Electromagnetic Transient - Transient Stability Hybrid Simulation for Electric Power Systems with Converter Interfaced Generation

by

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ABSTRACT

With the increasing penetration of converter interfaced renewable generation into power systems, the structure and behavior of the power system is changing, catalyzing alterations and enhancements in modeling and simulation methods.

This work puts forth a Hybrid Electromagnetic Transient-Transient Stability simulation method implemented using MATLAB and Simulink, to study power electronic based power systems. Hybrid Simulation enables detailed, accurate modeling, along with fast, efficient simulation, on account of the Electromagnetic Transient (EMT) and Transient Stability (TS) simulations respectively. A critical component of hybrid simulation is the interaction between the EMT and TS simulators, established through a well-defined interface technique, which has been explored in detail. This research focuses on the boundary conditions and interaction between the two simulation models for optimum accuracy and computational efficiency.

A case study has been carried out employing the proposed hybrid simulation method. The test case used is the IEEE 9-bus system, modified to integrate it with a solar PV plant. The validation of the hybrid model with the benchmark full EMT model, along with the analysis of the accuracy and efficiency, has been performed. The steady-state and transient analysis results demonstrate that the performance of the hybrid simulation method is competent. The hybrid simulation technique suitably captures accuracy of EMT simulation and efficiency of TS simulation, therefore adequately representing the behavior of power systems with high penetration of converter interfaced generation.

ACKNOWLEDGMENTS

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Chapter 1

INTRODUCTION

1.1 Background

The use of fossil fuels, along with their increasing rate of depletion, is causing alarming levels of degradation to the environment. On the other hand, renewable energy is a completely clean and freely available resource.

However, they do pose a number of challenges. References [1], [2], [3], [4] and [5] elaborate on some of these challenges arising in power systems due to renewable energy integration. Renewable energy sources most often do not generate electricity in the same form that it can be utilized, transmitted or distributed. Power electronic converters are required for DC/AC conversion, step-up or step-down of voltages and power conditioning. As more and more distributed generation is being integrated with the grid, and more loads are being driven by electronic drives, the structure and behavior of power systems is changing, with a high fraction of the generation as well as loads being interfaced through power converters.

Such power electronic equipment is best modeled using electromagnetic transient (EMT) simulation, to represent the converters in full detail, including the precise, fast switching operations and non-linear nature. However, these programs also require large computation times. On the other hand, transient stability analysis programs are suitable for modeling the electromechanical transients and hence are extensively used for assessing the rotor angle stability of power networks with a much smaller computation time, but not adequate to represent the dynamic response under many conditions [6, 7].

A simulation method, called Hybrid Simulation, is explored in this thesis. This technique tries to capture the advantages of both EMT and TS simulations, in order to represent the behavior of a system, with a large number of distributed generators (DGs), both accurately and efficiently.

MATLAB, being flexible, user-friendly, commonly used and easily accessible, would be an ideal platform on which to perform hybrid simulation. With this goal, a hybrid simulation process has been developed using MATLAB and Simulink. This hybrid simulation method has been tested and validated using the IEEE 9-bus system.

1.2 Thesis Objectives

The contributions of this research are outlined below:

- Development of an effective hybrid simulation method to study networks with penetration of converter interfaced generation and loads
- Implementation of hybrid simulation in MATLAB/Simulink
- Proposal of an improved interface algorithm or method between the two simulations (EMT and TS) for Hybrid Simulation in MATLAB environment
- Development of a MATLAB-based communication framework for the interaction between the EMT and TS models
- Validation of the effectiveness of the proposed simulation technique
- Analysis and comparison of the boundary conditions (solvers, time steps, interaction protocol and exchanged variables) used and their impact on simulation performance, in terms of accuracy and speed or efficiency
- Creation of a flexible, user-friendly and easily accessible hybrid simulation scheme

1.3 Thesis Outline

This thesis is organized as follows:

- Chapter 1 discusses the motivation behind this research, including the impacts and challenges of converter interfaced generation, along with the background and previous work. The main contributions of this thesis are outlined as well.
- Chapter 2 gives a broad overview of the simulation techniques widely in use. It addresses the need for hybrid simulation and introduces the hybrid simulation technique.
- Chapter 3 summarizes the proposed hybrid simulation method developed in MATLAB-Simulink and highlights its salient features.
- Chapter 4 describes the transient stability modeling and simulation techniques in MATLAB-Simulink for the particular network under study.
- Chapter 5 explains the EMT solar PV inverter system model developed and its simulation in MATLAB-Simulink.
- Chapter 6 presents the interfacing algorithm between the EMT and Phasor simulations and its implementation in detail.
- Chapter 7 provides a comprehensive validation of the proposed hybrid simulation method for the system under consideration, for a range of conditions. In addition, an analysis of the simulation performance is carries out, for a variation in the interface time step.
- Chapter 8 summarizes the research work and contributions of this thesis, while giving direction to future work.

Chapter 2

HYBRID SIMULATION

2.1 Simulation Techniques

In power system studies, depending on the type of study to be conducted, a suitable simulation tool must be selected [7].

2.1.1 Electromagnetic Transient (EMT) Simulation

Electromagnetic transients represent the response of the power system to perturbations or fast dynamic events such as switching, lightning, loading, etc. The analysis of these phenomena requires detailed modeling, which is realized by Electromagnet Transient simulation tools.

The system is represented by a set of differential equation and the step size is usually very small, in the range of microseconds. The presence of frequencies other than the fundamental frequency, such as harmonics and switching frequencies, necessitate the use of instantaneous, three phase quantities.

Some examples of EMT tools include PSCAD-EMTDC, EMTP-RV, eMEGAsim of Opal-RT, etc.

EMT simulators, however, prove to be unsuitable for the simulation of large networks of account of the relatively small time steps used. This would be time consuming and highly computationally intensive, requiring large processing power.

Due to their low simulation speed but high accuracy, EMT-domain simulation tools are used to simulate only small sections of networks, that require detailed simulation [7, 22].

2.1.2 Transient Stability (TS) Simulation

Electromechanical Transient simulation and transient stability studies focus on analyzing the ability of the power system to remain in synchronism and maintain voltage and frequency, following a small or large disturbance and analyze the dynamic behavior of the system. As transient stability simulation captures slow dynamics, these studies are carried out during the planning, operation, control and analysis of power systems.

In transient stability analysis, the power system under consideration is represented nonlinear algebraic equations. In power networks, this usually involves solving a large number of equations. It can be assumed that the fundamental power frequency of 50Hz or 60Hz is maintained throughout the system under most conditions. Phasors of the electrical quantities are therefore sufficient to model these system. Transient stability simulators generally use comparatively large integration timesteps, in the range of milliseconds, to run efficiently.

Some examples of TS tools include OpenDSS, PSS/e, PSLF, PowerWorld, ePHASORsim of Opal-RT, ETAP, etc. On account of their speed, Phasor-domain simulation tools are used to simulate large-scale networks. On the other hand, the large timesteps used in TS programs prevent them from representing non-linear elements such as power electronic converters, FACTS devices and HVDC equipment, insulation coordination as well as fast dynamics in detail in the power system [7, 22].

The key points of comparison between the two simulation techniques has been summarized below, in Table 2.1.

Point of Comparison	Comparison of Simulation Methods	
	Electromagnet Transient (EMT) Simulation	Transient Stability (TS) or Phasor Simulation
Modeling Requirements	Instantaneous waveforms, three-sequence, three-phase analysis, all frequencies	Phasors, positive sequence single-phase analysis, fundamental frequency
Time Step	Few microseconds	Few milliseconds
Accuracy	High, captures fast transients	Lower, captures slow dynamics
Speed	Slow	Fast
Efficiency	Lower	Higher
Computational Power	Computationally exhaustive	Lower computational power required
System Size	Small	Large
Tools	PSCAD-EMTDC, EMTP-RV, PLECS, eMEGAsim	OpenDSS, PSS/e, PSLF, PowerWorld, ETAP, ePHASORsim
Applications	Protection design, insulation coordination, fault rating, converter design, islanding detection, power quality analysis	Power system planning and operation, voltage regulation studies, reactive power management, storage management

Table 2.1: Comparison between EMT and TS Simulation Methods

2.2 Need for Hybrid Simulation

Today, as a large number of renewable energy distributed generators (DGs) are being integrated into distribution system, it is important to represent their impacts on the network. The presently used transient stability simulation technique is not sufficient to portray the complex behavior and dynamics of these systems [7]. Their true dynamics are best represented accurately by electromagnetic transient simulation. This would however reduce the simulation efficiency drastically for a large system.

For instance, TS simulation is suitable for the analysis of phenomena such as voltage fluctuation, flicker, voltage regulation, etc., occurring due to DG penetration in power systems. However, to study DG impacts on power quality such as harmonic distortion, resonance and voltage sag, EMT studies with high accuracy and small time steps, representing high frequency dynamics, are required. Moreover, EMT simulation is also important for analyzing the operation and control of power electronic converters [7]. Since the impacts of renewable energy penetration impacts vary over a wide range of time scales, depending on the whether slow or fast dynamics are to be studied, TS simulation or EMT simulation must be chosen accordingly.

EMT simulation offers the required accuracy, while, TS simulation is computationally efficient. Therefore, a combined hybrid simulation that could incorporate the advantages of both types of tools is the need of the hour.

2.3 Introduction to Hybrid Simulation

In hybrid simulation, only certain parts of the network, which require detailed studies, are simulated in the EMT domain and the rest of the system in the phasor domain. The system is split into two subsystem models, at the interface bus, with different simulation engines and solution methods. The EMT tool solves the time-domain differential equations with a very small time step and the phasor tool solves the power flow equations with a larger time step, at the fundamental frequency [7]. The two simulation models interact with each other through an interface. Hybrid simulation is very beneficial in analyzing large systems with penetration of converter interfaced generation and loads, as these systems require both accurate as well as fast simulation. It thus enables the study of large systems, while providing detailed dynamic information about them, which is impossible to achieve with either EMT or TS simulation tools alone.

Hybrid simulation however poses a number of challenges, which are explored in detail in this work.

2.4 History and Current Status of Hybrid Simulation

A number of progressive hybrid simulation techniques have been proposed in literature up to date.

The concept of Hybrid Simulation was first introduced in references [8], [9] and [10], for the purpose of High Voltage Direct Current (HVDC) converter studies in 1981.

References [11], [12] and [13] focus on progressively incorporating EMT models of nonlinear elements such as flexible AC transmission (FACTS) and HVDC systems into traditional TS simulation programs. They integrate a static VAR compensator (SVC), modeled at the device level, concentrating on interaction protocol and other interface requirements to be taken into consideration.

Reference [22] classifies and addresses the main requirements and challenges faced in interfacing EMT and TS simulators for hybrid simulation. It also proposes an integrated EMT-TS simulation using frequency adaptive modeling and simulation, including frequency shifting and companion models.

Reference [19] puts forward a relaxation approach applied to time interpolation and phasor extraction. It also summarizes the main equivalent models or boundary conditions used in hybrid simulation literature.

In reference [6], an open-source hybrid simulation tool, OpenHybridSim, is developed. It uses InterPSS for TS simulation and can be integrated with various EMT simulators, with a socket communication based interface. Reference [14] employs this tool for fault-induced delayed voltage recovery (FIDVR) studies, using PSCAD/EMTDC and InterPSS. A combined interaction protocol with automatic switching as well as multi-port three-phase Thvenin equivalent was also introduced in the tool.

References [7] and [16] introduce an open-source hybrid simulation tool, using the OpenDSS TS simulator and a Matlab-scripted EMT simulator interfaced with a component object model (COM) server. It is designed to perform solar PV impact studies in distribution systems. Reference [17] demonstrates the tools ability to perform islanding detection studies in such distribution networks. Reference [15] extends this tool to use Python-scripted EMT simulation instead of Matlab scripts.

Reference [20] proposes a distributed hybrid simulation method, with a combined interaction protocol and a two-level Schur complement interfacing technique. In reference [21], a dynamic phasor-based interface model (DPIM) has been developed, to study the interactions between HVDC systems and the AC grid.

In reference [23], an EMT modular multilevel converter (MMC) based HVDC system in in PSCAD/EMTDC is combined with the AC grid programmed in C language as a user-defined model in PSCAD.

An implicitly-coupled solution method is presented in reference [24], where the EMT and TS equations are combined and solved simultaneously.

Reference [25] focuses on the application of hybrid simulation to VSC-HVDC systems and techniques to improve accuracy.

The above mentioned hybrid simulation implementations use EMT and TS off-line software.

OPAL-RT's real-time simulation tools primarily include ePHASORsim, HYPERSIM, eMEGAsim and eFPGAsim, suitable for simulation time-steps ranging from milliseconds to nanoseconds and large to small model sizes respectively [27]. The RT-

LAB suits simulation environment has the potential to run two types of simulations, namely The TS simulator ePHASORsim and the EMT simulator eMEGAsim, in one working model, thus enabling hybrid simulation [26, 28]. Reference [30] explains this capability and the interfacing method in detail. Reference [29] explores parallelization techniques for real-time simulation and the suitability of hybrid simulation, using the OPAL-RT real time digital simulator, for islanding detection.

Chapter 3

DEVELOPMENT OF THE PROPOSED HYBRID SIMULATION METHOD IN MATLAB

3.1 Advantages of using MATLAB/Simulink for Hybrid Simulation

As seen in Chapter 2, hybrid simulation methods and tools have been developed which combines two different software to run the EMT and TS simulations separately. However, there is are complexities, inconsistencies and inaccuracies involved when interfacing two different simulation platforms. There lacks a hybrid simulation tool or methodology that can run the entire simulation on a single simulation platform.

Matlab/Simulink has the capacity to run EMT as well as phasor domain simulations. It serves as a suitable platform to integrate both simulations to build a hybrid simulation. Hybrid simulation has not yet been implemented in Matlab alone. There are potentially added capabilities arising since a single simulation software is being employed.

This work puts forth a Hybrid EMT-TS simulation method in MATLAB, to study power electronic based power systems. The entire simulation is run on a single simulation platform, MATLAB. The purpose of selecting Matlab over individual softwares optimized for TS and EMT simulation is to deliver a more general simulation environment, to test the hybrid simulation algorithm and procedure, particularly the interface between the TS and EMT simulations. It also ensures improved and less complex interfacing, communication and compatibility between the EMT and TS simulation models.

3.2 Requirements of Hybrid Simulation

In hybrid simulation, only certain parts of the network, which require detailed studies, are simulated in the EMT domain and the rest of the system is simulated in the phasor domain. The system is split into two subsystem models, at the interface bus and the two simulation models interact with each other through an interface.

In order to carry out hybrid simulation of a given system, the basic components listed below should be in place:

1. A simulation model of the power network in the Phasor or TS domain
2. A simulation model of the portion of the system requiring detailed analysis in the EMT domain
3. An interface between the two simulation models, which considers the following:
    (a) Network Partitioning
    (b) Selection of the Interface Bus
    (c) Equivalents Models of the Detailed and External Systems
    (d) Selection of the Exchanged Data Variables
    (e) Data Extraction
    (f) Interaction Protocol
    (g) Communication

[6, 15, 19, 22]

3.3 Hybrid Simulation Scheme

The flow chart for running the proposed hybrid simulation method is shown in Fig. 3.1. The following steps have been followed:

1. Select the power network to be studied
2. Split the power system under study into the TS-modeled external network and EMT-modeled detailed system for the hybrid simulation
3. Set the interface conditions such as the boundary bus, interaction protocol, data exchange time step, simulation duration, etc.
4. Initialize the TS and EMT simulation models
5. Measure the Thevenin equivalent impedance of the network, as seen from the interface bus, in the TS model
6. Solve the power flow in the TS simulation model
7. Run the TS simulation for ΔTts seconds
8. Convert the phasor quantities to instantaneous waveforms by Time Interpolation
9. Transfer the required instantaneous quantities to the EMT model and update the TS equivalent model in the EMT simulation model
10. Run the EMT simulation for ΔTts seconds with a time step of ΔTemt seconds
11. Measure the real and reactive power at the interface bus in the EMT model
12. Convert the instantaneous waveforms to phasor quantities by Phasor Extraction

