Spring 5-13-2016

Sensitivity Analysis of Synchronous Generators for Real-Time Simulation

Sowmya Munukuntla
University of New Orleans, sowmya.munukuntla@gmail.com

Sensitivity Analysis of Synchronous Generators for Real-Time Simulation

A Thesis

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements of the degree of

Master of Science
in
Engineering
Electrical Engineering

By

Sowmya Munukuntla

B-Tech. Jawaharlal Nehru Technological University, 2012

May, 2016

Acknowledgement

Firstly, I would like to thank my parents and brother for their encouragement and unconditional support in every aspect of my life. Without their support, this would not be possible.

I sincerely acknowledge the support and encouragement received from my research and academic adviser Dr. Parviz Rastgoufard for his continuous support through out my graduate study and research. His patience and unfailing encouragement have been the major contributing factors in the completion of my thesis research.

I heartfully thank Dr. Ittiphong Leevongwat for his valuable suggestions and technical support throughout my thesis and research work. He was available in all the tough times and strongly supported and corrected the work throughout my academics.

I sincerely thank Dr. Ebrahim Amiri for his continuous moral support throughout my study at the school. I thank him for keeping me motivated and boost up the confidence during my research.

I further sincerely appreciate and thank my friends Rastin Rastgoufard and Ram Mohan Snaboyina for their time and help in achieving the software knowledge. I also thank UNO-Entergy Power and Energy Research Laboratory (PERL) for giving me access to all the software needed.

Finally, I would like to thank all the faculty and staff members of the College of Engineering at University of New Orleans for their support and contribution in providing quality education.

Thank you All!

Contents

List of Figures

List of Tables

Abstract

The purpose of this thesis is to validate generator models for dynamic studies of power systems using PSS/E (Power System Simulator for Engineering), EMTP (ElectroMagnetic Transient Program), and Hypersim. To thoroughly evaluate the behavior of a power system in the three specified software packages, it is necessary to have an accurate model for the power system, especially the generator which is of interest. The effect of generator modeling on system response under normal conditions and under faulted conditions is investigated in this work. A methodology based on sensitivity analysis of generator model parameters is proposed aiming to homogenize the behavior of the same power system that is modeled in three software packages. Standard IEEE 14-Bus system is used as a test case for this investigation. Necessary changes in the exciter parameters are made using the proposed methodology so that the system behaves identical across all three software platforms.

Keywords: PSS/E, EMTP, Hypersim, Real-Time Modeling, Generator Modeling, Exciter Modeling, Exciter Parameters, Sensitivity Analysis, IEEE 14-Bus System, Dynamic Analysis.

Chapter 1
Problem Statement and Historical Review

1.1 Introduction

In a power system network consisting of generation, transmission and distribution, synchronous generators are the major power generating units where as motors are the major loads which makes the synchronous machine an important element in the power system. In order to have a more reliable power system and quick response for the faults in the system, more accurate modeling of the synchronous machine is necessary.

Two groups of investigators developed ways to accurately model a synchronous generator starting from later part of twentieth century during which there was an increased interest in modeling of synchronous machines. One group among the two tried to compare the performance of the synchronous machine models with the measured performance of the machines with a fault applied on the system. The other group developed an alternate method of finding the machine parameters which can be used in the models so that the performance matches the actual measurements.

There are quite different kinds of power system software used by the Engineers but every software platform has their own limitations. Few software packages only allow the modeling of the components of the power system such as PSS/E, PSLF, PowerWorld. Few others have a capability of simulating the transients on a power system such as EMTP, ETAP. There are

other software platforms where a physical device can be connected to the test system using the Input-Output devices which interlink the software with the equipment and a real time study can be performed. The software packages such as Hypersim, RTDS, Opal-RT real time simulator can perform such kind of real time analysis. When there is a need to study the system behavior with a hardware connected in the loop with in a laboratory environment, a real-time simulator is useful which can capture the behavior in micro seconds.

In order to learn the system behavior or the transient analysis to be performed on a power system with an equipment to be connected such as FACTS devices, relays, e.c.t., an accurate modeling of both the power system and the equipment to be tested is necessary if the modeling software is used without which the accuracy in the results can not be achieved. A question "Is the model used to study the behavior of the equipment accurate and capture all the dynamics of the system?" is raised when a model of the equipment is used within the software package. In order to answer the above question, the test system needs to be modeled in the desired software packages and the dynamic analysis is performed on the test system assuming a disturbance in the system, once the dynamic behavior is identical in both the software packages the equipment is to be connected, at the same time the mathematical model of the equipment is assumed and a comparative analysis is performed to actually identify the accuracy of the modeling of the equipment performing the computer analysis.

For performing and analyzing the dynamic behavior of the system at least on dynamic model of the system needs to be included. There are certain components in the power system which can be modeled in both steady state and dynamic models such as Transformers, Transmission Lines, Synchronous Machines, and Loads.

The objective of this thesis is to use the existing capability to model, analyze and predict

the dynamic behavior of the electric power system, specially synchronous generators. With the increasing demands on the power systems along with the growth in size and complexity, this work becomes increasingly important. This thesis analyzes the dynamic and transient stability of a power system to severe disturbances in the power system. This analysis is performed in three power system software packages (PSS/E, EMTP and Hypersim) and the behavior of the generator to specific three phase bus fault is compared and necessary modifications of the excitation system parameters are made so that the system behaves similar in the three software packages. This analysis and modifications are helpful for the selection of approximate parameters of the generator when a set of parameters suitable for the system in one software package is given.

1.2 Types of Models

There are different types of modeling in a power system. Depending on various situations and requirements, type of models used for power system study varies [14]. Following gives some basic idea of different types of models used in studies.

- **Steady State Models** are phasor based, and useful for power flow and fault studies.

- **Dynamic Models** are phasor based and used in stability programs to study dynamic power system phenomena in the time frame longer than about 0.05 seconds. They consist of a series of power flow solutions with parameters automatically adjusted between each solution.

- **Transient Models** are based on instantaneous solutions of power system phenomena

in time frames much shorter than applicable to stability models. The outputs of these models are instantaneous values of current and voltage in small time steps (much smaller than one power frequency cycle).

Dynamic stability can be categorized based on the following considerations:

- Physical nature of the resulting instability.
- Size of considered disturbance. This leads to small-signal and transient stability of the system.
- Devices, processes, and time span that must be taken into consideration in order to determine stability.
- The most appropriate method of calculation and prediction of stability.

1.2.1 Application of generator models in stability studies

Power system stability studies are generally conducted for one of the following purposes:

- **Power system planning and design:** To aid in decisions regarding future transmission network requirements, equipment specifications, and selection of parameters for control and protective systems.
- **Power system operation:** To determine operating limits and determine the need for arming emergency controls or special protection schemes.
- **Post-disturbance analysis:** To simulate events following major system disturbances or blackouts.

As the present study deals with the selection of parameters of the control blocks, this research can be categorized under power system planning and design.

1.3 Historical Background

The importance of real time modeling, simulation and analysis of a power system is recognized by many utilities later when they found that the analysis made with the steady state tests are not accurate since the power system is reduced to an equivalent lumped impedance network. [15] Later after the development of EMTP in 1960's, utilities started using EMTP in a real time mode for digital power system modeling. The authors in [15] uses three PC's, one for receiving the test source, one for recording the data and the other for connecting to the hardware.

The modeling of the generator control systems including speed governor and excitation control system with a particular interest in simulation of an existing realistic size AC network is shown in [3]. As there is no access to the dynamic modeling of the components in all the power system software in use, it becomes impossible for the user to manipulate the model or settings. So the author implemented the dynamic modeling of the generator along with the exciter and the governor in MATLAB and validated the work using PSS/E software with the similar components and parameters used. A severe fault i.e., a three phase bus fault is applied on a test system and a subsequent transmission line removal is applied and a comparative analysis is performed.

Modeling of IEEE 14-bus system in dynamic mode and finding the series of results associated with stability issues of the base test system and the inclusion of some controllers

is achieved in [18]. The static and dynamic load margins associated with the test system, beyond which the system goes to unstable mode is obtained by PV curve analysis and the eigen values and eigen vectors are found so as to know the ability of the system to maintain stable operating condition even under large perturbations using the transient stability analysis module of Power System Toolbox (PST).

The importance of using modern Real-Time Simulators for various studies in general and voltage stability in particular is discussed and the results showing the patterns of voltage stable and unstable operating conditions of the 10 bus system are showed and analyzed in [25]. This paper also states that with the increased computing ability, power system planers and operation planning analyzers may perform "what if" scenarios for different system conditions and configurations, with the obvious benefit of increasing system security with the use of Real-Time Simulator.

[7] shows different ways and proposed a new method to increase the speed of calculations (fast dynamics) using EMTP simulator without loosing the accuracy. The author used a differentially extended network which is the combination of the differential network and the original network for illustrating the work. In this work the author uses the IEEE 14-Bus System as the test case to simulate the rotor angle oscillations in transient stability studies. For the validation purposes the system is also simulated using PSCAD/EMTDC, which is a traditional EMTP type simulator.

The modeling and the transient stability analysis of the IEEE 14 test bus system using Matlab Power System Toolbox (PST) package is implemented in [17] with a three-phase fault located at two different locations, to analyze the effect of fault location and critical clearing time on the system stability. In order to protect overhead transmission line, conductors and

insulators, it is suggested that the faulted part to be isolated rapidly from the rest of the system so as to increase stability margin and hence decrease damage.

To analyze the effect of the distance of the fault location and critical clearing time on the system stability, a three-phase fault has been applied at five different locations in the IEEE 14-Bus system [13]. The stability of the system has been observed based on the simulation graphs of terminal voltage, machines rotor angle, machines speed and output electrical power. This paper presents a transient stability analysis of the test system using Dynamic Computation for Power Systems (DCPS) software package. The author states that from the simulation results the t_{CCT} decreases as the fault location becomes closer to the main generator.

In [5], the dynamic analysis is performed with the variation of the turbine of the wind generator. This study is similar to the present study with a difference of the fault/variation in the system creating system dynamics. Simulations use the PSS/E dynamic program, real power system planning databases and vendor-specific WTG (Wind Turbine Generator) stability models. Experiments for normal operation and fault conditions have shown that wind variation can cause WTGs to go into low-frequency oscillations (in particular, with frequency below the first natural frequency of the mechanical drive train) and/or to trip. EMTP simulations are performed for validation purposes.

The effect of detailed models of Hydro Turbine on simulation results of power system analysis is studied in [10]. All these different detailed hydro turbine models are implemented in power system simulation and the results of all these different models on power system transient stability analysis and small signal stability analysis are analyzed in the paper and concludes that the effect of different hydro turbine models is not great during the transient

stability analysis.

The computer representation of the excitation systems used in modeling of the power system is shown [22] in which the different types of exciters approved and widely used in the modeling of a power system are explained with the control block diagrams. The author [22] states that the type 1 excitation system is representative of the majority of modern systems now in service and presently being supplied.

The paper [21] focuses on the accuracy of the calculated transients of the synchronous machines when digital simulations are performed. This paper has attempted to take a closer look at the assumptions that go into a transient stability study of a large system. While it is theoretical in nature it does point out some pitfalls and possible improvements. This analysis points out a possible answer to the question of which machines should be represented in detail for a study.

The detailed description of all the different types of exciters available in a power system network including the parameters, definition of the parameters in different models, equivalent models using control blocks is shown in [1]. The acceptable range for each parameter in all the types of exciters is shown. This development is made to meet necessary requirements for the transmission system operators, which exchange data in the areas of system operations, network planning and integrated electricity markets.

The procedure for performing load rejection tests for salient pole synchronous generator and sudden short-circuit test for cylindrical rotor synchronous generator and to obtain the values of the synchronous generator electrical operational parameters which are important data to perform generator and electrical power system dynamic studies is explained in [24]. Matlab/Simulink/SimPowerSystems software is used for the analysis and simulation to

provide reliable operational parameters of synchronous generators.

The paper [20] gives the detailed explanation of the procedure to evaluate the dynamic parameters of the synchronous machine. The paper states that the parameters of the generator d-axis can be identified with sufficient accuracy when processed according to the voltage variation where as the data of the stopped generator frequency response test allows identify the main parameters of the d and q axis and the resistances of the stator and the rotor. The procedure for identifying those parameters performing the tests is explained.

According to the historical review of the papers, it can be seen that comparing the transient stability analysis in real time across the steady state dynamic analysis is never performed. Also evaluating the dynamic parameters of the synchronous generators required for real time studies by performing the sensitivity analysis on the excitation system is not developed. This research mainly focuses on the method of finding the parameters of the synchronous generator by performing the sensitivity analysis and narrowing down the number of parameters to be tweaked in order to achieve a set of parameter values used for both the steady state and real time platforms during the performance of transient analysis.

1.3.1 Scope of Work

The aim of the research is to analyze the behavior of the test system with the dynamic model of the synchronous generator by comparing the system bus voltages when a three phase bus fault is applied on the system and cleared after certain time using three different power system modeling and simulation tools. chapter 2 describes the mathematical background of the components used in the test system of the research. This chapter is considered as the base

for the research because a mathematical model is used to predict and analyze the behavior of any component in a power system network. chapter 3 is considered as the backbone of the thesis as this chapter explains the main focus of the thesis and describes the complete methodology developed and used in the research. chapter 4 lists all the components and their parameters used in the study. This chapter describes the development of IEEE 14-bus system model.The case study and the results from the test system are presented in chapter 5 followed by conclusions and future works in chapter 6.

Chapter 2

Mathematical Background

2.1 Introduction

In power systems different types of modeling of the equipment are available based on the type and requirements. Here a question ”Why an algebraic model is used to describe the power system in steady state?” is raised. One way of answering this is ”In power system there are always small load changes, switching actions and other transients occuring so that in a strict mathematical sense most of the variables are varying with the time. However, these variations are most of the time so small that an algebraic i.e., not time varying model of the power system is justified.”

This chapter deals with the general mathematical modeling of all the electrical equipment used in the test system used for the study.

2.2 Generator Modeling

There are different modeling types of a synchronous generator depending on the requirement and the type of analysis. The requirement for a synchronous machine consists of the structure (Round-Rotor or Salient-Pole) and the design (with or without damper windings) of the

mechanical part of the machine. In general, a synchronous machine is modeled as a constant voltage source with an equivalent impedance connected. There used to be complex modeling of the synchronous generator in the early days. Later on simplified modeling of the synchronous machine was developed which greatly simplifies the modeling by considering a reference frame rotating with the rotor. In this analysis, all the voltages and currents of the armature are converted into two axis. The first set is aligned with the field winding magnetic axis, also called as the rotor direct axis (d-axis) and the second set is aligned 90 electrical degrees to the d-axis. This axis is known as the rotor quadrature axis (q-axis). This analysis is often referred to as the d-q-0 or Park transformation. Figure 2.1 shows the generator rotor circuit with the modified outputs.

The modified armature voltages and currents are then converted into their pu form and fed to the excitation system of the generator which controls the voltage output of the generator when there is a disturbance in the system and the voltage level varies.

By considering a synchronous machine with three-phase armature winding and a cylindrical rotor which is the one used in this thesis, the flux current relations for this machine can be written in the form shown in Equation 2.1.

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \end{bmatrix} = \begin{bmatrix} L_a & L_{ab} & L_{ab} & L_m \cos\theta \\ L_{ab} & L_a & L_{ab} & L_m \cos(\theta - \frac{2\pi}{3}) \\ L_{ab} & L_{ab} & L_a & L_m \cos(\theta + \frac{2\pi}{3}) \\ L_m \cos\theta & L_m \cos(\theta - \frac{2\pi}{3}) & L_m \cos(\theta + \frac{2\pi}{3}) & L_f \end{bmatrix} \times \begin{bmatrix} -i_a \\ -i_b \\ -i_c \\ i_{fd} \end{bmatrix} \quad (2.1)$$

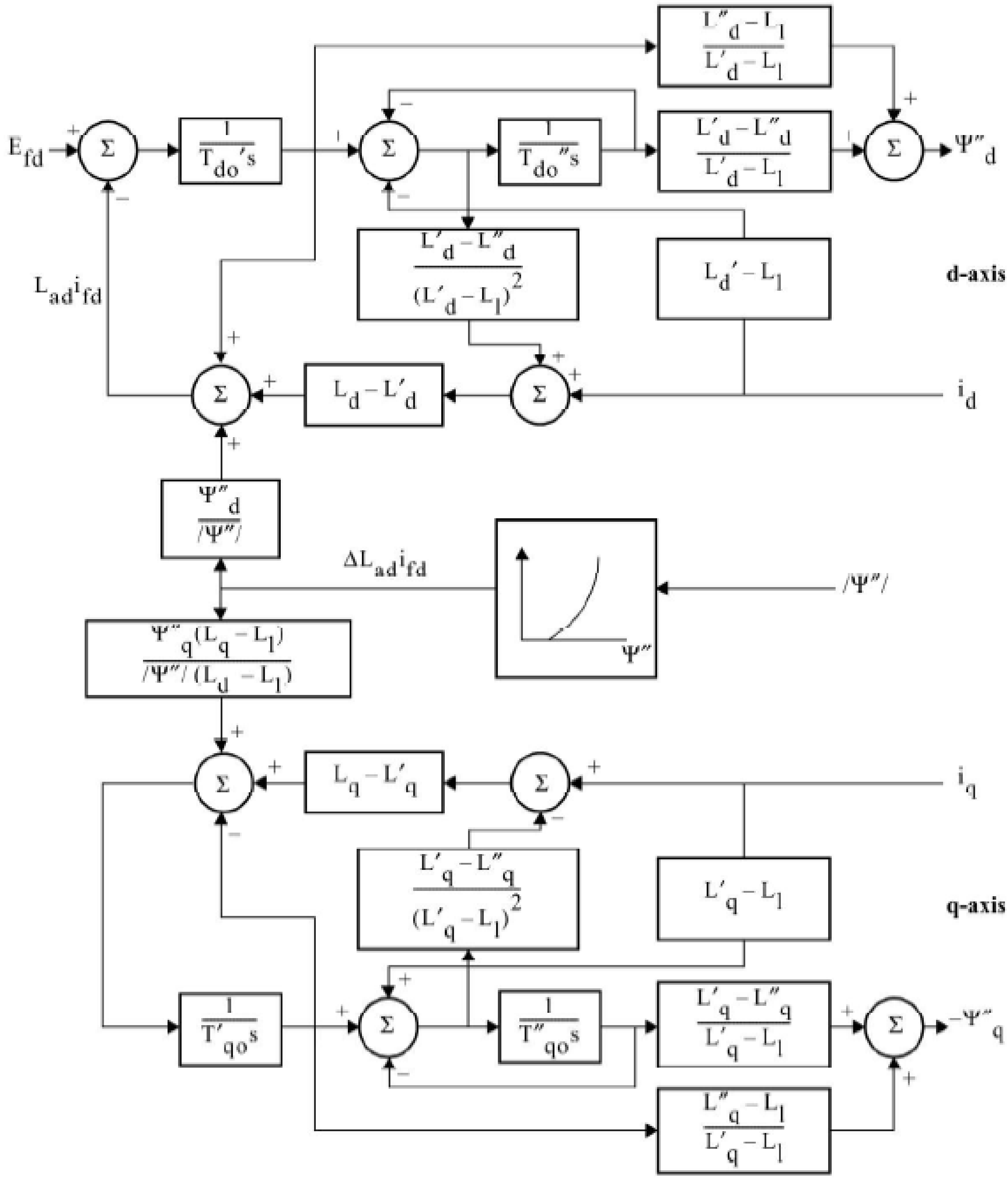

Figure 2.1: Round Rotor Generator(GENROU) Model Block Diagram [3]

and the voltage equations can be written as shown in Equation 2.2.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ e_{fd} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 \\ 0 & 0 & R_a & 0 \\ 0 & 0 & 0 & R_{fd} \end{bmatrix} \times \begin{bmatrix} -i_a \\ -i_b \\ -i_c \\ i_{fd} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_{fd} \end{bmatrix} \tag{2.2}$$

Subscripts a, b, c, and fd refer to the three armature phases and the field winding respectively. The time dependence of the inductance matrix of Equation 2.1 can be clearly seen when one substitutes the fact that under steady-state operating conditions the rotor angle has the time dependence

$$\theta = (\frac{N_p}{2})\omega_m t = \omega t \tag{2.3}$$

where ω_m is the rotor mechanical angular velocity and ω is the rotor electrical angular velocity.

With S representing a variable to be transformed, the d-q-0 transformation can be written as

$$\begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{2.4}$$

$$\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{\sqrt{2}} \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \times \begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} \tag{2.5}$$

Applying Equation 2.5 on Equation 2.1 and Equation 2.2 gives

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_{fd} \\ \psi_0 \end{bmatrix} = \begin{bmatrix} L_a - L_{ab} & 0 & \sqrt{\frac{3}{2}}L_m & 0 \\ 0 & L_a - L_{ab} & 0 & 0 \\ \sqrt{\frac{3}{2}}L_m & 0 & L_f & 0 \\ 0 & 0 & 0 & L_{al} \end{bmatrix} \times \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \tag{2.6}$$

Equation 2.6 can be rewritten as

$$\begin{bmatrix} \psi_d \\ \psi_q \\ \psi_{fd} \\ \psi_0 \end{bmatrix} = \begin{bmatrix} L_d & 0 & L_{af} & 0 \\ 0 & L_q & 0 & 0 \\ L_{af} & 0 & L_f & 0 \\ 0 & 0 & 0 & L_{al} \end{bmatrix} \times \begin{bmatrix} -i_d \\ -i_q \\ i_{fd} \\ -i_0 \end{bmatrix} \tag{2.7}$$

The voltage equations can be written as

$$v_d = -i_d R_a - (\frac{N_p}{2})\omega_m \psi_q + \frac{d\psi_q}{dt} \tag{2.8}$$

$$v_q = -i_q R_a + (\frac{N_p}{2})\omega_m \psi_q + \frac{d\psi_q}{dt} \tag{2.9}$$

$$e_{fd} = i_{fd} R_f + \frac{d\psi_{fd}}{dt} \tag{2.10}$$

$$v_0 = -i_0 R_a + \frac{d\psi_0}{dt} \tag{2.11}$$

The above equations for the flux and voltages after d-q-0 or park transformation are fed to the excitation circuit converting them into a pu voltage.

2.3 Exciter Modeling

The main purpose of the excitation system connected to the synchronous generator in the power system is to provide the proper field voltage and to maintain the desired active and reactive power at the generation terminals. The excitation system is also known as the Automatic Voltage Regulator (AVR) since it regulates the voltage at the terminals of the generator rapidly when there is a voltage deviation in the system during both normal and emergency conditions so that there is no drop in the voltage for a long time creating a blackout in the system. The most commonly used AVR models are those defined by the IEEE, specially Type-1 exciter model (IEEET1) [23].The differential equations of the IEEE Type 1 AVR model can be written in a matrix form convenient for the system simulation as following

$$\begin{bmatrix} \dot{V}_R \\ \dot{V}_A \\ \dot{V}_F \\ \dot{V}_r \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_R} & 0 & 0 & 0 \\ -\frac{K_A}{T_A} & -\frac{1}{T_A} & -\frac{K_A}{T_A} & 0 \\ 0 & \frac{K_F}{T_F T_E} & -\frac{1}{T_F} & -\frac{K_F(K_E+S_e)}{T_F T_E} \\ 0 & \frac{1}{T_E} & 0 & -\frac{K_E+S_e}{T_E} \end{bmatrix} \times \begin{bmatrix} V_R \\ V_A \\ V_F \\ V_r \end{bmatrix} + \begin{bmatrix} \frac{K_R}{T_R} V_t \\ \frac{K_A}{T_A}(V_{ref} + \frac{V_s}{K_A}) \\ 0 \\ 0 \end{bmatrix} \tag{2.12}$$

where $S_e = f(V_r)$ is the exciter saturation function. The synchronous generator field voltage E_{fd} is related to the excitation voltage V_r by :

$$E_{fd} = K_f V_r \tag{2.13}$$

where $K_f = \frac{L_{sfd}}{\sqrt{3} R_{fd}}$ is characteristic parameter of the generator (L_{sfd}: mutual inductance

between stator and field windings, R_{fd}: resistance of the field winding). All the variables must be in the per unit-system. The one per-unit (1 p.u.) generator voltage is defined as rated voltage. The one per-unit (1 p.u.) exciter output voltage is that voltage required to produce rated generator voltage on the generator air gap line. Hence in the per-unit system E_{fd} equals V_r.

