A Wide-Band Dynamic Equivalent Model of Wind Power Plants for the Analysis of Electromagnetic Transients in Power Systems

by

Dalia Nabil Mahmoud Mohammed Hussein

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Doctor of Philosophy
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High depth of penetration of wind power and proliferation of wind-turbine generator (WTG) units, clustered as wind power plants (WPPs), have invoked significant effort for development of WPP mathematical models to reflect the WPP behavior with respect to power system electromagnetic transients (EMTs). The detailed modeling of WPPs is neither practical nor possible due to its significant computational burden. Therefore, it is necessary to represent the WPP with an equivalent model that captures its EMTs behavior.

This thesis proposes and develops a novel accurate and computationally efficient reduced-order dynamic-equivalent of Type-4\(^1\) and Type-3\(^2\)-based WPPs for the analysis of EMTs in the power system, external to the WPP. The proposed model significantly reduces the computational resources and the simulation run time while preserving the WPP response fidelity in the desired frequency range, e.g., 0 to 50 kHz. The proposed WPP equivalent model is composed of two parts: 1) a frequency-dependent equivalent model which represents the WPP passive components in the entire frequency range and 2) a dynamic equivalent model that represents the WPP supervisory control and the aggregated low-frequency dynamics of wind-turbine generator (WTG) units. The proposed model is implemented in the PSCAD/EMTDC environment. Extensive case studies, that compares the equivalent model results with those of a detailed model, are

\(^1\)Type-4 refers to the WTG units with full capacity back-to-back converter interface
\(^2\)Type-3 refers to the WTG units with doubly-fed asynchronous generators
conducted to validate the efficiency and accuracy of the proposed equivalent model. The case studies cover different types of faults at different locations, external to the WPP, with respect to the WPP terminal.

This thesis also presents three applications of the developed WPP equivalent model.

1. The real-time simulation of the Type-4 WPP based on the developed equivalent model.

2. The real-time simulation of the Type-3 WPP based on the developed equivalent model.

3. The real-time hardware-in-the-loop (HIL) testing of the WPP supervisory control which is realized on an industrial controller platform (NI–cRIO) whereas the rest of the WPP equivalent model is simulated on a real-time digital simulator RTDS®.

Real-time simulation case studies are performed to demonstrate (i) the accuracy of the developed models and (ii) the computational efficiency and the saving in the hardware resources associated with simulating the WPP equivalent model in comparison with the the WPP detailed modeling.
Dedication

To my dear mother, and my late father

To Mahmoud and Mostafa who always bring the joy to my life
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<td>DFAG:</td>
<td>Doubly-Fed Asynchronous Generator</td>
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<td>DLFE:</td>
<td>Dynamic Low-Frequency Equivalent</td>
</tr>
<tr>
<td>DSOGI-PLL:</td>
<td>Dual Second Order Generalized Integrator-PLL</td>
</tr>
<tr>
<td>DVR:</td>
<td>Dynamic Voltage Restorer</td>
</tr>
<tr>
<td>EMT:</td>
<td>Electromagnetic Transient</td>
</tr>
<tr>
<td>EMTDC:</td>
<td>Electromagnetic Transients Program for DC</td>
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<td>FDNE:</td>
<td>Frequency Dependent Network Equivalent</td>
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<td>FRT:</td>
<td>Fault-Ride Through</td>
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<tr>
<td>GSC:</td>
<td>Grid-Side Converter</td>
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<tr>
<td>HIL:</td>
<td>Hardware-in-the-Loop</td>
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<td>IGBT:</td>
<td>Insulated-Gate Bipolar Transistor</td>
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<tr>
<td>LVRT:</td>
<td>Low-Voltage Ride Through</td>
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<td>MSC:</td>
<td>Machine-Side Converter</td>
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<tr>
<td>NI–cRIO:</td>
<td>National Instrument—Compact Real-time Input and Output</td>
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<tr>
<td>PCC:</td>
<td>Point of Common Coupling</td>
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<td>PI:</td>
<td>Proportional Integral</td>
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<td>PLL:</td>
<td>Phase Locked Loop</td>
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<td>PSC:</td>
<td>Positive Sequence Calculator</td>
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<tr>
<td>QSG:</td>
<td>Quadrature Signal Generator</td>
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<tr>
<td>RTS:</td>
<td>Real-Time Simulator</td>
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<tr>
<td>RTDS:</td>
<td>Real-Time Digital Simulator</td>
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<tr>
<td>RSC:</td>
<td>Rotor-Side Converter</td>
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<td>SPWM:</td>
<td>Sinusoidal Pulse Width Modulation</td>
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<td>SRF-PLL:</td>
<td>Synchronous Reference Frame-PLL</td>
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<tr>
<td>TSO:</td>
<td>Transmission System Operator</td>
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<td>VF:</td>
<td>Vector Fitting</td>
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<tr>
<td>VSC:</td>
<td>Voltage-Sourced Converter</td>
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<tr>
<td>WECC:</td>
<td>Western Electricity Coordinated Council</td>
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<td>WPP:</td>
<td>Wind Power Plants</td>
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<td>WTG:</td>
<td>Wind Turbine Generator</td>
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Chapter 1

Introduction

During the last two decades, generation of electricity from wind energy has increased drastically. The amount of energy generated from wind doubles almost every three years and the rate is expected to go even higher [1],[2].

Traditionally, a wind power plant (WPP) was designed to disconnect from the system during grid disturbances [3]. However, with the continuous increase in the depth of penetration of wind power into the power system and as the generating capacity of each individual WPP can reach hundreds of megawatts, disconnection during transients may cause system instability, frequency drop, and disruption of service. Thus, recent grid codes [4],[5] require that WPPs ride through faults, remain connected to the grid, and even actively contribute to grid operation during dynamic conditions. Therefore, the impact of a WPP on the power system, during both steady state and power system dynamics, needs to be analyzed and quantified. This necessitates the developments of appropriate WPP models that reflect the behavior of WPPs with respect to different types of power system phenomena and a wide range of studies, i.e., from planning to fast electromagnetic transients (EMTs). EMTs studies are conducted either within a WPP or in the power system external to the WPP. The latter is the focus of this thesis. EMTs occur frequently in the power system due to faults and switching events and include frequencies from DC to multi-MHz. Although the EMTs last only for short periods of time, i.e., up to tens of cycles, it is necessary to conduct EMTs studies to obtain detailed information about the study system behavior during EMTs. In addition, EMTs studies have a vital role in the design/verification of control/protection platforms.
Chapter 1. Introduction

1.1 Statement of the Problem and Thesis Motivations

Analysis of EMTs in a power system inherently necessitates the system model to accurately represent the overall system, including WPPs, within the required frequency range. Thus, the brute force approach to model a WPP for EMTs studies is to represent all components of each WPP based on their detailed models. However, a typical WPP consists of tens or even hundreds of wind turbine generator (WTG) units, their power electronic interfaces, local controllers, the collector network, and the WPP supervisory controller. As such, with the significant size and complexity of a WPP combined with the required high resolution (small time-step for numerical integrations), associated with EMT-type time-domain simulation programs, the detailed modeling of a WPP necessitates (i) significant hardware computational resources, and (ii) imposes formidable run-time for each case study. The former is practically a major limitation for EMTs studies in a real-time simulation environment where the WPP detailed modeling imposes a drastic computational burden on the real-time simulator (RTS) and hence will require extensive increase in the size and cost of the expensive RTS hardware. Therefore, there is a need to adopt a more computationally efficient modeling approach to represent WPPs for EMTs studies. The system under study, Figure 1.1, can be virtually divided into two zones. The first (study) zone, Figure 1.1, encompasses that part of the system where the EMTs are investigated and consequently all the corresponding components need to be modeled in detail. The second (external) zone, Figure 1.1, covers the rest of the system which has secondary impact on the study zone transients; yet, it cannot be discarded or represented by an approximated, simplified, fundamental-frequency model. Thus, the external zone can be represented by an equivalent model that reflects its impact on the EMTs of the study zone in the frequency range of interest. This strategy is adopted in this thesis and the WPP forms (for transients initiated outside the WPP) the external zone that needs to be represented by a reduced-order, wide frequency-band WPP equivalent model, connected to the point of common coupling (PCC).

WPP reduced-order models have been developed in the technical literature, e.g., the WPP generic, non-proprietary models [6]–[10] and the WPP aggregated models that lump all WTG units within the WPP into single or multiple units with re-scaled power capacity [11]–[13]. However, these models are neither tailored for EMTs studies nor
adequately represent the EMTs behavior of the WPP of interest. The main reasons are:

- These models are designed for power flow and transient stability studies, and valid only for a very narrow frequency range of 0-2 Hz [10].

- These models do not represent the EMTs behavior of the WPP collector network in response to external EMTs. This shortcoming results from either omitting the collector system from the equivalent or only considering its fundamental-frequency short-circuit equivalent [14],[15].

- These models are not suitable for the hardware-in-the-loop testing of control/protection platforms since they do not represent the EMTs behavior of the WPP, and due to the computational burden associated with the multiple WTG representation.

EMT-type WPP equivalent models do not exist; previously there was no real need for them since the WPPs were designed to disconnect from the system during transients. However, such models are now crucial since the current grid codes require WPPs to remain connected to the grid during disturbances.

The aforementioned limitations and the fact that EMT-type WPP equivalent models do not exist, are the main motivations behind the development of a new computationally-efficient dynamic equivalent model of WPPs proposed in this thesis.
1.2 Thesis Objectives

Based on the aforementioned discussion, the objectives of this thesis are:

1. Develop a wide-band reduced-order dynamic equivalent model of a Type-4 and a Type-3 based WPPs for the analysis of EMTs in the power system external to the WPP. The salient features of the proposed equivalent model are:
   - It represents the dynamic behavior of the WPP components including: (i) the WPP collector network and passive components, (ii) the WPP supervisory control, and (iii) WTGs and their local controls.
   - It is computationally efficient, i.e., significantly reduces the hardware/software computational burden as compared to the WPP detailed models.
   - It accurately mimics the terminal response of the WPP with respect to the power system EMTs over a wide-band of the frequency spectrum, e.g., ranging from DC to 50 kHz.
   - It represents the fault-ride through behavior of the WPP which is a mandatory requirement of the grid codes.
   - It is suitable for real-time simulation based on practically available computational resources.

2. Implement the proposed equivalent model in a time-domain simulation platform (PSCAD/EMTDC) for the off-line analysis.

3. Develop a benchmark system for Type-3 and Type-4 based WPPs.

4. Validate the accuracy of the proposed equivalent models with respect to detailed WPP models.

5. Implement the proposed equivalent model in a real-time simulation platform.

6. Utilize the real-time simulated WPP equivalent model in the testing of control/protection platforms in a hardware-in-the-loop (HIL) environment.

---

1 Type-4 refers to the WTG units with full capacity back-to-back converter interface
2 Type-3 refers to the WTG units with doubly-fed asynchronous generators
1.3 Proposed Wide-Band Dynamic Model of WPP

Figure 1.2(a) shows a schematic diagram of a power system which also includes a WPP. The WPP is composed of: 1) multiple WTG units and their local controls, 2) a collector system, and 3) the WPP supervisory control. The main objective of this work is to represent the WPP, with respect to the PCC, by an equivalent model that can accurately represent the impact of the WPP on EMT phenomena that occur in the power system, external to the WPP, e.g., EMTs due to the faulted line, Figure 1.2(a). To achieve this objective, the WPP model is mathematically represented by the following two segments as symbolically shown in Figure 1.2(b).

- Passive (static) Frequency Dependent Network Equivalent (FDNE) Model: This represents the response of all passive components of the WPP, i.e., WPP substation transformer(s), overhead lines and underground cables of the collector system, filter and capacitor banks, passive loads, and any other passive component within the WPP. The frequency bandwidth of the passive equivalent model is determined based on the type and the characteristics of the EMTs to be investigated external to the WPP, e.g., 0 to 50 kHz.

- Dynamic Low-Frequency Equivalent (DLFE) Model: This represents the dynamic behavior of the WTG units (and their local controls) within the WPP and the WPP supervisory controller with respect to the WPP external power system. The DLFE model represents the WPP low-frequency dynamics about the nominal power frequency.

The combined FDNE model and the DLFE model constitutes the net model of the WPP with respect to its host power system at the PCC, Figure 1.2(b), in the desired wide frequency range.

1.4 Methodology

In order to achieve the aforementioned thesis objectives, the following methodology is employed:
Chapter 1. Introduction

Benchmark Test System Development

Two test systems, one includes a Type-4 based WPP and the other includes a Type-3 based WPP connected to a power system are used. Each test system is simulated in the PSCAD/EMTDC time-domain simulation platform based on the detailed modeling of all components of the WPP that include WTG units (17 and 8 WTGs for the Type-4 and Type-3 WPPs respectively), their local controls, a collector network, and a WPP supervisory control. The detailed model of each WPP is used in the development of the WPP equivalent model and the simulation results of that detailed model are considered as benchmark results. The detailed models of the Type-4 WPP and the Type-3 WPP are in Appendices A and D respectively.

Equivalent Model Development

The PSCAD/EMTDC detailed model is used to develop the FDNE model of the WPP, with respect to the PCC. The FDNE development approach is detailed in Chapter 2 of this thesis. The DLFE model of each WPP is then developed as described in chapters 3 and 4. The proposed dynamic WPP equivalent model is the combination of the FDNE and the DLFE as symbolically depicted in Figure 1.2(b). The equivalent model is constructed and implemented in the PSCAD/EMTDC.
Equivalent-Model Accuracy Validation

The numerical accuracy and computational efficiency of the developed dynamic equivalent model are validated by comparing the time-domain simulation test case results when the WPP is represented once by its detailed model and once by the proposed equivalent model.

Real-Time Simulation/HIL Testing

To demonstrate the effectiveness and the computational efficiency of the proposed equivalent model for real-time applications, the equivalent models of both Type-3 and Type-4 based WPPs are embedded in a real-time digital simulator (RTDS) and investigated. The equivalent model of a Type-4 based WPP is also used for the HIL testing of the WPP supervisory control.

1.5 Thesis Outlines

The rest of this thesis is organized as follows:

Chapter 2 presents the development of the WPP passive network equivalent model. It describes the mathematical model and procedures to generate the frequency dependent network equivalent; this includes the formation of the WPP driving point admittance matrix and fitting the frequency dependent response to a rational function representation based on the vector fitting technique. This chapter also describes the discretization of the frequency-domain model of the FDNE for the implementation in the PSCAD/EMTDC and the RTS environments.

Chapter 3 presents the development of the dynamic low-frequency equivalent model of the Type-4 WPP and its integration with the FDNE to form the wide-band dynamic equivalent model of Type-4 WPPs. It also provides the validation and performance evaluation of the proposed Type-4 WPP equivalent model in the PSCAD/EMTDC environment.

Chapter 4 presents the development and validation of the dynamic low-frequency equivalent (DLFE) model of WPPs based on doubly-fed asynchronous generator (DFAG) WTG, Type-3, units. The integration of the DLFE with the equivalent model of the WPP collector network model to form a wide-band equivalent model of Type-3 WPP is also presented in this chapter. The accuracy of the developed model is demonstrated through
several case studies, using the PSCAD/EMTDC.

**Chapter 5** is devoted to the implementation of the proposed WPP dynamic equivalent models, developed in chapters 2 to 4, in the RTDS® real-time simulation platform. This chapter also presents the real-time HIL testing of the WPP supervisory control of the Type-4 WPP, realized in an industrial controller platform (NI-cRIO).

**Chapter 6** summarizes the conclusions, main contributions, and suggestions for future work.
Chapter 2

Frequency-Dependent Network Equivalent (FDNE) Model of WPP

2.1 Introduction

To provide accurate and computationally efficient simulation of EMTs external to a WPP, the computationally expensive detailed modeling of the WPP passive network needs to be replaced by a frequency-dependent equivalent model to (i) provide the required accuracy, and (ii) alleviate the computational burden associated with detailed modeling.

This chapter presents the development of the frequency dependent network equivalent (FDNE) model as an accurate and computationally efficient representation of the WPP passive network. The FDNE reflects the behavior of the WPP passive network at the WPP terminals (PCC) which is critical for assessing the impact of the WPP on its host power system EMTs transients. The FDNE reproduces the frequency response of the WPP passive components over the required wide-band of the frequency spectrum. This frequency range is usually determined based on the type of the EMTs to be investigated. In this work it is considered to be from DC to about 50 kHz.

This chapter describes, in section 2.2, the mathematical model and procedures to generate the FDNE; this includes determining the frequency response of the original WPP passive network and fitting that frequency-dependent response to a rational function representation based on the vector fitting technique [16]. This chapter also describes, in section 2.3, the discretization of the frequency-domain model of the FDNE for the realization of the WPP passive network equivalent model in both PSCAD/EMTDC and RTDS® simulation environments. However, the validation of the accuracy of the FDNE
in modeling the passive components of the WPP is presented in Chapter 3 where the
WPP benchmark system is first described.

2.2 FDNE of WPP Passive Network

The development of the FDNE model \[17\] consists of two main steps:

1. Determining the frequency response of the original WPP passive network with
   respect to the PCC.

2. Representing the frequency response based on a rational function approximation
   \[16\],\[18\].

2.2.1 WPP Driving Point Admittance Matrix

The first step in developing the FDNE is to construct the frequency-dependent admittance matrix of the WPP passive network over the frequency range of interest. This can be done based on an analytical approach or by conducting a frequency scan at the terminals of the WPP. The construction of the frequency dependent admittance matrix can be summarized in the following steps:

1. At PCC, disconnect the WPP power circuit from the power system and open-circuit all WTG units at their connection point with their local step-up transformers.

2. Inject a current signal into the WPP from the PCC. The current signal is the summation of a set of sinusoidal current components at unity amplitudes, zero phase angles, and discrete frequencies that cover a prespecified frequency bandwidth and prespecified frequency steps. The frequencies of these currents are logarithmically distributed over the desired frequency bandwidth.

3. Measure the WPP voltage at the PCC. This voltage represents the WPP equivalent impedances at the frequencies of the injected currents.

4. Decompose the voltage, based on the Fourier analysis, into its components at the frequencies of the injected current components.

