Probabilistic Evaluation of Transient Stability of Active Distribution Networks

By:

Mayssam Amiri

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Faculty of Engineering

University of Manitoba

Winnipeg, Canada

Abstract

The main objective of the research described in this thesis is to develop appropriate models and techniques for the probabilistic transient stability assessment of active distribution networks and extend the conventional well-being framework to the area of power system transient stability assessment. Transient stability assessment is one of the important aspects in power system planning and operating. The transient stability performance of power systems can be evaluated using either a deterministic method or a probabilistic approach. Deterministic methods are unable to fully recognize and reflect the actual risk associated with a given system and therefore the industry is leaning towards using probabilistic methods. This is particularly true with the introduction of non-dispatchable renewable generation in the energy supply. A probabilistic approach based on Monte Carlo simulation is, therefore, proposed in this thesis to accurately model and evaluate the risk of various uncertainties associated with active distribution networks transient stability performance. The approach utilizes the calculation accuracy of Electromagnetic Transient (EMT) simulator such as PSCAD/EMTDC and computationally-efficient algorithms such as parallel computing to facilitate the probabilistic transient stability evaluation of active distribution networks. A framework for advancing the industry knowledge in the area of power system transient stability well-being analysis is also proposed. Well-being analysis uses an acceptable deterministic criterion incorporated into probabilistic assessment to assign a comfort level to the power system in terms of healthy, marginal, and risk states probabilities. The concepts, models and methodologies are illustrated using the results obtained from studies on a practical active distribution network.

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Dedicated to Mr. Mohammad Reza Nikoukar

My Fifth Grade Teacher (R.I.P)

Contents

Abstract **i**

Acknowledgements **ii**

Contents **iv**

List of Figures **viii**

List of Tables **x**

Abbreviations **xi**

1 Introduction **1**
- 1.1 Relevant Terms . . . 3
  - 1.1.1 Transient Stability . . . 3
  - 1.1.2 Monte Carlo Method . . . 4
  - 1.1.3 Parallel Computing . . . 5
  - 1.1.4 Distributed Generation and Distributed Energy Resources . . . 5
  - 1.1.5 Active Distribution Network . . . 6
  - 1.1.6 Well-Being Analysis . . . 7
- 1.2 Research Objectives and Overview of the Thesis . . . 7

2 Evaluation of Power System Transient Stability **10**
- 2.1 Introduction . . . 10
- 2.2 Transient Stability Evaluation Methods . . . 11
  - 2.2.1 Equal-Area Criterion Method . . . 12
  - 2.2.2 Time-Domain Approach . . . 13
  - 2.2.3 Direct Methods . . . 16

2.2.4 Automatic Learning Approaches . . . 18
2.3 Types of Transient Stability Evaluation . . . 18
2.3.1 Deterministic Assessment . . . 18
2.3.1.1 Transient Stability of Transmission Systems and Bulk Power Systems . . . 19
2.3.1.2 Transient Stability of Power Systems Incorporating Renewable Energy Resources and Distributed Generation . 20
2.3.1.3 Transient Stability of Active Distribution Networks . . . 21
2.3.2 Probabilistic Evaluation . . . 22
2.4 A Review of Applications of Parallel Computing in Power Systems . . . 26
2.5 Well-Being Analysis of Power Systems . . . 28
2.6 Conclusions . . . 30

3 Transient Stability of Synchronous and Induction Machines 32
3.1 Introduction . . . 32
3.2 Transient Stability of Synchronous Generators . . . 33
3.2.1 *dq0* Transformation . . . 34
3.2.2 Dynamic Models of a *SG* . . . 35
3.2.2.1 *Model 0.0* . . . 35
3.2.2.2 *Model 1.0* . . . 36
3.2.2.3 *Model 1.1* . . . 36
3.2.2.4 *Model 2.1* . . . 37
3.2.2.5 *Model 2.2* . . . 37
3.2.3 *EMT* Response of *SG* Connected to an Infinite Bus . . . 38
3.3 Transient Stability of Induction Generators . . . 39
3.3.1 Analytical Treatment of Transient Stability of an Induction Generator 40
3.3.2 Confirmation of the Analytical Approach Results with *EMT* Simulation . . . 44
3.4 Summary and Conclusions . . . 45

4 Effect of Modeling Details on Transient Stability Results 47
4.1 Introduction . . . 47
4.2 Simulation Tools for Transient Stability Evaluation . . . 48
4.3 Transient Stability of *SG* Connected to an Infinite Bus . . . 50
4.4 Stability Analysis Using Linearized Models . . . 53
4.5 Influence of the Controller on the Stability of *IG* . . . 54
4.6 Summary and Conclusions . . . 57

5 Anomalous Stability Behavior of Synchronous Machine 58
5.1 Introduction . . . 58
5.2 Identification of the Phenomenon . . . 59
5.3 Test System . . . 60

5.3.1 Simple Explanation of Phenomenon . . . 61
5.4 Explanation of Phenomenon Using the Equal Area Criterion . . . 62
5.5 Dependence of the Stable Clearing Intervals on Fault Resistance . . . 66
5.6 Summary and Conclusions . . . 67

6 Probabilistic Evaluation of Transient Stability 68
6.1 Introduction . . . 68
6.2 Description of the Methodology . . . 70
6.2.1 Modeling Load Dynamics and Uncertainties . . . 72
6.2.2 Modeling Generator Dynamics and Uncertainties . . . 72
6.2.2.1 Induction Generator (IG) . . . 73
6.2.2.2 Photovoltaic (PV) Systems . . . 73
6.2.2.3 Synchronous Generator (SG) . . . 75
6.2.3 Modeling Uncertainties Associated with Power System Disturbances 75
6.3 Computational Repercussions . . . 76
6.4 Monte Carlo Simulation Method and Parallel Computing . . . 77
6.4.1 Probabilistic Indexes for Transient Stability Assessment . . . 81
6.5 Feasibility of Application of the Monte Carlo Method to Probabilistic Transient Stability Study . . . 82
6.6 Application of the Proposed Approach . . . 85
6.6.1 Details of the Test System Modeling . . . 86
6.6.2 Minimum Number of Replications, Stopping Criterion, and $PLOTS$ Calculation . . . 90
6.6.3 Simulation Results and Discussions . . . 93
6.7 Conclusions . . . 98

7 Incorporating Well-Being Considerations in Probabilistic Transient Stability Assessment 100
7.1 Introduction . . . 100
7.2 The Proposed Methodology . . . 102
7.3 Incorporating Deterministic Criterion into a Probabilistic Transient Stability Assessment . . . 104
7.3.1 Selecting Criteria for System Health . . . 104
7.3.1.1 Recommended Clearing Time Criterion . . . 105
7.3.1.2 Damping Ratio Threshold . . . 105
7.3.2 Prony Analysis . . . 106
7.4 Application of the Proposed Well-being Approach . . . 107
7.4.1 Sensitivity Analyses for Well-being Criteria . . . 109
7.4.2 Well-being Analyses Results . . . 110
7.5 Summary and Conclusions . . . 114

8 Conclusions and Future Work 115

8.1 Publications . . . 118
8.2 Future Work . . . 119

A Stability Analysis Using Linearized Models 122

B Derivation of Critical Clearing Time of an Induction Generator 127

C Test System Data 130

References 135

List of Figures

3.1 Diagram of *SMIB* system . . . 38
3.3 The electrical torque versus speed characteristic of the *IG* . . . 42
3.4 Trajectory of stable case . . . 43
3.5 Trajectory of unstable case . . . 44
3.6 Transient equivalent circuit of an induction machine . . . 45

4.1 *SMIB* system used in the sensitivity analysis . . . 51
4.2 Sensitivity analysis for effect of modeling detail on transient stability of a *SG* . . . 52

5.1 Diagram of test system. . . . 60
5.2 Evolution of the rotor angle for three different fault clearing times; (a) stable system for a fault duration of 0.2 (s), (b) unstable system for a fault duration of 0.6 (s), and (c) stable system for a fault duration of 1.2 (s). . . 61
5.3 Pre-fault thevenin equivalent circuit. . . . 62
5.4 During-fault thevenin equivalent circuit. . . . 62
5.5 Post-fault thevenin equivalent circuit. . . . 63
5.6 Equal area criterion method analysis; acceleration and deceleration areas for unstable case (Fig. 2.b case). . . . 64
5.7 Equal area criterion method analysis; acceleration and deceleration areas for stable case (Fig. 2.c case). . . . 65
5.8 Stable margin of clearing rotor angle. . . . 65
5.9 Evolution of A for fault clearing time. . . . 65
5.10 Transient stability scanning for test system; (a) voltage source behind reactance machine model, and (b) 6th order machine model . . . 66

6.3 Diagram of the test system with random parameters: fault position, type and duration. . . . 82
6.4 Probability density functions of fault impedance and duration . . . 83
6.5 Utilization of 32 cores by Xoreax engine . . . 84
6.6 Modified IEEE 34-bus distribution test system with *DG* units . . . 87
6.7 Selection of minimum number of replications . . . 92
6.8 The convergence criterion of the simulation process . . . 93
6.9 *PLOTS* associated with different fault types . . . 94

6.10 Conditional *PLOTS* associated with different fault types 95
6.11 Conditional *PLOTS* associated with different fault types on Line 28 . . . 96
6.12 Conditional PLOTS associated with all lines in the test system 96
6.13 Sensitivity analysis result for fault resistance and duration 97
6.14 Instability sensitivity analysis for fault position and starting time and duration. 98

7.3 Prony analysis for rotor angle evolution of a synchronous generator . . . 107
7.4 Oscillatory modes of the rotor angle of SG_1 from Prony analysis; a) magnitude, b) phase, and c) damping ratio 108
7.5 Impact of *DRT* on system health, marginal and risk 110
7.6 Impact of RCT on system health, marginal and risk 111
7.7 System health, margin and risk in terms of conditional probabilities (DRT) 112
7.8 System health, margin and risk in terms of conditional probabilities (RCT) 112
7.9 Well-being analysis using *DRT* for different generators 113
7.10 Well-being analysis using *RCT* for different generators 113

A.1 Root Locus plot of the *SMIB* system 125
A.2 Bode diagram of the SMIB system 126

List of Tables

3.1 Parameters of the *SMIB* system . . . 38
3.2 Parameters of the *IG* . . . 41
3.3 Parameters of the substation . . . 41

4.1 Stable and unstable cases for different *SG* models . . . 53
4.2 Input data for the IG . . . 54

5.1 Input data for the test system . . . 60

6.1 Results of Monte Carlo simulation . . . 83
6.2 Input data for the IG . . . 88
6.3 Wind energy conversion system parameters . . . 88
6.4 Input data for the SG . . . 89
6.5 Fault type probabilities . . . 90
6.6 Fault Probability density Functions . . . 90

7.1 Base-case well-being indexes . . . 108

A.1 Eigenvalues of the *SMIB* system . . . 124

C.1 Shunt capacitors . . . 130
C.2 Overhead line configurations . . . 130
C.3 Distributed loads . . . 131
C.4 Line Segment data . . . 132
C.5 Regulators data . . . 133
C.6 Spot loads . . . 133
C.7 Regulators data . . . 134

Abbreviations

CCT	**C**ritical **C**learing **T**ime
CPU	**C**entral **P**rocessing **U**nit
CSV	**C**omma **S**eparated **V**alues
DAE	**D**ifferential **A**lgebraic **E**quation
DER	**D**istributed **E**nergy **R**esources
DFIG	**D**oubly **F**ed **I**nduction **G**enerator
DG	**D**istributed **G**eneration
DRT	**D**amping **R**atio **T**hreshold
EMT	**E**lector**M**agnetic **T**ransinet
FACTS	**F**lexible **A**lternating **C**urrent **T**ransmission **S**ystems
GPU	**G**raphics **P**rocessing **U**nit
GUI	**G**raphical **U**ser **I**nterface
HPC	**H**igh **P**erformance **C**omputing
HVdc	**H**igh **V**oltage **d**irect **c**urrent
IG	**I**nduction **G**enerator
IGBT	**I**solated **G**ate **B**ipolar **T**ransistor

LG	**L**ine to **G**round fault
LL	**L**ine to **L**ine fault
LLG	**L**ine to **L**ine to **G**round fault
LLL	**L**ine to **L**ine to **L**ine fault
LLLG	**L**ine to **L**ine to **L**ine to **G**round fault
MC	**M**onte **C**arlo
OLTC	**O**n **L**ine **T**ap **C**hanger
PDF	**P**robability **D**ensity **F**unction
PLOTS	**P**robability of **L**oss **O**f **T**ransient **S**tability
PMF	**P**robability **M**ass **F**unction
PV	**P**hoto **V**oltaic
SAIFI	**S**ystem **A**verage **I**nterruption **F**requency **I**ndex
SCR	**S**hort **C**ircuit **R**atio
SG	**S**ynchronous **G**enerator
SMIB	**S**ingle **M**achine **I**nfinite **B**us system
VSC	**V**oltage **S**ourced **C**onverter

Chapter 1

Introduction

Risk based or probabilistic reliability evaluation is widely accepted in the power industry to determine the ability of a component, a subsystem or a system to perform its intended function. The numerous uncertainties facing industry generate a need to use probabilistic evaluation methodologies in power systems. Further, interconnection of renewable power generation sources to the power system has increased the uncertainties that a power system operator or planner faces [1].

Traditionally, deterministic methods have been used to analyze transient stability of power grids. Using this method, typically, nominal or worst-case operating conditions are considered. This approach is reasonable when the generation is dispatchable. However, these methods face a challenge with renewable generation, whose availability is random in nature. Hence, it is proposed in this thesis to use a probabilistic method for transient stability assessment, which includes the uncertainties associated with generation, network changes and system loads.

The research described in this thesis is focused on the development of a Monte Carlo simulation based methodology for performing probabilistic transient stability assessment of active distribution networks. The first practices and standards which have developed for interconnecting distributed generation to distribution networks indicated that distributed generation should cease energizing the system immediately after a fault [2]. This implies that the transient stability of active distribution networks was not of interest. However, the latest standards have considered fault ride-through capability of distributed generation as well as intentional islanded operation of active distribution networks [3]. The aforementioned changes aim to keep distributed generation connected to the system during the faults and imply that the transient stability of active distribution systems should be considered.

The proposed approach takes the advantage of the calculation accuracy of Electromagnetic Transient Simulation programs such as PSCAD/EMTDC and the efficiency of fast computing techniques such as parallel computing to perform probabilistic transient stability evaluation of power systems. The proposed method also extends the conventional well-being approach to power system transient stability assessment. The applicability of the approach is illustrated by performing probabilistic transient stability studies on a representative example of an active distribution network.

In this chapter, relevant terms to the research field are described. The research objectives and outline of the thesis are also provided in this chapter.

1.1 Relevant Terms

1.1.1 Transient Stability

Transient stability is the ability of power system to keep its synchronism when a severe transient disturbance happens in some part of it. The disturbances may include faults, loss of generation, load, etc. [4]. This definition can also be applied to transient stability of an active distribution network.

Generally, there are two approaches for transient stability analysis. The classical method of transient stability assessment is based on a deterministic approach in which a boundary of the operating limit is determined based on the worst-case scenario analysis [1]. The worst-case stability scenario is usually assumed to be the most stressed transmission and maximum load operating condition disturbed with a few severe contingencies such as a three phase fault at the generator bus.

The deterministic worst-case scenario approach has served the industry well over many years and still remains as the most common technique being used in power system transient stability assessment. However, such analysis based on the worst-case design can often lead to an over-constrained operating solution, particularly as the worst-case may often have a very low chance of occurring. Meanwhile, the power industry is facing many challenges due to various factors such as the liberalization of utility business and the increased penetration of intermittent energy sources. These challenges have made the application of the traditional deterministic approaches for planning and operation of power systems more difficult than in the past. The use of probabilistic planning approaches are, therefore, becoming a beneficial supplement to the existing power system planning and operation process. The focus of the research described in this thesis is in the domain of probabilistic transient stability assessment. Although probabilistic transient stability assessment requires extensive computational effort, high performance computational techniques can be used to overcome this drawback [5].

1.1.2 Monte Carlo Method

The *Monte Carlo method* is proposed in this thesis to perform probabilistic transient stability assessment. Monte Carlo methods deal with uncertainties via repeated solutions of a mathematical problem, each with a different set of values for the random parameters. These values are selected by sampling the parameter space using the nature of their random distributions [6]. By increasing the number of samples, the error of approximation decreases and the accuracy of the Monte Carlo method increases [7], but the time required to obtain results also increases [5]. The Monte Carlo method is easy to use and robust. These properties make it applicable to many fields of science and engineering.

1.1.3 Parallel Computing

The computational effort of application of the Monte Carlo simulation to transient stability problem consists of two parts:

- Simulation and generating the results
- Post-processing of the results to analyze and produce desired representation

By increasing the number of simulations in the Monte Carlo method, the error of the evaluation will substantially decrease but at the same time the overall time of the evaluation will increase. Often this makes it impractical to run simulations sequentially on a single computer. The simplest way is to exploit the multiple cores available on a modern computer to basically divide the task into sub-tasks and use the cores to solve them separately [8]. Parallel computing is a well-known technique to manage massive computational tasks. In such an approach, the computational tasks are distributed to be done by different computing cores in a computer network [8]. Parallel computing is used in this thesis to facilitate the necessary computation for performing probabilistic transient stability evaluation of power systems.

1.1.4 Distributed Generation and Distributed Energy Resources

Since the main test system of the thesis considers *Distributed Generation (DG)* units as energy resources, a brief explanation about *DG* and its definition are provided in this section.

There is no standard definition for *DG* in the industry. Some of the accepted attributes of *DGs* in the literature are as follows:

- *DGs* unlike the bulk power system generating units are not centrally planned.
- *DGs* are small in units and there is no specific limit in the literature for their power generation capacity [9–11], but it is normally considered less than 50 MW [12].
- *DGs* are normally connected to distribution networks, so the voltage level of their connection point is directly related to the voltage levels in those networks.

It is not easy to consider all of the attributes of a *DG* in its definition. Ackermann et al. have proposed a definition for *DG* as "an electric power source connected directly to the distribution network or on the customer site of the meter" [13]. This definition is considered in this research.

Distributed Energy Resource (DER) is another widely used term in literature. DERs are DGs or energy storage units that are connected directly to distribution networks or micro-grids [14].

1.1.5 Active Distribution Network

Traditionally, electrical distribution networks are passive networks, since no electric power sources are connected to them. Incorporation of *DERs* to the passive distribution networks will change them to active networks. An active distribution network is a distribution network which has at least one *DER* connected to it [12]. Some changes should be considered for studies related to these networks in comparison to the passive distribution networks. The transient stability problem is one of the issues that should be considered and analyzed for planning of the active distribution networks.

1.1.6 Well-Being Analysis

Well-being analysis assigns a measure to the system operating condition that indicates its relative state of health. In such an analysis, an acceptable deterministic criterion is incorporated into a probabilistic evaluation [15]. Normally, the well-being of a system is classified into healthy, marginal and at-risk states.

1.2 Research Objectives and Overview of the Thesis

The main objective of the research described in this thesis is to develop a consistent and useful technique and methodology for probabilistic transient stability evaluation of active distribution networks. Also, this research aims to advance the state-of-the-art in the area of power system well-being analysis. The objectives of this research have been accomplished by focusing on the followings:

- To develop a Monte Carlo simulation based approach for transient stability evaluation of ADNs which is suitable for conduction advanced analyses such as well being analysis, etc.

- To incorporate fast computing algorithm for facilitating the probabilistic transient stability assessment of active distribution networks.
- To extend the conventional well-being technique to transient stability assessment.
- To test the accuracy, applicability and efficiency of the models, techniques and evaluation methods by examining results obtained from simulating a small manageable system.
- To examine the feasibility of application of the proposed approach in probabilistic transient stability assessments of a practical active distribution network.

The thesis is divided into eight chapters.

In Chapter 2, literature review and research background are presented with a focus on the transient stability evaluation of power systems and probabilistic models of power systems and active distribution networks.

Chapter 3 provides the mathematical and analytical representation of synchronous and induction machines as two main means of electric power generation.

Chapter 4 discusses the effect of modeling details on transient stability evaluation and the capability of different tools for transient stability evaluation, in order to select the proper simulation tool for this research.

Chapter 5 is about an anomalous transient stability behavior of synchronous generators facing a high impedance resistive fault. In this study, the possibility of stability after the critical clearing time is investigated.

In Chapter 6, the details of the proposed framework for probabilistic transient stability assessment of active distribution networks are explained. Details on the modeling of an active distribution network for transient stability analysis, and the associated uncertainties are discussed. Also, *PSCAD/EMTDC* Monte Carlo interface is introduced and the results of the probabilistic transient stability evaluation of a practical active distribution network are presented.

Chapter 7 presents the proposed framework for transient stability well-being analysis as well as the results of application of the proposed well-being framework.

Chapter 8 provides a summary of the thesis, major conclusions drawn from the results obtained from the research, the main contributions of the research described in the thesis and suggestions for future extension of the research.

Chapter 2

Evaluation of Power System Transient Stability

2.1 Introduction

In this chapter, a review of the power systems transient stability assessment methods is presented. A brief explanation of each method is provided and then the literature review pertinent to the application of these methods on power systems is presented. Also, two main types of transient stability evaluation studies are addressed and using the review of the published literature, advantages and disadvantages of each type are reviewed. The literature review is divided into subsections in order to consider different methods and types of the transient stability evaluation. Finally, a research background on well-being analysis of power system is provided.

2.2 Transient Stability Evaluation Methods

Transient stability is a non-linear problem. Solving differential and algebraic equations are necessary in assessment of transient stability of a power system. In order to find the dynamic response of a power system to a disturbance, the differential and algebraic equations should be solved for the duration of the disturbance (start to end).

The differential equations for the transient stability problem are a set of first order differential equations and represent the dynamics of generators, controllers, loads, etc. The algebraic equations are related to the topology of the power system and network impedances. The algebraic equations are used to find the power flow solution.

It should be realized that network elements like inductors and capacitors will have a dynamic response, but traditional transient stability deals with low frequency, primarily electromechanical transients. At these frequencies, quasi-steady state conditions can be assumed and the dynamics of the electrical network can be ignored. Thus, the network can be solved by phasor analysis. However, if transient stability is evaluated using *Electromagnetic transient (EMT)* simulation, the higher frequency network dynamics are also included leading to improved accuracy.

The aforementioned two sets of differential and algebraic equations for transient stability problem can be summarized as follows [16]:

$$\begin{aligned} \dot{x} &= f(x, y, u) \\ 0 &= g(x, y, u) \end{aligned} \tag{2.1}$$

Transient stability of a multi-machine power system is a high-dimensional problem [16]. Nonlinearity of the transient stability problem, large number of differential equations and high dimension of the problem for a complex power system make transient stability evaluation a challenging task.

In order to overcome the aforementioned challenges, generally, traditional methods for assessing power system transient stability have been used. these traditional methods can be categorized in four groups:

- Equal-area criterion method [17]
- Time-domain approach [4]
- Direct methods [18]
- Automatic learning approaches [16]

A brief review and discussion of each of these methods is provided in the following subsections.

2.2.1 Equal-Area Criterion Method

The equal-area criterion is a graphical method to analyze the transient stability problem. This method is usually applied to a *Single Machine Infinite Bus (SMIB)* system. The critical parameter in this method is the energy and transient stability is analyzed using the concepts of potential and kinetic energies. Using the equal-area criterion, the margin of stability of the power system can be found. The method is useful in providing a physical understanding of the phenomenon, but is not directly amenable to determining stability in a large network.

The equal-area criterion is actually a particular case of the Lyapunov's method which is among the direct methods of the transient stability analysis [16]. A great deal of research were focused on the equal area criterion [19–21]. Simplicity and visionary property of the equal-area criterion method are among its advantages. The main disadvantage of this method is that the application of it to a multi-machine system needs considering many simplifications in modeling of power systems. Also, by increasing the dimension of the transient stability problem, it is hard to use this method for transient stability assessment, if not impossible.

Extended equal area criterion was also introduced and applied for multi-machine system. However, the application of this method to large power systems is still complicated and not well-established.

A comprehensive discussion of the equal area criterion method and demonstrating examples of its application can be found in Reference [17].

2.2.2 Time-Domain Approach

Using time-domain approach, differential and algebraic equations of the transient stability problem (Equation 2.1) should be solved for the power system under large disturbances.

By solving these equations, the synchronism of the power system can be examined using the evolution of angle and speed of the generators.

Considering the time at which disturbance occurs and being removed (by itself or a protection system that isolates the fault), time-domain analysis is divided into three time durations:

- Pre-fault
- During-fault
- Post-fault

Time-domain simulation, should continue solving the equations for seconds in post-fault period to examine if the power system finds a stable equilibrium. In other words, after finishing the time-domain simulation, it is possible to determine whether the power system is stable or not.

The simulation time for assessing transient stability using time-domain approach depends on the generators' inertia and the degree of detail in modeling of the power system. Depending on the aforementioned characteristics of power system under study, the simulation time is usually selected between 3 to 15 seconds [16].