13. Transfer the required phasors to the TS model and update the EMT equivalent model in the TS simulation model

14. Repeat steps 6 to 14 until the simulation end time is reached

15. Stop the Hybrid Simulation

16. Plot the desired results

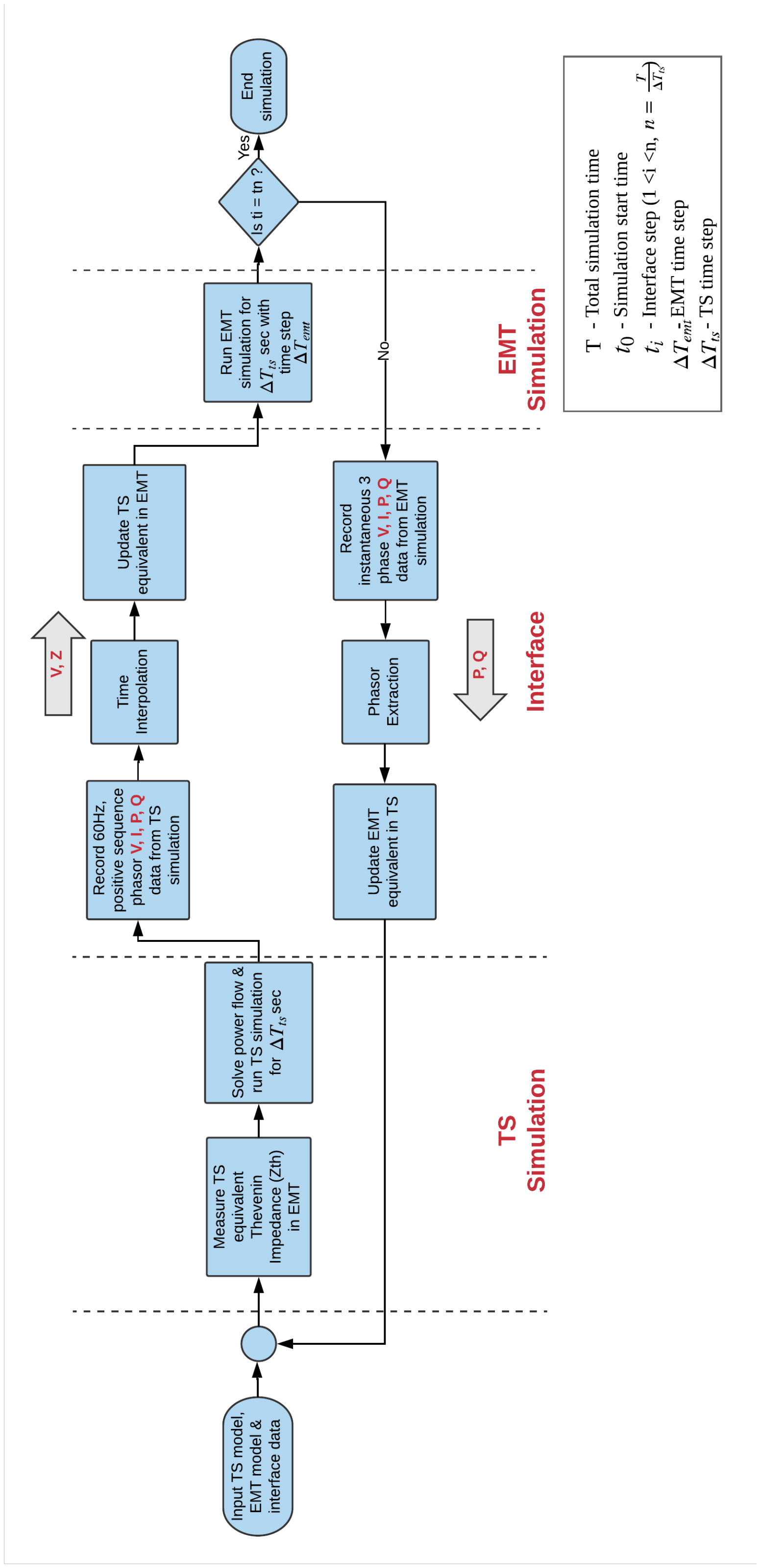

Figure 3.1: EMT-TS Hybrid Simulation Scheme in MATLAB/Simulink

Chapter 4

TRANSIENT STABILITY (TS) MODELING AND SIMULATION

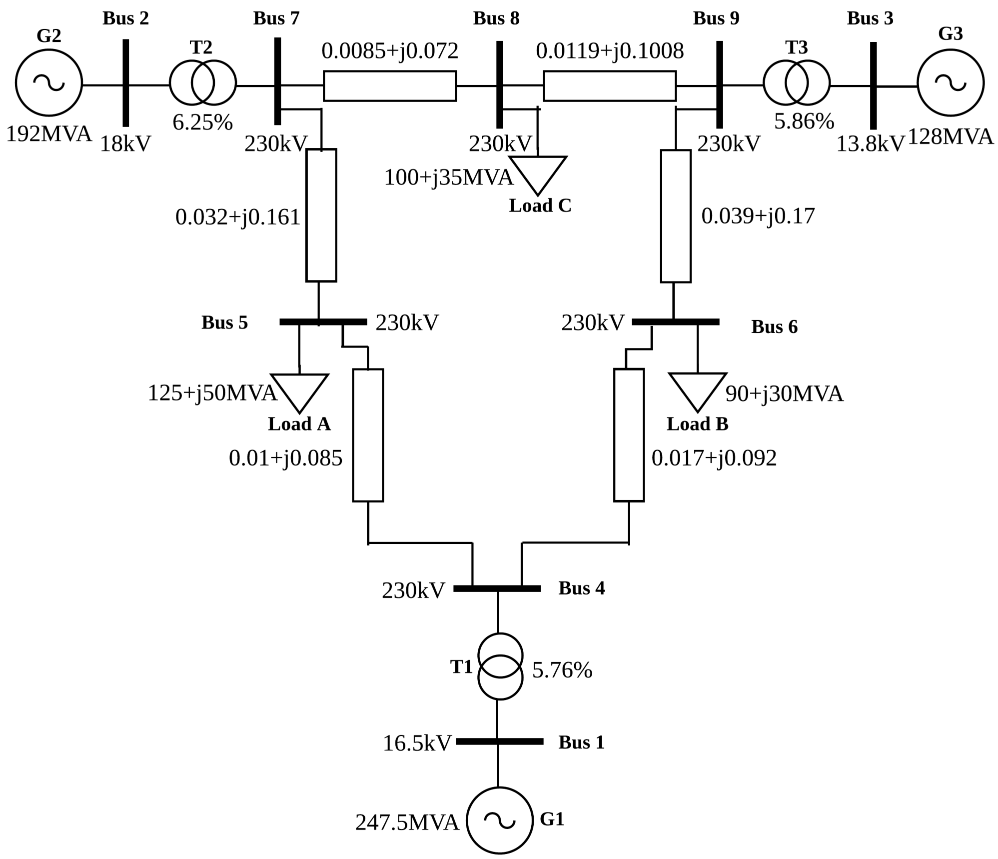

Figure 4.1: Single-Line Diagram of the WSCC IEEE 9-Bus System

4.1 Description of the System

The network being considered in this work is the WSCC IEEE 9-bus test system, also known as P.M Anderson 9-bus [40]. It represents a simple approximation of the Western System Coordinating Council (WSCC) to an equivalent system with nine buses and three generators. This test system includes three two-winding transformers, six transmission lines and three loads. The base voltage levels are 13.8 kV, 16.5 kV, 18 kV, and 230 kV. The single-line diagram of the WSCC 9-bus case is shown in Fig. 4.1. The key information of this test case has been elaborated in more detail in Appendix A [36, 37, 38].

In this study, the WSCC 9-bus system has been modified to replace the synchronous generator at bus 3 by a solar photovoltaic plant with a capacity to generate maximum 85 MW of power.

It must be noted that the real merits of hybrid simulation are striking in much larger systems. However, in order to develop the hybrid simulation framework in MATLAB and enable feasible validation, a 9-bus system has been employed in this work.

4.2 Modeling and Simulation of the IEEE 9-Bus System

Simulink has been used to run the power flow solution and dynamic simulation of the network in the Phasor domain [35, 39]. The implementation of this modified 9-bus system in the TS domain in Simulink is depicted in Fig. 4.2. The Powergui block offers the ability to set the solution method to 'Phasor'. There are nine Load Flow Bus blocks in the model, defining the bus locations, parameters to solve the load flow and base voltages at their respective buses. The Load Flow tool of Powergui is used to compute the voltage, real power and reactive power flows at each bus using the Newton-Raphson method, initialize the network and start the simulation in steady-state. In this case, positive-sequence load flow is applied to the three-phase system [32].

Every block that can be potentially used in Load Flow studies has a Load Flow tab, where the Load Flow parameters are specified. The loads are modeled using the

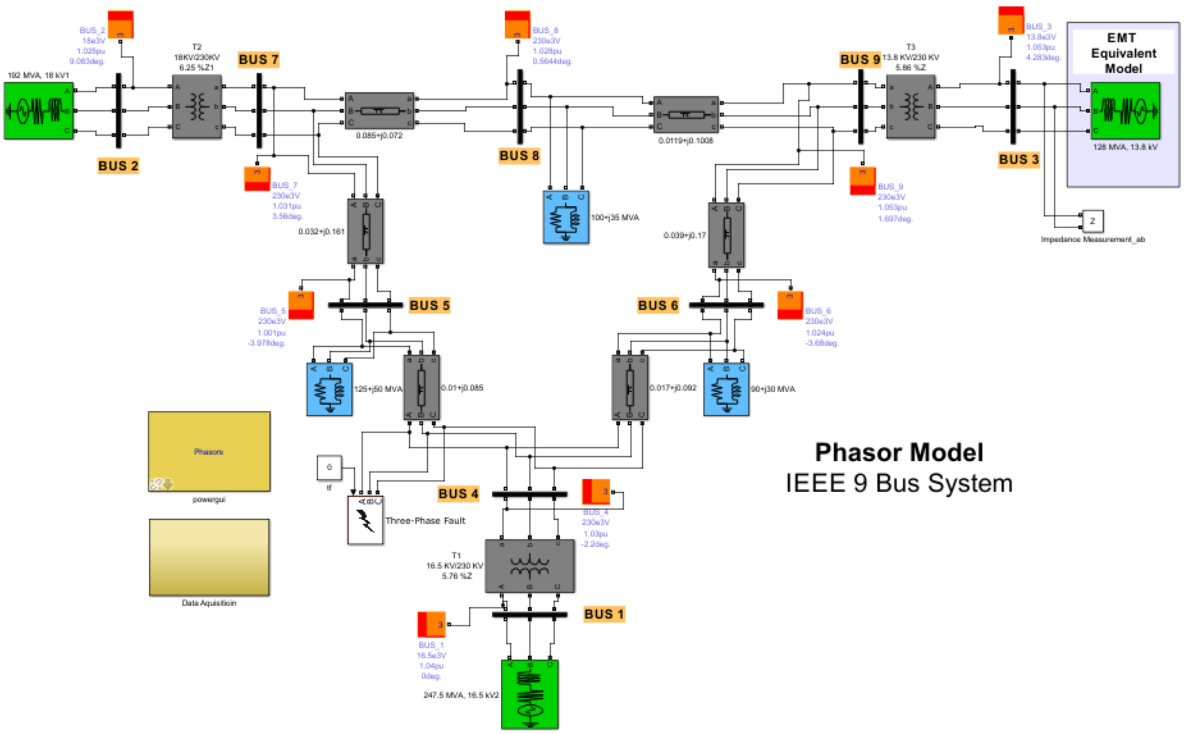

Figure 4.2: Transient Stability Simulation Block Diagram in Simulink

Constant PQ Three Phase Parallel RLC load blocks, where real and reactive powers are specified. The solar PV plant at bus 3 is represented by the EMT equivalent model in the TS simulation model, the PQ type Three-Phase Source block, as explained in detail in Chapter 6. The generators at buses 1 and 2 are implemented using Three-Phase Source blocks. The Three-Phase Transformer and Three-Phase PI Section Line blocks are used to model the transformers and transmission lines respectively. The load flow results are tabulated in Table 4.1. The ODE4 (Runga-Kutta) solver and a step size of 10 ms has been used in the TS simulation.

	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)
1	SM	swing	BUS_1	16.50	1.0400	0.00	163.00	0.00	-Inf	Inf	1.0400	0.00	72.20	18.74
2	Bus	-	BUS_4	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0305	-2.22	0.00	0.00
3	RLC load	PQ	BUS_5	230.00	1	0.00	125.00	50.00	-Inf	Inf	1.0014	-4.01	125.00	50.00
4	RLC load	PQ	BUS_6	230.00	1	0.00	90.00	30.00	-Inf	Inf	1.0239	-3.72	90.00	30.00
5	Bus	-	BUS_7	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0315	3.51	0.00	0.00
6	Bus	-	BUS_9	230.00	1	0.00	0.00	0.00	0.00	0.00	1.0531	1.62	0.00	0.00
7	RLC load	PQ	BUS_8	230.00	1	0.00	100.00	35.00	-Inf	Inf	1.0282	0.50	100.00	35.00
8	SM	PV	BUS_2	18.00	1.0250	0.00	163.00	0.00	-Inf	Inf	1.0250	9.03	163.00	-2.59
9	Vsrc	PQ	BUS_3	13.80	1.0250	0.00	85.00	3.00	-Inf	Inf	1.0536	4.19	85.00	3.00

Table 4.1: Summary of Load Flow Results

Chapter 5

ELECTROMAGNETIC TRANSIENT (EMT) MODELING AND SIMULATION

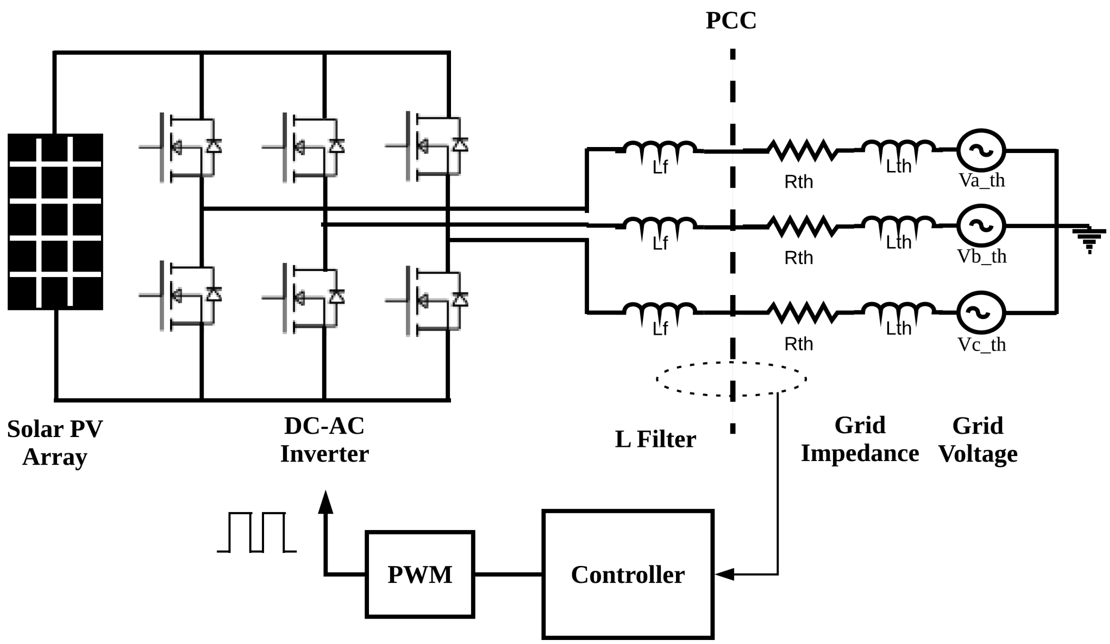

Figure 5.1: Circuit Diagram of Solar PV Inverter System

5.1 Description of the System

The grid-tied 85 MW Solar Photovoltaic (PV) Plant at Bus 3 of the 9-bus network is modeled in Simulink for the EMT simulation. Fig. 5.1 depicts the three-phase circuit diagram of this system, including all the components that have been modeled. It consists of a PV array, a three-phase pulse width modulated (PWM) voltage source inverter, a current controller, an AC inductive filter and the Thevenin equivalent model of the TS simulation represented in the EMT simulation model.

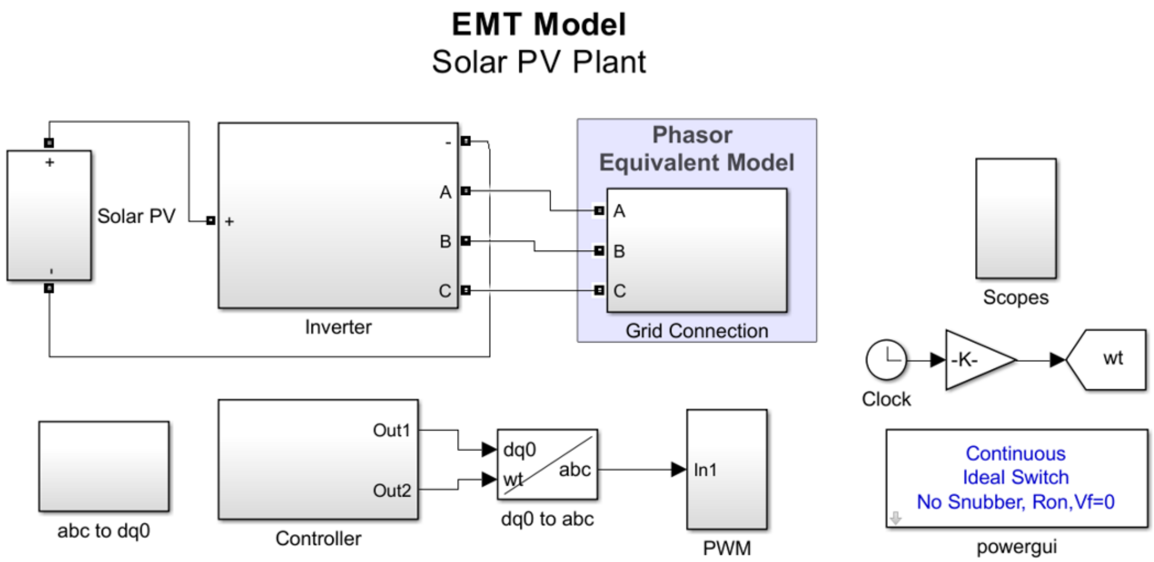

Figure 5.2: Electromagnetic Transient Simulation High-Level Block Diagram in Simulink

The high-level block diagram of the detailed switching EMT simulation model in Simulink is shown in Fig. 5.2. The ODE 4 solver and a step size of 5 μs has been used. The solution method in the Powergui block has been set to 'Continuous' and uses ideal switches.