2.4 Transformer Modeling

Transformers are the devices which transfers power from one circuit to other and enables the usage of different voltage levels across the system, also controls the voltage and reactive power flow [19]. Transformers use the electromagnetic induction process for the transfer of the electric energy between the circuits.

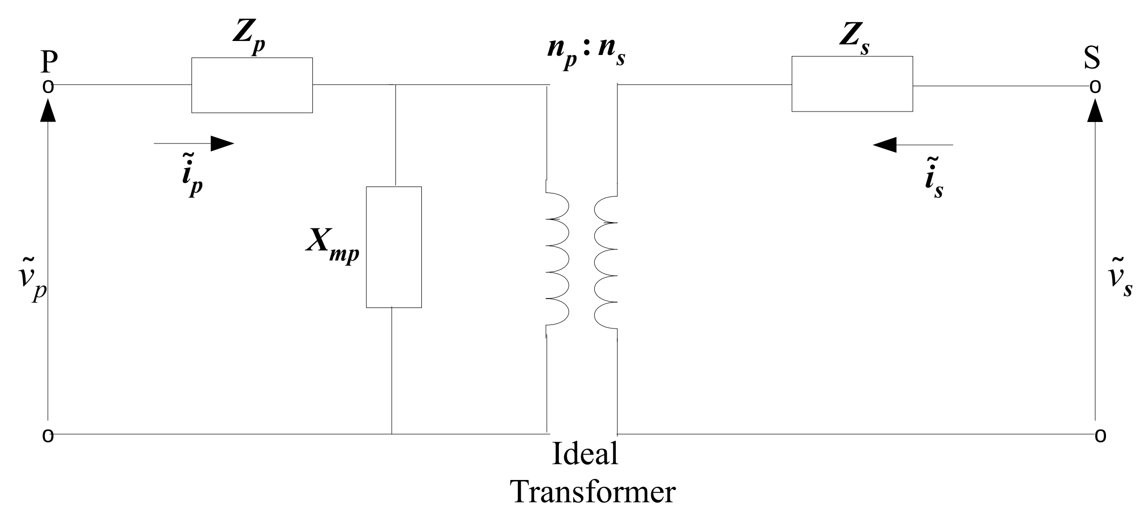

Figure 2.2: Equivalent circuit of two-winding transformer

$Z_p = R_p + jX_p$; $Z_s = R_s + jX_s$

R_p, R_s = primary and secondary winding resistances

X_p, X_s = primary and secondary winding leakage reactances

n_p, n_s = number of turns of primary and secondary winding

X_{mp} = magnetizing reactance referred to the primary side

The per unit equivalent circuit of the transformer with the choice of base quantities on primary and secondary side is shown in Figure 2.2. Subscript p and s in the figure represent primary and secondary side of the transformer. From the equivalent circuit with the magnetizing reactance neglected, we get

$$\bar{v}_p = Z_p \bar{i}_p + \frac{n_p}{n_s}\bar{v}_s - \frac{n_p}{n_s} Z_s \bar{i}_s \tag{2.14}$$

$$\bar{v}_s = \frac{n_s}{n_p}\bar{v}_p - \frac{n_s}{n_p} Z_p \bar{i}_p + Z_s \bar{i}_s \tag{2.15}$$

Let

$Z_{po} = Z_p$ at nominal primary side tap position

$Z_{so} = Z_s$ at nominal secondary side tap position

n_{po} = primary side nominal number of turns

n_{so} = secondary side nominal number of turns

Equation 2.14 and Equation 2.15 are represented in terms of the above nominal values as

$$\bar{v}_p = (\frac{n_p}{n_{po}})^2 Z_{po} \bar{i}_p + \frac{n_p}{n_s}\bar{v}_s - \frac{n_p}{n_s}(\frac{n_s}{n_{so}})^2 Z_{so} \bar{i}_s \tag{2.16}$$

$$\bar{v}_s = \frac{n_s}{n_p}\bar{v}_p - \frac{n_s}{n_p}(\frac{n_p}{n_{po}})^2 Z_{po} \bar{i}_p + (\frac{n_s}{n_{so}})^2 Z_{so} \bar{i}_s \tag{2.17}$$

The nominal number of turns related to the base voltages as

$$\frac{n_{po}}{n_{so}} = \frac{v_{pbase}}{v_{sbase}}$$

$$v_{pbase} = Z_{pbase} i_{pbase}$$

$$v_{sbase} = Z_{sbase} i_{sbase}$$

Using the above per unit quantities, Equation 2.16 and Equation 2.17 can be modified as

$$\bar{v}_p = \bar{n}_p^2 \bar{Z}_{po} \bar{i}_p + \frac{\bar{n}_p}{\bar{n}_s} \bar{v}_s - \bar{n}_s^2 \frac{\bar{n}_p}{\bar{n}_s} \bar{Z}_{so} \bar{i}_s \tag{2.18}$$

$$\bar{v}_s = \frac{\bar{n}_s}{\bar{n}_p} \bar{v}_p - \bar{n}_p^2 \frac{\bar{n}_s}{\bar{n}_p} \bar{Z}_{po} \bar{i}_p + \bar{n}_s^2 \bar{Z}_{so} \bar{i}_s \tag{2.19}$$

The bar indicates the per unit values.

$$\bar{n}_p = \frac{n_p}{n_{po}} \tag{2.20}$$

$$\bar{n}_s = \frac{n_s}{n_{so}} \tag{2.21}$$

The equivalent circuit representing the above equations is shown in Figure 2.3.

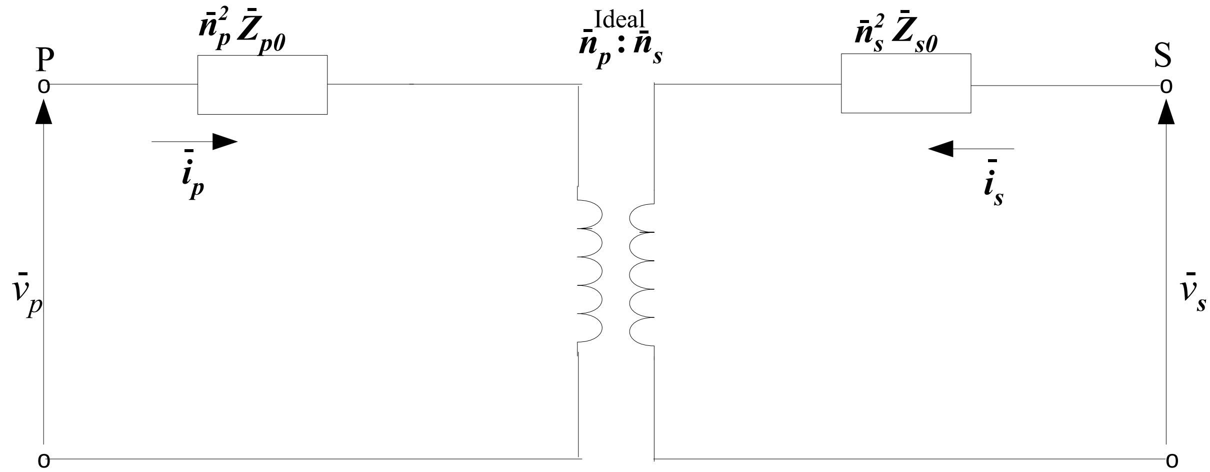

Figure 2.3: Per unit equivalent circuit

2.5 Transmission Line Modeling

Transmission lines are considered as the carriers of the power from the generating stations to the load centers. There are different types of transmission lines classified based on the capability of amount of power transfer, length of the line, the material used for the construction of the line, e.c.t.,There are four basic elements by which the transmission line is characterized, they are the series resistance (R), shunt conductance (G), series inductance (L) and the shunt capacitance (C) of the transmission line.

The voltage and current equations at a distance x from the receiving end of a transposed distributed parameter line per phase is given as

$$\bar{V} = \frac{\bar{V}_R + Z_c\bar{I}_R}{2}e^{\gamma x} + \frac{\bar{V}_R - Z_c\bar{I}_R}{2}e^{-\gamma x} \tag{2.22}$$

$$\bar{I} = \frac{\bar{V}_R/Z_c + \bar{I}_R}{2}e^{\gamma x} - \frac{\bar{V}_R/Z_c - \bar{I}_R}{2}e^{-\gamma x} \tag{2.23}$$

where

$$Z_c = \sqrt{z/y},$$

$$\gamma = \sqrt{yz} = \alpha + j\beta$$

Z_c is the characteristic impedance, γ is called the propagation constant, α is the attenuation constant, and β is the phase constant.

These equations represents the complete description of the performance of the transmission lines. This thesis considers only the π-transmission lines, so the equivalent circuit and the π equivalent circuit of the transmission lines is discussed.

Equivalent circuit model:

In Equation 2.22 and Equation 2.23, by letting $x = l$ and rearranging, we get

$$\bar{V}_S = \bar{V}_R \cosh(\gamma l) + Z_c \bar{I}_R \sinh(\gamma l) \tag{2.24}$$

$$\bar{I}_S = \bar{I}_R \cosh(\gamma l) + \frac{\bar{V}_R}{Z_c} \sinh(\gamma l) \tag{2.25}$$

The equivalent circuit based on the above equations is drawn as in Figure 2.4. Here S, R represents the sending and receiving end of the transmission line. From the circuit, sending end voltage is given as

$$\bar{V}_s = Z_e(\bar{I}_R + \frac{Y_e}{2}\bar{V}_R) + \bar{V}_R \tag{2.26}$$

Comparing Equation 2.24 and Equation 2.26, we get

$$Z_e = Z_c \sinh(\gamma l) \tag{2.27}$$

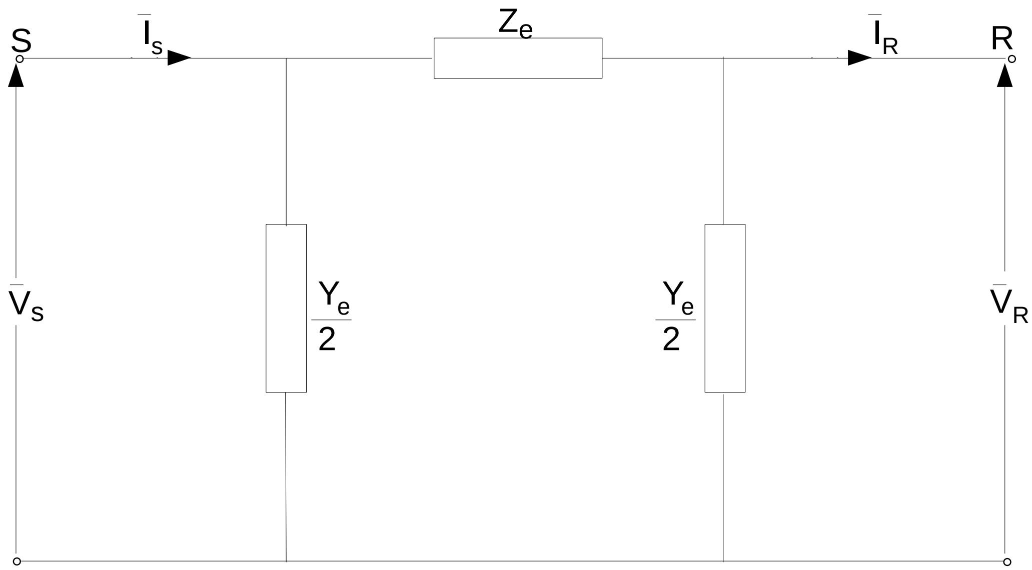

Figure 2.4: Equivalent π transmission line

and

$$\frac{Z_e Y_e}{2} + 1 = \cosh(\gamma l) \Rightarrow \frac{Y_e}{2} = \frac{1}{Z_c}\tanh(\frac{\gamma l}{2}) \tag{2.28}$$

If the transmission line is considered negligible i.e., $\gamma l \ll 1$, Z_e and Y_e can be approximated as

$$Z_e = Z_c \sinh(\gamma l) \approx Z_c \gamma l \approx zl = Z \tag{2.29}$$

and

$$\frac{Y_e}{2} = \frac{1}{Z_c}\tanh(\frac{\gamma l}{2}) \approx \frac{1}{Z_c}\frac{\gamma l}{2} \approx \frac{\gamma l}{2} = \frac{Y}{2} \tag{2.30}$$

2.6 Load Modeling

Load modeling is one of the important part in terms of modeling a power system. Load is the crucial part in a power system network, this is considered as a base for limiting the power

generation. There are different types of loads exist in a network, like Industrial, Residential, Commercial, e.c.t., Each type of load contains different elements such as Induction motors, Furnaces, Compressors, Refrigerators, Lamps, e.c.t., Not all the loads are constant, there will be a variation in the load level every hour. As there cannot be any constant load, it becomes difficult to model a load. In general for planning purposes (load-flow analysis), the load can be considered as a static load but when the dynamics of the system are included the dynamic model of the load need to be included.

Static Modeling: A static load model expresses the characteristics of the load at any instant of time as algebraic functions of the bus voltage magnitude and frequency at that instant. The active and reactive power components are considered separately. Traditionally, the voltage dependency of load characteristics has been represented by the exponential model as

$$P = P_O(\bar{V})^a \tag{2.31}$$

$$Q = Q_O(\bar{V})^b \tag{2.32}$$

Here, P and Q are active and reactive components of the load and the voltage $\bar{V} = \frac{V}{V_O}$, V is the magnitude of bus voltage. Subscript o indicates the initial operating condition.

The parameters a and b represents constant power, constant current or constant impedance for the values 0, 1, or 2 respectively. [19] gives the detailed explanation of the alternate polynomial model which is used to represent the voltage dependency of loads.

Dynamic Modeling: Studies of internal oscillations, voltage stability and long-term stability require the modeling of dynamic load models. A composite load model allows the

representation of the wide range of characteristics exhibited by the various load components. The load components that require dynamic load modeling includes induction motors, discharge lamps, thermostat controlled loads, transformer with saturation, shunt capacitors, e.c.t., The realistic modeling of these loads and the characteristics are described in [19].

Chapter 3

Main Focus and Contribution

3.1 Introduction

The main focus of the thesis is to compare the performance of a test system in real time against the steady state dynamic analysis. The steady state dynamic analysis is the usual practice in any electric utility for planning purposes and never performs a real time study by which the analysis can not be considered precise for the real time operation. In this thesis the differences are shown by comparing both the real time and steady state dynamic analysis. Furthermore, a methodology for equating the dynamic performance of the three software packages (discussed below) by identifying and adjusting the parameters contributing to output Overshoot, Ripples, and Settling time is introduced. For the comparison purposes, the power system software used are

- PSS/E - For Steady State Dynamic Analysis
- Hypersim - For Real Time Analysis
- EMTP - For validation purposes

PSS/E: Power System Simulator for Engineering (PSS/E) is a software tool used for electrical transmission networks. PSS/E is composed of a comprehensive set of programs for studies of

power system transmission network and generation performance in both steady-state and dynamic conditions. PSS/E is a high-performance transmission planning software which supported the power community with meticulous and comprehensive modeling capabilities since its introduction in 1976.

EMTP: The ElectroMagnetic Transient Program (EMTP) was originally developed by Professor Hermann W. Dommel in Germany in the late 1960's [16]. Since then, EMTP has been continuously developed through international contributions. In 2003, the Development Coordination Group (DCG) released a new restructured version, EMTP-RV, developed under the technical leadership of Hydro-Quebec. It features new and improved functionalities, as well as state-of-the-art analysis tools.

Hypersim: Hypersim is the only real-time digital simulator with the power to simulate and analyze very large-scale power systems with more than 2000 three-phase buses. Based on decades of research by Hydro-Quebec on one of the worlds most complex transmission power systems, Hypersim is an ever-improving solution with a proven track record. Hypersim is used every day in extremely demanding situations and is constantly updated to increase performance, reliability and ease of use. As a result, it is rapidly becoming the new standard for very large power systems.

3.2 Methodology

The methodology of this thesis is based on performing sensitivity analysis of the transfer function of the excitation system and identifying the parameters for each of the three dynamic performances overshoot, oscillation, and settling time. Steady state (or Power Flow Analysis)

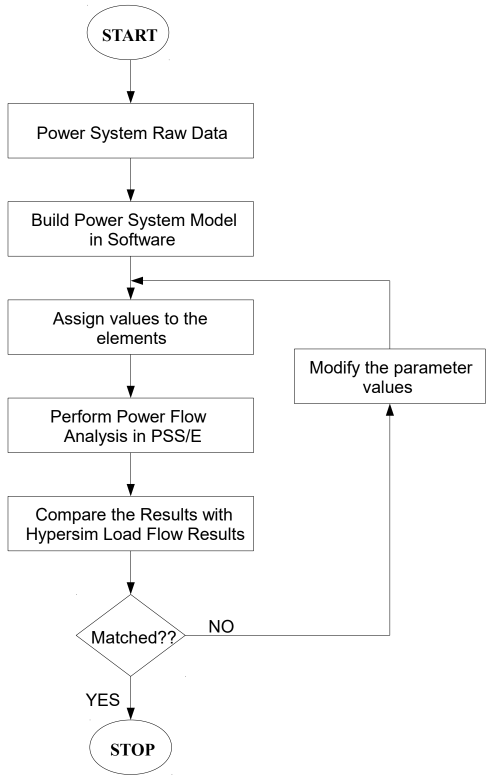

Figure 3.1: Flow chart for performing Steady State Analysis

is to be performed prior to performing the Dynamic simulations on any power system when the power system software packages are used. The flow charts in Figure 3.1 and Figure 3.2 shows the step-by-step procedure for performing, modifying, and analyzing the Steady State Analysis and Dynamic Analysis respectively. Following two sections clearly describes the parameter considerations and the proposed methodology for the IEEE-14 Bus Test System considered in the thesis.

3.3 Steady State Analysis

The steady state phasor models are used for power flow and fault studies. This type of studies are performed on networks modeled with pure sinusoidal voltage sources connected

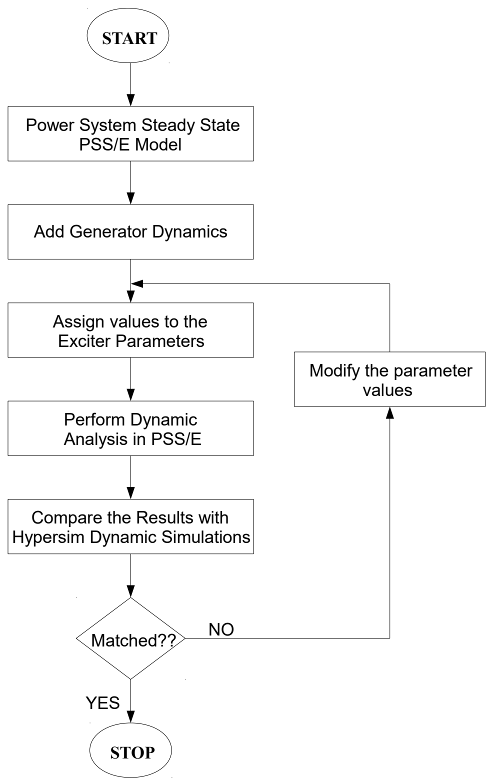

Figure 3.2: Flow chart for performing Dynamic Analysis

with impedances and loads, all represented at fundamental frequency. During the steady state analysis, the power system model is considered as a balanced three-phase system with balanced voltages and balanced loads. As the system is considered balanced, it becomes easy for the analysis.

The general procedure of performing the steady state analysis as shown in Figure 3.1 is as follows. First the raw data of the voltage sources, loads, transmission lines, shunt capacitors, transformers of a desired test system is considered as the base for the steady state analysis. Then the single line diagram of the test system is to be modeled in the power system software package. After building the model, the previously considered values are assigned and then load flow analysis is to be performed on the system. If the results from the steady state analysis matches with the other software package results, stop the procedure

else the parameters of the network elements are modified accordingly such that the power flow results like Bus voltage magnitudes, Bus voltage angles, Active power flow, Reactive power flow matches.

In the thesis, IEEE-14 Bus system is considered as the test system and the test data is shown in chapter 4. The test data is assigned to the models built in PSS/E, EMTP, and Hypersim on which the power flow/load flow analysis (Newton Raphson method is used) is performed. The results obtained from the three software packages is then compared. The results are shown in chapter 5. In the present case, the steady state analysis results were matched without any modifications of the parameters.

3.4 Dynamic Analysis

The dynamic analysis models uses a series of solved power flow cases with appropriate adjustment of the system's dynamic parameters between each power flow calculation. So the first step in matching the dynamic response among the three platforms is to add a dynamic element with its dynamic parameters. For the thesis dynamic generator model is considered in the test case.

The procedure for the dynamic analysis considers the power flow model of the test case as the base. A dynamic element on which the analysis is to be performed is added to the base case. Appropriate parameters are assigned to the dynamic element and the dynamic analysis is performed where the results are captured and compared with that obtained from the other software packages. If the results are not quite similar, the parameters are to be tweaked until the desired match is seen in the results.

In the thesis, PSS/E analysis is considered as the reference for the results. After matching the steady state results, the dynamics of a synchronous generator (GENROU) along with the excitation system (IEEE Type-1) is added to the case under consideration. A three-phase bus fault is applied on the system to see the response of the generator and the excitation system. The windowed rms values of the bus voltages at the desired buses are captured and are overlapped with the one obtained from the other two software packages. A large difference is observed between PSS/E and EMTP, Hypersim when considered as a package since EMTP and Hypersim gives similar results. So the parameters of the excitation system of the generator are tweaked carefully so that the resulting waveform of the desired buses matches with the one obtained from EMTP, Hypersim.

The details of the generator models, the procedure for tweaking the parameters is discussed in the following sections.

EMTP and Hypersim can generate voltages even with the static voltage source whereas PSS/E cannot run dynamics on any network without a dynamic model. Therefore, it is mandatory to add dynamic models in the test case. Dynamic modeling of a generator is considered here which includes

- Rotor model
- Excitation system model
- Governor model
- Stabilizer model

As the governor and stabilizer are the mechanical moving parts of the generator and they

are slow in reacting to the sudden changes (faults) in the system and does not respond quickly for the electromagnetic transients during faults, the governor and stabilizer models are ignored. From generator rotor and exciter models, as the excitation system parameters are tweaked, the procedure for the selection of the parameters to be tweaked, the exciter transfer function, the sensitivity ranking of the parameters are required for finding the most sensitive parameter for a small change in the system. This analysis is considered as the most important part of the thesis as this simplifies the selection of the parameter to be tweaked. The following section covers the calculation of the transfer function of the exciter, then follows the sensitivity analysis.

3.4.1 Exciter Transfer Function

The exciter used in this thesis is IEEE Type-1 as shown in Figure 3.3. Transfer function i.e., input-output relationship of the excitation system is calculated in the present section for the detailed study of sensitivity analysis of the system. IEEE Type-1 excitation system is one of the 63 types of exciters approved by IEEE [9]. However, we have selected IEEE Type-1 to be compatible with the software used for modeling and simulation of an actual electric utility topology. The transfer function of the block diagram of Figure 3.3 is calculated as shown in the following paragraphs. As the control block has more than one input, according to [15] the transfer function is the algebraic sum of the transfer functions obtained by individual inputs when the other inputs set to zero. This statement is valid only when the step response (in S-domain) is to be obtained. As the three inputs for the excitation system in the thesis are not the same always and are not the step inputs, this analysis is not valid. However the

step response of the excitation system is also shown and is verified with Matlab Simulink. In the following calculations, first E_c alone is considered assuming V_{Ref} and V_s as zeros and is followed by V_{Ref} and V_s.