The disturbance clearing time has a crucial effect on the stability of the power system. As for a specified disturbance, if the protection system clears the fault fast enough, the power system will remain stable. However, if the disturbance is sustained or removed with delay, the power system may lose stability. The *Critical Clearing Time (CCT)* is defined as the maximum time that a specified disturbance for a particular pre-fault condition of the power system can be tolerated before the system loses its stability [4]. *CCT* is usually considered as the transient stability margin in time-domain method.

The time-domain approach is usually used as a reference for assessing and comparing the accuracy of other evaluation methods of transient stability. If high detailed models of the power system components are used, time-domain approach can provide the most accurate results of the transient stability analysis among all of the evaluation methods. However, application of this method (especially for a detailed model of power system) needs extensive computational effort.

The advantages and disadvantages of the time-domain approach can be summarized as follows [16]:

- Advantages:
  - Providing necessary information about the power system such as generator speeds and their evolution by time;
  - Ability to model power systems with different sizes and various disturbance;
  - Providing required accuracy based on the details of modeling;
- Disadvantages:

- Traditional transient stability programs do not provide screening tools to avoid analysis of disturbances which are not necessary, such as faults which do not force the power system to its stability margins;
- Inability to give information about the relative stability (whether the system is stable or unstable and how close the system is to its margin of stability);
- Inability of providing sensitivity analysis information;
- Inability to provide protective and controlling remedies in order to avoid instability;

It should be mentioned that by improving the hardware technologies and possibility of high performance computing techniques such as parallel computing, the time-domain method is becoming less onerous in terms of computing time.

2.2.3 Direct Methods

An alternate approach to evaluate transient stability of power systems is through direct methods. Direct methods use the concept of energy functions [18]. Energy functions are measures of the change in system “energy”. The energy is calculated for a power system under a disturbance at during-fault and post-fault conditions and defined as accelerating and decelerating energy, respectively. The stability of the system is determined by investigating the properties such as positive definiteness of this energy function [22].

Energy functions based direct methods were first proposed in [23], and the idea pursued in [24]. Although direct methods have over 60 years of history, practical application of these methods to power system transient stability evaluation is not extensively reported in literature. Most of the published papers consider the reduced-order model of the machines and networks to make the direct methods applicable to a multi-machine system. Also, in most cases, a lossless power system is considered as the case study [25–32].

By using direct methods, it is possible to evaluate transient stability performance without the need for solving the equations for the post-fault condition. As mentioned in the previous section, the time-domain solution of the post-fault condition of the power system is time-consuming. One of the advantage of direct methods to time-domain methods is that the time-domain solution of during-fault condition is used to find whether the post-fault system is stable or not. Hence, much less computational effort is needed for direct methods. Direct methods also have the advantage of revealing relative stability information of the power system. This property of direct methods is useful when a comparison between two planning strategies for the same power system is the goal of the study. Also, using relative stability information, the operator of the power system can have a good understanding about the state of the health of the system. Direct methods can also provide useful information for controlling and protective designs to prevent instability of a system or help the stabilization of a system which is critically stable [18]. A detailed review of direct methods and their application can be found in [18].

2.2.4 Automatic Learning Approaches

The automatic learning can be classified as modern or non-conventional transient stability evaluation approaches [16]. A framework for these methods is provided in [32]. Most of the automatic learning approaches assist in a faster and more efficient application of the time-domain or direct methods in the transient stability assessment. Artificial neural networks, statistical-based methods and decision making methods have been used in automatic learning approaches [32].

2.3 Types of Transient Stability Evaluation

Power system stability can be evaluated deterministically or probabilistically using the basic transient stability evaluation methods. As deterministic approach cannot fully reflect and recognize the true risks associated with a particular power system, probabilistic approach is gaining more and more attention.

2.3.1 Deterministic Assessment

The deterministic transient stability evaluation is considered to be the classical method for power system planning and operation. In such an evaluation, a deterministic transient stability criterion namely the ability of the power system to withstand the worst-case scenario is used. The worse-case scenario is usually considered a contingency in which a three phase fault occurs near a critical generator bus at the time of highest operational stress of the power system (full-load operating condition) [1]. Although the probabilistic methods are getting more popular in industry, the deterministic assessment is still the main stream method for power system transient stability analysis. In the next subsections, a brief literature review on the applications of the deterministic transient stability evaluation is presented.

2.3.1.1 Transient Stability of Transmission Systems and Bulk Power Systems

Transient stability of transmission systems and bulk power systems has many years of research background. The pioneering work on power system stability is date back to 1925 [33]. The authors of [33] has addressed transient stability as a topic that has an important bearing on the power system development in the future [33]. Interconnection of power systems spanning vast geographical areas increased the necessity of transient stability analysis. Stability and power limits of large power systems were studied in [34] with focus on simple power circuits and synchronous generators. A review of transient stability in transmission systems and bulk power system can be found in [16].

More recently, the effects of new components of power systems such as *Flexible Alternating Current Transmission Systems (FACTS)* devices [35–38], *High Voltage direct current (HVdc)* transmission lines to transient stability of the transmission systems have been also examined [39, 40].

Review of the literature in this area shows that deterministic evaluation method of transient stability of bulk power systems is well-developed and examined.

2.3.1.2 Transient Stability of Power Systems Incorporating Renewable Energy Resources and Distributed Generation

With the increase of non-dispatchable renewable energy resources such as large scale wind farms, power system transient stability assessment must also consider these new sources. Also, by increasing the penetration level of *DGs* in distribution networks, transmission systems will be affected by *DGs* and they should also be considered in transient stability analysis.

Power system transient stability with large amount of wind generation was addressed in literature [41–43]. The results show that, considering the increasing use of wind energy in power systems, wind farms should be considered in the transient stability studies. Assuming that all of the wind turbines of a wind farm are usually identical in structure and loading, it is possible to replace the wind farm with a single turbine representing the dynamics of the wind farm [41–43]. However, interactions between the generators in the wind farm is not represented in this approach. Effect of high penetration of *DGs* on power system transient stability was reported in [44–48]. The research results show that if there is a high penetration level of the intermittent power sources, the transmission systems transient stability will be affected [44–48]. In some of these studies, a sensitivity analysis was done to find the optimum penetration level of *DGs* considering the transient stability performance of power systems [44, 45, 47].

2.3.1.3 Transient Stability of Active Distribution Networks

In this subsection, a review of the studies of transient stability of active distribution networks are provided. Studies are categorized considering *DG* technologies, type of studies, type of networks and simulation tools.

Different types of *DG* technologies are surveyed in transient stability literature. *DGs* with Synchronous generators were considered in [49–52] and also as micro-turbines in [53–55]. Induction machines [49, 56], fuel cells [50, 53, 57] and doubly fed induction generators [51, 58] are other types of technologies that have been studied with emphasis on their effects on the power system transient stability performance. Some *DG* technologies such as fuel cells use inverters to provide AC power to the power networks. However, in some research, a general term of inverter-based *DGs* was used and the prime energy was not mentioned [52, 59]. So, the dynamics of the prime energy was not considered in the studies. Energy storage systems are also included in some transient stability studies. Among the energy storage systems, ultra capacitors and super capacitors are the types of energy storage technologies which were reported in literature of transient stability analysis [50, 51]. It can be concluded that most of the available technologies are considered in transient stability studies and researchers have evaluated their effect on the transient stability performance of the system.

Most of the studies of transient stability of micro-grids and active distribution networks in literature consider specific operating scenarios. Usually a predefined fault (duration, position and impedance) and predetermined position and penetration level of *DGs* were assumed in the studies (for example :[50, 53]). Due to the limited number of considered operating scenarios, realistic results for transient stability cannot be obtained from these studies.

However, some studies have performed sensitivity analysis for penetration level [47, 51] and effect of inverter-based *DGs* [52] and storage systems on transient stability of active distribution networks. In this way, more accurate and applicable results can be obtained.

All of the published research in transient stability studies of active distribution networks were done using time-domain method. Distribution networks were used as case study of the most of the published research in this area. Micro-grid case studies involved a distribution network connected via a transformer to an upstream sub-transmission network. With disconnection from the upstream network, islanded operation was considered [49, 54, 55, 57, 60]. An operational radial distribution network [60] and practical micro-grids [50, 52] were considered as case studies of transient stability evaluation.

Different time-domain simulation tools such as *PSCAD/EMTDC* [61], *MATLAB* [62], *PSS/E* [63] and *DIgSILENT* [64] were used for transient stability analysis in [59], [51], [65], and [52, 60], respectively. The aforementioned simulation tools show that both *EMT* and *phasor domain* approaches are utilized in transient stability studies.

2.3.2 Probabilistic Evaluation

The results of deterministic transient stability evaluation are conservative and may have significant cost implications in power system planning and operation. On the other hand, unlike the deterministic approach, the probabilistic evaluation technique does not consider only the worst-case scenario as the only operating scenario for transient stability evaluation. Therefore, the probabilistic approach which considers different types and locations of disturbances as well as different load and generation scenarios reveals a more realistic evaluation of transient stability performance of power systems. Furthermore, calculation of the risks of transient instability in deterministic evaluation is not possible. Whereas, the results of probabilistic method can be used to calculate the probability of the events that may cause the system's outage. Based on the aforementioned reasons and considering that in a power system many parameters such as loads, renewable energy based generation (especially in active distribution networks) and faults are random in nature, the probabilistic evaluation method should be used to assess the transient stability of power systems. Probabilistic methods have been applied to transient stability evaluation of power systems since late 70's [66, 67]. In this section the application of the probabilistic methods to transient stability of power systems is reviewed.

Reference [68] has provided an algorithm to show the feasibility of application of the Monte Carlo method to the transient stability analysis of power systems. Also, the possibility of measuring the probability of stability, which was not possible to enhance using deterministic methods, is introduced. A probabilistic evaluation of transient stability for a multi-machine system was presented in [69]. A computer program for performing stochastic transient stability analysis was introduced in [70]. In Reference [71], authors have focused on the modeling of protection systems for a stochastic transient stability analysis. Transient stability study of the Taiwanese power system was conducted using the conditional probability approach in [72]. The authors of [72] also mentioned in their research that the reported analysis helped them to find the weak points of the Taiwanese power system. A two-point estimate method was suggested for probabilistic transient stability assessment to find the maximum relative rotor angles' probability distribution functions [73]. In a point estimation method, the *Probability Density Functions (PDF)* of the random variables were replaced and redistributed by a finite number of points. Because of fast computing time of this method in comparison to the classical *Monte Carlo* method (only 2n replications needed for n random input values), the authors of [73] have proposed the application of this approach to on-line power system security assessment. However, the results of the proposed approach will not be accurate enough because of the drastic reduction of number of replications in the *Monte Carlo* simulation. A bisection method was presented in [74] as a tool for probabilistic transient stability assessment in order to reduce the required simulation time. In such a method, a time interval is assumed first to find the *CCT*. As the search for finding *CCT* goes on, the search time interval is divided by two and narrowed, until a good estimation for *CCT* is found. This method was shown to be useful in reduction of the number of simulations for assessing probabilistic transient stability of a power system [74].

When renewable energy based generation is available, the uncertainty of the power output of the generators should be considered. In other words, the random nature of wind speed or solar radiation will influence the available generation. Probabilistic transient stability studies have considered this type of uncertainty in some literature. Probabilistic evaluations of power system transient stability considering wind farms were presented in

[1, 75]. In Reference [1], authors have proposed a wind turbine model for the probabilistic assessment of transient stability considering other uncertainties associated with a power system. Fault type, location and clearing time were considered as probabilistic aspects of the power system to analyze the impacts of doubly fed and squirrel cage induction machine wind turbines on a power system [75].

An alternative method which is used for the probabilistic evaluation of transient stability considers the differential equations of a power system as stochastic differential equations. In such method, the coefficients of the differential equations which represent the dynamics of power systems are considered to change randomly. In [76], power system was modeled based on stochastic differential equations to consider the effect of uncertainties of power systems in the transient stability studies. Numerical integration methods were used to solve the stochastic differential equations.

The literature review shows that the application of the probabilistic method in transient stability evaluation of power systems has been examined by researchers. However, there is no reported research on application of this method to the transient stability of active distribution networks.

2.4 A Review of Applications of Parallel Computing in Power Systems

Parallel computing technique is increasingly used in power system studies and simulations to enhance the computational burden. The challenges and problems in parallel computing and basic computing tasks in power systems are reviewed in [77].

Application of *High Performance Computing (HPC)* to electrical power systems and related research has reported in literature since 1980s. The early research were concentrated on two main branches [77]:

- Parallel computing (Monte Carlo simulation and contingency analysis)
- Coupled problems (electromagnetic transient simulation)

Some of the results of these early research are provided in [78, 79]. Application of *HPC* to power system analysis needs use of multi-core processing and computer clusters. In this way, the computational task of the simulation is divided into sub-tasks and each subtask is assigned to a core of the computers in the cluster [77]. Recently, because of availability of these processors and software for controlling clusters of computers, interests in research on *HPC* in power system have increased [77]. Review of recent commercially available high performance technical computing applications are given in [80, 81].

Real-time or fast transient stability analysis of power systems will have impacts on future design and operations of power systems. Some of the aspects of power systems that will be affected are [82]:

- Analysis of restoration of the system
- Economic and environmental dispatch studies
- Planning for expansion of the system

High performance hardware and more computationally-efficient algorithms enable the transient stability results to be generated faster [82]. Reference [83] was investigated the use of *Differential-Algebraic Equations (DAE)* solvers which used in other areas of science and engineering research to be applied in power system transient stability problem. Using these solvers, parallel computation is proposed in [83] via Multi-computer Toolbox.

A unified approach of filtering, ranking and assessment of contingencies in a power system for transient stability analysis is proposed in [84]. This approach has two blocks; the first block is responsible for screening of the contingencies and the second one for ranking and assessing the interested contingencies. A distributed computing is used to decrease the time of simulation. The proposed method is tested on two different power systems having different topology, protection system and control scheme and the results are explained as desirable and reliable by the authors [84].

Parallel computing is also used for direct methods transient stability analysis. Reference [85] presents the implementation of *TEPCO-BCU* program [86] for large scale power systems transient stability evaluation. It is shown that this program is able to provide accurate results of stability and energy margin computation for every contingency of a large-scale power system [85]. A 12,000 bus power system is used as the case study.

A large-scale transient stability simulation is addressed in [87]. Researchers use a large parallel cluster of *Graphics Processing Units (GPU)* for this purpose. A fast linear solver of *Jacobian matrix* is used to increase the speed of calculations. Several large test systems were also used to evaluate this method (maximum number of buses and generators are 9,984, and 2,560, respectively) [87].

The literature review shows that the parallel computing methods have been applied to power system studies and it can be concluded that this method is well-established in the power system research area.

2.5 Well-Being Analysis of Power Systems

Over the years industry has used deterministic criteria such as the *CCT* to assess the transient stability performance of a power system. The reluctance for performing probabilistic transient stability could be partly due to the difficulties in interpreting and using probabilistic reliability indices. This complexity can be eliminated using the well-being approach by incorporating deterministic considerations into a probabilistic evaluation [15, 88–100]. Well-being analysis assigns a measure to the system operating condition that indicates its relative state of health. The basic framework associated with the well-being analysis of power systems is reasonably well established in the assessment domains of generating capacity adequacy, operating reserve, composite generation, transmission system, and *HVdc* systems [15, 88–100].

The basic concept for incorporating a deterministic consideration in a probabilistic assessment was first proposed to evaluate the operating reserve requirements in power systems [15]. The well-being technique was later extended to evaluate spinning reserve allocation and unit commitment in generation systems [88–91] and composite generation and transmission systems [92, 93]. A well-being framework for composite generation and transmission system reliability assessment was first proposed in [94]. The well-being technique was extended and applied to evaluate the reliability of sub-transmission and transmission systems in [95–97]. Incorporation of the deterministic considerations with probabilistic assessment in power system reliability evaluation considering *HVdc* links is proposed in [98, 99]. A number of papers on the development and utilization of the well-being approach for generating capacity reliability evaluation were mostly focused on the evaluation of the impact of wind energy on power system reliability [100–106]. A simulation technique was proposed to extend the conventional well-being analysis of generating systems to incorporate energy storage in [107].

Despite efforts that has been devoted to establishing the well-being framework for various areas in power system reliability assessment, there is no literature available on the utilization of well-being technique in transient stability evaluation. A new technique is, therefore, proposed in this thesis to extend the conventional well-being approach to power system transient stability analysis.

2.6 Conclusions

Based on the provided literature review in this chapter, the concluding points can be summerized as follows:

- In comparison to deterministic approach, the probabilistic evaluation of transient stability results in more realistic evaluation of transient stability performance of power systems. Hence, in this thesis probabilistic transient stability assessment method is proposed and used in transient stability analysis of active distribution networks.
- In order to get a more realistic evaluation of transient stability performance, uncertainties associated with power systems should be considered in the assessment of transient stability of power systems. Fault type, location, impedance, clearing time and duration are random in nature and need to be recognized and reflected in the transient stability assessment of a power system. Further, random characteristics of system loads and renewable energy based generation should also be considered in transient stability performance analysis of power systems.
- The use of small-scale renewable energy based generation is common in active distribution networks. This will result in introducing more uncertainties to the power

generation. So, like bulk power system, the probabilistic aspects of active distribution systems should also be considered in transient stability studies.

- Although the basic probabilistic approach for transient stability has been reported earlier, the ADNs are intrinsically different from traditional bulk power systems as they contain very different components such as solar panels, small scale generators, etc. Suitable models have to be developed for these elements in the formulation.
- Also, Based on the literature review on well-being analysis provided in Section 2.5, there is no reported research on using transient stability in the determination of the wellness of a power system. In this thesis, a new well-being analysis framework will be proposed. The proposed framework uses damping ratio as a deterministic criteria to categorize the results of probabilistic evaluation of transient stability in different well-being states (at-risk, marginal, healthy). The result of the well-being analysis will provide valuable insight of the transient stability performance of the ADN.

Chapter 3

Transient Stability of Synchronous and Induction Machines

3.1 Introduction

Synchronous generators are used in power generation stations all over the world to convert the kinetic energy to electric power. The transient stability of power systems is directly related to these machines. If most of the synchronous machines which are connected to the power system can remain synchronized and connected to the power system when a disturbance occurs, the power system will remain stable. On the other hand by introducing wind energy systems as sources of electric energy to the power system, analysis of the stability of induction machines also became necessary.

In this chapter, the equations which are necessary to model synchronous machines are provided and dynamic response of a synchronous machine to a disturbance is simulated. Also, using an anlytical method, the stability of an induction generator is discussed. The results of the analytical method is confirmed using an EMT simulation.

3.2 Transient Stability of Synchronous Generators

The *synchronous generator (SG)* can be used as a *DG* in active distribution networks. Different levels of detail are possible in the *EMT* modeling of a *SG*. *IEEE Standard 1110-2002* [108] describes different models of synchronous generators for power systems stability analysis.

Most of the *SG* models are provided in *dq0* reference frame. "*Model x.y*" notation is used in Reference [108] to identify different models of *SG*. 'x' is a number from 0 to 3 that shows the total number of field circuit and damper circuits in the d-axis, and 'y' is also a number between 0 and 3 that shows the number of damper circuits in the q-axis. For example, *Model 1.0* considers only field circuit in the d-axis and no dampers in the q-axis, whereas *Model 2.1* considers field circuit and one damper circuit in the d-axis and one damper circuit in the q-axis.

3.2.1 *dq0* Transformation

Describing a synchronous machine in *abc* reference frame (stator reference frame) results in having equations which vary with mechanical angle of the rotor (θ). Representing the machine equation in the stator reference frame equations increases the complexity of power system stability problem [4]. Transformation of the machine equations into *dq0* reference frame which is rotating with rotor will eliminate θ from machine equations [4].

Transformation of machine variables from *abc* phase variables to *dq0* can be shown in the following matrix form [4]:

$$\begin{bmatrix} x_d(t) \\ x_q(t) \\ x_0(t) \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin(\theta) & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \times \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \tag{3.1}$$

The inverse transformation can also be written as [4]:

$$\begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) & 1 \end{bmatrix} \times \begin{bmatrix} x_d(t) \\ x_q(t) \\ x_0(t) \end{bmatrix} \tag{3.2}$$

where, $x_{abc}(t)$ can be any phase variable in *abc* reference frame and $x_{dq0}(t)$ is the representation of it in *dq0* reference frame.

3.2.2 Dynamic Models of a *SG*

In this section, different dynamic models of a *SG* for transient stability analysis are provided. These models can be used in *EMT* simulation tools.

3.2.2.1 *Model 0.0*

This model only considers mechanical swing equations to explain the dynamics of a synchronous machine. Two differential equations which are used in this model are as follows [4, 108]:

$$\begin{aligned} p\Delta\omega_r &= \tfrac{1}{2H}\left(T_m - T_e - K_D\Delta\omega_r\right) \\ p\delta &= \omega_0\Delta\omega_r \end{aligned} \tag{3.3}$$

In Equation 3.3, $\Delta\omega_r$ is the per unit speed deviation, δ is the rotor angle (electrical radians), ω_0 is the synchronous speed (rad/sec) and p is the differential operator (d/dt). T_m and T_e are mechanical and electrical torques in per unit, respectively, K_D is the damping factor coefficient (per unit torque/per unit speed deviation) and, H is the inertia of machine (sec) [4, 108].

3.2.2.2 *Model 1.0*

Model 1.0 considers the effect of field circuit flux variations. This model adds a field circuit equation to *Model 0.0*. Equation 3.4 describes this model [4, 108].

$$\begin{aligned} p\Delta\omega_r &= \tfrac{1}{2H}\left(T_m - T_e - K_D\Delta\omega_r\right) \\ p\delta &= \omega_0\Delta\omega_r \\ p\psi_{fd} &= \omega_0\left(e_{fd} - R_{fd}i_{fd}\right) \end{aligned} \tag{3.4}$$

In Equation 3.4, e_{fd} , R_{fd} and i_{fd} are the per unit field circuit voltage, resistance and current, respectively [4, 108].

3.2.2.3 *Model 1.1*

Model 1.1 considers the effect of one damper circuit in the q-axis. This model adds one damper circuit equation in the q-axis to *Model 1.0*. Equation 3.5 describes this model [4, 108].

$$\begin{aligned} p\Delta\omega_r &= \tfrac{1}{2H}\left(T_m - T_e - K_D\Delta\omega_r\right) \\ p\delta &= \omega_0\Delta\omega_r \\ p\psi_{fd} &= \omega_0\left[e_{fd} - \tfrac{R_{fd}}{L_{fd}}\psi_{fd} + \tfrac{R_{fd}}{L_{fd}}L''_{ad}\left(-i_d + \tfrac{\psi_{fd}}{L_{fd}}\right)\right] \\ p\psi_{1q} &= \omega_0\left[-\tfrac{R_{1q}}{L_{1q}}\psi_{1q} + \tfrac{R_{1q}}{L_{1q}}L''_{aq}\left(-i_q + \tfrac{\psi_{1q}}{L_{1q}}\right)\right] \end{aligned} \tag{3.5}$$

In Equation 3.5, ψ_{1q}, R_{1q} and L_{1q} are the first q-axis damper flux, resistance and inductance in per unit, respectively. L''_{aq} and L''_{ad} are per unit sub-transient mutual inductances of the q-axis and the d-axis, respectively [4, 108].

3.2.2.4 *Model 2.1*

Model 2.1 considers two damper windings, one in the d-axis and one in the q-axis. This model adds the first damper circuit equation in the d-axis to *Model 1.1*. Equation 3.6 describes this model [4, 108].

$$\begin{aligned}
p\Delta\omega_r &= \tfrac{1}{2H}\left(T_m - T_e - K_D\Delta\omega_r\right)\\
p\delta &= \omega_0\Delta\omega_r\\
p\psi_{fd} &= \omega_0\left[e_{fd} - \tfrac{R_{fd}}{L_{fd}}\psi_{fd} + \tfrac{R_{fd}}{L_{fd}}L''_{ad}\left(-i_d + \tfrac{\psi_{fd}}{L_{fd}} + \tfrac{\psi_{1d}}{L_{1d}}\right)\right]\\
p\psi_{1d} &= \omega_0\left[-\tfrac{R_{1d}}{L_{1d}}\psi_{1d} + \tfrac{R_{1d}}{L_{1d}}L''_{ad}\left(-i_d + \tfrac{\psi_{fd}}{L_{fd}} + \tfrac{\psi_{1d}}{L_{1d}}\right)\right]\\
p\psi_{1q} &= \omega_0\left[-\tfrac{R_{1q}}{L_{1q}}\psi_{1q} + \tfrac{R_{1q}}{L_{1q}}L''_{aq}\left(-i_q + \tfrac{\psi_{1q}}{L_{1q}}\right)\right]
\end{aligned} \tag{3.6}$$

In Equation 3.6, ψ_{1d}, R_{1d} and L_{1d} are the first d-axis damper flux, resistance and inductance in per unit, respectively [4, 108].

