TRANSIENT VERIFICATION OF GENERIC WIND TURBINE MODELS

BY

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THESIS

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ABSTRACT

This thesis addresses the verification, or model-to-model comparison, of the four existing generic dynamic wind turbine models in three different commercial transient stability packages. It is known that transient stability results can, and do, differ across simulation platforms, and this work illustrates further this fact with special emphasis on generic wind turbine models. Two simulation approaches are considered for comparison of results as part of this work: three-phase bus faults with single machine infinite bus systems and two-bus frequency disturbance injections. This thesis is organized as follows: Chapter 1 provides the reader an introduction to wind turbine generic models, as well as details about each of the four model types; Chapter 2 outlines in detail the verification procedures developed and executed for this work, as well as the approach for building appropriate simulation cases for such comparisons; Chapter 3 provides results of the verification procedures with comparisons of machine terminal voltage and real and reactive power output for each model type; Chapter 4 summarizes the work performed in this thesis and outlines future work to extend the concepts presented.

To Mom and Dad, for a life filled with guidance, love, and support.

ACKNOWLEDGMENTS

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To all of my fellow students and friends in Urbana-Champaign—there are too many names to list, but I hope you all know who you are. Your lively discussions, advice, walks around the Quad, coffees, brunches, bike rides, concerts, and celebrations all comprise an experience in my life which I will forever cherish. You all opened my eyes to the world in so many ways, and I look forward to the great things we will accomplish together in the years to come.

Lastly, I thank my family, who has always believed in and supported me throughout all aspects of my life, and who taught me that hard work, self-motivation, and humility are indeed the ingredients for a life of happiness.

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LIST OF ABBREVIATIONS

REMTF	Renewable Energy Modeling Task Force
SMIB	Single Machine Infinite Bus
WECC	Western Electricity Coordinating Council
WPP	Wind Power Plant
WTG	Wind Turbine Generator

CHAPTER 1

WIND TURBINE GENERIC MODELS

1.1 Introduction, Background, and Motivation

Interest in the development and deployment of renewable electrical energy generation resources has grown considerably in the past decade. This is due in large part to overwhelming evidence of anthropogenic climate change and the need for cleaner, more resilient, flexible, controllable, and modernized electric power grids by the industry. Among those technologies at the forefront of this advancement, wind energy penetration has grown considerably in electric power grids worldwide. At the end of 2012, the United States had 60,078 MW of installed wind capacity, and annual capacity additions exceeded 13 GW, making wind the leading source of new national electrical energy capacity, renewable or otherwise, and members of the Western Electricity Coordinating Council (WECC), among others, have acknowledged this growth [2]. Wind power plants (WPPs) containing many wind turbines are often placed in geographic regions where wind flow is consistent and sufficient for such systems, but these locations also tend to be in weaker portions of the transmission network [1].

Given these trends, there is increasing need and interest in understanding and modeling accurately the behavior of power grids containing wind-based electricity generation under various operating conditions and at different analytical timescales. In transmission planning and design studies, transient stability simulations, those simulations which assess the ability of the machines in a power system to return to synchronous frequency with new steady-state power angles following a significant disturbance (e.g., significant generation or transmission capability loss), are of interest. Such analyses are examined in timeframes on the order of 10^{-2} to 10^{2} seconds. These and other such studies require dynamic, or transient, models of the machines in the network for appropriate analysis. As the dominant generation components in the North American power system, synchronous machine transient models have existed for decades, are well understood in the industry, and are typically easily modifiable by engineers and designers in simulation software to represent accurately a system under test [3], [4], [5].

However, despite their increasing penetration, similar flexibility in wind turbine generator (WTG) models in these studies has become possible only recently via the development of generic, non-proprietary models. Prior to efforts of the WECC Renewable Energy Modeling Task Force (REMTF) in the mid- to late-2000s and early 2010s, models of these devices were manufacturer-developed and "black-box" in nature. These models were deficient and causes for struggle in analyses by system planners and compliance organizations. As of 2010, four WTG models have been implemented by the WECC REMTF for bulk power system studies, representing those WTG model types which are most widely used in the Western Interconnection [6]. An excellent description of both the necessity and definition of generic models is found in [7], which states:

> In principle, generic WTG models should exhibit the following characteristics: a) allow for an easy exchange of model data between interested parties, b) facilitate comparisons of system dynamic performance between different simulation programs, c) allow for the implementation of WTG models in different simulation programs, and d) provide a mechanism by which manufacturers can tune the model parameters to best represent their equipment, without having to reveal proprietary information.

1.2 Model Types

While there are numerous varieties of utility-scale WTGs available from a variety of vendors, there are four basic classifications that describe the majority of commercial turbine systems, and these four classifications comprise the generic WTG transient models which have been developed. The models are commonly referred to as Type-1, Type-2, Type-3, and Type-4, corresponding to an induction generator model with fixed rotor resistance, an induction generator with variable rotor resistance, a doubly-fed asynchronous generator with rotor-side converter, and a variable speed generator with full-power converter interface, respectively. These models are shown pictorially in Figure 1.1 [1], [8], [9], [10].

In addition to the generator models, other models comprising the full WTG transient model have also been developed. Typically, generator systems consist of devices including exciters, governors, and stabilizers. However, while WTG systems do not have such devices as part of their physical make-up, components are used in commercial software packages for purposes of creating an analogous set of such models for WTGs. As [10] explains, the full dynamic WTG model consists of five components—the wind machine model, the wind electrical model, the wind mechanical model, the wind pitch control, and the wind aerodynamic model—which are analogously represented in commercial software as the machine model, the exciter, the governor, and the stabilizer, respectively (pitch control and aerodynamic details are lumped into the "stabilizer" model). The sections that follow provide additional information about the four WTG model types in more detail from the standpoint of their development. This information is useful when considering the results of the verification sections given later in this thesis. While the material presented here is mostly to summarize some aspects of these models, more detailed explanations of these models can be found in [7].

1.2.1 Type-1 WTG

The Type-1 WTG model is described as an "induction machine directly connected to the grid" with few controls [6], [11]. As these devices absorb reactive power, commercial installations commonly include shunt capacitors for power factor correction purposes, the Mvar values of which will vary with reactive power demand of the device. It is possible for these devices to introduce a substantial reactive power imbalance with variation in wind speed or greater system operating conditions [6].

1.2.2 Type-2 WTG

The Type-2 WTG model is very similar to the Type-1 model in that it is also an induction machine that requires power factor correction capacitors;

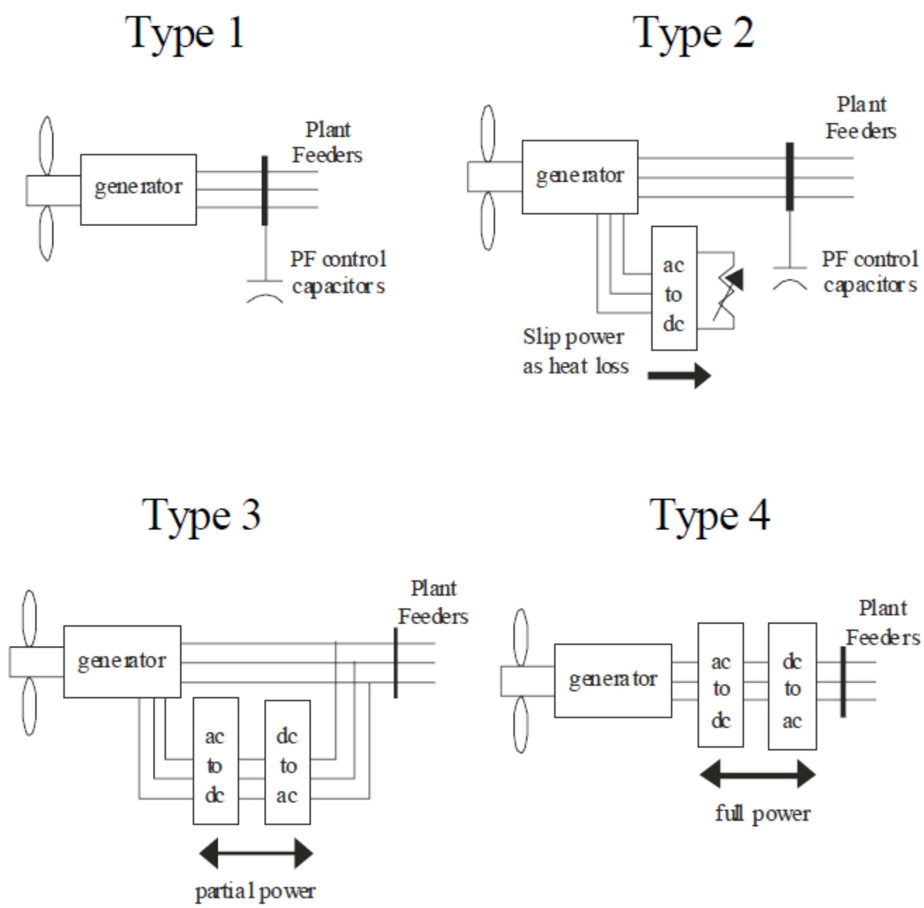

Figure 1.1: Pictorial representations of the four generic WTG models. Image taken from [1]

thus the steady state behaviors of these models tend to be quite similar. However, the Type-2 WTG model's primary difference is its ability to adjust its rotor resistance very rapidly. This permits variable slip operation of the machine well above the rated slip; thus dynamic operation of this device differs substantially from the Type-1 machine [6].

1.2.3 Type-3 WTG

The turbine model with the greatest presence in the bulk power system is the Type-3 WTG. This device is a doubly-fed induction generator, and it can operate over a broader range of speeds than the Type-1 and Type-2 machines [11]. Much of the dynamic and steady-state behavior of these devices is governed by a power converter, which allows for independent control of real and reactive power output. As this section is purely to summarize some aspects of these devices, further explanation of the details of this converter is beyond the scope of this work, and additional information can be found in [7], [12], and [13].

1.2.4 Type-4 WTG

The most recently introduced model, the Type-4 WTG model is internally equipped with the capability of converting power from the turbine at any frequency to the synchronous frequency of the larger grid. These devices, like the Type-3 machines, can operate at a broad range of speeds to optimize energy capture. This machine is unique in that the converter permits decoupling of the generator from the grid; thus a grid-side disturbance should have little impact on the machine itself, and a response would depend most upon the behavior of its converter [11]. Again, details of the modeling of this converter are beyond the scope of this work, and additional information can be found in [11] and [14].

1.3 Developments and Future Goals

Despite tremendous successes in the development of generic WTG models for bulk power system studies, their development is still an active research pursuit. Much effort is being given to model validation as more data is collected, but many scenarios still lack actual data for model-to-data comparison for validation. As [7] indicates, the development of wind power demands accurate modeling, and all parties involved in the deployment of wind power into the bulk power system must be involved in those efforts. Specifically, those manufacturers who hold key insights into dynamic representation of their WTGs must also engage with those developing generic models. Future efforts will produce generic models which are flexible and easily modifiable for those performing system studies, but "[only] with [manufacturer] involvement and cooperation can generic models be developed" to that end [7].

CHAPTER 2

WIND TURBINE TRANSIENT MODEL VERIFICATION

2.1 Background and Motivation

As mentioned previously, a generic model for a wind turbine refers to a member of a class of positive sequence models that attempt to create accurate simulation software implementations of turbine system responses without complete manufacturer design specifications. Such models were developed out of necessity to more accurately understand the impacts of power system stability in the presence of increasing amounts of wind power generation. Much of the effort in their development has focused on producing dynamic responses that align as closely as possible to a limited set of real-world data, while also adhering to the physical nature of the machines.