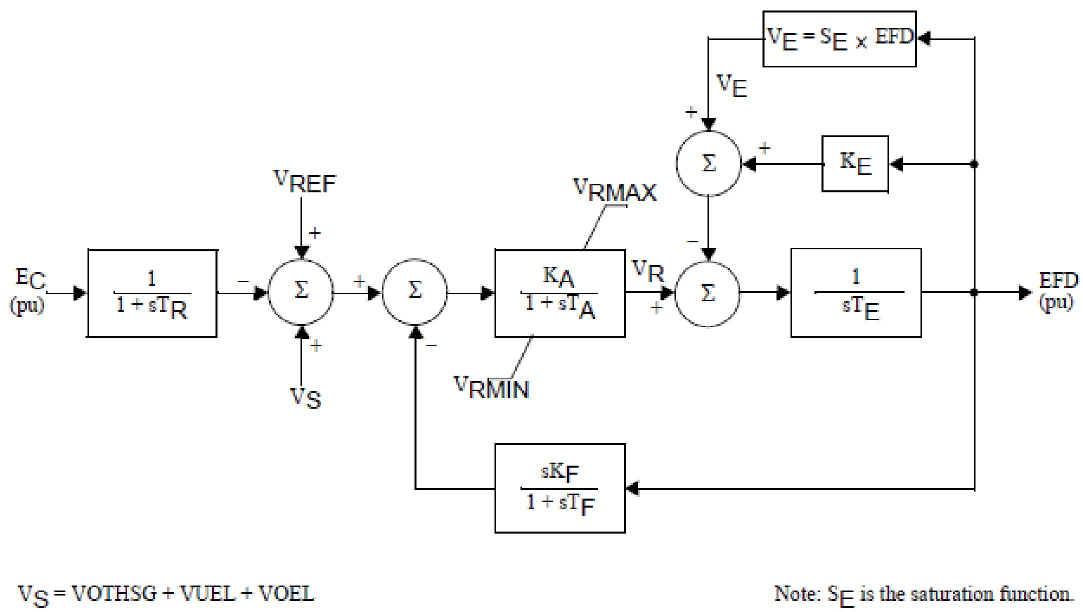

Figure 3.3: IEEE Type-1 Exciter Block Diagram [9]

where

T_R - Transducer time constant in Seconds

T_A - AVR time constant in Seconds

T_E - Exciter time constant in Seconds

T_F - Field voltage feedback time constant in Seconds

K_A - AVR gain in pu

K_E - Exciter K_E in pu

K_F - Field voltage feedback gain in pu

V_{RMax} - AVR limit max in pu

V_{RMin} - AVR limit min in pu

E_1 - Saturation voltage at point 1 in pu

E_2 - Saturation voltage at point 2 in pu

$S(E_1)$ - Saturation at E_1 in pu

$S(E_2)$ - Saturation at E_2 in pu

Input: E_c

Step-1: Consider the blocks with gain K_E and S_E of the excitation voltage model. Here though S_E is a saturation function which is not a constant, we consider a value at particular instant for the calculation of the transfer function and performing sensitivity analysis.

$$y1 = K_E + S_E \tag{3.1}$$

Step-2: Consider the blocks with gain y1 and $\frac{1}{sT_E}$.

$$y2 = \frac{\frac{1}{sT_E}}{1 + (\frac{1}{sT_E} * y1)}$$

$$y2 = \frac{\frac{1}{sT_E}}{1 + (\frac{1}{sT_E} * (K_E + S_E))}$$

$$y2 = \frac{1}{sT_E + K_E + S_E} \tag{3.2}$$

Step-3: Consider the blocks with gain y2 and $\frac{K_A}{1+sT_A}$.

$$y3 = \frac{K_A}{1+sT_A} * \frac{1}{sT_E + K_E + S_E} \tag{3.3}$$

Step-4: Consider the blocks with gain y3 and $\frac{sK_F}{1+sT_F}$.

$$y4 = \frac{y3}{1 + (\frac{sK_F}{1+sT_F} * y3)}$$

$$y4 = \frac{K_A * (1 + sT_F)}{((1 + sT_A)(1 + sT_F)(sT_E + K_E + S_E)) + K_A sK_F} \tag{3.4}$$

Step-5: Consider the blocks with gain y4 and $(-\frac{1}{1+sT_R})$.

$$y5 = (-\frac{1}{1 + sT_R}) * y4$$

$$T.F_1 = \frac{-K_A * (1 + sT_F)}{(1 + sT_R) * (((1 + sT_A)(1 + sT_F)(sT_E + K_E + S_E)) + K_A sK_F)} \tag{3.5}$$

Input: V_{Ref}

The process of the reduction of the block diagram with V_{Ref} is the same as with E_c. Repeat the steps 1 through 4 and the transfer function with V_{Ref} is given by Equation 3.6 which is same as that in Equation 3.4.

$$T.F_2 = \frac{K_A * (1 + sT_F)}{((1 + sT_A)(1 + sT_F)(sT_E + K_E + S_E) + K_A sK_F)} \tag{3.6}$$

Input: V_S

The process of the reduction of the block diagram with V_S is the same as with E_c. Repeat the steps 1 through 4 and the transfer function with V_S is given by Equation 3.7 which is same as that in Equation 3.4.

$$T.F_3 = \frac{K_A * (1 + sT_F)}{((1 + sT_A)(1 + sT_F)(sT_E + K_E + S_E) + K_A sK_F)} \tag{3.7}$$

Therefore, the total transfer function relating input-output of the excitation system block diagram assuming all the three inputs are the same and has a magnitude one is the combination of Equation 3.5, Equation 3.6 and Equation 3.7 and is given by Equation 3.8.

$$\boxed{G(s) = \frac{Y(s)}{U(s)} = \frac{K_A * (1 + sT_F) * (1 + 2sT_R)}{(1 + sT_R) * (((1 + sT_A)(1 + sT_F)(sT_E + K_E + S_E)) + K_A sK_F)}} \tag{3.8}$$

The overall transfer function shown in Equation 3.8 is verified using Matlab Simulink. Figure 3.4 and Figure 3.5 shows the actual block diagram of the IEEE Type-1 exciter with all the inputs set to one and the output respectively. Figure 3.6 and Figure 3.7 are the overall transfer function obtained in Equation 3.8 with a step input and the output of the transfer function block respectively. In both the cases, a set of parameters are chosen and from the results it is clearly seen that both the blocks gives the same output which verifies that the calculation of the transfer function of the excitation system is accurate.

As discussed earlier in this section, the overall transfer function shown in Equation 3.8 is not considered for the sensitivity analysis. As the overall transfer function for this exciter is not known, performing sensitivity analysis on this system is not possible. The definition

and the clarification on the sensitivity analysis of the particular excitation system is given in subsection 3.4.2.

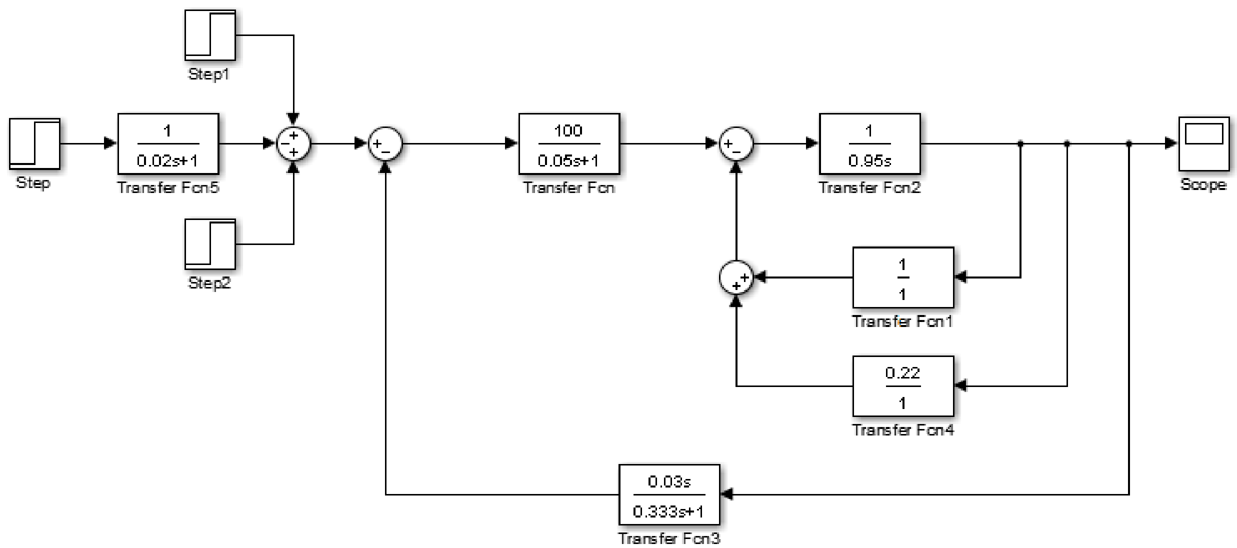

Figure 3.4: Transfer function block diagram with three step inputs

3.4.2 Sensitivity Analysis of Excitation System

The sensitivity analysis of a function F(s) with respect to a parameter k can be defined as the percent change in the function, F(s) to the percent change in the parameter, k. This analysis basically reveals how sensitive is the gain of the transfer function to the changes of a particular parameter. The larger the magnitude of the transfer function gain, the more sensitive is the parameter. The sensitivity function can be written as

$$S_k^{F(s)} = \frac{\% changeinF(s)}{\% changeink}$$

$$S_k^{F(s,k)} = \frac{\partial F(s,k)/F(s,k)}{\partial k/k} \tag{3.9}$$

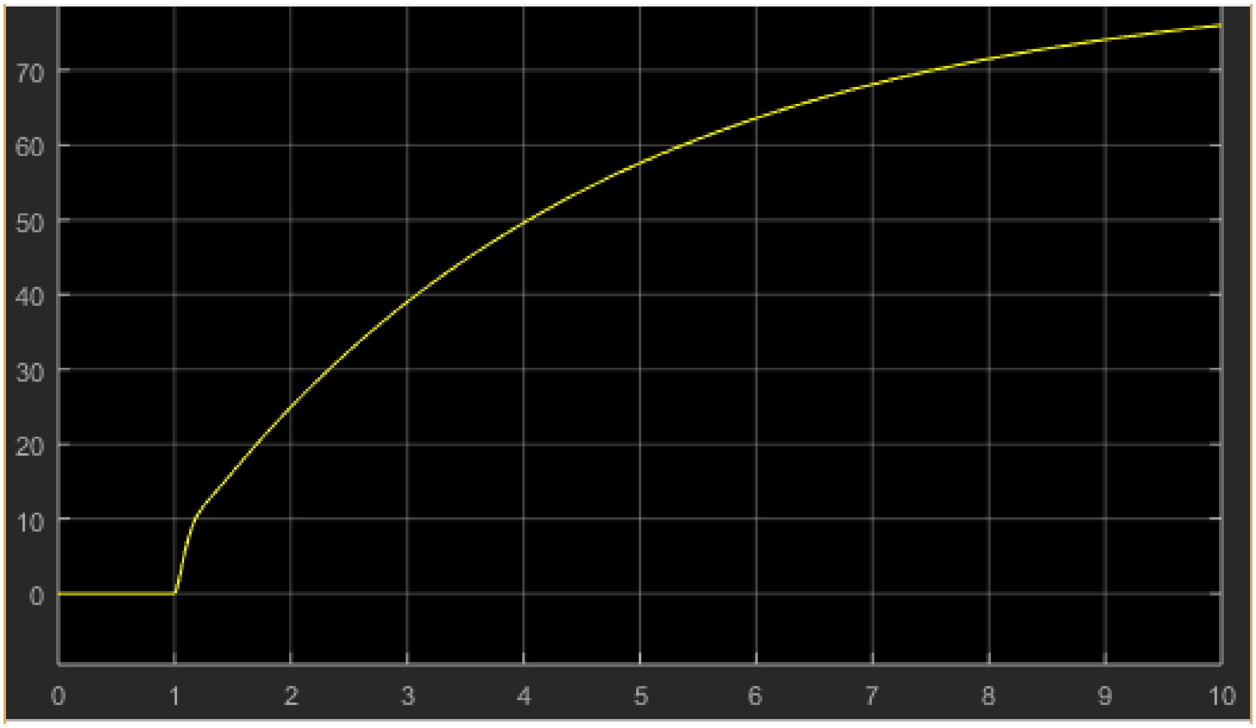

Figure 3.5: Output of the transfer function block diagram with three step inputs

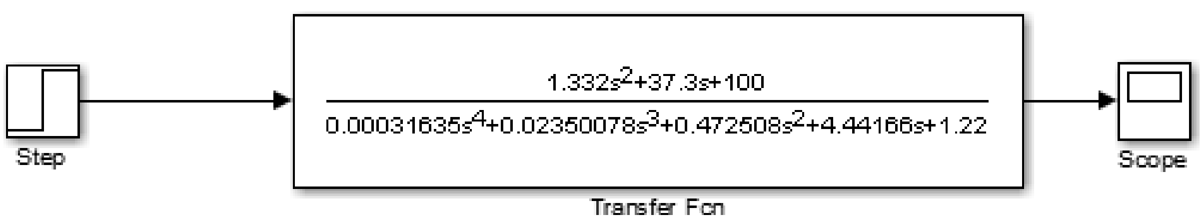

Figure 3.6: Overall transfer function with a step input

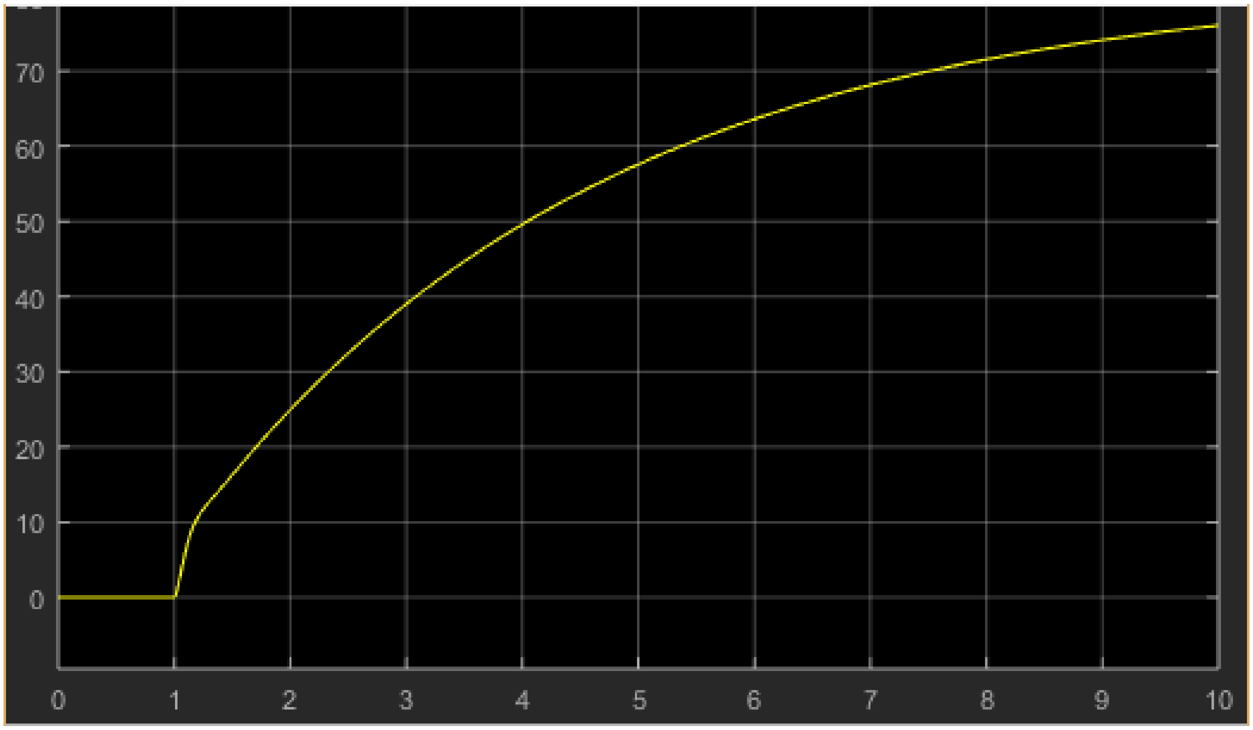

Figure 3.7: Output of the overall transfer function with a step input

Equation 3.9 can also be written as

$$S_k^{F(s,k)} = \frac{\partial \ln F(s,k)}{\partial \ln k} \tag{3.10}$$

where ln represents the natural log of the variable. From the basics, we know that

$$F(s,k) = \frac{N(s,k)}{D(s,k)} \tag{3.11}$$

Substituting Equation 3.11 in Equation 3.10 and rearranging, we get

$$S_k^{F(s,k)} = \frac{\partial \ln N(s,k)}{\partial \ln k} - \frac{\partial \ln D(s,k)}{\partial \ln k} \tag{3.12}$$

Using Equation 3.10, Equation 3.12 can be rewritten as

$$S_k^{F(s,k)} = S_k^{N(s,k)} - S_k^{D(s,k)} \tag{3.13}$$

In Equation 3.13 if the numerator or the denominator of F(s,k) is not a function of the parameter k, the corresponding sensitivity in the right hand side of Equation 3.13 will vanish. Also note that the sensitivity of Equation 3.13 depends on both the frequency s=σ+jω and the parameter k. To quantify the measure of sensitivity, Equation 3.13 is evaluated at a specific frequency $s = s_0$ and at the nominal value of the parameter $k = k_0$.

For the closed loop system, Equation 3.13 can be used with the appropriate numerator and denominator functions. With the feedback function, H(s)$\neq$0, the transfer function is written as shown in Equation 3.14

$$T(s,k) = \frac{G(s,k)}{1 + G(s,k)H(s,k)} \tag{3.14}$$

If there are any poles in the transfer function of Equation 3.14 that gives negative sign in the sensitivity analysis, that indicates that the gain of the transfer function reduces as the parameter is increased. However with the increase of this pole, the stability of the system is increased while reducing the transfer function gain. When a parameter appears in both numerator and the denominator of the closed-loop transfer function, changing the parameter may cause a change in the magnitude of the transfer function while at the same time impacting transient and steady-state response of the system including system stability, settling time, and steady state error at different operating conditions. There are several

metrics which may be used to quantify performance of a system in steady-state or while in transient to a new operating state and they are all based on optimizing a performance measure corresponding to different design criterion or operating conditions. Often using a metric for minimizing the steady-state error of a system will cause undesired transients by introducing a more oscillatory response. So while considering a sensitivity analysis on any system model with parameters in both numerator and denominator and Equation 3.13 is to be applied on the system, we may place the parameters into different categories if they are independent from each other. This would simplify the sensitivity analysis. However if the parameters are dependent, then we may observe changes in both steady state and transient response of the system impacting system overshoot, oscillations, and or settling time.

As discussed earlier in this chapter,the transfer function of the exciter considered in this thesis cannot be written as an input output relation. So the transfer function which has high impact on the overall control block and in turn on the test system is considered. In this case the transfer function related to the input E_C (Equation 3.5) is considered the most effective transfer function. Now the sensitivity analysis is applied on this transfer function. Though this transfer function cannot give the exact ranking of the parameters, they can be grouped into different categories by comparing the effect of the variation of the parameters obtained by the software simulations with the calculated sensitivities. There are 7 parameters in the transfer function (considering saturation function is not present for simplicity) which are varied one at a time and find both the sensitivity from the calculations and that obtained from plots. Here EMTP simulations are considered for the sensitivity analysis.

The parameters [22] shown in Table 3.1 are used for finding the sensitivity of the exciter transfer function.

Table 3.1: Parameter values for calculating sensitivity

Parameter	Value
K_A	400
T_A	0.05
T_E	0.95
K_E	-0.17
K_F	0.04
T_F	1.00
T_R	0.00
S_E	0.00

By varying one parameter at a time and calculating the sensitivity, the ranking of the parameters is given as shown in Table 3.3. Here all the parameters are varied according to the range of the parameters shown in obtained from [1]. Hundred values are considered within the range of the parameter values and out of the hundred different sensitivity ranking, the rank for a particular parameter occuring highest number of times is considered as its rank and the resulting parameter rankings are as given in Table 3.3.

Table 3.2: Parameter's range for the sensitivity analysis

Rank	Parameter
1	$0 \leq T_R < 0.5$
2	$10 < K_A < 500$
3	$0 \leq T_A < 1$
4	$-1 \leq K_E \leq 1$
5	$0.04 < T_E < 1$
6	$0 < K_F < 0.3$
7	$0.04 < T_F < 1.5$
8	$5 \leq T_F/K_F \leq 15$

From the 100 calculations of sensitivities, both T_F and K_F shared rank 1 but as T_F ranked 1 a little more number of times, it is considered as Rank-1. Though they are considered in one group. Similarly K_A and T_E are considered as the second group and K_E, T_A, and T_R

Table 3.3: Parameter Ranking based on Sensitivity

Rank	Parameter
1	T_F
2	K_F
3	K_A
4	T_E
5	K_E
6	T_A
7	T_R

are considered in the third group. For the validation of these groupings and the sensitivity analysis, the simulations are performed in EMTP by varying the parameters of the exciter. The response of the system voltages to the fault with the variation in the parameters are captured. These are grouped according to the effect of the variation of the parameter value on overshoot, oscillations and/or the settling time.

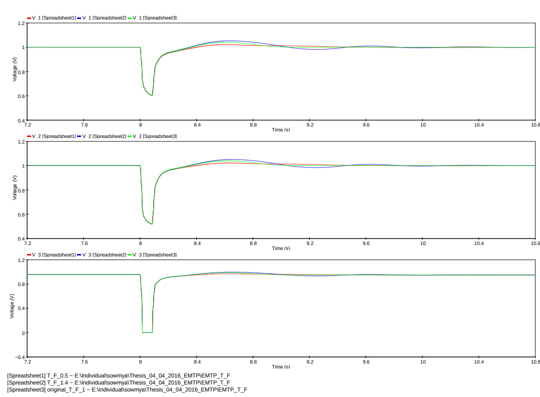

Figure 3.8: Variation of T_F; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

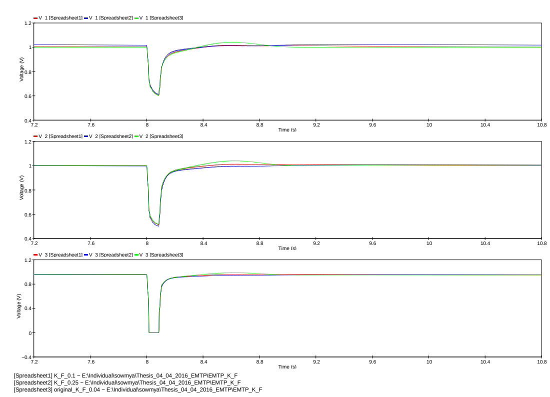

Figure 3.9: Variation of K_F; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

The graphs shown in the Figure 3.8 through Figure 3.14 are the windowed rms voltages of Bus-1, Bus-2, and Bus-3 with a short circuit fault applied on Bus-3. Three different values for each parameter are considered and are overlapped one on other in the same plots. By

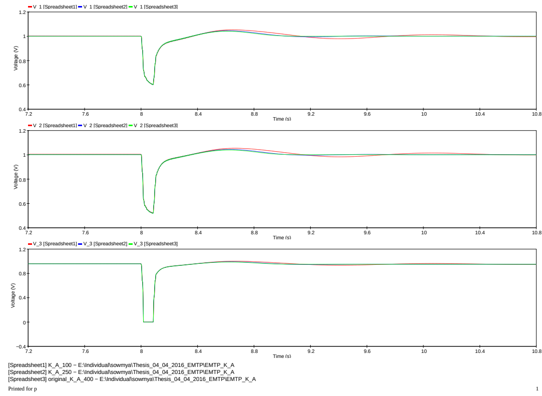

Figure 3.10: Variation of K_A; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

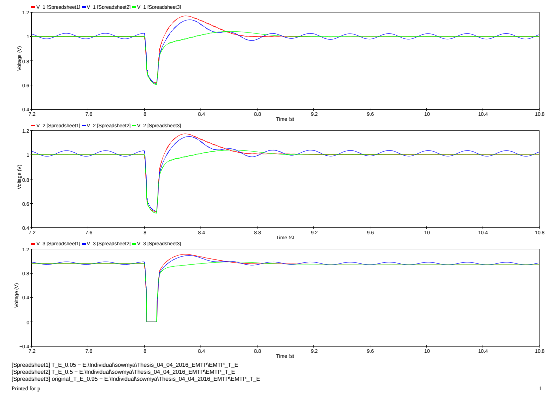

Figure 3.11: Variation of T_E; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

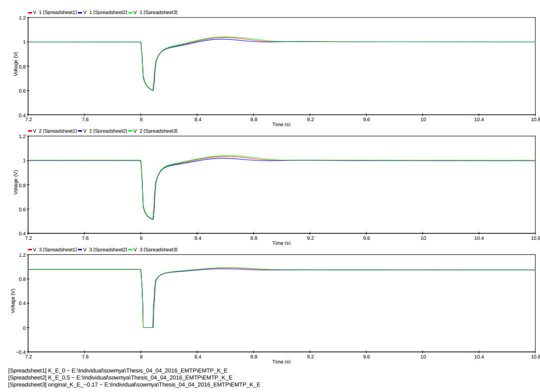

Figure 3.12: Variation of K_E; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

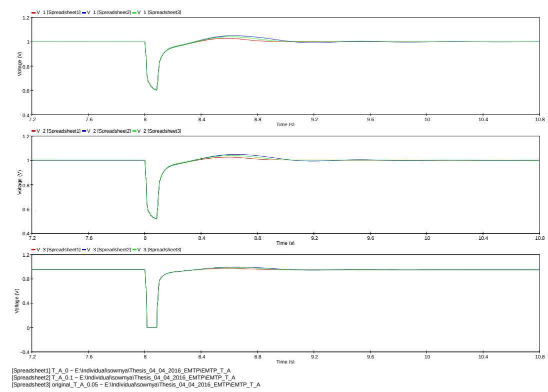

Figure 3.13: Variation of T_A; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

observing the graphs closely, they are grouped as following.