5.2 Modeling of the Solar PV Array

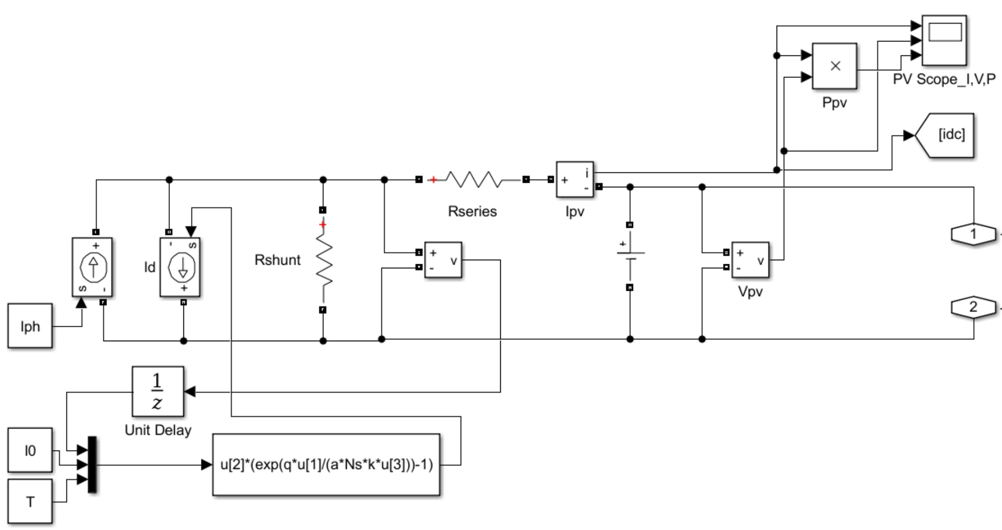

Figure 5.3: EMT Solar PV Array Implementation in Simulink

The Solar PV array is modeled using the five-parameter model, as seen in Fig. 5.3. The basic practical PV cell is modeled as a current source supplying a current equal to the photon current from the P-N junction (Iph) under irradiance, in anti-parallel with a forward diode. The current of the diode (Id) is dependent on the dark current flowing through it, temperature, diode ideality factor, Boltzman constant and charge of an electron in Coulombs. A series resistor (Rs) represents the surface resistance, cell body resistance between the electrodes and the PV cell and metal conductor resistance. A shunt resistor (Rsh) represents the leakage currents and irregularities [7, 33, 34].

The open-circuit voltage, short-circuit current, maximum power point voltage and maximum power point current of the cell are extracted from the datasheet. The output current and voltage from the PV cell follow a typical V-I characteristic. The V-I characteristic of a particular PV cell along with the datasheet parameters are used to determine the parameters for that cell's model at the Standard Test Conditions (STC) of 1000W/m^2 irradiance, 25°C cell temperature and 1.5 air mass. The model parameters are affected if the conditions deviate from the STC conditions and in turn the cell output [7, 33, 34].

In order to obtain the desired voltage and current from the solar plant, cells are connected in series to form a module, modules in series to form strings and strings in parallel to form an array. The model shunt and series resistances, voltage and current are modified accordingly [33].

A 300kW Jakson solar PV module "JP300W24V" has been selected for this case study. Appendix B elaborates on the specifications of the module, as obtained from the datasheet. 152 panels in series and 1776 series strings in parallel together meet the required power, voltage and current.

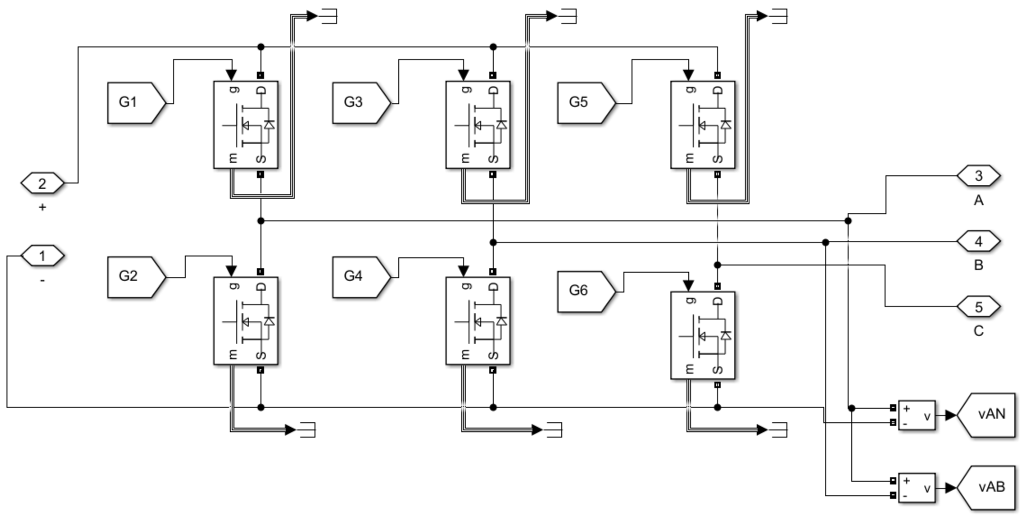

Figure 5.4: EMT Inverter Implementation in Simulink

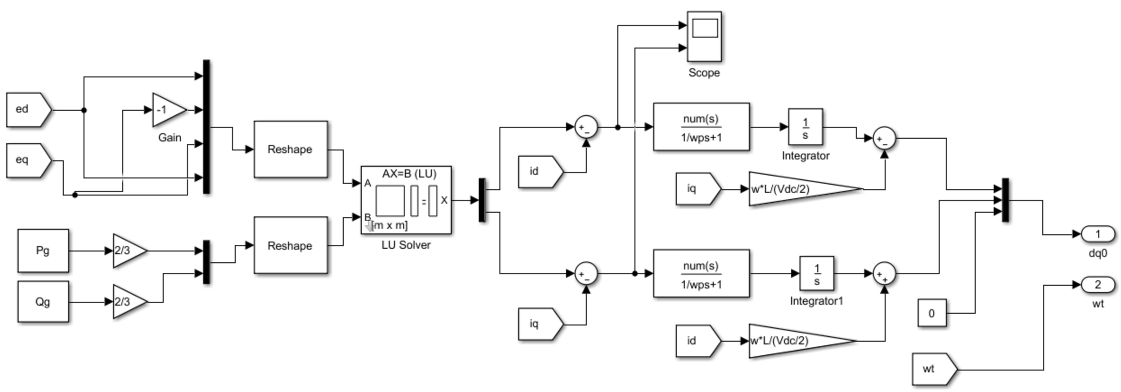

Figure 5.5: EMT Current Controller Implementation in Simulink

The voltage source inverter converts DC voltage at its input terminals across the capacitor to AC voltage at its output terminals. It is modeled with a detailed switching model, as shown in Fig. 5.4 [33].

The switching of the inverter is controlled by PWM gate pulses, generated by a Type 2 current controller. Sinusoidal Pulse Width Modulation (SPWM) has been used in this case, where a low frequency sinusoidal modulating signal is compared with a high frequency triangular carrier signal. Whilst the carrier signal has a constant magnitude and frequency, the magnitude and phase angle of the modulating signal is varied by the controller in order to achieve the desired output from the inverter. A 20 kHz carrier frequency or switching frequency is used here.

In this case, the output AC current is to be controlled. In order to simplify the control scheme, the dq frame of reference is used. This transformation is beneficial as the system is changed from three dimensional to two dimensional and decoupled control of the d-axis and q-axis quantities is possible. The natural abc quantities sensed at the output of the inverter are transformed into synchronously rotating dq quantities and fed into the controller. The Proportional-Integral (PI) or Type 2 controller controls the dq components of the inverter current injected into the network. The reference currents are derived from the desired output voltage, real power and reactive power. id and iq indirectly controls real power and reactive power respectively. This system is designed to supply a real power of 85 MW and a reactive power of 3 MVArs. The implemented controller is depicted in Fig. 5.5.

Large solar power plants, such as the one modeled at bus 3, typically utilize a number of MW-scale inverters. There could be individual string inverters assigned to separate strings of solar panels or one central inverter assigned to the entire array of panels.

5.4 Modeling of the Filter and Network Interconnection

An inductive (L) filter is designed to filter out the high switching frequency component in the AC current and limit the total harmonic distortion (THD) in the AC current to 5%. The solar PV inverter system is interfaced with the network through the L filter.

The Thevenin equivalent circuit represents the TS model in the EMT domain. It consists of a Thevenin AC voltage source in series with a Thevenin impedance for

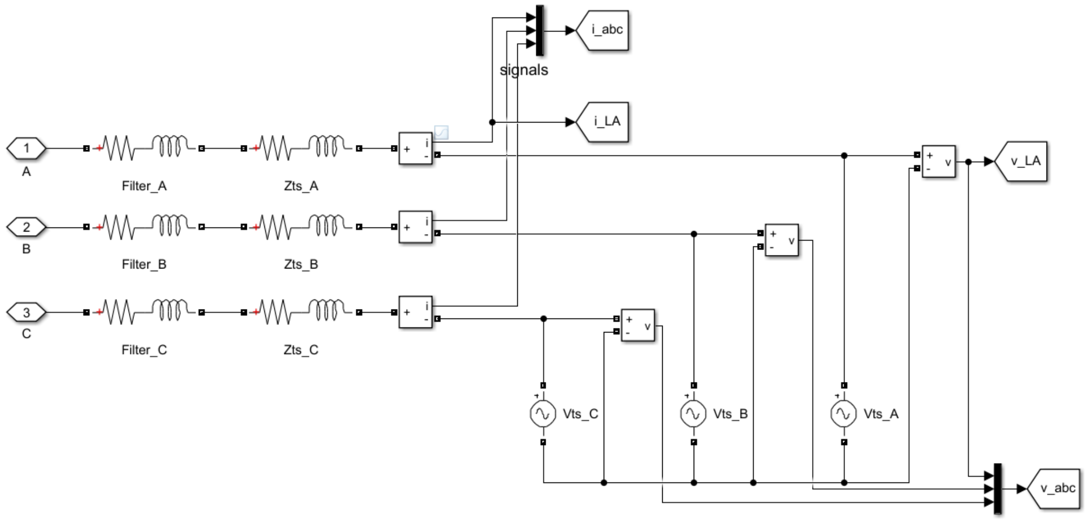

Figure 5.6: EMT Filter and Network Interconnection Implementation in Simulink

each of the three phases.

The filter and network equivalent, as implemented in Simulink, are shown in Fig. 5.6.

Chapter 6

INTERFACE BETWEEN TS AND EMT SIMULATIONS

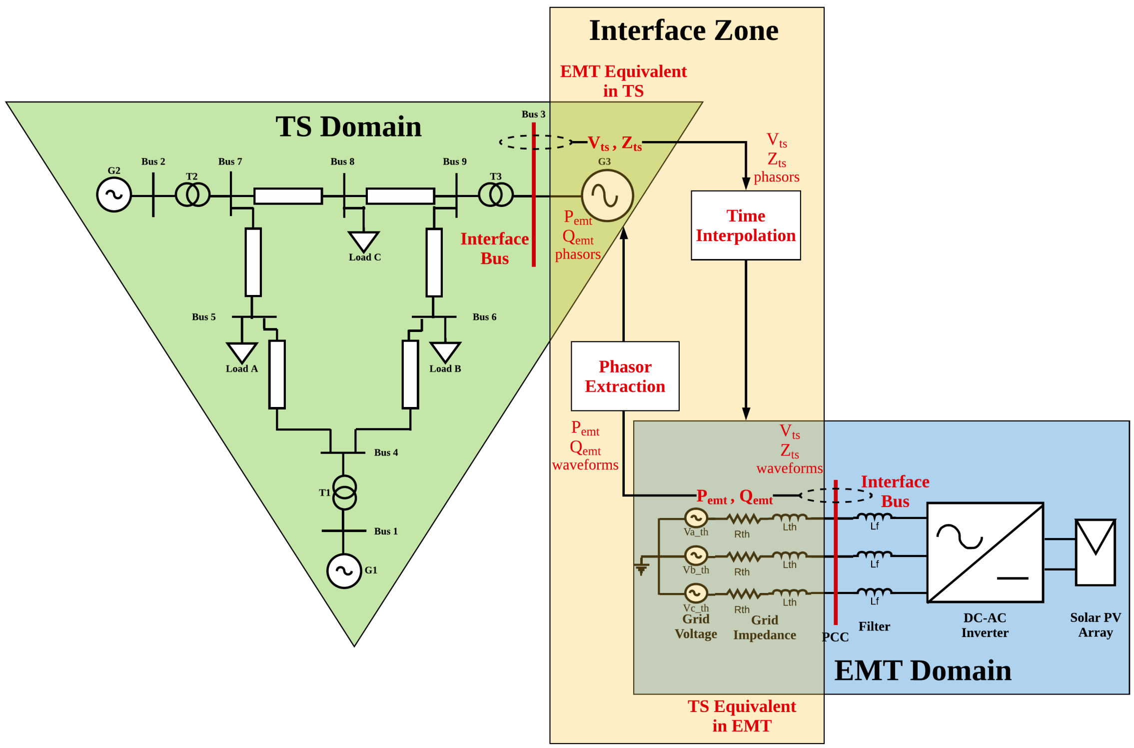

Figure 6.1: EMT-TS Hybrid Simulation Interface in MATLAB/Simulink

A critical component of hybrid simulation is the interaction between the EMT and TS simulators, established through a well-defined interface technique. The structure of the interface designed in this research has been depicted in Fig. 6.1 and described in detail in this chapter.

6.1 Network Partition and Selection of Interface Bus

In the first step of the hybrid simulation, the network is partitioned into the detailed EMT system and the external TS system at the interface bus. The choice of the interface bus is important in obtaining the boundary conditions.

This selection is based on the understanding of which part of the system requires a detailed study [7, 22]. Expanding the detailed system increases the accuracy, but also increases the complexity and decreases the efficiency.

Usually, in grid-connected renewable energy systems, the distributed generation system is the portion requiring EMT simulation, therefore the point of common coupling (PCC), where the distributed generator connects to the grid, is chosen as the interface bus.

In the 9-bus system under study, bus 3 is selected as the interface bus, as it separates the PV system, which has been modeled in detail, from the rest of the system.

6.2 Equivalent Models and Selection of Exchanged Data

Since the EMT and TS simulation models are solved independently, each must contain an equivalent representation of the other in its own model. The equivalent model of the EMT system in the TS simulation model should appropriately represent the behavior of the EMT simulation and must be updated dynamically at each interface time step during the hybrid simulation and vice versa.

The phasor system is represented in the EMT simulation model as a Thevenin voltage source in series with a Thevenin impedance. The required values of the external system must be transformed into three-phase time-varying quantities for the detailed system model. [6, 7, 15, 19, 21, 24]

The equivalent Bus 3 voltage magnitude and phase angle is obtained from the phasor simulation results. These values are fed into three AC Voltage Source blocks in Simulink, one representing each of the three phases. They generate sinusoidal voltages at the specified frequency (fundamental frequency in this case), magnitude and phase obtained from the phasor model [32].

The equivalent grid impedance is measured at Bus 3 in the phasor simulation model. It is measured during the initialization and does not usually change during the simulation, unless there are changes in the network configuration, such as faults. The Impedance Measurement block in Simulink measures the impedance between two nodes of the network, as seen from Bus 3, as a function of frequency. Using the Impedance Measurement tool of the Powergui block, the impedance measurement at the fundamental frequency is stored in the Workspace and retrieved by the EMT simulation. This block has two input measurement terminals and consists of a current source between them and a voltage source across the current source terminals. The transfer function of the state-space model, from the current input to voltage output is the measured impedance of the network. The positive-sequence impedance is 0.5 times the impedance measured between two phases in a three-phase circuit [32].

Apart from a fundamental Thevenin equivalent circuit, a simple voltage source, a Norton equivalent or a Frequency-Dependent Norton Equivalent (FDNE) may also be used to represent the equivalent of the external system in the EMT simulation [19, 22, 31].

In this case, the EMT system is represented in the phasor simulation model as a Three-Phase Voltage Source, specifically a PQ type generator injecting a real and reactive power [7, 15, 25].

A PQ generator has controlled real or active power (in Watts) and reactive power (In VArs) generation. The specified real and reactive power generation is obtained from the results of the EMT simulation. The time-varying quantities from the EMT simulation results undergo phasor extraction in order for them to be converted into a fundamental frequency, phasor form usable in the TS simulation [32].

The network equivalent of the detailed system in the TS simulation is also often a current source, a voltage source, an impedance, a time varying Norton equivalent or a Thevenin equivalent [19, 21, 22, 24, 25].

6.3 Data Extraction

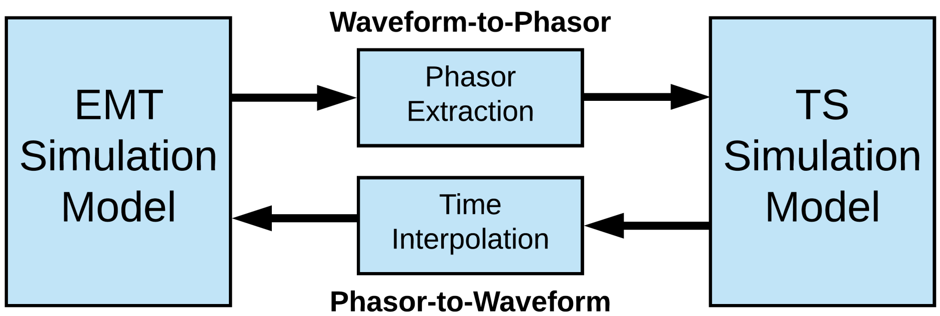

Figure 6.2: Data Extraction

The phasor equivalent model in the EMT simulation model requires the instantaneous voltage at the interface bus whereas the EMT equivalent model in the phasor simulation requires the phasors of the injected real and reactive powers. Therefore, before the selected data is exchanged between the simulation models, it must be transformed into the appropriate form, as depicted in Fig. 6.2.