The above procedure results in a matrix of the form of (2.1) where a, b, and c are the three phases of the WPP terminal bus (PCC); the diagonal elements are the self
admittances while the off-diagonal elements are the mutual admittances, each element is a function of the frequency,

\[ Y(f_i) = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}. \] (2.1)

### 2.2.2 Vector Fitting Technique

The second step in developing the FDNE is to fit the obtained frequency response into a rational function representation of the form (2.2) which can be efficiently implemented in the time-domain simulation programs

\[ f(s) = \sum_{i=1}^{n} \frac{c_i}{s - a_i} + d + sh. \] (2.2)

In (2.2), residues \( c_i \)'s and poles \( a_i \)'s can be either real numbers or complex conjugate pairs, \( d \) and \( h \) are real numbers, and \( n \) is the number of poles. The goal of the fitting process is to estimate the parameters of (2.2) such that a least square approximation of \( f(s) \) is obtained over the frequency range of interest. It is to be noted that in (2.2) the unknown poles \( a_i \)'s appear in the denominator which make the above problem a nonlinear one [18].

The vector fitting technique is a well established, accurate, and stable method to obtain the parameters of (2.2) [16], [18]–[21]. The concept of this technique is based on solving the nonlinear problem, (2.2), sequentially in two stages of linear problems based on the known initial poles. The rational function form of (2.2) can be written as

\[ f(s) \approx f_{fit}(s) = \sum_{i=1}^{n} \frac{\tilde{c}_i}{s - \tilde{a}_i} + d + sh = h \prod_{i=1}^{n+1} \frac{s - y_i}{s - a_i}. \] (2.3)

Function \( \sigma(s) \) with known poles \( \tilde{a}_i \), (2.4), is introduced such that the product of \( \sigma(s)f(s) \) takes the form of (2.5) where \( \sigma(s)f(s) \) has the same poles as \( \sigma(s) \)

\[ \sigma(s) = 1 + \sum_{i=1}^{n} \frac{\tilde{c}_i}{s - \tilde{a}_i} = \prod_{i=1}^{n} \frac{s - z_i}{s - a_i}, \] (2.4)

\[ \sigma(s)f(s) = \sum_{i=1}^{n} \frac{e_i}{s - \tilde{a}_i} + l + sm. \] (2.5)
From (2.3) and (2.4), $\sigma(s)f(s)$ is expressed as

$$\sigma(s)f_{fit}(s) = h \prod_{i=1}^{n}(s - z_i) \prod_{i=1}^{n+1}(s - y_i) \prod_{i=1}^{n}(s - a_i).$$

To force the poles of $\sigma(s)$ to be the same as poles of $\sigma(s)f_{fit}(s)$, the condition is $\prod_{i=1}^{n}(s - z_i) = \prod_{i=1}^{n}(s - a_i)$. This indicates poles of $f_{fit}(s)$ become equal to the zeros of $\sigma(s)$. Thus, the steps to perform the vector fitting technique are

1. Select a set of starting initial poles $\bar{a}_i$. These poles can be chosen as complex conjugate pairs with their imaginary parts distributed over the frequency range of fitting [16].

2. Substitute $\sigma(s)$ from (2.4) in (2.5) as

$$\sum_{i=1}^{n} \frac{e_i}{s - \bar{a}_i} + l + sm = \left(1 + \sum_{i=1}^{n} \frac{\tilde{c}_i}{s - \bar{a}_i}\right)f(s),$$

or

$$\sum_{i=1}^{n} \frac{e_i}{s - \bar{a}_i} + l + sm - \left(\sum_{i=1}^{n} \frac{\tilde{c}_i}{s - \bar{a}_i}\right)f(s) = f(s).$$

Equation (2.8) is linear in terms of its unknowns $\tilde{c}_i, e_i, l, m$. For a given frequency point $s_k$, (2.8) can be written in the form of $A_kx = b_k$ where

$$A_k = \begin{bmatrix} \frac{1}{s_k - \bar{a}_1} & \ldots & \frac{1}{s_k - \bar{a}_n} & 1 & s_k & -f(s_k) & \ldots & -f(s_k) \\ s_k - \bar{a}_1 & \ldots & s_k - \bar{a}_n & 1 & s_k - \bar{a}_1 & \ldots & s_k - \bar{a}_n \end{bmatrix},$$

$$x = [e_1 \ldots e_n \ l \ m \ \tilde{c}_1 \ldots \tilde{c}_n]^T,$$

and $b_k = f(s_k)$ which is an element of the admittance matrix, obtained from the frequency scan, at frequency $s_k$. Expressing (2.8) at a series of frequency points gives an overdetermined linear problem of $Ax = b$, since the number of frequency points is much larger than the number of unknowns.

3. Solve the overdetermined linear problem with a standard least square technique and obtain residues $\tilde{c}_i$ of the function $\sigma(s)$.

4. Calculate zeros $z_i$ of the function $\sigma(s)$, (2.4). Based on the poles and residues of $\sigma(s)$, the zeros $z_i$ are calculated as the eigenvalues of matrix [16]

$$H = A - b \tilde{c}^T,$$
where $A$ is a diagonal matrix containing the initial poles, $b$ is a unity column, and $\tilde{c}^T$ is a row vector containing the residues of $\sigma(s)$. The zeros $z_i$ are then the new poles of $f_{fit}(s)$.

5. Check the stability of the new poles. For any unstable pole, invert the sign of its real part [16].

6. Theoretically, residues $c_i$ are calculable as the follow up of the above steps. However, a more accurate fitting can be obtained by using the new poles obtained in Step 4 as the starting poles in Step 2, in an iterative manner [16], [18]. The iterative process stops when the change in the pole values between two consecutive iterations is below a selected threshold.

7. Calculate residues $c_i$, $d$, and $h$ by solving the linear least square problem (2.2).

The aforementioned steps are summarized in the flowchart of Figure 2.1

### 2.2.3 Passivity Enforcement

The WPP collector network is physically a passive network, i.e., the network components absorb active power for any applied voltage at any frequency. However, this may not be the case when fitting the elements of the network admittance matrix $[Y]$ with rational functions [22]. The fitting process may result in an admittance with negative real part. This may result in unstable simulation results although the elements of $[Y_{fit}]$ are fitted with stable poles [22], [23]. To prevent this problem, the passivity of the approximated network need to be enforced, i.e., the components must absorb active power for any applied voltage at any frequency.

The active power absorbed by network components is given by:

$$ P = Re\{v^*Yv\} = Re\{v^*(G + jB)v\} = Re\{v^*Gv\} $$  \hspace{1cm} (2.10)

where $v$ is the voltage and the asterisk denotes transpose and conjugate. The power $P$ will always be positive only if all eigenvalues of $G = Re\{Y_{fit}\}$ are positive definite (PD) [22]. Therefore, the criterion for passivity is to enforce all eigenvalues of $G$ to be positive. It is to be noted that since $G$ is a symmetric, real matrix, all of its eigenvalues are real.
Figure 2.1: Flowchart of the Vector Fitting Technique

The real-part of the rational approximation of element $m, n$ of the $Y_{fit}$ matrix can be expressed as

$$G_{fit,m,n}(s) = d + Re\left\{ \sum_{i=1}^{n} \frac{c_i}{s-a_i} \right\} = d_{m,n} + p_{m,n}(s).$$  \hspace{1cm} (2.11)
For the full matrix (2.11) becomes

$$G_{fit}(s) = D + P(s).$$  \hspace{1cm} (2.12)

At each frequency $s$, matrix $G_{fit}$ is diagonalized as

$$T \Lambda T^{-1} = D + P(s),$$  \hspace{1cm} (2.13)

where $\Lambda$ is a diagonal matrix that contain the eigenvalues of $G_{fit}$ and $T$ contains the corresponding eigenvectors. $\Lambda$ is then separated into $\Lambda_+ \text{ and } \Lambda_-$ which contain the positive and negative eigenvalues respectively.

$$T(\Lambda_+ + \Lambda_-)T^{-1} = D + P(s).$$  \hspace{1cm} (2.14)

The reorganization of (2.14) produces the modified positive definite $G_{fit}$

$$G_{fit PD} = T \Lambda_+ T^{-1} = D - T \Lambda_- T^{-1} + P(s).$$  \hspace{1cm} (2.15)

The matrix $G_{fit}$ is modified such that its negative eigenvalues are replaced by zeros by adding a correction to $D$. The above procedure is repeated for all frequencies for which passivity enforcement is required, Figure 2.2 [22].

### 2.3 Implementation of the FDNE in a Time-Domain EMT Platform

In a time-domain EMT simulation programs where a numerical integration is used, power system components such as $R$, $L$, and $C$ are converted to Norton equivalent circuits (known as companion circuits). A companion circuit consists of a conductance and a current source whose value depends on the circuit solution from the previous time step (called a history current source) [24]. To implement the FDNE in the PSCAD/EMTDC and the RTDS environments, each rational function is represented with a companion circuit [25]–[27]. The discrete time-domain of a rational functions is obtained based on the bilinear transformation

$$s = \frac{2}{\Delta t} \left[ \frac{1 - z^{-1}}{1 + z^{-1}} \right],$$  \hspace{1cm} (2.16)

where $z^{-1}$ represents a one time-step delay in the time-domain, and $\Delta t$ is the integration time-step. The poles and residues of the rational functions (2.2) are either real or complex.
conjugate pairs. For every partial fraction of the rational function that has a real pole and a residue, i.e., \( \frac{c}{s + a} \), the discrete time-domain representation is shown in Figure 2.3 where the value of the history current source \( I_h \), Figure 2.3, is updated every simulation time-step based on (2.17) [26]

\[
I_h(t) = v(t) G \left[ 1 - \frac{(a - \alpha)}{(a + \alpha)} \right] - \frac{a - \alpha}{a + \alpha} I_h(t - \Delta t),
\]

where the conductance \( G \) is

\[
G = \frac{c}{\alpha + a},
\]
and

\[ \alpha = \frac{2}{\Delta t}. \]  (2.19)

For every two partial fractions of the rational function that have complex conjugate poles \((a_r \pm ja_i)\) and residues \((c_r \pm jc_i)\), the discrete time-domain representation is shown in Figure 2.4. The values of the history current sources \(I_{1h}\) and \(I_{2h}\), Figure 2.4, are updated using

\[
I_{1h}(t) = \left[ \frac{4A - 2(B - \alpha^2)G}{C} \right] v(t) - \left[ \frac{2(B - \alpha^2)}{C} \right] [I_{1h}(t - \Delta t) + I_{2h}(t - 2\Delta t)], \quad (2.20)
\]

\[
I_{2h}(t) = \left[ \frac{(2A - 2c_r\alpha) - (\alpha^2 - 2\alpha + B)G}{C} \right] v(t) - \left[ \frac{\alpha^2 - 2\alpha + B}{C} \right] [I_{1h}(t - \Delta t) + I_{2h}(t - 2\Delta t)], \quad (2.21)
\]

where \(A = a_r c_r + a_i c_i\), \(B = a_r^2 + a_i^2\), \(C = \alpha^2 + 2a_r\alpha + B\), and the conductance \(G = \frac{2c_r\alpha + 2A}{C}\).
2.4 Conclusions

This chapter presented the development of the FDNE model that reflects the frequency response of the WPP passive network. The FDNE is developed by: 1) conducting a frequency scan of the WPP passive system at the PCC based on the WPP PSCAD/EMTDC model, and 2) representing the frequency scan results by a rational function using the vector fitting technique. The rational function is then represented based on the companion circuit approach, in the time-domain simulation package used to conduct the EMT studies of the power system external to the WPP. Development and the results associated with the FDNE of the passive networks of the test systems are presented in the following chapters.
Chapter 3

Dynamic Low-Frequency Equivalent Model of Type-4 WPP

3.1 Introduction

This chapter presents the development and evaluation of the dynamic low-frequency equivalent (DLFE) model of the Type-4 WPP which represents the aggregated dynamic behavior of the active components within a Type-4 based WPP. The proposed equivalent model includes (i) the WPP supervisory control model, and (ii) the equivalent model of the Type-4 WTGs and their local controls. The integration of the aforementioned DLFE model and the FDNE of the WPP collector network (presented in chapter 2) forms the reduced-order, wide-band, dynamic-equivalent model of Type-4 WPPs. The proposed equivalent model represents the transient behavior of the WPP in response to EMTs in the power system external to the WPP.

The structure of this chapter is as follows: Section 3.2 is a brief overview of the Type-4 WTG and the hierarchical control of the WPP. Section 3.3 states the equivalent model assumptions. The structure of the dynamic-equivalent model is demonstrated in Section 3.4. Sections 3.5 - 3.7 describe the model of the phase-locked loop (PLL), the WPP supervisory control model, and the equivalent model of WTG units and their local controls respectively. The integration of the DLFE model in conjunction with the FDNE to form the complete WPP equivalent model is presented in Section 3.8. Sections 3.9 - 3.11 demonstrate the validation process of the proposed equivalent model and the discussion of the study results respectively. The conclusions of this chapter are in Section 3.12. The detailed model of the Type-4 WPP that is used as the benchmark system to
verify the accuracy of the equivalent model is presented in Appendix A.

### 3.2 Background

The hierarchical control of a WPP is composed of three-levels of controls, Figure 3.1, [28], [29]. At the highest level, the control center of the transmission system operator (TSO) communicates with the WPP supervisory control and provides reference values of the required active and reactive power components based on the WPP state of generation and the power system requirements. This level of control is not discussed here as it does not impact the dynamics of interest.

The second level of control is the WPP supervisory control that coordinates the operation of all WTG units within the WPP such that the collective WPP power injection at the PCC satisfies the active and reactive power requirements of the TSO. The reference signals from the supervisory control are then sent to the next control level, i.e., the WTG local control. The WTG operation is controlled through the control of the corresponding rotor-side converter (RSC) and grid-side converter (GSC) whose functions are to adjust the WTG injections to satisfy the WPP supervisory control requirements. Figure 3.2 depicts a Type-4 WTG unit with its collector network interface of a full rated back-
Figure 3.2: Schematic Diagram of Type-4 WTG Unit

to-back converter and a step-up transformer. The back-to-back converters decouple the turbine-generator from the collector network such that disturbances that take place on the collector network side have insignificant effects on the machine side of the converter [6],[30]–[32].

The second and third levels of control, i.e., the WPP supervisory control and the local WTG unit control respectively, are discussed in Appendix A.

3.3 Equivalent Model Assumptions

To develop the Type-4 WPP equivalent model, the following assumptions are made:

1. The WTG units within the WPP of interest are assumed to be of the same type (Type-4 in this chapter).

2. The proposed equivalent model represents the WPP dynamic response with respect to transients in the host power system, i.e., external to the WPP.

3. The low-frequency dynamics of the WTG units are represented by those of the grid-side converters (GSCs) and their local controls. This assumptions is justified since the turbine-generators and the rotor-side converters (RSCs) have secondary impact on the collective WPP dynamic behavior at the PCC. This is due to the decoupling effect of the WTG back-to-back converter system [6],[30]–[32].
3.4 Structure of the Dynamic Low-Frequency Equivalent (DLFE) Model of Type-4 WPP

The DLFE model of the Type-4 WPP, Figure 3.3, proposed in this chapter represents the low-frequency dynamics of the WPP active components, e.g., in a range of 0 up to 20 Hz and intends to represent low-frequency dynamics of the WPP and the natural modes of controls. In order to represent the dynamics of the WPP, the DLFE model of the WPP active components, Figure 3.3, consists of four components:

(i) The measurements module represents the sensors and measurement devices within the WPP. It monitors the instantaneous WPP terminal voltages and output currents at the high-voltage side of the WPP substation transformer and provides the measured signals to the other blocks.

(ii) The supervisory control represents the functions and dynamics of the WPP supervisory control. For this purpose, this module includes control loops that process the input reference values of the active and reactive power components, $P$ and $Q$, determines the corresponding active and reactive current commands $I_{Pcmd}$ and $I_{Qcmd}$, and sends them to the WTGs equivalent model. More details of this block are given in Section 3.6.

Figure 3.3: Dynamic Model of WPP with Type-4 WTGs
(iii) The WTGs equivalent model represents the equivalent aggregated dynamics of the WTGs within the WPP which are dominated by the dynamics of the GSCs and their local controls. This module generates the active and reactive current components to be injected at the PCC in response to $I_{Pcmd}$ and $I_{Qcmd}$ received from the supervisory control module.

(iv) The phase-locked loop (PLL) synchronizes the modules of the equivalent model with the positive sequence voltage at the PCC.

The aforementioned modules form the proposed reduced order model which represents the WPP EMTs behavior without modeling the components of the WPP in detail. Sections 3.5 - 3.7 elaborate on the details of the above modules.

### 3.5 Phase Locked Loop

The phase-locked loop (PLL) block, Figure 3.3, represents the function of the PLL in a WPP. It synchronizes the equivalent model blocks with the PCC voltage, i.e., aligns the d-axis of the dq-reference frame with the WPP terminal voltage, at both steady state and transient conditions. The advantages gained from developing the controllers in the dq-frame are:

- The control signals are DC values which simplifies the control design and allows the use of PI controllers.
- Active and reactive power components can be independently controlled by controlling $i_d$ and $i_q$ respectively.

In this work, the dual second order generalized integrator-PLL (DSOGI-PLL) [33] is used as a generic PLL in the proposed WPP equivalent model. The performance of the DSOGI-PLL surpasses that of the basic synchronous reference frame PLL (SRF-PLL) [34] whose performance degrades under unbalanced and distorted grid conditions [35], [36]. The DSOGI-PLL is accurate in detecting the fundamental frequency positive-sequence component of the voltage and its phase angle even under extreme unbalanced and distorted grid operation [33]. In addition, the DSOGI-PLL has a relatively simple structure. The structure of the DSOGI-PLL and its mathematical representation are given in Appendix B.
3.6 Type-4 WPP Supervisory control

The WPP supervisory control, Figure 3.3, represents the control functions to coordinate WTGs such that their collective operation satisfies the grid requirements at the PCC (the high voltage side of the substation transformer). The model proposed in this thesis includes the WPP active and reactive power control and a fault-ride through (FRT) control according to [29].

Figure 3.4: Block Diagram representation of the WPP Supervisory Control

Figure 3.4 depicts the main building blocks of the WPP Supervisory Control. The active and reactive power (P and Q) control receives the reference values of $V_{ref}$, $P_{ref}$ and $Q_{ref}$ and measured feedback signals $V_{PCC}$, $I_{PCC}$, $P_{PCC}$, and $Q_{PCC}$; and then determines the active and reactive reference current values of $I_{Pcmd}$ and $I_{Qcmd}$ to be sent to the WTGs equivalent model [37]. The supervisory control model also includes a FRT control, Figure 3.4, which is activated during transient conditions that are accompanied with voltage fluctuations at the PCC. The objective of the FRT control is to comply with grid codes that require WPP to remain in service and ride through the fault to support the grid voltage through the exchange of reactive current with the grid [4],[38].
Both the P and Q controls apply limits over $I_{P_{cmd}}$ and $I_{Q_{cmd}}$. These limits are determined in the WPP current limits block to meet the operational priority and requirements [31],[39]. The following subsections elaborate on the details of the components of the supervisory control model.