- T_F, K_F - Overshoot
- K_A, T_E - Oscillations
- K_E, T_A, and T_R - Slight Overshoots, Slight Settling time.

From the plots and the grouping, it is clear that the transfer function considered has a high impact on the system however it is not considered as the overall transfer function of the

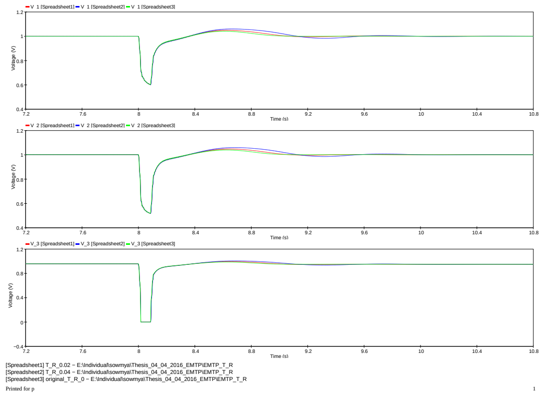

Figure 3.14: Variation of T_R; Voltage at Bus 1, Bus 2, Bus 3 (in pu) with respect to time

excitation control block. According to the requirement of the research, the ranking is given to the parameters. For example if the purpose of the study is to reduce the oscillations in the output voltage, the either one of K_A, T_E is varied and with trial and error method starting from the base or reference values, exact values for the parameters are considered. Note that the reference values also play an important role in performing the sensitivity analysis.

3.4.3 Sensitivity Analysis of an unknown power system model

Power system dynamics may be studied in electromagnetic, electromechanical, or steady state time frames. While for steady state dynamics we consider 60 Hz dynamics (377 rad/sec), for electromagnetic or electromechanical dynamics, we need to include transient response of the system to parameter changes, change in system configuration due to operation and maintenance requirements, or occurance of undesired faults in the system. It is therefore unfeasible to perform sensitivity analysis while system is in transient, and one may perform the analysis using linearized system models in the vicinity of a specific operating condition.

Due to complex non-linearity of power systems, the sensitivity analysis performed in the vicinity of an operating condition is only suitable at the specific frequency and at the given operating conditions. In addition to modeling issues, we encounter difficulties when simulating power systems which are modeled for different time frames a model which is developed for capturing electromechanical dynamics is not suitable for study of dynamics appearing in electromagnetic time frame.

For dynamic analysis of power systems using three software platforms used in PSS/E, EMTP, and Hypersim; we have shown by simulation that all three platforms produce identical steady state response while producing erroneous response when electromechanical or electromagnetic transients appear in the system. Each of these software platforms may use different model for representing power system components such as generators, transformers, and transmission lines and may use different numerical integration methods for simulating the system model. To overcome these difficulties when requiring identical system dynamic response using these platforms, one needs to tweak parameters in one platform, for example in the models used in PSS/E, while not altering parameters in the other platforms, for example in EMTP and in Hypersim and determine the numerical values of the set of parameters which will cause identical system response when using any of the three platforms. Because the system model is not known to the user, sensitivity of the system response to parameter changes is done by observing the system output while changing system parameters of interest instead of using Equation 3.13. Analytical system model is not known to the user, and hence, use of Equation 3.13 is unfeasible and we need to seek alternative approaches for performing system sensitivity.

Alternatively, let us assume that we have found the numerical values of a set of parameters

which cause identical power system response to exerting specific faults to the system. Staring from these numerical nominal values, we may tweak the parameters from their nominal values while observing the system output and identify the parameter or the group of parameters which have impacts on response overshoot, rise time, oscillations, or settling time by performing numerous simulations and observing the system response to apply faults at different locations in the system. Coupling groups of parameters to different system response "performance measure" - metrics is useful for real time modeling and simulation when the user does not have access to the overall system model and different software platforms use different numerical integration methods.

Chapter 4

Test System

4.1 Introduction

IEEE 14 Bus System is used as a test system for this thesis. The IEEE 14 Bus Test System is an equivalent system of a portion of the American Electric Power System (in the Midwestern US) as of February, 1962. It has 14 buses, 2 synchronous generators, 3 synchronous condensers, 1 shunt capacitor, 3 transformers (2 two-winding, 1 three-winding), 11 loads and 18 transmission lines (considering two-winding equivalent of the three-winding transformer). Here, for simplicity we considered a two-winding equivalent of the three winding transformer which is originally in the system. The system's base voltage is 138 kv with 100 MVA power base. The total load of the system is 254 MW and 73.4 MVar. Bus-1 is considered as the slack/swing bus. The Test system is as shown in Figure 4.1.

4.2 Bus Data

The voltage in pu and angles in degrees initially set for each bus are as shown in Table 4.1. 100 MVA is used as the base value along with the voltage bases for the pu representation of the bus voltages. Bus-2 is the PV bus and Bus-1 is considered as the slack bus. All the

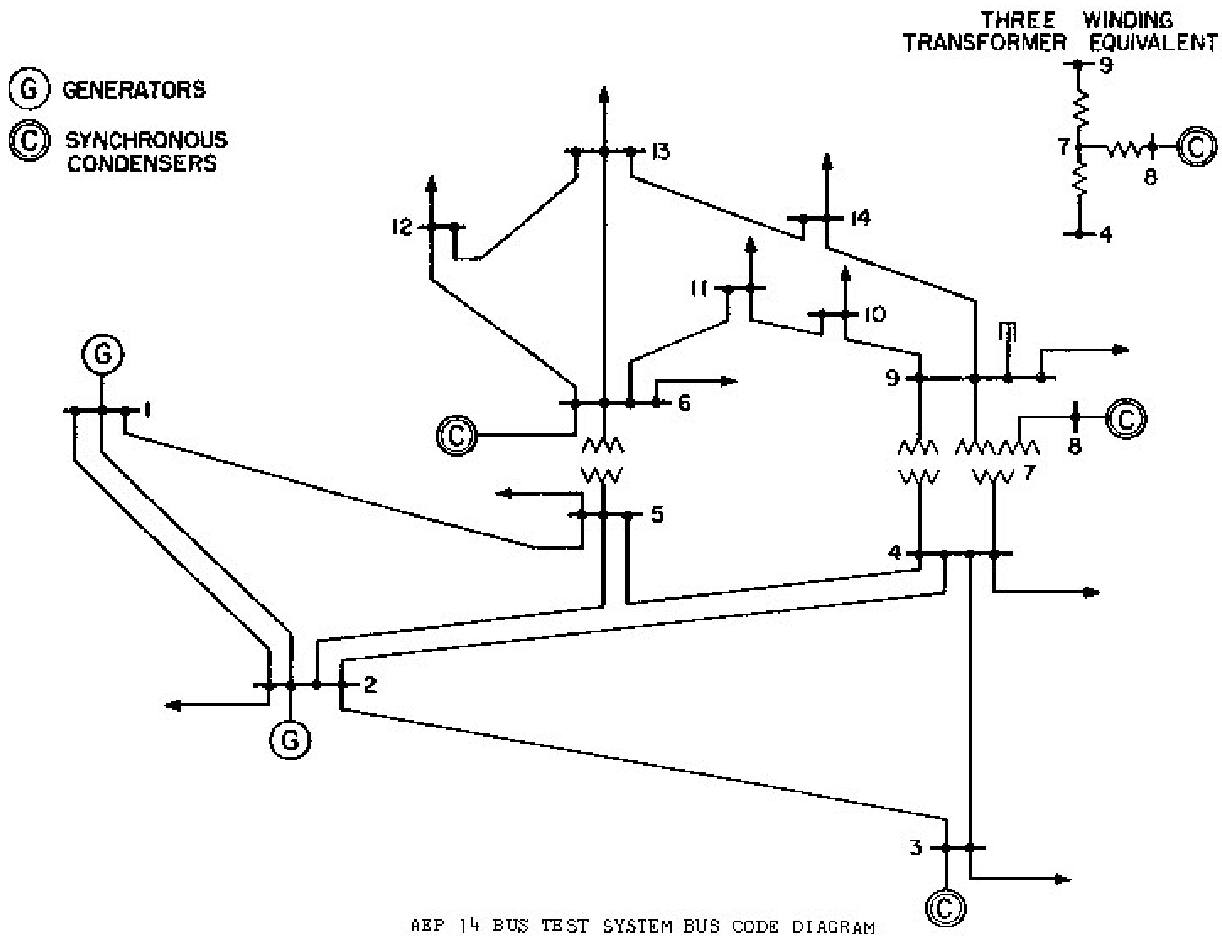

Figure 4.1: IEEE 14 Bus Test System [8]

remaining buses are considered as the PQ buses.

Table 4.1: Bus Data

Bus	Base Voltage (kV)	Voltage (pu)	Angle (Deg)
1	138	1.06000	0.0000
2	138	1.04500	-4.9826
3	138	1.01000	-12.7250
4	138	1.01767	-10.3128
5	138	1.01951	-8.7738
6	138	1.07000	-14.2209
7	138	1.06152	-13.3596
8	138	1.09000	-13.3596
9	138	1.05593	-14.9385
10	138	1.05099	-15.0972
11	138	1.05691	-14.7906
12	138	1.05591	-15.0755
13	138	1.05038	-15.1562
14	138	1.03553	-16.0336

4.3 Transmission Lines

The transmission lines are of different lengths and made of different materials so they have different resistance, reactance and susceptance per unit length. The double line between bus-1 and bus-2 is converted to a single line. Table 4.2 shows the transmission line parameters for all the 17 transmission lines. Transmission lines considered in this thesis are all π lines.

4.4 Transformer

With the consideration of the equivalent of the three-winding transformer, we have a total of 3 two-winding transformers and the parameters are as shown in Table 4.3.

Table 4.2: Transmission Line Parameters

Bus	Resistance (pu)	Reactance (pu)	Suceptance (pu)
1 to 2	0.01938	0.05917	0.05280
1 to 5	0.05403	0.22304	0.04920
2 to 3	0.04699	0.19797	0.04380
2 to 4	0.05811	0.17632	0.03400
2 to 5	0.05695	0.17388	0.03460
3 to 4	0.06701	0.17103	0.01280
4 to 5	0.01335	0.04211	0.00000
6 to 11	0.09498	0.19890	0.00000
6 to 12	0.12291	0.25581	0.00000
6 to 13	0.06615	0.13027	0.00000
7 to 8	0.00000	0.17615	0.00000
7 to 9	0.00000	0.11001	0.00000
9 to 10	0.03181	0.08450	0.00000
9 to 14	0.12711	0.27038	0.00000
10 to 11	0.08205	0.19207	0.00000
12 to 13	0.22092	0.19988	0.00000
13 to 14	0.17093	0.34802	0.00000

Table 4.3: Transformer Parameters

Bus	Reactance (pu)	Ratio (pu)
4 to 7	0.20912	0.978
4 to 9	0.55618	0.969
5 to 6	0.25202	0.932

4.5 Loads

The loads considered in the thesis for steady state are constant PQ loads. The active and reactive power drawn by the loads are shown in MW and MVar respectively in Table 4.6.

Table 4.4: Load Parameters

Bus	Pload (MW)	Qload (MVar)
2	21.700	12.700
3	94.200	19.000
4	47.800	-3.900
5	7.600	1.600
6	11.200	7.500
9	29.500	16.600
10	9.000	5.800
11	3.500	1.800
12	6.100	1.600
13	13.500	5.800
14	14.900	5.000

4.6 Generators and Reactors

There are two synchronous generators and three synchronous condensers in the system as mentioned earlier. The synchronous condensers are the generators with no active power generated (Pgen = 0.0 MW) as seen in Table 4.5. Later on these synchronous condensers are converted into shunt capacitors for easy analysis during dynamic simulations. The generator connected to bus-1 is the slack generator so it supplies the excess power needed for the system when the rest of the generators are at their maximum limit. The initial load flow parameters of the generators are given in Table 4.5.

Table 4.5: Generator Parameters

Bus	Base (MVA)	PGen (MW)	QGen (MVar)	QMax (MVar)	QMin (MVar)	VSch (pu)
1	615	232.392	-16.549	0.000	0.000	1.060
2	60	40.000	43.556	50.000	-40.000	1.045
3	60	0.000	25.075	40.000	0.000	1.010
6	25	0.000	12.730	24.000	-6.000	1.070
8	25	0.000	17.623	24.000	-6.000	1.090

There is only one shunt reactor in the system. It is a fixed shunt capacitor at bus-9 with a fixed reactive power generation of 19 MVar.

The above given parameters for the generator are sufficient for performing load flow and steady state analysis of the system. In order to study the dynamic system (transient and sub-transient) detailed parameters are to be included and the parameters are as given below.

Table 4.6: Generator (GENROU) Dynamic Parameters

Parameter	Value (pu)
$T_{do}^{'}$	4.5000
$T_{do}^{''}$	0.0350
$T_{qo}^{'}$	0.5000
$T_{do}^{''}$	0.0500
H	2.5000
D	0.0000
X_d	1.6300
X_q	1.5900
$X_d^{'}$	0.3050
$X_q^{'}$	0.9360
$X_d^{''} = X_q^{''}$	0.2260
X_I	0.2000
$S(1.0)$	0.0000
$S(1.2)$	0.0000

Table 4.7: Exciter (IEEET1) Parameters

Parameter	Value
T_R (sec)	0.0000
K_A	400
T_A (sec)	0.0500
V_{RMAX}	99.9999
V_{RMIN}	-99.9999
K_E	1.0000
T_E (sec)	0.9500
K_F	0.0300
T_F (sec)	0.3330
switch	0.0000
E_1	0.0000
SE_{E1}	0.0000
E_2	0.0000
$SE_(E2)$	0.0000

Chapter 5

Analysis of Results

5.1 Introduction

Bus voltages, current through the transmission lines are considered as the base for the comparison of the analysis of the test system across the three platforms. For the dynamic analysis, 52 μ sec is considered as the time step and the analysis is taken for 20 seconds. The fault is applied at 8 seconds (480 cycles) and cleared at 8.0833 seconds (485 cycles).

5.2 Modeling of the test case

Figure 5.1,Figure 5.2 and Figure 5.3 are the models built in PSS/E, EMTP, and Hypersim respectively with synchronous generators for dynamic analysis. For steady state analysis, ideal voltage sources are used as the generating unit. The test case was modeled in the three platforms using the GUI (Graphical User Interface) available in the software. For dynamic analysis, built in exciter control block was not used, instead standard exciter IEEET1 was modeled using the control blocks and is attached to the existing synchronous generator block. The exciter block is built using the available control blocks in EMTP and Hypersim as shown in Figure 5.4 and Figure 5.5 whereas PSS/E has a built in IEEET1 exciter. The test system

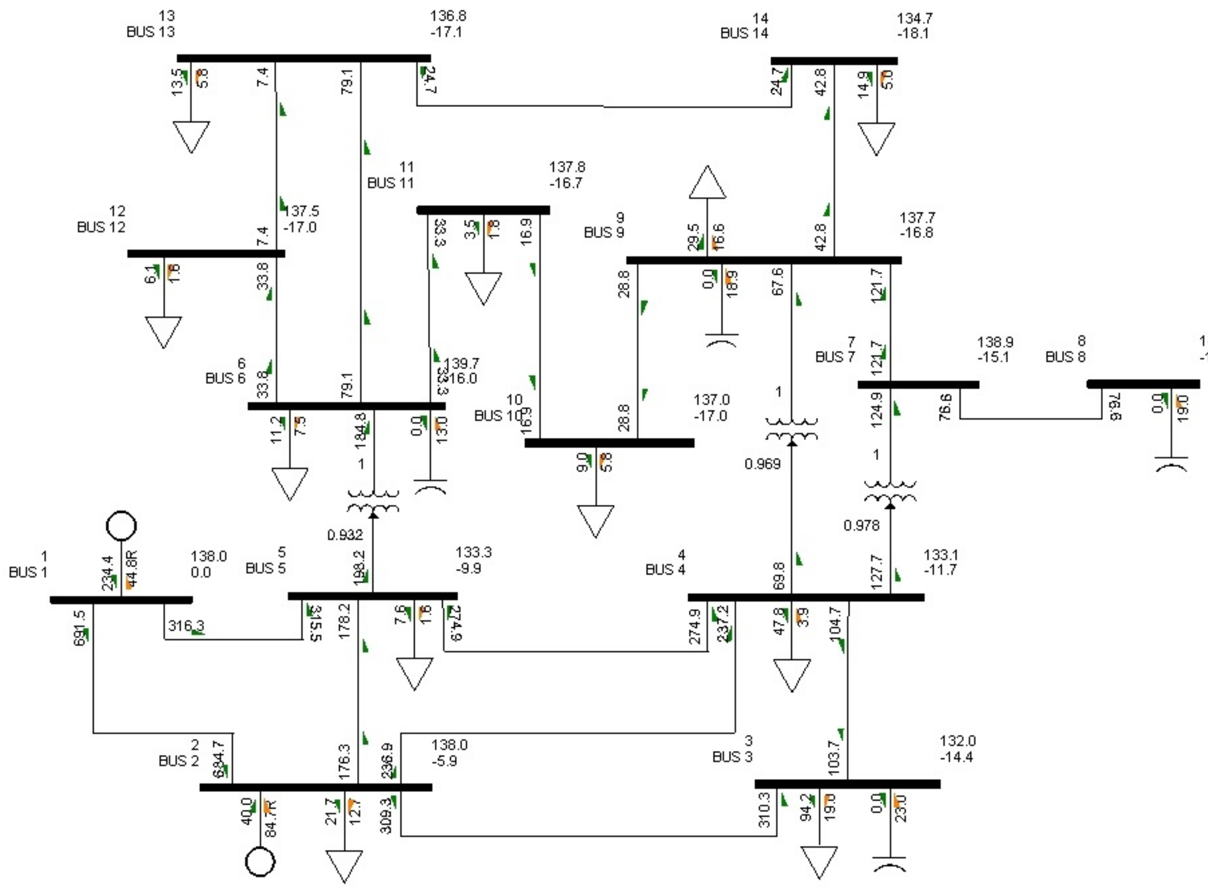

Figure 5.1: IEEE 14 Bus Test System in PSS/E

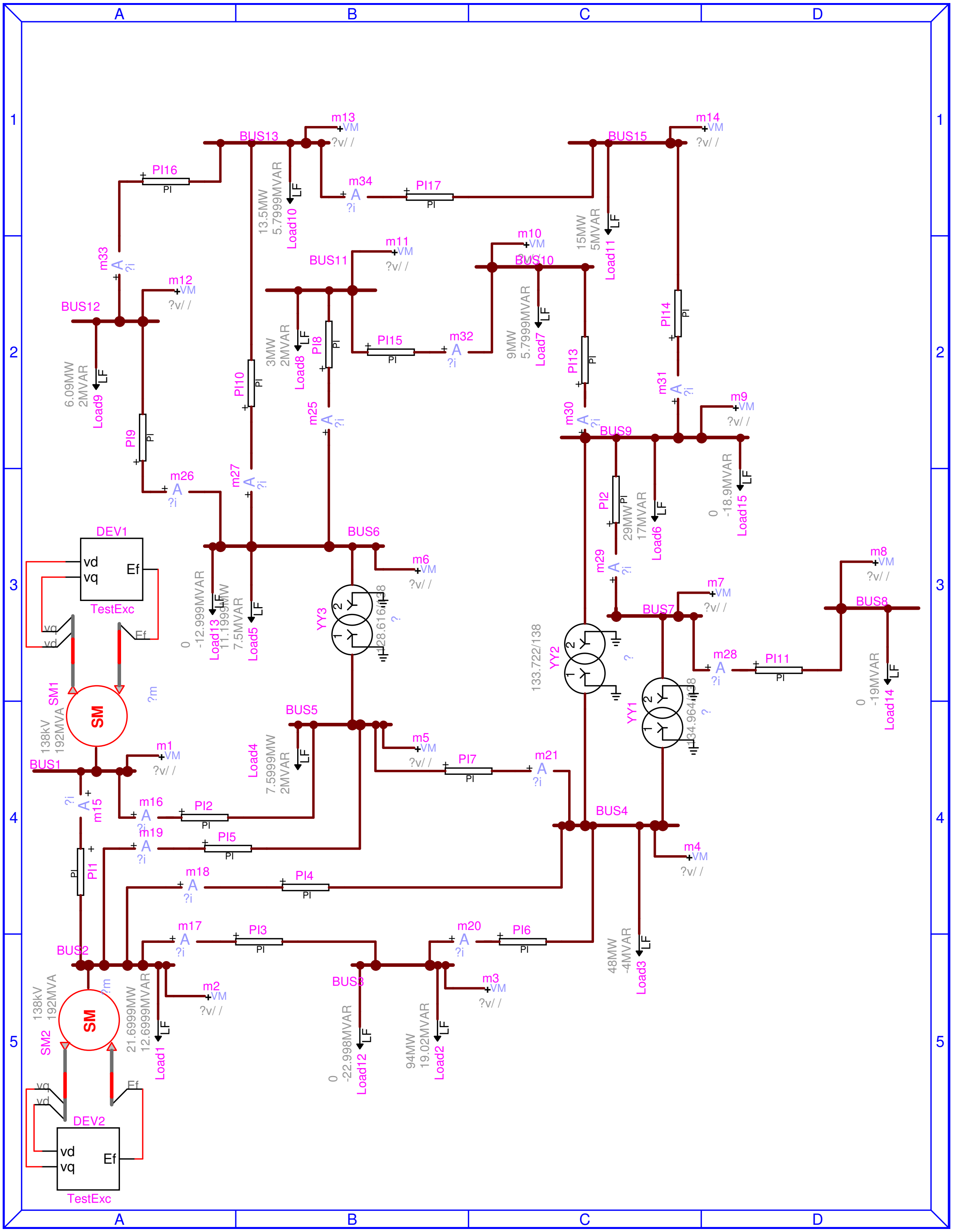

Figure 5.2: IEEE 14 Bus Test System in EMTP

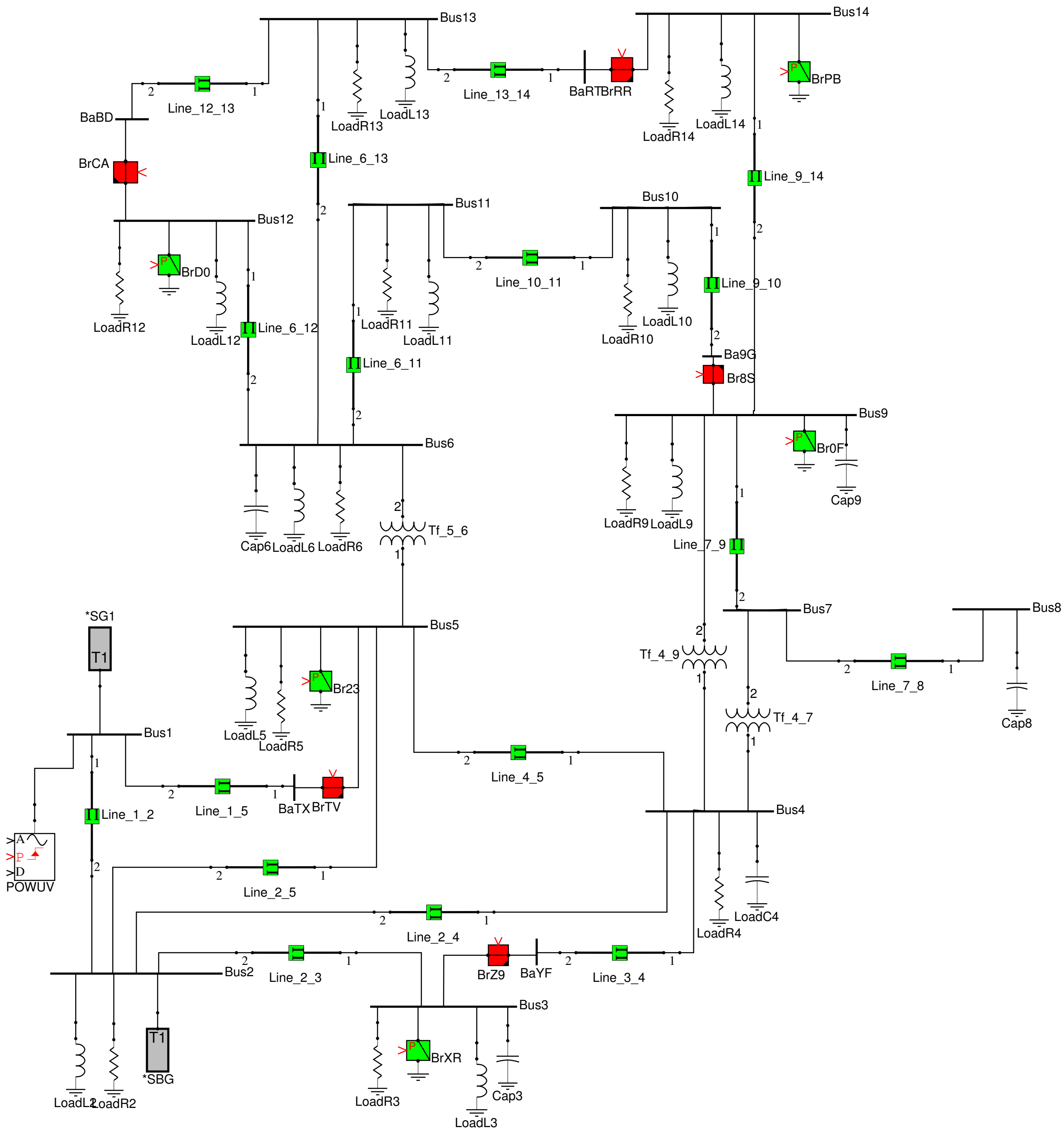

Figure 5.3: IEEE 14 Bus Test System in Hypersim

along with the dynamic models of the synchronous generators were modeled so that all three platforms has an identical system. A difference in the bus voltages was observed with identical parameters after few simulations when dynamic analysis is performed. So the final test case in PSS/E has slightly different parameters compared to the other two platforms which is shown in the following sections.