In order to convert the instantaneous three-phase waveforms of the quantities from the EMT simulation into phasor quantities at the fundamental frequency, Phasor Extraction technique such as RMS Approximation, Digital Filtering, Fourier Transform, Curve Fitting and Projection on Synchronously Rotating Axes can be implemented [22, 19, 25].

In this work, at every TS time step, the RMS values of the real and reactive powers for that given time period are calculated using the dq currents and voltages, extracted and sent to the TS simulation. The high-frequency component is also eliminated before phasor extraction for better accuracy. In order to implement Fourier Transform or Curve Fitting, on the other hand, the TS time step should be of the length of the fundamental time period window or more, which imposes a restriction on the minimum interface time step.

To obtain instantaneous waveforms for the EMT simulation from phasor values of the TS simulation parameters, Time Interpolation is implemented [19, 15].

Here, time interpolation using an AC voltage source controlled by peak amplitude, phase and frequency has been used in Simulink, to perform the phasor-to-waveform conversion. The magnitude and phase angle for each phase is updated at every interaction time step.

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6.4 Interaction Protocol

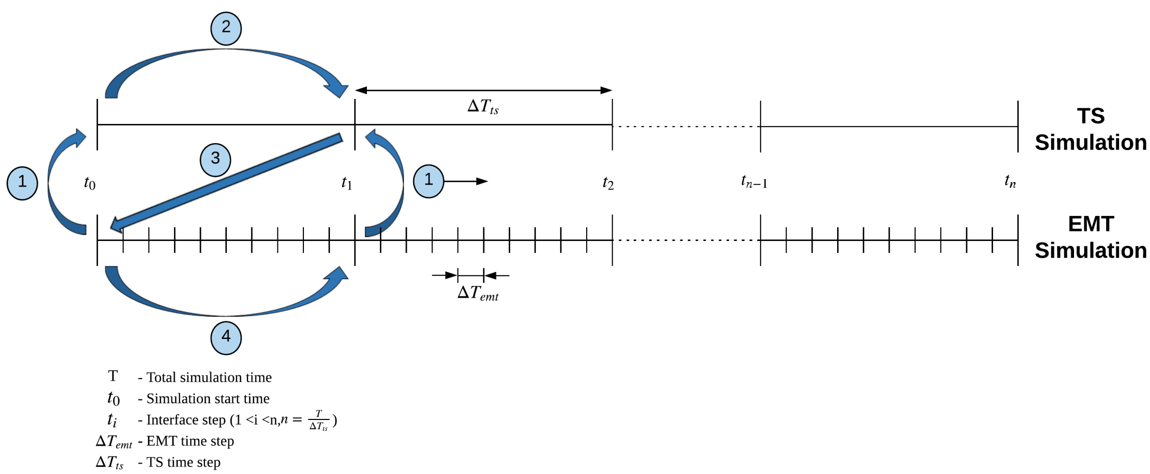

Figure 6.3: Serial Interaction Protocol

The interaction protocol of the hybrid simulation determines the order of data exchange at the EMT-TS interface [7]. The protocols for data transfer between the EMT and TS models may be either serial, parallel or a combination of both. The serial protocol ensures better accuracy, whereas the parallel protocol improves efficiency [6].

The process followed in this work, when a serial protocol is used, is illustrated in Fig. 6.3. The four main interaction protocol steps are also stated in more detail below:

1. At t0, transform the active and reactive power instantaneous waveforms, from the previous interface step EMT simulation result, to phasors. Transfer these phasors from the EMT domain to the TS simulation model.

2. Solve the power flow and execute the TS simulation with a time step of ΔTts until t1 is reached.

3. Transform the current and voltage phasors to instantaneous waveforms. Transfer these quantities from the TS domain to the EMT simulation model.

4. Execute the EMT simulation from t0 to t1 with a timestep of ΔTemt.

This process is repeated until the total simulation time T is reached.

Therefore, at any give time instant during the simulation, only one model is running whilst the other one is idle.

6.5 Communication

Interaction and data transfer between the two simulation models is facilitated by the MATLAB Workspace. The EMT and TS simulations are each modeled in the EMT and phasor domains, respectively, in separate Simulink files. The interface algorithm is implemented in an m-file, using Matlab code. Fig. 6.4 depicts the communication framework between the EMT and TS simulation models through the Matlab interface.

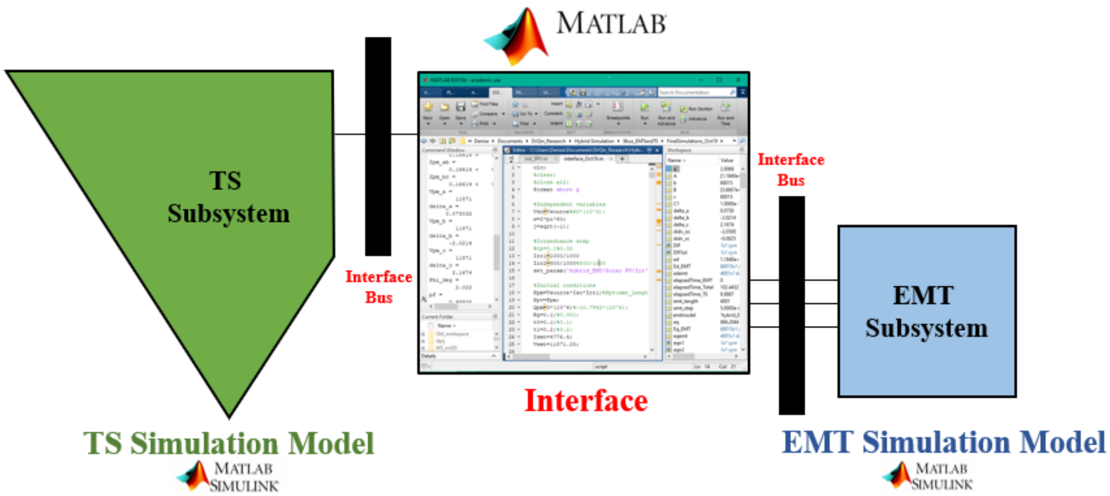

Figure 6.4: Communication

At the start of the hybrid simulation, the boundary conditions are established and both the EMT and TS models are initialized according to the base case. The simulation is executed according to the interaction protocol. The exchanged parameter values are constantly updated at every interaction timestep in the Matlab Workspace, throughout the simulation. Hence they are easily accessible to both the interacting simulation models during the simulation, which are updated at every interaction step.

Matlab serves are a suitable platform for efficient communication between the two simulation models.

6.6 Plotting

In order to plot continuous waveforms of the quantities, such as current, voltage and powers, at the completion the hybrid simulation, it is essential to stitch the quantities measured during each interaction step. This is executed in Matlab by creating vectors of the required signals at the end of each interaction time step and feeding them to a larger, encompassing vector, which is plotted at the end of the entire simulation. This process is illustrated in detail in Fig. 6.5.

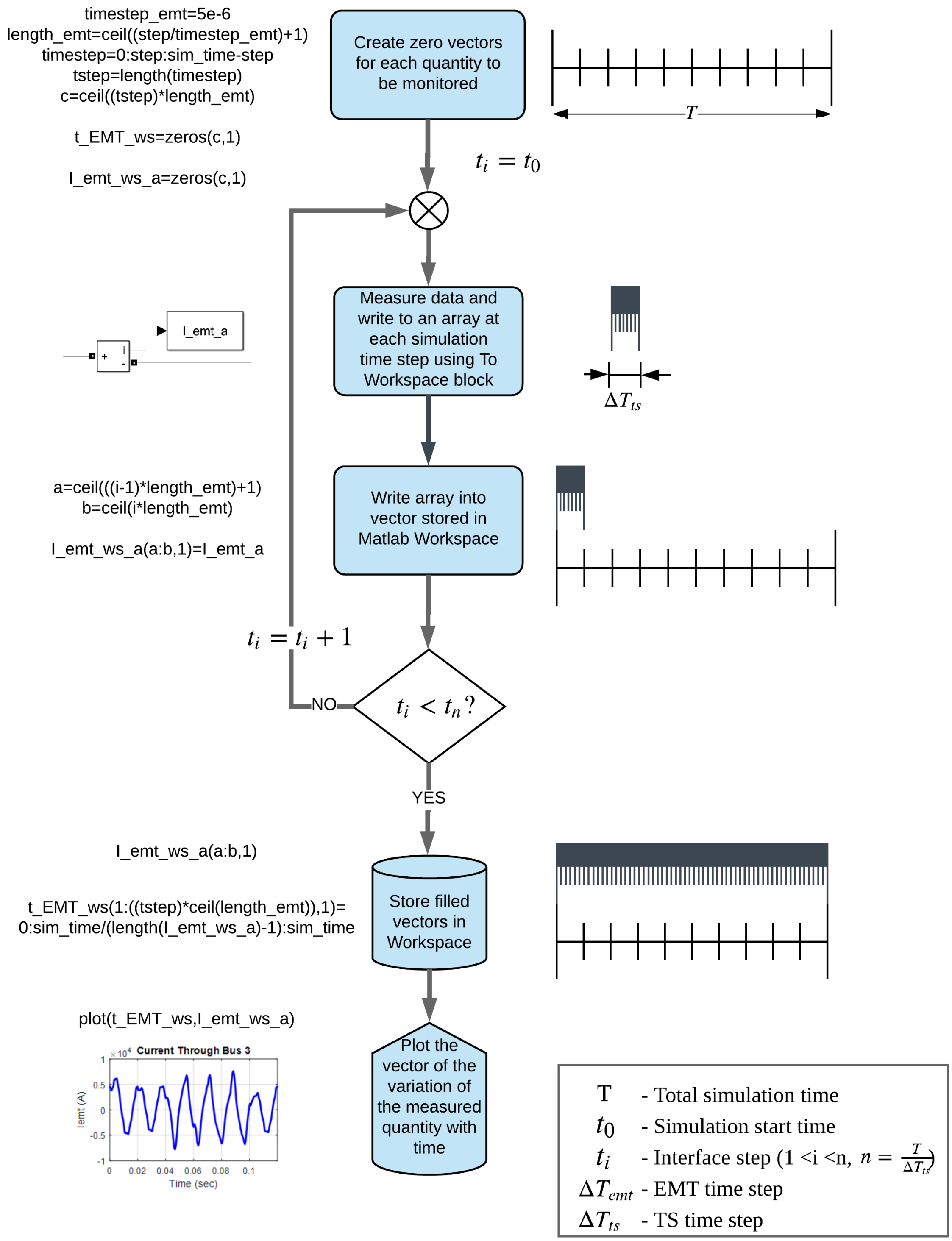

Figure 6.5: Procedure for Plotting

Chapter 7

TESTING AND VALIDATION

In this section, the hybrid simulation method described in the previous chapters is tested and validated. The system under consideration is the WSCC IEEE 9 bus network, modified to replace the synchronous generator at bus 3 by a solar PV plant. It has been described in detail in chapters 4 and 5.

Steady-state analysis and transient analysis case studies have been performed, and the results have been documented in this chapter. The transients considered here include a Single Phase Line-to-Ground Fault and Variation in Solar PV Power Output, which represent transients in the TS and EMT domains respectively.

Table 7.1 indicates the general hybrid simulation parameters for these case studies. Voltage, current, real power and reactive power at the interface bus, which is the Bus 3, which is the point of common coupling (PCC), and Bus 7, have been observed in all cases. The results have been compared with the benchmark full EMT simulation model of the network under consideration, including the solar PV inverter system, implemented in Simulink.

Parameter	Value
EMT Time Step	5 μs
TS Time Step	10 ms
Interface Time Step	10 ms

Table 7.1: Simulation Parameters

7.1 Steady-State Analysis

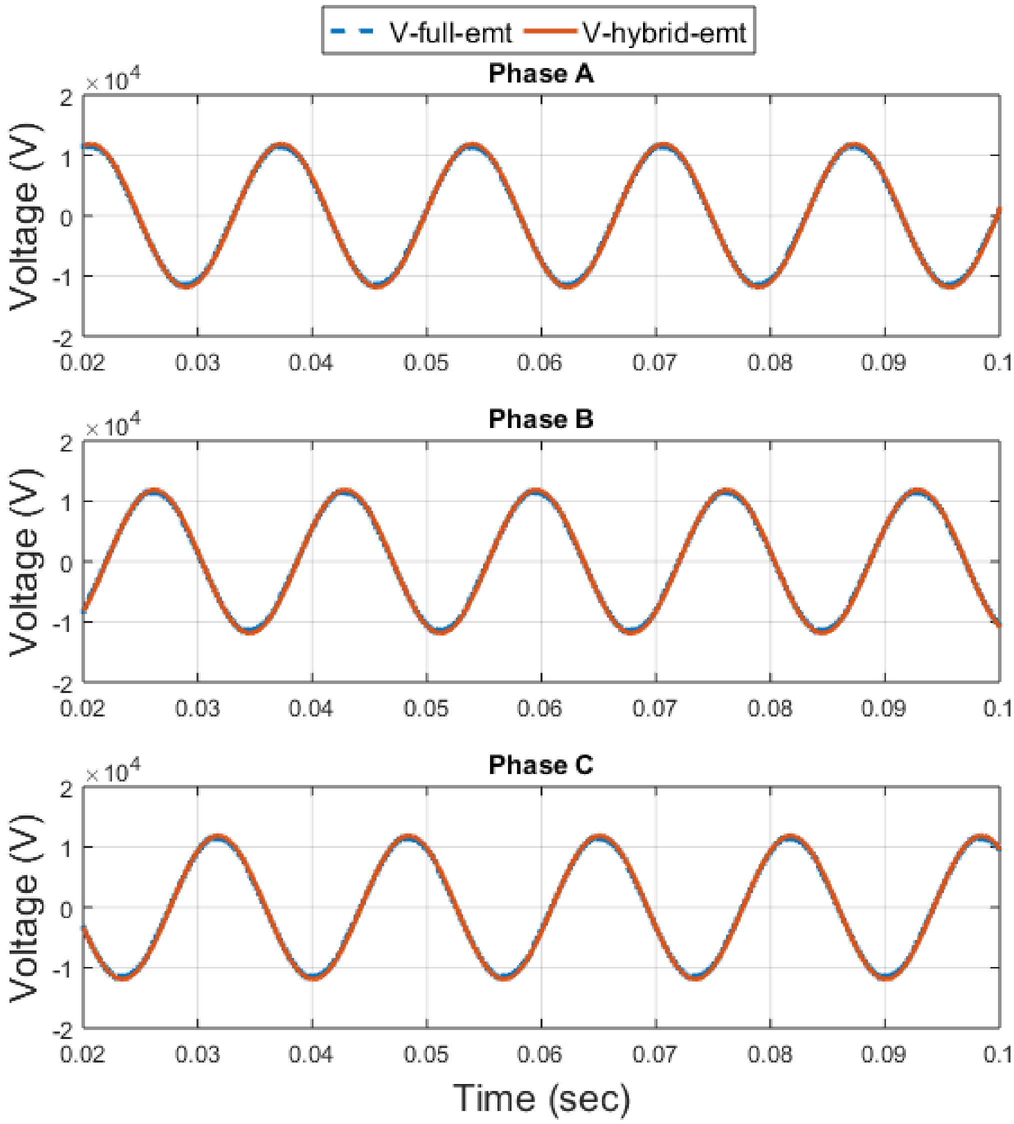

Figure 7.1: Instantaneous Voltage at Bus 3 (Interface Bus) during Steady State

Fig. 7.1 and Fig. 7.2 show the instantaneous voltages and currents at the PCC during steady state. The errors in the magnitude and phase of these quantities are negligible. Table 7.2 compares the RMS values of the boundary currents and voltages during steady-state. It can be seen that the maximum error between the PCC quantities in the EMT and TS subsystems is only around 0.53%. Closely matching

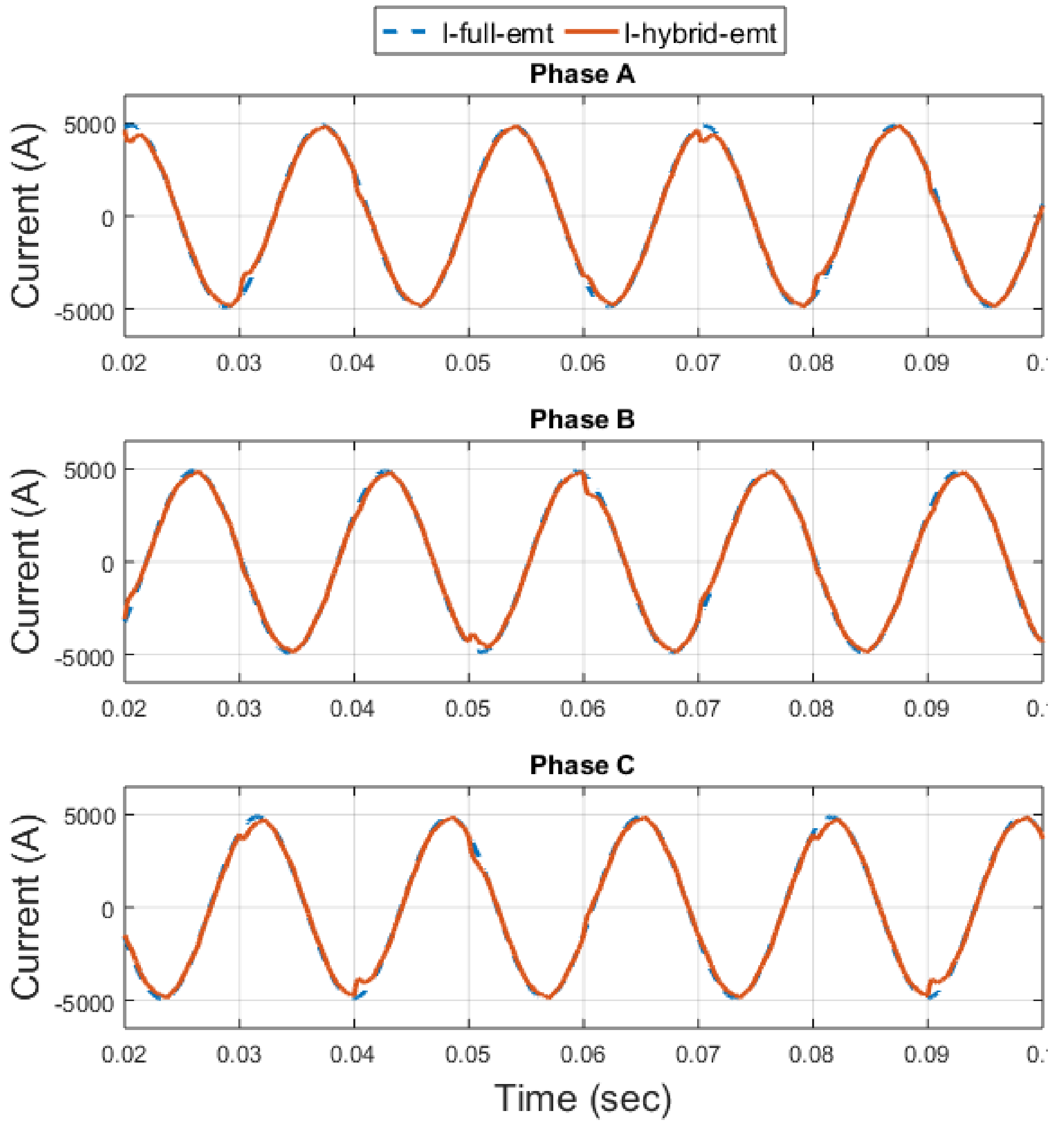

Figure 7.2: Instantaneous Current through Bus 3 (Interface Bus) during Steady State

boundary currents, voltages, real power and reactive power, signify that the model is running fairly accurately.

