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Implementation of draft IEC Generic Model of Type 1 Wind Turbine Generator in PowerFactory and Simulink

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Abstract— This paper presents the implementation work of IEC generic model of Type 1 wind turbine generator (WTG) in two commercial simulation tools: DIgSILENT PowerFactory (PF) and Matlab Simulink. The model topology, details of the composite blocks and implementation procedure in PF and Simulink environments are described. Case studies under both normal and fault conditions have been conducted with the implemented IEC Type 1 WTG model. The dynamic responses are captured and analyzed. The simulation results of both models are compared and analyzed. It is verified that the IEC generic model can correctly represent the performance of Type 1 WTG for power system stability studies.

Keywords- IEC, Type 1 WTG, generic model, PF, Simulink.

I. INTRODUCTION

With the increasing installed capacity of wind power, the validated dynamic Wind Turbine Generator (WTG) models are of particular interest for the grid operators to investigate the impact of the high penetration of wind power on the stability of the whole system. Most existing dynamic models were developed by manufacturers and consultants as proprietary user-defined models. These vendor-specific models reproduce the behavior of their machines with a great level of accuracy and detail. However, it creates a major roadblock for efficiently performing stability studies. Firstly, many inputs required for the models are proprietary and can’t be publicly exchanged or distributed. Secondly, these vendor-specific models are either user written or object code and needed to be complied and implemented in different simulation programs. The simulation would be very time-consuming. Therefore, it is of high importance to develop publicly available WTG generic dynamic models. According to [1], the term generic refers to a model that is standard, public and not specific to any vendor.

According to IEEE definition, the present wind turbines can generally be divided into four types [2]:
- Type 1: Wind turbine with directly grid connected induction generator with fixed rotor resistance (typically squirrel cage).
- Type 2: Wind turbine with directly grid connected induction generator with variable rotor resistance.
- Type 3: Wind turbines with double-fed asynchronous generators (directly connected stator and rotor connected through power converter).
- Type 4: Wind turbines connected fully through a power converter.

Based on the above definition, the Wind Generation Modeling Group (WGMG) of the Western Electricity Coordinating Council (WECC) and the IEEE Working Group on Dynamic Performance of Wind Power Generation (DPWG) have developed the generic WTG models. The joint report has been published in [3]. The WECC generic models were developed by simplifying a detailed transient stability model. It is primarily focused on generic positive sequence models and doesn’t address electromagnetic transients. These models have been released in the latest versions of two commercial software packages GE PSLF and Siemens PTI PSS/E.

International Electrotechnical Commission (IEC) started the standardization work- IEC 61400-27 to define standard, public dynamic simulation models for wind turbines and wind power plants. It is composed of both modeling and validation subgroups. The working group WG27 held the first meeting in October 2009 [4]. The first committee draft has been finished at the end of 2011 specifying wind turbine models and validation procedures. Until now, some modeling details are still in discussion. These models should be applicable for dynamic simulations of power system events such as short circuits (low voltage ride through), loss of generation or loads, and typical switching events [4]. The modeling part of the standard draft has a substantial overlap with WECC WGMG. However, it also considers input from other sources including the publications from European researchers and vendors. The aim is that the generic models should have a reasonable coverage of the actual wind turbines.

DIgSILENT PowerFactory (PF) is widely used commercial power system analysis software, especially in Europe. A number of transmission system operators (TSOs) are using it for planning and operation purposes, e.g. Energinet.DK (Denmark), National Grid (UK), etc. It is
also widely used in universities and research institutes. For stability studies, PF can provide both positive sequence (RMS) and detailed electro-magnetic transient (EMT) results. It is necessary to implement IEC generic WTG models in PF to serve the needs of both industry and academia.

Simulink is a graphical software package for modeling, simulating and analyzing dynamic system based on Matlab environment. It supports linear and nonlinear systems, modeled in continuous time, sampled time or a hybrid of the two. It provides a powerful interface for building and verifying new mathematical models as well as new control strategies for the wind turbine system [5]. Besides, using a dSPACE prototype these new control strategies can be easily implemented and tested in a Hardware-In-the-Loop (HIL) structure. In the last few years, Simulink has become the most widely used software package in academia and industry for modeling and simulating dynamic systems [6][7].