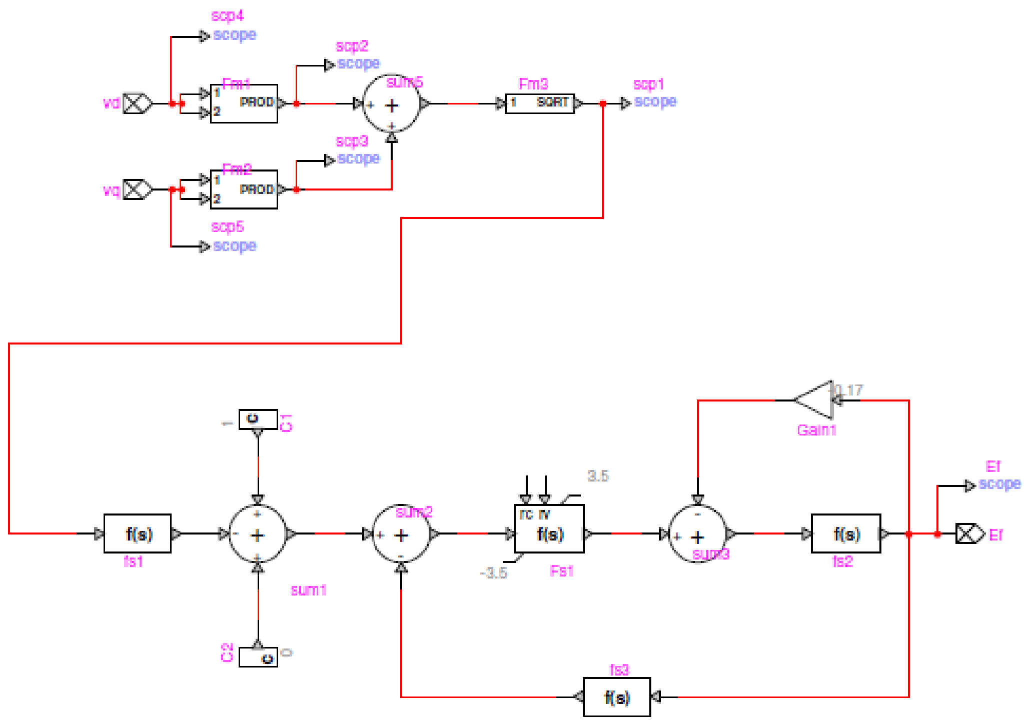

Figure 5.4: IEEE Type-1 Exciter modeled in EMTP

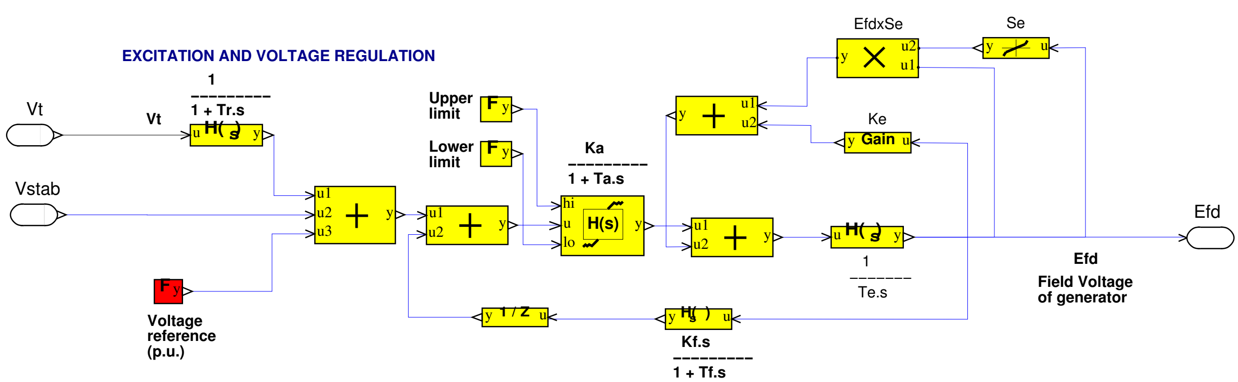

Figure 5.5: IEEE Type-1 Exciter modeled in Hypersim

5.3 Steady State Analysis

Table 5.1, Table 5.2 and Table 5.3 shows the comparison tables of the magnitude of bus voltages, line currents and the transformer currents (both on primary and secondary side) across PSS/E, EMTP and Hypersim when a load flow analysis is performed. From the tables it is clear that all the platforms gives the similar output during steady state analysis and there is no need for the modification of the parameters as discussed in the flow chart for performing steady state analysis in chapter 3.

A comparative analysis is performed on the results obtained and the differences in the magnitudes in terms of percentage values are calculated and are as shown below.

Difference (PSS/E and EMTP):

- Bus Voltage Magnitude - 0.0065%
- Bus Voltage Angles - 3.7194%
- Line Current Magnitude - 0.0085%

Difference (PSS/E and HyperSim):

- Bus Voltage Magnitude - 0.0075%
- Bus Voltage Angles - 2.76%
- Line Current Magnitude - 0.1166%

From the comparative analysis of the test system in steady state, the difference in terms of percentage is negligible and hence it can be concluded that the test system is matched in the steady state across the three platforms.

	PSS/E		EMTP		Hypersim	
Bus	$\|V\|$	$\angle\theta$	$\|V\|$	$\angle\theta$	$\|V\|$	$\angle\theta$
1	138.00	0.00	138.00	0.00	137.99	0.00
2	138.00	−5.87	138.00	−6.10	138.00	−6.08
3	132.04	−14.40	132.04	−14.94	132.04	−14.85
4	133.12	−11.70	133.12	−12.15	133.11	−12.15
5	133.31	−9.90	133.31	−10.35	133.31	−10.13
6	139.65	−16.00	139.64	−16.67	139.63	−16.20
7	138.87	−15.10	138.86	−15.68	138.86	−15.53
8	143.32	−15.10	143.31	−15.68	143.31	−15.53
9	137.73	−16.80	137.72	−17.53	137.72	−17.55
10	136.99	−17.00	136.97	−17.71	136.97	−17.55
11	137.79	−16.70	137.78	−17.35	137.78	−16.88
12	137.49	−17.00	137.48	−17.66	137.48	−17.55
13	136.80	−17.10	136.78	−17.78	136.78	−17.55
14	134.69	−18.10	134.68	−18.81	134.68	−18.90

Table 5.1: Voltages (kV RMS) compared between PSSE, EMTP, and Hypersim

Line	PSS/E	EMTP	Hypersim
1 to 2	691.5	690.77	690.99
1 to 5	316.3	316.11	315.35
2 to 3	309.3	309.25	310.28
2 to 4	236.9	236.86	237.19
2 to 5	176.3	176.33	178.26
3 to 4	103.7	103.71	104.76
4 to 5	274.9	274.86	274.86
6 to 11	33.3	33.32	33.29
6 to 12	33.8	33.78	33.80
6 to 13	79.1	79.13	79.13
7 to 8	76.6	76.53	76.53
7 to 9	121.7	121.66	121.65
9 to 10	28.8	28.83	28.84
9 to 14	42.8	42.75	42.75
10 to 11	16.9	16.87	16.87
12 to 13	7.4	7.43	7.41
13 to 14	24.7	24.67	24.66

Table 5.2: Currents (A RMS) compared between PSSE, EMTP, and Hypersim

From and To Buses	PSS/E		EMTP		Hypersim	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
4 to 7	127.7	124.9	127.61	124.79	127.59	124.79
4 to 9	69.8	67.6	69.80	67.63	69.77	67.61
5 to 7	198.2	184.8	198.20	184.73	198.25	184.77

Table 5.3: Transformer currents (A RMS) compared between PSSE, EMTP, and Hypersim

5.4 Dynamic Analysis

In this analysis the generator dynamics are considered as the most effective dynamics in the system so the voltage waveform of the generator buses (Bus-1 and Bus-2) and the bus voltage where the fault is applied are plotted using the parameters shown in chapter 4. The most severe fault is applied on the system (three phase bus fault) so that the system is stressed a lot and the dynamics can be observed clearly. Figure 5.6 shows the bus voltage waveforms when a short circuit is created at Bus-5 for 5 cycles and then clearing the fault along with the line tripping between Bus-1 and Bus-5. Figure 5.6 shows the windowed rms values of the voltages of Bus-1, Bus-2, and Bus-5 from PSS/E, EMTP, and Hypersim overlapped one on other on the same plot so that the difference between the graphs from different software platform can be easily identified.

The output voltage waveforms can be divided into three time frames.

1. Pre-fault $\Rightarrow 0\mu$ sec to 2 sec
2. During fault $\Rightarrow$ 8 sec to 8.0833 sec
3. Post-fault $\Rightarrow$ 8.0833 sec to 20 sec

1. **Pre-fault:**

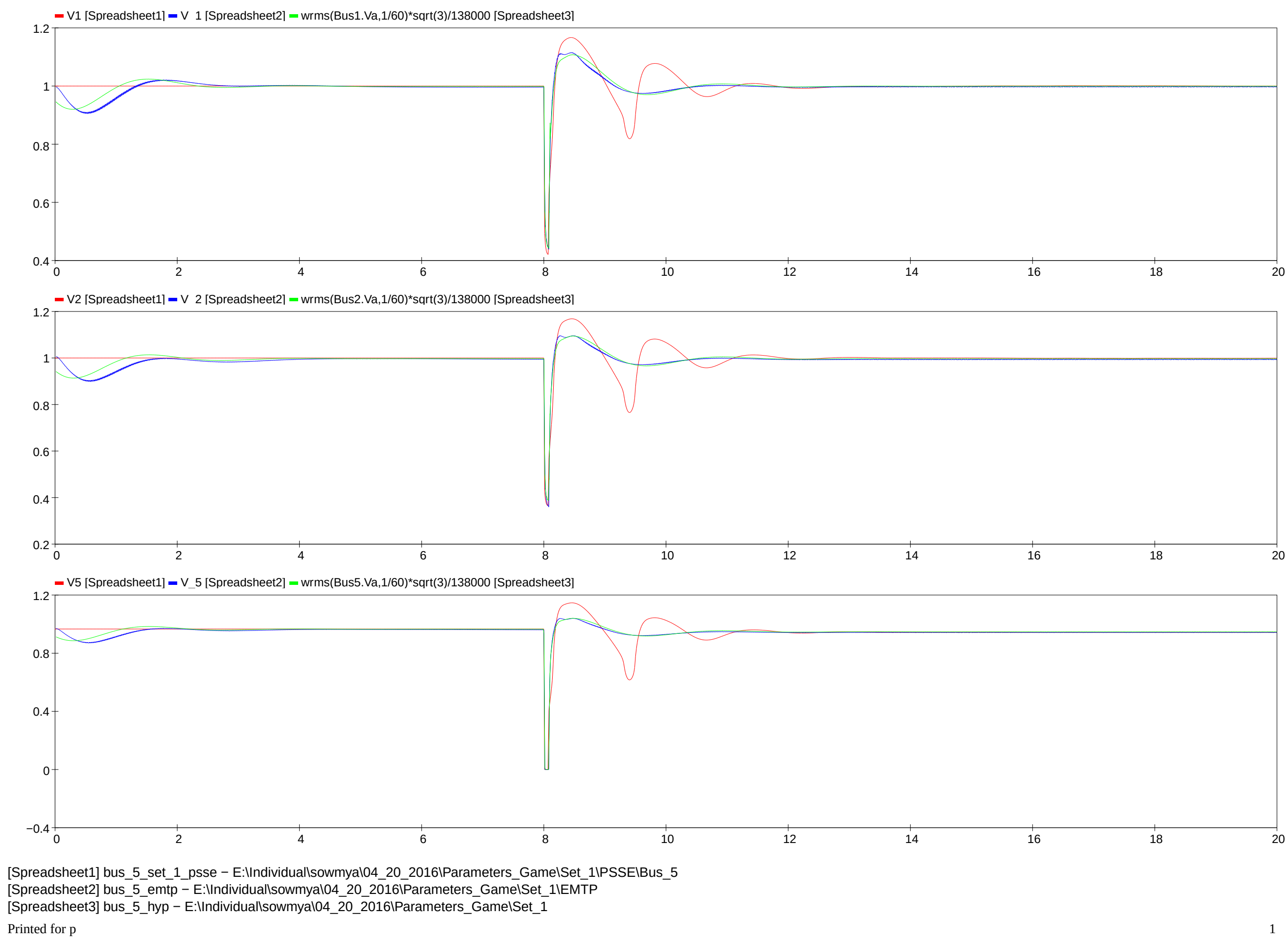

Figure 5.6: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP and Hypersim for fault at Bus-5.

- *PSS/E:* When dynamics are performed on a system using PSS/E, it will not experience any transients until a fault or disturbance is applied on the system. From the output voltage waveform we can clearly see that it starts from the steady state (load flow) value and will be constant until 8 sec i.e., till the fault is applied.
- *EMTP, Hypersim:* During the pre-fault time frame it is clear (from Figure 5.6) that both EMTP and Hypersim experience the initial transients when a synchronous machine is used in the test system. These transients are considered as the rotor dynamics and they appear when the machine starts rotating and in general are considered to remain for a quarter of a cycle when a 60 Hz fundamental frequency is considered. However these transients starts from the initial conditions and not the load flow values as that of PSS/E.

Conclusion: From the above analysis, it can be concluded that PSS/E cannot see the initial transients and hence cannot be used for those which include the detailed study of the system including the initial transients i.e., μ sec to m sec study.

2. **During fault:** During fault, the voltage dip from all the three platforms is almost the same. There is a very minor (about 0.01 - 0.02 pu) difference in the dip across all the three which is negligible. Hence it can be concluded that all the three software platforms behave similarly during the faulted condition.

3. **Post-fault:**

- *PSS/E:* Immediately after clearing the fault the voltages at the buses are supposed to retain their steady state voltages whereas from Figure 5.6 it can be seen that

in PSS/E the voltages are delayed by about 4 seconds to reach the steady state value (1 pu) and it also has oscillations which is undesirable.

- *EMTP, Hypersim:* From Figure 5.6 with EMTP, Hypersim the voltage magnitudes are tracing their steady state voltages after clearing the fault with a minimal (negligible) overshoot.

  Conclusion: From the above discussion of post-fault analysis, it is clear that with the use of same parameters for the exciter in the three platforms, the response of the bus voltages is not going to be identical.

From the above analysis of the bus voltages in dynamic analysis, it is clear that there is a non identical behavior when PSS/E software is used for the same test system with the same parameters as that in EMTP and Hypersim. PSS/E cannot capture the electromagnetic responses of the system. To make this identical, the parameters of the excitation system are tweaked. The sensitivity analysis and the methodology discussed in chapter 3 is used here to tweak these parameters. Trial and error method is used (as there is no particular sensitivity ranking as discussed in chapter-3) for choosing good parameter sets for the platforms so that the dynamic response is identical. The procedure for finding the parameters to be used in PSS/E to match its response with EMTP and Hypersim is given in subsection 5.4.1.

5.4.1 Procedure for finding the parameters for IEEET-1

Starting from the parameters shown in chapter 4 the parameters are modified according to the characteristic of the bus voltage to be modified. Here K_F and T_F are modified together as the first step and Figure 5.7 shows the plot after the modification. These plots contains

the bus voltage waveform plots from PSS/E and EMTP overlapped one on other.

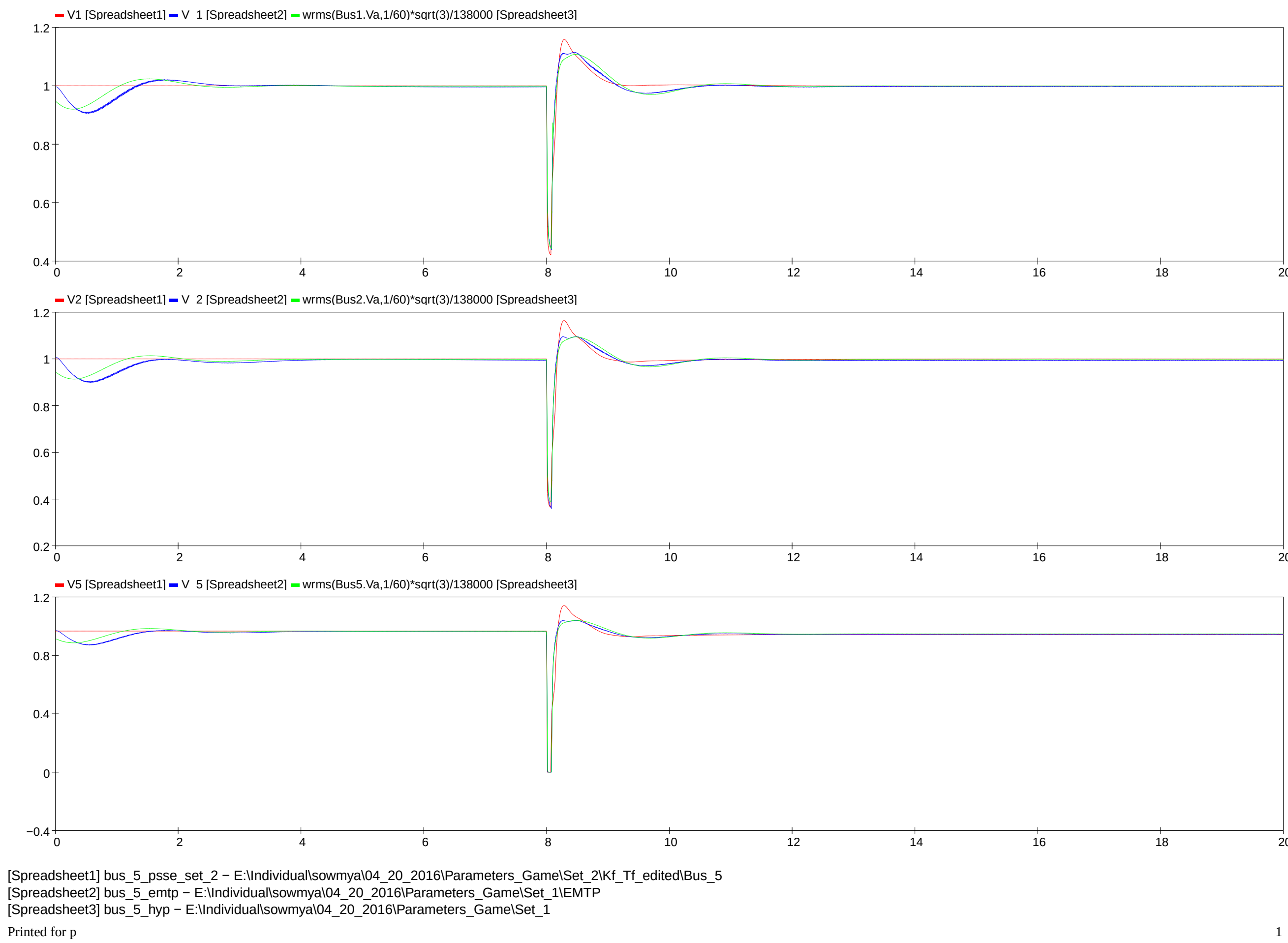

Figure 5.7: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP, and Hypersim with variation of K_F and T_F in PSS/E for fault at Bus-5.

As a next step T_E is modified to achieve the plot shown in Figure 5.8.

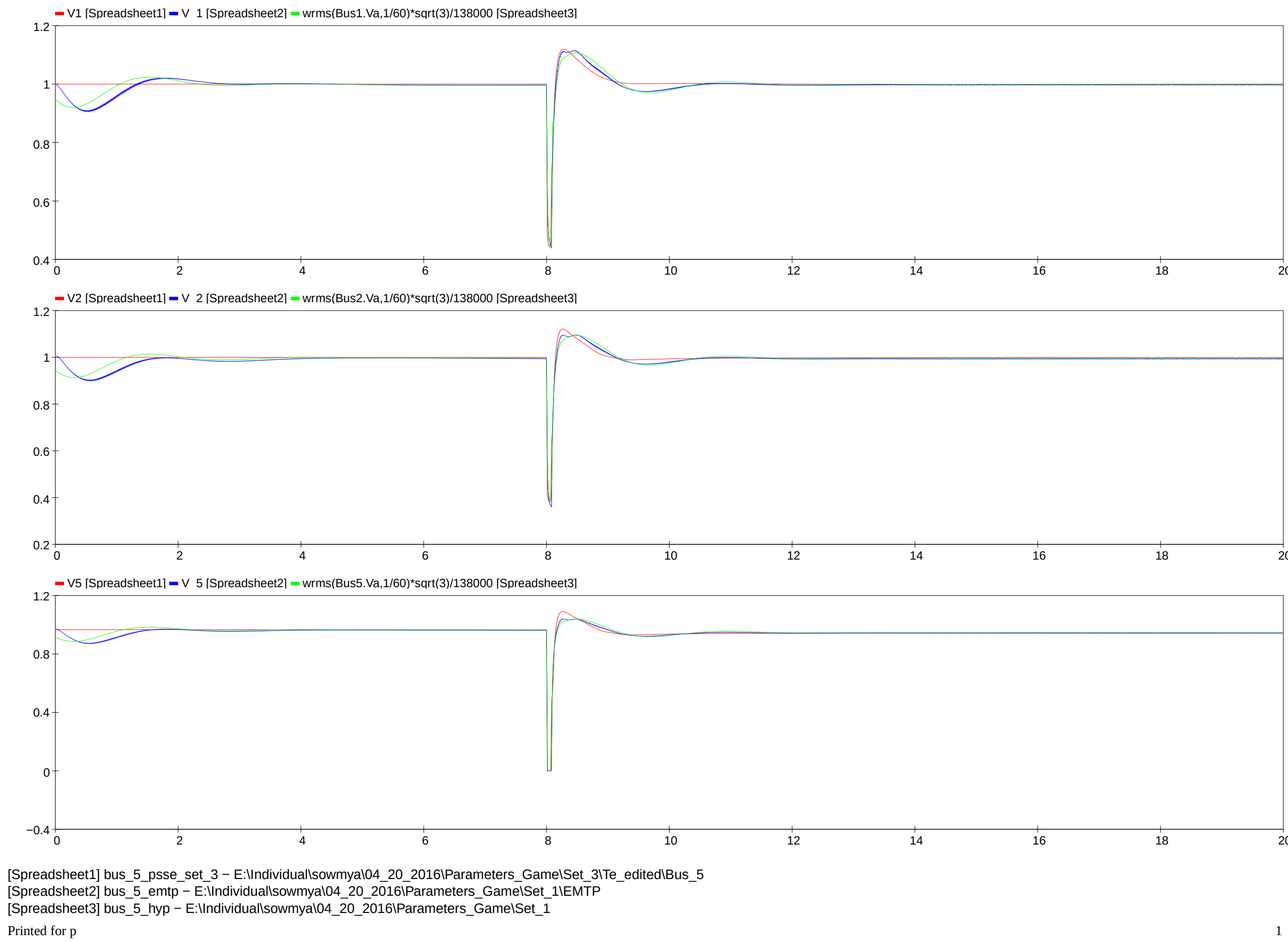

Figure 5.8: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP, and Hypersim with variation of T_E in PSS/E for fault at Bus-5.