These models do provide key functionality for addressing transient stability issues in the power system when considering the impacts of wind generation, but their implementation and simulation results across different software packages can, and do, differ. For example, consider the two implementations of the Type-3 WTG given in Figure 2.1 and Figure 2.2, which are the models used in two commercial transient stability simulation packages [15]. Figure 2.1 shows the terminal voltage of the machine ($V_{term}\angle\theta$) being fed to the Low Voltage Active Current Regulation block with the injection current component I_{Xinj} as its only output. This serves as only one of two inputs into the coordinate transformation producing the source current of the unit. Appropriate angles are determined within the Low Voltage Active Current Regulation block, allowing for coordinate transformation without the ange δ being an input. However, the implementation given in Figure 2.2 offers an alternative approach in which the current injection component is calculated directly via a lag block, and the transformation angle δ is calculated explicitly and serves as an input to the transformation. Such implementations might

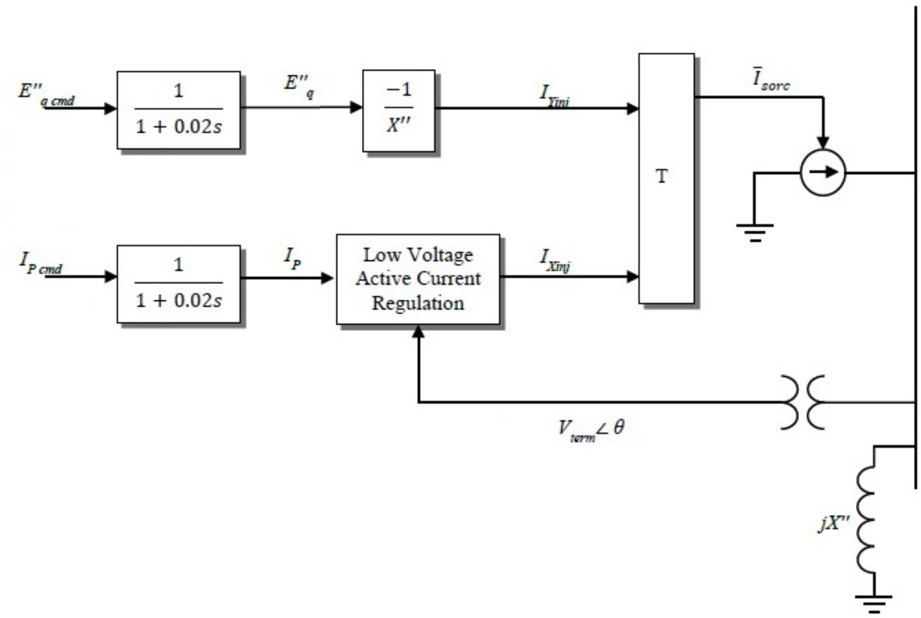

Figure 2.1: Block diagram for Type-3 WTG

be effectively equivalent, but it is possible for these differences to have potentially significant impacts on final results. Please note that this example is not meant to indicate completely disparate implementation objectives or disagreements in the differential equations describing the machines—it is only meant to show that implementations do vary, which is a source of variation in transient stability results in simulation software packages.

With this in mind, as these systems continue to penetrate power grids around the globe, a verification methodology is needed to examine and address such inconsistencies across these packages. This work focuses primarily on the examination and exposure of differences in software implementations and results, as it is important for users of these programs to be aware of the possibility for simulation results to vary. Therefore, the objective of this thesis can be summarized as follows: to apply concepts of model-to-model verification to WTG systems such that variation in transient stability simulation software is acknowledged and addressed. It is the author's goal to inform the power system community and the users of such software of these possible variations as studies containing such systems become more prevalent. Details of this approach and its results are described in the subsequent sections of this thesis.

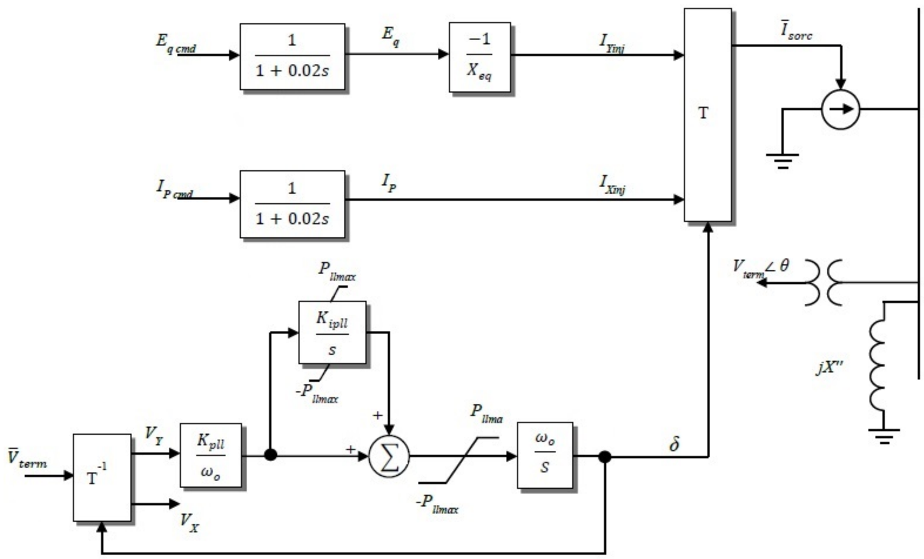

Figure 2.2: Block diagram for alternative implementation of the Type-3 WTG

2.2 Verification: Objectives, Definitions, and Approaches

Traditionally, validation of power system transient stability simulation software is defined as a one-to-one comparison of simulation results with real-world data, with the objective being the choice of transient model parameters that achieve near-matching responses. It should be noted that these results may not always be exact, and that simulation tolerances are typically dependent upon the engineering judgment of those conducting the validation work. However, due to a lack of real-world data for many such dynamic scenarios, and ultimately of transient stability analysis results in general, we adopt the methodology described in [16] and pursue model-to-model verification of software implementations. That is, we will perform dynamic simulations in various commercial power system transient stability software packages and compare their results directly without the consideration of real-world data. Three widely-used transient stability software packages are considered for this work; to preserve confidentiality, the names of these packages will not be specified, but instead referred to as Package A, Package B, and Package C.

In this work, two transient conditions are simulated for the purposes of model verification: a balanced three-phase bus fault at the location of the WTG model in a Single Machine Infinite Bus (SMIB) system and a system frequency disturbance injection in a similar two-bus representation. The former follows a similar verification approach to the one outlined and used in [16], while the latter is considered for the purposes of extension of those concepts to other transient conditions. It should be noted that the specific simulations performed in this thesis are not necessarily representative of real power system transient conditions, and these simulations may not produce results which reflect reality. However, it is important to acknowledge the potential for differences across commercial software packages, and this work seeks to illustrate this concept. The subsequent sections motivate and provide further detail about the development of the cases used for this work, as well as further detail about the two simulation approaches considered.

As there are nearly infinite simulation cases and transient condition combinations which could be examined and compared, it is impossible and unnecessary to test every possible transient scenario. However, these simulations will provide insights about the nature of the model implementations and serve as an indication of the possible variations between them. These and other such validation and verification studies may reduce differences in software implementations, allowing for congruency across engineering and planning platforms as wind-based power generation continues to expand.

2.2.1 Simulation Case Development

The SMIB equivalent circuits used in the simulations, which are created using well-understood network reduction techniques described in [17], consist of the full wind generator model connected to an infinite bus through its driving point impedance. Figure 2.3 shows the full SMIB representation of WTG models in most simulation cases (figure taken from [1]). All of the SMIB equivalent circuits were developed using Package A, because it has the capability of translating both static and dynamic case data to other simulation package file formats. In addition, it allows the user to simulate both Package B- and Package C-implemented models. Each case was created using a larger system model containing each of the four WTG model types developed for practical system studies (i.e., a ‘working case’). This approach was used to ensure that model parameters and operating conditions would be such that the equivalent circuits would represent actual, and practical, device operation as closely as possible. In these analyses, we set WTG output at values higher than that of an individual turbine, effectively using a single WTG to represent a WPP. This is common practice for the dynamic modeling of WPPs [18].

The larger working case from which the WTG SMIB equivalents were developed was originally built using only Package B models; therefore Package C cases were created by changing the corresponding dynamic models directly and matching model parameters as closely as possible. As mentioned previously, models between Package B and Package C are not necessarily identical; therefore, for the purposes of these specific simulations (as well as others that are not considered in this thesis), modifications are often necessary to compensate for differences in parameter inclusion and/or exclusion. Details of such modifications are discussed later.

To limit possible issues with the simulations, and since we are strictly concerned with direct comparisons of simulations using the same model types, the operational dynamic parameters, real and reactive power output, etc., for each generator are all preserved following their respective equivalencing for the three-phase fault condition. As machine outputs are effectively arbitrary in the context of SMIB systems, real and reactive power outputs are adjusted for the frequency disturbance simulations for purposes of variation in operating conditions. Additionally, some specific simulation considerations for each model type were considered according to [1]. A general WTG SMIB representation taken from [1] is shown in Figure 2.3. Some elements of this model, such as the plant-level reactive compensation, were not included in this analysis because their impacts can effectively be neglected in the time frame of transient stability examinations.

2.2.2 Balanced Three-phase Fault with SMIB System

For the SMIB bus fault simulations, a dynamic condition is introduced by applying a balanced three-phase fault at the bus location of the WTG model under test for all four WTG model types. As explained in [16], this approach provides an indication of the stability of the WTG in the greater network, and

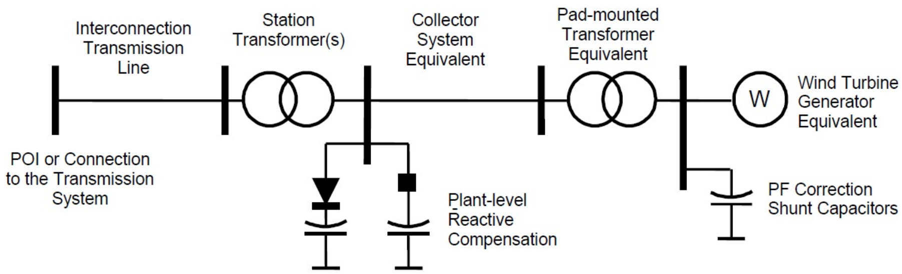

Figure 2.3: Full SMIB representation of WTG models in simulation software

transmission faults are examinations among those of interest to the WECC REMTF as generic WTG models continue their development and refinement [6]. The fault is introduced at 1 second and cleared 0.05 seconds later. A simulation time step of one-quarter cycle was used in all studies. Parameters including the real and reactive power output of each WTG and bus voltage are compared in this study as they convey effectively the degree of discrepancy among the simulation platforms considered. These parameters are also among those which are consistent as outputs across the simulation packages. Some output parameters of particular interest in transient stability simulations, such as bus frequency, are not always available for all models used in the software packages considered; thus limits exist on what we can observe and compare for verification studies.

2.2.3 Frequency Disturbance Injection

Broadening the scope of the dynamic simulation verification approach, frequency disturbance injections are applied to an equivalent two-bus system for each WTG model via signal play-in modeling. The systems used are equivalent to those of the balanced three-phase bus fault studies with the exception of their respective real and reactive power outputs. The disturbance is comprised of a frequency drop of 1% of the 60 Hz synchronous frequency. The disturbance is applied at 1 second, and the system is returned to the 60 Hz synchronous frequency at the 15 second point in the simulation. A plot of the disturbance considered is shown in Figure 2.4.

