}}^* + v_{\text{Gq}}^* i_{\text{Gq}}^* + v_{\text{Gd}}^- i_{\text{Gd}}^- + v_{\text{Gq}}^- i_{\text{Gq}}^- \right), \tag{14}
\]

\[
P_{s2} = \frac{3}{2} \left( v_{\text{Gd}}^* i_{\text{Gd}}^* + v_{\text{Gq}}^* i_{\text{Gq}}^* + v_{\text{Gd}}^+ i_{\text{Gd}}^+ + v_{\text{Gq}}^+ i_{\text{Gq}}^+ \right), \tag{15}
\]

\[
Q = \frac{3}{2} \left( v_{\text{Gq}}^* i_{\text{Gd}}^- - v_{\text{Gd}}^* i_{\text{Gq}}^- + v_{\text{Gq}}^- i_{\text{Gd}}^+ - v_{\text{Gd}}^- i_{\text{Gq}}^+ \right), \tag{16}
\]

\[
Q_{s2} = \frac{3}{2} \left( v_{\text{Gq}}^* i_{\text{Gd}}^- - v_{\text{Gd}}^* i_{\text{Gq}}^- + v_{\text{Gq}}^- i_{\text{Gd}}^+ - v_{\text{Gd}}^- i_{\text{Gq}}^+ \right), \tag{17}
\]

\[
Q_{s2} = \frac{3}{2} \left( v_{\text{Gq}}^* i_{\text{Gd}}^- - v_{\text{Gd}}^* i_{\text{Gq}}^- + v_{\text{Gq}}^- i_{\text{Gd}}^+ - v_{\text{Gd}}^- i_{\text{Gq}}^+ \right). \tag{18}
\]

The second-order oscillations of reactive power are not considered for the control design [36]. However, the oscillations of active power cause the fluctuation of the DC-link voltage at a second-order harmonic. To cancel such fluctuation, the oscillatory terms of \( P_{s2} \) and \( Q_{s2} \) are set to zero. Thus, the references of negative and positive sequence currents are given by (20).

\[
\begin{bmatrix}
  i_{\text{Gd}}^* \\
  i_{\text{Gq}}^* \\
  i_{\text{Gd}}^+ \\
  i_{\text{Gq}}^+
\end{bmatrix} = \begin{bmatrix}
  v_{\text{Gd}}^+ & v_{\text{Gq}}^+ & v_{\text{Gd}}^- & v_{\text{Gq}}^-
\end{bmatrix}^{-1} \begin{bmatrix}
  P \\
  Q \\
  P_{s2} \\
  P_{s2}
\end{bmatrix} \tag{20}
\]

The GSC controller shown in Fig. 5(a) regulates the DC voltage and reactive power. Overall, this controller has two control loops: inner current and outer voltage/reactive power control loop. The current control loop receives the reference signals generated from the outer loop. While the reference of reactive power \( (Q^*) \) is received directly from the upper control layer, the reference of active power \( (P^*) \) is provided by the
voltage control loop. Under abnormal conditions, the outer control loop is frozen, and the reactive and active currents injected into the grid are defined following WECC current limit logic. The sequence current generator calculates the current references based on (20). The phase-locked loop (PLL) generates the phase angle (θ). To accurately track the phase angle under unbalanced conditions, the second-order generalized integrator (SOGI) is used in this paper as SOGI-PLL offers the advantage of high accuracy under such conditions. The sequence components are generated accordingly, as depicted in Fig. 5(b). It should be noted that (8) to (10) are used to derive the second-order oscillations of active and reactive power. The positive and negative sequence components are obtained by the sequence extractor shown in Fig. 5(b).

One of the important functions of the WTG model to meet the requirements of industry standards is the low-voltage ride-through (LVRT) function. To fulfill this requirement, the current injection function, which is adapted from the generic turbine model [37], is developed to manage the reactive and active current under low-voltage conditions. The current injection function is shown in Fig. 5(c). The reactive and active current injected into the grid are limited accordingly based on the voltage condition. The VDL1 and VDL2 curves shown in Fig. 6 are used to manage the injected current during low-voltage conditions. These curves use four pairs of numbers to determine the current injection. These curves are designed to force the active and reactive current to zero during very low voltage conditions. The current limit logic defined in the WECC generic model [37] is adapted in this paper for the positive sequence currents, as given by Algorithm 1.
Algorithm 1: Modified WECC Current Limit Logic.