### 3.6.1 Active Power Control

The active power control block, Figure 3.4, represents the WPP supervisory active power control function. In this block, Figure 3.5, the active current command $I_{P_{cmd}}$, which is the overall active current required from all WTGs, is calculated and sent to the WTGs equivalent model. $I_{P_{cmd}}$, Figure 3.5, is calculated based on the active power reference $P_{ref}$ and the WPP terminal voltage $V_{PCC}$ [37]. However, during transients that result in voltage fluctuations, $I_{P_{cmd}}$ has to be reduced to allow the WTG converters to generate more reactive current to support the grid voltage and to avoid over charging the converters DC link. This reduction in $I_{P_{cmd}}$ is represented in the active control block by multiplying $P_{ref}$ by a factor ($P_{multiplier}$) which becomes less than unity when the PCC voltage drops below certain threshold. $P_{multiplier}$ is determined in the FRT control block as explained in Section 3.6.4. It is to be noted that the active power control block applies limits on both its input and output signals to satisfy the operational requirements; the input signal $P_{ref}$ is limited by the WPP available power from the wind, $P_{max_{wind}}$, Figure 3.5, and the output active current is limited by the maximum active current limit, $I_{P_{max}}$, which is calculated in the current limits block, section 3.6.3. It is to be noted also that all values used in this control block are normalized quantities; this is advantageous as the base values can be re-scaled to the size and voltage level of the WPP of interest, i.e., the structure of this control is scalable and independent of the size of the WPP.

### 3.6.2 Reactive Power Control

The reactive power control block, Figure 3.6, represents the Q-control function of the WPP supervisory control, Figure 3.4. In this block, the reactive current command $I_{Q_{cmd}}$ of all WTGs is determined based on the control option that may include: PCC voltage control, power factor control, and PCC reactive power control [6],[37]. Based on the control option, $Q_{ref}$ is determined and limited to the WPP rated reactive power. The output reactive current $I_Q$ is limited by the reactive current limits calculated in the current limits block and this results in the reactive current command $I_{Q_{cmd}}$ that is sent
to the WTGs equivalent model. However, during intervals where the voltage is beyond certain threshold,  $I_{Q_{cmd}}$ is determined by the FRT control as discussed in section 3.6.4.

### 3.6.3 WPP Current Limits

The function of the WPP current limits block, Figure 3.4, is to calculate the limits that have to be imposed on the dq-current commands to prevent their net component from exceeding the rated current of converters within the WPP. The dq-current limits are calculated based on the capability of the aggregated WPP converters and the WPP terminal voltage that determines the priority of generation. During the steady state operation, the active current priority mode is typically enabled to supply the maximum available active power to the grid while during transients under voltage fluctuations, the
reactive current priority is enabled such that the WPP can supply extra reactive current to support the grid voltage as required by the grid code. During P-priority, Figure 3.7, the upper limit of the active current $I_{P\text{ max}}$ is set to the aggregated rating of the converters $I_{\text{max}}$ while the maximum reactive current limit $I_{Q\text{ max}}$ is determined based on both the aggregated converter rating $I_{\text{max}}$ and the active current command $I_{P\text{ cmd}}$

$$I_{P\text{ max}} = I_{\text{max}}, \quad I_{Q\text{ max}} = \sqrt{I_{\text{max}}^2 - I_{P\text{ cmd}}^2}. \quad (3.1)$$

For Q-priority, the upper limit for the reactive current is set to be $I_{\text{max}}$ while the active current limit is calculated based on both the aggregated converter rating $I_{\text{max}}$ and the reactive current command $I_{Q\text{ cmd}}$ as in (3.2). The minimum reactive current $I_{Q\text{ min}}$ is the negative of the maximum limit $I_{Q\text{ max}}$.

$$I_{Q\text{ max}} = I_{\text{max}}, \quad I_{P\text{ max}} = \sqrt{I_{\text{max}}^2 - I_{Q\text{ cmd}}^2}. \quad (3.2)$$

Figure 3.7: The WPP Current Limits Block

### 3.6.4 Fault-Ride-Through (FRT) Capability

During system transients that are accompanied with severe voltage fluctuations, the tripping of WPPs may result in a significant loss of generation which could be disruptive to the grid especially if the tripped WPP is considered large in the context of its host grid [40]. Thus, it is necessary to include the FRT control in the proposed WPP equivalent model to enable simulations of realistic scenarios.
The FRT control block, Figure 3.4, represents the control action taken within a WPP to comply with the grid codes [4], [41], [42] that require WPP to ride through the fault and supply reactive current to support the grid voltage during transient events when the PCC voltage deviates more than 10% of the nominal value (1 p.u.). This work adopts the Western Electricity Coordination Council (WECC) grid code at which the WPP should stay in service and supply the grid with reactive current even when the PCC voltage drops and remains at zero for at least 150 ms (9 cycles), Figure 3.8, [4]. Within the no trip boundary, Figure 3.8, the WPP is required to supply reactive current to support the grid voltage according to Figure 3.9, [38], [42]. The aforementioned grid code and the corresponding control actions are included in the WPP equivalent model through the FRT control block, Figure 3.4.

Based on the value of the terminal voltage $V_{PCC}$, the FRT control is activated and the $I_{Q_{cmd}}$ control moves from the Q-control to the FRT control, Figure 3.4. The FRT control block determines the reduction in $I_p$ and the value of $I_Q$ that should be supplied by the WPP based on $V_{PCC}$. $I_{Q,FRT}$ is determined based on the characteristics of Figure 3.9 at which $I_{Q,FRT}$ should reach 1 p.u. of the rated current when the voltage drops to 50% of its nominal value [38], [42]. An increase in reactive current/reactive power injected by the WPP must be coordinated with real current/power injection to keep the WPP converters net currents within limits, avoid overload conditions, and maintain the WPP in service [37]. Therefore, a factor $P_{multiplier}$ has been defined as a function of the PCC voltage. This factor is initially equal to unity and linearly decreases with the PCC.
3.7 WTGs Equivalent Model

The WTGs equivalent model, Figure 3.3, represents the aggregated dynamics of the WTGs within a WPP. Due to the design of Type-4 WTGs and the decoupling effect of the back-to-back converter interface, the dynamics of the turbine-generator and the rotor-side converter have secondary impact on the net WPP dynamic behavior at the voltage dip, Figure 3.11. This factor is sent to the active power control block to reduce the value of $P_{ref}$. 
Chapter 3. DLFE Model of the Type-4 WPP

Figure 3.11: Active Power Reduction During Voltage Dips

PCC [6],[30]–[32]. Consequently, the dynamic model of the WTG units can be adequately represented by those of the corresponding GSCs and their local controls.

The equivalent representation of the GSC and its local control is deduced from the detailed model of Type-4 GSC, Figure A.2 of Appendix A, with the assumption that the WTG interfacing converter is three-phase, two-level, current-controlled voltage-sourced converter. The equivalent model of one WTG is first developed in per unit at the WTG unit base values. By scaling the base values, the equivalent will represent the aggregated dynamics of all WTGs within the WPP. The dynamics of the AC side can be described in the dq-frame by [43]:

\[
L \frac{di_d}{dt} = L \omega_o i_q - Ri_d + V_{td} - V_{Sd},
\]

\[
L \frac{di_q}{dt} = -L \omega_o i_d - Ri_q + V_{tq} - V_{Sq}.
\]

Representing (3.3) and (3.4) in the S-domain results in

\[
i_d(Ls + R) = L \omega_o i_q + V_{td} - V_{Sd},
\]

\[
i_q(Ls + R) = -L \omega_o i_d + V_{tq} - V_{Sq}.
\]

The above two equations represent the dynamics of the GSC AC-side, Figure 3.12, in which \(i_d\) and \(i_q\) are the state variables; \(V_{td}\) and \(V_{tq}\) are the control inputs; and \(V_{Sd}\) and \(V_{Sq}\) are the disturbance inputs. In (3.5) and (3.6) \(V_{tdq}\) are the GSC terminal voltages and are given by [43]:

\[
V_{td}(t) = \frac{V_{DC}}{2} m_d(t),
\]

\[
V_{tq}(t) = \frac{V_{DC}}{2} m_q(t).
\]
The above two equations represent the model for the two-level GSC in the dq-frame, Figure 3.13, where $m_d$ and $m_q$ are the dq-component of the modulation signal sent to the GSC switches. The modulation signals are determined by the GSC closed loop control that regulates the GSC output currents ($i_{dq}$). The GSC local control is discussed in Section A.2 and employed in this section. The integration of the models of the GSC, the dynamics of the AC side, and the current control, i.e., Figures 3.13, 3.12, and A.3 respectively forms the model of the current controlled GSC, Figure 3.14 [43]. The model of Figure 3.14 can be simplified into the equivalent block diagram of Figure 3.15 where the d- and q-compensators are PI-controllers that track the reference values ($i_{dref}$ and $i_{qref}$).

The block diagram of Figure 3.15, re-scaled to the base values of the WPP, represents
Figure 3.14: Block Diagram of the Current Controlled GSC System

Figure 3.15: Equivalent Model of WTG Units

the equivalent model of the aggregated GSCs and their local controls. The input reference currents $i_{d\text{ref}}$ and $i_{q\text{ref}}$ are the command currents from the supervisory control ($I_{P\text{cmd}}$ and $I_{Q\text{cmd}}$) while the output currents $i_d$ and $i_q$ represent the WPP output currents that are injected to the grid at the PCC.
3.8 Wide-Band Equivalent Model of Type-4 WPP

The proposed reduced-order dynamic-equivalent model of Type-4 WPP is based on the integration of the FDNE, Chapter 2, and the DLFE, Figure 3.3. These two parts are represented by two circuit blocks that are in parallel with respect to the PCC, Figure 3.16. The FDNE is implemented in the PSCAD/EMTDC, based on the companion circuit approach [25], [26]. The trapezoidal numerical integration method is utilized to convert the rational function, obtained from the vector fitting, to a resistive network in conjunction with a set of history current sources as explained in Chapter 2. The DLFE model is represented in the PSCAD/EMTDC based on the transfer function method and is interfaced to the electrical network through a three-phase controlled current source, Figure 3.16.

![Diagram of the proposed wind power plant dynamic-equivalent model](image)

Figure 3.16: The Proposed Wind Power Plant Dynamic-Equivalent Model

3.9 Test System

The system of Figure 3.17 which is a modified form of the Lake Erie [44],[45] WPP and connected to the Hydro One system is used to evaluate and verify performance of the proposed WPP equivalent model.

The WPP is composed of (i) one 34.5/115-kV transformer, (ii) a 34.5-kV collector system, (iii) 0.6-kV Type-4 WTG units and their local controllers that are connected to the collector system through 0.6/34.5-kV delta/wye-grounded transformers, and (iv) the
Chapter 3. DLFE Model of the Type-4 WPP

WPP supervisory control. For the reported studies, WTG units in the collector branches are represented by 17 Type-4 units where power rating of each unit is given on Figure 3.17. The original Lake Erie WPP includes 66, 1.5-MW WTG units. The collector system includes four main branches and 17 sub-branches. Each sub-branch is connected to 3, 4, 5, or 6 WTG units. Due to the computational burden to run a simulation with such a high number of units, the units in each sub-branch are represented by one unit as shown in Figure 3.17. Appendix C provides the line parameters.

Each WTG unit of Figure 3.17 is equipped with a $dq$-current controller that determines its $i_d$ and $i_q$ current injection into the collector system. The WPP supervisory control provides reference values for each WTG unit to meet the grid power requirements and FRT requirements during transients. The adopted FRT characteristics are described in [4],[42].

The power system external to the WPP is composed of two parallel 115-kV overhead lines that connect the WPP to the load bus, Figure 3.17. The load bus is also connected by a short overhead line to the grid which is represented by a three-phase source behind a three-phase impedance.

To evaluate performance of the proposed equivalent model and verify its accuracy, the following procedures were followed.

A. The study system of Figure 3.17 is modeled in detail in the PSCAD/EMTDC platform as described in Appendix A. The WPP is represented by 17 WTG units, Figure 3.17. The VSC of each WTG unit is represented by a three-phase two-level VSC and constructed with six IGBT valves. The converter operates based on a 3060-Hz SPWM. The local controller of each VSC is based on a decoupled d- and q-current approach that utilizes PI-controllers to enable each WTG output current to track the reference $dq$-current components provided by the WPP supervisory control [43]. The $dq$-current reference values for each WTG are determined by the WPP supervisory control based on the P and Q components to be delivered by the WPP. The AC-side terminal of each VSC is connected to the collector system through a three-phase LC filter and a three-phase transformer. Each 3-km section of the collector system is represented by a $\pi$-equivalent. The WPP interface transformer is represented as a three-phase transformer, including the magnetization branch. The overhead lines in the AC power system are represented by $\pi$-equivalent models.
Chapter 3. DLFE Model of the Type-4 WPP

B. The PSCAD/EMTDC detailed model of part A above is used to develop the FDNE model of the WPP, with respect to the PCC, Chapter 2. The PSCAD/EMTDC model is used to obtain the frequency scan of the WPP using 5000 logarithmically-distributed frequency points in the range of 0 to 50 kHz. Then fitted to a 56th-order rational function given by (2.2), using the vector fitting technique, Chapter 2.

C. The DLFE model of the WPP is developed as described in the previous sections of this chapter.

D. Based on the models of parts B and C, the overall equivalent model of the WPP is constructed and implemented in the PSCAD/EMTDC.

Figure 3.18 compares the input admittance of the WPP passive network obtained from the detailed model and the FDNE. In this Figure, the two solid waveforms represent the self and mutual admittances of the passive network of the detailed model while the two dashed waveforms represent the same admittances, but of the FDNE. The close agreement between the two groups of waveforms demonstrates the accuracy of the FDNE in modeling the WPP passive network.
3.10 Case Studies

A set of case studies is performed on the system of Figure 3.17 to quantitatively demonstrate and verify the accuracy of the WPP equivalent model when line T2 is subjected to different faults and switching events. For each fault study, the power system (right-side of the PCC of Figure 3.17) is represented in the PSCAD/EMTDC environment and the WPP (left-side of the PCC of Figure 3.17) is represented once by its detailed model (Section 3.9-A), and once by its equivalent model (Section 3.9-D) and the corresponding study results are identified by the “Detailed Model” and the “Equivalent Model”, respectively. Each reported case study is simulated for up to 6-second of real-time to allow the supervisory control, units control, and the system reach a steady state condition before
imposing a fault on line T2.

### 3.10.1 Case I

The system is subjected to a 150-ms temporary L-L-L-G fault, 15-km from the PCC on line T2 at $t = 4.5s$. Prior to the fault, the system is under steady-state conditions and the WPP delivers 99-MW to the system at PCC. Figures 3.19-3.21 show the system response to the fault based on the detailed model and the equivalent model of the WPP.

Figure 3.19 shows the instantaneous PCC voltages prior, during, and immediately after the fault and illustrates close agreement between the results of the equivalent model and the detailed model. Figure 3.20 shows the injected current by the WPP into the system (at the WPP transformer HV-side) during and after the fault clearance and also indicates close agreement between the results of the two models. Figure 3.21 shows real and reactive power and current components and the PCC rms voltage. Figure 3.21 also illustrates the PCC voltage FRT characteristic [4]. Figure 3.21 indicates that during the fault, the WPP remains in service even when the PCC voltage, Figure 3.21(e), drops to 15% of its nominal value and the WPP output reactive current increases to 1.0 p.u. while the active current drops to zero, Figures 3.21(c) and 3.21(d).

### 3.10.2 Case II

This case is to investigate the accuracy of the developed equivalent model as the location of the fault changes along the line T2. The worst case scenario is considered here when the fault takes place at the PCC. The fault type, application time, and the prefault steady-state conditions are the same as those of Case I. The protecting circuit breakers on the terminals of the line T2 will react to clear the fault after five cycles.

Figures 3.22 to 3.24 show and compare the time-domain simulation results of both the detailed system and the corresponding results obtained from the developed equivalent. The close agreement between the results verifies the accuracy of the developed equivalent.

### 3.10.3 Case III

The system of Figure 3.17 is subjected to a 150-ms temporary L-G fault at $t = 4.5s$ at the same location where the L-L-L-G fault of Case I was imposed. The prefault steady-state conditions are the same as those of Case I. Figures 3.25 and 3.26 show the PCC voltages
Figure 3.19: PCC Voltages of the Detailed and the Equivalent Models - Case I
Figure 3.20: WPP Output Currents of the Detailed and the Equivalent Models - Case I
Figure 3.21: WPP Output (a) P and Q (b) $I_{P_{pcc}}$ and $I_{Q_{pcc}}$ (c) PCC Voltage of the Detailed and the Equivalent Models - Case I
Figure 3.22: PCC Voltages of the Detailed and the Equivalent Models - Case II
Figure 3.23: WPP Output Currents of the Detailed and the Equivalent Models - Case II
Figure 3.24: The WPP Output (a) $P$ and $Q$ (b) $I_{P_{pcc}}$ and $I_{Q_{pcc}}$ (c) PCC Voltage of the Detailed Network and the Developed Equivalent of Case II
and the WPP output currents; they demonstrate close agreement between the results of the detailed and the equivalent models which verifies the accuracy of the developed equivalent even under unbalanced conditions.

3.10.4 Case IV

This case is to investigate the effect of a sequence of multiple transients on the accuracy of the developed model. The system of Figure 3.17, is subjected to the L-L-L-G fault of Case I at t=4.5s, after 5 cycles the circuit breakers CB1 and CB2 react and disconnect the faulted transmission line. The circuit breakers remain open for 15 cycles, during which the fault clears, and then the circuit breakers successfully reclose. Figure 3.27 shows the WPP terminal voltages over the aforementioned sequence of operation and demonstrate the close agreement between the simulation results of both the detailed and the equivalent models. Figures 3.28 and 3.29 depict the WPP output currents, power components, and the PCC rms voltage of both the detailed and the equivalent models. The close agreement between the results of the two models verifies the accuracy of the developed equivalent model.