Now the parameter K_E is modified to achieve the plots shown in Figure 5.9.

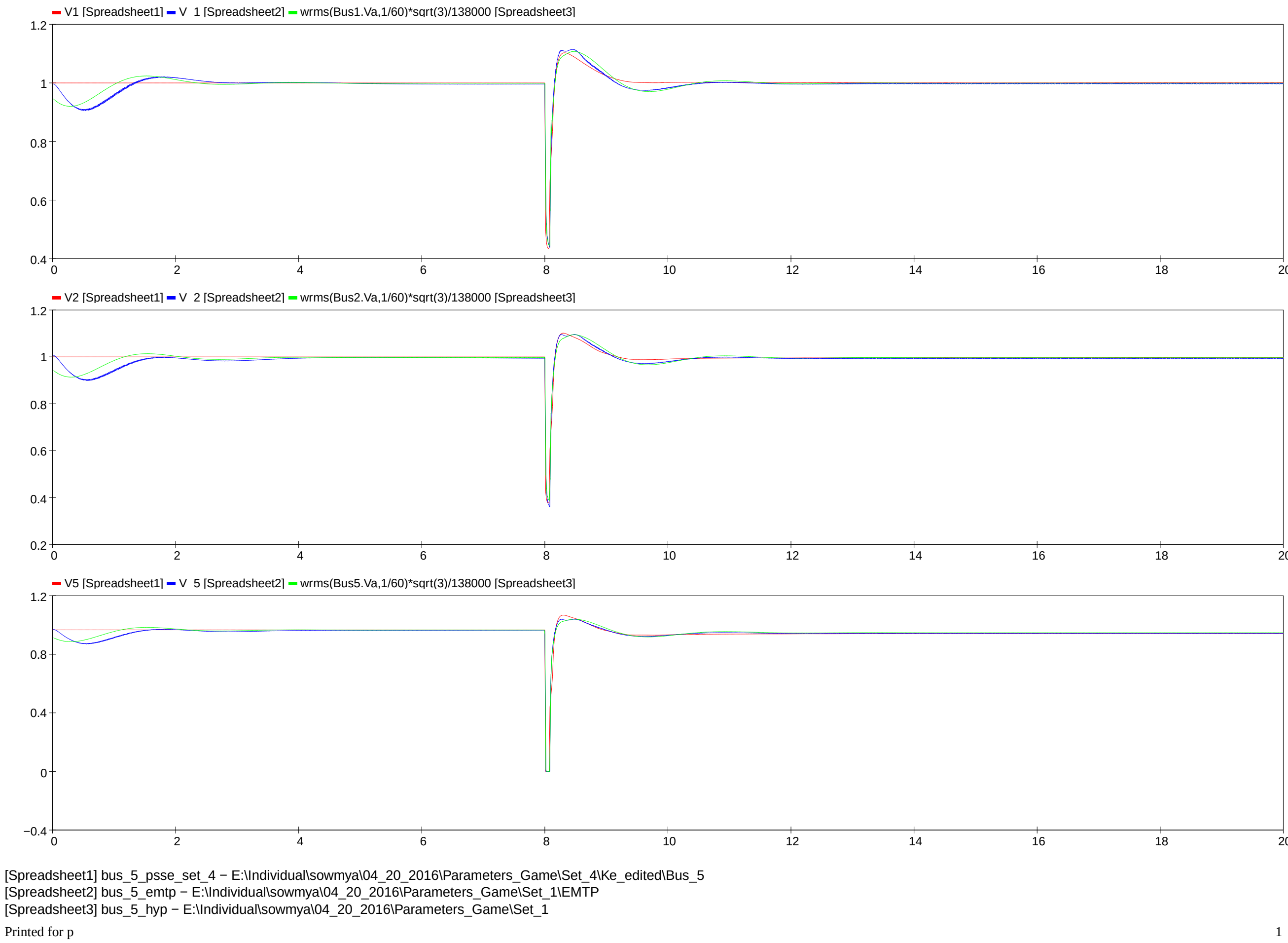

Figure 5.9: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP, and Hypersim with variation of K_E in PSS/E for fault at Bus-5.

The parameter K_A is now tweaked to achieve the plots shown in Figure 5.10.

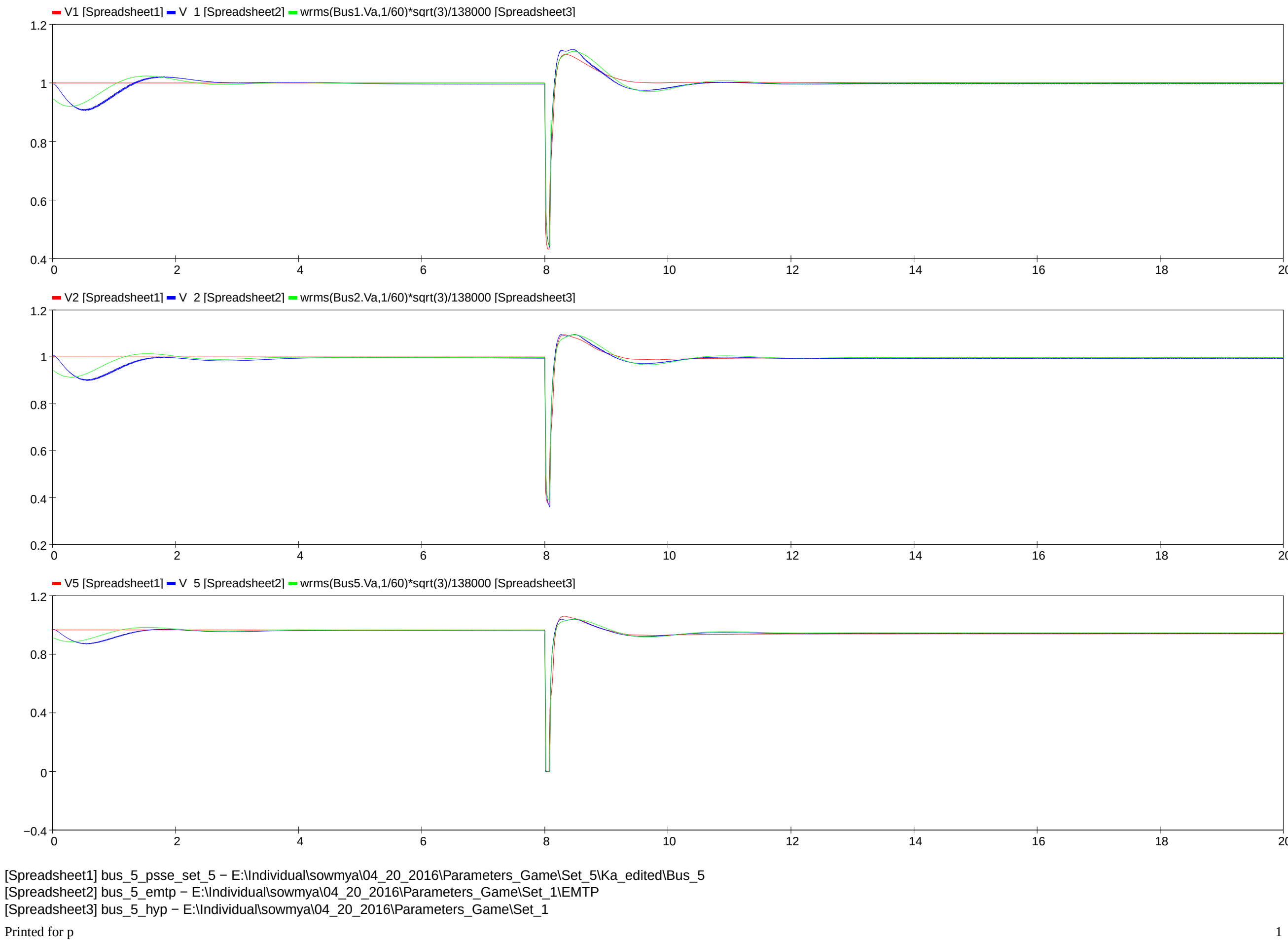

Figure 5.10: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP, and Hypersim with variation of K_A in PSS/E for fault at Bus-5.

The above procedure of tweaking parameters for the excitation system results in the new set of tweaked parameters to be used in PSS/E are shown in Table 5.4. These parameter sets gives similar bus voltage variations after a fault is applied.

Figure 5.11 is the result of the test system with short circuit fault at bus-5 with the tweaked parameters.However Figure 5.11 looks promising, the analysis at buses with shunt capacitance attached behaves little different in Hypersim as seen in Figure 5.12. As the

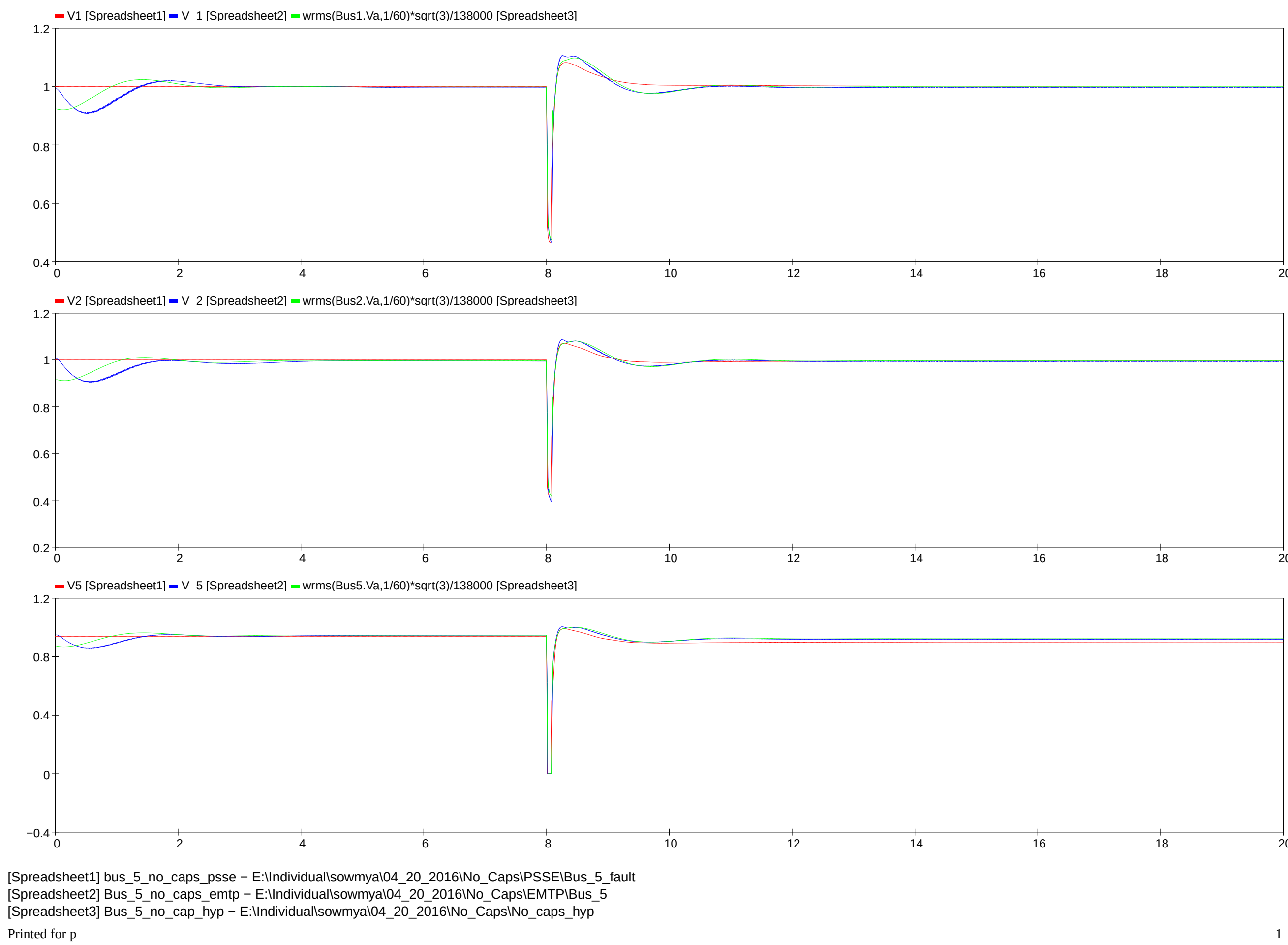

Figure 5.11: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP and Hypersim for fault at Bus-5.

Table 5.4: New IEEET1 Parameters for PSS/E

Parameter	Value
T_R	0.0
K_A	300
T_A	0.05
V_{RMax}	99.9999
V_{RMin}	-99.9999
K_E	0.0
T_E	0.10
K_F	0.067
T_F	1.0
Switch	0.0
E_1	0.0
$S_E(E_1)$	0.0
E_2	0.0
$S_E(E_2)$	0.0

main focus of the thesis is the generator dynamics and matching the behavior of the test system using different platforms, the result of the dynamic behavior of the capacitor is of least concern where as this could possibly be sorted in the future when more detailed study of the test system with the dynamics of the shunt capacitors is considered. For the analysis in present thesis, in order to make the system and its behavior match, the shunt capacitors attached at Bus-3, Bus-6, and Bus-9 were removed.

The analysis is performed again and found that the voltages at all the buses behaves approximately the same as other, as an example the analysis of the system with a bus fault applied at Bus-6 is shown in Figure 5.13. Sample results are shown here in this chapter. The results of all the bus faults with the removal of shunt capacitors are shown in Appendix.

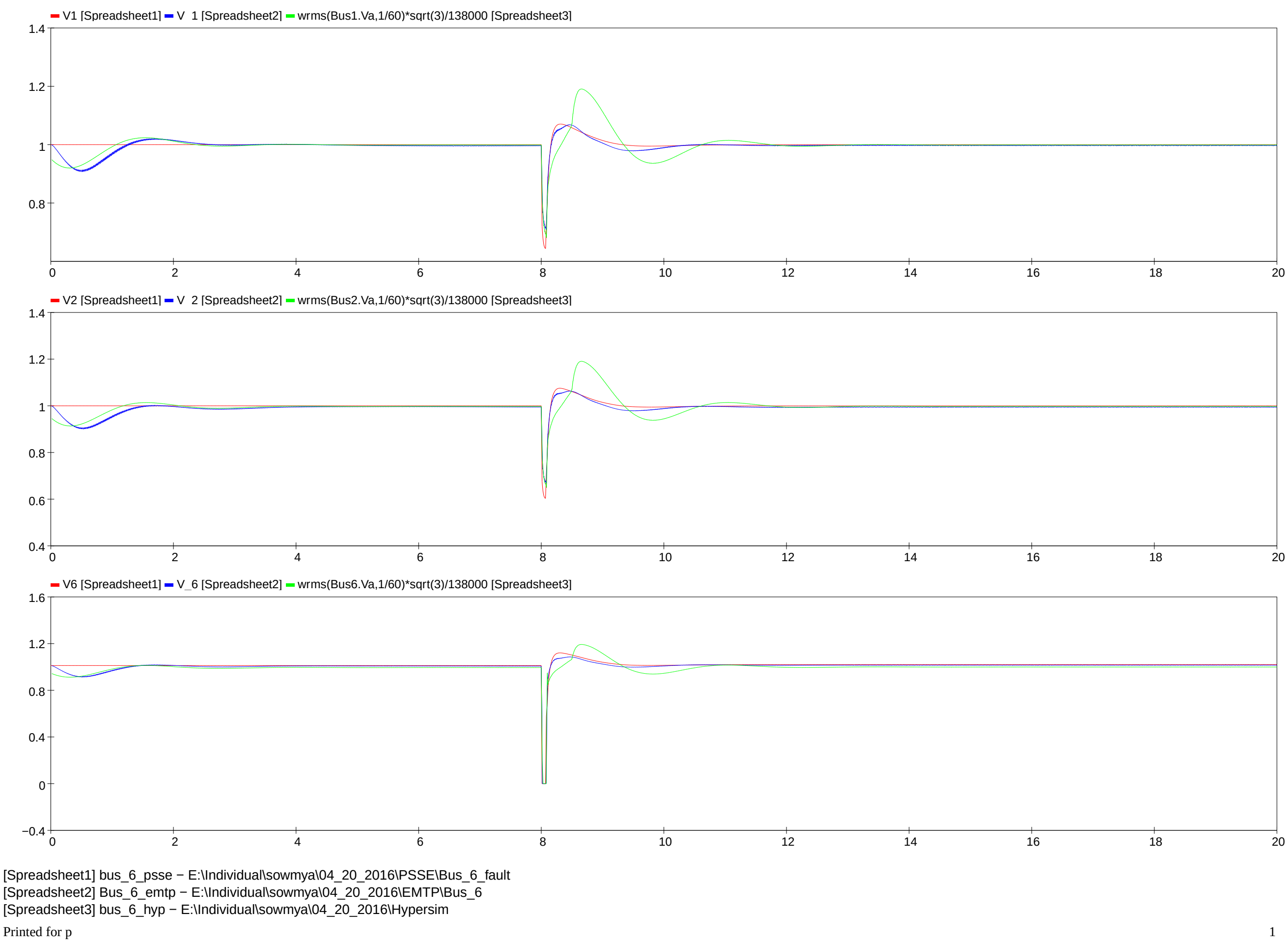

Figure 5.12: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-6 from PSS/E, EMTP and Hypersim for fault at Bus-6.

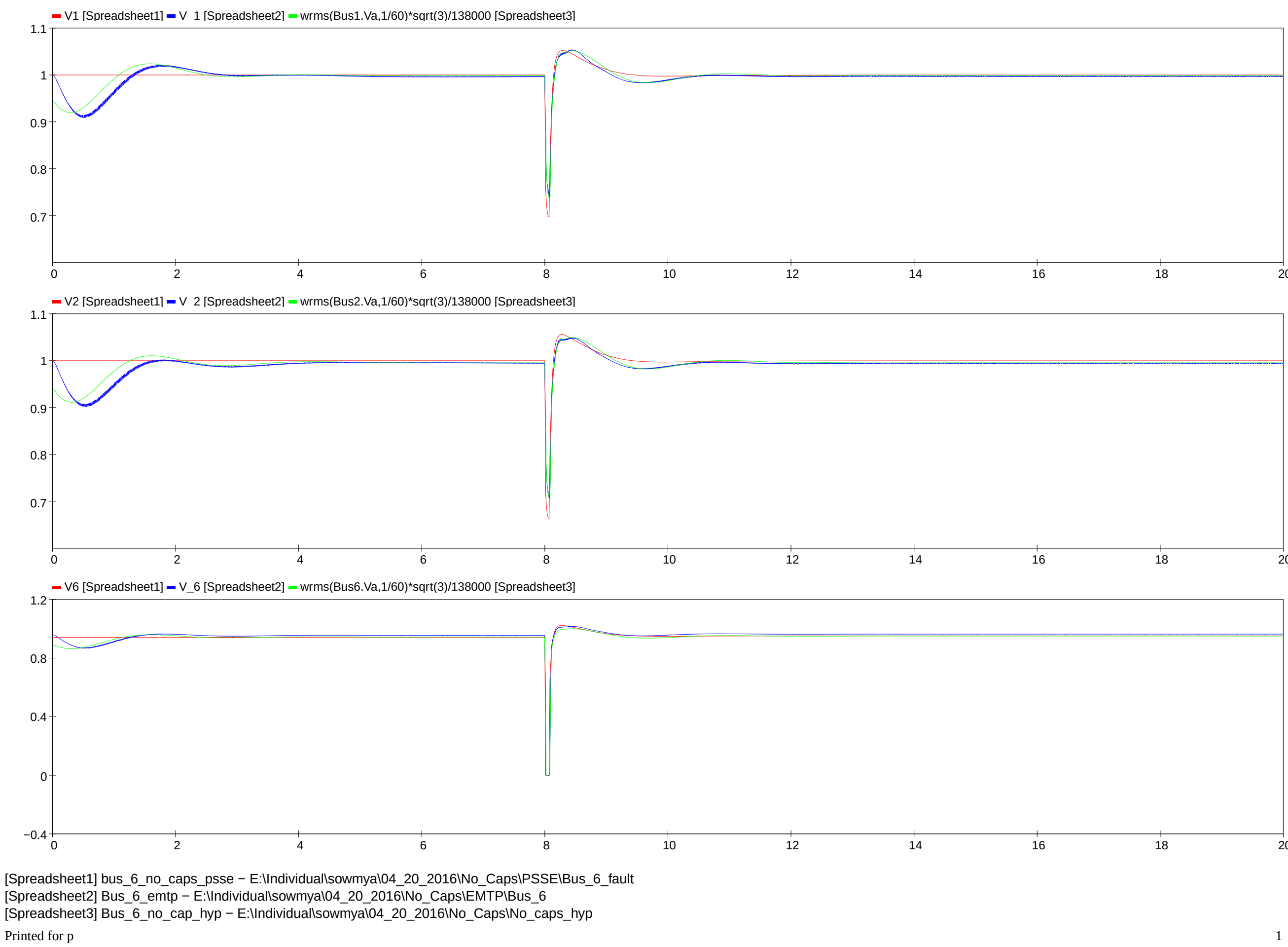

Figure 5.13: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-6 from PSS/E, EMTP and Hypersim for fault at Bus-6 with removal of shunt capacitor.

Chapter 6

Concluding Remarks and Future Work

6.1 Conclusion

As stated in chapter 1, the objective of this thesis is to use the existing capability to model, analyze and predict the dynamic behavior of the electric power system, specially synchronous generators. With the increasing demands on the power systems along with the growth in size and complexity, this work becomes increasingly important.We analyzed the dynamic and transient stability of IEEE 14-Bus system when exposed to severe disturbances in the system. The analysis was performed in three power system software packages (PSS/E, EMTP and Hypersim) and the behavior of the generator to specific three phase bus fault was compared and necessary modifications of the excitation system parameters were successfully implemented so that the system behavior is similar in the three software platforms. In summary the following are the main achievements of the research.

- Modeling of the test system is successfully done using PSS/E, EMTP, and Hypersim.
- The steady state analysis are performed on the test system with an ideal voltage source

used as a voltage generator.

- The results of the steady state analysis were matched among the three software platforms.

- From the dynamic analysis the variation in the output voltage at the buses in PSS/E is found.

- The transfer function of the block (exciter) which gives the difference in the output voltage is calculated and a sensitivity analysis is performed on the transfer function.

- According to the sensitivity analysis and the range, the parameters of the excitation system are varied so that the system dynamic response captured in all the software platforms is identical.

- The thesis methodology stated in chapter 3 was used to perform the comparative analysis by finding and tweaking the most sensitive parameters of the excitation block. The step by step development of the methodology used for comparing generator output in the three platforms could be used for performance analysis of other power system components.

6.2 Continuation of the Work

The following are few works that can be continued starting from the result of this thesis.

- Dynamics of other components than generators may be analyzed by using the proposed methodology.

- The dynamics of the shunt capacitor seen after tweaking the parameters of the dynamic model of the excitation system may be analyzed by replacing the shunt capacitors by the original synchronous condensers in the IEEE 14-Bus system or by finding a value for the added capacitors in the system which may be different in Hypersim/EMTP and PSS/E platforms.