1: if $Pqflag = 0$ then
2:   $I_{q_{\text{max}}} = \min (VDL1, I_{\text{max}})$
3:   $I_{q_{\text{min}}} = -I_{q_{\text{max}}}$
4:   $I_{p_{\text{max}}} = \min (VDL2, \sqrt{I_{p_{\text{max}}}^2 - i_{Gdq}^{++} - i_{Gdq}^{-+}}^2}$
5:   $I_{p_{\text{min}}} = -0.5I_{p_{\text{max}}}$ (%For DC-link control)
6: else
7:   $I_{q_{\text{max}}} = \min (VDL1, \sqrt{I_{q_{\text{max}}}^2 - i_{Gdq}^{++} - i_{Gdq}^{-+}}^2)$
8:   $I_{p_{\text{min}}} = -I_{q_{\text{max}}}$
9:   $I_{p_{\text{max}}} = \min (VDL2, I_{\text{max}})$
10:  $I_{p_{\text{min}}} = -0.5I_{p_{\text{max}}}$ (%For DC-link control)
11: end if

The positive component of voltage ($v_{Gd}^+$) is used to detect the normal and abnormal conditions, as given by (21). The current injection function is activated when the $V_{\text{dip}}$ signal is equal to one. The active power injected into the grid is determined based on the machine-side power, while the injected reactive power is proportional to voltage drop.

$$V_{\text{dip}} = \begin{cases} 1 & \text{if } V_I \leq v_{\text{dip}} \text{ or } V_I \geq v_{\text{up}} \\ 0 & \text{otherwise} \end{cases} \quad (21)$$

$$V_I = v_{Gd}^+ \quad (22)$$

where $v_{\text{dip}}$ and $v_{\text{up}}$ are the pre-defined values that are used to detect low-voltage and high-voltage conditions, respectively.

Once the injected amounts of positive sequence reactive and active currents are obtained, the negative sequence currents are calculated with the objective of suppressing the second-order oscillation of active power, $P_{c2}$ and $P_{e2}$. As the oscillatory terms of $P_{c2}$ and $P_{e2}$ in (15) and (16) are zero and sequence voltages $v_{Gdq}^*$ are known, the negative sequence currents are derived as follows:

$$i_{Gdq}^{++} = \frac{1}{v_{Gd}^+ + v_{Gq}^+} \left[ -(i_{Gdq}^{++}v_{Gd}^+ v_{Gd}^- + i_{Gdq}^{-+}v_{Gq}^+ v_{Gq}^-) + i_{Gdq}^{++} v_{Gd}^+ v_{Gd}^- + i_{Gdq}^{-+} v_{Gq}^+ v_{Gq}^- \right] ; \quad (23)$$

$$i_{Gdq}^{--} = \frac{1}{v_{Gd}^+ + v_{Gq}^+} \left[ -(i_{Gdq}^{++}v_{Gd}^- v_{Gd}^+ + i_{Gdq}^{-+}v_{Gq}^- v_{Gq}^+) + i_{Gdq}^{++} v_{Gd}^- v_{Gd}^+ + i_{Gdq}^{-+} v_{Gq}^- v_{Gq}^+ \right] ; \quad (24)$$

A sequence current limit function shown in Fig. 7 is additionally used to ensure that the RMS value of each phase current is limited. Under normal conditions, the current limit gain ($k_{CL}$) is equal to one. Thus, there is no limit on the current in these conditions. Under abnormal conditions, the largest value of the RMS current among three phases is used to activate the current limit function. It is higher than the maximum current ($I_{\text{max}}$). $k_{CL}$ is adjusted accordingly to reduce the current references. It should be noted that although there is no limit on the current under normal conditions, the current limiter is always enabled.

In addition, different strategies of sequence current limiting can be applied to the proposed models. For example, an extended strategy reported in [38] can be used in the proposed models to enhance the fault current contribution in all relevant phases.