Simulations of such a disturbance are not a recent development, but this functionality is fairly new in Package C. Because of this, frequency distur-

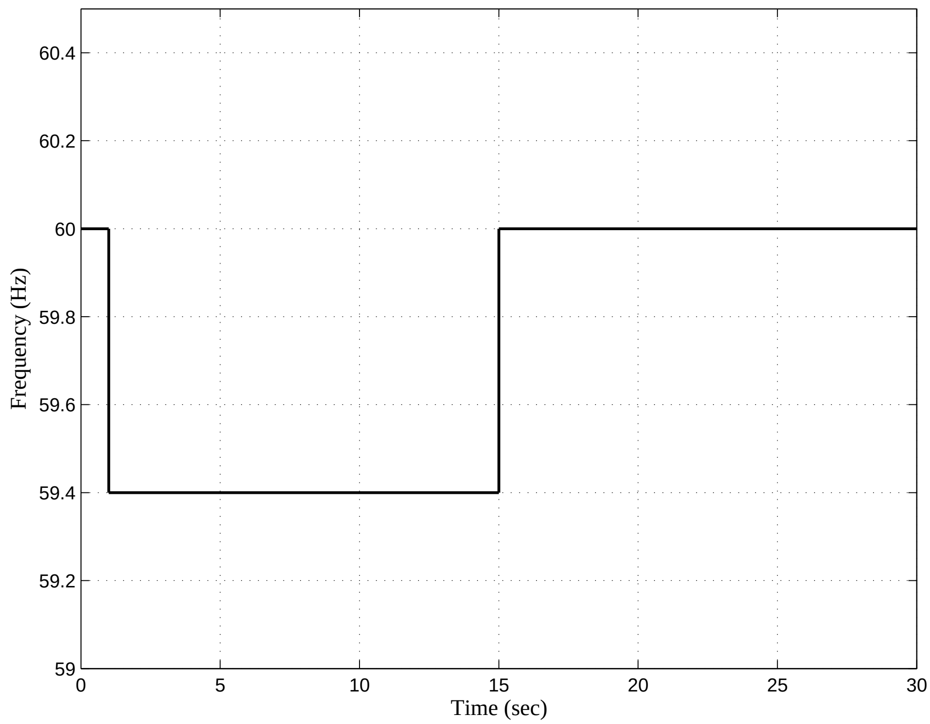

Figure 2.4: Frequency disturbance used in WTG verification approach

bance play-in functionality in Package C requires simulation considerations which, based on the judgment of the author, are not conducive for making one-to-one comparisons between the packages. Due to these limitations, the author neglects it in this component of the verification procedure and instead focuses on a comparison between Package A and Package B, which have more well-developed frequency play-in modeling functionality. Despite this, it is still important that frequency disturbance results be examined and compared using Package C, and this is mentioned again later in the "Future Work" section of this thesis. It should be noted that Package B guidelines indicate that its wind turbine models were not developed to be necessarily accurate in frequency excursion simulations. However, this study will still provide insights into the response of these devices to such disturbances as they exist today.

CHAPTER 3

VERIFICATION RESULTS

In this chapter, the results of the balanced three-phase fault and frequency disturbance verification approaches are presented for the four WTG model types. In essence, these simulations are a collection of case studies intended to illustrate potential variation in equivalent networks containing WTGs, and more detailed discussion of the potential source of these variations is a future component of this work. Good references for appropriate modeling of power systems with WTGs are [1] and [18], where guidelines are presented for ensuring systems reflect reality as closely as possible.

3.1 Single Machine Infinite Bus Verification Approach

3.1.1 Type-1 WTG Model

From [6] we know that specific considerations must be given to each WTG model type for proper SMIB modeling setup. In the case of the Type-1 WTG, power factor correction capacitors, which can be modeled as a single capacitor unit, are added to bring the unit's power factor to unity at nominal voltage. With this in mind, these are modeled as fixed shunt devices in the power flow, and are added following SMIB equivalencing. Arguably the simplest of the four WTG model types, the Type-1 dynamic models are nearly identical across Packages A, B, and C. Therefore, no further modifications are necessary to compensate for implementation differences.

Comparative plots of bus voltage and real and reactive power output of the Type-1 WTG are shown in Figures 3.1, 3.2, and 3.3, respectively. In every case, results were nearly equivalent across all the simulation packages. This can be attributed to both the simplicity of the model, as well as the extensive development of this generic model over time. [bb=0 0 966 503,scale=0.4]

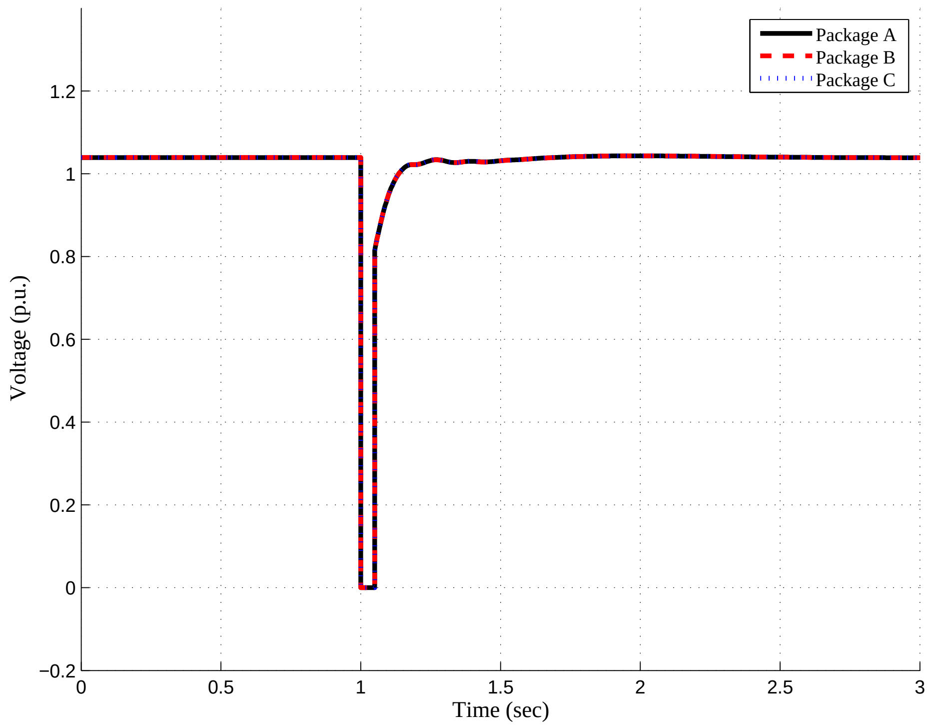

Figure 3.1: Bus fault verification approach—voltage comparisons, Type-1 WTG model

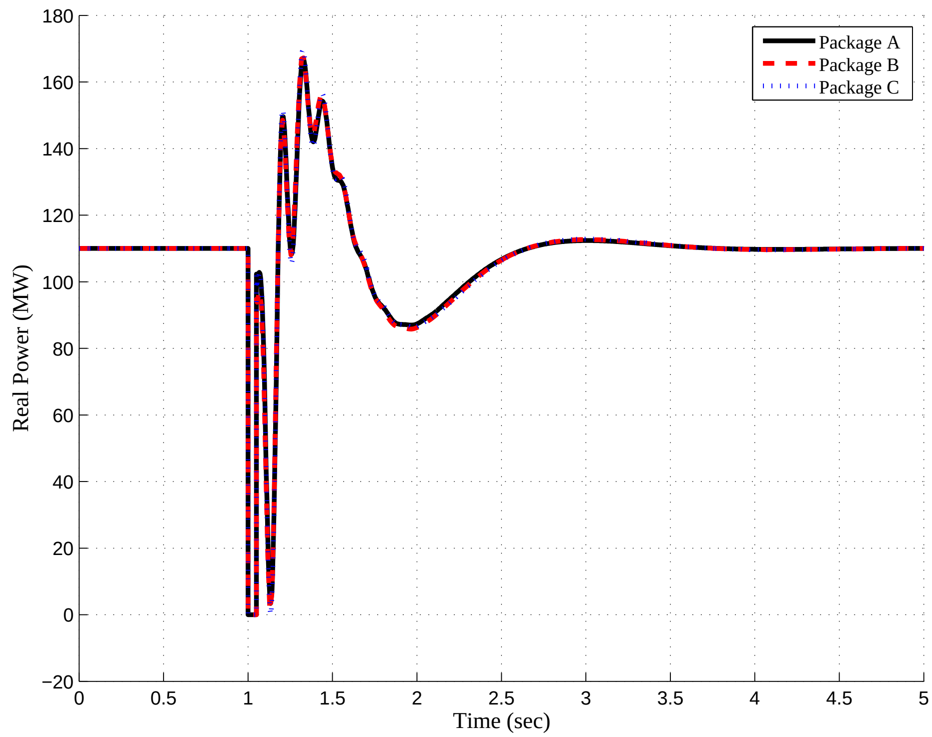

Figure 3.2: Bus fault verification approach—real power comparisons, Type-1 WTG model

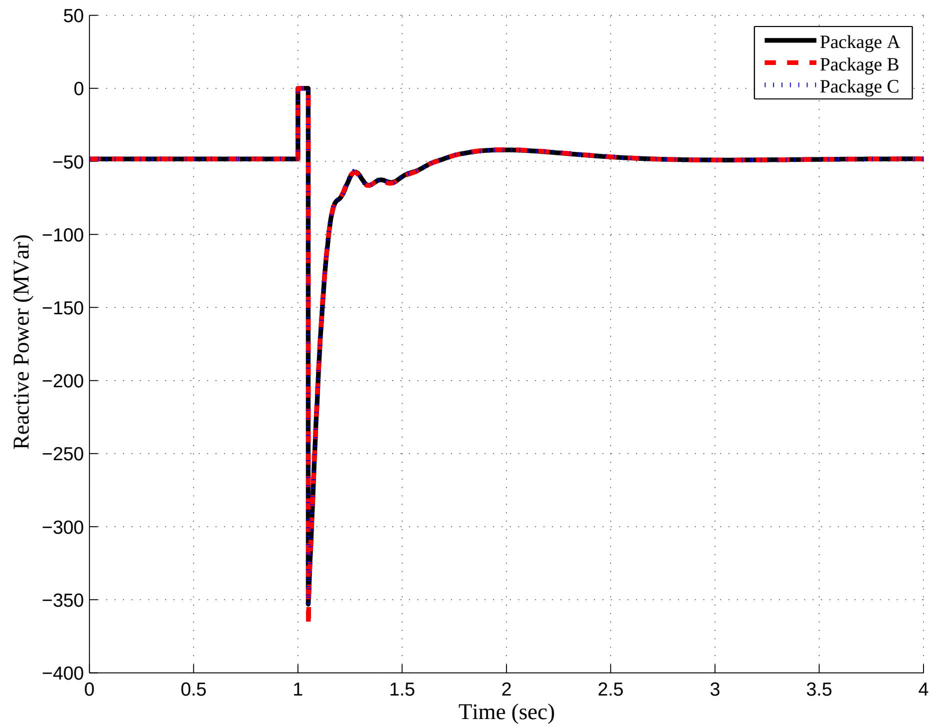

Figure 3.3: Bus fault verification approach—reactive power comparisons, Type-1 WTG model

3.1.2 Type-2 WTG Model

As was the case for the Type-1 model, Type-2 WTG simulations should include shunt power factor correction capacitors to bring the nominal power factor to unity, and, like in the Type-1 cases, these devices were added following equivalencing. Unlike the Type-1 WTG model, not all implementations of the Type-2 WTG are identical across simulation platforms. Due to this fact, there were issues of the dynamic simulation not flat-starting, i.e. an unsuccessful no-disturbance run. That is, derivatives prior to the bus fault were nonzero following the translation of Pack-age B models in the working case of Package C models. Specifically, the rotor reactance and the exciter parameter ROTRV_MAX, the maximum external rotor resistance, for the WTG were not properly assigned upon initialization in Package C, and were adjusted from values of 0.18 and 0.0977 to values of 0.30138 and 0.25, respectively, in order to account for those unstable initialization issues. Package B had no such issues and flat-started without problems. These parameter changes were also made in Packages A and B for consistency.