3.10.5 Case V

The system of Figure 3.17 is subjected to the L-L-L-G fault of Case I at t=4.5s. The fault is cleared after 5 cycles by circuit breakers CB1 and CB2. After another 15 cycles CB1 and CB2 automatically reclose and since the fault is permanent, the reclosure is unsuccessful and subjects the system to another L-L-L-G fault. The second fault is cleared by CB1 and CB2 which permanently remain open after the second fault clearing. Figure 3.30 shows transients of the PCC voltages corresponding to the fault and its subsequent switching events. Figure 3.30 also illustrates close agreement between the corresponding results of the two models. Figure 3.31 depict the time-domain simulation results of the WPP output currents of both the detailed system and the corresponding results obtained from the developed equivalent. Close agreement between the corresponding results of Figures 3.30 and 3.31 also verifies accuracy of the results obtained from the equivalent model.
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Figure 3.25: PCC Voltages of the Detailed and the Equivalent Models - Case III
Figure 3.26: WPP Output Currents of the Detailed and the Equivalent Models - Case III
Figure 3.27: PCC Voltages of the Detailed and the Equivalent Models - Case IV
Figure 3.28: WPP Output Currents of the Detailed and the Equivalent Models - Case IV
Figure 3.29: The WPP Output (a) P and Q (b) I_{PCC} and I_{Q_{PCC}} (c) PCC Voltage of the Detailed Network and the Developed Equivalent of Case IV
Figure 3.30: PCC Voltages of the Detailed and the Equivalent Models - Case V
Figure 3.31: WPP Output Currents of the Detailed and the Equivalent Models - Case V
3.10.6 Case VI

This case introduces more complex transients which combines multiple transients, unbalanced fault, and unbalanced fault clearance. The system of Figure 3.17, is subjected to the L-G fault at $t=4.5s$, after 5 cycles the circuit breakers CB1 and CB2 disconnect the faulted transmission line through only one pole operation. The circuit breakers will remain open for 15 cycles, during which the fault clears, and then the circuit breakers successfully reclose. The transient scenario includes an unbalanced fault transient that is followed by an unbalanced circuit breaker operation at which only one phase of the transmission line is disconnected to clear the fault; then, the faulted phase successfully recloses after 15 cycles.

The time-domain simulation results of both the detailed and the equivalent models are shown in Figures 3.32 and 3.33. The close agreement between the corresponding results of Figures 3.32 and 3.33 verifies the accuracy of the developed equivalent model for EMT-type studies.

3.10.7 Case VII

This case is similar to Case VI, but with double line to ground fault and in consequence double pole circuit breaker operation. The time-domain simulation results of both the detailed and the equivalent models are shown in Figures 3.34 and 3.35. The close agreement of the corresponding results verifies the accuracy of the developed equivalent model.
Figure 3.32: PCC Voltages of the Detailed and the Equivalent Models - Case VI
Figure 3.33: WPP Output Currents of the Detailed and the Equivalent Models - Case VI
Figure 3.34: PCC Voltages of the Detailed and the Equivalent Models - Case VII
Figure 3.35: WPP Output Currents of the Detailed and the Equivalent Models - Case VII
3.11 Discussions

The case studies have been conducted to investigate the accuracy of the proposed equivalent model. These case studies cover different types of faults that occur at different locations. In addition, case studies were conducted where a sequence of multiple and unbalanced transients occurred in the power system external to the WPP. The close agreement between the time-domain simulation results obtained from the detailed model and the corresponding results obtained from the developed equivalent model, Figures 3.19 to 3.35, verifies the accuracy of the developed equivalent model for EMT-type studies. In addition, the errors between the maximum overvoltages and overcurrents obtained from the detailed and the equivalent models are 1.6% and 1.3% respectively.

The developed equivalent model drastically reduces the computational burden and hence the computation time required to conduct EMT-type studies. For instance, the time required to conduct a 6-second real-time simulation run with a $5 \mu s$ time-step, using the detailed model is approximately 5 hours and 8 minutes on a quad cores Intel 3.07 GHz i7 machine with 6 GB of memory. On the other hand the proposed equivalent only requires approximately 110 seconds to solve the same case study and with the same simulation time-step, i.e., the equivalent model reduces the computation time by a factor of 218 as compared to the detailed model.

Figures 3.36 and 3.37 compare the PCC voltage of phase c, Case I, obtained from the detailed and the equivalent models when the WPP equivalent model only consists of (i) the FDNE model, Figure 3.36, and (ii) the DLFE model, Figure 3.37. Figures 3.36 and 3.37 demonstrate that neither the FDNE model nor the DLFE model individually can accurately represent the WPP for EMT type studies. In Figure 3.36 the equivalent model is represented by the DLFE which represents only the low frequency dynamics of the WPP active components. This representation misses the high frequency response resulted from the exchange of energy between the inductances and capacitances of the WPP passive network, due to system transients. Comparing Figures 3.19, 3.36, and 3.37 clearly demonstrates that the FDNE model and the DLFE model jointly can provide an accurate model of the WPP. This justifies the need for a wide-band equivalent model of WPP for EMT studies.
3.12 Conclusions

This chapter developed and validated a reduced-order, dynamic-equivalent model of Type-4 based WPPs, for the analysis of EMTs external to the WPP, within a frequency
range of 0-50 kHz. The proposed equivalent model captures (i) the frequency response of the WPP passive components, and (ii) the dynamics of the WPP active components. The accuracy and computational efficiency of the proposed equivalent model have been validated through multiple case studies that compare the simulation results of the equivalent model and those of the detailed model of a modified version of the Lake Erie WPP in the PSCAD/EMTDC. The case studies covered different types of transients due to faults at different locations with respect to the WPP terminal. The study results concluded that:

- The developed equivalent model simulation results and the corresponding detailed model results closely agree and confirm accuracy of the proposed equivalent model.

- Compared to the detailed model, the equivalent model adopts a simpler structure and does not explicitly model the VSCs.

- The developed equivalent model is computationally efficient. Compared to the detailed model, the equivalent model reduces the computational time for the test system by factor of about 218.

- The developed equivalent model is a scalable model, i.e., its per unit signals can be scaled to the base values of the WPP of interest. In other words, the size and number of WTGs units within the WPP do not affect the structure of the equivalent.

- The developed equivalent model is a wide band model that represents the WPP response in a frequency range of about 0-50 kHz. This frequency range is determined based on the phenomenon of interest. The equivalent model can be adapted to a new frequency range based on modification to the FDNE.
Chapter 4

Dynamic Low-Frequency Equivalent Model of Type-3 WPP

4.1 Introduction

This chapter presents the development and validation of the dynamic low-frequency equivalent (DLFE) model of WPPs with doubly-fed asynchronous generator (DFAG) WTG units known as Type-3 units. The DLFE of Type-3 WPP represents the aggregated dynamic model of the DFAG-WTGs, their local controls, and the WPP supervisory control and it includes (i) the equivalent model of the wind turbines, (ii) the equivalent model of the Type-3 generation units and their converters local controls, and (iii) the WPP supervisory control. The above mentioned DLFE is integrated with the equivalent model of the WPP collector network model to form a wide-band equivalent model of Type-3 WPP. The Type-3 WPP equivalent model reproduces the dynamic behavior of the WPP in response to an electromagnetic transient in the host power system.

The structure of this chapter is as follows: section 4.2 is a brief overview of the DFAG unit, its advantages, and the motivation behind developing the equivalent model of this chapter. Section 4.3 states the equivalent model assumptions. Section 4.4 presents the structure of the DLFE. The modules of the DLFE, i.e., the equivalent model of the wind turbines, the WPP supervisory control, and the equivalent model of the generators with their converters are presented in Sections 4.5, 4.6, and 4.7 respectively. Section 4.8 integrates the DLFE with the WPP collector network equivalent model. The accuracy of the developed model is demonstrated through several case studies, using the PSCAD/EMTDC in sections 4.9 and 4.10. Discussion of the study results and the con-
conclusions of this chapter are in Sections 4.11 and 4.12 respectively. The detailed model of Type-3 WPP, including the local and central controls, which is used to guide the development and validation of the equivalent model is presented in Appendix D.

4.2 Background

The DFAG-based WTG is widely used in existing WPPs [46] where each DFAG unit is connected to the collector network directly through its stator while its rotor is interfaced to the network through a back-to-back converter system, Figure 4.1. The back-to-back converter allows the independent control of the active power delivery and the reactive power exchange with the grid. Typically the RSC controls the stator power flow through a smaller percentage of power injected into the rotor circuit; therefore, the back-to-back converter is typically rated to 30-40% of the machine rated power [47]. The reduced size of the converter translates to a reduced cost of both the converter and its filter. In addition, it results in a reduced converter losses, compared to the full rated converters, and potentially higher efficiency [32], [48].

With the wide use and increased capacity of the Type-3 WPP, it is vital to develop an appropriate model to analyze its response to different transients in the power system. For EMTs studies, the full order models that include differential equations of the whole WPP are used to simulate the WPP in time-domain simulation programs which in turn use a small integration time-step to solve the model equations. The small integration time-step along with the significant number of differential equations corresponding to the complex configuration of the DFAG and the typical large number of units within the WPP result in a significant computational burden and therefore prolonged simulation time. The computationally efficient equivalent model developed in this chapter overcomes the aforementioned limitations. The developed equivalent model is simple yet accurate in modeling the response of the active components of Type-3 WPPs to EMTs, external to the WPP in the power system, within the frequency range of 0 up to 20 Hz.

There are various control schemes for a DFAG-based WTG in a WPP [49]. In order to develop the equivalent model of this thesis, the DFAG detailed model of Appendix D is considered. In this detailed model, the local control of the RSC controls the generator torque and the stator reactive power flow while the local control of the GSC controls the DC-link voltage and the reactive current at the machine terminal. The local controls are decoupled current controllers with inner $dq$ current control loops. This detailed model
is also used as a benchmark system to validate the accuracy of the developed equivalent model. Multiple control strategies and hardware apparatus have been introduced in the literature to enable the DFAG-based WPPs to satisfy the fault-ride-through requirements [46],[50]–[53]. Each of these techniques has its own merits and limitations; however, many of them fail to achieve their objective during transients which impose severe voltage dips [52]. In this thesis, a dynamic voltage restorer (DVR) [51],[52] at the unit terminal is assumed to assist in boosting the unit terminal voltage during transients and thus enable the DFAG unit and the WPP to provide ride-through capability subsequent to a fault, Figure D.2, Section D.3.

![Figure 4.1: Schematic Diagram of the Doubly-Fed Asynchronous Generator (DFAG) Unit](image)

### 4.3 Equivalent Model Assumptions

The equivalent model of Type-3 based WPP is developed based on the following assumptions:

- The proposed equivalent model represents the collective terminal behavior of the WPP and not the individual behavior of each WTG unit.
- The disturbance is considered to take place in the power system external to the WPP.
- The WTG units within the WPP are considered to be of the same type (Type-3 in this chapter) and their local controls adopt the same control objectives.
The dynamics of the pitch control is not represented in this equivalent model since the time constant of the pitch control and the mechanical inertia are assumed to be very large relative to the time frame of the EMTs of interest.

4.4 Structure of the Dynamic Low-Frequency Equivalent Model of the Type-3 WPP

The DLFE model of the Type-3 based WPP, Figure 4.2, represents the dynamics of the aggregated WTG units and the natural modes of controls, typically, in a frequency range of 0 up to 20 Hz. Based on the DFAG structure and its components, described in Appendix D, the DLFE of Figure 4.2 is proposed. The DLFE, Figure 4.2, constitutes a complete equivalent of the DFAG-based WPP low-frequency dynamics.

The measurement block represents the function of the measuring devices of the WPP. It acquires instantaneous three-phase PCC voltage and the WPP net current (at the HV-side of WPP substation transformer) and generates the required signals for control and PLL blocks. The PLL provides synchronization to the positive-sequence PCC voltages. The wind turbines equivalent block represents the dynamics of the aggregated wind turbines. It determines the WPP equivalent mechanical power that corresponds to the wind speed, taking into consideration the wind turbine characteristics. This block also includes an equivalent drive-train model that computes the equivalent angular frequency $\omega_{req}$, Figure 4.2. The supervisory control block represents the conceptual functions of the WPP supervisory control which includes the control of active and reactive power components injected by the WPP into the system [31], [37], [39]. This block determines the $d$- and $q$-current references corresponding to the WPP $P$ and $Q$ reference values. The FRT control function is also represented in this block. The FRT control provides the reference currents to enable the WPP fault ride-through subsequent to transients [4],[38]. The generators and converters equivalent block represents the dynamics of the aggregated machines, converters, and their local controllers. This block injects currents into the system at the PCC, in response to the current references from the supervisory control.

The following sections elaborate on the details of each block. The PLL block in Figure 4.2 is identical to the PLL described in Section 3.5 and not discussed in this chapter.
4.5 Equivalent Model of Wind Turbines

This model is an equivalent of the WPP wind turbines mechanical rotating systems. This model provides transformation of the wind energy into mechanical power and the aggregated dynamic behavior of the drive-trains. This equivalent model is composed of two main parts, Figure 4.3:

(i) The aerodynamic-equivalent model that determines the mechanical power harnessed from the wind based on the wind speed and the power coefficient \( C_p \).

(ii) The drive-train model that determines the equivalent generator and turbine angular speeds \( \omega_{req} \) and \( \omega_{teq} \) respectively.

It is to be noted that the parameters of the \( C_p \) equation, (4.3) and (4.5), required by the aerodynamic model are not necessarily available from the turbine manufacturer; therefore, to set a systematic method to obtain those parameters, an optimization algorithm is introduced to estimate the parameters, using either field measurements or simulation of the turbine detailed model, Figure 4.3. The next three subsections elaborate on the components of the wind turbines equivalent model.
4.5.1 Aerodynamic Equivalent Model

This equivalent model computes the mechanical power $P_{\text{mech}}$ extracted from the wind energy as a function of the wind speed and the turbine power coefficient $C_p$. Equation (4.1), [54],[55], calculates $P_{\text{mech}}$ of one WTG unit which then has to be scaled to all the units within the WPP.

$$P_{\text{mech}} = \frac{1}{2} \rho A v_{\text{wind}}^3 C_p(\lambda, \beta) / S_{\text{WTG}},$$  

where $\rho$, $A$, $v_{\text{wind}}$, $\lambda$, $\beta$ and $S_{\text{WTG}}$ are the air density in kg/m$^3$, the area of the rotor blades in m$^2$, the wind speed in m/s, the blade tip speed ratio, the blade pitch angle, and the base power of one WTG respectively; the output $P_{\text{mech}}$ is in per unit. $\lambda$ is the ratio between the speed at the blade tip and the wind speed.

$$\lambda = \frac{v_{\text{tip}}}{v_{\text{wind}}} = \left(\frac{\omega_{\text{req}}}{G}\right) \frac{r}{v_{\text{wind}}},$$  

where $r$ is the blade radius and $G$ is the gearbox ratio. The turbine power coefficient $C_p(\lambda, \beta)$ is usually represented by a set of curves; each curve relates $C_p$ and $\lambda$ for a certain pitch angle $\beta$. Typically these curves are mathematically represented by [55],[56]:

$$C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda^i} - c_3 \beta - c_4 \beta^2 - c_5 \right) \exp \left( \frac{-c_7}{\lambda^i} \right),$$  

Figure 4.3: Wind Turbine Equivalent Model
\[ \lambda_i = \left[ \frac{1}{\left( \frac{1}{\lambda + c_8 \beta} \right)} - \left( \frac{c_9}{\beta^3 + 1} \right) \right]^{-1}, \]  

(4.4)

where constants \( c_1 \) to \( c_9 \) are determined such that the resulting equation/curves represent the performance of the actual turbine [54], [56], [57]. The optimization algorithm, described in subsection 4.5.2 is used to determine these constants based on the simulation results or field measurements.

Typically, all units within the WPP are of the same size and type; therefore, the per unit mechanical power calculated from (4.1), based on the WTG unit MVA, represents also the total power of the WPP when multiplied by the WPP base MVA. If the units within the WPP are of different sizes or have different turbine characteristics, units can be grouped into groups of identical units. For each group, the total mechanical power is calculated as described and then the WPP total power is the summation of the groups mechanical powers. If the units experience different wind speeds with small deviations, then

\[ \nu_{eq} = \frac{1}{n} \sum_{i=1}^{n} \nu_i, \]  

(4.5)

where \( \nu_{eq} \) is the WPP equivalent wind speed, \( n \) is the number of WTG units, and \( \nu_i \) is the wind speed at unit \( i \). If wind units are exposed to noticeably different wind speeds, then the WPP equivalent speed is calculated using the WPP power curve [13] as follows.

(i) For each unit, based on its wind speed, the WTG output power \( P_i \) is obtained using the WTG power curve, Figure 4.4, and the total WPP output power is the summation of power components of all units \( P_{WPP} = \sum_{i=1}^{n} P_i \).

(ii) An equivalent WPP power curve is obtained by summing the individual WTG units power curves. This is done by summing the powers of the individual WTG units for each incoming wind speed.

(iii) From the curve of (ii), the WPP equivalent wind speed, corresponding to the WPP power of (i) is obtained.
4.5.2 Parameter Estimation of Wind Turbine Equivalent Model

If the wind turbine manufacturers data is not available, an optimization algorithm is used to identify the parameters for the wind turbine model. This is based on results from simulation of detailed model or field measurements.

The constants $c_1$ to $c_9$ of (4.3) need to be determined to minimize deviation between $P_{\text{mech}}$ of the equivalent model (4.1), calculated with the optimized constants, and that of the original WTG unit ($P_{\text{m,org}}$). This requires measurements results or detailed simulation results of $P_{\text{m,org}}$, $v_{\text{wind}}$, $\beta$, and $\omega_r$. Based on this data and a least square minimization process, an optimization with the objective function

$$F = \frac{\|P_{\text{mech}} - P_{\text{m,org}}\|}{\|P_{\text{m,org}}\|},$$

(4.6)

is constructed. The MATLAB optimization toolbox is used for minimizing (4.6) [58].