The current limit function restricts the output load current $i_{Gdq}^L$, however, the reference of inductor filter current $i_{Gdq}^r$ is required for the current control loop. The current compensator block based on (25) and (26) is used to transform the output load current into the inductor filter current.

$$i_{Gdq}^{++} = i_{Gdq}^{++} + (i_{Gdq}^{++} - i_{Gdq}^{--}), \quad (25)$$

$$i_{Gdq}^{--} = i_{Gdq}^{--} - (i_{Gdq}^{++} - i_{Gdq}^{--}). \quad (26)$$

Fig. 5(d) shows the sequence inner current control loop, in which $v_{dc}$ is the DC voltage, $\omega_0$ is the angular frequency, and $L$ is the filter inductance. This control loop includes the negative and positive sequence controller, which uses the references of inductor filter current as inputs.

III. REAL-TIME MODELLING OF AVERAGE AND DETAILED SWITCHING TURBINE MODELS

A. Real-Time Models and Non-Real-Time Model

Both average (AVG) and detailed switching (DSW) turbine models are implemented by the OPAL-RT eMEGASIM simulator. Opal-RT is widely used by international industries for real-time applications. In Fig. 8, the difference between DSW and AVG models lies in the converter modeling while the turbine controllers are alike, except for the pulse width modulation block. The design of the WTG controller presented in Section II is used for both DSW and AVG models.

The differences between real-time (RT) models and conventional non-real-time (NRT) models in MATLAB/Simulink are
the converter, pulse width modulation, and decoupling models.

In the real-time DSW model, the two-level time-stamped bridges (TSB) with high-impedance capability from the RT-events library are used to model the detailed switching converter, while the Universal Bridge modules are used in the NRT models. The real-time event (RTE) space-vector pulse width modulation (SPWM) generates the pulse signals for the DSW converter, while the PWM generator modules are used in the NRT models. Since the voltage of the DC link does not change significantly for a time-step simulation, the DC-bus decoupling method provided by the ARTEMiS library is used to accelerate the real-time simulation, which is not available in the NRT models. The DC-bus decoupling block also includes the DC chopper. Both RT-DSW and RT-AVG models use the DC-bus decoupling block for efficient real-time computation. The AVG model, which uses the ideal voltage and current sources to model the converter, is built using the Universal Bridge block from the SimPowerSystems library. It should be noted that the NRT AVG model also uses the same converter modeling. The three-phase two-level converter is modeled as this study focused mainly on the converter controller. For the multi-MW WTGs, different converter models such as multi-level converters or parallel structures can be retrofitted with a slight modification in the converter models and the pulse width modulation techniques.

The real-time models are optimized by choosing an appropriate control sampling time for each control loop. Each control loop has different bandwidth. For example, the current control loop is the fastest loop, while the outer DC-link voltage or torque control loop is much slower than the inner current loop. The optimal setting of each control loop is given in Table I. It should be noted that the sampling time has to be an integer multiple of the based sampling time (50 µs in this paper). The optimization process is based on the manual trial and error strategy.

| Control loop        | Sampling time (µs) | Control loop    | Sampling time (µs) |
|---------------------|--------------------|-----------------|--------------------|
| Inner current       | 100                | DC-link voltage | 500                |
| Torque control      | 500                | Pitch control   | 1000               |

### B. Computational Evaluation

The real-time simulator OP5700, which is equipped with an 8-core Intel Xeon processor E5 3.2 GHz, is used to evaluate the real-time performance. Monitoring models provided by RT-Lab monitors the real-time capability. The percentage of CPU usage indicates the CPU capacity that is in use to execute the turbine models. The total CPU time includes all time spent by RT-Lab services to execute the model. Both DSW and AVG models are implemented in RT-Lab with 50 µs of sampling time.