Comparative plots of bus voltage and real and reactive power output of the Type-2 WTG are shown in Figures 3.4, 3.5, and 3.6, respectively. Variations among the implementations are more apparent in this case, but in general the results follow similar profiles and approach the same steady state values. Of particular interest are the post-fault transient behavior of the real power output waveforms. These curves tend to match reasonably well across the three models, with the exception of the lower damping in the real power transient behavior shown by Package C's results, and the lower-magnitude spike in the initial response of the Package B real power results. These variations suggest that dynamic model parameter adjustment should be able to address most of the issues causing variation for the remainder of the simulation.

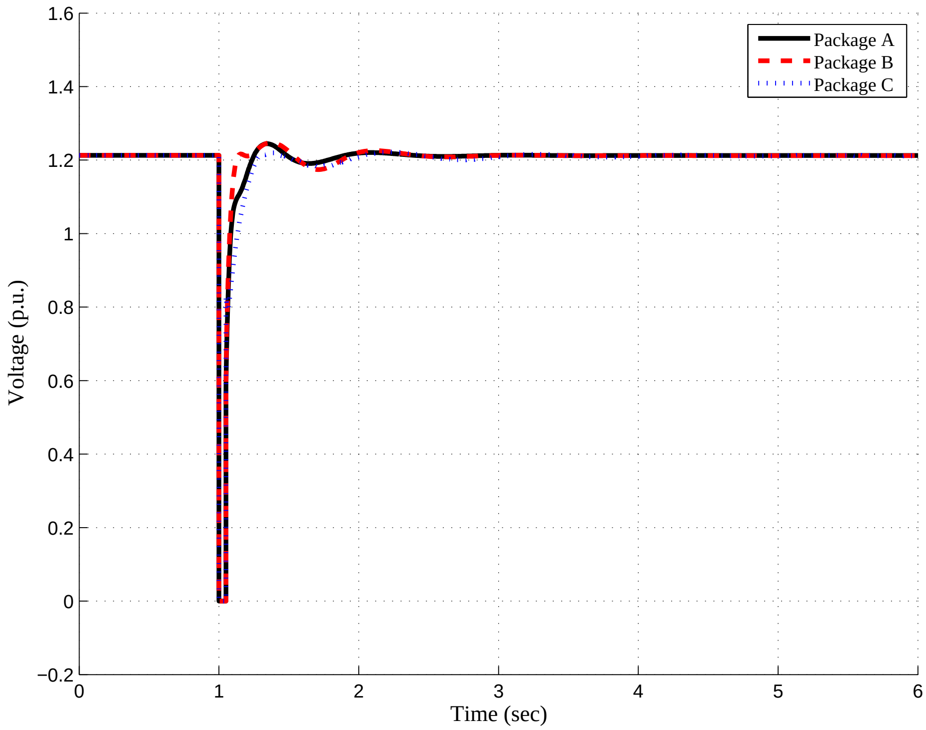

Figure 3.4: Bus fault verification approach—voltage comparisons, Type-2 WTG model

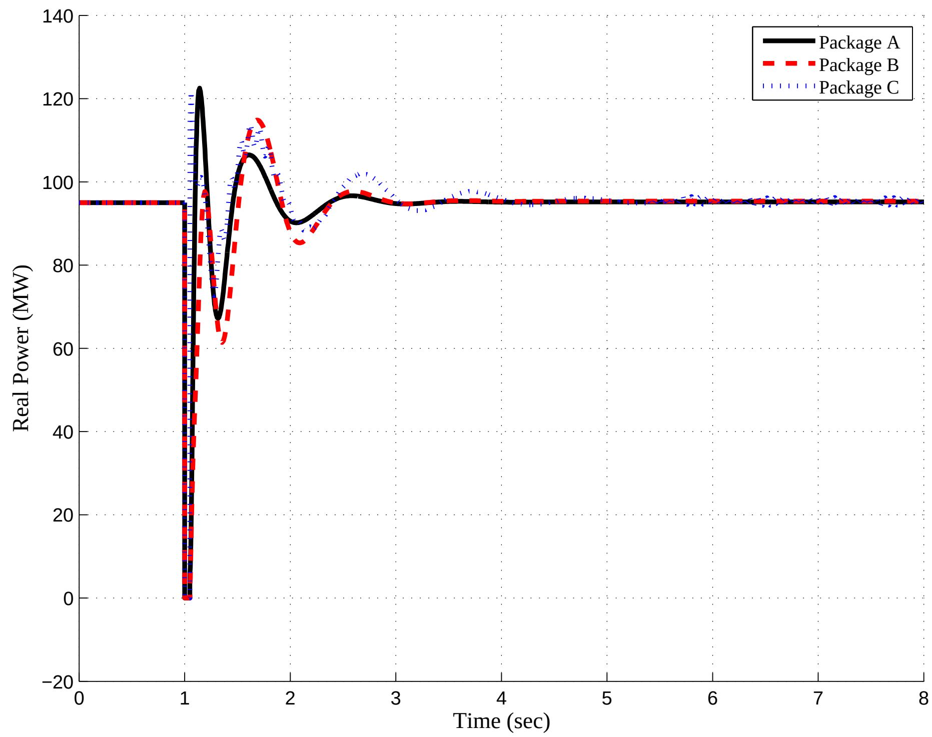

Figure 3.5: Bus fault verification approach—real power comparisons, Type-2 WTG model

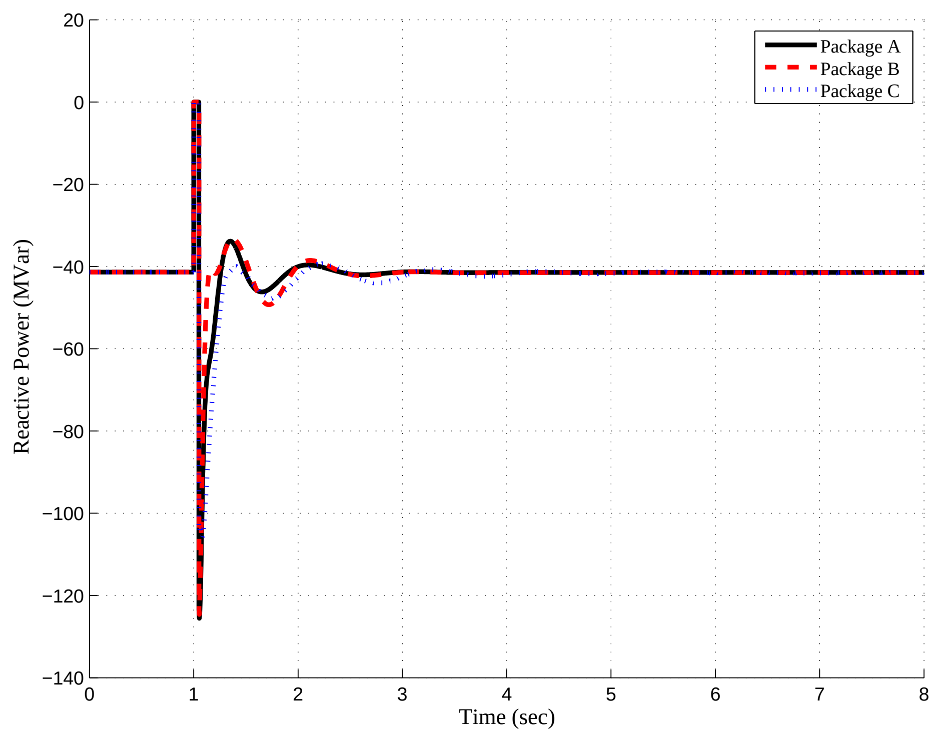

Figure 3.6: Bus fault verification approach—reactive power comparisons, Type-2 WTG model

3.1.3 Type-3 WTG Model

Unlike Type-1 and Type-2 models, the controls inherent to the Type-3 WTG allow for systems without power factor correction capacitor units. The Type-3 simulations, also due to some degree of discrepancy in implementation, would not initially flat-start upon translation using Package A. In [18], dynamic simulation parameters are specified which provide a reasonable order of magnitude for assigning various values when such data is unknown. Those values which did not directly translate between the different software packages were assigned according to these reference values as opposed to using default values in the software. Additionally, dynamic parameter values were adjusted according to [18] in Package A, producing a case which still flat-started, and resulted in a case in Package B and Package C that also flat-started.

Comparative plots of bus voltage and real and reactive power output of the Type-3 WTG are shown in Figures 3.7, 3.8, and 3.9, respectively. Results are similar, but more obvious variation appears in these simulations compared to those of the previous two model types. As shown, Package A and Package B results tend to match quite well, while results in Package C tend to have differences across the simulations.

In the voltage waveform comparisons for this model, Package C exhibits an overshoot higher than that of Package A and Package B, as well as a voltage initialization approximately 0.04 p.u. higher than Package A and Package B. The initialization error is likely due to a slight variation in the power flow solution result used for initialization. In the real power comparisons, Package C exhibits a sudden spike following the fault clearance before settling to its final value. In this simulation, Package C also tends to oscillate more before reaching steady-state when compared to the other packages' results. The reactive power comparison shows reasonably consistent results across all packages, with the exception of Package A and Package B exhibiting momentary spikes of absorption of over 100 Mvar.

With this in mind, some degree of modification to dynamic parameter limits should be made to restrict the values shown in the figures to some that more accurately depict reality, and this is a goal of future validation work. Such potential issues should be recognized by those using different simulation packages for studies. It should be noted that modifications were

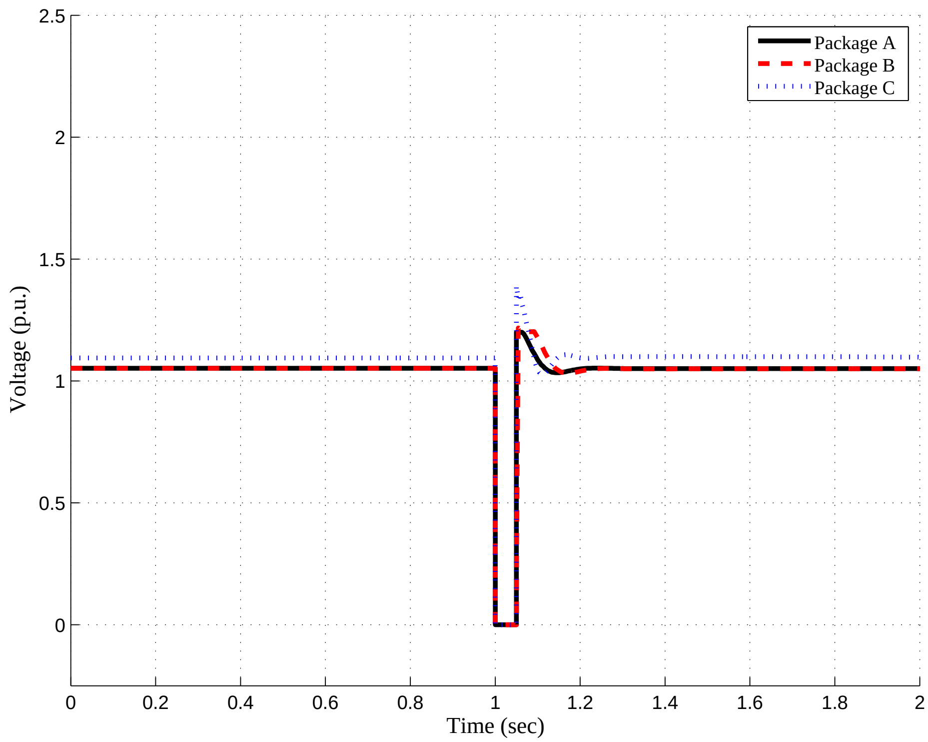

Figure 3.7: Bus fault verification approach—voltage comparisons, Type-3 WTG model

held to a minimum during these studies in an attempt to preserve as closely as possible those parameter values being used in actual real-world working cases.