The purpose of this paper is to present the implementation work of the IEC Type 1 WTG model in PF and Simulink. The features in the model structure and blocks are introduced. The reasonable agreement has been achieved between various approaches presented in [3] and [8].

The rest of the paper is organized as follows: Section II describes the details about model structure and implementation in PF and Simulink. Dynamic responses of the model in normal and fault situations are captured, elaborated and compared in Section III. In the end, a brief conclusion is drawn in Section IV.

II. IMPLEMENTAION

A. Model description

The main electrical and mechanical components of Type 1 WTG are shown Fig. 1.

The Wind Turbine Rotor (WTR) is connected to the Asynchronous Generator (AG) via a Gearbox (GB). The capacitor bank provides reactive power compensation. Most Type 1 WTGs are equipped with mechanically switched capacitor (MSC) banks which are considered to be fixed during short-term simulations. Therefore, the capacitor is denoted as fixed capacitor (FC). As the protection device, the main circuit breaker (CB) disconnects generator and capacitor simultaneously. The Wind Turbine Terminal (WTT) is located at the low voltage side of the step-up Transformer (TR). The blade pitch angles of the Type 1 wind turbines can either be fixed or controllable. The blade angle control in some Type 1 wind turbines is used for Fault-Ride Through (FRT) control. In the modified IEC committee draft, Type 1 WTGs can therefore be divided into two subgroups:

- Type 1A: without FRT control.
- Type 1B: with blade angle FRT control.

It should be noticed that Type 1B model is removed from the newly modified IEC committee draft. However, it is also implemented in this study.

1) Structure of generic Type 1A WTG model: Fig. 2 shows the structure of the generic Type 1A WTG model. It is comprised of aerodynamic, mechanical, generator system, electrical equipment and grid protection blocks.

\[
\begin{array}{c}
\text{Grid Protection} \\
\text{Aerodynamic} \quad p_{\text{aero}} \\
\text{Mechanical} \quad \omega_{\text{wtr}} \\
\text{Generator System} \quad \omega_{\text{gen}} f_{\text{gen}} \\
\text{Electrical Equipment} \quad u_{\text{wtt}} f_{\text{wtt}} \\
\end{array}
\]

Figure 2. Runtime WTG model structure of Type 1A

a) Aerodynamic block: The aerodynamic torque is assumed to be constant during the short time period is constant. Therefore, constant aerodynamic torque model is used instead of pseudo governor model described in [3]. The model parameters are given in Table I and the block diagram is given in Fig. 3.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{init}} )</td>
<td>p.u.</td>
<td>Initial steady state torque</td>
<td>Initialization</td>
</tr>
</tbody>
</table>

Table 1: Parameter for Constant Aerodynamic Torque Model

b) Mechanical block: The mechanical part is implemented by a two-mass model. The separated masses represent the low-speed turbine and the high-speed generator. The connecting resilient shaft is modeled as a spring and a damper. The block diagram of IEC standard model is shown in Fig. 4.

In the IEC standard, it is assumed the built-in induction generator model in simulation software doesn’t include its inertia equation. It is available for Simulink, while the inertia part is integrated in the PF induction generator model. Consequently, instead of generator rotation speed \( \omega_{\text{gen}} \) as input, the mechanical power is the input. Therefore, a modified block diagram is used which is shown in Fig. 5.
The parameters of the two-mass block are listed in Table II.

### TABLE II
#### PARAMETER FOR THE TWO MASS MODEL

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{WT}$</td>
<td>p.u.</td>
<td>Inertia constant of wind turbine rotor</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$H_{gen}$</td>
<td>p.u.</td>
<td>Inertia constant of generator</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$k_{sh}$</td>
<td>p.u.</td>
<td>Shaft stiffness</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$c_{sh}$</td>
<td>p.u.</td>
<td>Shaft damping</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$w_{init}$</td>
<td>p.u.</td>
<td>Initial steady state shaft rotor speed</td>
<td>Initialization</td>
</tr>
<tr>
<td>$T_{init}$</td>
<td>p.u.</td>
<td>Initial steady state shaft torque</td>
<td>Initialization</td>
</tr>
</tbody>
</table>

The wind turbine model structure should also be changed accordingly for implementation purpose. The modified part is shown in dashed rectangle in Fig. 6.