A comparison with the NRT models is conducted. The NRT detailed and average models (NRT-DSW, and NRT-AVG), which are provided by MathWorks [39], [40], are evaluated in this paper. They were developed based on the SimPowerSystems library. Two models are compiled and executed on Opal-RT real-time simulator without any modification. Table II shows the computation of the RT and NRT models. It should be noted that the NRT-DSW model must be discretized at 2 µs to achieve acceptable accuracy [39]. However, eMEGASIM can only simulate models with time steps as low as 10 µs [41]. The eFGASIM is required to run the NRT-DSW model in real time, as it can simulate models with time steps of 2 µs [42]. However, in order to achieve a fair comparison, all models will be tested on eMEGASIM to evaluate their real-time performance. Since eMEGASIM cannot simulate the NRT-DSW model, the CPU usage of the real-time simulator for NRT-DSW model given in Table II is not applicable (N/A).

The CPU usage of NRT-AVG is 9.06%, and the total CPU time to execute is 4.53 µs. The CPU usage and time values are still more significant than those of the proposed RT-DSW models (8.56% of CPU usage and 4.28 µs of CPU time). The proposed RT-AVG model consumes 30% less CPU usage and time than the RT-DSW model. The comparison of the optimized and non-optimized RT models also are conducted and shown in Table II. The non-optimized RT models use the same control structure described in Section II but only one control sampling time for all control loops. The non-optimized RT-AVG model (RT-AVG\textsuperscript{non-opt}) consumes a higher CPU than the NRT-AVG model, as it incorporates more control functions, such as sequence current control, current limiting functions, etc. By optimizing the control sampling time of each control loop, the CPU usage of the optimized RT models (RT-DSW and RT-AVG) is significantly reduced. Although the proposed RT models include heavy controllers with multiple control functions, they are computationally efficient compared to the NRT models.

### IV. VALIDATION OF WIND TURBINE MODEL

The turbine model validation is demonstrated in this section to show the compliance with the industry standards of the proposed models. Various conditions of voltage dip are used to evaluate the proposed wind turbine models, as suggested in [16]. The WECC generic model is used as a reference model for comparison.
A. Test Setup

Fig. 9 shows the setup to test the wind turbine generator under different voltage-dip conditions. The controlled voltage source mimics the voltage behavior of the grid. Four test cases shown in Fig. 10 are used to validate the proposed wind turbine models. These cases represent various conditions of voltage dips, including the severe case where the voltage drops to zeros. The reactive and active power of the proposed wind turbine models during these voltage cases are recorded to compare with the WECC model’s performance. The 15 MW WTG model is tested in this study. Table III depicts the WTG parameters used in this study.

B. Validation Result and Comparison With the WECC Model

Fig. 11 depicts the validation results of the proposed WTG model operating in region 3. As shown in these figures, the detailed wind turbine can inject power during voltage-dip conditions, which is the same as the WECC generic model. At 15 m/s wind speed, when the voltage dips to zeros (case 1), the power is forced to zero, as shown in Fig. 11(a). When the voltage decreases to 0.6 and 0.8 pu, as shown in cases 3 and 4, the turbine can maintain active power at the same value as in the pre-fault condition. The reactive power injected into the grid in such cases is 0.4 and 0.32 pu, respectively. The injected amount of power is depended on the voltage-dip levels and operation modes of turbines. It is observed that the performances of the proposed WTG models and the WECC generic model are well matched. Therefore, the proposed wind turbine models comply with the industry standard utilized by WECC.

V. EVALUATION OF AVG AND DSW MODELS UNDER NORMAL AND ABNORMAL CONDITIONS

The DSW and AVG models are evaluated in this section under different scenarios such as dynamic wind, power curtailment, balanced and unbalanced fault conditions. The dynamic wind scenario is performed to evaluate the region operation of WTGs. The power curtailment scenario is used to verify the operation of WTGs when they receive power commands from wind plant control systems. Finally, to evaluate the efficacy of the proposed models, balanced and unbalanced fault studies are conducted.
A. Turbine Performance Under Wind Dynamics

The performances of both DSW and AVG models are evaluated in the condition of increasing wind speed from 6 m/s to 25 m/s, as shown in Fig. 12. The speed of the generator’s rotor is controlled at 0.6 pu in region 1.5. When the wind speed increases to 10 m/s, the generator torque is optimally regulated to capture the wind power maximally. The pitch controller is activated when the wind speed is above the rated wind speed. It regulates the blade pitch angle to maintain the output power of the wind turbine generator at the rated value. Fig. 12(b) shows the pitch angle in this condition. The speed of the generator’s rotor is controlled constantly at 1 pu in this region. The reactive output power and DC voltage are maintained constantly during the wind speed variations. It can be observed that the performance of AVG and DSW models is matched.