4.5.3 Drive-Train Mechanical Model

The wind turbine drive-train is modeled as a set of two lumped rigid masses that are connected to each other through the corresponding shafts [17],[59]. This thesis adopts the widely accepted approach of representing the wind turbine drive-train with two masses [60]–[63]. One mass represents the turbine inertia and the other mass represents the generator inertia, (4.7), Figure 4.5, and represented by
where 

\[
\begin{align*}
\frac{d\theta_t}{dt} &= \omega_t, \\
\frac{d\theta_r}{dt} &= \omega_r,
\end{align*}
\]

and \( T_m \) and \( T_e \) are the mechanical and electrical torques respectively. \( H, D, \) and \( K \) are the inertia constant, damping coefficient, and stiffness coefficient respectively. \( \theta \) is the angular position. The subscripts \( t \) and \( g \) refer to the turbine and generator respectively. Figure 4.6 illustrates the block diagram of the the drive-train of Figure 4.5. The inputs to the model are the equivalent mechanical and electrical power components from the aerodynamic model and the WPP supervisory control respectively. The outputs of the model are the turbine and generator equivalent angular frequencies, Figure 4.6. It is to be noted that this model represents the low-frequency dynamics of aggregated WTG units drive-trains in a frequency range up to 3 Hz [37].

The model of (4.7) can be further simplified to a single-mass model in which the inertia constant is the sum of those of the generator and turbine \((H_t + H_g)\) and the damping coefficient represents the net damping of the drive-train. \([8],[37],[64],[65],\),

\[
2(H_t + H_g) \frac{d\omega}{dt} = T_m - T_e - D\omega.
\]

\[\text{(4.9)}\]

### 4.6 WPP Supervisory Control

The performance of the DFAG units is dictated by a hierarchical structure of central and local controls, Appendix D.
The supervisory control module is the part of the WPP DLFE equivalent model, Figure 4.2, that represents the operation of the WPP central control. It includes (i) P control (ii) Q control (iii) fault-ride through (FRT) control and (iv) current limits calculations. The collective operation of these parts reflects the performance of the WPP supervisory control and the outer control level of the WTG units controls before, during, and after the grid transients. The functions of this equivalent module include:

- Generation of the dq-current references to satisfy the grid requirements corresponding to P and Q and/or to satisfy certain control objectives, e.g., PCC voltage control, taking into consideration feedback signals from the PCC.

- Representing the active and reactive power generation availability of WTG units, taking into consideration the available wind and the units generation limits.

- Enabling the FRT control based on the grid requirements.

- Enabling the limits that should be imposed on the WTG units reference currents/power based on the operation requirements.

The above functions are implemented through the control structure of Figure 4.7. The P control block, Figure 4.7, can be switched between two modes:
Figure 4.7: Block Diagram of the Supervisory Control Module
1. **Maximum Power Tracking Mode:** The maximum power that can be extracted from the wind is calculated from 
\[ P_{\text{ref}} = K_{\text{opt}} \omega^3_{\text{req}} \] 
more details regarding this expression is in Appendix D. This power set point is limited to the rated power of the WPP to avoid over loading.

2. **Operator Requirement Mode:** The active power set point \( P_{\text{ref}} \) is received from the operator. \( P_{\text{ref}} \) is limited to the power value at point 1, Figure 4.7, to guarantee that the control set point does not exceed either the WPP rating or the power available from the wind.

The ramp rate applied on \( P \) set point, Figure 4.7, serves to limit the power rate of increase during the post-fault recovery; this limit can be set to a very large value if there is no requirement for it in the design of the actual WPP.

The \( Q \) control, Figure 4.7, is a coordinated \( Q/V \) controller that determines the reactive current command \( I_{Q_{\text{ref}}} \) to satisfy the requirements of both \( Q_{\text{ref}} \) and voltage control at the PCC. \( Q_{\text{ref}} \) is determined based on the PCC voltage control, power factor control, or PCC reactive power control as explained in chapter 3.

During transients, e.g., faults, that are accompanied with voltage fluctuations at the PCC, the FRT should retain the WPP in service and enable ride through the fault [4], [38]. Based on the voltage at the WPP terminals, the FRT control determines the value of the supplied \( I_{Q_{\text{ref}}} \) during the ride-through process [42]. It also coordinates the increase in reactive current/reactive power injected by the WPP with a decrease in real current/power injection through the less than unity \( P_{\text{multiplier}} \), Figure 4.7, to avoid overload conditions.

The limits applied on \( Q_{\text{ref}} \) represent the WTG limits with respect to the reactive power generation/absorption. The limits on \( I_{P_{\text{ref}}} \) and \( I_{Q_{\text{ref}}} \) are applied such that their net effect does not exceed the total current limit of the aggregated WTG units. The priority of generation may be given to the active or the reactive current based on the steady state/transient operation. The detail of the current limits block is similar to that of section 3.6.3. The outputs of the supervisory control module are: (i) the dq-current references to the module of the generators and converters equivalent model, and (ii) the electrical power \( P_e \), Figure 4.7, to the wind turbines equivalent module.
4.7 Equivalent Model of the Generators Electrical Side and Converters

This section presents the dynamic equivalent model of the DFAG units, their converters, and local controls. This equivalent model represents the response of the WTG units to commands from the WPP supervisory control, Figure 4.2. The equivalent model of one WTG unit is developed in per unit on the unit base values. By scaling the base values, the equivalent model is used to approximate the response of all units within the WPP. The equivalent model is deduced based on the detailed model of the DFAG unit, (D.1)-(D.4), Appendix D as follows

By substituting $i_s$ in (D.4) from (D.3)

$$\vec{\psi}_r = \frac{L_m}{L_s} \vec{\psi}_s + \left( L_r - \frac{L_m^2}{L_s} \right) \vec{i}_r. \quad (4.10)$$

Defining $\sigma = 1 - \left( \frac{L_m^2}{L_s L_r} \right)$, $\sigma_s = \frac{L_s}{L_m} - 1$, and $\sigma_r = \frac{L_r}{L_m} - 1$, (4.10) becomes,

$$\vec{\psi}_r = \left( \frac{1}{1 + \sigma_s} \right) \vec{\psi}_s + \sigma \left( 1 + \sigma_r \right) L_m \vec{i}_r. \quad (4.11)$$

By differentiating (4.11) and substituting for $\frac{d\vec{\psi}_r}{dt}$ from (D.2),

$$\sigma (1 + \sigma_r) L_m \frac{d\vec{i}_r}{dt} = \vec{V}_r - R_r \vec{i}_r - j \Delta \omega \vec{\psi}_r. \quad (4.12)$$

Note that the stator flux derivative is neglected, i.e., $\frac{d\vec{\psi}_s}{dt} = 0$ [31], [43], [49], [66]. This assumption is valid because of the adopted approach of installing a voltage controller in series with the WTG unit that limits the stator voltage variations.

Substituting $\vec{\psi}_r$ from (4.11) in (4.12) and dividing the equation by $R_r$

$$\sigma \tau_r \frac{d\vec{i}_r}{dt} = \frac{\vec{V}_r}{R_r} - \vec{i}_r - j \Delta \omega \left( \frac{\vec{\psi}_s}{(1 + \sigma_s) R_r + \sigma \tau_r \vec{i}_r} \right), \quad (4.13)$$

where $\tau_r = \frac{(1 + \sigma_r) L_m}{R_r}$.

Re-arranging (4.13) results in (4.14), and represented by the block diagram of Figure 4.8.

$$\sigma \tau_r \frac{d\vec{i}_r}{dt} + \vec{i}_r = \frac{\vec{V}_r}{R_r} - j \frac{(1 - \sigma) \tau_r}{L_m} \Delta \omega \vec{\psi}_s - j \Delta \omega \sigma \tau_r \vec{i}_r. \quad (4.14)$$
The inputs to the block diagram of Figure 4.8 are the rotor voltages $\vec{V}_r$ and the outputs are the rotor currents. $\vec{V}_r$ is controlled by the RSC control as described in Section D.1.

Based on Figure D.3, the RSC inner control can be represented as shown in Figure 4.9. Figure 4.9 and Figure 4.8 conclude the DFAG model depicted in Figure 4.10. To further simplify the model and present it in a form that relates the inputs and outputs of the WTG unit, independent of the internal parameters, the following can be considered [31]:

\[
\vec{V}_r \quad \frac{1}{R_r} \quad \Sigma \quad \frac{1}{1 + \sigma_r S} \quad j \Delta \omega \sigma_r \quad \vec{i}_r
\]

\[
(1-\sigma)_{qr} \Delta \omega \frac{V_s}{L_m \omega_s}
\]

\[
\vec{i}_{ref} \quad \Sigma \quad PI \quad \Sigma \quad R_r \quad \vec{V}_r
\]

\[
j \sigma_r \Delta \omega \vec{i}_r + \frac{(1-\sigma)_{qr} \Delta \omega V_s}{L_m \omega_s}
\]

\[
\vec{i}_{ref} \quad \Sigma \quad PI \quad \Sigma \quad R_r \quad \vec{V}_r \quad \frac{1}{1 + \sigma_r S} \quad j \Delta \omega \sigma_r \quad \vec{i}_r
\]

\[
j \sigma_r \Delta \omega \vec{i}_r + \frac{(1-\sigma)_{qr} \Delta \omega V_s}{L_m \omega_s}
\]
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Figure 4.11: Equivalent Model of the Generator and Converter

- The feedback and the cross coupling terms in the machine model, Figure 4.10, are canceled out by a similar terms in the RSC control model. This is analogous to that of the Type-4 GSC as explained in Chapter 3.

- The magnetizing current is assumed to be negligible; thus, the per unitized rotor currents are replaced with the per unitized stator currents.

Considering the above simplifications, the resultant machine and converter equivalent model is composed of one \( PI \) controller and one first order function as depicted in Figure 4.11. This model can be used to represent the entire WTG; however, in this case, the parameters of the equivalent model are no longer directly related to the WTG parameters. These parameters can be directly obtained from an optimization process that minimizes the error between the responses of the equivalent model and a detailed DFAG model [67].

4.8 Wide-Band Equivalent Model of Type-3 WPP

The proposed reduced-order dynamic-equivalent model of Type-3 WPP is based on the FDNE and the DLFE as described in Chapters 2 and the previous sections of this chapter respectively. These two parts are represented by two circuit blocks that are in parallel with respect to the PCC, Figure 4.12. The FDNE is implemented in the PSCAD/EMTDC, based on the companion circuit approach [25], [26] where the trapezoidal integration method is utilized to convert the rational function, obtained from the vector fitting, to a resistive network in conjunction with a set of history current sources as explained in Chapter 2. The DLFE model is represented in the PSCAD/EMTDC based on the transfer function method and is interfaced to the electrical network through a three-phase controlled current source, Figure 4.2.
4.9 Test System

The system of Figure 4.13 is used to validate the accuracy of the proposed WPP equivalent model in representing the dynamic response of Type-3 based WPPs. The WPP (left side of the PCC) is composed of (i) one 13.8/115-kV transformer, (ii) a 13.8-kV collector system, (iii) 2.3-kV DFAG WTG units and their local controllers that are connected to the collector system through voltage controllers (DVRs) and 2.3/13.8-kV wye-grounded/delta transformers, and (iv) the WPP supervisory control. The WPP includes eight Type-3 units and power rating of each unit is 1.7 MW. The collector system, connecting the WTGs, includes two main branches and eight sub-branches. Appendix E provides the transmission lines and WTG unit parameters [43],[68]. The test system of Chapter 3 with 17 WTG units could not be used in this validation because of the prohibitive computational requirements to simulate the detailed model of 17 DFAG-based WTGs.

Each WTG unit of Figure 4.13 is composed of a turbine and a DFAG unit equipped with AC/DC/AC voltage sourced-converter. The AC-side terminal of each grid-side converter is connected to a three-phase $RL$ filter and a three-phase 0.6/2.3-kV wye/delta transformer. Each converter is equipped with a $dq$-current controller that regulate its $i_p$ and $i_q$ current injection. The WPP supervisory control provides reference values for each WTG unit to meet the grid power requirements and FRT requirements during transients. The design of the supervisory and local controls and the control objectives are similar to what has been described in Appendix D of the DFAG detailed modeling. The adopted FRT characteristics are described in [4],[42].

The power system external to the WPP is composed of two parallel 115-kV overhead lines that connect the WPP to the grid which is represented by a three-phase source
behind a three-phase impedance, Figure 4.13.

The procedures to verify the accuracy of the proposed equivalent model are similar to what introduced in Chapter 3, Section 3.9. It is adapted to this test system as follows:

A. The system of Figure 4.13 is modeled in detail in the PSCAD/EMTDC platform based on the DFAG detailed model of Appendix D. This include the detailed representation of:

(a) The WPP supervisory control which determine the dq-current references for each WTG such that the collective operation of all WTGs satisfies the generation objectives.

(b) Eight WTG units, Figure 4.13. Each unit is represented by a turbine model, DFAG unit detailed model with RSC and GSC connected back-to-back. Each converter is represented by a three-phase two-level converter and constructed with six IGBT valves. Each converter operates based on a 2340-Hz SPWM. The local controllers of RSC and GSC are based on a decoupled d- and q-current approach that utilizes PI controllers to enable each WTG output current to track the references provided by the WPP supervisory control as explained in Appendix D. The WTG units operate in the maximum power tracking mode. With wind speed of 12 \text{ m/s}, the WPP generates a total power of 12.08
(c) The WPP collector network which consists of 3-km sections. Each section is represented by a π-equivalent.

(d) The WPP interface transformer is represented as a three-phase transformer, including the magnetization branch.

(e) The overhead lines in the AC power system are represented by π-equivalent models.

B. The detailed model of part A above is used to develop the FDNE model of the WPP as discussed in Chapter 2. The admittance frequency response is generated for the frequency range of 0-50 kHz with 5000 logarithmically-distributed frequency points, then fitted to a 12th-order rational function given by the expression (2.2), using the vector fitting technique, Chapter 2.

C. The DLFE model of the WPP is developed as described in sections 4.4, 4.5, 4.6, and 4.7.

D. Based on the models of parts B and C, the overall equivalent model of the WPP is constructed and implemented in the PSCAD/EMTDC.

4.10 Case Studies

A set of case studies, similar to the ones performed in Chapter 3, are performed on the system of Figure 4.13 to demonstrate the performance and verify the accuracy of the WPP equivalent model when line T2 is subjected to different faults and switching events. For each fault study, the power system (right-side of the PCC of Figure 4.13) is modeled in the PSCAD/EMTDC environment and the WPP (left-side of the PCC of Figure 4.13) is represented once by its detailed model (Section 4.9-A), and once by its equivalent model (Section 4.9-D) and the corresponding study results are identified by the “Detailed Model” and the “Equivalent Model”, respectively. Each reported case study is simulated for up to 5-second of real-time to allow the supervisory control, units control, and the system reach a steady state condition before imposing a fault on line T2.
4.10.1 Case I

The system is subjected to a 150-ms temporary L-L-L-G fault, 15-km from the PCC on line T2 at $t = 3.8s$. Prior to the fault, the system is under steady-state conditions and the WPP delivers 12.08-MW to the system at PCC. Figures 4.14-4.16 show the system response to the fault based on the detailed model and the equivalent model of the WPP.

Figure 4.14 shows the instantaneous PCC voltages prior, during, and immediately after the fault and illustrates close agreement between the results of the equivalent model and the detailed model. Figure 4.15 shows the injected currents by the WPP into the system (at the WPP transformer HV-side) during and after the fault clearance and also indicates close agreement between the results of the two models. Figure 4.16 shows real and reactive power and current components and the PCC rms voltage. Figure 4.16 also illustrates the PCC voltage FRT characteristic [4]. Figure 4.16 indicates that during the fault, the WPP remains in service even when the PCC voltage, Figure 4.16(e), drops to 35% of its nominal value. Figures 4.16(c) and 4.16(d) show the WPP output reactive current increases to 1.0 p.u. while the active current drops to zero when the voltage drop.

4.10.2 Case II

The system of Figure 4.13 is subjected to a 150-ms temporary L-G fault at $t = 3.8s$ at the same location where the L-L-L-G fault of Case I was imposed. The prefault steady-state conditions are the same as those of Case I. Figure 4.17-4.19 show the PCC voltages, the WPP output currents, and the real and reactive power and current components respectively. Figure 4.17-4.19 demonstrate close agreement between the results of the detailed and the equivalent models under unbalanced conditions.
Figure 4.14: PCC Voltages of the Detailed and the Equivalent Models - Case I
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Figure 4.15: PCC Output Currents of the Detailed and the Equivalent Models - Case I.
(a) Phase a (b) Phase b (c) Phase c
Figure 4.16: WPP Outputs (a) Active Power (b) Reactive Power (c) Active Current (d) Reactive Current (e) PCC Voltage of the Detailed and the Equivalent Models - Case I.
Figure 4.17: PCC Voltages of the Detailed and the Equivalent Models - Case II
(a) Phase a (b) Phase b (c) Phase c

Figure 4.18: PCC Output Currents of the Detailed and the Equivalent Models - Case II.
Figure 4.19: WPP Outputs (a) Active Power (b) Reactive Power (c) Active Current (d) Reactive Current (e) PCC Voltage of the Detailed and the Equivalent Models - Case II.
4.10.3 Case III

This case is conducted to investigate the accuracy of the developed equivalent model as the location of the fault on line T2 changes along the line. The scenario of Case I is introduced in this case with the fault location at the PCC. This scenario represents the worst fault scenario and the extreme case in evaluating the accuracy of the equivalent model since the fault is applied at the interface point between the WPP (external zone) and the grid system (study zone). Figures 4.20 to 4.22 show and compare the time-domain simulation results of both the detailed model and the corresponding results obtained from the developed equivalent model. The close agreement between the results of the two models verifies the accuracy of the developed equivalent model.

4.10.4 Case IV

The system of Figure 4.13 is subjected to the L-L-L-G fault of Case I at t=3.8s. The fault is cleared after 5 cycles by circuit breakers CB1 and CB2. After another 15 cycles CB1 and CB2 automatically reclose and since the fault is cleared, the reclosure is successful. Figures 4.23 and 4.24 illustrate close agreement between the corresponding results of the two models.