Fig. 7.3 indicates the runtime of each, the full EMT and the hybrid simulation models, for a simulation of 0.3 seconds. It is evident that the hybrid simulation method drastically reduces the simulation time, by almost 82%, yet maintaining a suitable level of accuracy.

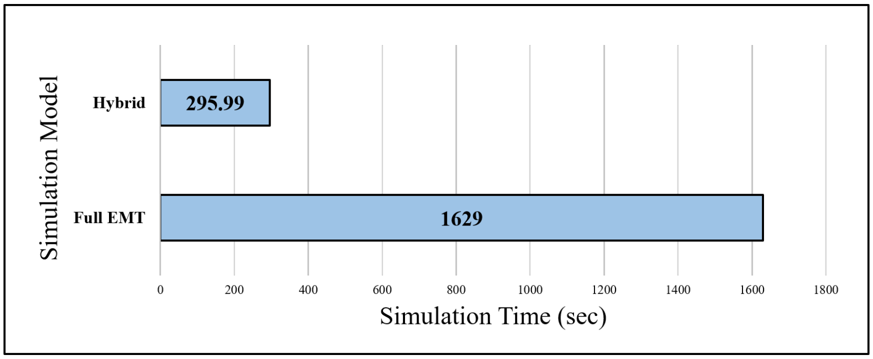

Figure 7.3: Comparison of Simulation Speed

Parameter	Phase	Value		Error (%)
		Hybrid EMT	Hybrid TS	
Current (A)	A	3408.25	3390.08	0.5332
	B	3404.01	3390.08	0.4092
	C	3401.18	3390.08	0.3264
Voltage (V)	A	8392.86	8392.79	0.0008
	B	8400.71	8400.36	0.0042
	C	8400.75	8400.99	0.0029

Table 7.2: Error Evaluation between the Hybrid Simulation EMT Subsystem and TS Subsystem RMS Currents and Voltages at Bus 3 during Steady State

7.2 Transient Analysis

7.2.1 Single-Phase Line-to-Ground Fault

This case represents a transient in the Phasor domain. At the instant of 0.1 s, a single phase line-to-ground (SLG) fault between phase A and ground is applied at bus 4. It is implemented by the Three-Phase Fault block in the TS model in Simulink. The fault resistance Ron is 0.001 and ground resistance Rg is 0.1 . It is cleared after 0.1 s (6 cycles), with the original configuration of the network restored. The Thevenin Impedance is altered, from 0.45078 + 0.36572i Ohm before and after the fault to 0.25576 + 0.35426i Ohm during the fault.

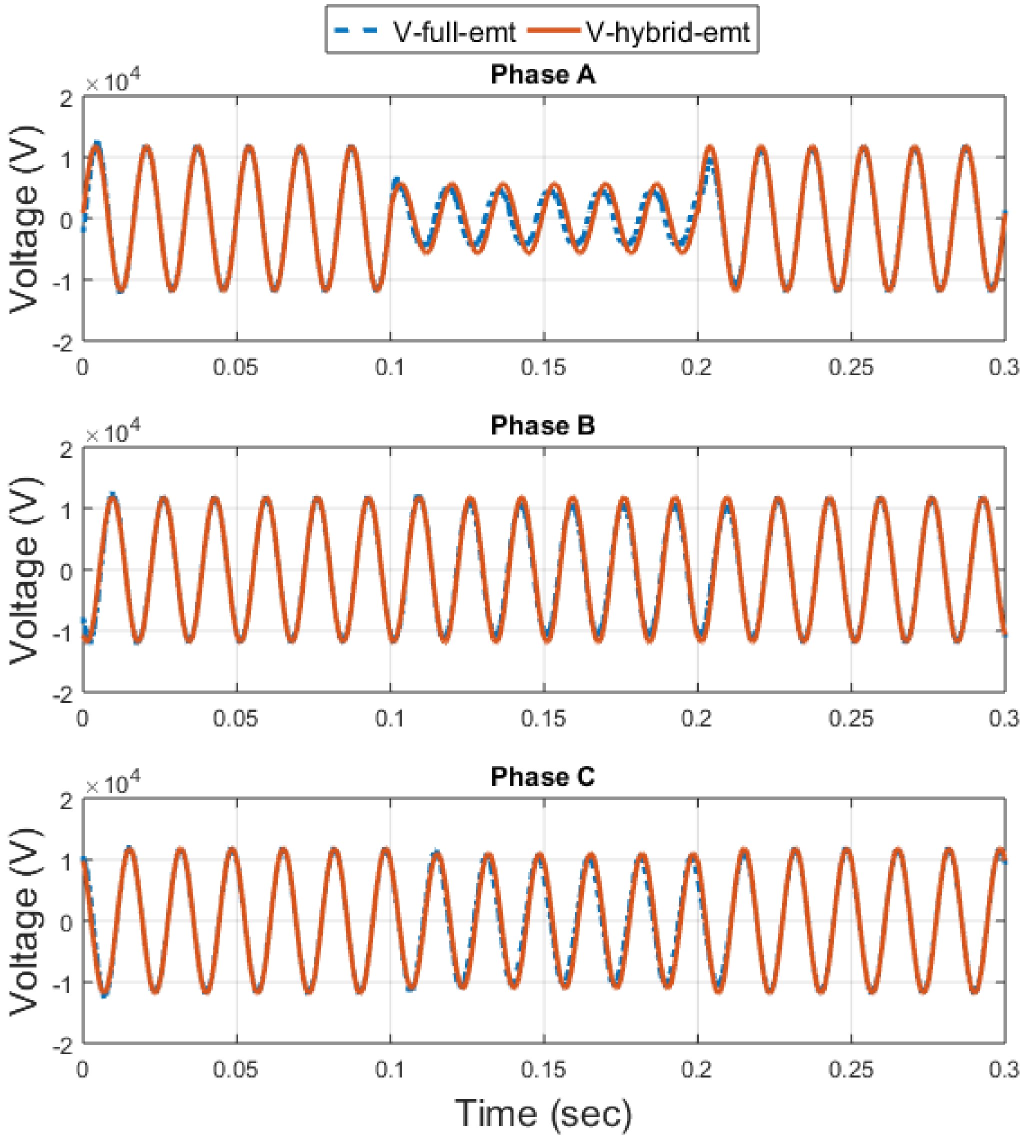

Figure 7.4: Instantaneous Voltage at Bus 3 (Interface Bus) during a SLG Fault at Bus 4

Fig. 7.4 and Fig. 7.5 show the instantaneous voltages and currents at the PCC during the SLG fault. There is a good match between the hybrid simulation and full EMT simulation results before and after the fault and a negligible error in phase shift and magnitude during the fault. It is important to note that such results are not possible to acquire using only a phasor-domain tool.

Fig. 7.6 depicts the real power and reactive power at the PCC. During the SLG

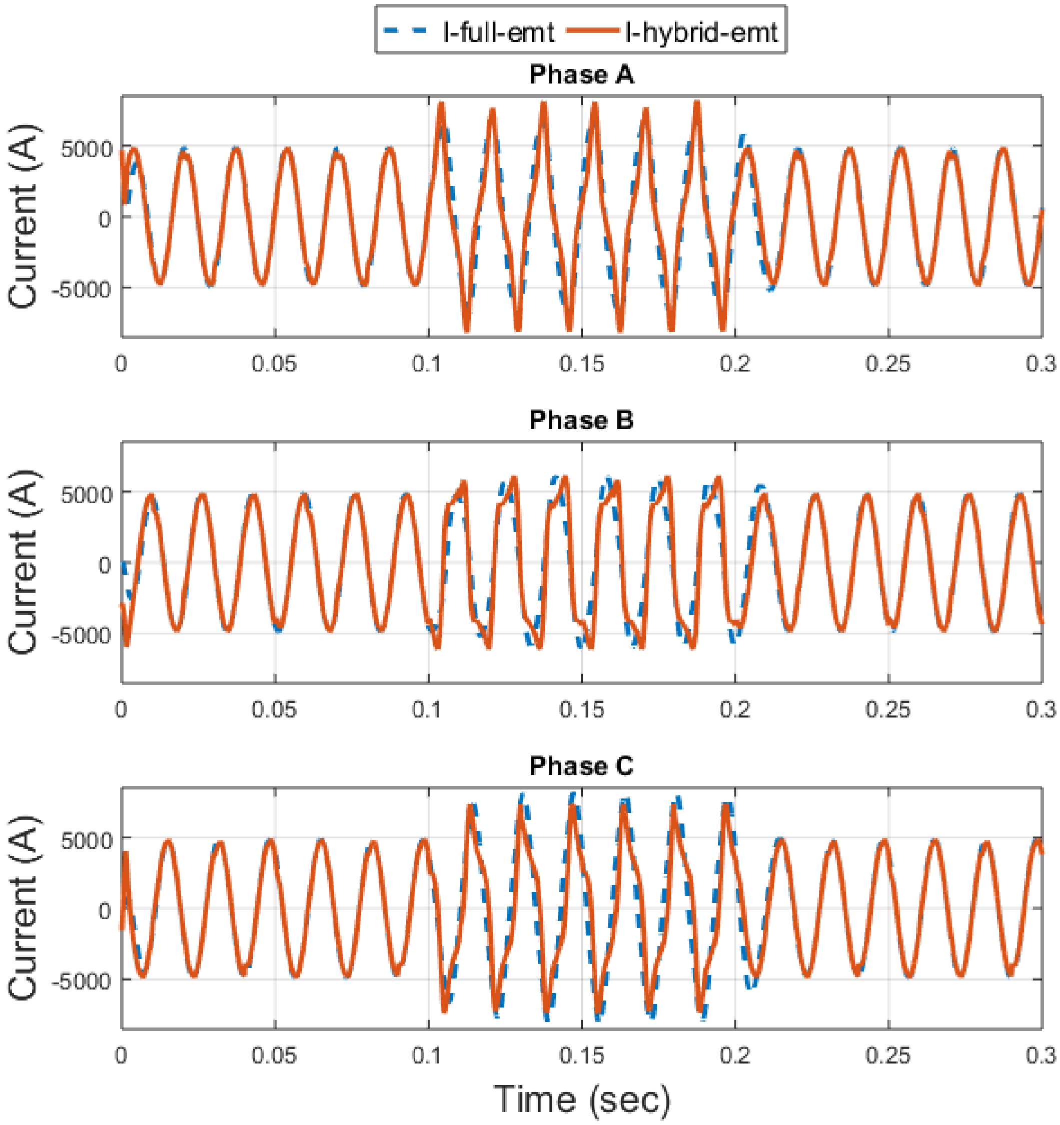

Figure 7.5: Instantaneous Current through Bus 3 (Interface Bus) during a SLG Fault at Bus 4

fault, the full EMT simulation PCC power results have an oscillation at double the fundamental frequency, which is not seen in the hybrid simulation results.

The minor errors observed during the transient can be attributed to loss of some information at the EMT-TS interface. For instance, all the harmonics injected by the inverter in the EMT simulation are not represented in the TS simulation, as the latter only considers the fundamental frequency components of voltage and current.

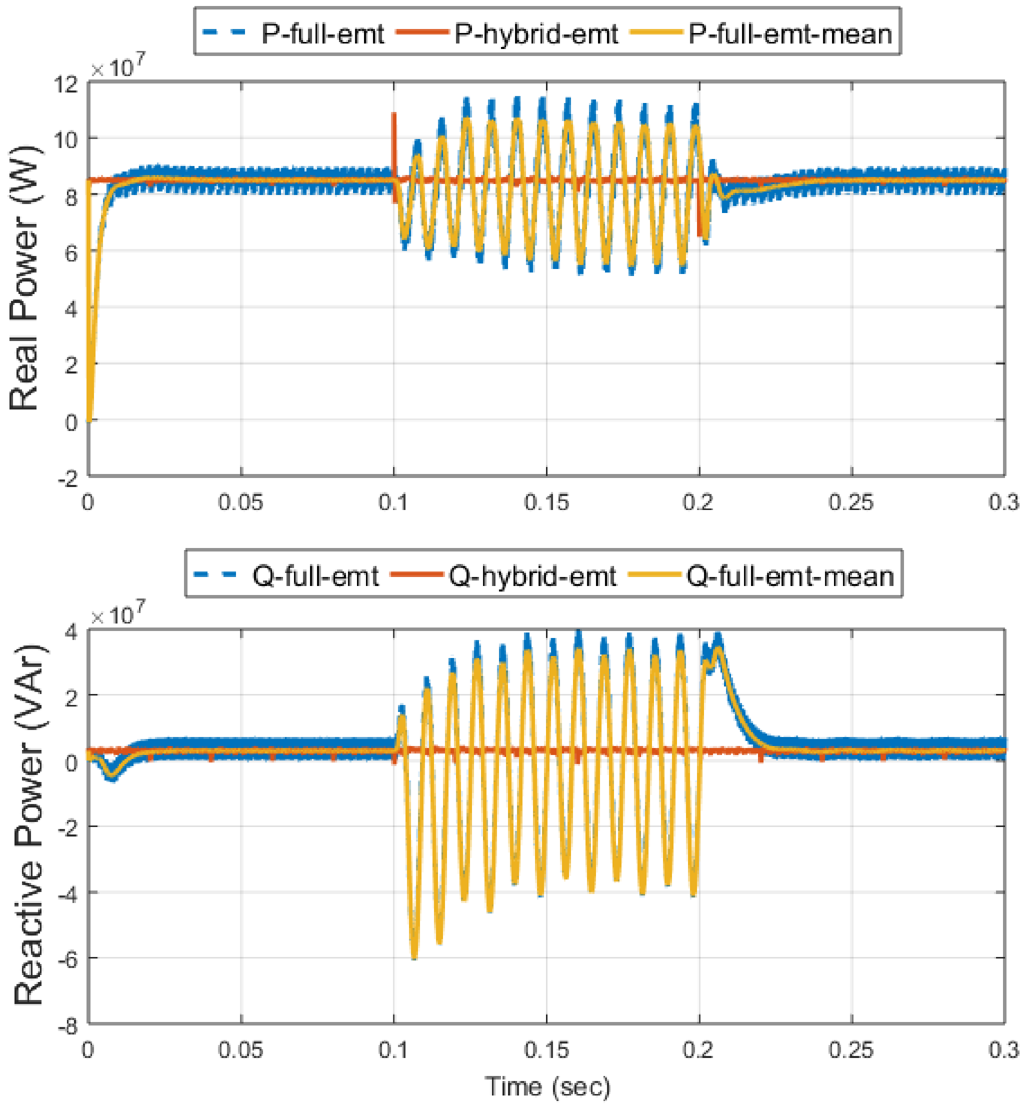

Figure 7.6: Power at Bus 3 (Interface Bus) during an SLG Fault at Bus 4

Also, inadequacies in data extraction, equivalent models and data exchanged can contribute towards errors or deviation from the true results as obtained from the full EMT simulation.