Fig. 13 shows the measured voltage and current of the AVG and DSW wind turbine models. The total harmonic distortion (THD) of phase A voltage is 2.78% while the THD of phase A current is 4.78%, which indicates that an acceptable value of total harmonic distortion is achieved by the DSW model. It is observed in Figs. 12 and 13 that dynamic responses of the DSW and AVG models are well matched, except for the high-frequency harmonic distortion in the DSW model.
B. Active and Reactive Power Regulation

The proposed WTG models are capable of regulating reactive and active power as requested by the transmission system operator. The performance of reactive and active power regulation of both DSW and AVG models is depicted in Fig. 14. The active power reference decreases from 1 pu to 0.8 pu, then 0.5 pu, and then it increases to 0.8 pu and 1 pu. The reference of reactive power reduces from +0.5 pu to −0.5 pu. The positive sequence reactive power reference indicates the wind turbine supplying reactive power for the grid and vice versa. The pitch controller regulates the pitch angle to control active power, as shown in Fig. 14(b). The wind turbine controllers detect the voltage dips and limit the injected reactive and active current. The DC-link power increases significantly as the wind turbine still captures wind power, which results in the rise in voltage of the DC link. It is shown in Fig. 17(d) that the DC chopper activates to prevent the damage caused by overvoltage in the DC link. When the fault is cleared, the DC chopper is disabled, and the DC voltage controller is re-activated to control the DC-link voltage. An increase in output active power from 0.3 pu to 1 pu causes a rapid drop in DC-link voltage to 0.91 pu, which is acceptable as an analysis of the minimum allowable operation of DC-link voltage presented in [43] showed that the Type-4 WTG could operate with the DC-link voltage as low as 0.78 pu. When the fault is cleared, the output power and DC voltage are recovered to the nominal values. It is observed that the transient responses of the AVG and DSW models are matched.

C. Balanced Fault Studies

Figs. 15, 16, and 17 show the validation results in condition of three-phase-to-ground fault. The fault is applied at 500 s and cleared at 500.15 s, which results in the voltage drop to zero, as depicted in Figs. 15 and 16. The wind turbine controllers detect the voltage dips and limit the injected reactive and active current. The DC-link power increases significantly as the wind turbine still captures wind power, which results in the rise in voltage of the DC link. It is shown in Fig. 17(d) that the DC chopper activates to prevent the damage caused by overvoltage in the DC link. When the fault is cleared, the DC chopper is disabled, and the DC voltage controller is re-activated to control the DC-link voltage. An increase in output active power from 0.3 pu to 1 pu causes a rapid drop in DC-link voltage to 0.91 pu, which is acceptable as an analysis of the minimum allowable operation of DC-link voltage presented in [43] showed that the Type-4 WTG could operate with the DC-link voltage as low as 0.78 pu. When the fault is cleared, the output power and DC voltage are recovered to the nominal values. It is observed that the transient responses of the AVG and DSW models are matched.

D. Unbalanced Fault Studies

The future requirement for the integration of inverter-based renewable energy sources is the ability to control negative sequence current under unbalanced conditions, which is essential for the correct operation of the protection system. The performance of the proposed models under phase-a-to-ground fault is compared with the typical turbine model used in [7], [8], [20]. One of the differences between the two models is the capability of negative sequence control in the proposed models. Figs. 18 and 19 show the transient three-phase current and voltage of the proposed WTG model under unbalanced fault. The positive and negative sequence current under the proposed and typical controllers are shown in Fig. 20. During an unbalanced fault condition, the proposed controller injects negative sequence current into the grid to suppress the second-order oscillation in active power output, which results in lowering the negative sequence current compared to the typical controller, as shown in Fig. 20(b). The IEEE Std 2800-2022, which has been approved recently [44], requires that IBR has the capability of injecting negative sequence current during unbalanced faults,
the injected negative sequence current is dependent on the IBR terminal negative sequence voltage. However, this standard mentioned that it intentionally does not specify the magnitude of incremental negative sequence current injection during a fault condition because it is impractical to specify a value or range of values that meet the needs for all IBR plant interconnections. Therefore, the negative sequence current can be used to suppress the second-order harmonic oscillation as long as it is proportional to the negative sequence voltage, which is adopted in this paper.