4.10.5 Case V

The system of Figure 4.13 is subjected to the L-L-L-G fault of Case I at t=3.8s. The fault is cleared after 5 cycles by circuit breakers CB1 and CB2. After another 15 cycles CB1 and CB2 automatically reclose and since the fault is permanent, the reclosure is unsuccessful and subjects the system to another L-L-L-G fault. The second fault is cleared by CB1 and CB2 which permanently remain open after the second fault clearing. Figure 4.25 shows transients of the PCC voltages corresponding to the fault and its subsequent switching events. Figures 4.25- 4.26 also illustrate close agreement between the corresponding results of the two models.
Figure 4.20: PCC Voltages of the Detailed and the Equivalent Models - Case III
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III. (a) Phase a (b) Phase b (c) Phase c

Figure 4.21: PCC Output Currents of the Detailed and the Equivalent Models - Case III. (a) Phase a (b) Phase b (c) Phase c
Figure 4.22: WPP Outputs (a) Active Power (b) Reactive Power (c) Active Current (d) Reactive Current (e) PCC Voltage of the Detailed and the Equivalent Models - Case III.
Figure 4.23: PCC Voltages of the Detailed and the Equivalent Models - Case IV
Figure 4.24: PCC Output Currents of the Detailed and the Equivalent Models - Case IV. (a) Phase a (b) Phase b (c) Phase c
Figure 4.25: PCC Voltages of the Detailed and the Equivalent Models - Case V
Figure 4.26: PCC Output Currents of the Detailed and the Equivalent Models - Case V.
(a) Phase a (b) Phase b (c) Phase c
4.10.6 Case VI

In order to test the accuracy of the equivalent model for more complex transients, this case combines multiple transients, unbalanced fault, and unbalanced fault clearance. The transient scenario is similar to Case IV, but with single line to ground fault. The circuit breaker reaction to clear the fault is through only one pole operation. Thus, the unbalanced fault transient will be followed by an unbalanced circuit breaker operation at which only one phase of the transmission line is disconnected to clear the fault; then, this phase will be successfully reconnected after 15 cycles.

The time-domain simulation results of both the detailed system and the corresponding results obtained from the developed equivalent are shown in Figures 4.27 and 4.28. The close agreement between the results of the two models verifies the accuracy of the developed equivalent model.

4.10.7 Case VII

This case is similar to Case VI, but with double line to ground fault and in consequence double pole circuit breaker operation. The time-domain simulation results of both the detailed system and the corresponding results obtained from the developed equivalent are shown in Figures 4.29 and 4.30. The close agreement between the results of the two models verifies the accuracy of the developed equivalent model.

4.11 Discussions

The close agreement between the time-domain simulation results obtained from the detailed and the equivalent models of the WPP, Figures 4.14-4.30, verifies the accuracy of the proposed equivalent model for EMT-type studies external to the WPP. Case studies of Section 4.10 are conducted to investigate the accuracy of the developed equivalent model as the type of the fault and the location of the fault on line T2 change. Even in the worst fault scenario when the fault is imposed at the PCC, the results obtained from the detailed model and the equivalent model show close agreement verifies the accuracy of the equivalent model. In addition, the errors between the maximum overvoltages and overcurrents obtained from the detailed and the equivalent models are 1.42% and 1.3% respectively. Figures 4.15, 4.21, 4.24, and 4.26 show the WPP output current measured at the high voltage side of the WPP substation transformer. The aforementioned Fig-
Figure 4.27: PCC Voltages of the Detailed and the Equivalent Models - Case VI
Figure 4.28: PCC Output Currents of the Detailed and the Equivalent Models - Case VI. (a) Phase a (b) Phase b (c) Phase c

atures are for case studies that include three phase-to-ground faults; such fault is cleared one phase at a time at the zero crossing of the fault current at each phase. Therefore, when the fault at the first phase is cleared while the currents in the other two phases did not reach their zero crossing, an unbalance takes place and a zero sequence current
Figure 4.29: PCC Voltages of the Detailed and the Equivalent Models - Case VII
contribution from the system side appears with a high value. This explains the spikes that appear in the transient currents at the clearance of the three phase-to-ground faults.

The proposed equivalent model significantly reduces the computational time and resources and hence enables comprehensive time-domain simulation studies of the system transients, e.g., statistical EMT-type studies to identify and evaluate worst case fault scenarios, e.g., fault instant on the voltage waveform. The time required to conduct a 5-second real-time simulation run, with a 5 µs time-step, using the detailed system model, corresponding to case I, requires approximately 31 hours and 34 minutes using a quad-
core Intel 3.07 GHz i7 computer with 6 GB of memory. The proposed equivalent model reduces the computational time for the same case study (and with the same simulation time-step) to about 45.12 seconds, i.e., a reduction in computation time by a factor of 2480.

It has to be noted that the equivalent model can be tuned based on field measurements, if available. However, those measurements are not necessarily available especially at the design stage prior to the actual installation of the WPP; therefore, detailed models supplied by the vendors are typically used to accurately represent the WPP for system impact studies as well as in developing the WPP equivalent model.

4.12 Conclusions

This chapter introduced, developed, evaluated, and verified an equivalent model that represent the Type-3-based WPP for the analysis of EMTs external to the WPP within the desired frequency bandwidth, e.g., 0 to 50 kHz. The numerical accuracy and computational efficiency of the proposed equivalent model were verified by comparing time-domain simulation test case results when a wind power plant is represented once by its detailed model and once by the proposed equivalent model. The test cases cover different types of faults at different locations outside the WPP. The studies show that the proposed method can reduce computational time and resources by a factor of 2480 and for example enables statistical studies that require a large number of simulation runs.
Chapter 5

Real-Time Simulation and HIL Evaluation of Equivalent Models

5.1 Introduction

A real-time simulator (RTS) plays a vital role in the verification of the control/protection platform functions/performances as they enable the testing of the physical controller in a hardware-in-the-loop (HIL) configuration. In the HIL arrangement, a RTS, simulates the power system under consideration in real-time and the physical controller is interfaced to the RTS in a closed-loop fashion, Figure 5.1. In this arrangement, the device under test is interfaced to the simulator in the same manner as it is integrated in the actual power system [69]. The HIL testing has the following advantages:

- The physical control/protection is tested instead of its off-line simulated model which may neither reflect all the functions nor preserve its fidelity.

- The control platform can be tested even before its installation and commissioning which allows for modifications and improvements in the design.

- The control/protection can be tested under extreme scenarios that are not allowed in a real system.

For a credible HIL testing results, the power system has to be accurately modeled on the RTS. Due to the high penetration and the increased capacity of WPPs integrated with the power system, it has become inevitable to include the WPPs model in the simulated power system in the real-time simulator to study their effect on the overall performance.
Chapter 5. RTS and HIL Evaluation of Equivalent Models

of the power system. The detailed modeling of WPPs in the RTS is neither practical nor possible due to its drastic computational burden. Therefore, in order to practically use the RTS to simulate the power system including the WPPs, it is required to represent the WPP with an equivalent model that accurately captures the electromagnetic transients behavior.

The accuracy and computational efficiency of the WPP equivalent model developed in this thesis make it a prime choice for real-time simulation. This chapter presents the real-time simulation of the developed Type-3 WPP and Type-4 WPP equivalent models. Case studies are carried out to evaluate the performances of the developed models in the RTDS® and to compare the hardware resources required for simulating both the detailed and the equivalent WPP models. This chapter also presents hardware-in-the-loop (HIL) testing of the WPP supervisory control. This is possible since the WPP equivalent model is developed from self-contained blocks and the supervisory control can be excluded from the equivalent model and realized on a reconfigurable control and acquisition system (NI—cRIO).

The structure of this chapter is as follows. Section 5.2 highlights the challenges associated with the real-time simulation of WPPs. Section 5.3 describes the real-time simulation of the developed WPP equivalent model. Section 5.4 presents real-time Simulation case studies of the Type-4 and Type-3 WPPs based on the developed WPP equivalent models of Chapters 3 and 4. The real-time HIL testing of a Type-4 WPP supervisory control is discussed in section 5.5. The conclusions are stated in section 5.6.

Figure 5.1: Real-Time HIL Closed-Loop Arrangement
5.2 Challenges Associated With Real-Time Simulation of WPPs

The RTS hardware typically includes a number of digital processors, either digital signal processors or general purpose processors, that share the computational burden. To simulate a large system, the system has to be divided into parts (subsystems) such that each of them is simulated in a separate processor. Since the solution algorithm applied in a RTS is based on the nodal admittance matrix technique, the system division is then based on traveling wave transmission line models to break up the large nodal admittance matrix into smaller matrices. These matrices can be solved in parallel, each on a processor, if the solution time-step is smaller than the traveling wave of the transmission lines, e.g., for a simulation time-step of 50 $\mu$s, the transmission line separating any two subsystems should be at least 15 km in length [70]. The parallel operation of these processors enables the simulator to simulate power systems without violating the real-time constraints, i.e., the computation time to solve the system mathematical model is less than the simulation time-step.

Meeting the real-time constraints when simulating WPPs, based on their detailed model, is a challenging task not only because of the significant number of components within a WPP which translates to a large number of equations, but also because of the nature of these components and their simulation requirements. These can be summarized as follows.

- The simulation of power electronic devices, which form the main part of WTG unit, adds an additional computational burden on the RTS hardware due to the need to invert/refactorize the admittance matrix due to switchings.
- The presence of power electronic converters necessitates the use of small simulation time-step, i.e., few microseconds.
- The significant number of components within a WPP makes it inevitable to divide the WPP model into smaller subsystems connected together with long fictitious transmission line. The presence of these lines alters, to some extent, the behavior of the collector network.
- The high cost of the associated hardware required for simulating practical WPP with hundreds of components could be prohibitive.
In the light of the above challenges, it is necessary to use an equivalent WPP model that can accurately represent its EMTs behavior without imposing prohibitive computational burden on the RTS and without the need to divide the WPP model into multiple subsystems.

5.3 Real-Time Simulation of the WPP Equivalent Model

The WPP equivalent models developed in Chapters 2 to 4, also provide substantial advantages for real-time simulation and hardware-in-the-loop real-time simulation, i.e.,

- There is no explicit modeling of the WTGs power electronic interface. Therefore, there is no need to use a very small simulation time-step or corrective algorithms, e.g., interpolations/extrapolations, that accounts for the converters switching events [71].

- The FDNE submodule replaces the detailed WPP passive network that utilizes significant number of nodes with an equivalent that utilizes far less hardware resources, e.g., for a single port equivalent, the WPP collector network, irrespective of its size, is replaced with an equivalent that adds only 3 extra nodes to the system admittance matrix without compromising the accuracy of the simulation results,

- The developed equivalent model is scalable as the DLFE is represented on the RTS using the per unit system. Hence, increasing/decreasing the size and capacity of the WPP is accommodated through changing the base MVA. If there is a change in the passive elements, the FDNE has to be reconstructed.

- The developed equivalent model makes use of the standard blocks and transfer functions already available in the RTS components library. Therefore, there is no need to develop user-defined models or custom submodules.

To imbed the developed equivalent model in a digital real-time simulator, it needs to be represented with its discrete time-domain model. As depicted in Figure 5.2, the WPP equivalent model is composed of the FDNE and the DLFE. To incorporate the FDNE into the nodal solution of the system equations (the solution technique utilized by RTS) the rational functions, representing the FDNE, are represented with the companion circuits
Figure 5.2: Structure of the Wide-band Equivalent Model of a Type-4/3 WTGs-based WPP

based on the trapezoidal numerical integration technique and the bilinear transform, i.e., each of the rational functions is represented by a conductance and a current source whose value depends on the circuit solution from the previous time step (a history current source) [26],[72],[73] as described in Chapter 2.

Unlike the FDNE, the DLFE consists of a set of transfer functions that are interfaced to the electric circuit through a controlled current source, Figure 5.2. Hence, the DLFE is constructed in the RTS interfacing time-domain simulation software with the available standard control blocks. The instantaneous voltages and currents at the PCC are measured and converted to phasor values to be used by the DLFE. The outputs of the DLFE are in the dq-reference frame which are converted back to instantaneous values in the abc-frame to be injected to the system through controlled current sources.

5.4 Case Studies

The main objective of this section is to demonstrate the suitability of the proposed WPP equivalent model for real-time applications. Two case studies are carried out on the systems of Figures 3.9 and 4.13 to demonstrate the feasibility and accuracy of the real-time simulation of large WPPs based on the proposed equivalent models for the analysis of EMTs in the power system. In this work a real-time simulator from RTDS® Technologies [74] is used as the implementation platform. The software interface of the RTDS® is the RSCAD time-domain simulation program. The RTDS® platform used in this work is a single rack device with five PB5 and GPC processing cards. For this rack,
the maximum number of nodes in a single network solution is 72 single-phase nodes. Two network solutions can be included in one rack, i.e., two 72 nodes subsystems can be included in one rack.

For each case study, the test system including the WPP is simulated in the RTDS® environment. The WPP is represented based on its equivalent model proposed in this thesis and simulated in the RTDS® based on its discrete time-domain model as described in Section 5.3. The test systems, system prefault steady state conditions, and the fault scenarios of Case I and Case II are identical to that of the offline case studies in Sections 3.10.1 and 4.10.1 respectively. In response to a fault in the power system external to the WPP, the real-time simulation results of each case study are compared to that of the offline PSCAD/EMTDC simulation presented in the corresponding case study in Chapters 3 and 4.

5.4.1 Case I: Type-4 WPP

The test system of Figure 3.17 that includes a Type-4 WPP is simulated in the RTDS® environment with an integration time-step of 50 $\mu$s. The Type-4 WPP is represented by its equivalent model developed in Chapters 2 and 3 and simulated in real-time in the RTDS®. The system is subjected to a 150-ms temporary L-L-L-G fault, 15-km from the PCC on line T2. Prior to the fault, the system is under steady-state conditions and the WPP delivers 99 MW to the system at PCC. Figure 5.3 shows an oscilloscope snap shot of the instantaneous PCC voltages prior, during, and immediately after the fault. Figure 5.4 shows the injected current by the WPP into the system (at the WPP transformer HV-side) during the fault and after the fault clearance. Figures 5.5 and 5.6 compare the real-time simulation results, Figures 5.3 and 5.4, to those obtained from simulating the system detailed model in the offline PSCAD/EMTDC, Section 3.10.1. The close agreement between the real-time and the off-line results, Figures 5.5 and 5.6, verifies the accuracy of the developed equivalent model in a real-time platform.

5.4.2 Case II: Type-3 WPP

The test system with Type-3 based WPP of Figure 4.13 is simulated in the RTDS® environment. The Type-3 WPP is represented by its equivalent model developed in chapters 2 and 4 and simulated with the host power system in the RTDS® environment with a time-step of 50 $\mu$s. The system is subjected to a temporary fault that takes place
in the power system external to the WPP. The system prefault steady state condition and the fault scenario are identical to that of Section 4.10.1. Figure 5.7 shows an oscilloscope snap shot of the instantaneous PCC voltages prior, during, and immediately after the fault. Figure 5.8 shows the injected current by the WPP into the system (at the WPP transformer HV-side) before, during, and after the fault clearance. Figures 5.7 and 5.8 demonstrate the expected behavior of the Type-3 WPP as compared to the off-line results presented in Section 4.10.1 which verifies the feasibility and accuracy of the real-time simulation of WPPs based on the proposed equivalent model.
Figure 5.5: PCC Voltages of the Equivalent Model From the RTDS and the Detailed Model From PSCAD/EMTDC - Case I

5.4.3 Discussion

The simulation of the test systems of chapters 3 and 4 with their WPPs represented by the proposed equivalent models has been completed in the RTDS\textsuperscript{®} with 50 $\mu$s solution time-step and the terminal behavior of the WPP in response to an EMT in the power system has been investigated. In order to evaluate the reduction in the computational hardware resources associated with simulating the WPP based on its equivalent model, an attempt was made to compare the hardware resources required to simulate the test system of Figure 3.17 with its WPP represented once by its detailed model and once with its equivalent model. The test system with its WPP represented by its equivalent model has utilized only 27 nodes in the RTDS\textsuperscript{®}. On the other hand, the WPP host power system and the detailed model of only the WPP passive network formed a system of 146 nodes which is beyond the capability of the single rack RTDS\textsuperscript{®}. Even with the
assumption that additional RTDS® rack(s) are available, in order to divide the network solution of the test system between racks, the simulated system has to be broken down into a number of subsystems, each with maximum of 72 nodes. These subsystems are interfaced to each other with long fictitious transmission lines to decouple the solution of each subsystem from the others. The presence of these transmission lines alters, to some extent, the behavior of the collector network.

As can be concluded from the aforementioned discussion, the WPP equivalent model enables the real-time simulation of large WPPs at a fraction of the required hardware resources as compared to the detailed WPP. This reduction of the required hardware is due to the computationally efficient design of the WPP equivalent model that accurately represent the dynamic behavior of the WPP.

It has to be noted that the time-step of 50 $\mu$s is a limitation of the RTDS® that results in reducing the frequency range of the simulation results.
Figure 5.7: Real-Time Oscilloscope trace of the WPP Terminal Voltages - Case II

Figure 5.8: Real-Time Oscilloscope trace of the WPP Output Currents - Case II

5.5 Real-Time Controller HIL Testing of a Type-4 WPP Supervisory Control

Another potential application of the proposed equivalent model is the HIL testing of the WPP supervisory control. This is possible due to the modular structure of the
developed WPP equivalent model. The WPP supervisory control is excluded from the model simulated in the RTS platform and its physical hardware counterpart is interfaced to the real-time simulator for the purpose of HIL testing.

For the purpose of validating this concept, a WPP supervisory control has been realized in a reconfigurable industrial control platform (NI−cRIO) comprised of an 800 MHz real-time powerPC processor and a Virtex-5 LX110 FPGA. LabVIEW software is used to program the NI−cRIO and to develop the user interface for the WPP supervisory control. On the other hand, the WPP, excluding the WPP supervisory control module, and the WPP host power system are simulated in the RTDS® simulator. Figure 5.9 shows a schematic diagram of the HIL test bed. In this arrangement, the supervisory control on the NI−cRIO platform receives feedback signals of the instantaneous PCC voltages and currents through the I/O analog interface and sends back the d- and q-reference current components to the RTDS® in order to satisfy the control objectives. Figure 5.10 shows a picture of the real-time HIL testing environment.

### 5.5.1 Case III

This case demonstrates the capability of the equivalent model to be used in the HIL testing of the WPP supervisory control. Instead of simulating the full equivalent model in the RTDS®, the WPP supervisory controller module is omitted from the WPP equivalent
model and a physical WPP supervisory controller is interfaced to the RTDS® instead. In this work, the WPP supervisory controller is realized on the NI–cRIO platform. The test system and the fault condition of this case are similar to those of Case - I. Figures 5.11 and 5.12 depict the measurements of the voltages, currents, active and reactive power components at the PCC that correspond to the control signals sent by the NI–cRIO platform to the RTDS®. The results match those of Case I which verifies the effectiveness of using the WPP equivalent model in validating the performance of parts of the WPP through real-time HIL testing configuration.
Figure 5.11: PCC Voltages and WPP Output Currents - Case III
Figure 5.12: WPP Output (a) $I_{dqcc}$ (b) $I_{Qqcc}$ (c) $P$ (d) $Q$ - Case III
5.6 Conclusions

This chapter presented the real-time simulation of WPPs based on the developed WPP equivalent model of both Type-3 and Type-4 WPPs. The study results conclude that:

- The use of the developed WPP equivalent model enhances the capability of RTS to simulate large power systems with multiple WPPs. The size of the simulated system is not affected by the number of units and the MW size of the simulated WPPs.