7.2.2 Interface Time Step Analysis

The interface time step has been varied from 10 ms to 50 ms, for the SLG fault transient case. In Fig. 7.7, it can be seen that the total time taken by the hybrid simulation to run decreases as the time step increases. However, the accuracy of the results is affected. This can be noticed in Fig. 7.8 and Fig. 7.9, which depict the instantaneous phase A voltage and current at the PCC during the SLG fault case, for a range of interface time steps. Fig. 7.10 and Fig. 7.11 show the phasors of these voltages and currents at the PCC.

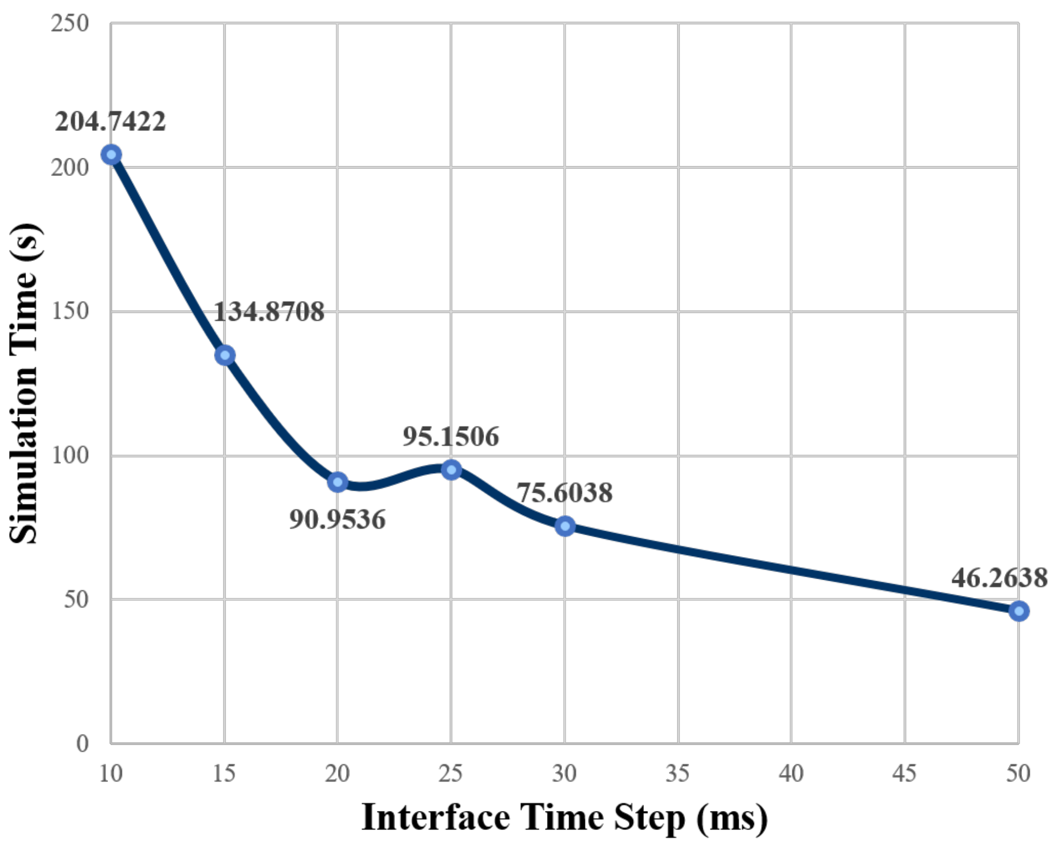

Figure 7.7: Effect of Interface Time Step Variation on Simulation Time

These inaccuracies observed particularly during the transient, can be attributed to interaction timing inconsistencies. As the TS simulation time step is the same as the

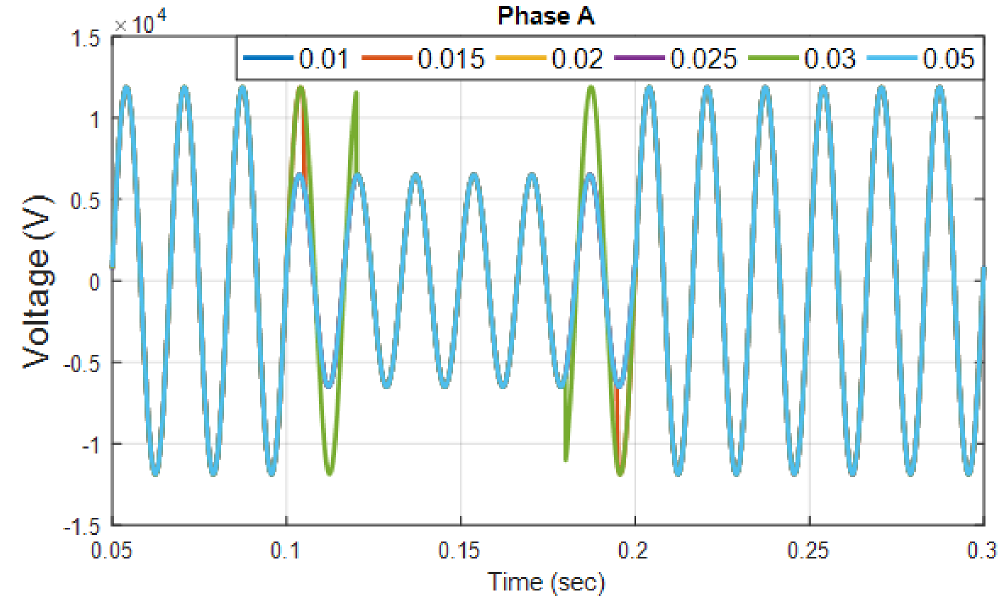

Figure 7.8: Instantaneous Voltage at Bus 3 (Interface Bus) during a SLG Fault at Bus 4 for a Range of Interface Time Steps

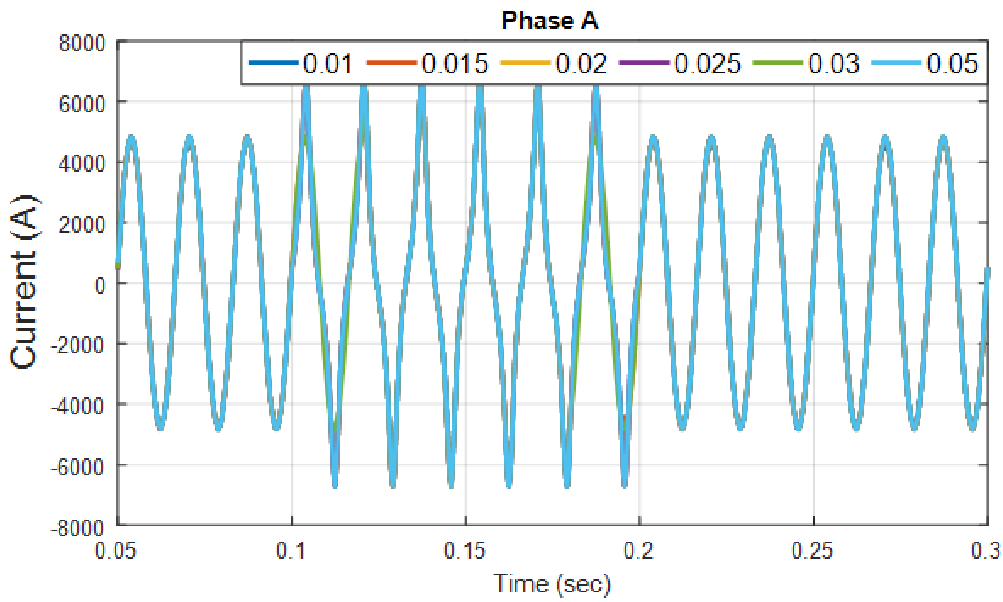

Figure 7.9: Instantaneous Current through Bus 3 (Interface Bus) during a SLG Fault at Bus 4 for a Range of Interface Time Steps

interface time step, a transient occurring in the external system at any instant within the interface time step is reflected only at the end of that interval in the TS model, unless it occurs on instances that are multiples of the interface time step. Also, in

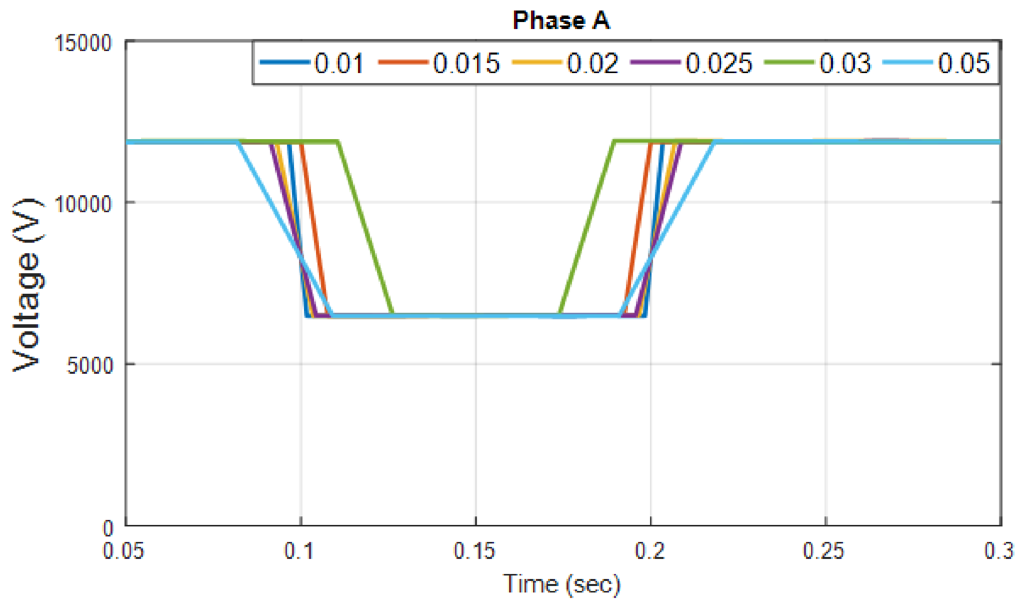

Figure 7.10: Phasor Voltage at Bus 3 (Interface Bus) during a SLG Fault at Bus 4 for a Range of Interface Time Steps

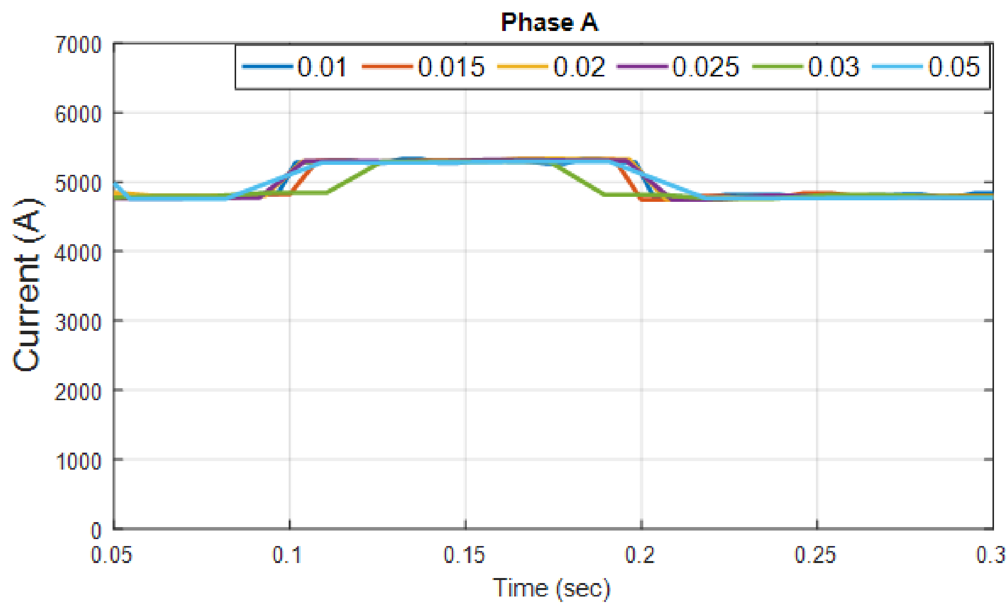

Figure 7.11: Phasor Current through Bus 3 (Interface Bus) during a SLG Fault at Bus 4 for a Range of Interface Time Steps

the serial protocol, a transient occurring in the external system at any instant within the interface time step is reflected at the beginning of the EMT simulation for that interval, through the Thevenin equivalent of the TS subsystem in the EMT subsystem.

Therefore, a smaller time step would deliver more accurate results, whereas a larger time step might pick up the transient at a slightly different instant than the exact instant of occurrence.

7.2.3 Variation in Solar Irradiance

This case represents a transient in the EMT domain. The solar irradiance drops from 1000 W/m^2 to 800 W/m^2 at 0.1 s. This causes a decrease in current and hence in real power output from the solar PV plant, from 85 MW to 68 MW at 0.1 s, as seen in Fig. 7.16.

Fig. 7.12 and Fig. 7.13 show the instantaneous voltages and currents at the PCC during the fluctuation in solar irradiance, where as Fig. 7.14 and 7.15 depict the phasors of the voltages and currents at the PCC (bus 3) and bus 7 respectively. There is a good agreement between the results from the hybrid simulation and those from the benchmark full EMT simulation.

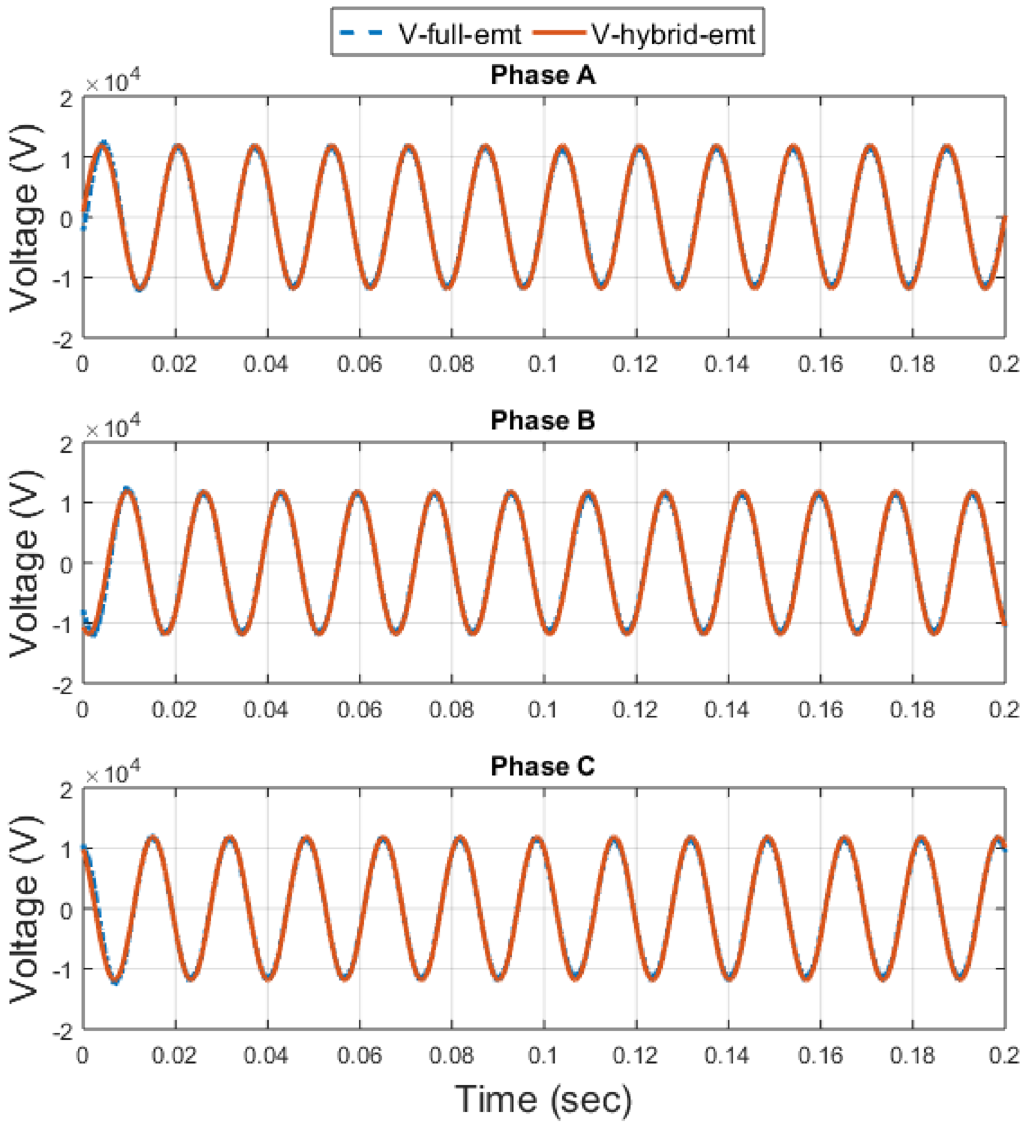

Figure 7.12: Instantaneous Voltage at Bus 3 (Interface Bus) during a Decrease in Solar Irradiance