3.2.2.5 *Model 2.2*

Model 2.2 considers the effect of the second damper circuit in the q-axis and one damper in the d-axis. Equation 3.7 describes this model [4, 108].

$$\begin{aligned}
p\Delta\omega_r &= \tfrac{1}{2H}\left(T_m - T_e - K_D\Delta\omega_r\right)\\
p\delta &= \omega_0\Delta\omega_r\\
p\psi_{fd} &= \omega_0\left[e_{fd} - \tfrac{R_{fd}}{L_{fd}}\psi_{fd} + \tfrac{R_{fd}}{L_{fd}}L''_{ad}\left(-i_d + \tfrac{\psi_{fd}}{L_{fd}} + \tfrac{\psi_{1d}}{L_{1d}}\right)\right]\\
p\psi_{1d} &= \omega_0\left[-\tfrac{R_{1d}}{L_{1d}}\psi_{1d} + \tfrac{R_{1d}}{L_{1d}}L''_{ad}\left(-i_d + \tfrac{\psi_{fd}}{L_{fd}} + \tfrac{\psi_{1d}}{L_{1d}}\right)\right]\\
p\psi_{1q} &= \omega_0\left[-\tfrac{R_{1q}}{L_{1q}}\psi_{1q} + \tfrac{R_{1q}}{L_{1q}}L''_{aq}\left(-i_q + \tfrac{\psi_{1q}}{L_{1q}} + \tfrac{\psi_{2q}}{L_{2q}}\right)\right]\\
p\psi_{2q} &= \omega_0\left[-\tfrac{R_{2q}}{L_{2q}}\psi_{2q} + \tfrac{R_{2q}}{L_{2q}}L''_{aq}\left(-i_q + \tfrac{\psi_{1q}}{L_{1q}} + \tfrac{\psi_{2q}}{L_{2q}}\right)\right]
\end{aligned} \tag{3.7}$$

In Equation 3.7, ψ_{2q}, R_{2q} and L_{2q} are the second q-axis damper flux, resistance and inductance in per unit, respectively [4].

Higher order models , e.g. *Model 2.3* or *3.3* provide marginally more accuracy but are not required in stability analysis [109]. Also, required data for modeling such higher order models is not generally available.

3.2.3 *EMT* Response of *SG* Connected to an Infinite Bus

Figure 3.1 shows the *SMIB* test system. The parameters of the *SG* and the data of the network are given in Table 3.1 [4].

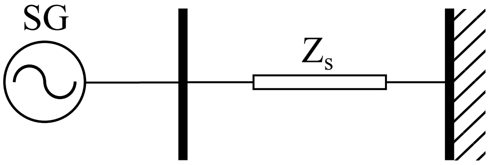


FIGURE 3.1: Diagram of *SMIB* system

TABLE 3.1: Parameters of the *SMIB* system

variable	value	variable	value
L_d	1.81 $(p.u.)$	L_q	1.76 $(p.u.)$
L_l	0.15 $(p.u.)$	R_a	0.003 $(p.u.)$
$L_d^{'}$	0.3 $(p.u.)$	$L_q^{'}$	0.65 $(p.u.)$
$L_d^{''}$	0.23 $(p.u.)$	$L_q^{''}$	0.255 $(p.u.)$
$T_{d0}^{'}$	8.0 $(sec.)$	$T_{q0}^{'}$	1.0 $(sec.)$
$T_{d0}^{''}$	0.03 $(sec.)$	$T_{q0}^{''}$	0.07 $(sec.)$
Z_s	$j0.475175$ $(p.u.)$	E_B	$0.90081\angle 0$
S_{base}	555 MVA	$V_{LL_{base}}$	24 KV

In order to see the dynamic response of the *SG* to a disturbance, it is assumed that Z_s is changed from its original value as in Table 3.1 to $j0.65$ at $t = 1$ (s). The evolution of the rotor angle (δ) for five different models of synchronous generator are shown in Figure 3.2.

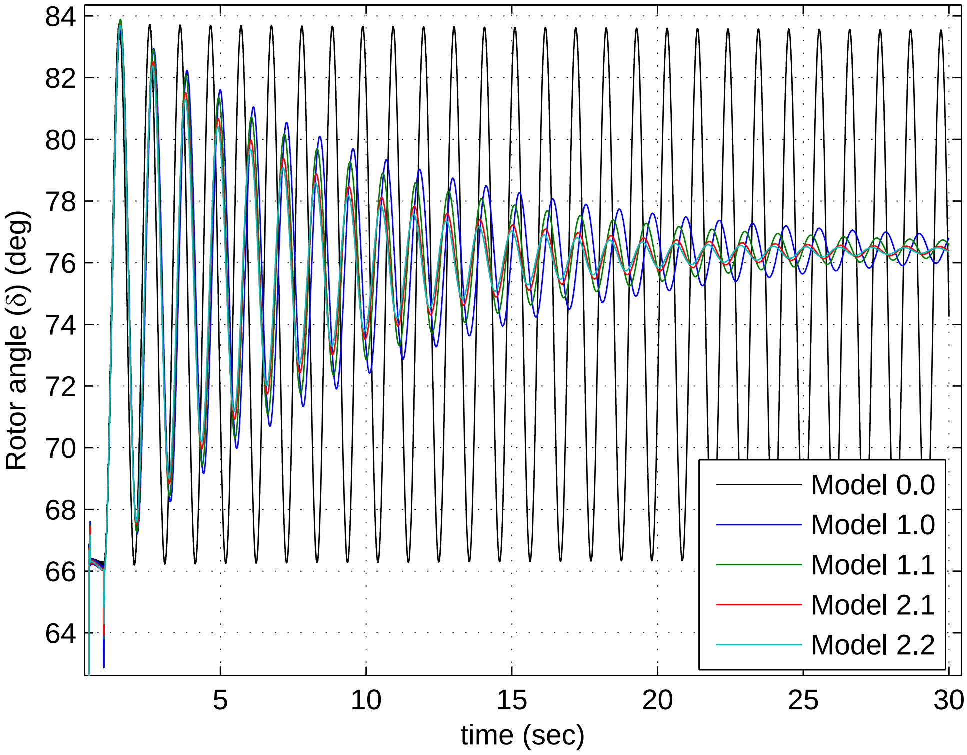


FIGURE 3.2: Rotor angle evolution for five different *SG* models

As can be seen from Figure 3.2, the models show different dynamic responses. The effect of details in modeling synchronous generators on the transient stability results will be discussed in Chapter 4.

3.3 Transient Stability of Induction Generators

Induction generators (IG) are widely used in wind turbines. For the small-scale wind turbines, it is the best option considering its low price and robustness. Due to the possibility of using IG as DG, its transient stability performance and impacts on transient stability of active distribution networks should be considered. It should be mentioned that transient stability of wind farms incorporating induction generators has been the topic of many published research [1, 110–112].

Usually, transient stability is defined for synchronous generators. The rotor angle dynamics of the SG is studied to investigate the synchronism of the generator with the system. In case of the IG, a critical slip is proposed in [113, 114] to be used as a transient stability index. Using the critical slip, the value of CCT for IG can be calculated and the transient stability performance of the IG can be studied. The CCT in this case is the time at which the slip attains its critical value [115, 116] as described in the following subsection. Reference [117] uses critical speed rather than critical slip as an equivalent criterion.

3.3.1 Analytical Treatment of Transient Stability of an Induction Generator

In this subsection, using the method presented in [115], the idea of critical speed and critical clearing time of an induction generator facing a fault is analyzed analytically. The concept of critical speed is explained using the electrical torque (T_E) versus rotor speed graph.

The case study is consisted of an IG connected to a substation. The parameters of the IG and substation are given in Tables 3.2 and 3.3.

Table 3.2: Parameters of the *IG*

variable	value	variable	value	variable	value
S_n	$10\ MVA$	V_{LL_n}	$2.4\ kV$	R_S	$0.01\ p.u.$
X_S	$0.1\ p.u.$	R_R	$0.014\ p.u.$	X_R	$0.098\ p.u.$
X_M	$3.5\ p.u.$	H	$1.5\ sec$	T_m	$-1.0\ p.u$

Table 3.3: Parameters of the substation

variable	value	variable	value
Z_s	$j0.475175\ p.u.$	V_S	$0.975\angle 0\ p.u.$
short circuit level	$1500\ MVA$	X/R *ratio*	10.0

The electrical torque versus speed plot of the *IG* is shown in Figure 3.3. The operating point of the *IG* is the junction of electrical and mechanical torque (T_M) curves. As can be seen from Figure 3.3, two operating points can be found for IG; *Point A*, and *point B*. *Point A* is the initial operating point of the machine whereas, *Point B* is an unstable operating point. To prove that *Point B* is an unstable operating point, the equation of motion of the *IG* (Equation (3.8)) should be studied.

$$\frac{d\omega_r}{dt} = \frac{1}{2H}(T_E - T_M) \tag{3.8}$$

According to Equation (3.8), if the operating point changes from A to a point with higher speed on the T_E curve, $d\omega_r/dt$ will be positive but $(T_E - T_M)$ is negative and makes the machine to decrease its speed and retain the stable operating point (*Point A*). But at *Point B*, if the operating point changes to a point with higher speed on the T_E curve, $d\omega_r/dt$ will be positive and $(T_E - T_M)$ is also positive, hence, there is no damping force to regain the stable operating point and *IG* will be unstable.

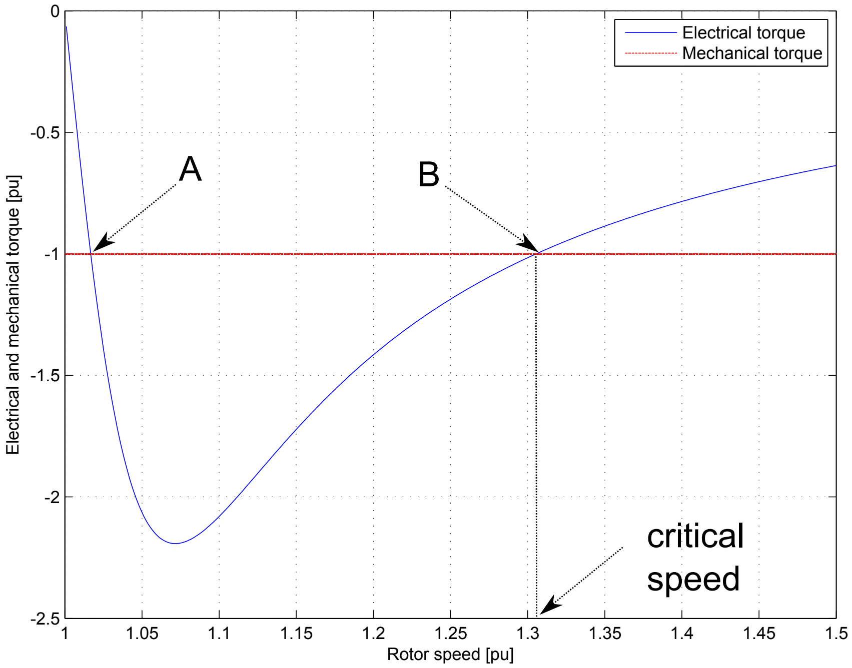


FIGURE 3.3: The electrical torque versus speed characteristic of the *IG*

To clarify this phenomenon, consider two faults with the same position and impedance but with different clearing times. The first fault (Figure 3.4) is removed before *IG* reaches to the critical speed (at C), but the second fault (Figure 3.5) is removed after machine exceeds the critical speed.

At stable equilibrium point (*Point A*), the input mechanical torque is $T_M = -1.0\ p.u.$ and so is the output electrical torque ($T_E = -1.0\ p.u.$). On fault application, T_E goes to zero (*Point B*) and the machine speed increases as input torque exceeds the output torque. On clearing, the regular characteristic becomes valid and operating point shifts to C. This creates an output torque magnitude larger than the input torque and decelerates the machine back to operating *Point A* (Figure 3.4). However, if fault is cleared too late so that the speed corresponds to that in Figure 3.5, the machine will experience accelerating torque and will not return to the initial operating point.

The trajectory of the operating points of the IG from its initial stable operating point towards the clearance of the fault is shown in Figures 3.4 and 3.5.

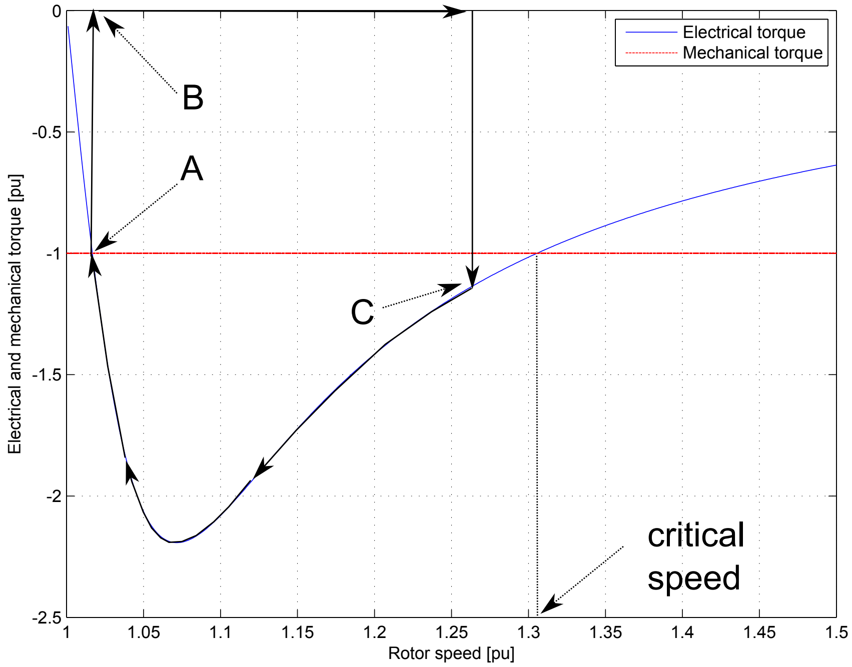


FIGURE 3.4: Trajectory of operating points of IG for stable case

As explained in [115], by calculation of T_E and solving $T_E = T_M$, the critical speed and critical clearing time can be calculated. The critical time has been derived as:

$$CCT = (\frac{-2H}{T_M}\frac{1}{R_{TH}^2 + (X_{TH} + X_R)^2})\sqrt{\frac{R_R^2}{T_M^2}(-4(X_{TH} + X_R)^2 T_M^2 - 4R_{TH}V_{TH}^2 T_M + V_{TH}^4)} \tag{3.9}$$

The derivation details of Equation 3.9 are given in Appendix B. The treatment as well as the results of studies of this chapter is also published in:

M. Amiri, T. Y. Vega and A. M. Gole, "Effect of DG modeling and controllers on the transient stability of micro-grids in EMT simulation," PowerTech, 2015 IEEE Eindhoven, Eindhoven, 2015, pp. 1-6.

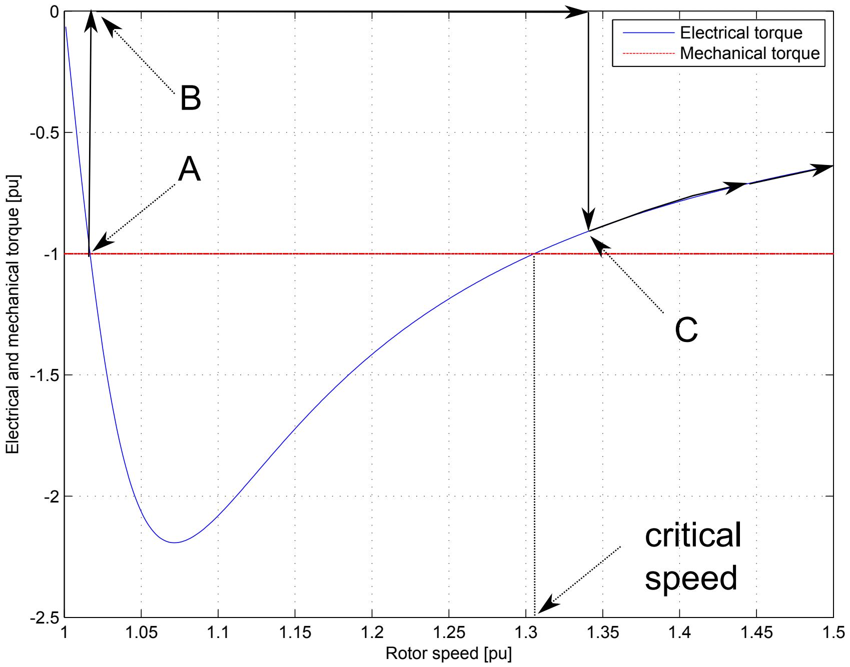


FIGURE 3.5: Trajectory of operating points of *IG* for unstable case

In order to check the accuracy of the results, the data of the *IG* which is used in [115] is exploited. The parameters of the *IG* are given in Table 3.2. Also, the data of the substation which *IG* is connected to is given in Table 3.3 [115].

Using the information provided in the tables, the steady-state speed, critical speed and critical clearing time are calculated as 1.0077 pu, 1.2909 pu and 880 msec, respectively. The results are the same as [115].

3.3.2 Confirmation of the Analytical Approach Results with *EMT* Simulation

The transient equivalent circuit of an induction machine is shown in Figure 3.6 [118].

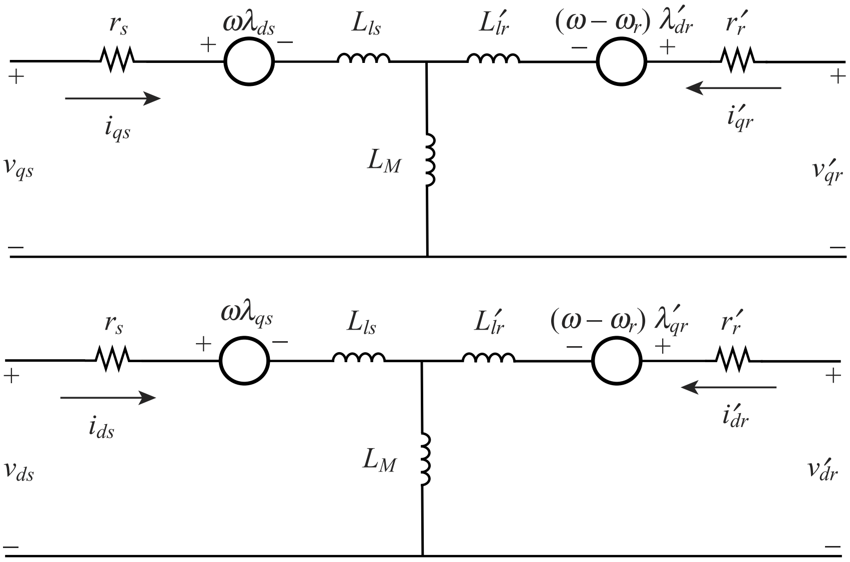


FIGURE 3.6: Transient equivalent circuit of an induction machine

In order to study the transient response of an *IG*, *EMT* model of an *IG* connected to a substation is developed (the same system of Tables 3.2, 3.3).

Figure 3.7 shows the evolution of the rotor speed of the *IG* if a solid LLLG fault occurs at the generator bus. As can be seen from Figure 3.7, the critical clearing time and critical speed match the values calculated using analytical method in previous section. In other words, for a fault with a clearing time of 0.880 (*sec*), the *IG* is stable whereas a fault with a clearing time of 0.890 (*sec*) (which is more than *CCT*), destabilizes the *IG*.

3.4 Summary and Conclusions

In this chapter, the transient stability of synchronous and induction machines as two main source of electric power were discussed. The equations for different models of a SG were provided. The results show that these models will provide different dynamic responses to

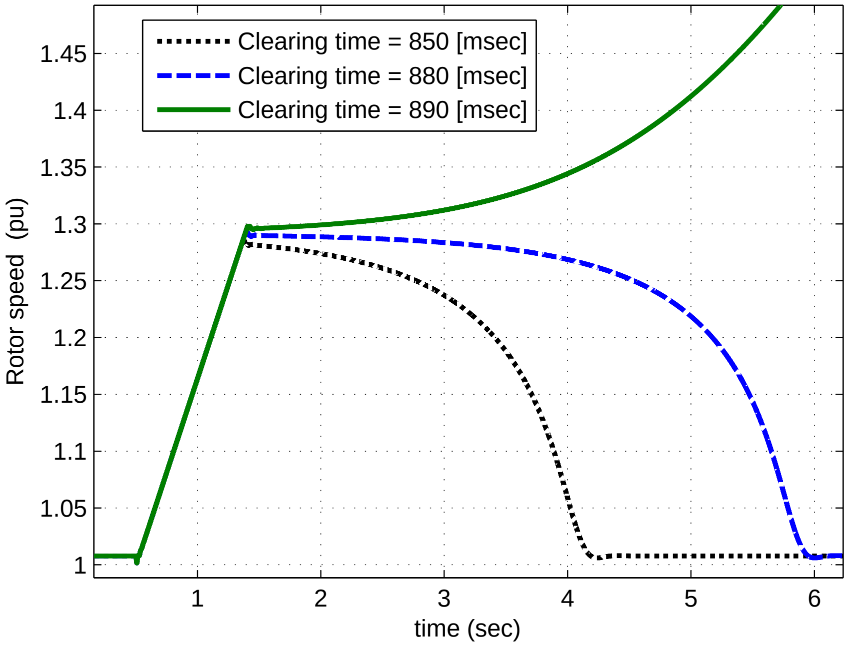


FIGURE 3.7: Rotor speed evolution of the *IG* for different fault clearing times

a disturbance. In Chapter 4, the effect of synchronous machines modeling details on the transient stability results will be discussed.

Also, using an analytical method,the stability of the induction machines are studied and the results were confirmed by comparing to the EMT simulation results. In chapter 4, the effect of controllers on the transient stability performance of induction machines is studied using a simple controller.

Chapter 4

Effect of Modeling Details on Transient Stability Results

4.1 Introduction

The aim of this chapter is to show that the results of transient stability evaluation is influenced by the degree of modeling detail of power system components. Using some examples in modeling generators and performing sensitivity analysis, the effect of modeling detail and controller actions on the accuracy of the results of transient stability are examined.

The feasibility of using linearized models of power system components in transient stability studies is also investigated. The possibility of using stability measures such as gain and phase margin as transient stability index are also examined.

The objective of these examinations and studies is to select appropriate models and tools for performing probabilistic transient stability assessment of active distribution networks.

4.2 Simulation Tools for Transient Stability Evaluation

Selection of a proper simulation tool for transient stability evaluation is important. The accuracy of the results provided by simulation tool will directly influence the accuracy of the transient stability assessment results.

In case of active distribution networks, simulation tools should be capable of modeling conventional distribution systems and new technologies such as energy storage systems and converter-based *DGs* [119]. Different tools for analysis and design of distributed resources were reviewed in literature from the point of view of feasibility studies [120], planning and design [119], market studies [121], and future trends [122]. Distribution networks simulation tools are mainly designed to perform passive network analyses such as load flow, capacitor placement, load balancing, switching optimization, etc. In case of active distribution networks and, dynamic analyses such as transient stability analysis should be performed and the simulation tools must be capable of performing these studies. Considering this fact, the simulation tools which mostly used for transmission systems dynamic analyses, can also be used for active distribution networks studies.

Using *EMT* simulators which exploit time-domain solution techniques is an option which can perform most of the distribution systems analyses, especially system dynamic performance analyses. In this case, one simulation model can be used for dynamic analysis as well as steady state analysis and the researchers do not need to model the system multiple times to be able to perform simulations in each of different simulation tools. The drawback of this approach is that using a highly detailed *EMT* model for steady state studies will need more time to get the results in comparison to using the load flow model for finding the same results. However, advanced computers along with new fast computational techniques can be used to overcome this extra computational burden.

PSCAD/EMTDC [123] is a well-known *EMT* simulator which has been selected to be used in this thesis. The reasons for selection of *PSCAD/EMTDC* are summarized as follows:

- *PSCAD/EMTDC* has a large number of pre-developed models of power system components.
- There is no intrinsic limit for the maximum number of electrical nodes in simulation cases.
- Modeling of the new components is possible via user-defined programming code and components.
- *PSCAD/EMTDC* can be used over a large frequency-spectrum.
- The *Graphical User Interface (GUI)* of *PSCAD/EMTDC* is easy to use.

- *Multi-Run* component of *PSCAD/EMTDC* gives the ability to the user to generate sets of data points for performing various analyses such as simulation using probabilistic method
- It allows interface with third party products, e.g. *Python*, can be used to manipulate the files generated by *PSCAD* and control the launching process of *EMTDC*. This flexibility is exploited extensively in this thesis.

Again, the details in modeling of power system components in *EMT* simulation have a great influence on the results of transient stability studies. The effect of different models of *DGs* and their controllers on the transient stability analysis results is investigated in the following sections.

4.3 Transient Stability of *SG* Connected to an Infinite Bus

In this section, the effect of modeling details of *SGs*, as a representative of power system components, on transient stability results is studied. In order to show this, the transient stability of the *SMIB* system with five different models of *SG* is analyzed. Using the *Multi-Run* module of *PSCAD/EMTDC*, a sensitivity analysis is performed to enhance the stability/instability of the *SG* (Figure 4.1). The data of the *SMIB* system is provided in Table 3.1.