- To achieve the ultimate goal of comparing hardware-in-the-loop simulation of a power system with the simulation results obtained from simulating the equivalent power system model; the proposed methodology outlines the steps for achieving the objectives of the research by only focusing on modeling of the generator. However, the generator model used in the analysis could be further developed to include electromagnetic transients of rotor windings, governor, and voltage stabilizer. When fully developed, we have a fairly accurate dynamic model of the system which may be used in conjunction with the built-in model of SVC in PSS/E for comparison of physical performance of SVC replica for hardware-in-the-loop analysis.

Bibliography

[1] NEPLAN AG. Standard Dynamic Excitation Systems in NEPLAN Power System Analysis Tool.

[2] G. Andersson. *Modelling and Analysis of Electric Power Systems*. 2004.

[3] Pedro Rafael Barros Martins Araújo. Dynamic Simulations in Realistic-Size Networks. Master's thesis, Instituto Superior Técnico, Universidade Técnica de Lisboa, October 2010.

[4] Arthur R. Bergen and Vijay Vittal. *Power Systems Analysis*. 2000.

[5] M. Y. Borodulin. Effect of Wind Variation on Wind Turbine Generator Dynamics in Power System Planning Stability Studies. In *T D Conference and Exposition, 2014 IEEE PES*, pages 1–5, April 2014.

[6] Hermann W. Dommel. *EMTP Theory Book*. 1995.

[7] S. Fan and H. Ding. Time Domain Transformation Method for Accelerating EMTP Simulation of Power System Dynamics. *IEEE Transactions on Power Systems*, 27(4):1778–1787, Nov 2012.

[8] Illinois Center for a Smarter Electric Grid (ICSEG). IEEE 14-Bus System. http://publish.illinois.edu/smartergrid/case-2-ieee-14-bus-systems/, 2014. [Online accessed 19-October-2015].

[9] Siemens Power System Simulation for Engineering (PSS/E) Documentation. *Model Library*. V-32.

[10] H. Gao and C. Wang. Effect of Detailed Hydro Turbine Models on Power System Analysis. In *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, pages 1577–1581, Oct 2006.

[11] Charles A. Gross. *Power System Analysis*. 1979.

[12] G. Gross and M. C. Hall. Synchronous Machine and Torsional Dynamics Simulation in the Computation of Electromagnetic Transients. *IEEE Transactions on Power Apparatus and Systems*, PAS-97(4):1074–1086, July 1978.

[13] N. Hashim, N. Hamzah, M. F. A. Latip, and A. A. Sallehhudin. Transient Stability Analysis of the IEEE 14-Bus Test System Using Dynamic Computation for Power Systems (DCPS). In *Modelling and Simulation (ISMS), 2012 Third International Conference on Intelligent Systems*, pages 481–486, Feb 2012.

[14] Charlie Henville, Ralph Folkers, Allen Hiebert, and Rudi Wierckx. *Dynamic Simulations Challenge Protection Performance*. 2004.

[15] ICDS. Transient Testing Using EMTP Modeling in an Automatic Playback Model. May 28-30 1997.

[16] IEEE. IEEE Guide for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses. *IEEE Std 1110-2002 (Revision of IEEE Std 1110-1991)*, pages 1–72, 2003.

[17] P. K. Iyambo and R. Tzoneva. Transient Stability Analysis of the IEEE 14-Bus Electric Power System. In *AFRICON 2007*, pages 1–9, Sept 2007.

[18] Sameh Kamel Mena Kodsi and Claudio A. Cañizares. Modeling and Simulation of IEEE 14 Bus system with FACTS Controllers. Technical report, 2003.

[19] Prabha Kundur. *Power System Stability and Control*. 2004.

[20] A. Jonaitis M. Ažubalis, V. Ažubalis. Digital Simulation of Synchronous Machine Transients. *IEEE Transactions on Power Apparatus and Systems*, PAS-87(8):1669–1675, Aug 1968.

[21] D. W. Olive. Digital Simulation of Synchronous Machine Transients. *IEEE Transactions on Power Apparatus and Systems*, PAS-87(8):1669–1675, Aug 1968.

[22] I. C. Report. Computer Representation of Excitation Systems. *IEEE Transactions on Power Apparatus and Systems*, PAS-87(6):1460–1464, June 1968.

[23] G. S. Stavrakakis and G. N. Kariniotakis. A general simulation algorithm for the accurate assessment of isolated diesel-wind turbines systems interaction. I. A general multimachine power system model. *IEEE Transactions on Energy Conversion*, 10(3):577–583, Sep 1995.

[24] J. C. Peqqueña Suni, E. Ruppert, and F. Fajoni. A guide for synchronous generator parameters determination using dynamic simulations based on ieee standards. In *2010 XIX International Conference on Electrical Machines (ICEM),*, pages 1–6, Sept 2010.

[25] C. S. M. Wong, P. Rastgoufard, and D. Mader. Voltage Stability Studies Using Real-Time Simulation Computing. In *SSST 2008. 40th Southeastern Symposium on System Theory, 2008.*, pages 410–414, March 2008.

[26] J. P. Yang, G. H. Cheng, and Z. Xu. Dynamic Reduction of Large Power System in PSS/E. In *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, pages 1–4, 2005.

Appendix

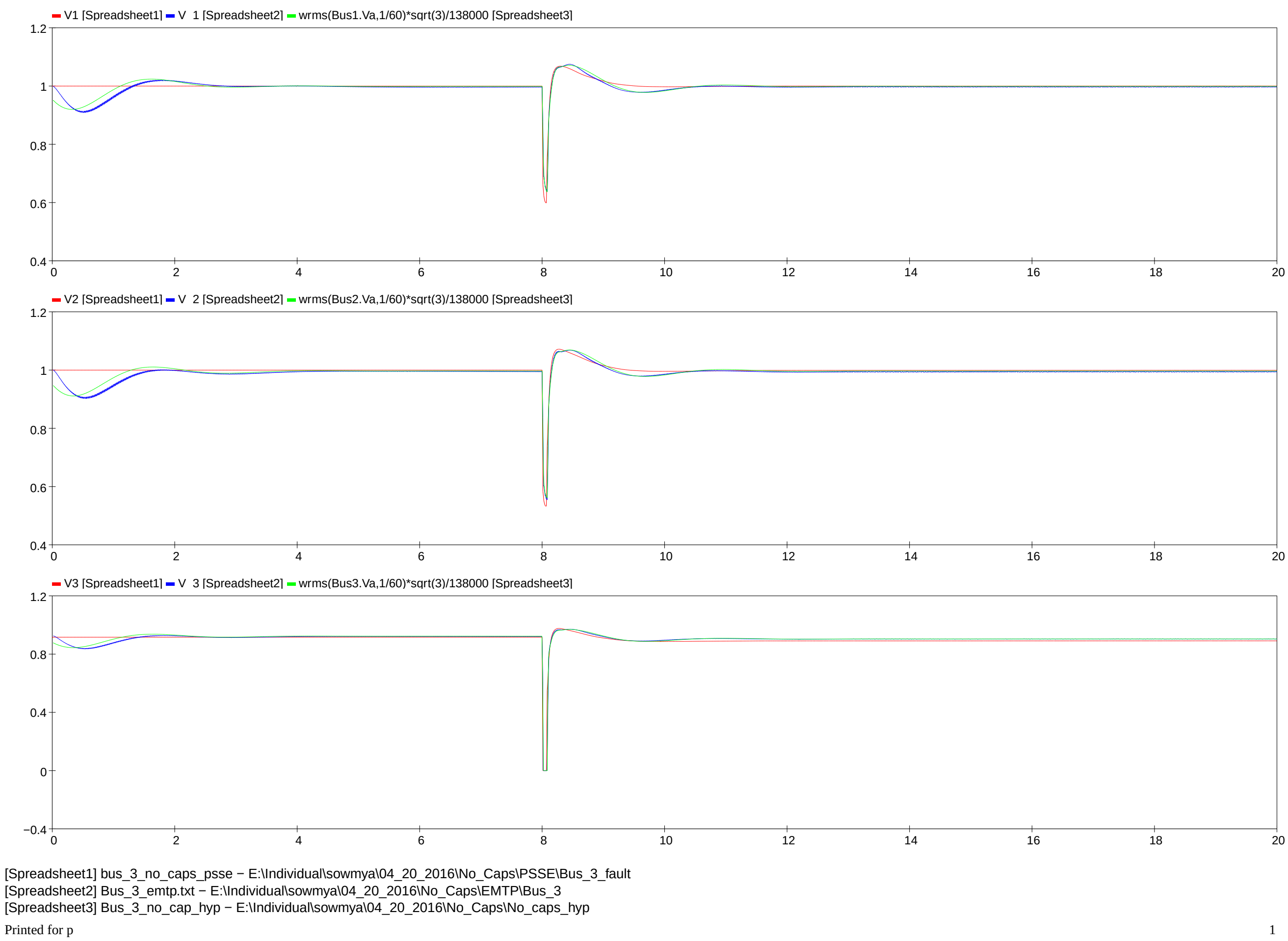

Figure 1: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-3 from PSS/E, EMTP and Hypersim for fault at Bus-3.

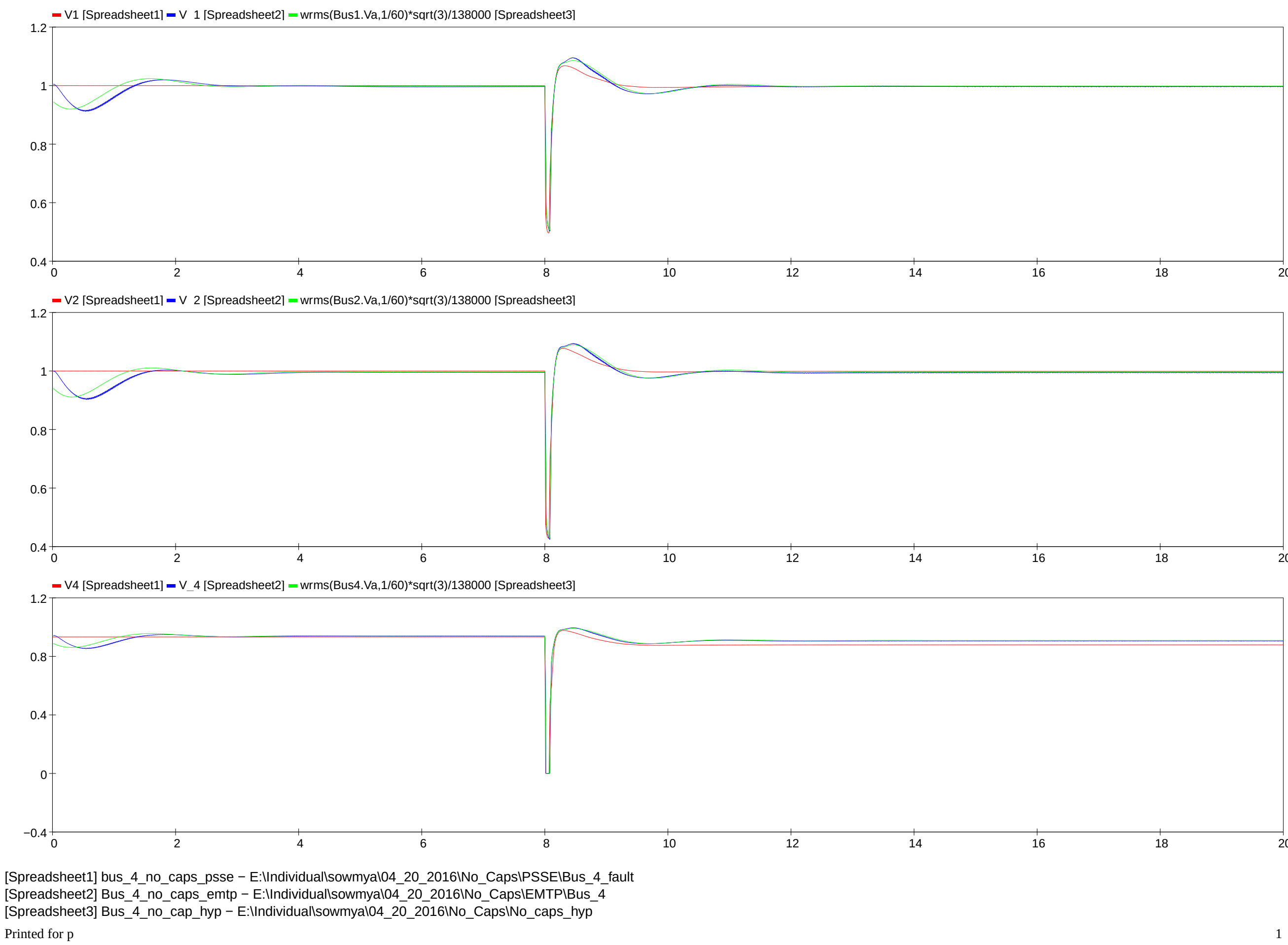

Figure 2: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-4 from PSS/E, EMTP and Hypersim for fault at Bus-4.

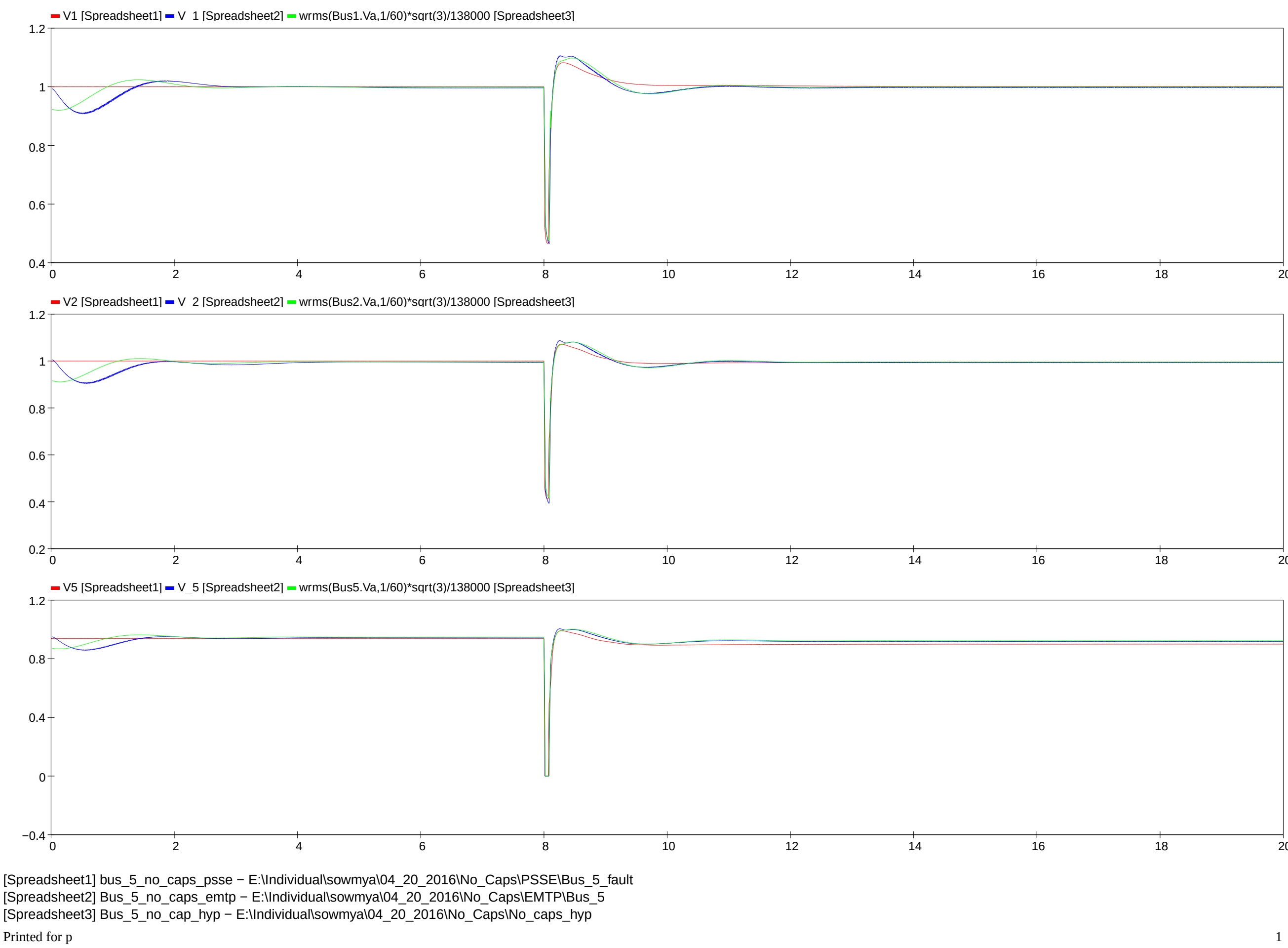

Figure 3: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-5 from PSS/E, EMTP and Hypersim for fault at Bus-5.

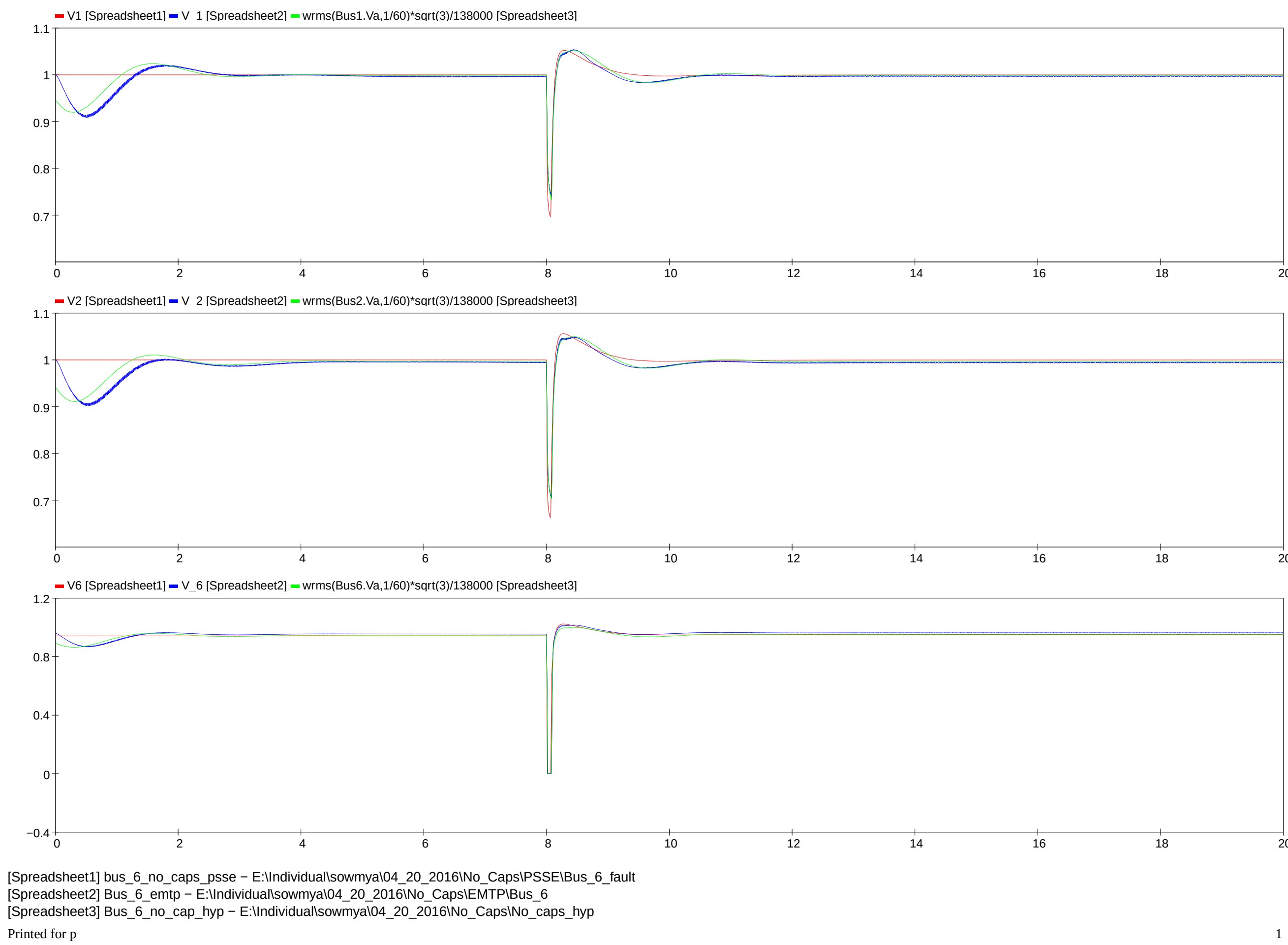

Figure 4: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-6 from PSS/E, EMTP and Hypersim for fault at Bus-6.

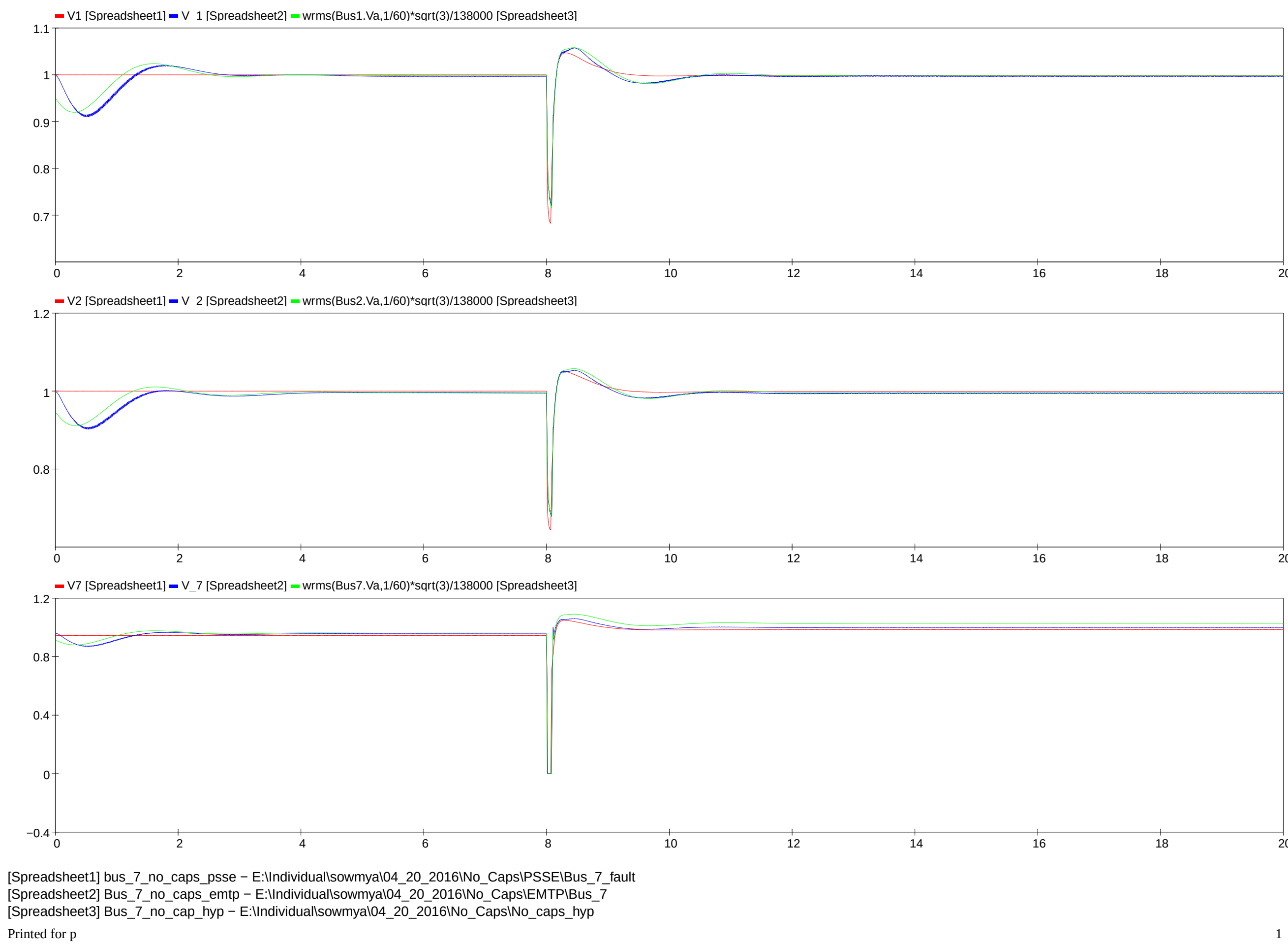

Figure 5: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-7 from PSS/E, EMTP and Hypersim for fault at Bus-7.