Fig. 21 shows the comparison of active power between the proposed models and the typical model, which shows that the proposed controllers effectively damp out the oscillation at the second-order harmonic. Although the provision of the negative-sequence current injection in this paper is to suppress the second-order harmonic oscillations, the ratio of negative sequence voltage to injected negative sequence current during fault condition is about 1.6.

VI. REAL-TIME PERFORMANCE OF OFFSHORE WIND FARM

A 450 MW offshore wind farm, including 30 units of 15 MW WTG, is used to evaluate the feasibility of the proposed models for modeling of large-scale offshore wind farm. The configuration of the tested system is depicted in Fig. 22, which includes 30 wind turbines splitting equally into six clusters. Every three clusters are connected to a collector bus. The three-winding transformer is used to boost the 66 kV level to 230 kV transmission level. The onshore transformer boosts the voltage level of 230 kV to the 345 kV level to be connected to the utility grid at POI. The 230 kV high voltage alternating current (HVAC) submarine cable is used to transfer wind power into the grid. The onshore and offshore shunt reactors are used to compensate for the shunt capacitance produced by HVAC cable.

The real-time simulator OP5700 with Intel Xeon E5 3.2 GHz CPU is used to simulate the above-tested system. The real-time capability of the DSW and AVG models given from Table II helps in splitting the wind farm model into multi-core processors. Each processor core can handle up to six RT-DSW models or twelve RT-AVG models. Based on the configuration of the wind farm system from Fig. 22, cluster 1 modeled in one slave core (SS_DSW) includes five RT-DSW TBs. The remaining five clusters consist of RT-AVG models. Each slave core (SS_AVG1 and SS_AVG2) models ten A VG TBs. The transmission system and onshore and offshore substations are modeled in the master core (SM_core) models.

The measurement of CPU usage for 450 MW offshore wind model is shown in Table IV. The total CPU usage of SS_DSW core to execute five RT-DSW models is 57.3%, while the SS_AVG1 core consumes about 60% of CPU to execute ten RT-AVG models. It can be seen that the proposed RT models allow modeling large-scale wind farms in real-time environments.

The three-phase-to-ground fault is applied to evaluate the control functions of turbine models in this case. The fault occurs at the offshore collector bus 1 (Bc1), which is applied at 80 s, and it is cleared at 80.3 s. Due to the line impedance, the terminal voltage of each turbine drops to 0.5 pu, as shown in Fig. 23(a).

In this condition, the active power of all turbines drops to zeros, and the reactive power of 0.5 pu is injected into the grid, which is consistent with the model validation section. It should be noted that Fig. 23 depicts the waveform of 30 wind turbines in the tested system.
The real-time WTG models have been presented in this paper, which is efficient for large-scale wind farm studies. The developed WTG models have been validated against the WECC generic model to verify their compliance with the industry standards. As the proposed wind turbine models are standardized models, they are suitable for practical studies. Both average and detailed switching models were presented, and their real-time performances were evaluated under normal and abnormal conditions. Real-time simulation results reveal that the dynamic responses of the detailed switching model and the average model are the same, except for the high-frequency harmonics in the detailed model due to the converter switching. Compared to the proposed models in [22] in which there is a discrepancy between the AVG and DSW models, the proposed AVG model in this paper well captured the dynamic responses of the DSW model.

The DSW model is suitable for studies related to high-frequency harmonics and dynamic performance of control systems over short periods of time, as it includes a detailed representation of power electronic converter, but it requires high computation resources. By comparison, the AVG model is well suited for analyzing control systems over long periods, such as control interaction of large-scale systems, as it preserves the dynamic responses resulting from control system and power system interaction and is computational efficiency. Compared to existing models, real-time models in this paper offers the advantages of computational efficiency and standards compliance, which allows for the practical study of large-scale offshore wind in real-time environments.

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