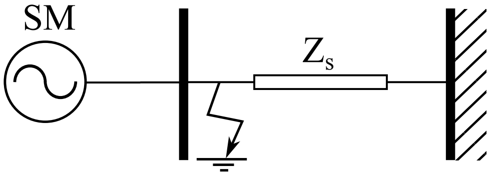


FIGURE 4.1: *SMIB* system used in the sensitivity analysis

In this sensitivity analysis, the values of resistance and duration of a three phase to ground (LLLG) fault are changed from 0 to 1 (Ω) and 0 to 1 (s), respectively (in steps of 0.05 for both). This selection of parameters will form 411 (21×21) *EMT* simulations. Figure 4.2 shows the results of the sensitivity analysis.

As can be seen from Figure 4.2, the number of stable and unstable cases are different for each *SG* model. Table 4.1 shows the summary of this analysis. It can be seen from Table 4.1 that the selection of the modeling detail has a significant effect on the results of transient stability simulations. For example, for the same analysis, the number of stable cases for *Model 2.2* and *0.0* are 328 and 309, respectively. In order to have a more accurate result, sufficiently detailed models of *SG* may be selected. This type of analysis allows transient stability to be viewed as a probability by taking ratio of stable cases to total cases. The table shows that there is negligible difference in the probability for all of the models, showing that in this special case, all of the models are equally good and we could use just the simplest model. However, for other simulation cases, the conclusion might be different and more detailed models should be selected to achieve sufficiently accurate results. Also, finding the parameters representing the highly detailed models of a *SG* (and other power system components) is not always easy.

There is also something peculiar about the graphs in Figure 4.2. Consider for example

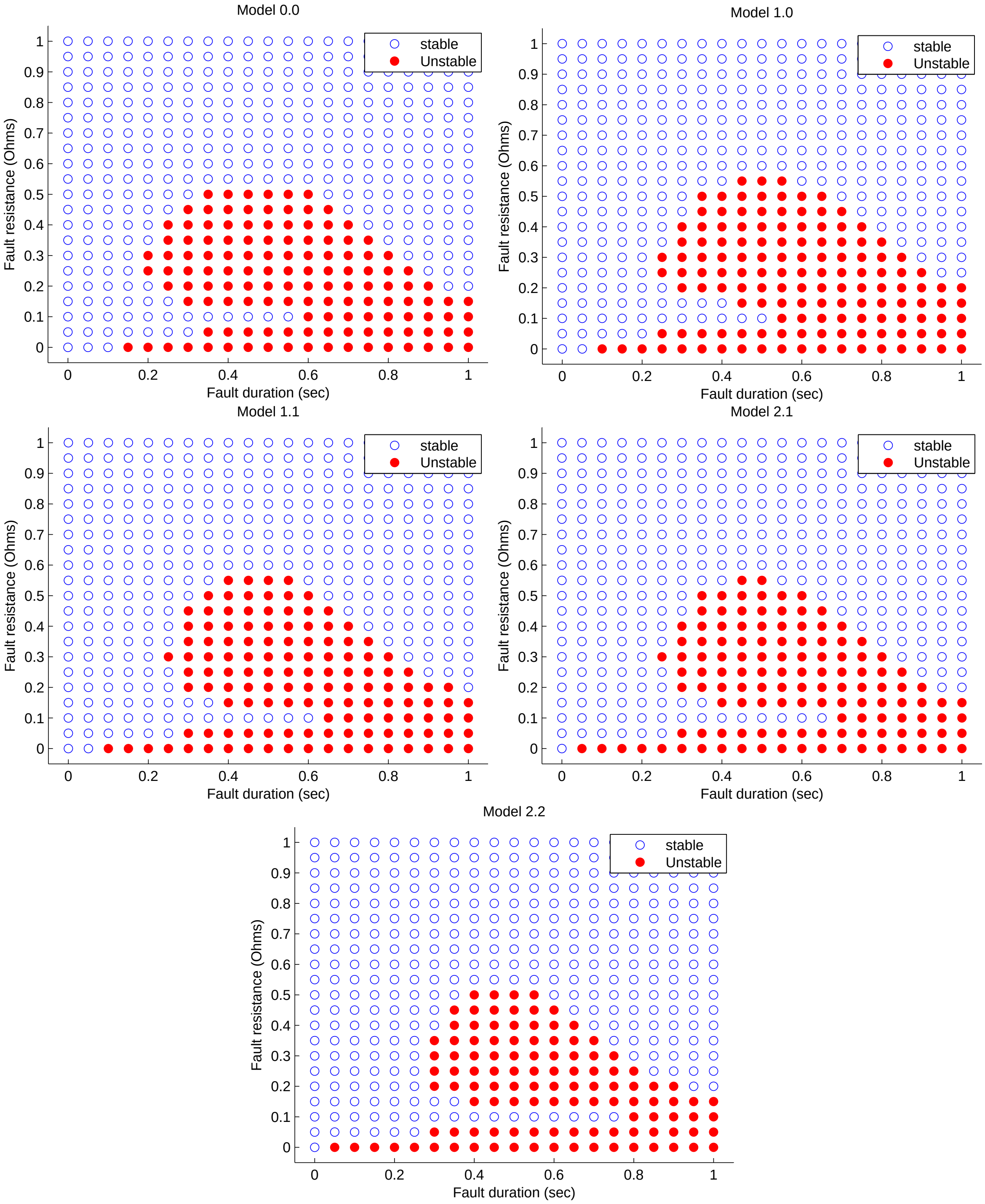


FIGURE 4.2: Sensitivity analysis for effect of modeling detail on transient stability of a *SG*

TABLE 4.1: Stable and unstable cases for different *SG* models

model	stable cases	unstable cases	probability
2.2	328	113	0.2749
2.1	315	126	0.3066
1.1	311	130	0.3163
1.0	303	138	0.3358
0.0	309	132	0.3212

the graph for *Model 2.2*. For a fault duration of 0.3 s, and a fault resistance of 0.3 Ω, the system becomes unstable. However, for the same fault resistance and a larger fault duration e.g. 0.8 s, it is stable. This is contrary to the concept of a single *CCT* traditionally given when analyzing transient stability of a single generator. The reason for this anomalous behaviour was investigated further in Chapter 5 and also published in:

M. Amiri, T. Y. Vega and A. M. Gole, "Anomalous Stability Behavior of Synchronous Machine With High Impedance Faults," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 4157-4158, Sept. 2016.

4.4 Stability Analysis Using Linearized Models

Linearized models of synchronous machines are widely used in small-signal analysis. Their attractiveness is that for finding the dynamic performance of the system, the time-domain simulation is not required. In other words, the parametric behavior of the system can be derived analytically. Therefore, the feasibility of assessing transient stability using linearized models is investigated in this thesis.

Later during the research, it was understood that the linearized models are not so useful for transient stability assessment of power systems. The main reason was that these models are highly dependent on the operating point which is used for the linearization. The selected operating point might not be accurate enough for later power system conditions. Also, that the linearized models do not consider large signal behavior of the power systems which is a key factor for determining probabilistic transient stability. More discussions and results on these studies are given Appendix A.

4.5 Influence of the Controller on the Stability of *IG*

In order to study the effect of controllers on the stability of IG, a wound rotor IG is considered in this section. The data of the IG is provided in Table 4.2. A simple proportional controller is used to elaborate the effect of controllers on transient stability results. The controller changes the resistance of the rotor of the IG when the speed of the machine changes.

TABLE 4.2: Input data for the IG

variable	value	variable	value
R_s	0.043 $(p.u.)$	X_s	0.06 $(p.u.)$
R_r	0.04 $(p.u.)$	X_r	0.06 $(p.u.)$
S_{base}	0.5 (MVA)	$V_{LL_{base}}$	0.48 (KV)
H	1 $(sec.)$	Mech. damping	0.01 $(p.u.)$

As can be seen from Figure 4.3, by increasing the rotor resistance, the torque-speed characteristic of the IG will change. Figure 4.3 also shows that by increasing the resistance of the rotor circuit for the same mechanical torque input the critical speed of the machine will increase.

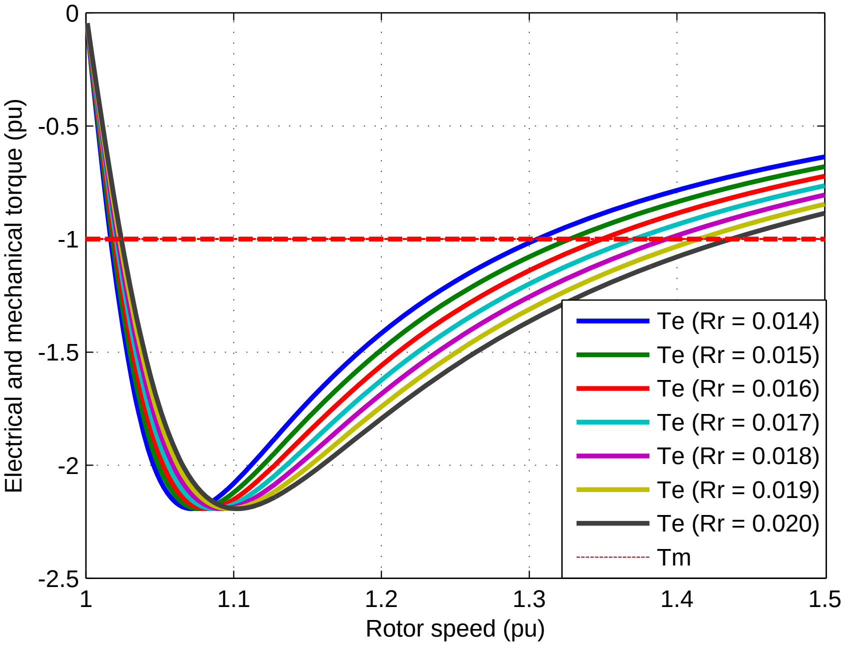


FIGURE 4.3: Effect of rotor resistance on the torque-speed characteristic of the *IG*

A simple proportional controller is added to increase/decrease the resistance of the rotor when the speed increases/decreases. The characteristics of the controller is shown in Figure 4.4. Figure 4.5 shows the change in rotor speed of the *IG* with time. As can be seen from Figure 4.5, using the proposed controller improves the stability performance of the *IG*. In other words, for a fault with a clearing time of 0.890 (*sec*), the *IG* without controller is unstable but the *IG* with proposed controller is stable.

The *CCT* of the *IG* without controller is shown in Figure 3.7 to be 880 (msec), while the same analysis shows that the *CCT* of the *IG* with the proposed controller is 1280 (msec).

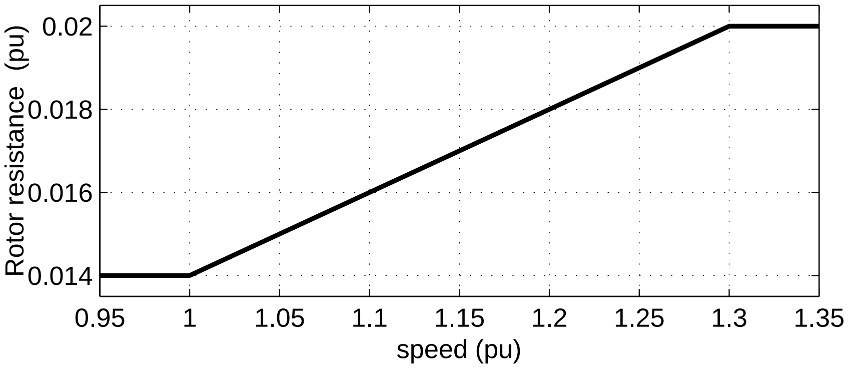


FIGURE 4.4: Rotor resistance versus speed characteristics of the controller

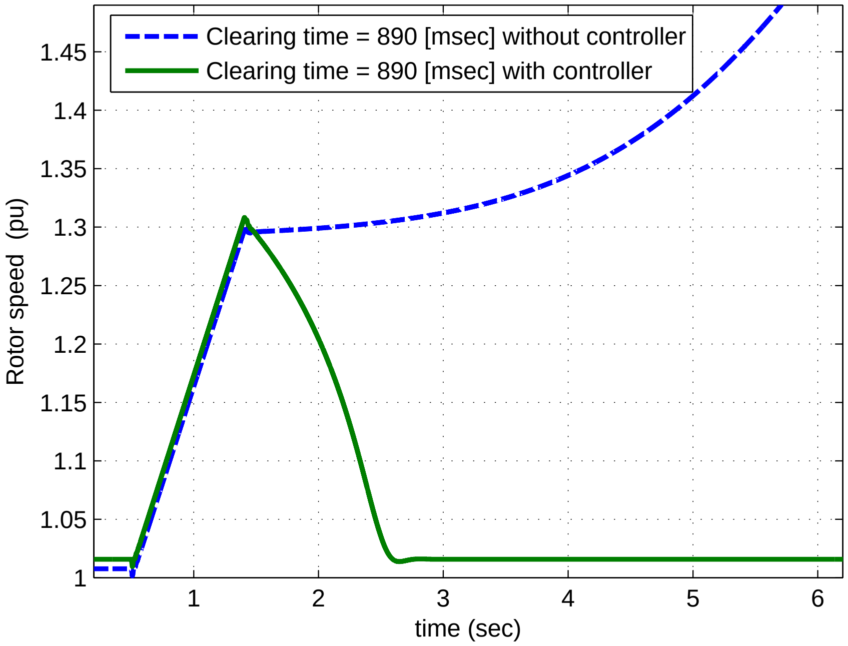


FIGURE 4.5: Rotor speed evolution of the *IG* with and without the controller

It should be noted that performing the analytical approach for a fixed rotor resistance is straightforward. However, with rotor resistance changes, the approach becomes difficult and so it is easier to use *EMT* simulation in order to find the *CCT*.

4.6 Summary and Conclusions

In this chapter, a sensitivity analysis is performed to study the effect of modeling details on the transient stability performance of a *SMIB* test system. The synchronous machine of the test system was modeled using 5 different detailed models and the results of the sensitivity analysis showed a noticeable difference in the stability performance. Also, the stability performance of an induction generator was studied with and without control actions.

The results and discussions of this chapter reveal that the evaluation of transient stability is directly influenced by the detail of components modeling in *EMT* simulation. *EMT* models are the most accurate simulation models of power systems but at the same time it requires the most complex component representation. Transient stability assessment of power systems using these models needs more computational effort. Depending on the accuracy of the results, the necessary detail of modeling should be considered.

It is also observed that controller actions which are common in power systems for generators and other components have significant influence on the transient stability results.

Chapter 5

Anomalous Stability Behavior of Synchronous Machine

5.1 Introduction

As mentioned in Section 4.3, an anomalous behavior of transient stability of synchronous generators is observed during the course of this research. In this chapter, the clarifications on this phenomenon is provided.

The detailed analysis of the anomalous stability behavior was not the main thrust of the thesis. However, as it was observed during simulations of the test system, it needed explanation. The conclusions were unexpected and interesting, and became a subject of a paper in the IEEE Transactions on Power Systems [124]. They are also considered one of the contributions of this research.

It is generally believed that following a fault, the system remains stable as long as the fault is cleared within a *"Critical Clearing Time"* or *CCT*. However, the study results of this chapter shows that when there is a high impedance resistive fault, there are later intervals such that if the fault is cleared within these intervals of time, the system is still stable notwithstanding that the clearing time is now larger than the conventionally calculated *CCT*.

This anomaly was first observed in the results of a sensitivity analysis performed in PSCAD. Further investigations were done in order to find an explanation. It should be noted that, the results are obtained precisely using digital simulation and explained qualitatively using the equal area criterion.

5.2 Identification of the Phenomenon

The *CCT* is the maximum permissible duration of a fault [4]. If the fault is cleared before the *CCT*, the system remains transiently stable; otherwise it loses stability. However, this chapter shows that for high impedance resistive faults, there may be a set of time intervals $T = \{[0, CCT], [t_1, t_2], [t_3, t_4] \cdots\}$ with $0 < CCT < t_1 < t_2 < t_3 < t_4$ where the system is once again stable.

In this thesis, this result is rationalized using the well-known equal area criterion which uses a comparison of the acceleration and deceleration energies [4]. Precise numerical values for t_1, t_2, t_3... can be obtained by detailed electromagnetic transient simulation. It should be noted that this phenomenon is not the same as multi-swing transient instability, which is a phenomenon where generators do not lose stability in the first post-clearance swing, but do so in subsequent swing(s) [125, 126].

5.3 Test System

Figure 5.1 shows the test system modified from the *SMIB* test system in [4]. The parameters and initial conditions of the system is given in Table 5.1. For the detailed machine model, the data are exactly the same as in [4].

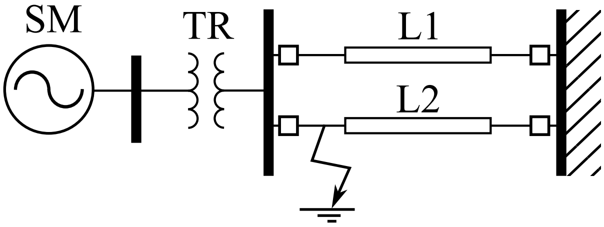


FIGURE 5.1: Diagram of test system.

TABLE 5.1: Input data for the test system

variable	value	variable	value
R_a	0.003 (p.u)	x'_d	0.3 (p.u)
E'_q	1.1440 (p.u)	δ_0	42.33 (^{o})
Z_{tr}	0.015 + j 0.15 (p.u)	Z_{L1}	0.05 (p.u) + j 0.5 (p.u)
Z_{L2}	0.093 + j 0.93 (p.u)	E_B	0.9008 (p.u)
$S_t(0)$	0.9 + j 0.436 (p.u)	P_{mech}	0.935 (p.u)
S_{base}	555 (MVA)	V_{LLbase}	24 (kV)
H	3.525 (s)	K_D	0.01 (p.u)

5.3.1 Simple Explanation of Phenomenon

Consider a simplified representation of the machine with a voltage source $E_q^{'}$ behind a synchronous impedance $x_d^{'}$. Figure 5.2 shows the simulation of the rotor angle evolution following a three phase fault of 0.1 p.u resistance. The CCT for this case is calculated as 0.25 (s).

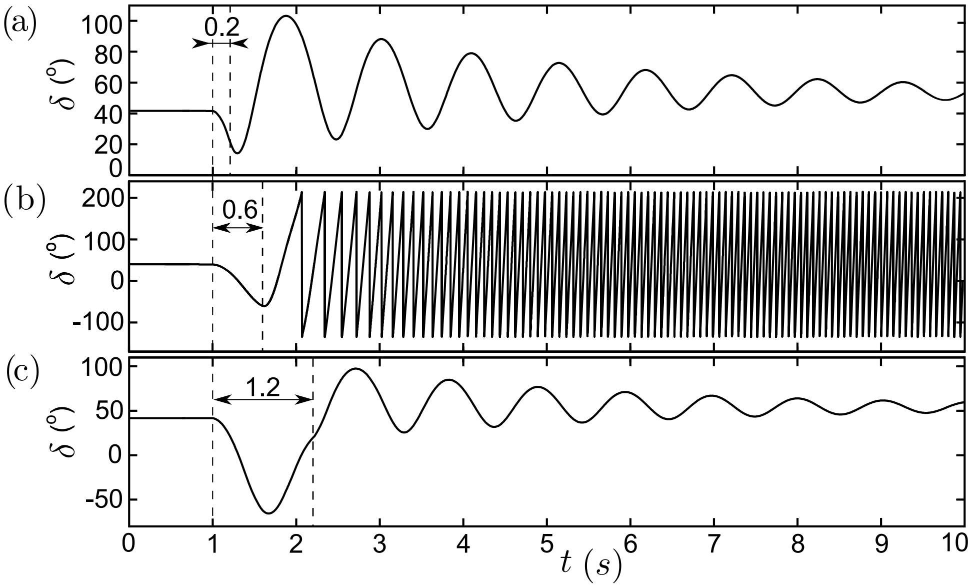


Figure 5.2: Evolution of the rotor angle for three different fault clearing times; (a) stable system for a fault duration of 0.2 (s), (b) unstable system for a fault duration of 0.6 (s), and (c) stable system for a fault duration of 1.2 (s).

For a fault clearing time of 0.2 (s) (less than the CCT) the system remains stable (Figure 5.2.a) but becomes unstable for a fault clearing time of 0.6 (s) (Figure 5.2.b), which is greater than the CCT. However, unexpectedly, if the fault is cleared after 1.2 (s), the system remains stable (Figure 5.2.c).It should be noted that the results shown in Figure 5.2 are obtained using EMT simulation.

5.4 Explanation of Phenomenon Using the Equal Area Criterion

The *SMIB* system and its simplified equivalent circuits before, during, and after the fault are shown in Figures 5.3, 5.4 and 5.5, respectively.

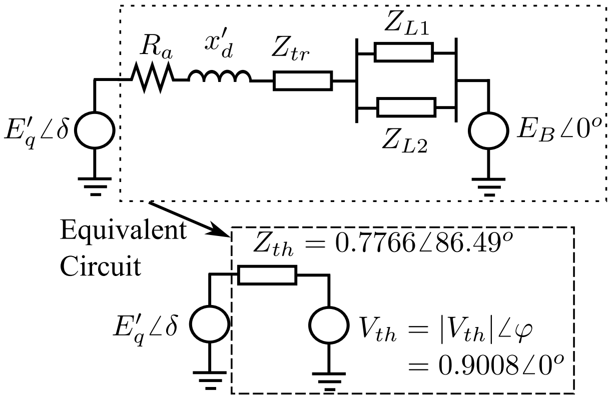


Figure 5.3: Pre-fault thevenin equivalent circuit.

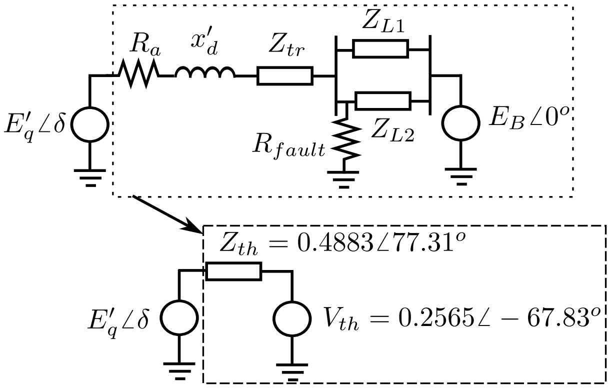


Figure 5.4: During-fault thevenin equivalent circuit.

Circuit analysis on these figures 5.3, 5.4 and 5.5 allows calculation of machine currents and hence the electric power. Mechanical dynamic equations are used to calculate the evolution of rotor angle. The equations for power and mechanical dynamic behavior are as follows:

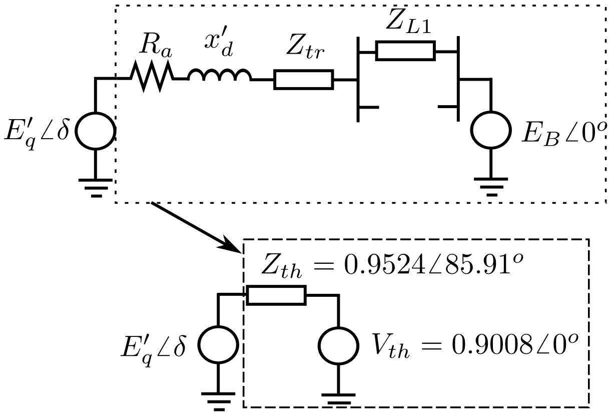


FIGURE 5.5: Post-fault thevenin equivalent circuit.

$$P = \frac{|E'q|}{R_{th}^2 + X_{th}^2}[R_{th}(|E'q| - |V_{th}|cos(\delta - \phi)) + |X_{th}||V_{th}|sin(\delta - \phi)] \tag{5.1}$$

$$\frac{d}{dt}\Delta\omega_r = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega_r) \tag{5.2}$$

$$\frac{d}{dt}\delta = \omega_0\Delta\omega_r \tag{5.3}$$

In Figure 5.6, the net accumulated energy (in the limit) can be calculated as:

$$A = A_{fault} + A_{post} \tag{5.4}$$

where:

$$A_{fault} = \int_{\delta_0}^{\delta_{clear}} (P_{mech} - P_{dur})d\delta \tag{5.5}$$

$$A_{post} = \int_{\delta_{clear}}^{\delta_1} (P_{mech} - P_{post})d\delta \tag{5.6}$$

Based on the equal area criterion, if $A > 0$, the accumulated energy cannot be dissipated before the maximum angle δ_1 and the system will be unstable. Conversely, if $A < 0$, the system is stable.

From Figure 5.6, $A_{fault} = |A_2| - |A_3|$, as A_2 is positive and A_3 is negative. The sum is a small positive number because A_2 and A_3 are close in magnitude. On clearing, $A_{post} = |A_4| - |A_1|$, because A_4 is positive (note direction in which δ moves is opposite to that during the fault), and A_1 is negative. Because A_4 is a large positive area and dominates, A_{post} is a large positive number. Hence $A > 0$ and the system is unstable.