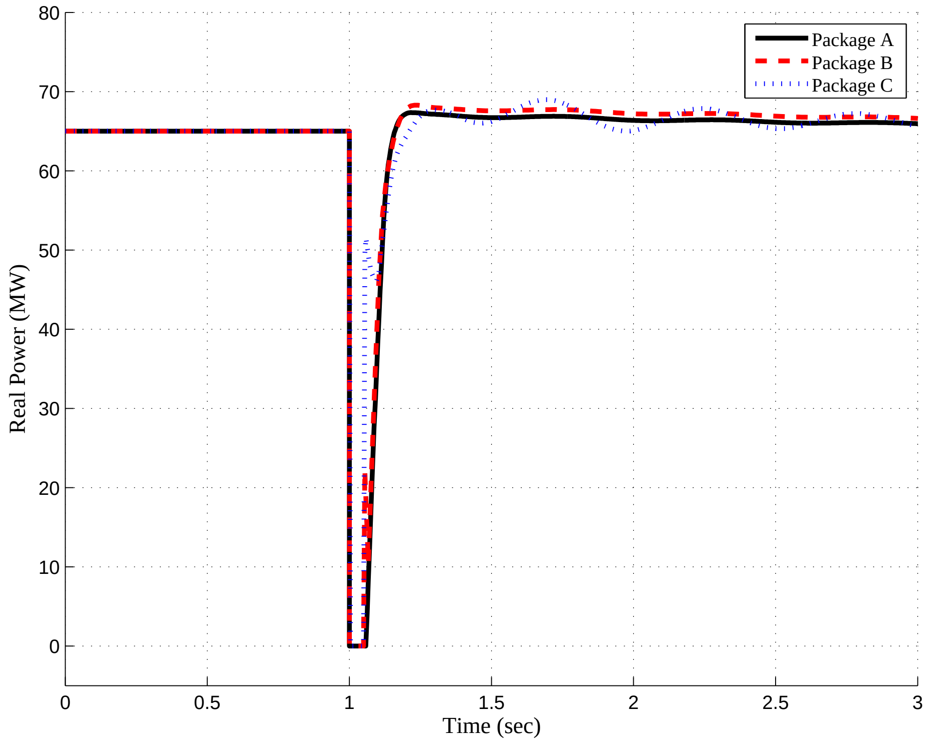

Figure 3.8: Bus fault verification approach—real power comparisons, Type-3 WTG model

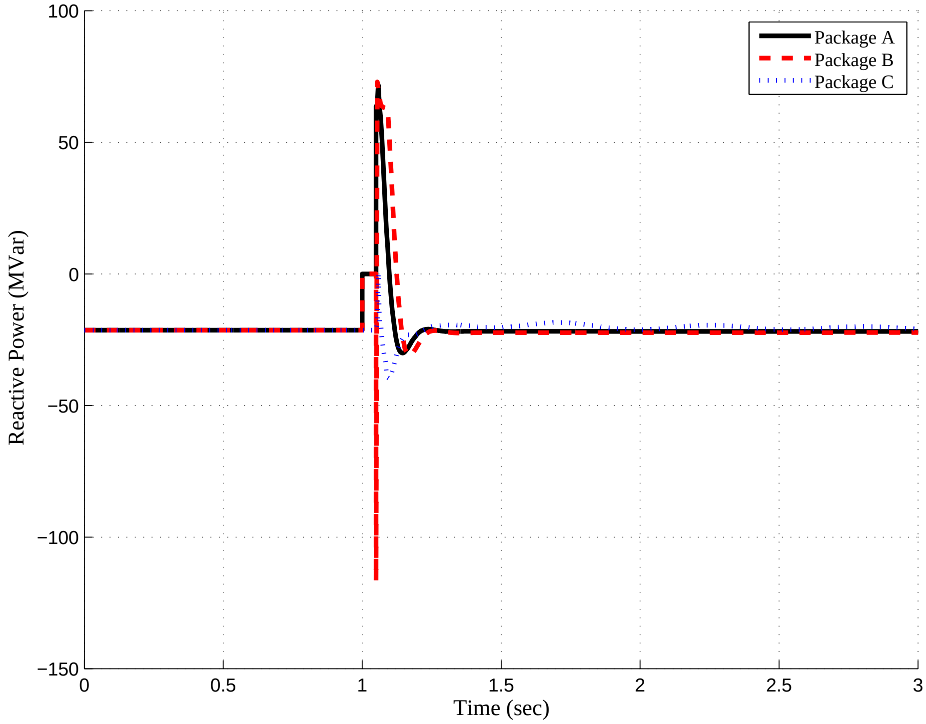

Figure 3.9: Bus fault verification approach—reactive power comparisons, Type-3 WTG model

3.1.4 Type-4 WTG Model

The Type-4 WTG Model is a full-converter model, and, as in the Type-3 simulations, does not require power factor correction capacitors. Its implementation is also quite consistent across the three simulation platforms, and no initialization issues were encountered.

Comparative plots of bus voltage and real and reactive power output of the Type-4 WTG are shown in Figures 3.10, 3.11, and 3.12, respectively. Here, similar to the results of the Type-1 models, overall consistency does appear between the model implementations. The bus voltage transient response shows only variation in the initial response of the Package B model, where the magnitude is approximately 0.19 p.u. higher than that of the other packages, but it quickly settles to a result very similar to Package A and Package C. The real power output results are of note, where the resulting waveform experiences little overshoot across all simulation platforms. This is due to the structure of the model and its internal power electronics models. This plot also indicates a near-identical response between Package A and Package B, while the Package C model approaches its final steady state value more slowly. The reactive power results for the Type-4 WTG model comparisons also indicate a near-identical match between Package A and Package C, while Package B has a much higher overshoot at the time the bus fault is introduced, and a sudden period of high reactive power absorption following fault clearing.

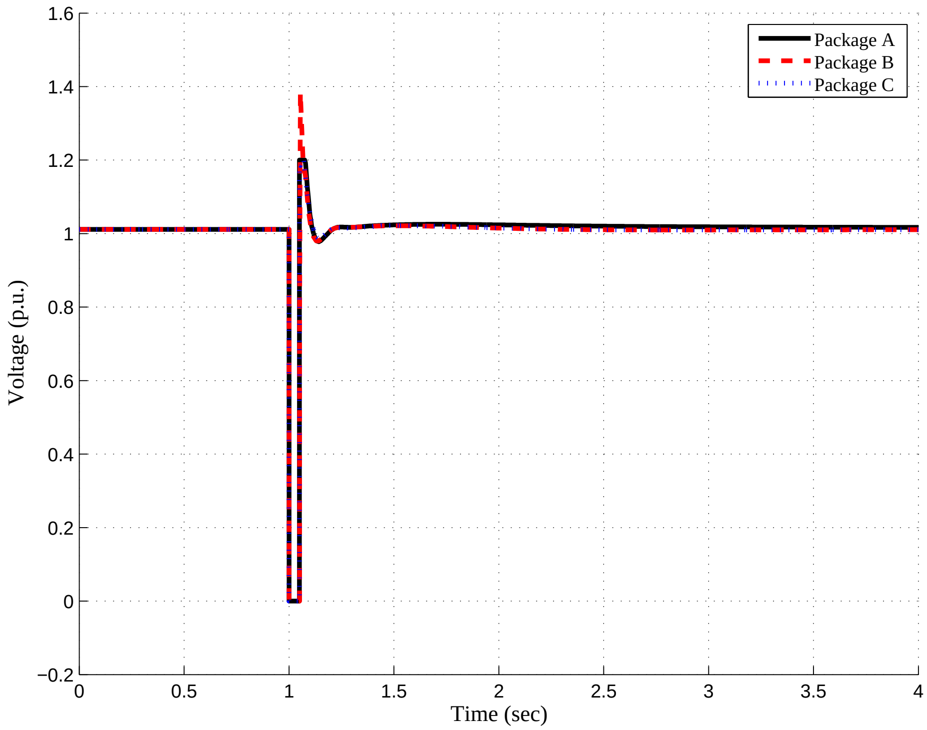

Figure 3.10: Bus fault verification approach—voltage comparisons, Type-4 WTG model

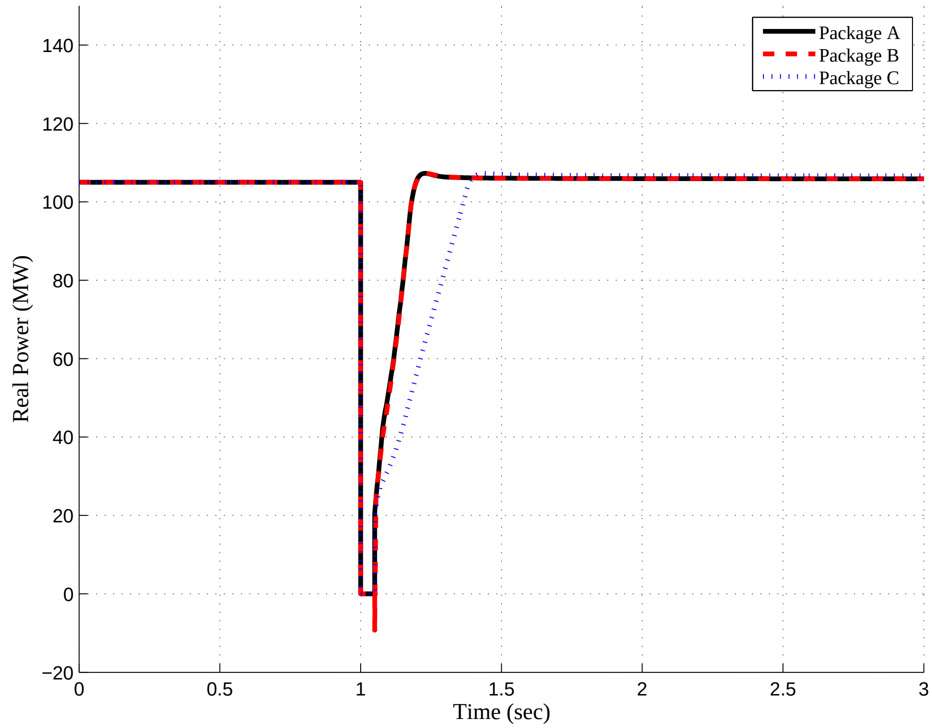

Figure 3.11: Bus fault verification approach—real power comparisons, Type-4 WTG model