![Figure 6. Modified runtime wind turbine model structure of Type 1A](image)

This modification doesn’t cause any difference of the simulation results. There are still two masses as a whole.

The interaction between the two masses will result in the torsional oscillation and has a significant impact on the dynamic behavior of WTG. The torsional oscillation is typically between 0.2 to 4 Hz. This dynamic response is presented in the simulation part. The nature frequencies can be calculated in [9].

c) **Grid protection:** WECC generic WTG models don’t have protection modules [3]. According to [2] and [10], the protection levels and disconnection time should be determined concerning measured voltage and frequency of WTT. As shown in Fig. 7, if either voltage or frequency violates the range constraint and if it lasts more than disconnection time $t_{disc}$, grid protection operates and disconnects WTG through CB.

![Figure 7. Block diagram for grid protection model](image)

### TABLE III
#### PARAMETER FOR GRID PROTECTION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{over}$</td>
<td>p.u.</td>
<td>Wind turbine over voltage protection setting</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$u_{under}$</td>
<td>p.u.</td>
<td>Wind turbine under voltage protection setting</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$f_{over}$</td>
<td>p.u.</td>
<td>Wind turbine over frequency setting</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$f_{under}$</td>
<td>p.u.</td>
<td>Wind turbine under frequency setting</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$t_{disc}$</td>
<td>sec</td>
<td>Delay time for opening the circuit breaker</td>
<td>Manufacturer</td>
</tr>
</tbody>
</table>

d) **Generator System:** The built-in induction generator model in the simulation tools is used. In PF, different detailing level of induction generator model is used depending on simulation types (RMS and EMT). RMS Type is based on simplified electromechanical transient models, where the stator transients are neglected [11][12]. However, the differential equation representing the stator flux transients is kept in Simulink model.

![Figure 8. Runtime wind turbine model structure of Type 1B](image)
2) **Structure of generic Type 1A WTG model**: The structure of the generic Type 1B WTG model (shown in Fig. 8) is mostly identical to the Type 1A model. The aerodynamic power is generated by blade angle FRT control model shown in Fig. 9. A similar model is used by WECC WTG model (pseudo governor model) which was designed and developed following a thorough investigation of aerodynamic characteristics and pitch control of several vendor detail WTG models [3]. Additionally, IEC model takes the FRT into consideration. Under normal operation, the controller regulates the output power $p_{\text{aero}}$ following the power reference $p_{\text{WTG ref}}$. During fault, it can be detected by comparing the filtered wind turbine terminal voltage $u_{\text{WTG}}$ and voltage threshold $u_{\text{dip}}$. FRT mode is activated to keep WTG connected with the grid. The controller adjusts the blade angle to constraint $p_{\text{aero}}$ by Proportional-Integral (PI) controller. The output power is limited within $[p_{\text{Amax}}, p_{\text{Amin}}]$. The ramping rate is also constrained within the range $[dp_{\text{Amin}}, dp_{\text{Amax}}]$. The parameters of the blade angle FRT control are listed in Table IV.

![Figure 9. Block diagram for blade angle FRT control model](image)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{filt}}$</td>
<td>p.u.</td>
<td>Filter time constant for power measurement</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$T_{\text{filt}}$</td>
<td>p.u.</td>
<td>Filter time constant for voltage measurement</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$u_{\text{dip}}$</td>
<td>p.u.</td>
<td>Voltage threshold for LVRT detection</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$p_{\text{Amax}}$</td>
<td>p.u.</td>
<td>Maximum power allowed by LVRT control</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$p_{\text{Amin}}$</td>
<td>p.u.</td>
<td>Minimum power allowed by LVRT control</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$p_{\text{WTG ref}}$</td>
<td>p.u.</td>
<td>Power reference during LVRT</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$dp_{\text{Amax}}$</td>
<td>p.u.</td>
<td>Maximum power ramp rate during LVRT</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>$dp_{\text{Amin}}$</td>
<td>p.u.</td>
<td>Minimum power ramp rate during LVRT</td>
<td>Manufacturer</td>
</tr>
</tbody>
</table>