- The drastic reduction in the computational time and burden associated with the equivalent model highly reduces the size and consequently the cost of the required real time simulator hardware as compared to the hardware required to implement detailed models.

This chapter also presents the real-time HIL testing of the WPP supervisory control which is realized on an industrial controller platform (NI–cRIO) whereas the rest of the WPP equivalent model is simulated in a RTDS simulator. This arrangement allows for the testing of the physical supervisory control prior to its actual installation in the WPP site and the testing of the control functions and the resultant system interaction.
Chapter 6

Conclusion and Future Work

6.1 Summary

This thesis proposed, developed, evaluated, and verified an accurate and computationally efficient reduced-order dynamic-equivalent model that represents a wind power plant (WPP) for the analysis of EMTs in the power system, external to the WPP. The proposed models have been developed to represent Type-3 based WPPs and Type-4 based WPPs within the desired frequency bandwidth, e.g., 0 to 50 kHz. The WPP equivalent model consists of two distinct sub-models,

1. a static wide frequency-band FDNE which captures the frequency response of all the passive WPP components within the desired frequency range,

2. a dynamic low-frequency equivalent (DLFE) model which represents dynamics of WPP supervisory control and dynamics of the WTG units and local controls, within the range of several Hz about the system nominal frequency.

This thesis presents a systematic approach to develop the wide-band WPP equivalent models. The numerical accuracy and computational efficiency of the proposed equivalent models were tested by comparing time-domain simulation test case results when a WPP is represented once by its detailed model and once by the proposed equivalent model, in the PSCAD/EMTDC environment. The test cases cover different types of faults at different locations with respect to the WPP point of common coupling (PCC).

This thesis also presents three applications of the developed WPP equivalent models.
1. The real-time simulation of the Type-4 WPP based on the developed equivalent model.

2. The real-time simulation of the Type-3 WPP based on the developed equivalent model.

3. The real-time HIL testing of the WPP supervisory control which is realized on an industrial controller platform (NI-cRIO) whereas the rest of the WPP equivalent model and the host power system is simulated in a RTDS® simulator.

6.2 Conclusions

The study results reported in this thesis conclude that:

- The developed WPP equivalent model significantly reduces the computational time and burden as compared to the WPP detailed model since the equivalent model represents all WTG units, local controls, and the WPP supervisory control with a single DLFE model and represents the collector network with the FDNE model.

- The developed WPP equivalent model accurately mimics the terminal behavior of WPPs in response to power system transients external to the WPP. The accuracy of the developed models has been validated through the performed case studies.

- The equivalent model represents the dynamic behavior of (i) the WPP collector network and passive components, (ii) the WPP supervisory control, and (iii) the WTG units and their local controls. In addition, it represents specific performance requirements, e.g., the fault-ride through behavior of the WPP which is a mandatory requirement by the grid codes.

- The developed equivalent is tailored for EMTs studies since it represents the WPP terminal behavior over a wide range of the frequency spectrum, e.g., from 0 up to 50 kHz.

- Various simulation scenarios that cover different types of faults at different locations outside the WPP and multiple switching transients demonstrate that the accuracy of the proposed model is neither affected by the type nor the location of the fault, even when the fault occurs at the WPP point of connection to the grid.
The equivalent model is a scalable model, since the DLFE is developed in per unit and can be scaled to the base values of any WPP of interest. Therefore, the size and number of WTGs units within the WPP do not affect the structure of the equivalent.

The equivalent model provides a platform portability in the sense that it is suitable to be implemented in different time-domain simulation platforms since it can be constructed using the standard power components and transfer functions available in the library of the production-grade time-domain simulation software tools; hence, it does not necessitates development of user-defined models or custom submodules.

The equivalent model has a flexible design such that for changes in the WPP of interest, the equivalent model can be adapted to these changes as follows.

1. Changes in the passive collector network are accommodated by updating only the FDNE.
2. Addition/disconnection of WTG units is represented by changing the equivalent model normalization base values.
3. Changes/Modifications in the functions of the WPP supervisory control is represented by updating the corresponding module at the equivalent model.

The computational efficiency of the equivalent model makes it a prime choice to represent a WPP in a real-time simulation environment. Based on the reported real-time simulation case studies, the following conclusions were drawn.

- The use of the equivalent model enhances the capability of the real-time simulator (RTS) to simulate large power systems with multiple WPPs. The size of the simulated equivalent WPP on the RTS, measured by the number of system nodes, is not affected by the number of units and the MW size of the simulated WPP.

- The drastic reduction in the computational time and burden associated with the equivalent model highly reduces the size and consequently the cost of the required RTS hardware platform as compared to the hardware required to simulate the detailed model of a WPP.

- The equivalent model alleviates the additional computational burden, on the RTS hardware, associated with simulating power electronic converters. Therefore, it
obviates the need for very small simulation time-steps or corrective algorithms, e.g., interpolations/extrapolations to account for the converters switching events.

- The WPP equivalent model is developed from self-contained blocks. Therefore, it is possible to test the physical WPP supervisory control in a HIL environment. In this test the WPP equivalent model (excluding the supervisory control) is simulated in the RTS whereas the WPP supervisory control is realized on a reconfigurable control and acquisition system (NI-cRIO). This arrangement allows for the testing of the physical supervisory control prior to its actual installation in the WPP site and the testing of the control functions and the resultant system interaction.

Based on the studies reported in this work, the following quantitative conclusions are deduced:

- As indicated in Chapter 3, compared to the detailed model of the test system with Type-4 based WPP, the developed equivalent model reduces the off-line simulation time from more than 5 hours to 110 seconds, i.e., a reduction in computation time by a factor of 218, without compromising the accuracy.

- As indicated in Chapter 4, compared to the detailed model of the test system with Type-3 based WPP, the developed equivalent model reduces the off-line simulation time from 31.5 hours to 45 seconds, i.e., a reduction in computation time by a factor of 2480, without compromising the accuracy.

- As indicated in Chapter 5, The real-time simulation of the test system of chapter 3 has utilized only 27 nodes and was carried out in a single RTDS rack, whereas the simulation of detailed model of only the test system passive network (not considering the WTG units) include 146 nodes which requires more than one RTDS® rack.

### 6.3 Contributions

The main contributions of this thesis are

1. Proposal and development of a novel reduced-order, wide-band frequency dependent dynamic-equivalent model of WPPs which to the best of the author’s knowledge has not been previously introduced in the technical literature. The developed
model significantly reduces the required computational resources and the simulation run time while preserving the WPP response fidelity in a desired frequency range.

2. Application of the developed model to represent realistic size Type-4 and Type-3 WPPs, that include (i) WTG units, (ii) collector network, and (iii) WPP supervisory control, with reasonable resources and computation time.

3. Development of a systematic approach to construct the proposed WPP equivalent model, incorporating the WTG controls and the WPP supervisory control.

4. Validation and evaluation of the practical feasibility of the real-time simulation of power systems with WPPs using limited hardware resources without sacrificing the simulation accuracy. This is possible due to the reduced hardware resource requirements for representing the proposed equivalent model.

5. Proposal of a framework for HIL testing of WPP supervisory control based on the developed WPP equivalent model.

6.4 Future Work

1. Validate the accuracy of the developed equivalent model against field measured data for an actual WPP installed in the field. Since it is not possible to apply a fault condition in the power system hosting the WPP only for the purpose of collecting data, the field measured data of interest is expected to be historically collected during previous fault incidents.

2. Utilize the model to investigate mutual interactions of electrically-close WPPs.

3. Utilize the WPP equivalent model simulated in RTDS to test protection devices connected to the high voltage side of the substation transformer in a HIL environment.

4. Develop an equivalent model to represent the EMT response of grid-connected photovoltaic (PV) power plants. The equivalent model of inverter-based PV generation is expected to be similar to that of Type-4 WTG units; hence, an equivalent model of PV system is an intuitive extension of the WPP equivalent model.
5. Based on the proposed equivalent model, develop equivalent models that represent Types-1 and -2 based WPPs.
Appendix A

Detailed Model of the Type-4 WPP

This appendix presents the detailed EMT model of the Type-4 WPP. Section A.1 presents the supervisory control of the WPP whose function is to control the exchange of power components between the WPP and the grid according to the power system requirements and grid code. Section A.2 presents the detailed model of the Type-4 WTG unit.

A.1 WPP Supervisory Control

This control coordinates the operation of all WTG units within the WPP such that the collective WPP power injection at the PCC satisfies the active and reactive power requirements of the TSO. For this purpose, there should be a two-way communication between the supervisory control and the WTG units such that each unit provides its generation availability and receives reference values from the WPP supervisory control. The inputs to the WPP control are:

1. Reference values of the voltage, and the active and reactive power components from the TSO
2. Feedback measurements of the voltages and currents from the PCC
3. The available power at each WTG unit

Based on the above inputs, the WPP supervisory control specifies the WPP power injection as follows [49]. For the active power:

1. Set the operating mode: either to supply certain active power reference or generate the maximum available power based on the available wind.
2. Calculate and send the power reference of each unit \( (P_{W,T,G}^{ref}) \). This is done by sending the WPP reference power \( (P_{ref}^{W,P,P}) \), calculated as a percentage of the WPP total capacity, to all WTG units such that each unit generates active power equal to the same percentage of its capacity. Another option is to calculate \( P_{ref}^{W,T,G} \) of each unit based on the power availability of the unit.

3. Reduce \( P_{ref}^{W,T,G} \) in case of grid transients accompanied with voltage fluctuations. This reduction is calculated based on the WPP terminal voltage and according to the grid code.

For the reactive power:

1. Set the operating mode either to supply certain reactive power reference or generate reactive power/current to regulate the voltage/power factor at the WPP terminal.

2. Calculate and send the reference \( Q_{ref}^{W,T,G} \) or its corresponding \( I_{Q,ref}^{W,T,G} \) to each WTG unit.

3. Change the value of \( I_{Q,ref}^{W,T,G} \) in case of voltage fluctuations resulting from grid transients. This change is calculated based on the the WPP terminal voltage and according to the grid requirements.

The reference signals from the supervisory control are then sent to the next control level, i.e., the WTG local control. Figure A.1 depicts a Type-4 WTG unit. The full-rated back-to-back converters decouple the turbine-generator from the collector network such that disturbances that take place on the collector network side have insignificant effects on the machine side of the converter [6], [30]–[32]. Consequently, the dynamic model of each WTG unit can be adequately represented by those of the corresponding GSC and its local control.

### A.2 Type-4 GSC Control Model

The GSC is modeled as a three-phase two-level current-controlled voltage-sourced converter with six IGBT valves as shown in Figure A.2 where the GSC is interfaced to the AC collector network through a series RL filter. GSCs within the WPP are synchronized with the positive sequence voltage at the WPP terminals through a phase-locked loop. This enables the derivation of the GSC control in the dq-frame of reference where the
d-axis is aligned with the PCC voltage and hence the voltage q-component $V_{sq}$ is zero. Therefore, the control of the GSC output power components ($P$ and $Q$) can be achieved through the independent control of the dq-output current components $I_d$ and $I_q$.

The AC-side power components are

\begin{align}
P_s(t) &= \frac{3}{2} [V_{sd}(t)i_d(t) + V_{sq}(t)i_q(t)], \quad (A.1) \\
Q_s(t) &= \frac{3}{2} [-V_{sd}(t)i_q(t) + V_{sq}(t)i_d(t)]. \quad (A.2)
\end{align}

Imposing $V_{sq} = 0$, (A.1) and (A.2) become,

\begin{align}
P_s(t) &= \frac{3}{2} V_{sd}(t)i_d(t), \quad (A.3) \\
Q_s(t) &= -\frac{3}{2} V_{sd}(t)i_q(t). \quad (A.4)
\end{align}

Hence

\begin{align}
i_{dref}(t) &= \frac{2}{3V_{sd}} P_{sref}(t), \quad (A.5) \\
i_{qref}(t) &= -\frac{2}{3V_{sd}} Q_{sref}(t). \quad (A.6)
\end{align}

The current control of the GSC is deduced based on Figure A.2 from

\begin{align}
L \frac{di_d}{dt} &= L\omega_o i_q - Ri_d + V_t - V_{Sd}, \quad (A.7) \\
L \frac{di_q}{dt} &= -L\omega_o i_d - Ri_q + V_{tq} - V_{Sq}, \quad (A.8)
\end{align}

where $V_{tdq}$ are the VSC terminal voltages and given by [43]:

\begin{align}
V_{td}(t) &= \frac{V_{DC}}{2} m_d(t), \quad (A.9)
\end{align}
Figure A.2: Schematic Diagram of a Typical GSC

\[ V_{td}(t) = \frac{V_{DC}}{2} m_d(t), \]  

(A.10)

where \( m_d \) and \( m_q \) are the dq-component of the modulation signal sent to the GSC switches. The modulation signals are determined by the GSC closed loop control that regulates the GSC output currents \( (i_{dq}) \). Equations (A.7) and (A.8) indicate that the presence of the terms \( L \omega_o i_d \) and \( L \omega_o i_q \) couple the dynamics of \( i_d \) and \( i_q \). Therefore, to decouple these dynamics, feed-forward \( L \omega_o \) is introduced [43]. For this purpose, \( m_d(t) \) and \( m_q(t) \) are introduced as

\[ m_d(t) = \frac{2}{V_{DC}} (u_d - L \omega_o i_q + V_{Sd}), \tag{A.11} \]

\[ m_q(t) = \frac{2}{V_{DC}} (u_q + L \omega_o i_d + V_{Sq}), \tag{A.12} \]

where \( u_d \) and \( u_q \) are new control inputs [75],[76]. Substituting for \( m_d \) and \( m_q \) from (A.11) and (A.12) into (A.9) and (A.10) and then substituting \( V_{td} \) and \( V_{tq} \) from (A.9) and (A.10) into (A.7) and (A.8) result in:

\[ L \frac{di_d}{dt} = -R i_d + u_d, \]

(A.13)

\[ L \frac{di_q}{dt} = -R i_q + u_q. \]

(A.14)

Based on (A.11) to (A.14), Figure A.3 shows a block representation of the \( dq \)-frame current controllers of the GSC where the \( d \)- and \( q \)-compensators process the reference and the feedback currents to provide \( u_d \) and \( u_q \) respectively.
Figure A.3: Block Diagram of the GSC Control
Appendix B

DSOGI-PLL

The structure of the DSOGI-PLL, Figure B.1, consists of three main components:

1. abc/αβ Clarke transformation block.

2. Dual SOGI with quadrature signal generator (QSG): it filters the input αβ voltages into ($V_{α,filtered}$, $V_{β,filtered}$) and extracts their 90° shifted version ($qV_{α,filtered}$, $qV_{β,filtered}$)

3. A Positive sequence calculator (PSC): processes its inputs from the dual SOGI and calculates the positive sequence fundamental frequency component of the voltage $V_{α}^+$, $V_{β}^+$ [33].

4. Basic SRF-PLL: estimates the phase angle $θ$ and use it to transform $V_{α}^+$, and $V_{β}^+$, from the PSC, to the dq-reference frame.

Figure B.1: Schematic Diagram of DSOGI-PLL
Mathematically, each SOGI-QSG is expressed by its characteristic transfer functions as follows [33]:

\[
D(s) = \frac{v_{\text{filter}}}{v}(s) = \frac{kw's}{s^2 + kw's + w'^2} \quad (B.1)
\]

\[
Q(s) = \frac{qv_{\text{filter}}}{v}(s) = \frac{k w'^2}{s^2 + kw's + w'^2} \quad (B.2)
\]

Equations B.1 and B.2 can be realized with the block diagram of Figure B.2 where \( q \) is the 90\( ^\circ \) phase shift operator, \( \omega' \) and \( k \) are the resonance frequency and the damping factor of the SOGI-QSG respectively. Both the components of \( v_{\text{filter}} \) and its 90\( ^\circ \) lag \( qv_{\text{filter}} \) are then used by the PSC to determine \( V_{\alpha\beta}^+ \). In order to have an accurate results under grid frequency variations, the grid frequency detected at the SRF-PLL is fed-back to the DSOGI-QSG to dynamically adapt its resonance frequency \( \omega' \) to match the estimated grid frequency as shown in Figure B.1.

The PSC calculates the positive-sequence component of the input \( V_{\alpha\beta} \) as follows: According to clarke transformation [77]:

\[
V_{\alpha\beta} = [T_{\alpha\beta}] V_{abc} \quad (B.3)
\]

Where

\[
[T_{\alpha\beta}] = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (B.4)
\]

Therefore, the positive-sequence component \( V_{\alpha\beta}^+ \) can be calculated as:

\[
V_{\alpha\beta}^+ = [T_{\alpha\beta}] V_{abc}^+ \quad (B.5)
\]

According to the symmetrical components method [78]:

\[
V_{abc}^+ = [v_a^+ \ v_b^+ \ v_c^+]^T = [T^+] V_{abc} \quad (B.6)
\]
where
\[
[T^+] = \frac{1}{3} \begin{bmatrix}
1 & a & a^2 \\
 a^2 & 1 & a \\
a & a^2 & 1
\end{bmatrix}, 
\]
\[
a = e^{j \frac{2\pi}{3}}. \tag{B.7}
\]

Hence, substituting from (B.6) in (B.5) and then from (B.3) in (B.5) result in,

\[
V_{\alpha+} = [T_{\alpha\beta}][T^+]V_{abc},
\]
\[
= [T_{\alpha\beta}][T^+][T_{\alpha\beta}^{-1}]V_{\alpha\beta},
\]
\[
= \frac{1}{2} \begin{bmatrix}
1 & -q \\
q & 1
\end{bmatrix} V_{\alpha\beta}, \quad q = e^{-j \frac{\pi}{3}}. \tag{B.8}
\]

\(q\) is the same phase shift operator used before which obtains the quadrature waveform from the original in-phase waveform [33]. The previous equation can be written as follows:

\[
V_{\alpha}^+ = \frac{1}{2}(V_{\alpha} - qV_{\beta}) \tag{B.9}
\]
\[
V_{\beta}^+ = \frac{1}{2}(qV_{\alpha} + V_{\beta}) \tag{B.10}
\]

Figure B.1 depicts the PSC as described in (B.9) and (B.10), its inputs are the filtered values of \(V_{\alpha\beta}\) and \(qV_{\alpha\beta}\) supplied by the DSOGI-QSG and its output are \(V_{\alpha\beta}^+\). \(V_{\alpha\beta}^+\) are then fed to the basic SRF-PLL to estimate the grid frequency and the phase angle \(\theta\) of the fundamental frequency positive sequence component of the voltage. The angle \(\theta\) is estimated through a feedback control loop that regulates the \(q\)-component to zero, Figure B.1, [33], [34].
Appendix C

Parameters of the Test System of Chapter 3

Parameters of the 34.5-kV and 115-kV transmission lines and the grid impedance of the test system are given in Tables C.1, C.2, and C.3. $Z_1$, $Z_2$, and $Z_0$ are the positive, negative, and zero sequence series impedances respectively where $Z = R + jX_L$. $X_c$ is the capacitive shunt reactance.