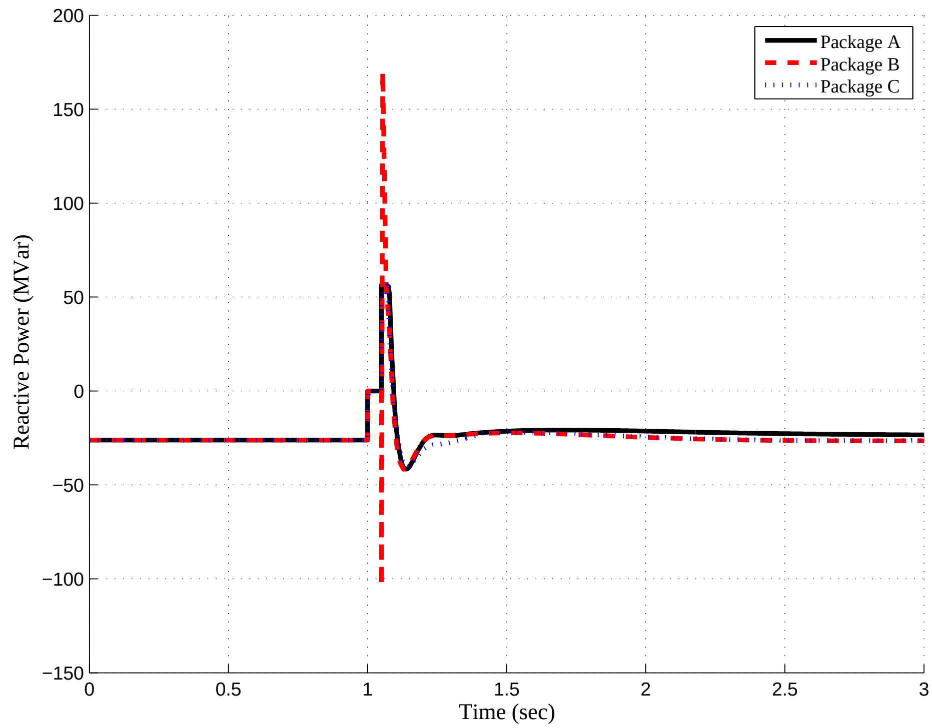

Figure 3.12: Bus fault verification approach—comparison of reactive power results, Type-4 WTG model

3.2 Frequency Disturbance Verification Approach

As in the previous section, specific considerations must be shown when simulating systems containing the various WTG model types (the inclusion/exclusion of power factor correction capacitors, dynamic model parameters, etc.). Differing from the previous section, WTG model voltage setpoint values and real and reactive power output values in the frequency disturbance simulations are changed from values given in the larger working case to values of 1.087 p.u., 5 MW, and -2.5 Mvar, respectively. The voltage setpoint value is a value retained from one of the bus fault verification cases, and power output values are assigned arbitrarily to illustrate further the possibility for variation in simulations despite differences in such initial values.

3.2.1 Type-1 WTG

Comparative plots of bus voltage and real and reactive power output of the Type-1 WTG are shown in Figures 3.13, 3.14, and 3.15, respectively. Overall, responses among Package A and Package B are very well-aligned, with a slight difference during the “intermediate” steady state portion of the frequency disturbance when the frequency drop is at its lowest.

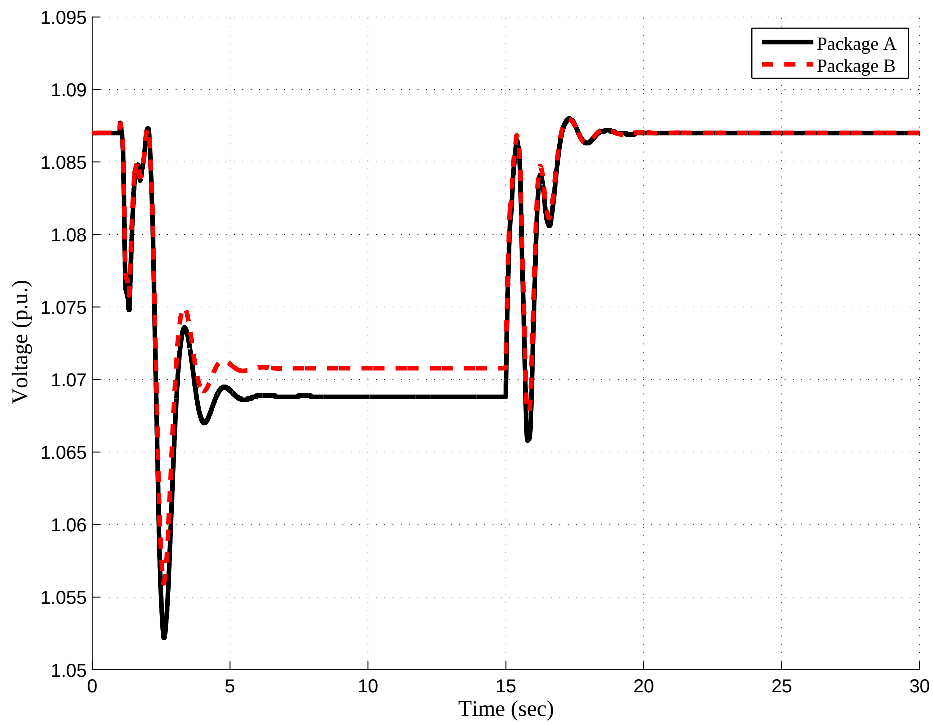

Figure 3.13: Frequency disturbance verification approach—voltage comparisons, Type-1 WTG model

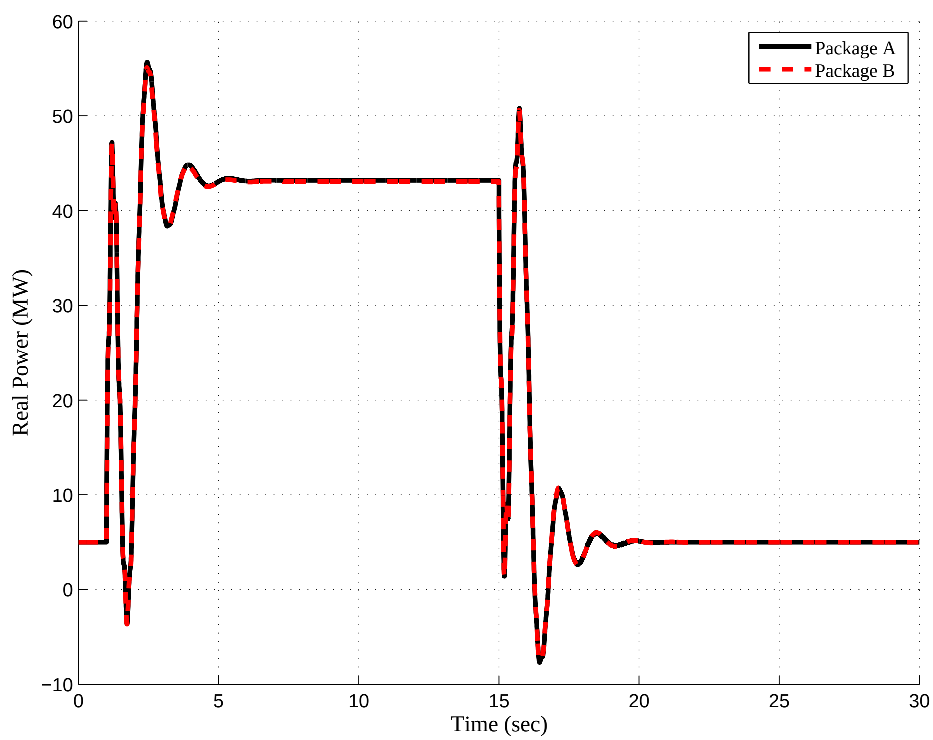

Figure 3.14: Frequency disturbance verification approach—real power comparisons, Type-1 WTG model

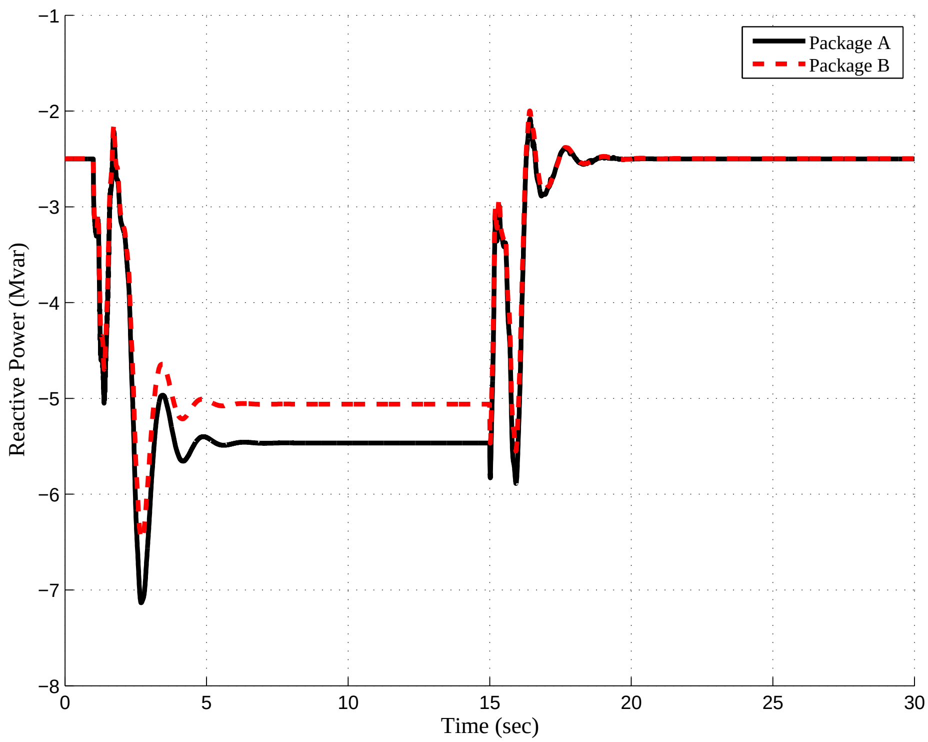

Figure 3.15: Frequency disturbance verification approach—reactive power comparisons, Type-1 WTG model

3.2.2 Type-2 WTG

Issues were encountered in frequency disturbance comparisons for the Type-2 WTG. Specifically, despite a near one-to-one translation of dynamic model data from Package A, those parameter values used in Package A did not produce a corresponding Package B simulation case which would flat-start. It should be noted that these values produced a successful flat-starting simulation in Package A. To maintain adherence to the goals of this work, dynamic parameter values were not drastically modified in an attempt to produce a flat-starting case in Package B, and a valid comparison of the Type-2 WTG frequency disturbance results for the two packages is not given here, and is instead considered for future research efforts. However, simulation results of bus voltage magnitude and real and reactive power outputs using Package A are given in Figure 3.16, Figure 3.17, and Figure 3.18, respectively, to provide an indication of the response of this device. Similar challenges were encountered in other simulations comprising this thesis, and relatively minor modifications to parameter values were necessary to produce equivalent