### B. Initialization

Correct initialization avoids the fictitious electrical transients and makes it possible to evaluate correctly the real dynamic performance of the system [13]. If the system is not properly initialized, the state variables do not stay at the value at which they were initialized, but start changing at the start of the dynamic simulation. In this case, it may take time to reach a steady state, and may even numerical instability. In both PF and Simulink, the initialization is executed in the following two steps:

- **Step 1**: Initialization of the built-in electrical models (Induction Generator) through load flow calculation. Both PF and Simulink provide PQ model for load flow. Besides, PF has alternative RX model (slip iteration) which is based on the equivalent circuit. It is more precise method of representing induction machine and suitable for initializing a transient analysis [12].
- **Step 2**: Initialization of control blocks: aerodynamic model, mechanical model and blade angle FRT control model.

### III. CASE STUDY

The test system from [14] has been used to carry out case studies. The single line diagram of the test system is shown in Fig. 10.

![Figure 10. Single line diagram of the test system](image)

The test system is comprised of an external grid using a Thevenin equivalent model, two step-up transformers TR1 and TR2, the collection cable, circuit breaker CB, reactive power compensation and wind turbine generator WTG. This test system represents a reduced wind power installation and is used for both Type 1A and Type 1B. The parameters of the electrical components are illustrated in Appendix.

Following are the analyses for different study cases scenarios. They are listed in Table V. As mentioned above, stability analysis of PF includes RMS and EMT simulation types. Similarly, there are three simulation types available in Simulink: continuous, discrete and phasor [7]. The phasor method is mainly used to study electromechanical oscillations of power systems consisting of large generators and motors. For power system stability analysis, the results of RMS (PF) and Phasor Simulation (Simulink) are shown and compared in this study. The simulation time is dependent on the cases.
### TABLE V
CASE STUDY SCENARIOS

<table>
<thead>
<tr>
<th>Study Scenario</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal operation</strong></td>
<td></td>
</tr>
<tr>
<td>Simulation time</td>
<td>50 s</td>
</tr>
<tr>
<td>For Type 1A,</td>
<td></td>
</tr>
<tr>
<td>aerodynamic torque</td>
<td></td>
</tr>
<tr>
<td>$T_{init}$ is specified as piece wise function.</td>
<td></td>
</tr>
<tr>
<td>$0$–$10$ s:</td>
<td>0.89</td>
</tr>
<tr>
<td>$10$–$25$ s:</td>
<td>1</td>
</tr>
<tr>
<td>$25$–$50$ s:</td>
<td>0.9</td>
</tr>
<tr>
<td>For Type 1B,</td>
<td></td>
</tr>
<tr>
<td>reference $p_{wttref}$ is specified as piece wise function:</td>
<td></td>
</tr>
<tr>
<td>$0$–$10$ s:</td>
<td>0.8894</td>
</tr>
<tr>
<td>$10$–$25$ s:</td>
<td>0.8</td>
</tr>
<tr>
<td>$25$–$50$ s:</td>
<td>1</td>
</tr>
<tr>
<td><strong>Fault condition</strong></td>
<td></td>
</tr>
<tr>
<td>Simulation time</td>
<td>20 s</td>
</tr>
<tr>
<td>3-phas short circuit on terminal MV1</td>
<td></td>
</tr>
<tr>
<td>Low frequency oscillation (both Type 1A and 1B)</td>
<td>The short circuit happens at 5 s and cleared at 5.1 s.</td>
</tr>
</tbody>
</table>

**Figure 11.** Generator rotation speed and active power in normal operation (Type 1A)

**Figure 12.** Generator rotation speed and active power in normal operation (Type 1B)

### A. Normal operation

For Type 1A, the blade angle is fixed. The output active power $p_{wtt}$ can only be affected by the aerodynamic torque $T_{init}$. $T_{init}$ can be specified as a linear piece-wise function to simulate the wind variation. The simulation procedure is described in Table V.