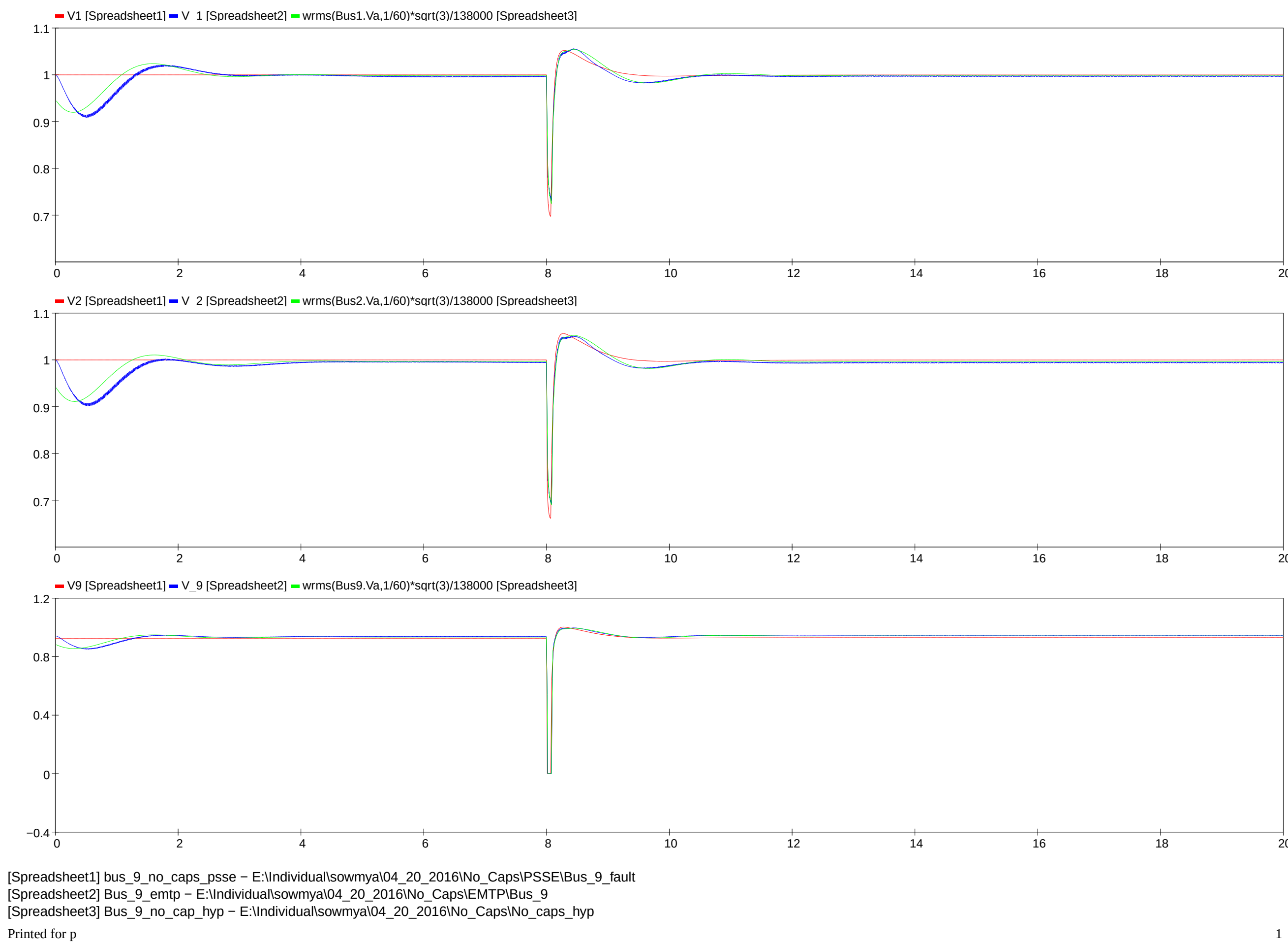

Figure 6: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-9 from PSS/E, EMTP and Hypersim for fault at Bus-9.

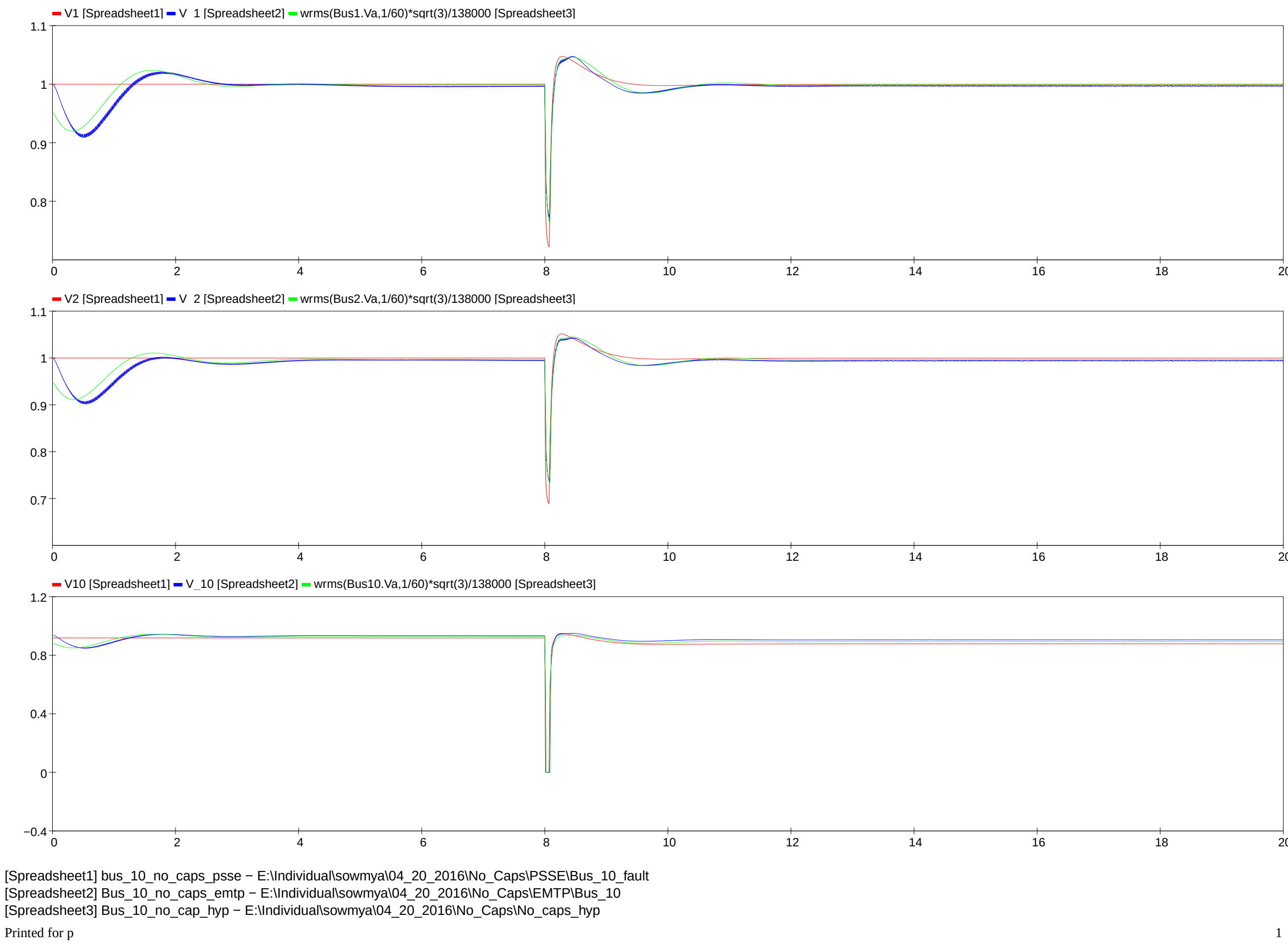

Figure 7: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-10 from PSS/E, EMTP and Hypersim for fault at Bus-10.

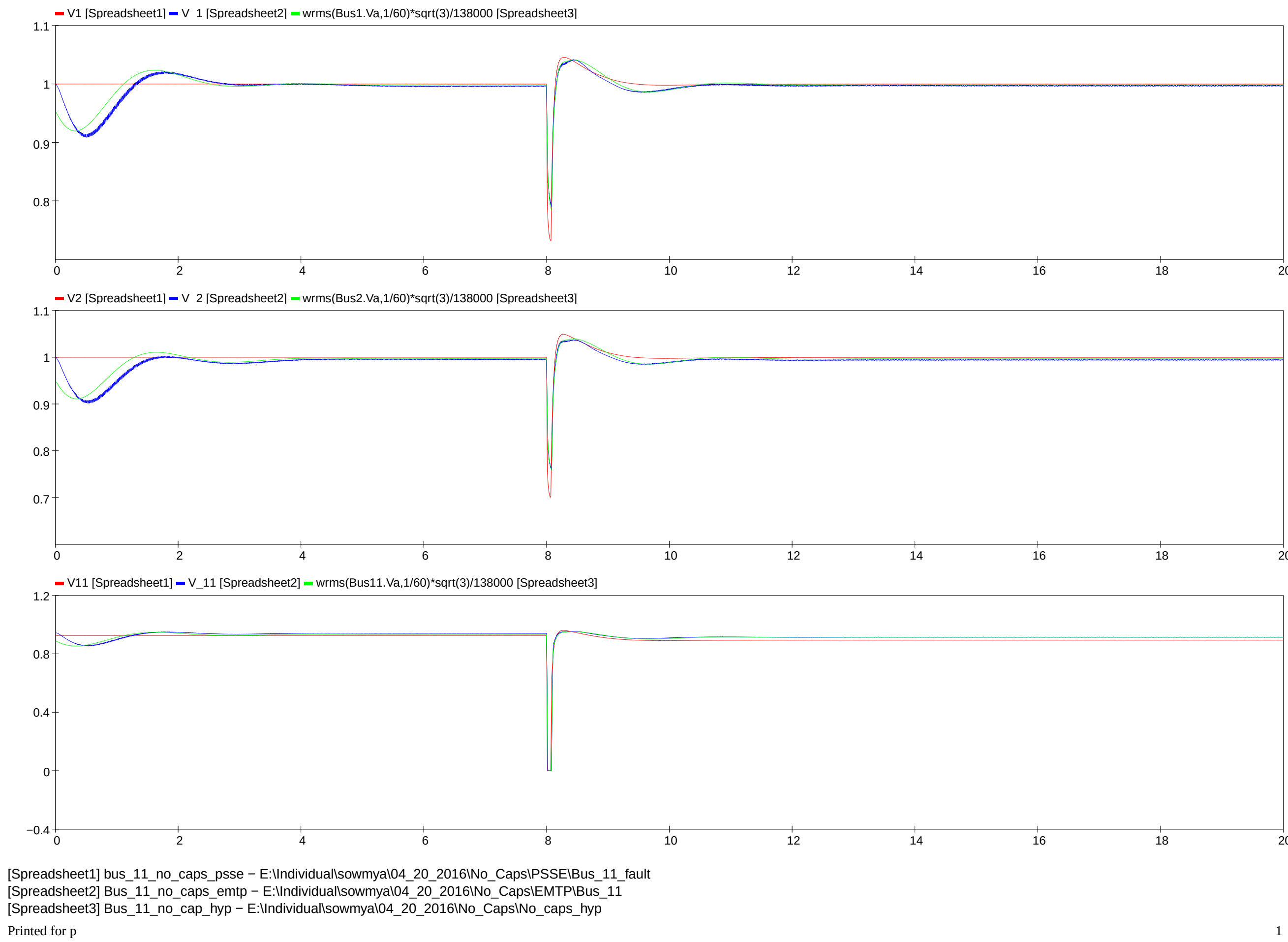

Figure 8: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-11 from PSS/E, EMTP and Hypersim for fault at Bus-11.

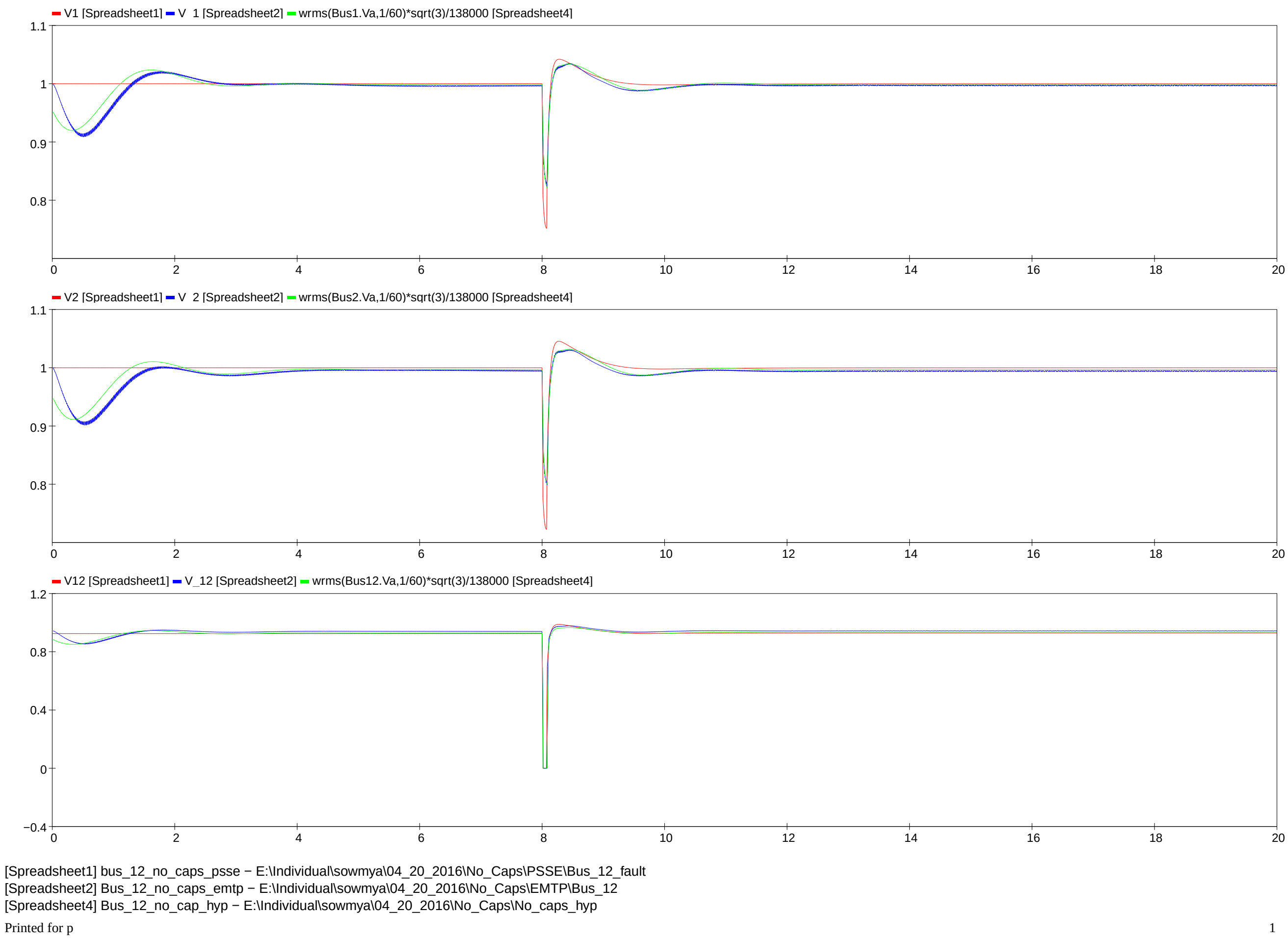

Figure 9: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-12 from PSS/E, EMTP and Hypersim for fault at Bus-12.

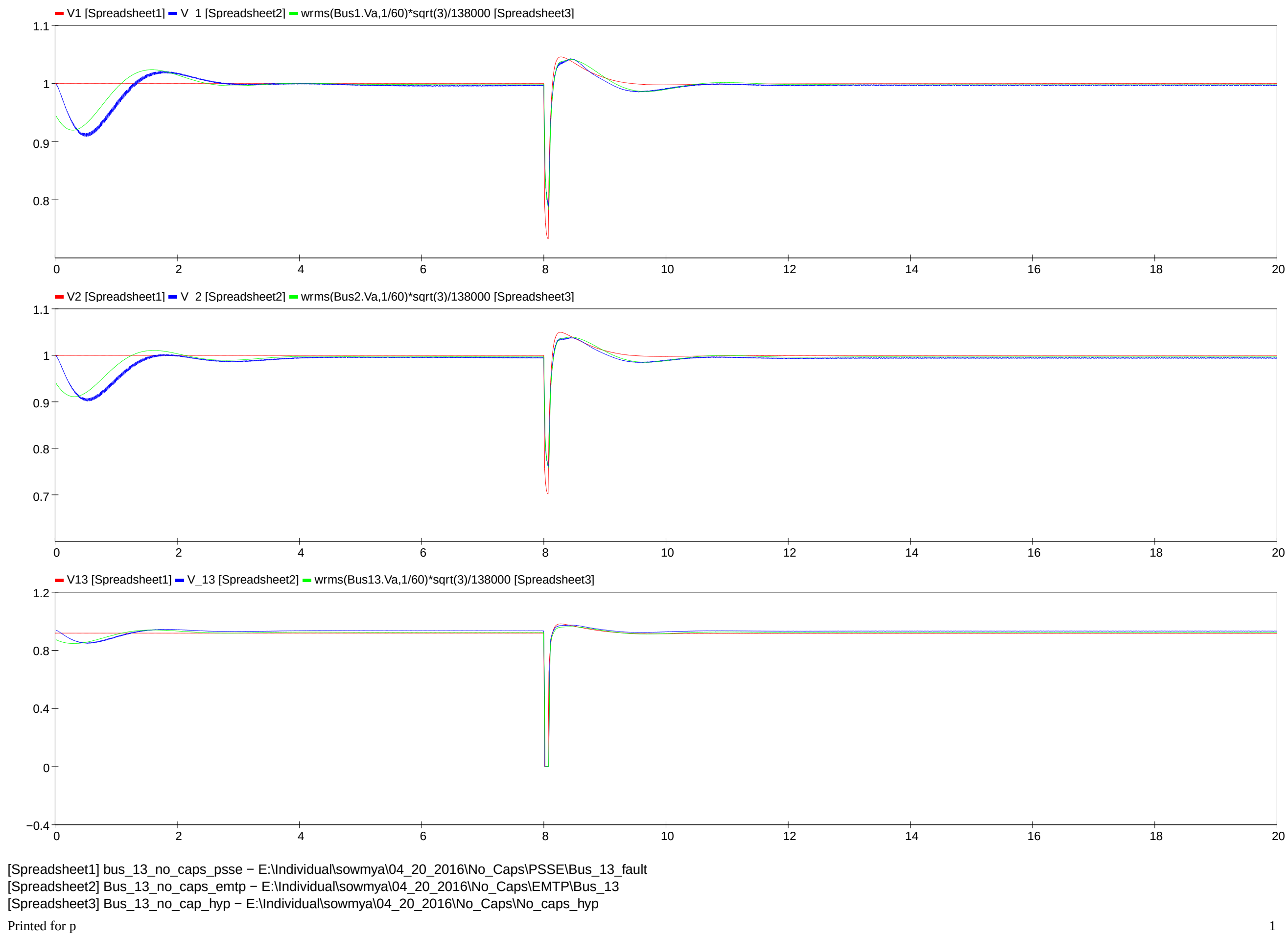

Figure 10: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-13 from PSS/E, EMTP and Hypersim for fault at Bus-13.

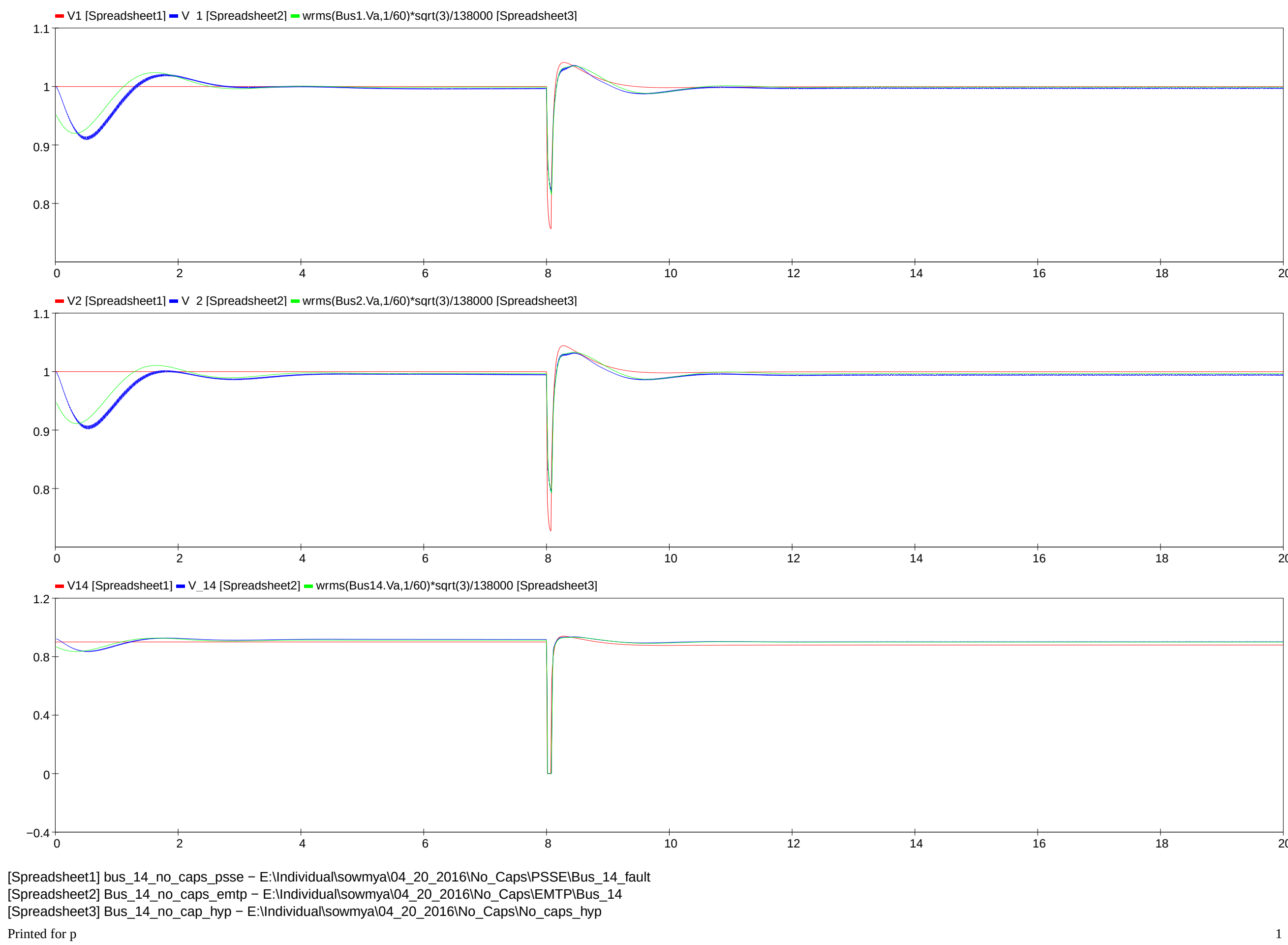

Figure 11: Overlapped voltages (in pu) at Bus-1, Bus-2, Bus-14 from PSS/E, EMTP and Hypersim for fault at Bus-14.

Vita

Sowmya Munukuntla was born in Andhra Pradesh, India, in 1990. She received her Bachelor of Technology degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad, India, in 2012. She joined the University of New Orleans in Spring, 2014 to pursue a Master's degree in Electrical Engineering.

She joined the research group of Dr. Parviz Rastgoufard in 2014 and worked on projects in the area of Power systems transmission modeling, simulation, and design and gained knowledge in using the software platforms such as PSS/E, EMTP, Hypersim for steady state, dynamic, and hardware-in-the-loop modeling and simulation of power systems. She is proficient in using software packages and platforms such as PSS/E, EMTP, Hypersim, MATLAB, Simulink, Python, C, PSLF, Latex, PSpice, and PowerWorld.