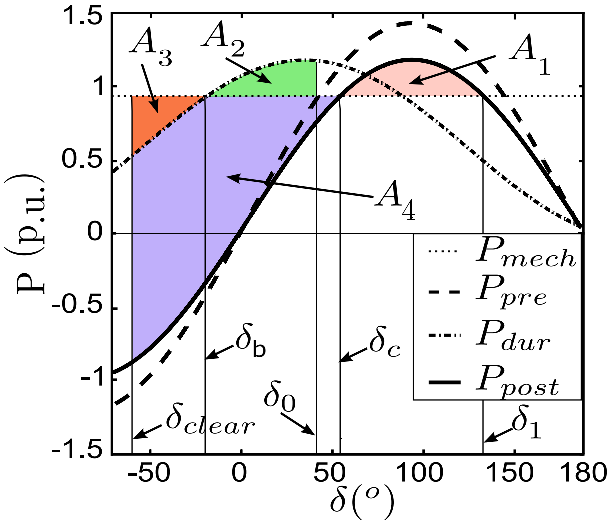


FIGURE 5.6: Equal area criterion method analysis; acceleration and deceleration areas for unstable case (Fig. 2.b case).

Likewise for Figure 5.7, $A_{fault} = A_2 = |A_2|$ which is positive and $A_{post} = |A_4| - |A_1|$. Hence $A = |A_2| + |A_4| - |A_1|$; which is negative and the system is stable. So, the equal area criterion confirms the results of the EMT simulation.

Further investigation is done to find the dependency of the stability to the rotor angle at which the fault is removed as well as the fault clearing time.

Figure 5.8 shows net accumulated energy (A) as a function of clearing angle (δ_{clear}). It can be seen that, when $\delta_{clear} \in [22.15^o, 128.80^o]$ the system remains stable.

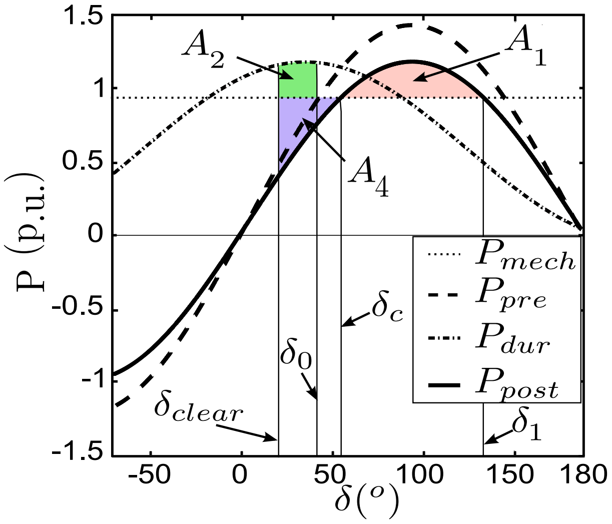


FIGURE 5.7: Equal area criterion method analysis; acceleration and deceleration areas for stable case (Fig. 2.c case).

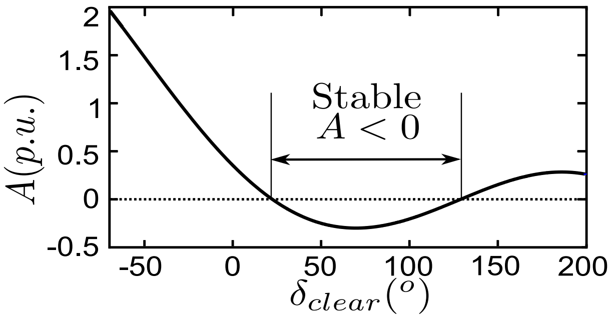


FIGURE 5.8: Stable margin of clearing rotor angle.

Figure 5.9 shows time variation of A following a fault. A is negative in regions $T = \{[0\ s, 0.24\ s], [1.07\ s, 1.55\ s], [2.39\ s, 2.76\ s]\}$, defining the intervals where there is an opportunity to clear the fault without causing instability.

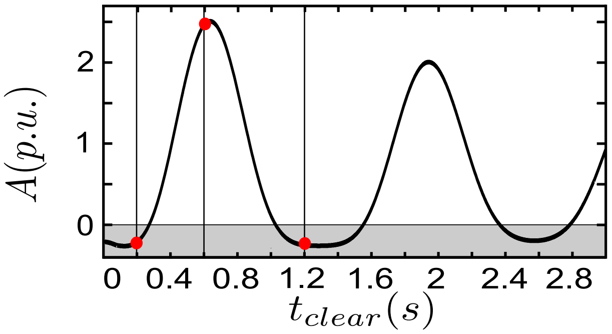


FIGURE 5.9: Evolution of A for fault clearing time.

5.5 Dependence of the Stable Clearing Intervals on Fault Resistance

As explained in Section 5.1, this phenomenon only happens if a large impedance fault is considered. This section shows how the stable fault clearing intervals are dependent on fault resistance. Figures 5.10.a and 5.10.b show results obtained from electromagnetic transient simulation using the simple voltage behind reactance model (Model 0.0) and a 6th order machine model (Model 2.2), respectively. Although numerically different, the two results are qualitatively similar. The points on the graph indicate unstable cases.

Note that for a low resistance fault, e.g, $R_{fault} = 0.05$ p.u, there is only a single CCT, and the fault must be cleared in the interval $[0\ ,CCT]$ for stability. However, additional stable clearing intervals become available for R_{fault} in the range $[0.1\ s, 0.656\ s]$, e.g. for $R_{fault} = 0.4 p.u., T = \{\ [0\ s, 0.25\ s]\ , [0.9\ s, 1.3\ s]\ , [2\ s, 2.5\ s]\ , [3.1\ s, 3.6\ s]\ , [4.2\ s, 4.7\ s]\ \}$.

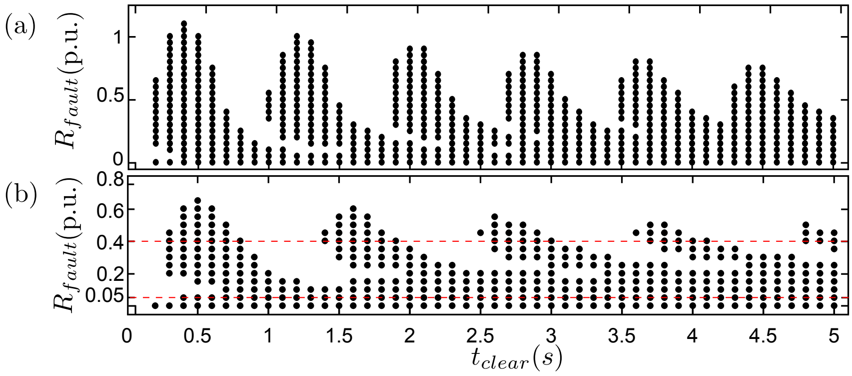


FIGURE 5.10: Transient stability scanning for test system; (a) voltage source behind reactance machine model, and (b) 6th order machine model

5.6 Summary and Conclusions

An anomalous transient stability behavior of synchronous generators was investigated in this chapter. The phenomenon was observed when a high impedance resistive fault was applied to a synchronous generator. It was shown that there are multiple intervals of time after CCT such that if the fault is cleared in any of these intervals, the system is stable. In other words, the generator might be stable if the fault is cleared with a delay larger than the CCT. However, for a zero resistance fault, there is only a single region $[0, CCT]$, whereas multiple stable opening intervals occur for larger resistance faults. The phenomenon was observed using an EMT simulator and explained using the well-known equal area criterion.

Chapter 6

Probabilistic Evaluation of Transient Stability

6.1 Introduction

The basic concepts and techniques associated with power system transient stability assessment are presented in the previous chapters. Using these concepts and techniques, the transient performance of electric power systems can be assessed either deterministically or probabilistically. In most deterministic assessment, the transient stability criterion is defined as the ability of a power system to withstand the worst-case scenario. The worst-case scenario is usually considered as a solid three phase fault near the generation buses at the time of highest operating stress of the power system [1]. However, the worst-case scenario represents just a few of the disturbances that may happen during the operation of a particular power system. Therefore, the planning of the power system based on worst-case scenario may often be too conservative. One of the salient disadvantages associated with deterministic transient stability assessment is that it fails to recognize and reflect various inherent uncertainties associated with power systems. On the other hand, the probabilistic assessment of power system transient stability considers various uncertainties associated with power system loads, generation, and disturbances. The use of a probabilistic approach would result in more realistic assessment of transient stability performance of power systems.

A framework for probabilistic assessment of transient stability is, therefore, proposed in this thesis. The proposed technique is based on a Monte Carlo simulation method and use of an EMT simulation engine for transient stability assessment. The generation, load and fault related uncertainties are modeled assuming that they follow known probability distributions. Fast computing techniques are incorporated in the framework for facilitating the Monte Carlo process.

The first practices and standards which have developed for interconnecting distributed generation to distribution networks indicated that distributed generation should cease energizing the system immediately after a fault [2]. This implies that the transient stability of active distribution networks was not of interest. However, the latest standards have considered fault ride-through capability of distributed generation as well as intentional islanded operation of active distribution networks [3]. The aforementioned changes aim to keep distributed generation connected to the system during the faults and imply that the transient stability of active distribution systems should be considered.

The proposed framework is applied to an actual distribution network [127]. The system transient stability performance is evaluated using a probabilistic index and a series of sensitivity analysis is performed to examine the impacts of key parameters on the system transient stability performance.

6.2 Description of the Methodology

A large number of operating scenarios need to be evaluated in probabilistic transient stability studies in order to incorporate the impacts associated with system operating conditions, disturbances, and other uncertainties. The basic idea of the proposed methodology is illustrated in Fig. 6.1. A brief description of the entire process and each part of the model is provided in the following subsections.

The first step of the evaluation process is to sample the operating scenarios for example load and generation patterns. Each sample operating scenario includes all the system information that is needed for transient stability simulations. Other potential source of uncertainties such as fault type, location, resistance, clearing time and duration are sampled next in the Monte Carlo process. Once the operating scenario and disturbance are generated, the *EMT* simulator is called upon to evaluate the system's transient performance for the particular case under the specific disturbance as determined from the

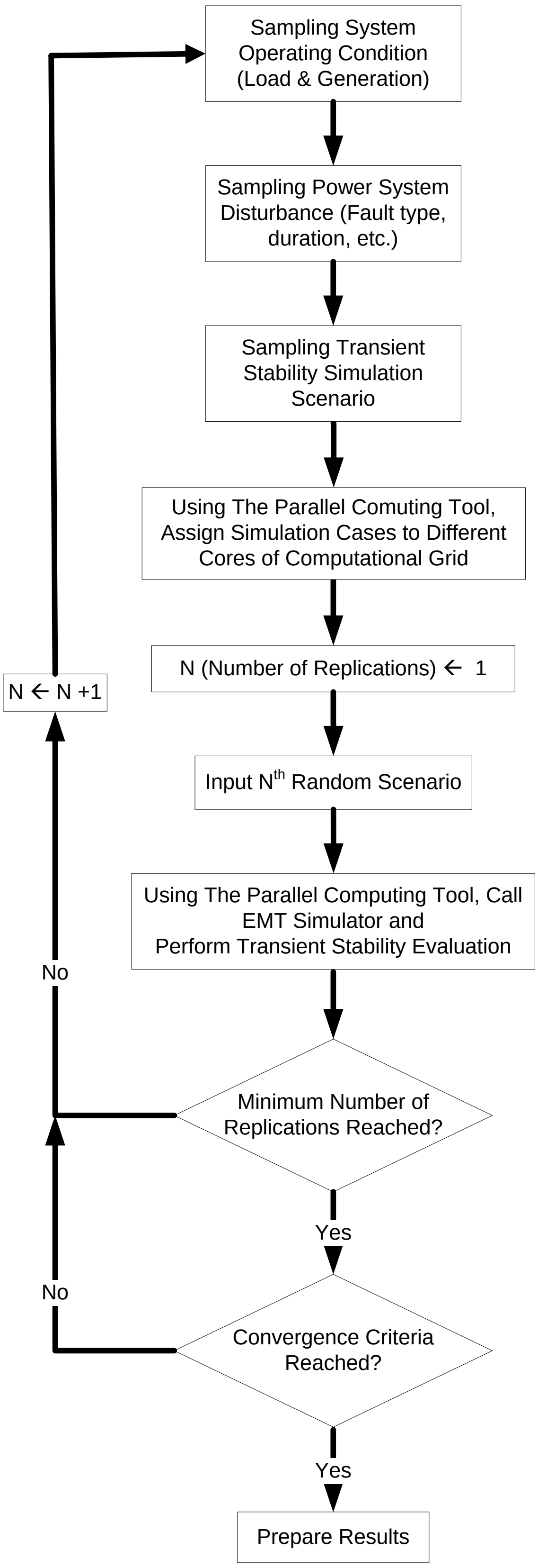


Figure 6.1: Probabilistic transient stability assessment framework

Monte Carlo draw. The technique allows conducting a Monte Carlo analysis to develop a vast number of permutations of stability cases and evaluating the dynamic performance of these potential operating scenarios under various disturbances. *PSCAD* [123] is used in this thesis as the transient stability simulation engine.

6.2.1 Modeling Load Dynamics and Uncertainties

The real and reactive parts of the loads are assumed to follow Normal distributions. The uncertainties associated with loads are, therefore, modeled by drawn random numbers that follow a Normal distribution. The model represents the load characteristic as a function of voltage magnitude and frequency. In this model, every half a cycle, the shunt resistor, capacitor and inductor in the load model is updated as a function of rms voltage magnitude and frequency to reflect the dynamics of the load [123].

Other applicable *PDFs* for representing the uncertainties of the loads can be used in the simulation. It is also possible to use different *PDFs* for loads at different buses. The *PDF* for Normal distribution is selected in this thesis for all of the loads. The values of the loads at different locations in each Monte Carlo replication are generated independently. Load dependence, however, can be modeled easily by drawing dependent random numbers.

6.2.2 Modeling Generator Dynamics and Uncertainties

Accurate modeling of generator dynamics is one of the most important tasks in transient stability assessment of a power system. Three types of generators which are common in active distribution networks are considered in this thesis.

6.2.2.1 Induction Generator (*IG*)

In this thesis, the *IG* is modeled as a wind turbine driven wound rotor type generator. In modeling the wind energy conversion system, wind speed is sampled first using the method proposed in [1] and the energy conversion is modeled using the power characteristic of a particular wind turbine [1] . The mechanical input torque of a wind turbine is determined by a randomly distributed wind speed and power characteristic of the wind turbine. Due to the random changes in the mechanical input torque of the *IG*, the generated power of the machine will change in each Monte Carlo simulation. In modern networks, *Doubly Fed Induction Generator (DFIG)* and converter connected wind turbines are increasingly being used, however, only directly connected windmills are modeled in this thesis as the main purpose of this thesis is to develop and demonstrate the essential approach. Also, these represent the most onerous conditions for transient stability and are the popular type of wind turbines for small scale applications [128].

6.2.2.2 Photovoltaic (*PV*) Systems

PV systems are common in active distribution networks. The *PV* arrays are assumed to be interfaced with *Voltage Sourced Converters (VSCs)*. The *VSCs* are therefore modeled and then the uncertainty of the generation output of *PV* arrays due to changes in solar radiation is considered. Three different approaches are proposed in existing literature for modeling *VSCs* [129–133]. The first approach is to model the power electronics representing each individual *Insulated-Gate Bipolar Transistor (IGBT)* switch. The accuracy of this model is the highest among the three available approaches [129]. The simulation time can, however, be large and may not be practical for Monte Carlo simulation [133]. Another approach is to use averaged models [130] which represent *VSCs* as voltage sources and neglect most of the dynamics of the *VSCs*. These assumptions in modeling *VSC* ensures a fast *EMT* simulation but reduces the accuracy of the results [130]. A third approach, which is used in this thesis, is switching functions model [131, 132]. This model is capable of providing a high accuracy as it generates the non-sinusoidal waveforms of the converter and a fast simulation at the same time [133]. Two typical controllers are modeled: An inner loop d-q controller that sets the real and reactive components of the *VSC* current, and an outer loop controller that outputs the orders to the inner loop controller to request the necessary real and reactive powers. The details on modeling of *VSCs* using the switching function method and their controllers can be found in [129]. The uncertainties associated with *PV* arrays are modeled as changes in the set points of power controller of the *VSC* (P_{ref},Q_{ref}). Figure 6.2 shows the schematic of the *PV* system used in this thesis.

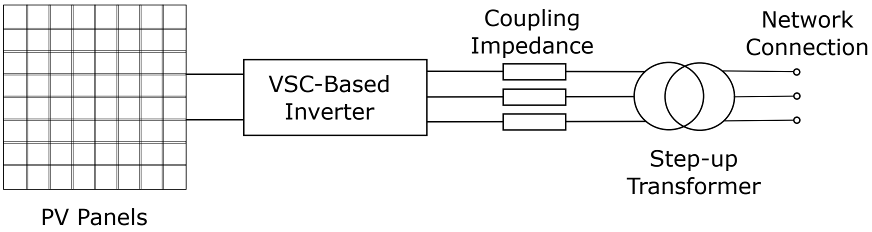


FIGURE 6.2: Schematic of the *PV* system used in this thesis

6.2.2.3 Synchronous Generator (*SG*)

The *SG* model represents one damping circuit on the d-axis, two damping circuits on the q-axis and a field circuit (*Model 2.2*) [108]. A detailed explanation about this model is provided in Chapter 3. No excitation system or governor is considered for the SGs in the simulations.

6.2.3 Modeling Uncertainties Associated with Power System Disturbances

Disturbances to power systems are random in nature. Fault type, resistance, duration, and starting time are, therefore, modeled as random variables in the studies described in this thesis. The faulted branch and the position of the fault on the branch are also selected randomly. The probabilities and distribution functions for modeling uncertainties associated with power system disturbances are provided in results and discussions Section 6.6. In each simulation, the fault is cleared after a given duration. In the Monte Carlo simulations, this duration is varied assuming a probability distribution function. The protection system delays or malfunctions (which would affect the transient stability) are not considered, as the purpose of the thesis is focused on the development of a methodology for probabilistic transient stability. It is, however, recommended to consider the protection system for future studies.

6.3 Computational Repercussions

The computational effort of application of the Monte Carlo simulation to $PSCAD$ consists of two parts; i) simulation and ii) post-processing of the output data to generate the desired reports (In this case, $PLOTS$). The simulation part also consists of three aspects; number of simulations, time period of each simulation, and EMT simulation time-step.

The number of simulations directly influences the quality of the approximation that Monte Carlo method provides. By increasing the number of simulations, the error of the evaluation will decrease but at the same time the overall time of the evaluation will increase. The time period of each transient stability simulation should run for between 10 - 15 seconds to capture the essential dynamics of transient stability simulations [16]. The EMT simulation time-step also has influence on the dynamics of the system. Typically, time-step of the simulation should be experimentally selected by checking that further reduction of time-step does not affect the accuracy of the results.

It should be noted that the preparation for the simulation, which is generation of all of the necessary random variables, depends on the dimension of the problem, this task could be time-consuming. Considering the computational efforts described above, it is impractical to run simulations sequentially on a single computer. Parallel computing is used to overcome this problem.

6.4 Monte Carlo Simulation Method and Parallel Computing

A simulation program written in *Python* programming language [134] is developed and used to control the Monte Carlo process as shown in Fig. 6.1. All of the random operating scenarios and disturbances are generated using the *Python* program. The random library of Python programming language [134] is used for generating the required random variables based on their *PDFs*. If 'N' is selected as the number of replications in Monte Carlo simulation, all of the random parameters are generated for each of these 'N' instances and saved in a file to be used by the program for the next step. Once the simulation scenarios are generated, the corresponding *EMT* simulation files are modified for performing transient stability simulations.

Highly detailed models for power system components are available in *EMT* programs. These have the most accurate models as compared to other power system simulation programs. For example, transient stability programs typically ignore high speed power electronic and other electromagnetic transients which *EMT* programs do not. The *EMT* simulator is, therefore, used in this thesis to more accurately evaluate transient stability performance of active distribution systems. *EMT* simulation is, however, computationally extensive, particularly when performing probabilistic transient stability analysis using Monte Carlo simulation method. Parallel computing techniques make this effort more practical. For example, using 100 cores in the Monte Carlo simulation can potentially speed up the simulation by a factor approaching 100. In this thesis, the transient stability simulation tasks are assigned to different cores in grid computers for parallel computation. *Xoreax Incredibuild* [135] is used as the manager of parallel computing. The *Python* program controls *Xoreax* and assigns the computation tasks to corresponding cores of the computer grid. The *Python* program runs the *EMT* simulation without opening the simulator (N times) by calling the Visual Fortran Compiler and reads the data generated by each Monte Carlo replication and saves the data in separate folders.

Xoreax IncrediBuild [135] is used in the research described in this thesis for parallel computing to facilitate the Monte Carlo simulation process. *Xoreax IncrediBuild* [135] is a tool for grid computing. It accelerates the computations by dividing them into sub-tasks and assigning them to different cores in a computer grid. For example, if there are four quad-core computers in a grid, it is possible to divide the computational task into 16 sub-tasks and assign them to all 16 cores in the grid.

An *IncrediBuild* environment consists of two components: The coordinator and the agents. The coordinator is actually the server and using peer-to-peer protocols utilizes the agents (clients) to perform grid computing [136]. The *Xoreax* engine can be used with different computing structures. This includes multi-core computers or multiple computers in a grid. The allocation of the parallelized tasks to each core or computer is handled by the *Xoreax* coordinator.

The *Python* program described previously incorporates parallel computing techniques. The *Python* program is designed to perform *PSCAD* simulations without opening the cases in *PSCAD* environment. A Python library named *"pypscad"* was developed to carry out the Monte Carlo simulation. The core modules of this library and their functions are presented as follows:

"***launchpscad***" module

This module is the manager of the program. It utilizes other modules to perform the task of probabilistic evaluation of transient stability. The rest of the modules that are utilized by this module are briefly described as follows.

"***Casedefinition***" module

This module reads the *Comma Separated Values (CSV)* file which includes the information of the case and builds an object with all the information of the network. The main tasks of this module are:

- Reading the *CSV* file including the information of the case and the value of the random variables
- Specifying the topology of the network (nodes, lines, loads, ...) with all the information which is necessary for the simulation.

"***Statistics***" module

This module generates the random variables for the *Monte Carlo* simulation. The main tasks are as follows:

- Generation of random variables associated with disturbances

- Generation of random variables associated with loads
- Generation of random output of the generators by generating random wind speeds and solar radiations

"*FileModifier*" module

This module defines the necessary *PSCAD* cases for running the simulations. Each case identifies a particular operating and contingency scenario (including a disturbance). Power system transient stability is assessed probabilistically using the results of this batch of simulations.

"*XGEinterface*" module

This module is developed to interface with the Xoreax engine for grid computing. The main tasks are:

- Creation of different folder for each *Central Processing Unit (CPU)* to save the results of simulations
- Creation of the *xml* file which is necessary for Xoreax engine to manage the parallel computing
- Running the Xoreax engine

6.4.1 Probabilistic Indexes for Transient Stability Assessment

Transient Stability of an example system is evaluated using the dynamic responses of the rotor angle of SG and the rotor speed of IG to a disturbance. It is assumed that if the rotor angle of SG or speed of IG is unbounded, for example beyond 200%, the generator will not find a new stable operating point and therefore it is considered to be unstable. The system is considered to be unstable, if all of its generators are unstable. However, other criteria for instability can also be considered; for example, the risk state of the system can be defined if one generator goes unstable.

Based on the stability/instability of the simulated scenarios the probability of the transient stability/instability can be evaluated. A probabilistic index referred to as the *Probability of Loss of Transient Stability (PLOTS)* is defined in Equation 6.1 is used:

$$PLOTS = \frac{number\ of\ unstable\ cases}{total\ number\ of\ evaluated\ cases} \tag{6.1}$$

Two types of $PLOTS$ indices referred to as system $PLOTS$ and conditional $PLOTS$ are used in this thesis. In case of the system $PLOTS$, the *total number of evaluated cases* is the total number of replications in the Monte Carlo simulation. In the case of the conditional $PLOTS$, the *number of evaluated cases* is the number of replications under a particular condition, for example under a specific disturbance such as line-to-ground fault. The conditional $PLOTS$ can provide valuable data to the protection system design for future developments. Using this index, the faults which destabilize the system can be determined and the protection system can be designed to accurately consider the most onerous contingencies.

The use of the *PLOTS* index would provide one more dimension to power system stability evaluation and the decision making process in addition to the conventional deterministic criterion such as *CCT* or the damping ratio. It can be seen from the discussions presented in the following sections that probabilistic evaluation would provide more insights into the transient stability performance of power systems.

6.5 Feasibility of Application of the Monte Carlo Method to Probabilistic Transient Stability Study

In this section, the proposed *PSCAD* interface is tested to perform a probabilistic evaluation of transient stability of a SMIB system (system in Figure 6.3).