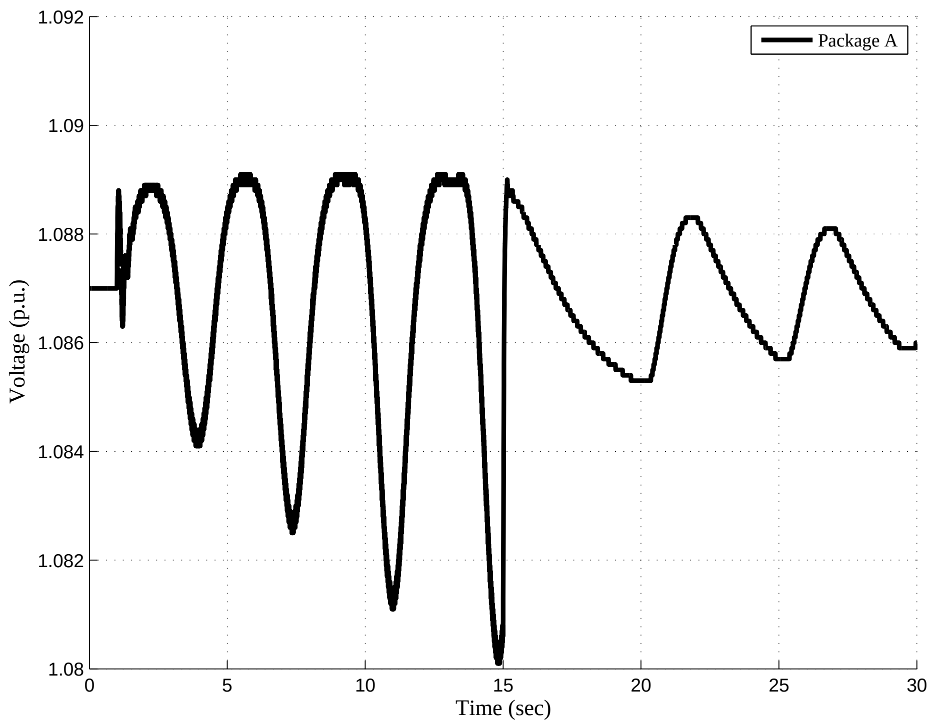

Figure 3.16: Frequency disturbance verification approach—voltage response, Type-2 WTG model

simulation cases, but this was not the case for this particular simulation.

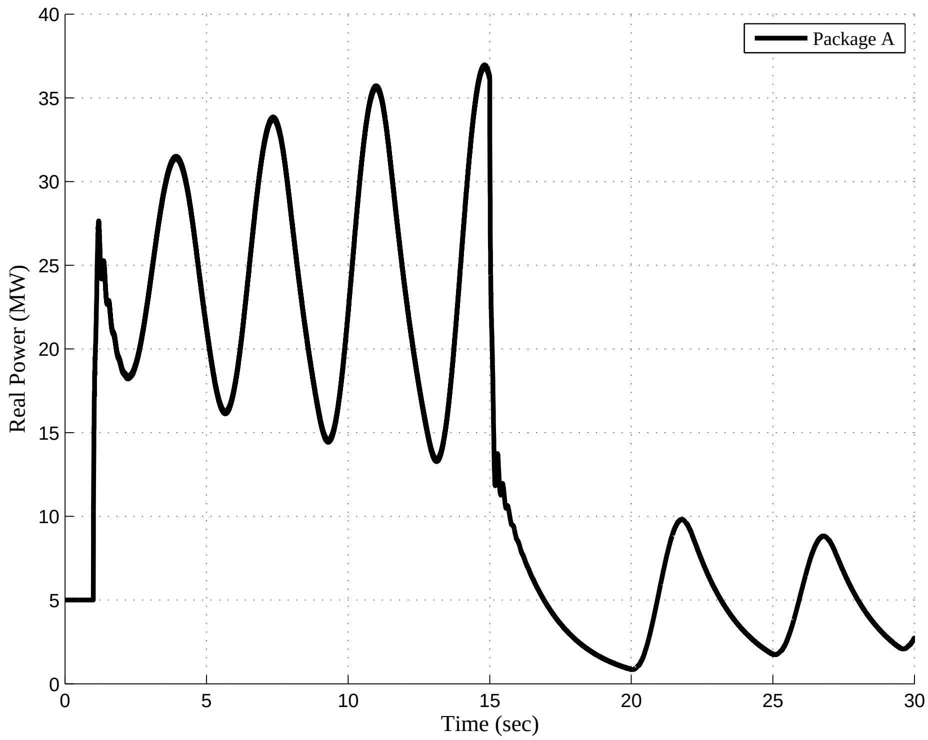

Figure 3.17: Frequency disturbance verification approach—real power response, Type-2 WTG model

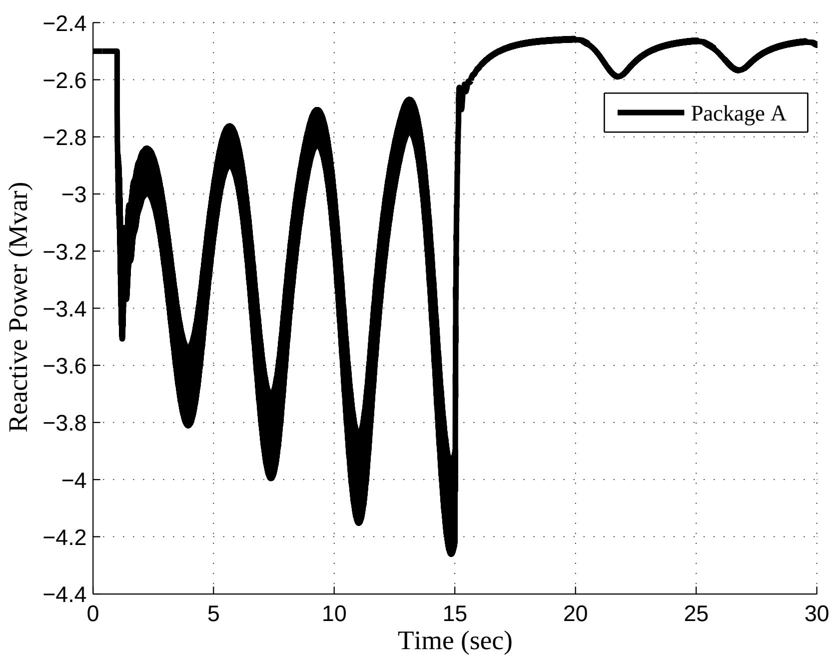

Figure 3.18: Frequency disturbance verification approach—reactive power response, Type-2 WTG model

3.2.3 Type-3 WTG

Comparative plots of bus voltage and real and reactive power output of the Type-3 WTG are shown in Figures 3.19, 3.20, and 3.21, respectively. In these results, Package B exhibits oscillatory response to the frequency disturbance, while Package A exhibits either very little or no response. In general, it is reasonable to assume that the results match well, with the only exception being the real power output result. Package A exhibits near zero (a change of +0.0002 MW according to numerical results) power output increase, while Package B increases to an average output of approximately 5.2 MW.

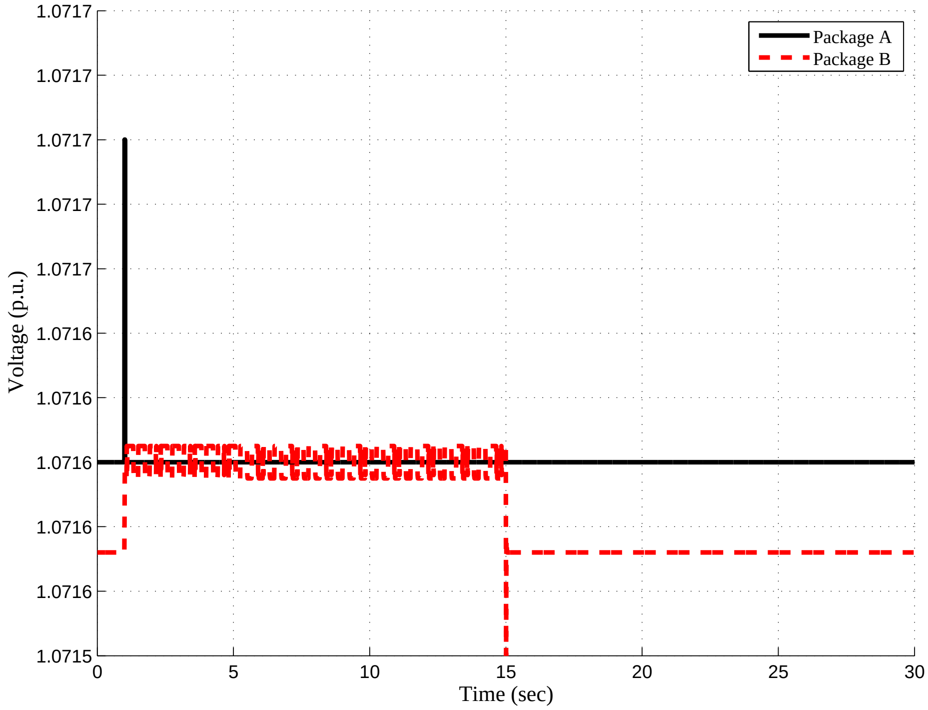

Figure 3.19: Frequency disturbance verification approach—voltage comparisons, Type-3 WTG model

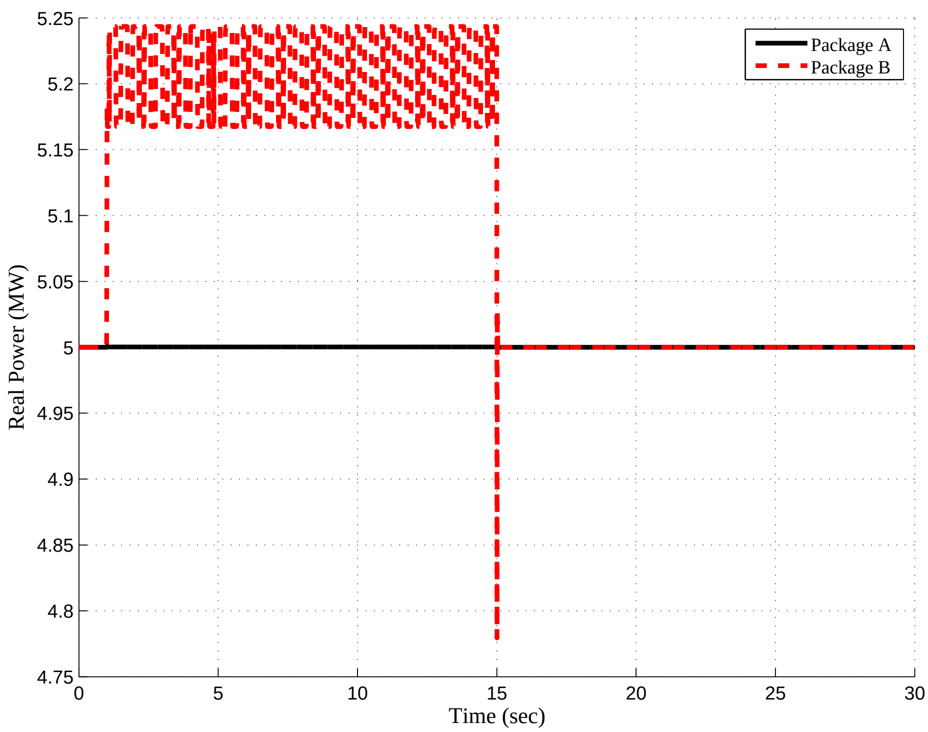

Figure 3.20: Frequency disturbance verification approach—real power comparisons, Type-3 WTG model