For Type 1B, the blade angle is controllable. The output active power $p_{wtt}$ can be regulated by reference $p_{wttref}$ through adjusting the blade angle. During the normal operation, this reference value can be specified as a linear piece-wise function to emulate the wind variation. The simulation procedure is shown in Table V.

The responses of active, reactive power of both types are illustrated in Fig. 11 and 12, respectively. The figures show first of all a very close agreement between PF and Simulink results. The active power waveforms of $p_{wtt}$ (subplot (a)) and $p_{wtt}$ (subplot (c)) follow the wind variation. Due to the direct coupling between the generator rotation speed $w_{gen}$ and system frequency, the normal slip of Type WTG is 1% to 2% [15]. The wind doesn’t influence $w_{gen}$ apparently. The range is between 1.01 p.u. and 1.013 p.u.. According to [16], there is a unique relation between active power, reactive power, terminal voltage and rotor speed. An increasing of the active power production will also cause the increasing reactive power consumption which leads to a relative low full-load power factor (about 0.8 in this case based on subplot (a) and (b)). In order to limit the reactive power absorption from the grid, the WTG
is always equipped with capacitor banks [17]. Form the plots, it can be seen that most reactive power required by induction generator is provided by the capacitor bank and the power factor at WTT is almost 1 (based on subplot (c) and (d)). The power loss of the capacitor bank is neglected.

B. Fault condition

The 3-phase short circuit event is used to represent the fault condition. During the short circuit, the dynamic responses of the models can be captured and tested. Two typical responses: low frequency oscillations (both Type 1A and Type 1B) and pitch regulation (FRT control of Type 1B) are described and analysed in this paper. The relevant simulation settings are listed in Table V.

1) Low frequency oscillation of the two-mass model:

The torsional oscillations between different sections of the turbine-generator rotor can be observed due to the perturbation in the short circuit. The electrical torque reduces immediately and it results in the sudden increase of the generator rotation speed. This phenomenon lasts until the fault is cleared. Due to interaction of two masses, the generator rotation speed variation causes the torsional oscillation. As mentioned above, the torsional oscillation is typically between 0.2 to 4 Hz. Here, according to the parameters listed in Appendix and equations by [9], the oscillation frequency modes are given by:

\[
f_1 = \frac{1}{2n} \sqrt{\frac{k_{th}}{2I_{WTR}}} = 0.7368 \text{ Hz} \tag{1}
\]

\[
f_2 = \frac{1}{2n} \sqrt{\frac{k_{th}(H_{WTR}+H_{gen})}{2I_{WTR}H_{gen}}} = 2.0839 \text{ Hz} \tag{2}
\]

The oscillations of both PF and Simulink simulations are plotted in Fig. 13. Through the comparison, the main waveforms are identical except the short period after the fault. However, a rotor speed dip is detected in Simulink simulation. This difference is due to the different induction generator models. As mentioned above, stator flux transients are not considered in PF RMS model. During the fault, the stator transients cause fundamental frequency oscillation which results in the underestimation of variation in the generator torque. Instead of decreasing, the generator torque increases in the first circle. That can explain the dip of generator rotation speed.

\[\text{Figure 13. Oscillation during the fault with } \zeta_{th} = 0\]

2) FRT Control of Type 1B:

Type 1B model has FRT control block which can detect the low voltage level \(u_{\text{dip}}\) at wind turbine terminal and reduce the power reference \(P_{\text{WTTref}}\) to constraint the output power \(P_{\text{WTT}}\). The short circuit fault will result in the voltage drop and trip the FRT control.

The voltage drop detection level \(u_{\text{dip}}\) is set 0.5 p.u. In order to trip the FRT control block correctly, it is important to avoid the disturbance of high frequency harmonics. Therefore, the low-pass filter is used for the measured voltage. As illustrated in Fig. 15, the voltage drop and recovery are detected through the filtered voltage \(u_{\text{WTT}}\).

\[\text{Figure 14. Filtered voltage of WTT } u_{\text{WTT}} \text{ during FRT}\]

\[\text{Figure 15. Power outputs during FRT. Above: PF RMS results; Below: Simulink results}\]
The curves of PF and Simulink simulations match and the trip time and recovery time are the same.