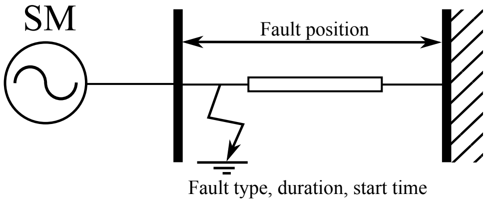


FIGURE 6.3: Diagram of the test system with random parameters: fault position, type and duration.

Two models of synchronous machine are used in this experiment (*Models 2.2 and 0.0*). The main goal of this section is to show the feasibility of the proposed approach. Fault impedance, duration and type are the only stochastic variables which are considered in this experiment. The probability density functions of fault impedance and duration are shown in Figure 6.4.

A grid of eight quad-core computers are used in this experiment. Hence, 32 computation cores are utilized by the Xoreax engine. The number of replication in Monte Carlo simulation is 10,000. Selection of the number of simulations is addressed in Section 6.6.2.

Figure 6.5 shows a snapshot of the utilization of 32 cores by *Xoreax* engine. Length of each bar shows the simulation time of the assigned core. The overall time of this experiment was 4 hours, 47 minutes and 53.44 seconds.

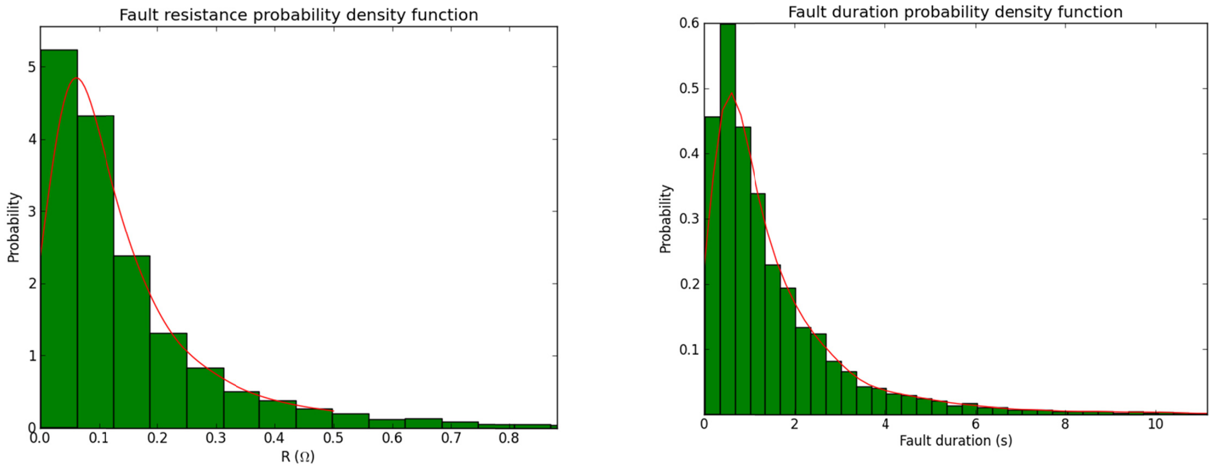
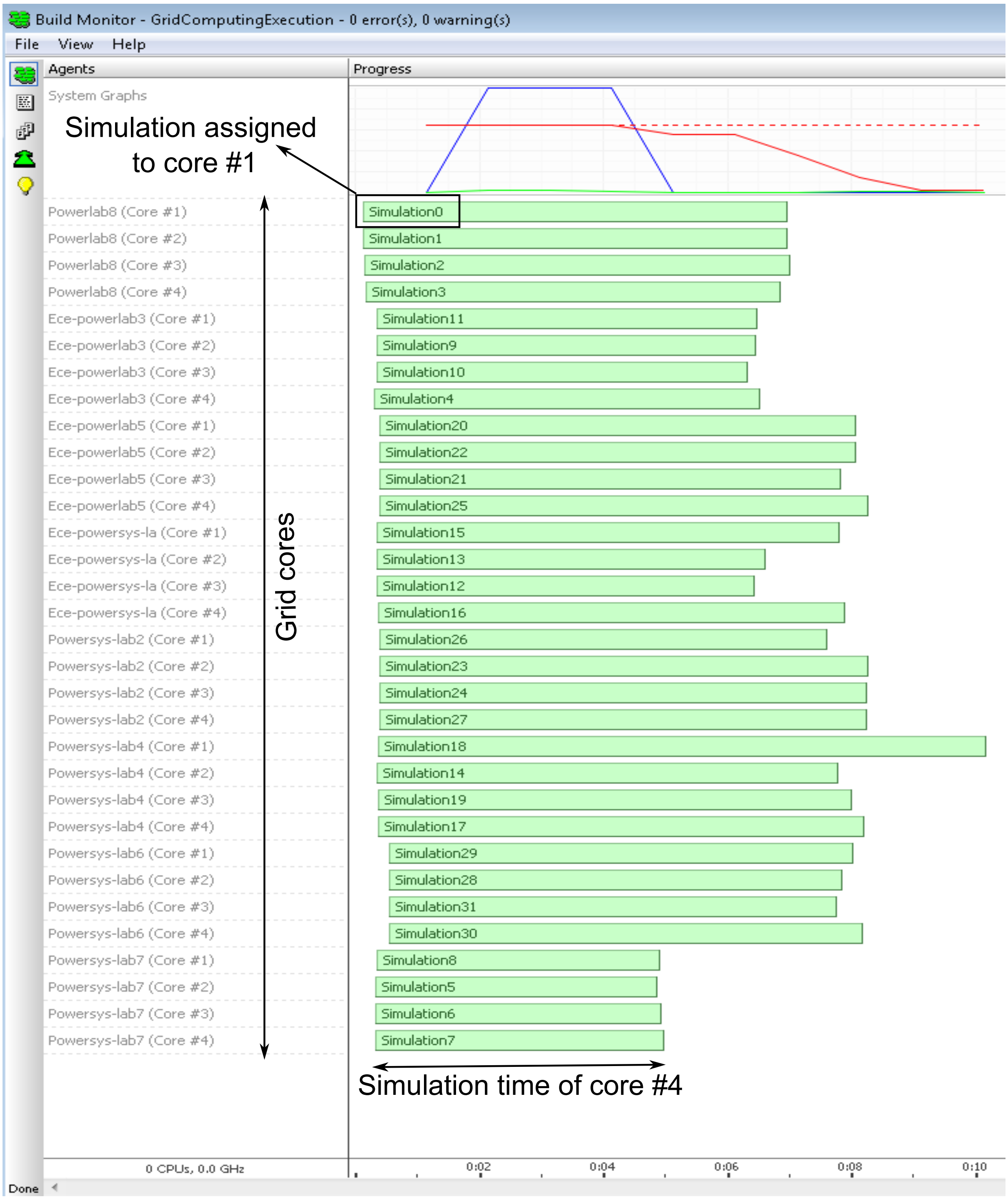


FIGURE 6.4: Probability density functions of fault impedance and duration

TABLE 6.1: Results of Monte Carlo simulation

SG model	unstable cases	PLOTS of 3ph faults	PLOTS of 2ph faults	PLOTS of 1ph faults	Overall PLOTS
0.0	2968	0.0367	0.1047	0.1557	0.7032
2.2	517	0.0254	0.0250	0.0013	0.9483



Simulation assigned to core #1

Grid cores

Simulation time of core #4

FIGURE 6.5: Utilization of 32 cores by Xoreax engine

Table 6.1 shows the results of Monte Carlo simulation. The results can be summarized as follows:

- Model 2.2 shows a better performance of stability, because the calculated *PLOTS* for this model is much less than Model 0.0. This is likely due to additional damping provided by the damper windings which are missing in Model 0.0.
- Although the probability of having single phase faults are higher in comparison with other types, their *PLOTS* is less than three phase fault in Model 2.2. The reason is that three phase faults are more severe and cause more instable cases.
- If the grid computing was not used in this experiment the required time would be about 32 times larger (almost a week!). By increasing the complexity of the case study to a practical power system with various number of loads, generators, lines, etc., performing the simulation without grid computing is very time-consuming and impractical.

6.6 Application of the Proposed Approach

The modified IEEE 34 bus distribution test feeder is used as the test system in this thesis [127]. The detailed information of the test system is given in Appendix C. The result of the load flow of the test system is available in [127]. The test system is an unbalanced network and has single phase feeders as well as three phase feeders which is typical for a practical distribution network. The original IEEE 34 bus distribution test feeder is a passive distribution network. *DG* units are added to change it to an active distribution network. Four *PV* arrays, one induction generator based wind turbine and two synchronous generators are added to the test system as shown in Figure 6.6 for transient stability evaluation. The name plate capacity of PV arrays, IG and SGs used in the test system are 100, 400 and 500 kVA, respectively. It should be noted that the upstream network (bulk power system) is modeled as a strong network and represented as a source in the simulations.

6.6.1 Details of the Test System Modeling

The voltage regulators of the test system are equipped with *On Load Tap Changer (OLTC)*. To model the regulators, three single phase transformers are used. The reason for selecting three single phase transformers instead of one three phase transformer is to model the capability of each phase tap changer to operate independently. The model of $OLTC$ is designed using the specifications proposed in [137] considering the dynamics of the controllers.

Transmission lines are represented as two PI section models in order to be able to apply a fault to any section of a line. Although the length of each segment is variable, the sum of the length of the two sections is always equal to the original line length. For example, if a fault is applied to the 25% of line length, the first and the second PI sections of the line have the length of 25% and 75% of the original line length, respectively. Using this approach, application of a fault with a random position is possible.

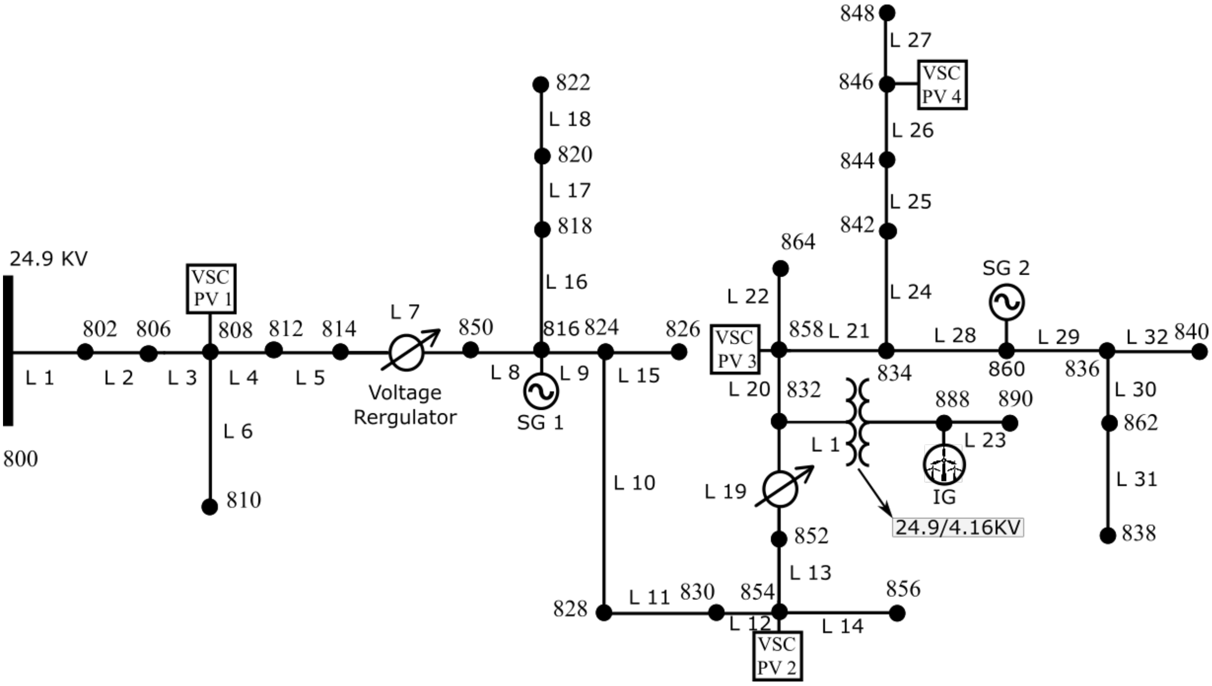


FIGURE 6.6: Modified IEEE 34-bus distribution test system with *DG* units

For load modeling, the average value of the *PDFs* for the Normal distribution of each load is assumed to be equal to the nominal values of active and reactive power provided in [127]. The standard deviation of Normal *PDFs* are selected as 5% of the average values.

The parameters used for dynamic modeling of *IG* are shown in Table 6.2. The wind speed is assumed to follow a two-parameter Weibull distribution with scale (λ) and shape (k) parameters of 11 and 2, respectively [1]. The wind energy conversion system power characteristic is defined mainly by three major parameters of cut-in, rated and cut-out wind speeds. Equation 6.2 is used for a hypothetical wind turbine generator.

Table 6.2: Input data for the IG

variable	value	variable	value
R_s	0.043 $(p.u.)$	X_s	0.06 $(p.u.)$
R_r	0.04 $(p.u.)$	X_r	0.06 $(p.u.)$
S_{base}	0.5 (MVA)	$V_{LL_{base}}$	0.48 (KV)
H	1 $(sec.)$	Mech. damping	0.01 $(p.u.)$

$$P(v) = \begin{cases} 0 & v < cut-in \\ \frac{0.5 C_P \rho A v^3}{rated\ power}\ p.u. & cut-in \leq v \leq rated \\ 1\ p.u. & rated < v < cut-out \\ 0 & v > cut-out \end{cases} \tag{6.2}$$

Where, C_P, ρ, A and v are the Betz constant, air density, turbine area and wind speed, respectively. Table 6.3 shows the values which are used in Equation 6.2. The cut-in, rated and cut-out wind speeds are 3, 11 and 20 m/s, respectively.

Table 6.3: Wind energy conversion system parameters

variable	value	variable	value	variable	value
C_P	0.472	ρ	1.25 $(\frac{kg}{m^3})$	A	1017.85 m^2

For PV systems, the power output reference set points for each simulation are determined randomly using a PDF that follows a Normal distribution with average value and standard deviation of 0.9 (p.u) and 0.25 (p.u.), respectively. These numbers are selected for demonstration purposes, and corresponds to a sunny area where the PVs are close to maximum power operation (as the average value is 0.9 p.u.). Other applicable $PDFs$ can be selected to represent the nature of the specific uncertainty. The parameters of the typical SG used in this thesis are summarized in Table 6.4. In order to connect DGs to higher voltage network, typical step-up transformers are used. The load flow results of the dynamic model developed in $PSCAD$ are compared with those provided in [127]. It is observed in one of published research papers of this thesis that the difference between the two power flow results are negligible [133].

Table 6.4: Input data for the SG

variable	value	variable	value
L_d	$1.93\ (p.u.)$	L_q	$1.77\ (p.u.)$
L_l	$0.13\ (p.u.)$	R_a	$0.0\ (p.u.)$
$L_d^{'}$	$0.23\ (p.u.)$	$L_q^{'}$	$0.5\ (p.u.)$
$L_d^{''}$	$0.22\ (p.u.)$	$L_q^{''}$	$0.2\ (p.u.)$
$T_{d0}^{'}$	$5.2\ (sec.)$	$T_{q0}^{'}$	$0.81\ (sec.)$
$T_{d0}^{''}$	$0.029\ (sec.)$	$T_{q0}^{''}$	$0.05\ (sec.)$
S_{base}	$0.5\ (MVA)$	$V_{LL_{base}}$	$0.48\ (KV)$
H	$1.5\ (sec.)$	$Mech.\ damping$	$0.01\ (p.u.)$

The occurrence probabilities assumed for different fault types are shown in Table 6.5. The fault type can be determined randomly using a PDF for Uniform distribution in $[0, 1]$. For example, if the generated random number is in $[0, 0.75]$, $(0.75, 0.78]$ or $(0.78, 0.95]$, the fault type is a single line to ground (LG), two lines (LL) or two lines to ground (LLG), respectively. Note that the probability of having phase A, B or C to ground is identical and equal to $0.75/3 = 0.25$. The $PDFs$ assumed for other random variables associated with a particular disturbance to a power system are shown in Table 6.6.

The proposed approach is performed on a grid of seven computers containing 98 cores. The overall time of the process was 21 hours, 26 minutes and 27 seconds. The simulation time for performing the same task on a single computer using one core is estimated to

TABLE 6.5: Fault type probabilities

type	probability	type	probability	type	probability
LG	0.75	LL	0.03	LLG	0.17
LLL	0.02	LLLG	0.03		

TABLE 6.6: Fault Probability density Functions

variable	distribution	parameters
faulted feeder number	uniform	$[0, 51]$
fault position	uniform	$[0, 100\%]$
fault starting time	normal	$\mu = 1.4\ s, \sigma = 0.01667\ s$
fault duration	lognormal	$\mu = 0\ s, \sigma = 1\ s$
fault resistance	lognormal	$\mu = 0\ \Omega, \sigma = 1\ \Omega$

be roughly 88 days (98 × grid computing time). This fact shows the necessity of using parallel computing in such evaluations that are computationally extensive. A 100 μsec time-step is used in *PSCAD EMT* simulations.

6.6.2 Minimum Number of Replications, Stopping Criterion, and *PLOTS* Calculation

The Monte Carlo simulation is repeated for a large number of replications in order to obtain the desired level of accuracy. The accuracy of the results estimated by a simulation technique is improved by increasing the number of sample replications. It is, however, not practical to run the simulation for a very large number of samples in order to achieve an extremely high level of accuracy. In this thesis, a minimum number of replications and a stopping criterion are selected based on a series of examinations to control the simulation process.

All of the selected *PDFs* representing the random variables are investigated in order to determine the minimum number of replications. The generated random variables are compared to their theoretical mean values. A ±1% error (ϵ) is considered as a satisfaction measure. By increasing the number of random draws, the mean value is calculated and compared to the error boundary. The first time that the average value of generated random variables enters the boundary and remains in it can be selected as the proper minimum number of Monte Carlo replications. Equation 6.3 shows the mathematical representation of the minimum number of simulation selection criterion.

$$N_{min} = min\{N : |\epsilon| < 0.01\} \tag{6.3}$$

Figure 6.7 shows the simulation results for wind speed based on a Weibull distribution with theoretical mean value of 9.823 m/s. It can be seen from Figure 6.7 that after 2,000 replications the mean values reside in the ±1% boundary. Based on the examinations of all of the other random variables used in the studies described in this thesis a minimum number of 2,000 replications is selected for avoiding premature convergence. Once the minimum number of replications is reached a stopping criterion as described mathematically in Equation 6.4 is used to check the convergence of the Monte Carlo process.

$$N_{max} = min\{N : |\epsilon| < 0.01 \ \& \ N > N_{min}\} \tag{6.4}$$

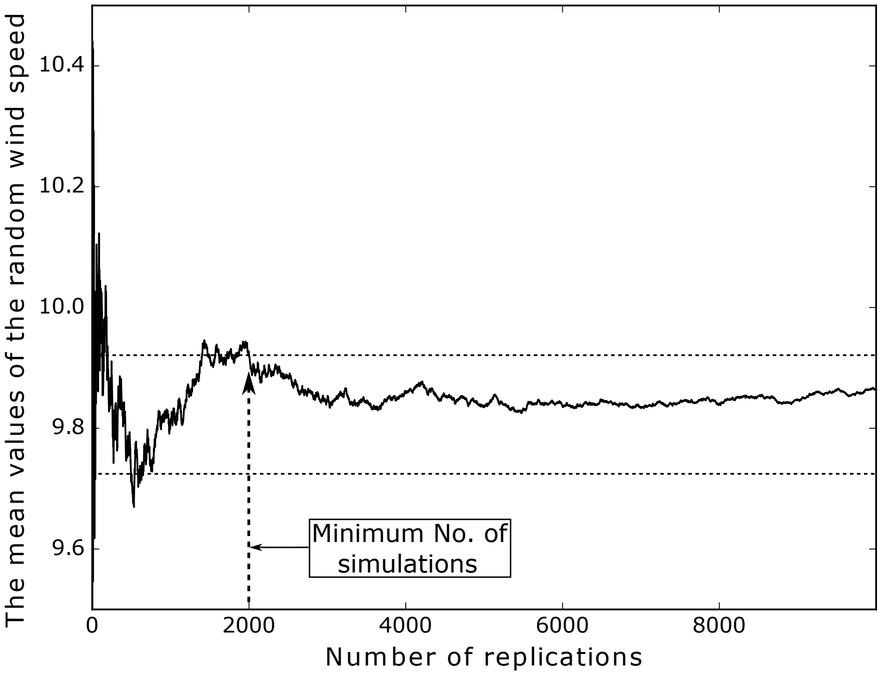


FIGURE 6.7: Selection of minimum number of replications

The index of system *PLOTS* is used to monitor the simulation convergence. In other words, if the system *PLOTS* stops changing for a certain number of replications (the change is within ±1% boundary), the simulation will stop. Figure 6.8 shows the convergence of the Monte Carlo simulation. It can be seen from Figure 6.8 that the simulation converges at around 8,700 replications. The rate of change of the system *PLOTS* lies within ±1% after approximately 8,700 replications. 10,000 replications are, therefore, performed to ensure the accuracy of the results.

Study results presented in Figure 6.8 show that among the 10,000 replications, 429 cases are unstable. The system *PLOTS* is, therefore, 0.0429 or 4.29%. The results obtained from the probabilistic transient stability simulation can be used to examine a wide range of aspects associated with power system dynamic performance. Some of the results that

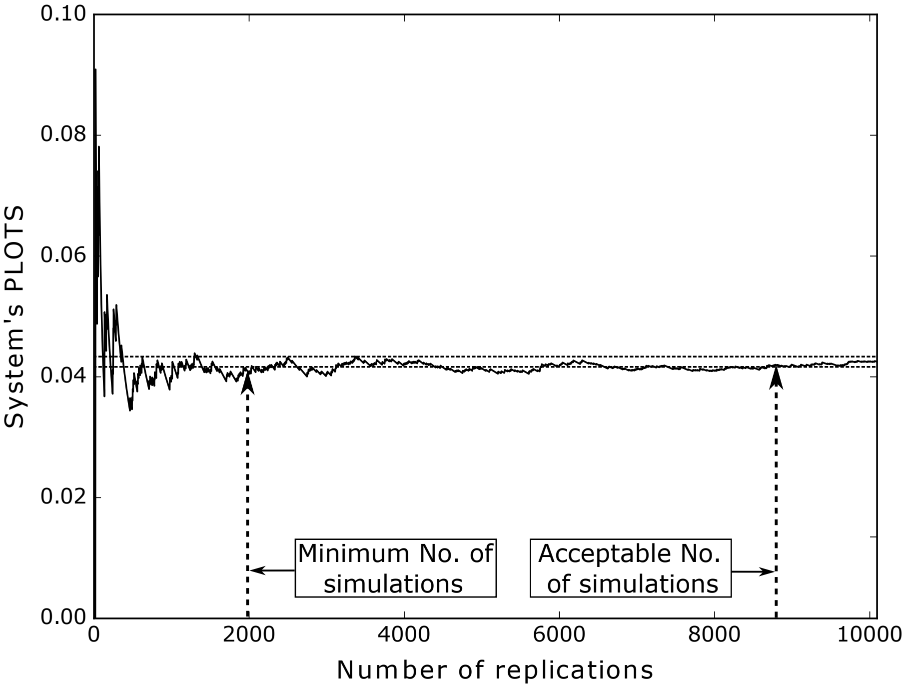


FIGURE 6.8: The convergence criterion of the simulation process

cannot be produced by traditional deterministic transient stability assessment are provided in the following sections.

6.6.3 Simulation Results and Discussions

A *PLOTS* index for the system of 4.29% is an aggregate considering all uncertainties. Sometimes it may be required to analyze the susceptibility of the power system to specific types of disturbance.

Figure 6.9 shows the *PLOTS* for different fault types for all 429 unstable cases in 10,000 replications. Normally the probability of occurrence of a LG fault is much higher than that of the other types of faults in actual power systems and therefore a higher probability is assigned for a LG fault in this study as shown in Table 6.5. The probability of instability due to other faults such as LLG and LLLG is, however, higher than LG fault because of the severity of these multiphase to ground faults as shown in Figure 6.9. It can also be seen from Figure 6.9 that the probability of instability due to LLG fault is the highest and therefore this type of faults should be examined in transient stability analysis in some cases. Simulating only three phase faults as in the traditional deterministic analysis is too pessimistic. It should be noted that the sum of all of fault types' $PLOTS$ is equal to the system $PLOTS$ of 0.0429 in Figure 6.9.