Table C.1: Parameters of The 34.5 kV Overhead Lines

<table>
<thead>
<tr>
<th></th>
<th>Overhead Line 1,2</th>
<th>Overhead Line 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1 = Z_2$</td>
<td>$0.128 + j 0.391 \text{ OHM/km}$</td>
<td>$0.162 + j 0.923 \text{ OHM/km}$</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>$0.306 + j 1.791 \text{ OHM/km}$</td>
<td>$0.481 + j 2.770 \text{ OHM/km}$</td>
</tr>
<tr>
<td>$X_{c1} = X_{c2}$</td>
<td>$0.239 \text{ M\text{OHM}km}$</td>
<td>$0.295 \text{ M\text{OHM}km}$</td>
</tr>
<tr>
<td>$X_{c0}$</td>
<td>$0.578 \text{ M\text{OHM}km}$</td>
<td>$0.738 \text{ M\text{OHM}km}$</td>
</tr>
</tbody>
</table>

Table C.2: Parameters of The 115 kV Overhead Lines

<table>
<thead>
<tr>
<th></th>
<th>Overhead Line 1,2</th>
<th>Overhead Line 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1 = Z_2$</td>
<td>$0.081 + j 0.462 \text{ OHM/km}$</td>
<td>$0.162 + j 0.923 \text{ OHM/km}$</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>$0.240 + j 1.385 \text{ OHM/km}$</td>
<td>$0.481 + j 2.770 \text{ OHM/km}$</td>
</tr>
<tr>
<td>$X_{c1} = X_{c2}$</td>
<td>$0.148 \text{ M\text{OHM}km}$</td>
<td>$0.295 \text{ M\text{OHM}km}$</td>
</tr>
<tr>
<td>$X_{c0}$</td>
<td>$0.369 \text{ M\text{OHM}km}$</td>
<td>$0.738 \text{ M\text{OHM}km}$</td>
</tr>
</tbody>
</table>
Table C.3: Grid Impedance

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1 = Z_2$</td>
<td>$0.1448 + j 2.8971 , \Omega$</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>$0.16068 + j 1.60699 , \Omega$</td>
</tr>
</tbody>
</table>
Appendix D

Detailed Model of the Type-3 WTG

This appendix presents the detailed dynamic model of the DFAG units for EMTs studies and the units local controls which control the operation of the DFAG units in order to satisfy the WPP generation requirements. Unlike Type-4 WTGs, the stator of each DFAG unit is directly connected to the grid; hence, the dynamics of the machine will reflect in the grid side.

The DFAG stator is connected to the WPP collector network through a step-up transformer, Figure D.1, whereas the rotor is interfaced to the collector network with back-to-back voltage-sourced converter, referred to as rotor-side converter (RSC) and grid-side converter (GSC). The converters control the active and reactive power exchange between the DFAG and the collector network. The differential equations that describe

![Figure D.1: Schematic Diagram of the Doubly-Fed Asynchronous Generator (DFAG) Unit](image-url)
Appendix D. Detailed Model of the Type-3 WTG

the performance of the DFAG in the synchronous reference frame [43], [49] are

\[ \vec{V}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} + j\omega_s \vec{\psi}_s, \] (D.1)

\[ \vec{V}_r = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} + j(\omega_s - \omega_r) \vec{\psi}_r, \] (D.2)

where \( \vec{V}_s \) and \( \vec{V}_r \) are the stator and rotor voltages; \( \vec{i}_s \) and \( \vec{i}_r \) are the stator and rotor currents; \( \vec{\psi}_s \) and \( \vec{\psi}_r \) are the stator and rotor fluxes; \( R_s \) and \( R_r \) are the stator and rotor resistances respectively. \( \omega_s \) is the stator synchronous frequency which is imposed by the grid; and \( \omega_r \) is the angular frequency of the rotor. All parameters of the above equations are referred to the stator side of the DFAG.

The stator and rotor fluxes of (D.1) and (D.2) are given by [43], [49]

\[ \vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r, \] (D.3)

\[ \vec{\psi}_r = L_m \vec{i}_s + L_r \vec{i}_r, \] (D.4)

\[ L_s = L_{\sigma s} + L_m, \] (D.5)

\[ L_r = L_{\sigma r} + L_m, \] (D.6)

where \( L_m \) is the magnetizing inductance; \( L_{\sigma s} \) and \( L_{\sigma r} \) are the stator and rotor winding leakage inductances respectively. The rotor dynamics are represented by

\[ \frac{d\omega_r}{dt} = \frac{1}{2H}(T_m - T_e), \] (D.7)

where \( T_m \) and \( T_e \) are the mechanical and electrical torques respectively and \( H \) is the inertia constant.

The RSC and the GSC are three-phase two-level VSCs, each is constructed with six IGBT valves whose operation is based on a SPWM strategy. The RSC and GSC local controls are developed in a synchronously rotating dq-frame of reference at which the steady-state voltages and currents appear as dc components. This approach simplifies the control design and enables the use of PI controllers. In addition, this approach enables independent control of d- and q-current components which translates to a decoupled control of the active and reactive power components [77]. The RSC with the decoupled current controller controls the amplitude and frequency of rotor voltages to control the generator torque and stator reactive power. The GSC controls its output voltages to maintain the dc-link voltage and to control the reactive power exchange with the network.
Multiple software control methods and/or hardware methods have been introduced in the literature to enable the DFAG-based WPPs to satisfy the fault-ride-through requirements [46],[50]–[53]. Each of these techniques has its own merits and limitations; however, many of them fail to achieve the objective during transients which impose severe voltage dips [52]. In this thesis, a dynamic voltage restorer (DVR) has been considered [51],[52] to be connected at the unit terminal to restore the terminal voltage during transients and thus enable the DFAG unit to provide ride-through capability subsequent to a fault, Figure D.2.

Figure D.2: Schematic Diagram of the Doubly-Fed Asynchronous Generator

The control of the WPP is composed of a three-level hierarchical control as discussed in Appendix A, Figure 3.1 [28]. Sections D.1 and D.2 discuss the WTG local control level which is divided into RSC and GSC controls.

### D.1 Rotor-Side Converter Control

The local control of the RSC controls the generator torque and the stator reactive power flow through an inner and outer control loops. In the outer control loop, the torque and reactive power references are translated to a corresponding q- and d-current references, respectively. The current references are then sent to the RSC inner decoupled current control loop [43],[49]. The control of the RSC is derived in a synchronously rotating dq-reference frame synchronized with the stator flux, i.e., its d-axis is aligned with the stator flux. In such case, a flux observer is used to estimate the flux and its angle [43],[49]; then, the rotor voltages and currents are transformed from the abc-stationary frame to the dq-frame using the angle between the d-axis and the rotor phases $\theta_r$. Alignment of
the d-axis with the stator flux space vector is equivalent to alignment of the q-axis with the stator voltage space vector and delaying the d-axis by 90° since the flux is shifted 90° with respect to the stator voltage. Therefore, a PLL [33] is used to obtain the angle of stator voltage space vector. In this thesis, the voltage orientation is considered and the PLL of Appendix B is adopted.

Based on (D.1)-(D.7), the stator reactive power and the electromagnetic torque are [43]

\[ Q_s = \left( \frac{3}{2} \right) \frac{\hat{V}_s^2}{(1 + \sigma_s)L_m \omega_s} - \left( \frac{3}{2} \right) \frac{1}{(1 + \sigma_s)} \hat{V}_s i_{rd}, \quad (D.8) \]

\[ T_e = \frac{P_e}{\omega_r} = - \left( \frac{3}{2} \right) \frac{\hat{V}_s}{(1 + \sigma_s)\omega_s} i_{rq}, \quad (D.9) \]

where \( \hat{V}_s = \sqrt{V_d^2 + V_q^2} \), and \( \sigma_s = \frac{L_s}{L_m} - 1. \quad (D.10) \)

The first component of (D.8) corresponds to the machine magnetizing current while the second component is a function of the d-component of the rotor current \( i_{rd} \). \( i_{rdref} \) is determined from (D.8) based on the reactive power reference value. To operate the machine at unity power factor, \( i_{rdref} \) takes the value of \( \frac{\hat{V}_s}{(L_m \omega_s)} \) to compensate for the magnetizing reactive power [43]. During transients in which PCC voltage drops, \( i_{rdref} \) is increased to boost the WTG output reactive current/power to meet the voltage requirements.

As mentioned before, the WTG may receive a value of \( P_{ref} \) or set to the maximum power tracking mode. In the former case, \( i_{rqref} \) is calculated directly from (D.9) based on the \( P_{ref} \) obtained from the WPP supervisory control. In the latter case, \( T_{eref} \) corresponding to the maximum power has to be calculated first and then the corresponding \( i_{rqref} \) is determined.

To operate in the maximum power tracking mode, the electromagnetic torque \( T_e \) is expressed as [43], [79], [80]:

\[ T_{eref} = T_{optpu} = -K_{opt} \omega_{rpu}^2, \quad (D.11) \]

where

\[ K_{opt} = \frac{0.5\rho A r^3 \omega_b^3 C_{pmax}}{G^3 P_b \lambda_{opt}^3}. \quad (D.12) \]

In (D.12) \( \rho, r, A, \omega_b, G, P_b, \lambda_{opt}, \) and \( C_{pmax} \) are the air density, turbine blade radius, turbine blade area, base value of the machine rotor speed, gear box ratio, base power,
Appendix D. Detailed Model of the Type-3 WTG

optimum tip speed ratio, and its corresponding maximum power coefficient which is obtained from the turbine power coefficient curve.

It is to be noted that during very high wind speeds, \((D.11)\) may result in a \(T_{\text{eref}}\) (and its corresponding \(P_{\text{eref}}\)) that is greater than the rated power. In this case, the reference will be limited to the rated value.

The reference \(d\)- and \(q\)-currents determined by \((D.8)\) and \((D.9)\) respectively are sent to the RSC inner current controller, Figure D.3. The outputs of this control are the modulation signals \(m_d\) and \(m_q\) which are sent to the pulse width modulator (PWM) to generate the gating signals for the RSC [43]. \(\sigma\) and \(\tau\) refer to the machine parameters, i.e., \(\sigma = 1 - (L_m^2/(L_s L_r))\) and \(\tau_r = L_r/R_r\).

D.2 Grid-Side Converter Control

The GSC independently controls the DC-link voltage of the back-to-back converter and the reactive current at the machine terminals. This control is derived in a dq-frame that aligns the \(d\)-axis with the PCC voltage phasor. The GSC control consists of an outer and inner control loops. The outer control loop receives references for the DC voltage and the terminal reactive current and generates the corresponding \(d\)- and \(q\)-current components which are the references for the converter decoupled inner current control, Figure D.4
To regulate the dc voltage ($V_{DC}$), the active power flow through the GSC is controlled to keep the power balance over the dc-link, Figure D.2 [43]

$$\frac{d}{dt} \left( \frac{1}{2} C_{dc} V_{DC}^2 \right) = P_R - P_G. \tag{D.13}$$

The left hand side of (D.13) represents the energy stored in the DC-capacitor, $P_R$ is the DC-side power of the RSC, and $P_G$ is the power flow into the GSC, Figure D.2. Assuming lossless converters, $P_R$ is the same as the AC-side rotor power $P_r$ and $P_G$ is the same as the AC power leaving the GSC $P_f$; therefore, (D.13) can be expressed as

$$\frac{d}{dt} \left( \frac{1}{2} C_{dc} V_{DC}^2 \right) = -P_r - P_f. \tag{D.14}$$

The compensator ($K(v)$), Figure D.4, determines the GSC reference power that regulates $V_{DC}$ to its reference value. The rotor power $P_r$ is included in the control loop as a feedforward term such that any change in $P_R$ is rapidly reflected in the output reference current [43],[81].

### D.3 DFAG Fault-Ride-Through Capability

The DFAG unit is sensitive to the grid transients at which the rotor windings experience overvoltages and overcurrents that can destroy the converter if no protection measures are
The traditional solution to protect the converter is to activate a crowbar that short-circuits the rotor through a resistance and deactivate the rotor converter. Nevertheless, the crowbar operation causes the DFAG to act as a squirrel cage machine that absorb reactive power from the grid which aggravates the voltage dip [46]. In an effort to comply with the grid codes and allow DFAG to supply reactive current during faults, a number of techniques have been introduced in the technical literature to improve the DFAG fault-ride-through, e.g., injecting a demagnetizing current into the rotor to reduce its voltage [49], [82]. Other approaches suggested using additional hardware like a series dynamic resistance in the rotor [83], a stator damping resistance [84], a series grid side converter [85], or the use of a parallel grid-side rectifier and a series-grid side converter [86]. Each of those approaches has its merits and limitations; however, during severe voltage dips the activation of the crowbar is inevitable in most of the cases and hence the continuous control of reactive current is not guaranteed [52].

In this thesis, a dynamic voltage restorer (DVR) [51],[52],[87]–[89] has been considered to allow DFAG to ride through the fault even during severe voltage dips. The DVR is a voltage sourced-converter connected in series between the machine stator and the step-up transformer and compensates for the voltage during the fault. With this approach, the stator voltage is kept constant even under severe balanced/unbalanced faults and hence the transients have limited effect on the machine operation. The use of this external device is useful in the already installed wind turbines that do not comply with the fault ride-through regulations. Since the detailed design and control of the DVR is not within the scope of this thesis, the DVR is simulated using a voltage source, connected between the stator and the step-up transformer, Figure D.2. During disturbances the DVR monitors the stator voltage and maintains it at its nominal value.
Appendix E

Parameters of the Test System of Chapter 4

Parameters of the 34.5-kV and 115-kV transmission lines of the test system of Figure 4.13 are given in Tables E.1, and E.2. $Z_1$, $Z_2$, and $Z_0$ are the positive, negative, and zero sequence series impedances respectively where $Z = R + jX_L$. $X_c$ is the capacitive shunt reactance.

Table E.1: Parameters of The 13.8 kV Overhead Lines

<table>
<thead>
<tr>
<th>$Z_1 = Z_2$</th>
<th>$0.128 + j 0.391$ Ω/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0$</td>
<td>$0.306 + j 1.791$ Ω/km</td>
</tr>
<tr>
<td>$X_{c1} = X_{c2}$</td>
<td>$0.239$ MΩ*km</td>
</tr>
<tr>
<td>$X_{c0}$</td>
<td>$0.578$ MΩ*km</td>
</tr>
</tbody>
</table>

Table E.2: Parameters of The 115 kV Overhead Lines

<table>
<thead>
<tr>
<th>$Z_1 = Z_2$</th>
<th>$0.081 + j 0.462$ Ω/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_0$</td>
<td>$0.240 + j 1.385$ Ω/km</td>
</tr>
<tr>
<td>$X_{c1} = X_{c2}$</td>
<td>$0.148$ MΩ*km</td>
</tr>
<tr>
<td>$X_{c0}$</td>
<td>$0.369$ MΩ*km</td>
</tr>
</tbody>
</table>

Parameters of the DFAG machine and the its interfacing transformer are given in Table E.3 where the subscripts of s, r, and M refer to the stator, rotor, and magnetization.
Appendix E. Parameters of the Test System of Chapter 4

parameter respectively. H and D are the inertia constant and the damping coefficient respectively.

Table E.3: Parameters DFAG Unit and its interfacing Transformer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Power</td>
<td>1.7</td>
<td>Mw</td>
</tr>
<tr>
<td>Base Voltage</td>
<td>2.3</td>
<td>Kv</td>
</tr>
<tr>
<td>Base Frequency</td>
<td>377</td>
<td>rad/s</td>
</tr>
<tr>
<td>Rs</td>
<td>0.00779</td>
<td>p.u.</td>
</tr>
<tr>
<td>Rs</td>
<td>0.025</td>
<td>p.u.</td>
</tr>
<tr>
<td>Ls</td>
<td>0.07937</td>
<td>p.u.</td>
</tr>
<tr>
<td>Lr</td>
<td>0.4</td>
<td>p.u.</td>
</tr>
<tr>
<td>LM</td>
<td>4.1039</td>
<td>p.u.</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>s</td>
</tr>
<tr>
<td>D</td>
<td>0.0001</td>
<td>p.u.</td>
</tr>
<tr>
<td>Transformer Nominal Power</td>
<td>2</td>
<td>MVA</td>
</tr>
<tr>
<td>Transformer Voltage Ratio</td>
<td>2.3/13.8</td>
<td>Kv</td>
</tr>
<tr>
<td>Transformer Leakage Reactance</td>
<td>0.0575</td>
<td>p.u.</td>
</tr>
</tbody>
</table>

Parameters of the back-to-back converters and the RSC interfacing transformer are given in Table E.4.

Table E.4: Parameters of Back-to-Back VSC and Transformer

<table>
<thead>
<tr>
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</thead>
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<tr>
<td>Switching Frequency</td>
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</tr>
<tr>
<td>DC Capacitor</td>
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<td>µF</td>
</tr>
<tr>
<td>RSC Interface Inductance</td>
<td>525</td>
<td>µH</td>
</tr>
<tr>
<td>Transformer Nominal Power</td>
<td>0.4</td>
<td>MVA</td>
</tr>
<tr>
<td>Transformer Voltage Ratio</td>
<td>0.6/2.3</td>
<td>Kv</td>
</tr>
<tr>
<td>Transformer Leakage Reactance</td>
<td>0.1</td>
<td>p.u.</td>
</tr>
</tbody>
</table>
Bibliography