The aerodynamic power $P_{aero}$ is controlled by the blade angle regulation. In the real operation, the blade angle is adjusted slowly because of the mechanical movement. The adjustment range is limited as well. Therefore, there are magnitude and ramp limitation in the controller (Fig. 9). As shown in Fig. 15, the regulated $P_{aero}$ decreases slowly during the fault condition to limit the output power $P_{WTG}$. After the fault, $P_{aero}$ varies in order to smooth the oscillations of $P_{WTG}$ caused by the two-mass mechanical model. The waveforms between $P_{aero}$ and $P_{WTG}$ are opposite. After several seconds, the system gets into steady state.

### IV. Conclusion

Through several simulation case studies, it has been illustrated that the implemented IEC generic Type 1 models in PF and Simulink can represent the relevant dynamics during normal operation and fault conditions. Since generic models are to be used primarily for power stability studies, positive sequence are sufficient for bulk system, RMS simulation in PF and phasor simulation in Simulink are performed in this study. In normal operation, the wind power variation is simulated by changing the aerodynamic torque (Type 1A) or power output reference set point (Type 1B). The results respond correctly and match the real operation. In fault case, the torsional oscillations of the two-mass mechanical model due to the disturbance are captured. The impact due to different built-in induction generator models is analyzed. The FRT capability of Type 1B with means of blade angle adjustment is tested. The practical limitations of the WTG behavior in real life are taken into consideration.

This generic model is the measurement-based model. Its accuracy and to what extent it reflects the practical operation are decided by the comparison between the simulation results and measurements data provided by manufacturers. This work will be carried out in the future.

### APPENDIX

#### PARAMETERS OF THE SIMULATION CASE

**A. External Grid**

It is modeled by the Thevenin equivalent circuit: $U_{Th} = 50$ kV, $R_{Th} = 2.516$ Ω, $X_{Th} = 8.2998$ Ω.

**B. 50/10 kV Transformer Tr1**

It is modeled by the T-equivalent. All the reactances are without saturation. No-load losses are excluded. The phase connection is YNd5. The transformer is directly grounded: $S_n = 16$ MVA, $U_p = 50$ kV, $U_s = 10.5$ kV, $R_p = 0.4052$ Ω, $X_p = 7.655$ Ω, $X_m = 19530$ Ω, $R_s = 0.4052$ Ω, $X_s = 7.655$ Ω.

**C. Short Circuit**

The 3-phase short circuit fault lasts 0.1 s. The error impedance before the fault is 1 MΩ (star impedance). The short circuit impedance is 0.00011 Ω (star impedance).

**D. 10 kV Collection Cable**

The wind farm 10 kV collection cable is modeled by the Π-equivalent: $C_1 = 1.58$ μF, $R = 0.7568$ Ω, $X = 0.4473$ Ω, $C_2 = 1.58$ μF.

**E. 10/0.96 kV Transformer Tr2**

It is modeled by the T-equivalent. All the reactances are without saturation. No-load losses are excluded. The phase connection is Dyn5. The transformer is directly grounded: $S_n = 2$ MVA, $U_p = 10.5$ kV, $U_s = 0.96$ kV, $R_p = 0.2756$ Ω, $X_p = 1.654$ Ω, $X_m = 6890$ Ω, $R_s = 0.2756$ Ω, $X_s = 1.654$ Ω.

**F. Capacitor Bank CB**

The capacitor bank in the wind turbine is delta connected, with the capacity $C = 1333$ μF in series with $RΔ = 0.003$ Ω.

**G. Wind Turbine Generator WTG**

The induction generator in the wind turbine is modeled by the $T$-equivalent: $S_n = 2.3$ MV, $U_n = 0.96$ kV, $N_0 = 1500$ rpm, $R_s = 0.004$ Ω, $X_s = 0.05$ Ω, $X_m = 1.6$ Ω, $R_g = 0.004$ Ω, $X_g = 0.05$ Ω. The inertias of the two-mass model: $H_{WTG} = 3.5$ p.u., $H_g = 0.5$ p.u., $k_{sh} = 150.0052$ p.u., $c_{sh} = 0$ p.u.

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