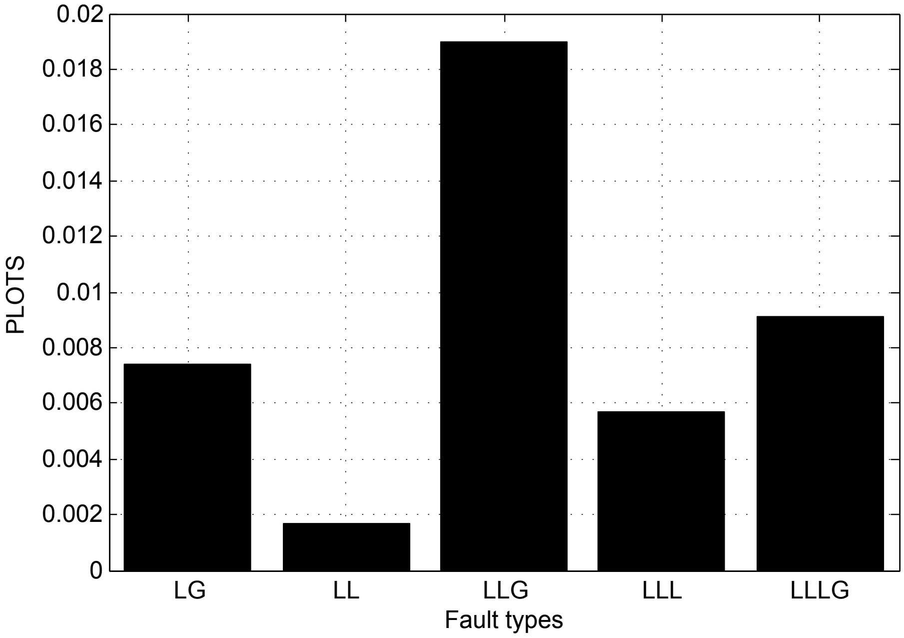


FIGURE 6.9: $PLOTS$ associated with different fault types

Further examinations are conducted to investigate the effect of the fault severity in terms of conditional $PLOTS$. These examinations are done considering only a specific type of disturbance in a subsample of the entire sample space. For example 307 replications represent the subsample of simulating only LLLG faults and 91 of them are unstable. The conditional $PLOTS$ in this case is equal to 0.2964. Figure 6.10 shows the conditional

PLOTS for different types of faults. It can be seen from Figure 6.10 that the probability of instability is higher for the conditions of three phase disturbances due to their severity.

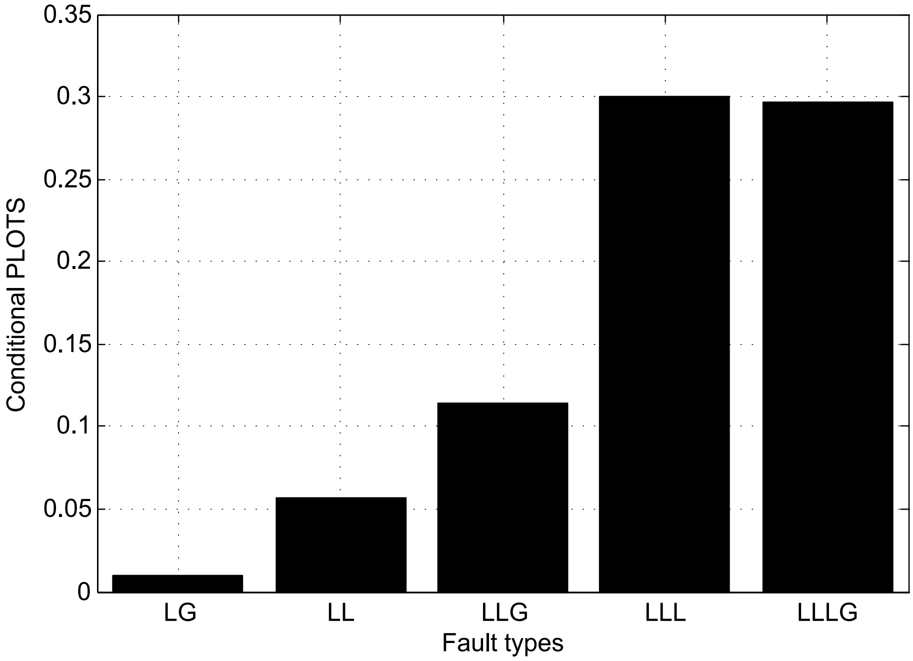


Figure 6.10: Conditional *PLOTS* associated with different fault types

Similar analysis is conducted to examine the effect of faults on a particular line in the stability simulations. From the simulation results, information related to Line 28 is extracted and analyzed. The results show that 399 disturbances were simulated on Line 28 (299 LG, 15 LL, 62 LLG, 10 LLL and 13 LLLG). Figure 6.11 shows the conditional *PLOTS* under these disturbances associated with Line 28. It can be seen from Figure 6.11 that no LG or LL fault on this line makes the system unstable. However, there are unstable cases with other fault types. This type of detailed stability performance analysis for a specific component of the system using probabilistic concepts is only possible in probabilistic assessments.

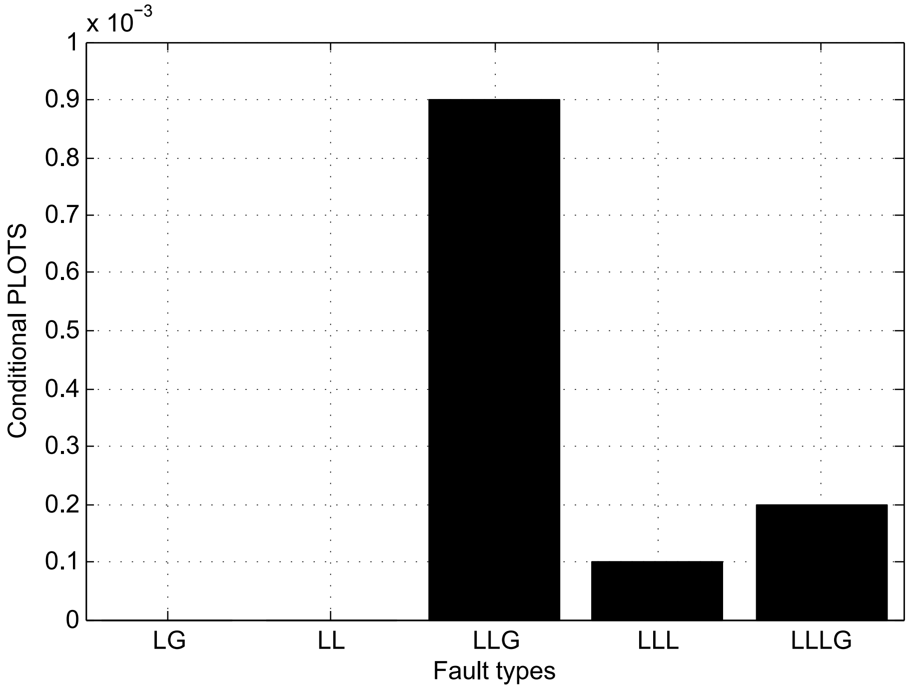


FIGURE 6.11: Conditional *PLOTS* associated with different fault types on Line 28

Figure 6.12 shows the conditional *PLOTS* under the disturbances on each line. It can be seen from Figure 6.12 that disturbances on Lines 7, 8, and 9 are more prone to instability as compared to disturbances on other lines. This is because these lines are very close to SG_1 and faults on these lines have more severe effects on the SG_1 stability and hence system stability. This type of analysis is useful in finding the weak points of a power system through transient stability assessment. Finding the weak area could have huge reliability and cost implications to power systems.

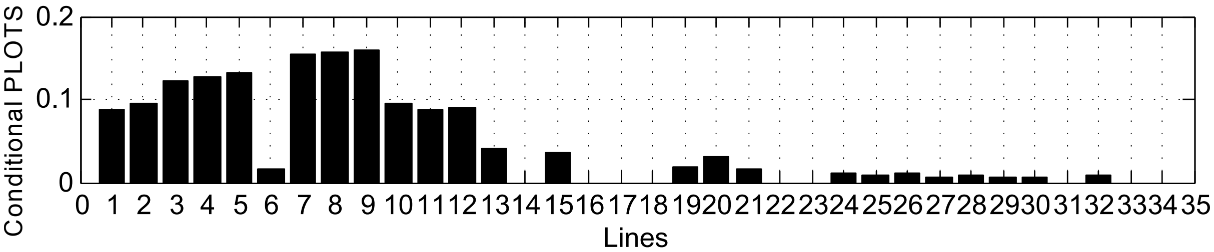


FIGURE 6.12: Conditional PLOTS associated with all lines in the test system

In order to appreciate the impacts of some of the major parameters on the transient stability performance of the system under study, sensitivity analyses are performed. Sensitivity analysis for major fault parameters are provided in this thesis. Each point in Figure 6.13 shows the fault resistance and duration combinations that yield unstable operation. It can be seen from Figure 6.13 that lower impedance faults will cause more unstable cases as expected. Special attention should therefore be paid to lower impedance faults particularly those sustained faults in power system planning or operating studies.

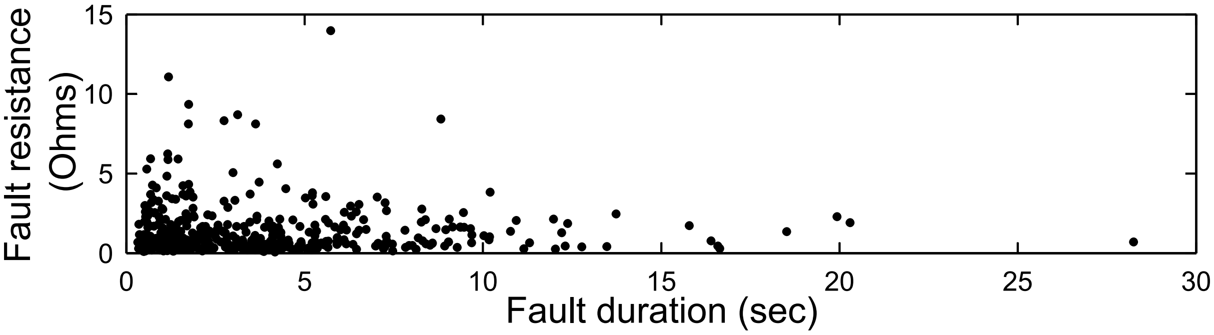


FIGURE 6.13: Sensitivity analysis result for fault resistance and duration

Figure 6.14 shows the results of the sensitivity analysis for the number of unstable cases with the changes in fault starting time and fault position. The distribution of the fault starting times and fault positions which make the system unstable are provided in Figure 6.14.It can be seen from Figure 6.14 that fault starting time (point on wave) and the position of the fault have influence on the transient stability performance. As discussed in Chapter 5, it should be noted that the time at which the fault is removed has also a crucial effect on the transient stability performance.

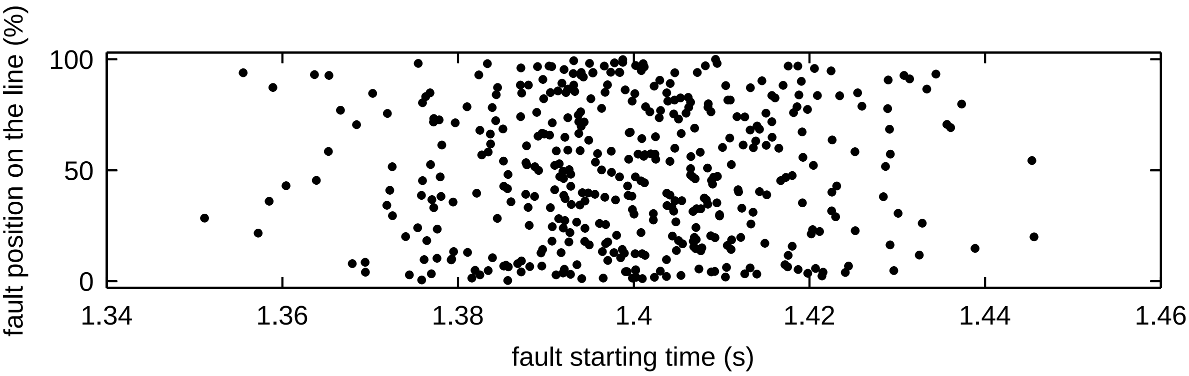


FIGURE 6.14: Instability sensitivity analysis for fault position and starting time and duration.

6.7 Conclusions

This chapter presents a Monte Carlo simulation approach for the transient stability evaluation of active distribution networks. The proposed approach takes the advantages of the calculation accuracy of *EMT* simulation and the efficiency of fast computing algorithms. Various uncertainties associated with power systems such as variations in system load, fluctuations in power from wind and solar energy based systems as well as the randomness of power system disturbance type, location, and impedance are modeled and evaluated.

A *Python* program was designed and used to control the overall probabilistic transient stability simulation process incorporating parallel computing. Probabilistic indices of system *PLOTS* and conditional *PLOTS* are introduced and used in the studies. A significant amount of detailed information in related with transient stability performance of power systems can be obtained using the proposed approach. This information cannot be produced from a deterministic assessment. The results also show the feasibility of the probabilistic transient stability evaluation for an active distribution system as well as the necessity and advantages of using probabilistic approach for transient stability evaluation of power system.

Chapter 7

Incorporating Well-Being Considerations in Probabilistic Transient Stability Assessment

7.1 Introduction

Over the years industry is using deterministic criteria such as the *critical clearing time (CCT)* to assess the transient stability performance of a power system. The reluctance for performing probabilistic transient stability could be partly due to the difficulties in interpreting and using probabilistic reliability indexes. This complexity can be eliminated using the well-being approach by incorporating deterministic considerations into a probabilistic evaluation [15, 88–100].

Well-being analysis assigns a measure to the system operating condition that indicates its relative state of health. The basic framework associated with the well-being analysis of power systems is reasonably well-established in the assessment domains of generating capacity adequacy, operating reserve, composite generation and transmission system, and *HVdc* systems [15, 88–100].

Despite great deal of efforts that has been devoted to establishing the well-being framework for various areas in power system reliability assessment, there is no literature available on the utilization of well-being technique in transient stability evaluation. A new technique is, therefore, proposed in this thesis to extend the conventional well-being approach to power system transient stability analysis. The technique uses Monte Carlo simulation and employs accurate transient stability assessment engine and computationally-efficient algorithms to facilitate the probabilistic evaluation of electric power system transient stability performance.

The transient stability performance of a power system can be categorized as healthy, marginal or at-risk. Figure 7.1 shows the Venn diagram of the hypothetical results of a probabilistic transient stability evaluation. The categorization is done by application of the deterministic criteria to the results of the probabilistic transient stability assessment. Two commonly used deterministic transient stability criteria are introduced and used in the well-being analysis of power systems described in this thesis. The feasibility of transient stability well-being studies are examined using the results of probabilistic transient stability assessment of an active distribution network.

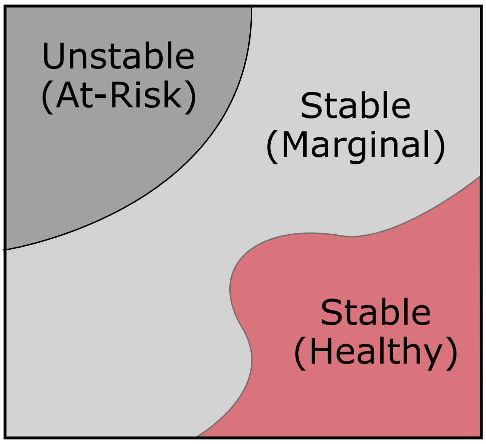


FIGURE 7.1: Venn diagram of the probabilistic transient stability evaluation

7.2 The Proposed Methodology

The procedure for evaluation of the risks associated with power systems transient stability performance and the incorporation of a deterministic consideration into a probabilistic transient stability assessment is graphically illustrated in Figure 7.2. Since the well-being framework uses the results of probabilistic transient stability assessment, the flowchart presented in Figure 7.2 is very similar to the one represented in Chapter 6 (Figure 6.1), except that the well-being analysis is added. A brief explanation of the entire process as well as a description for each part of the proposed approach was presented in Chapter 6. More details about the probabilistic transient stability assessment approach and probabilistic dynamic modeling of the test system are presented in Chapters 5 and 6.

After performing the probabilistic transient stability assessment and preparing the study results, for each simulated case, well-being analysis considering a deterministic criterion is performed to determine if it is a healthy, marginal or risk state and the probability of these states are estimated. In other words, the transient stability performance of the

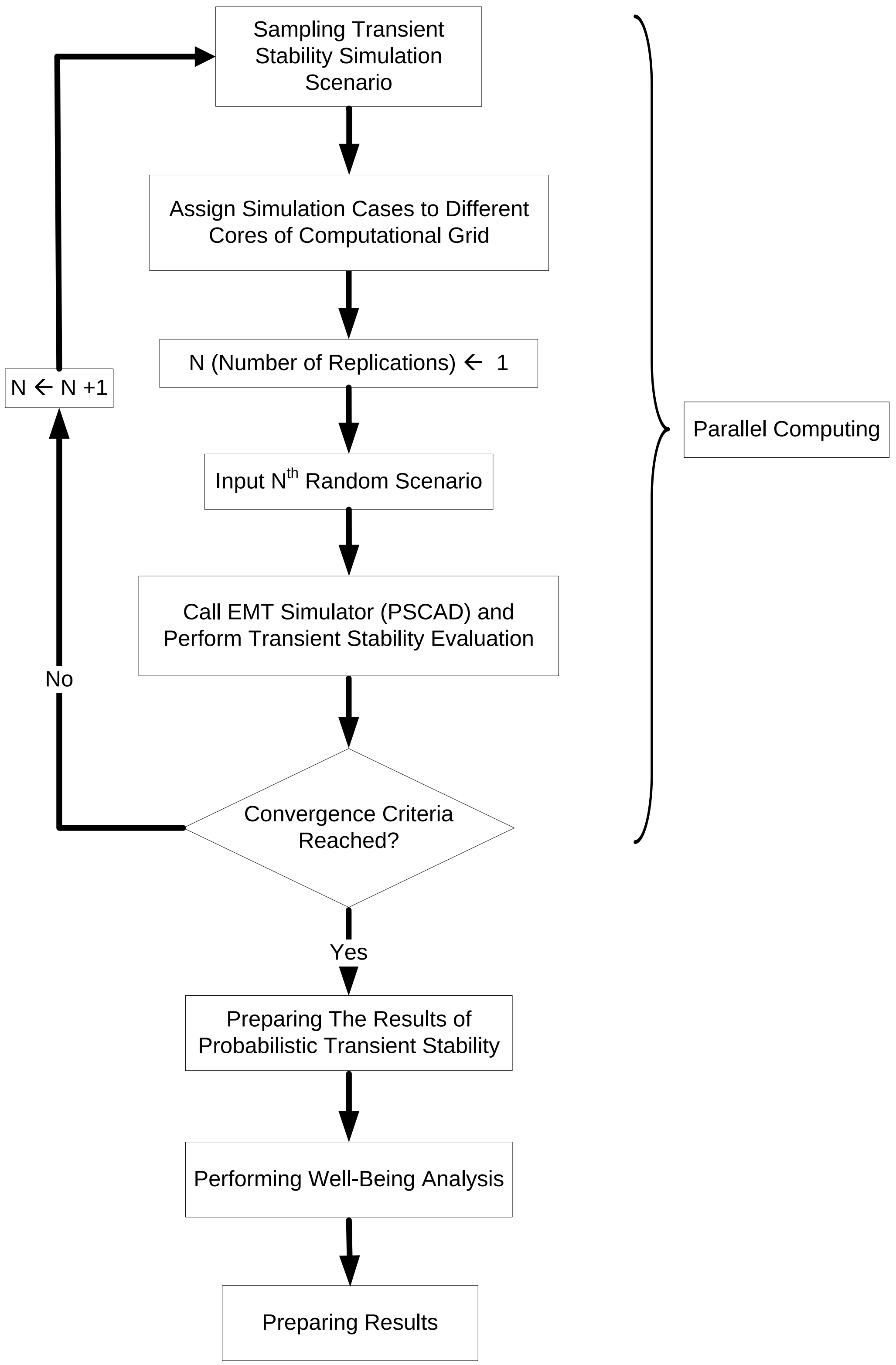


FIGURE 7.2: Framework of the proposed methodology

system is compared to the predefined margins of the deterministic well-being criterion and the state of the health of the system is determined.

7.3 Incorporating Deterministic Criterion into a Probabilistic Transient Stability Assessment

Well-being analysis incorporates a deterministic criterion into a probabilistic evaluation. The probability of instability is designated as risk state probability *P(R)* in this thesis. The degree of comfort associated with operating power system within the accepted deterministic criterion is given by the probability of residing within the healthy state *P(H)*. The marginal state probability *P(M)* is the probability of finding the system in a condition that violates the accepted deterministic criterion but is in a stable condition.

The aim should be to achieve a healthy state probability *P(H)* higher than a specified threshold. The thesis does not recommend a value for such a threshold. In the future, procedures may be found to suit each DG's requirements in determining such thresholds.

7.3.1 Selecting Criteria for System Health

In order to categorize the results of transient stability evaluation and perform the well-being analysis, it is necessary to define the deterministic criterion used in the well-being analysis. Two different criteria are used in this thesis for this aim. Based on the selected criterion, it is possible to identify the healthy or marginal category. However, the at-risk category in transient stability well-being analysis is decided regardless of the deterministic criterion and all of the unstable cases are considered in at-risk category.

7.3.1.1 Recommended Clearing Time Criterion

The first criterion which is used in this thesis is the fault clearing time. In other words, if the fault is cleared within *"Recommended Clearing Time" (RCT)*, the case is identified as healthy; otherwise it's identified as marginal or at risk. Therefore, by identifying all three categories of healthy, marginal and at-risk, the well-being analysis can be performed.

It should be noted that selection of RCT needs some historical knowledge of the power system. A clearing time between 0.1 and 1.0 second can be selected as an acceptable number for an active distribution network. Obviously, in transmission systems, a much less clearing time should be considered as RCT. Although the proposed method is capable of well-being analysis for any selected RCT value, it should be noted that RCT should be defined considering the utility operation codes. Unless otherwise specified, a RCT of 0.3 seconds is used for analyses presented in this thesis.

7.3.1.2 Damping Ratio Threshold

The second deterministic criterion used in this thesis is the damping ratio of all generator oscillatory modes (of SGs and IG). The damping ratio is the arc-cosine of the eigenvalue of the corresponding mode. Damping ratios can be evaluated using Prony Analysis of all the generator speed and angle waveforms of the *SGs* and *IG* [138]. The health of the system is the probability that all damping ratios are larger than a certain *"Damping Ratio Threshold" (DRT)*. The health will depend on what value is used for the *DRT*. A large *DRT* means that the system planning is conservative and expects all modes to be highly damped. Unless otherwise specified, a *DRT* of 5% is used for analyses presented in this thesis.

7.3.2 Prony Analysis

The method proposed in [138] is used in this thesis for the Prony analysis estimating 40 modes of the given waveform using 100 equally spaced samples.

Figure 7.3 shows the actual signal of the delta evolution of SG_1 in one of the Monte Carlo replications. The selected points for Prony analysis as well as Prony reconstructed waveform are also shown in Figure 7.3. As can be seen from Figure 7.3, the reconstructed waveform is pretty much the same as original one indicating that the developed Prony analysis algorithm is accurate.

The results of Prony analysis for speed evolution of SG_1 in one of the Monte Carlo replications is illustrated as an example in Figure 7.4. Figure 7.4 shows the magnitude, phase, and damping ratio of the largest magnitude oscillatory modes corresponding to the selected waveform. If the *DRT* is selected as 5% (a commonly used threshold for damping in large power networks), it can be seen from Figure 7.4.c that some of the oscillatory modes have damping ratios less than the *DRT*. This indicates that the studied scenario

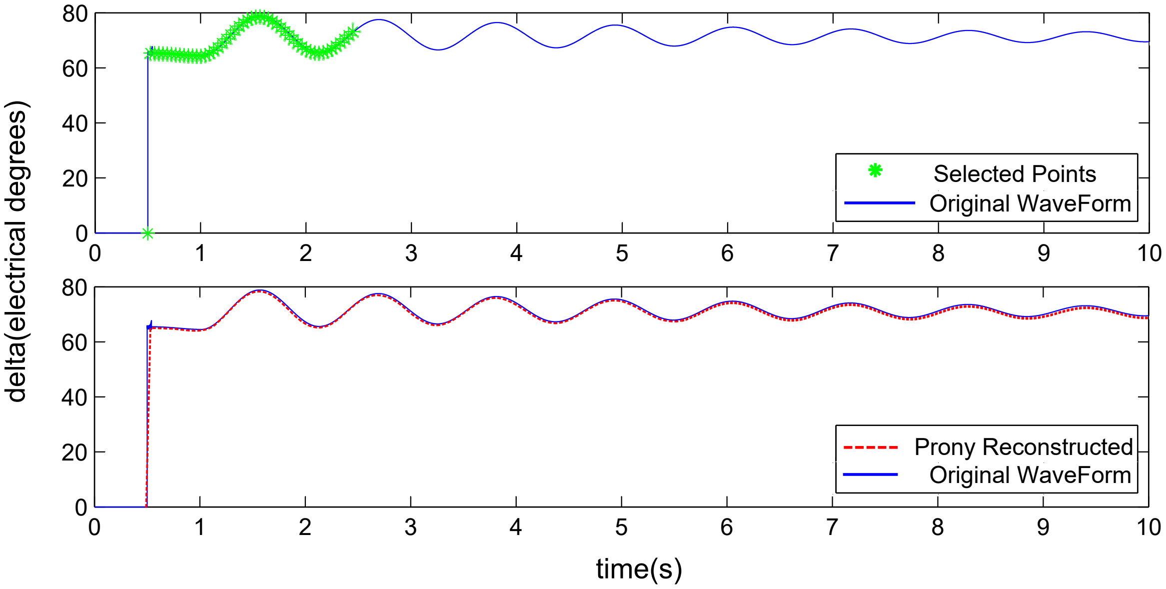


Figure 7.3: Prony analysis for rotor angle evolution of a synchronous generator

is considered as marginal in well-being analysis. For healthy state, all of the damping ratios of the oscillatory modes should be more than the selected *DRT*. The system would be in the risk state if at least one mode is unstable.