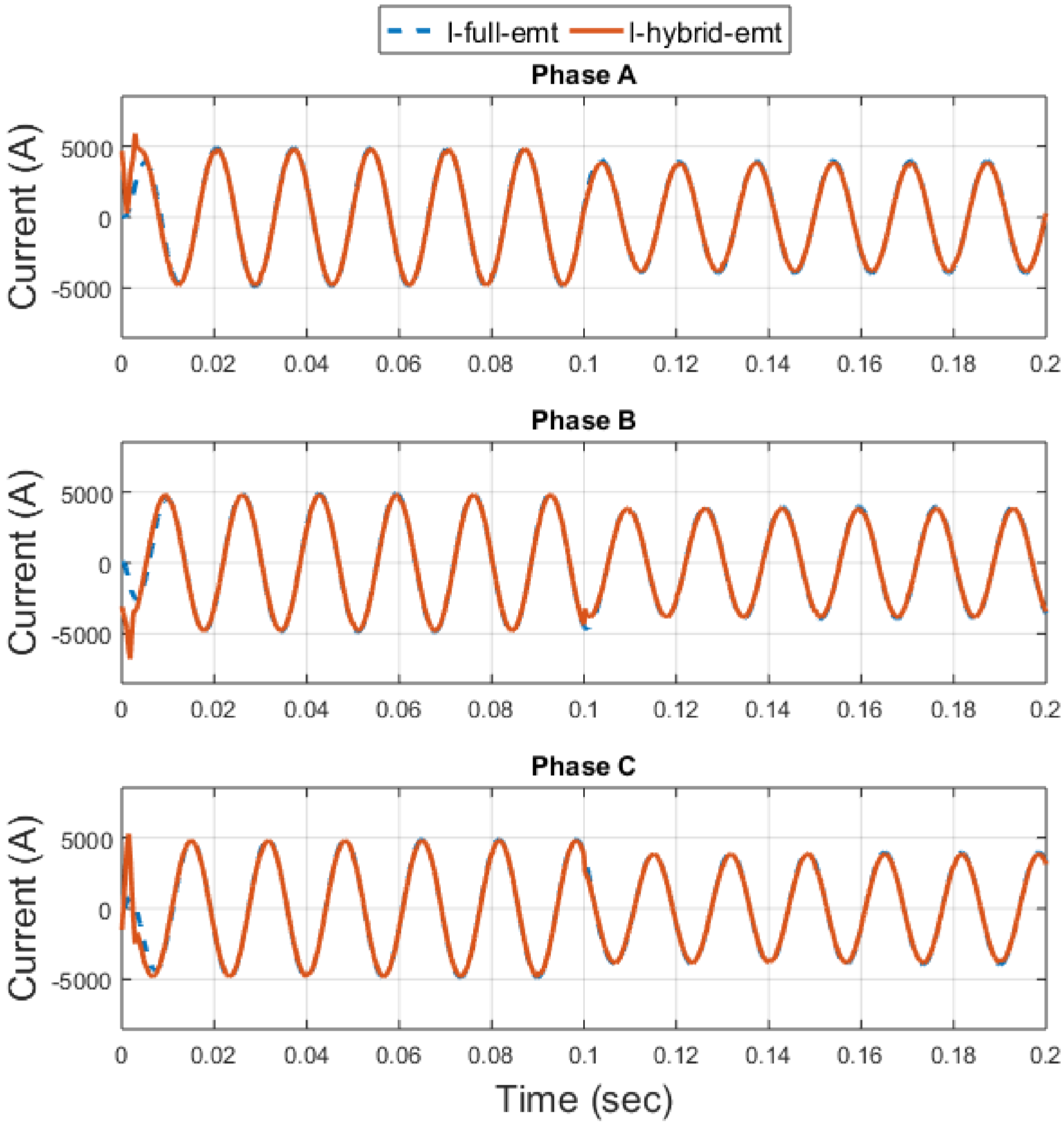

Figure 7.13: Instantaneous Current through Bus 3 (Interface Bus) during a Decrease in Solar Irradiance

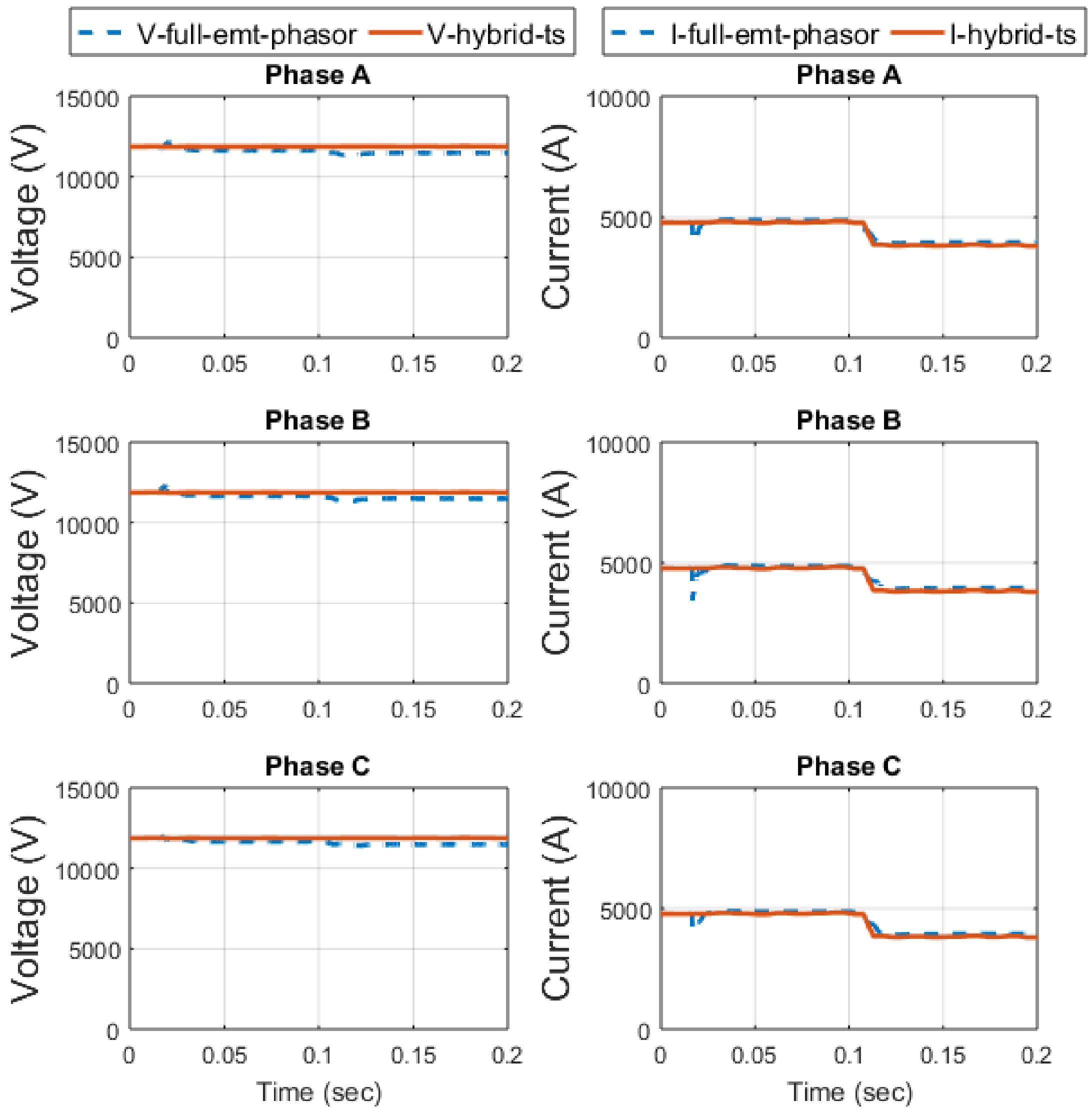

Figure 7.14: Phasor Voltage and Current at Bus 3 (Interface Bus) during a Decrease in Solar Irradiance

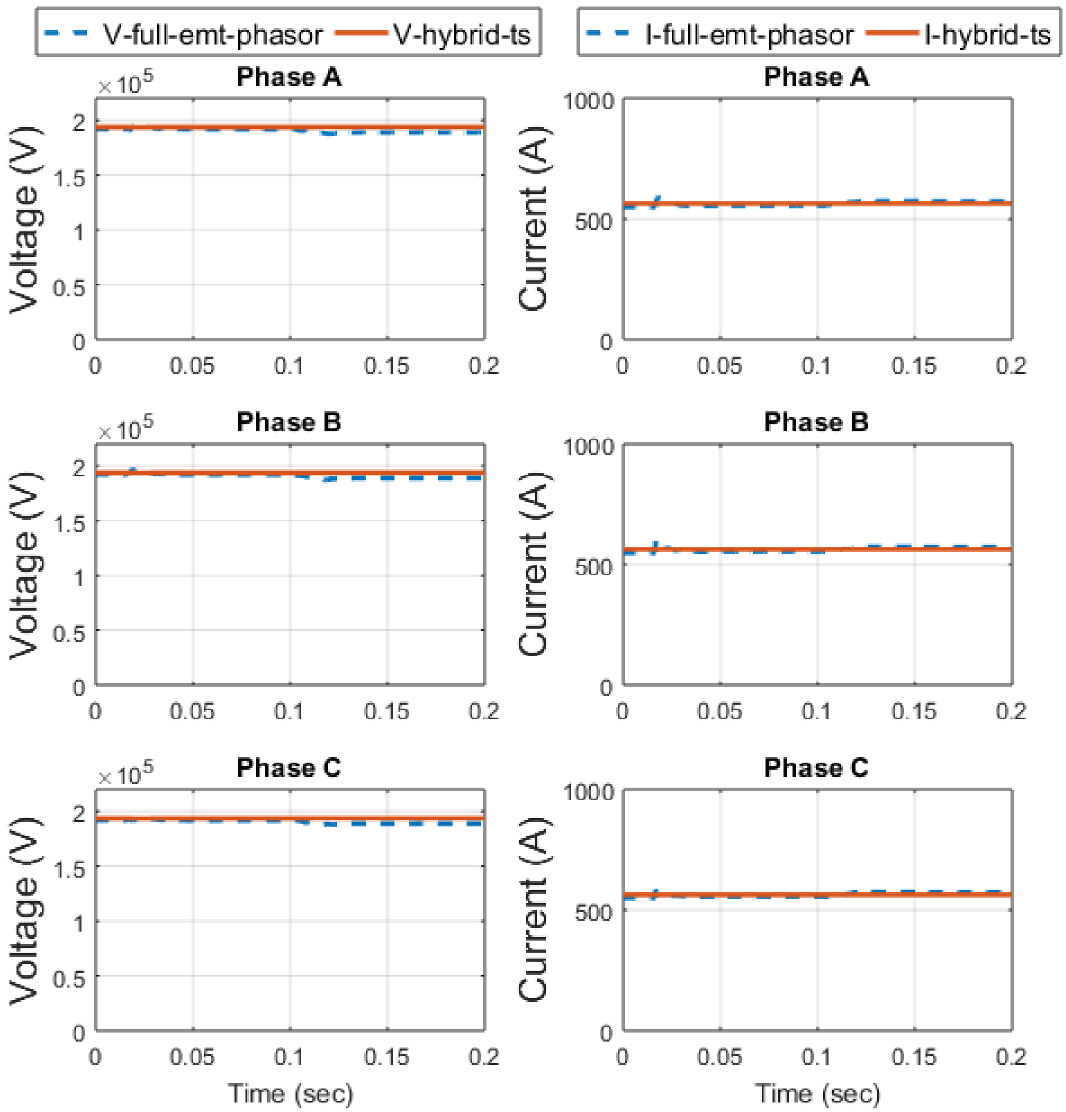

Figure 7.15: Phasor Voltage and Current at Bus 7 during a Decrease in Solar Irradiance

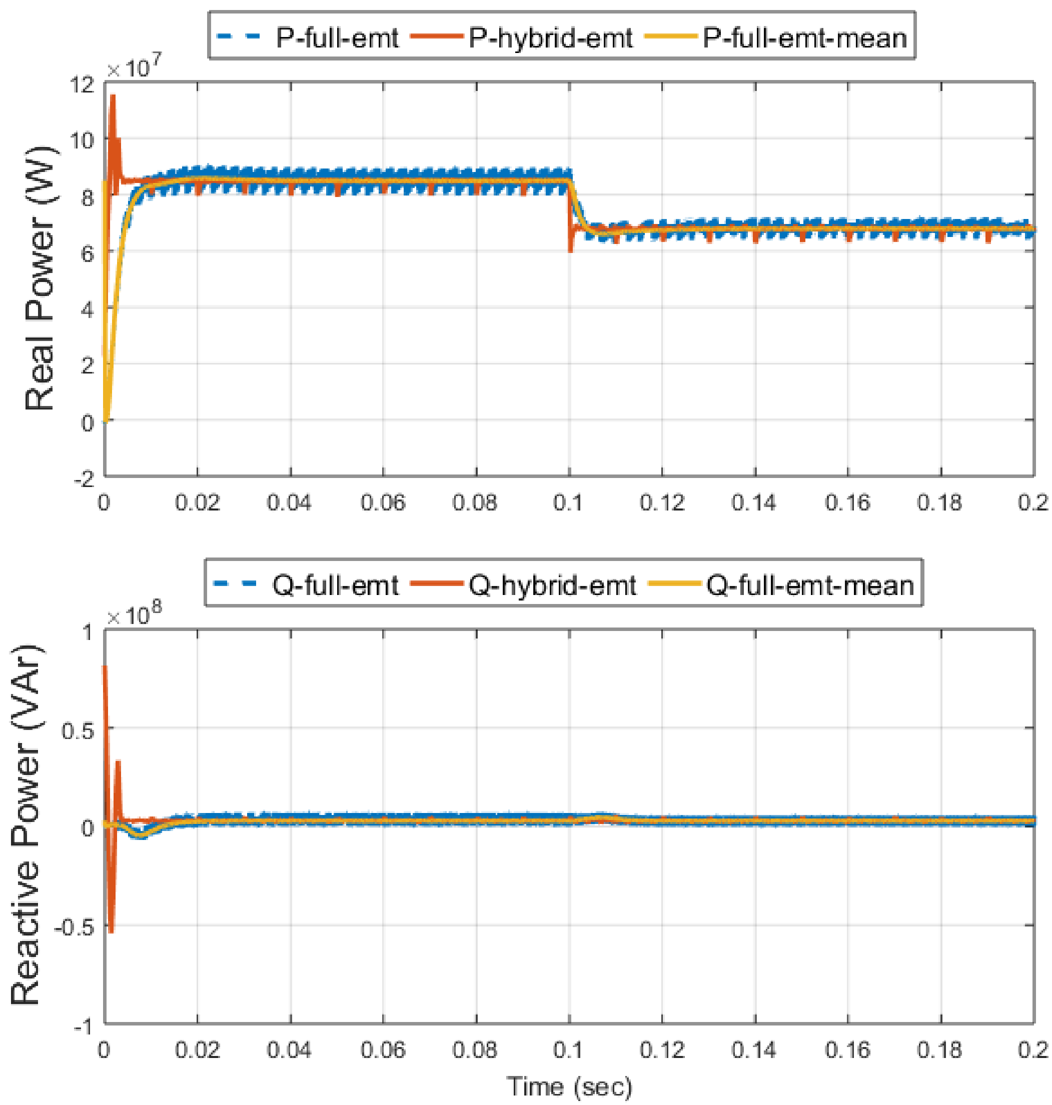

Figure 7.16: Power at Bus 3 (Interface Bus) during a Decrease in Solar Irradiance

Chapter 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

In this work, an electromagnetic transient and transient stability hybrid simulation method has been developed in MATLAB. This approach combines EMT simulation accuracy and TS simulation speed. It enables the study of power networks with penetration of power electronic converter interfaced generation and loads.

The process for implementation of Hybrid Simulation in MATLAB has been established and a suitable interface algorithm has been developed. This hybrid simulation scheme has been tested on the WSCC IEEE 9-bus system. The system behavior during steady state and under faults and solar irradiance variation has been studied. There is a close match between the measured quantities, such as current, voltage, real and reactive powers, obtained from the hybrid simulation and the benchmark complete EMT simulation, under steady state as well as during a range of transients. In comparison with a phasor-domain tool, this hybrid simulation method enables the assessment of accurate, instantaneous quantities, regularly only obtained through an EMT-domain tool. In addition, the simulation speed and efficiency increased substantially from the full EMT simulation. This indicates that the method meets the desired requirements and provides advantages over complete TS or complete EMT simulations, by combining the benefits and overcoming the drawbacks of the two kinds of simulation methods.

A significant contribution is made, in terms of simulation performance and user experience. The primary advancements concerning simulation performance include the development of a unique and simple interface algorithm, an analysis of the interaction parameters and communication, and an improvement in accuracy and efficiency. The most salient features of this method that enhance the user experience include the flexibility, accessibility, user-friendliness, and ease of access, on account of the implementation in MATLAB.

8.2 Future Work

The computational advantages of this simulation method will be even more prominent in the simulation of larger systems with high penetration of converter interfaced generation and loads. A case study with a larger system should be performed in future.

A more detailed error analysis, would be beneficial, in order to work on reduction in errors between the EMT and TS variables and loss of information at the interface. To further improve the accuracy of the hybrid simulation method, an analysis of the impact of the selection of boundary conditions, consideration of non-fundamental frequencies in the TS simulation, and incorporation of dynamic generator models, are some important steps that need to be taken.

To enhance the functionality of the hybrid simulation method, a graphical user interface should also be developed.