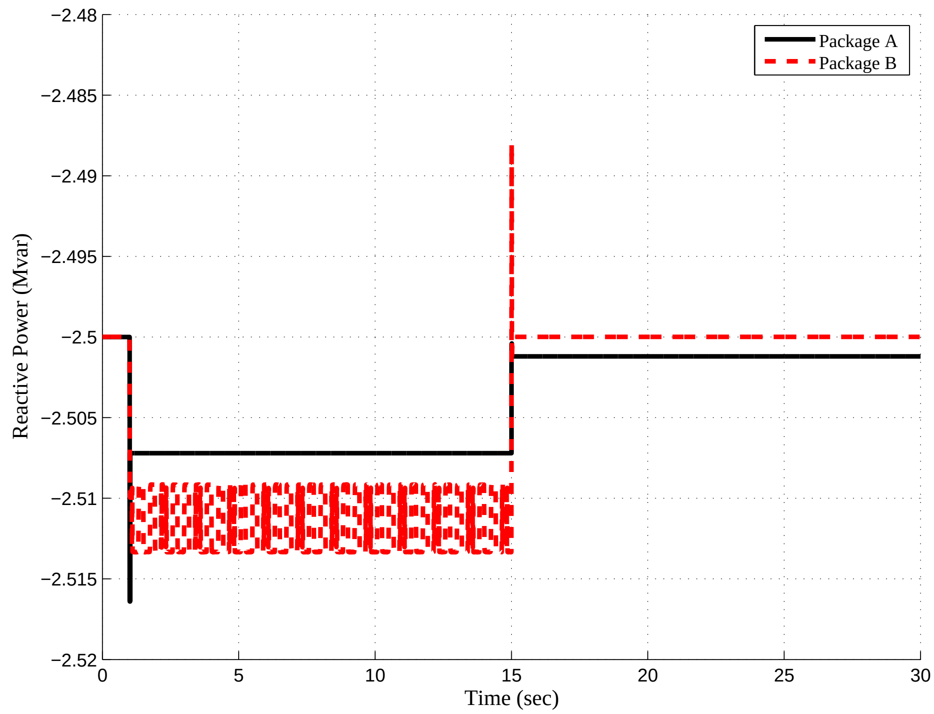

Figure 3.21: Frequency disturbance verification approach—reactive power comparisons, Type-3 WTG model

3.2.4 Type-4 WTG

Comparative plots of bus voltage and real and reactive power output of the Type-4 WTG are shown in Figures 3.22, 3.23, and 3.24, respectively. Interestingly, Package A exhibits zero response in all cases to the frequency disturbance in all results while Package B clearly demonstrates a response, though slight, given by a -0.02 MW and -0.06 Mvar deviation in real and reactive power output, respectively, and a slight (-0.002 p.u.) deviation in bus voltage during the disturbance. Given the order of magnitude in variation between the results of the two simulation packages, overall results in a larger simulation would align quite well despite the variation shown here.

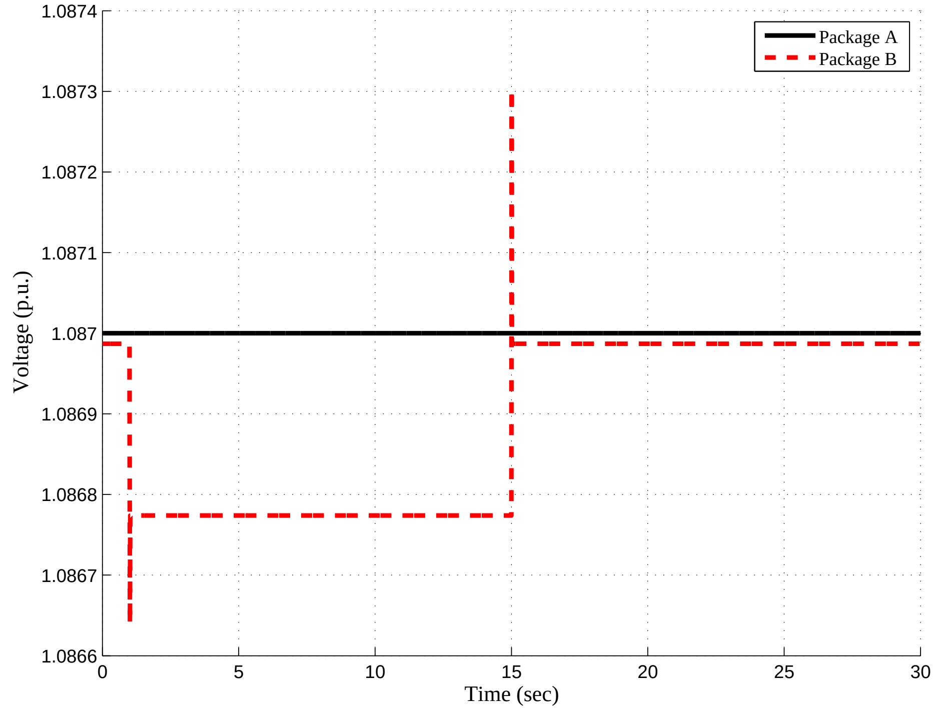

Figure 3.22: Frequency disturbance verification approach—voltage comparisons, Type-4 WTG model

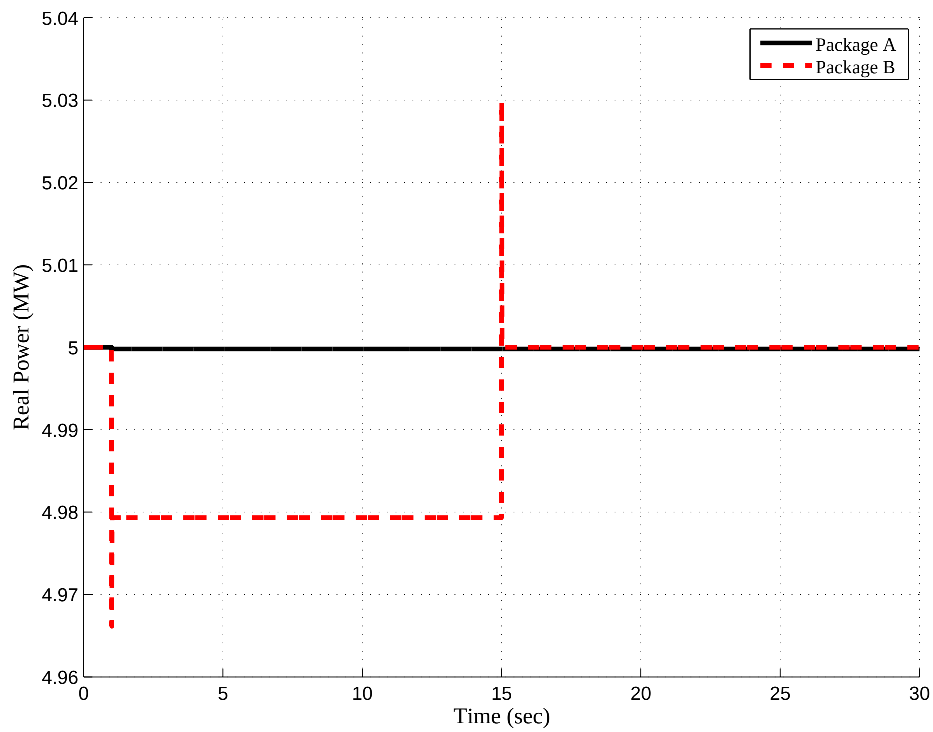

Figure 3.23: Frequency disturbance verification approach—real power comparisons, Type-4 WTG model

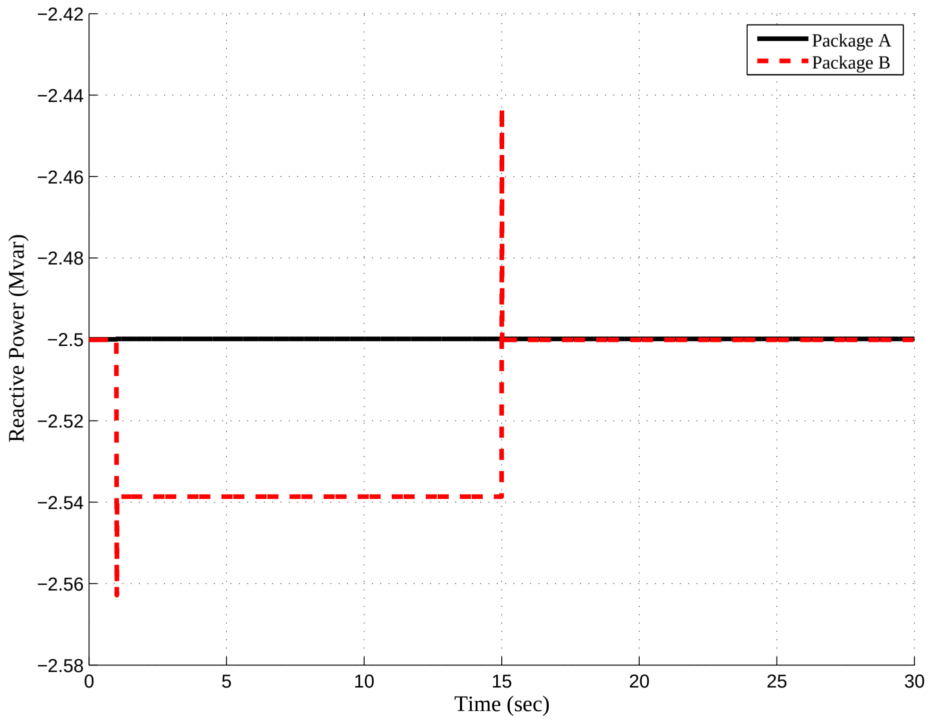

Figure 3.24: Frequency disturbance verification approach—reactive power comparisons, Type-4 WTG model

CHAPTER 4

CONCLUSION AND FUTURE WORK

Power grids across the globe are experiencing considerable changes in a variety of ways, particularly in the variety of their generation mix. Solar- and wind-based energy resources provide many environmental and economic benefits, but their increasing penetration is not without interesting technical challenges. As wind is the leading source of new electrical energy capacity in the United States, appropriately modeling its increasing impact on power grids is imperative. While proprietary models for wind turbines have been developed for power system studies, their inflexibility does not allow for appropriate representation in many power system simulations. Generic turbine models have been developed to account for these deficiencies, but due to implementation differences in commercial software, results of these models are not always accurate or consistent across the software.

As demonstrated by the results in this thesis, transient stability simulations using WTG models can produce inconsistent results across commercial simulation platforms. This work illustrates differences in power system transient stability results via a model-to-model verification approach in which single machine infinite bus cases for the four generic WTG model types are subjected to two types of disturbance conditions: a three-phase bus fault at the location of the WTG and operation in the presence of a frequency disturbance. In some cases, it was demonstrated that profiles for the various output parameters considered were reasonably consistent, while in others variations occurred in output signal magnitude, damping, and post-disturbance steady-state values, among others. Dynamic parameter input values for all cases were kept as closely as possible to those values in a working case from which the SMIB equivalents were derived in an attempt to reveal variation among models being used in actual, real-world studies.

Future work will attempt to address the variations among these models, and bring results of those models with the most variation more closely together. This will involve the determination of practical ranges of WTG dynamic model parameter values which studies using these models should adopt. In addition, more work is needed to track down and adjust the model implementation issues which produce these differences to allow for more consistent modeling across simulation platforms. More specific to the work performed in this thesis, comparisons of frequency disturbance simulations for the Type-2 WTG model are needed, and future developments of the frequency play-in modeling using Package C will require verification studies to compare its results to the other two packages considered here. Because of the limited set of real-world data for validation work using these models, as more data is gathered for these devices, validation against actual measurements will be critical for further refinement of generic models.

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