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APPENDIX A

WSCC IEEE 9-BUS SYSTEM DATA

Generator Parameters	Value		
	Bus 1	Bus 2	Bus 3
Rated power (MVA)	512	270	125
Rated voltage (kV RMS L-L)	24	18	15.5
Rated power factor	0.90	0.85	0.85
Unsaturated d axis synchronous reactance, Xd (pu)	1.700	1.700	1.220
Unsaturated d axis transient reactance, X'd (pu)	0.270	0.256	0.174
Unsaturated d axis subtransient reactance, X''d (pu)	0.200	0.185	0.134
Unsaturated q axis synchronous reactance, Xq (pu)	1.650	1.620	1.160
Unsaturated q axis transient reactance, X'q (pu)	0.470	0.245	0.250
Unsaturated q axis subtransient reactance, X''q (pu)	0.200	0.185	0.134
d axis transient open circuit time constant, T'do (s)	3.800	4.800	8.970
d axis subtransient open circuit time constant, T''do (s)	0.010	0.010	0.033
q axis transient open circuit time constant, T'qo (s)	0.480	0.500	0.500
q axis subtransient open circuit time constant, T''qo (s)	0.0007	0.0007	0.0700
Armature resistance, Ra (pu)	0.0040	0.0016	0.0040
Leakage reactance, Xl (pu)	0.160	0.155	0.0078
Inertia constant, H (s)	2.6312	4.1296	4.768
Machine load damping coefficient D (pu)	2	2	2
Machine saturation at 1.0 p.u. voltage, $S(1.0)$ (pu)	0.090	0.125	0.1026
Machine saturation at 1.2 p.u. voltage, $S(1.2)$ (pu)	0.400	0.450	0.432

Table A.1: Synchronous Generator Data

Load Parameters	Value		
	Bus 5	Bus 6	Bus 8
Nominal Active Power (MW)	125	90	100
Nominal Reactive Power (MVAr)	50	30	35

Table A.2: Load Data

Line Parameters	Value					
	Bus 4 → 5	Bus 4 → 6	Bus 5 → 7	Bus 6 → 9	Bus 7 → 8	Bus 8 → 9
Length (km)	89.93	97.336	170.338	179.86	76.176	106.646
R0 (Ω/km)	5.88e-1	9.24e-1	9.94e-1	1.15	5.90e-1	5.90e-1
L0 (H/km)	3.98e-3	3.98e-3	3.98e-3	3.98e-3	3.98e-3	3.98e-3
C0 (F/km)	5.89e-9	4.88e-9	5.41e-9	5.99e-9	5.89e-9	5.90e-9
R1 (Ω/km)	5.88e-2	9.24e-2	9.94e-2	1.15e-1	5.90e-2	5.90e-2
L1 (H/km)	1.33e-3	1.33e-3	1.33e-3	1.33e-3	1.33e-3	1.33e-3
C1 (F/km)	9.81e-9	8.14e-9	9.01e-9	9.98e-9	9.81e-9	9.83e-9

Table A.3: Line Data

Transformer Parameters	Value		
	Bus 1	Bus 2	Bus 3
Rated primary voltage (kV RMS L-L)	24	18	15.5
Rated secondary voltage (kV RMS L-L)	230	230	230
R1 (pu)	1.00e-10	1.00e-10	1.00e-10
L1 (pu)	2.88e-2	3.13e-2	2.93e-2
R2 (pu)	1.00e-10	1.00e-10	1.00e-10
L2 (pu)	2.88e-2	3.13e-2	2.93e-2
Rm (pu)	5.00e-3	5.00e-3	5.00e-3
Lm (pu)	5.00e-3	5.00e-3	5.00e-3

Table A.4: Transformer Data

APPENDIX B

SOLAR PV PANEL DATASHEET SPECIFICATION

Electrical Properties (STC)	250	300	325
Model	JP250W24V	JP300W24V	JP325W24V
No. of Cells	72	72	72
Maximum Power (Pmax)	250Wp	300Wp	325Wp
MPP Voltage (Vmpp) (V)	35.9	36.6	38.4
MPP Current (Impp) (A)	6.97	8.2	8.47
Open Circuit Voltage (Voc)(V)	44.5	44.8	46.3
Short Circuit Current (Isc) (A)	7.45	8.6	8.97

Table B.1: Electrical Specifications of Jakson Solar PV Module at STC

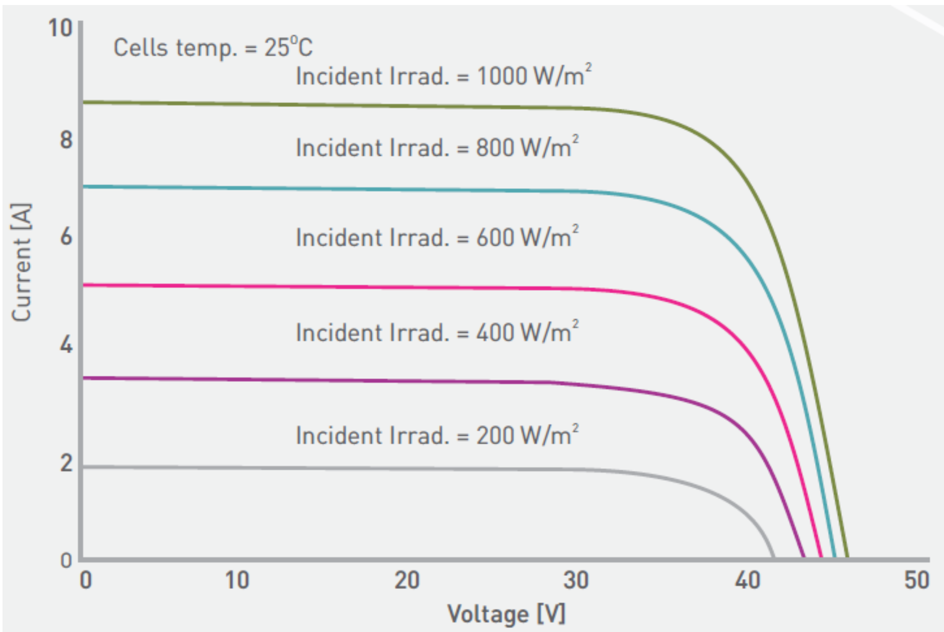

Figure B.1: I-V Curve Variation with Irradiance

APPENDIX C

MATLAB CODE FOR EMT-TS INTERFACE

```
%Written by Denise Athaide

clc;
clear;
close all;
format short g

%Solar PV Array Parameter Extraction and Initialization ...
    (JP300W24V module)
Nseries=1776
Nparallel=152
Temp=298;
k=1.38*10^-23;
q=1.6*10^-19;
Ns=72*Nseries;
didv_sc=-2.488*10^-3;
didv_oc=-2.05;
Voc=44.8*Nseries;
Vmp=36.6*Nseries;
Isc=8.6*Nparallel;
Imp=8.2*Nparallel;
Irr=1000/1000;
Vsource=Vmp

Iph=Isc*Irr;
Rsh=-Nseries*(didv_sc)^-1
C1=1*10^-12;

syms IO DIF Rs
eqn1 = IO == (Isc-(Voc/Rsh))/(exp((q*Voc)/(Ns*DIF*k*Temp))-1);
eqn2 = Imp == Isc - ...
    IO*exp(q*((Vmp+(Imp*Rs))/(Ns*DIF*k*Temp)))-((Vmp+(Imp*Rs))/Rsh);
eqn3 = Rs == -((didv_oc)^-1)- ...
    (1/(((q*IO)/(Ns*DIF*k*Temp))*(exp((q*Voc)/(Ns*DIF*k*Temp)))));
sol = solve([eqn1, eqn2, eqn3], [IO, DIF, Rs]);
IOSol = sol.IO;
DIFSol = sol.DIF;
RsSol = sol.Rs;
IO=vpa(IOSol,4);
DIF=vpa(DIFSol,4);

Rs=vpa(abs(RsSol),4)
I0=double(IO)
a=double(DIF)

%Independent variables
Vdc=Vsource
w=2*pi*60;
j=sqrt(-1);

%Initial conditions
Ppm=Vsource*Isc*Irr1;
Ppv=Ppm;
Qpm=3*(10^6)
Iemt=4776.4;
Vemt=11871.25;
```

```
ph_shift=0;

%Filter parameters
Rf=0.1;
Lf=0.0052;

%Controller parameters
wc=2*pi*2000;
PM=60;
s=j*wc;

%Simulation parameters
sim_time=0.3;
step=0.02;
timestep=0:step:sim_time-step;

%SLG fault parameters
tf=0;
tf_1=0;
Rg=0.1;
t0=0.1;
t1=0.2;

%Irrandiance step
tp=1;%0.1
Irr1=1000/1000
Irr2=800/1000%800/1000
set_param('hybrid_EMT/Solar PV/Irr','Value','Irr1')

%Creation and initialization of vectors for TS quantities
tstep=length(timestep);
ts_step=0.02
ts_length=ceil((step/ts_step)+1);
f=ceil((tstep)*ts_length);

Its_a=zeros(f,1);
Its_b=zeros(f,1);
Its_c=zeros(f,1);
Vts_a=zeros(f,1);
Vts_b=zeros(f,1);
Vts_c=zeros(f,1);
Pts=zeros(f,1);
Qts=zeros(f,1);
Tts=zeros(f,1);
Its7_a=zeros(f,1);
Its7_b=zeros(f,1);
Its7_c=zeros(f,1);
Vts7_a=zeros(f,1);
Vts7_b=zeros(f,1);
Vts7_c=zeros(f,1);
Its_a(1) = 4776.4;
Vts_a(1) = 11871.25;
Pts(1) = 85*(10^6);
Qts(1) = 3*(10^6);

I_emt_a(2001)=0;
I_emt_b(2001)=0;
```

```
I_emt_c(2001)=0;
V1_pm_mag_a(ts_length)=16500;
V2_pm_mag_a(ts_length)=18000;
P1_pm(ts_length)= 71*10^6;
P2_pm(ts_length)= 163*10^6;

%Creation and initialization of vectors for EMT quantities
emt_step=5e-6;
emt_length=ceil((step/emt_step)+1);
c=ceil((tstep)*emt_length);

t_EMT_ws=zeros(c,1);
I_emt_ws_a=zeros(c,1);
I_emt_ws_b=zeros(c,1);
I_emt_ws_c=zeros(c,1);
V_emt_ws_a=zeros(c,1);
V_emt_ws_b=zeros(c,1);
V_emt_ws_c=zeros(c,1);
P_emt_ws=zeros(c,1);
Q_emt_ws=zeros(c,1);
P_emt_avg=zeros(c,1);
Q_emt_avg=zeros(c,1);
Ed_EMT=zeros(c,1);
Eq_EMT=zeros(c,1);
Id_EMT=zeros(c,1);
Iq_EMT=zeros(c,1);

%Simulation timer initialization
elapsedTime_TS=0;
elapsedTime_EMT=0;


%Start hybrid simulation
for i=1:tstep
time=timestep(i);
time

%Transient 1: Single Phase L-G Fault at Bus 4
if (time≥t0) && (time≤(t1-step))
   set_param('hybrid_TS/tf','Value','1')
   tf_1=1;
else
   set_param('hybrid_TS/tf','Value','0')
   tf_1=0;
end

%Transient 2: Solar Irrandiance Variation
if (time≥tp)
   set_param('hybrid_EMT/Solar PV/Irr','Value','Irr2')
   Ppv=Vsource*Isc*Irr2
else
   set_param('hybrid_EMT/Solar PV/Irr','Value','Irr1')
   Ppv=Vsource*Isc*Irr1
end

%Calculation of TS equivalent Thevenin impedance in EMT
Zdata_B3 = power_zmeter('hybrid_TS',linspace(59,61,3));
```

```
Zpm=(Zdata_B3.Z(2))
Rgrid=real(Zpm);
Lgrid=imag(Zpm)/377;
Rpm=Rf+Rgrid;
Lpm=Lf+Lgrid;
L=Lpm;

tic

%Load TS simulation model
tsmodel = 'hybrid_TS';
load_system(tsmodel)
%Solve pflow, apply to model
LF1 = power_loadflow('-v2',tsmodel,'solve');
LF1;
%Run TS model for interface timestep
sim(tsmodel)

%Get V, Δ, I, P & Q data from TS simulation (saved in WS)
Vpm_a=V_pm_mag_a(ts_length)
Δ_a=V_pm_ang_a(ts_length)
phi_a=V_pm_ang_a(ts_length)-(I_pm_ang_a(ts_length));

Vpm_b=V_pm_mag_b(ts_length)
Δ_b=V_pm_ang_b(ts_length)
phi_b=V_pm_ang_b(ts_length)-(I_pm_ang_b(ts_length));

Vpm_c=V_pm_mag_c(ts_length)
Δ_c=V_pm_ang_c(ts_length)
phi_c=V_pm_ang_c(ts_length)-(I_pm_ang_c(ts_length));

Phi_deg=phi_a*180/pi %in degrees
pf=cos(phi_a)

%For plotting
g=ceil(((i-1)*ts_length)+1)
h=ceil(i*ts_length);

Its_a(g:h,1)=I_pm_mag_a;
Its_b(g:h,1)=I_pm_mag_b;
Its_c(g:h,1)=I_pm_mag_c;

Vts_a(g:h,1)=V_pm_mag_a;
Vts_b(g:h,1)=V_pm_mag_b;
Vts_c(g:h,1)=V_pm_mag_c;

Pts(g:h,1)=P_pm;
Qts(g:h,1)=Q_pm;

Its7_a(g:h,1)=I7_pm_mag_a;
Its7_b(g:h,1)=I7_pm_mag_b;
Its7_c(g:h,1)=I7_pm_mag_c;

Vts7_a(g:h,1)=V7_pm_mag_a;
Vts7_b(g:h,1)=V7_pm_mag_b;
Vts7_c(g:h,1)=V7_pm_mag_c;

```

```
toc
elapsedTime_TS = elapsedTime_TS + toc


tic

%Controller design

Gp=(Vdc/2)*(1/((s*Lpm)+Rpm));
Phi_sys=(angle(Gp))*(180/pi);
Phi_boost=PM-90-Phi_sys;
k=tan((pi/4)+((pi/180)*(Phi_boost/2)));
wz=wc/k;
wp=k*wc;
Gc_pre=(1/s)*((1+(s/wz))/(1+(s/wp)));%??
G_OL_pre=Gp*Gc_pre;
Kc=1/abs(G_OL_pre);

Pg=85*10^6
Qg=3*10^6;
set_param('hybrid_EMT/Controller/Constant_Ppm','Value','Pg')
set_param('hybrid_EMT/Controller/Constant_Qpm','Value','Qg')

%Update parameters in EMT model

Vgrid_mag_a=Vpm_a;
Vgrid_Δ_a=ph_shift+(Δ_a*(180/pi));
Vgrid_mag_b=Vpm_b;
Vgrid_Δ_b=ph_shift+(Δ_b*(180/pi));
Vgrid_mag_c=Vpm_c;
Vgrid_Δ_c=ph_shift+(Δ_c*(180/pi));

set_param('hybrid_EMT','SimulationCommand','update');

%Load EMT simulation model
emtmodel = 'hybrid_EMT';
load_system(emtmodel)
%Run EMT sim for interface timestep
sim(emtmodel)

%For plotting
a=ceil(((i-1)*emt_length)+1);
b=ceil(i*emt_length);
I_emt_ws_a(a:b,1)=I_emt_a;
I_emt_ws_b(a:b,1)=I_emt_b;
I_emt_ws_c(a:b,1)=I_emt_c;
V_emt_ws_a(a:b,1)=V_emt_a;
V_emt_ws_b(a:b,1)=V_emt_b;
V_emt_ws_c(a:b,1)=V_emt_c;
P_emt_ws(a:b,1)=P_emt;
Q_emt_ws(a:b,1)=Q_emt;
Ed_EMT(a:b,1)=edemt;
Eq_EMT(a:b,1)=eqemt;
Id_EMT(a:b,1)=idemt;
Iq_EMT(a:b,1)=iqemt;

%Optional Phasor Extraction of V, I, theta from instantaneous EMT ...
```

```
    waveforms using FFT in the Powergui
%(May be used only if the interface time step is greater than one ...
    fundamental cycle)

%get I
%FFTDATAI = power_fftscope(Scope_Iemt);
%%power_fftscope(FFTDATAI);
%Iemt=FFTDATAI.magFundamental

%get V
%FFTDATAV = power_fftscope(Scope_Vemt);
%%power_fftscope(FFTDATAV);
%Vemt=FFTDATAV.magFundamental

%Calculation of P & Q from I, V and cos theta using the equations
%thetaemt=(angle(Vpm)*angle(Ig))*(180/pi)
%Pemt_cal=(3/2)*Iemt*Vemt*cos(thetaemt)
%Qemt_cal=(3/2)*Iemt*Vemt*sin(thetaemt)

%Measurement of P & Q from EMT model
%get P
%FFTDATAP = power_fftscope(Scope_Pemt);
%Pemt=FFTDATAP.DCcomponent
%get Q
%FFTDATAQ = power_fftscope(Scope_Qemt);
%Qemt=FFTDATAQ.DCcomponent

%Ipv{i} = Iemt;
%Vpv{i} = Vemt;
%Ppv{i} = Pemt;
%Qpv{i} = Qemt;

Pemt=P_emt(emt_length)
Qemt=Q_emt(emt_length)

%Update Parameters (P & Q) in TS model
Ppm=Pemt
Qpm=Qemt

ph_shift=(((rem(step,0.016667))/0.016667)*360)*i;

xInitial_emt=xFinal_emt;
save myModel_init xInitial_emt

set_param('hybrid_TS','SimulationCommand','update');

toc
elapsedTime_EMT=elapsedTime_EMT+toc

end

%Total hybrid simulation time
elapsedTime_Total=elapsedTime_TS+elapsedTime_EMT

%Filled time vectors for plotting
Tts(1:((tstep)*ceil(ts_length)),1) = ...
    0:sim_time/(length(Its_a)-1):sim_time;
```

```
t_EMT_ws(1:((tstep)*ceil(emt_length)),1) = ...
    0:sim_time/(length(I_emt_ws_a)-1):sim_time;
```