7.4 Application of the Proposed Well-being Approach

A series of well-being analyses are conducted to illustrate the applicability of the proposed approach using the data and models presented in Chapter 6. The IEEE 34 bus distribution test feeder [127] which was used in Chapter 6 is also considered here. Table 7.1 shows the base-case well-being indexes obtained using deterministic criteria of $DRT = 5\%$ and $RCT = 0.3$ sec. These values shown in Table 7.1 constitute a reference set of system well-being index for the test system considered in this thesis.

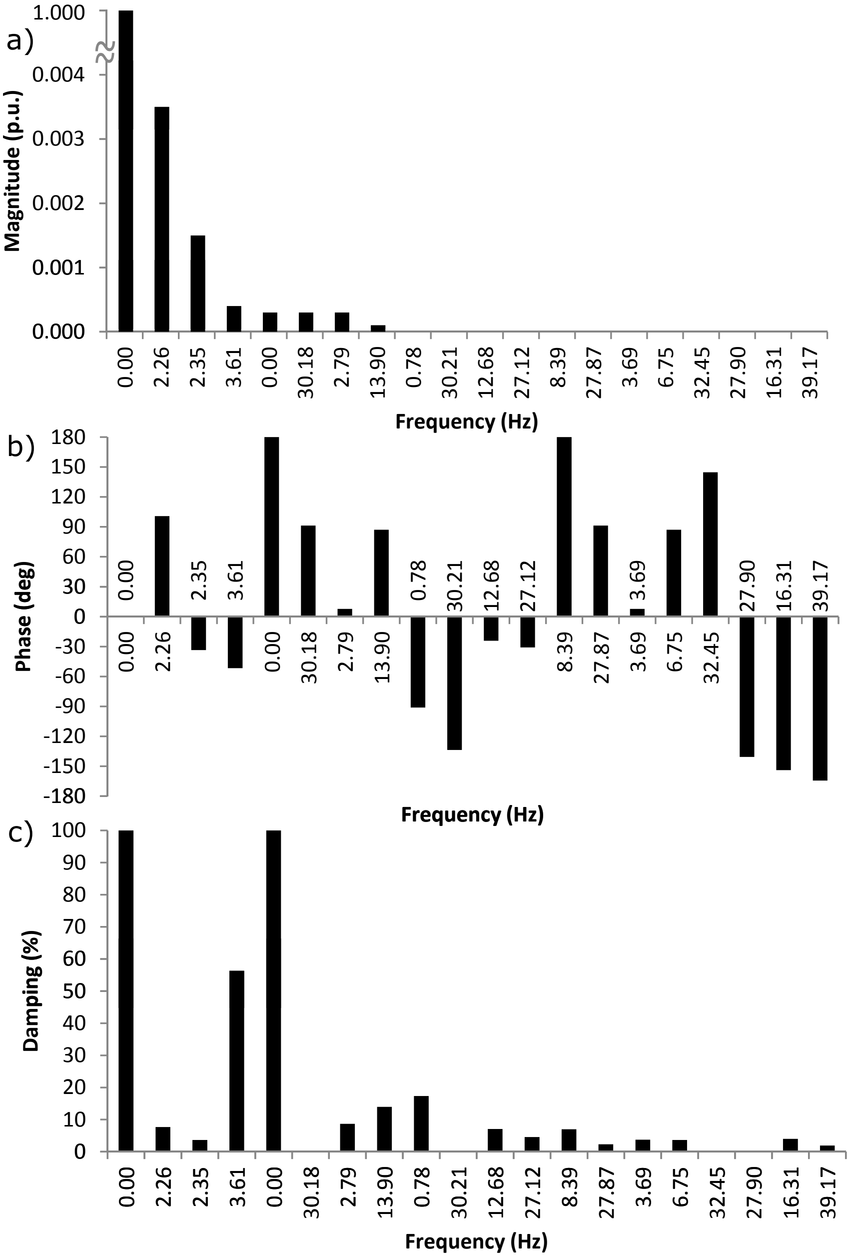


FIGURE 7.4: Oscillatory modes of the rotor angle of SG_1 from Prony analysis; a) magnitude, b) phase, and c) damping ratio

TABLE 7.1: Base-case well-being indexes

Deterministic Criterion	P(R)	P(H)	P(M)
$DRT = 5\%$	0.0425	0.5233	0.4342
$RCT = 0.3$ sec	0.0425	0.1136	0.8439

The *DRT* of 5% is recommended and used by Manitoba Hydro, Canada in power system planning.

The well-being indexes calculated using the proposed technique can be used in power system stability analysis. The desired boundaries of system stability should be determined such that a specified system risk, a specified system health or both are satisfied. Different utilities may use different deterministic criteria in their transient stability assessment. The selected deterministic criteria have impact on identifying the degree of comfort of system operating states.

7.4.1 Sensitivity Analyses for Well-being Criteria

In order to illustrate the effect, the *DRT* value was changed and the corresponding well-being indexes were calculated. Figure 7.5 shows the variation in the system health, marginal and risk probabilities as a function of the *DRT*. It can be seen from Figure 7.5 that with increase in the *DRT*, the healthy state probabilities decrease whereas the marginal state probabilities increase. The healthy state probability is directly related to an accepted deterministic criterion. For a more stringent deterministic criterion, the system will be deemed to be less healthy. The risk state probability is a fixed value for a given system, because a risky state is associated with instability, which is not a function of *DRT*. The sum of the three operating state probabilities is unity, and therefore, the marginal state probability increases as the healthy state probability decreases.

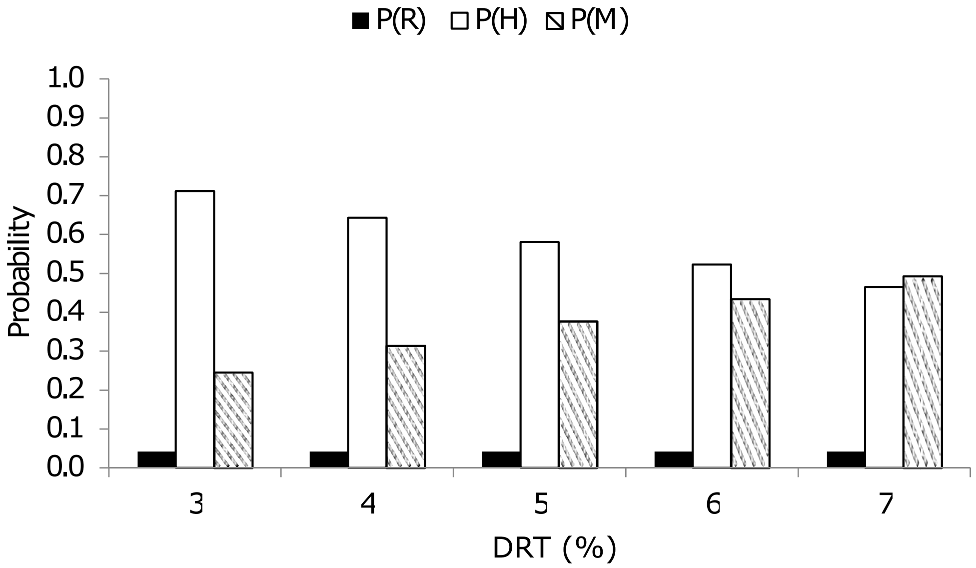


FIGURE 7.5: Impact of DRT on system health, marginal and risk

The same study is done for the RCT. The RCT value was changed and the corresponding well-being indexes were calculated. Figure 7.6 shows the variation in the system health, marginal and risk probabilities with the RCT as a function of the RCT. It can be seen from Figure 7.6 that with increase in the RCT, the healthy state probabilities increase whereas the marginal state probabilities decrease.

7.4.2 Well-being Analyses Results

Further studies are conducted to examine the effect of different fault types on the system transient stability performance in terms of the well-being indexes. From the 10,000 samples simulated for transient stability, the results related to each fault type are filtered for well-being analysis. Figures 7.7 and 7.8 show the system health, margin and risk in terms of conditional probabilities upon different types of faults using $DRT = 5\%$ and $RCT = 0.3$ (s) as deterministic criterion, respectively.

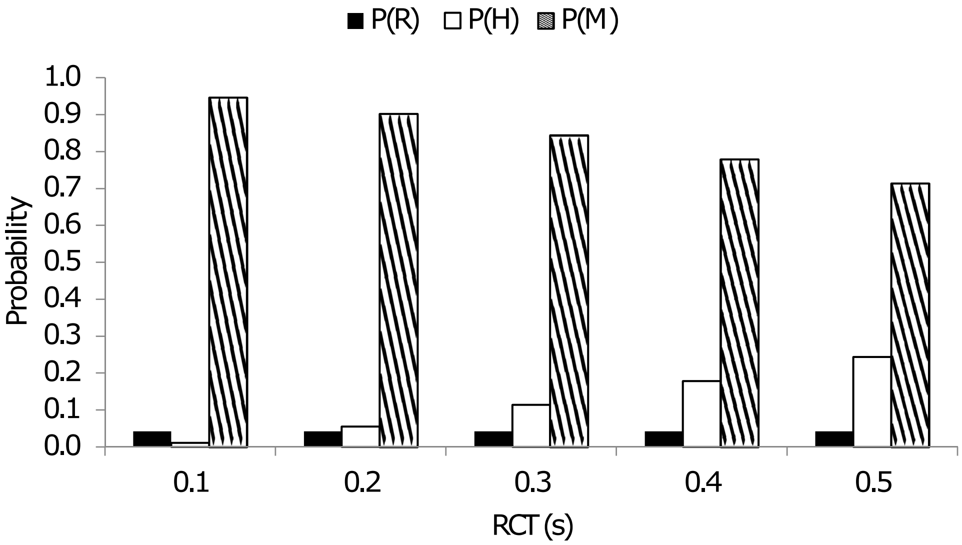


FIGURE 7.6: Impact of RCT on system health, marginal and risk

It can be seen from Figures 7.7 and 7.8 that the risk probabilities associated with a three-phase fault is higher. It should be noted that the probability of occurrence of a single phase fault is much higher than a three phase fault as shown in Table 6.5. The healthy state and marginal state probabilities are also changed under different fault conditions. In the traditional deterministic transient stability evaluations, the power system is designed to withstand the worst disturbances which are usually assumed to be three-phase to ground faults. It can be seen from Figure 7.8 that this assumption leads to healthy, marginal and risk probabilities equal to 0.4723, 0.2313, and 0.2964 respectively. If different types of disturbances are modeled in addition to the three-phase to ground fault, healthy, marginal and risk probabilities are 0.5233, 0.4342 and 0.0425, respectively as presented in Table 7.1. These results show that considering only LLLG faults in deterministic transient stability assessment results in a more pessimistic assessment of power system stability.

Well-being analysis is also performed to examine the degree of comfort for the system

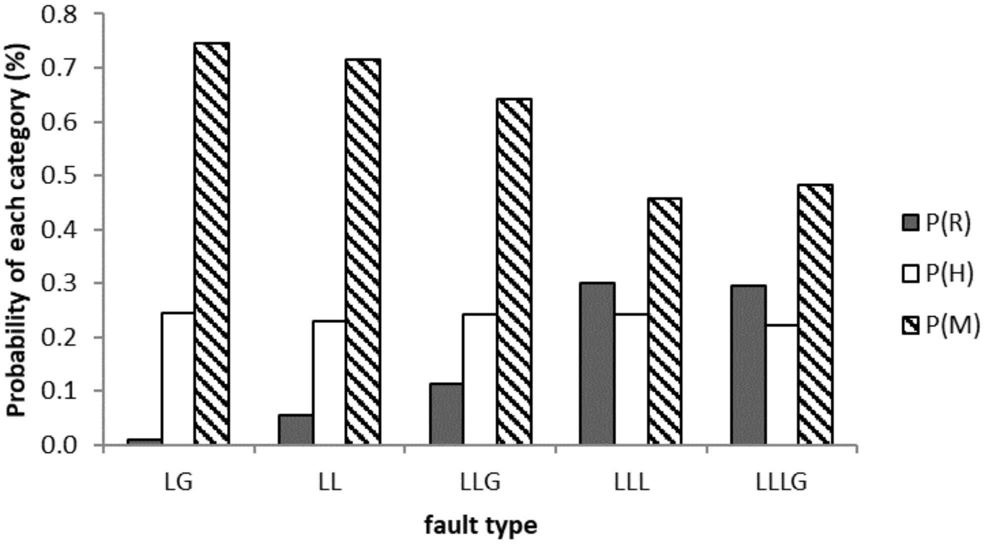


FIGURE 7.7: System health, margin and risk in terms of conditional probabilities (DRT)

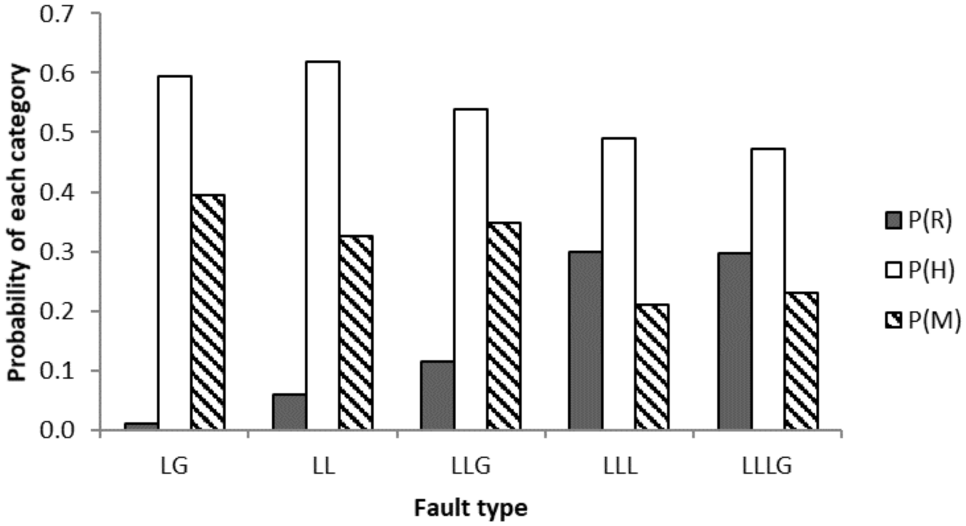


FIGURE 7.8: System health, margin and risk in terms of conditional probabilities (RCT)

associated with different generators. Figures 7.9 and 7.10 show the results for all generators modeled in the test system considering $DRT = 5\%$ and $RCT = 0.3$ (s) as the deterministic criterion, respectively. It can be seen from Figures 7.9 and 7.10 that SG_1

is the most stable generator as the health risk probability is the least. Figures 7.9 and 7.10 also show that SG1 has the highest probability of healthy state, but probability of marginal state is less than that associated with SG_2. This information is very useful and can be used to identify the weak points of the system.

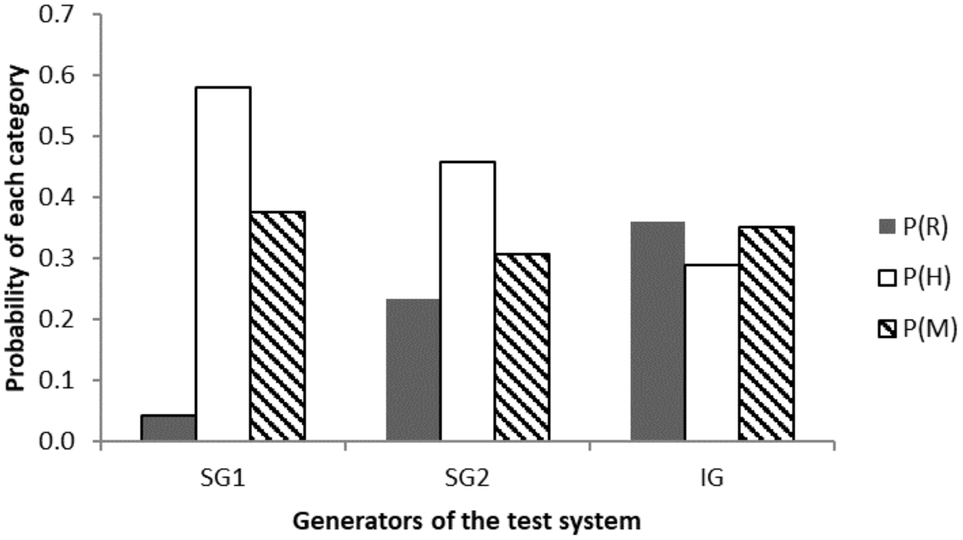


FIGURE 7.9: Well-being analysis using *DRT* for different generators

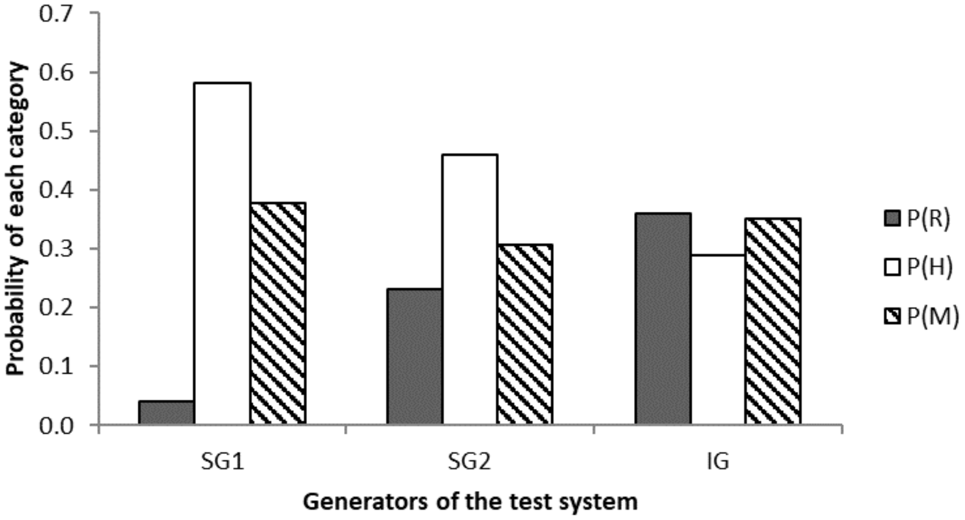


FIGURE 7.10: Well-being analysis using *RCT* for different generators

7.5 Summary and Conclusions

This chapter extends the well-being analysis to power system transient stability. The proposed approach is based on a Monte Carlo simulation and uses the computation accuracy of *EMT*-based transient stability assessment engine. The Monte Carlo process for probabilistic transient stability assessments is enhanced with a parallel computing technique to facilitate the simulation. Various uncertainties associated with a power system are modeled and considered in the well-being assessment. The overall system well-being is defined in terms of the system healthy and marginal probabilities based on two widely used deterministic criterion in addition to the conventional risk index.

The technique is illustrated using an example test system. A range of results which are not available from deterministic transient stability evaluation are produced and discussed. These results should provide a good insight into the transient stability performance of power systems and are very useful in power system planning and operation.

The well-being analysis is focused on the single objective of transient stability performance in this thesis. However, true “well-being” should include other factors such as power quality. The other objectives could be included in well being analysis in the future.

Chapter 8

Conclusions and Future Work

Power system stability performance can be evaluated using either a deterministic approach or a probabilistic method. Deterministic assessment of power system stability typically considers the worst-case scenario of the system and therefore most often results in a conservative evaluation of power system stability performance. A review on literature shows that there is extensive research on the application of deterministic methods for power system transient stability assessment. Based on the literature review results, *PSCAD/EMTDC* is selected as an engine for performing power system dynamic simulation in the research described in this thesis because of the higher accuracy of the EMT-based time domain method for transient stability assessment. The effects of modeling details on the accuracy of transient stability simulation results are examined through deterministic assessments on a small example system. Increase in modeling details of synchronous generators results in higher accuracy as well as higher computational burden.

The system transient performance is improved if the controllers of induction generators are modeled.

the capability of these models for performing transient stability assessment. It is found that these linear models are dependent on the point of linearization and cannot be used for all the operating points of the system.

An anomalous transient stability behavior of synchronous generators with high impedance faults was found and examined during the course of the research described in this thesis. It is shown that for a high resistive impedance fault, there are time windows after critical clearing time that if the fault is removed in this time windows, the system remains stable. The phenomenon was observed in EMT simulation and rationalized using equal area criterion method.

Power system behavior is stochastic in nature and the numerous uncertainties facing the industry drive a need to use probabilistic evaluation methodologies in power system stability assessment. Incorporation of distributed energy resources to the passive distribution networks changes their nature by transforming a purely passive system into an active network. Disconnection from the upstream network (if possible) enables the islanded operation of a micro-grid. Active distribution networks and micro-grids like typical power systems may not be accurately assessed through conventional deterministic stability studies and many random operating scenarios are needed to be considered. Literature review shows that relatively less work has been done on transient stability evaluation of micro-grids and active distribution networks using probabilistic approaches.

It is, therefore, both necessary and important to develop appropriate probabilistic models and techniques to investigate transient stability performance of such active networks. New models, approaches and techniques for probabilistic transient stability assessment of power systems are, therefore, proposed in the research described in this thesis.

A Monte Carlo simulation based approach for the probabilistic evaluation of transient stability of power systems is proposed. The approach takes the advantages of the calculation accuracy of EMT simulation and the efficiency of fast computing algorithms such as parallel computing to perform probabilistic transient stability evaluation of power systems. Probabilistic models for simulating various uncertainties associated with several new components in ADNs such as IM, PV panels, etc. are developed and incorporated in the proposed technique. These uncertainties include but are not limited to variations in system load, fluctuations in power from variable energy sources such as wind and solar and randomness associated with power system disturbances for example fault type, location, and impedance. A probabilistic index referred to as the $PLOTS$ is proposed. Two types of $PLOTS$ indices referred to as system $PLOTS$ and conditional $PLOTS$ are used in the studies described in this thesis. The applicability of the proposed approach is illustrated by performing probabilistic transient stability studies on a representative active distribution network as an example system. The effects of some of the major system parameters on the $PLOTS$ index are also examined. A significant amount of detailed information in related with transient stability performance of power systems can be obtained using the proposed approach. This information cannot be produced from a deterministic assessment. The results also show the feasibility of the probabilistic transient stability evaluation for an active distribution system as well as the necessity and advantages of using probabilistic approach for transient stability evaluation of power systems.

The proposed approach is also extended to establish a well-being framework for transient stability assessment. Probabilistic models are developed to extend the conventional well-being approach to power system transient stability assessment. The overall system well-being is defined in terms of the system healthy and marginal probabilities based on the accepted deterministic criterion in addition to the risk index of the $PLOTS$. A range of well-being analysis is performed to illustrate the applicability of proposed well-being framework. The effects on the system wellbeing of some of the major parameters including the deterministic criterion are illustrated. The results which are not available from deterministic transient stability evaluation are produced and discussed. These results should also provide a good insight into the transient stability performance of power systems and are very useful in power system planning and operation.

8.1 Publications

Some of the study and research results are published in or submitted to academic journals and conference proceedings for sharing the fidings of the research with others and for disseminating the new knowledge obtained through the research described in this thesis in the power industry and academia. The following is a list of papers published and/or developed during the course of this research.

- Journal Paper

  1. M. Amiri, T. Y. Vega and A. M. Gole, “Anomalous Stability Behavior of Synchronous Machine With High Impedance Faults,” in IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 4157-4158, Sept. 2016.

- Conference Papers

  1. M. Amiri, B. Bagen, A. Gole, “Probabilistic Analysis of the Effect of Wind Speed Variations on Power Quality of Power Systems,” 2016 International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2016, Beijing, China.
  2. M. Amiri, T. Y. Vega, A. Gole, “Effect of DG modeling and controllers on the transient stability of micro-grids in EMT simulation”, PowerTech, 2015 IEEE Eindhoven, Eindhoven, 2015, pp. 1-6.
  3. M. Amiri, T. Y. Vega, A. Gole, “Evolving from a distribution system simulation platform to a micro-grid simulation platform for transient studies,” Renewable Power Generation Conference (RPG 2014), 3rd, Naples, 2014, pp. 1-5.

8.2 Future Work

Potential future extensions to the research are suggested as follows:

- A Monte Carlo based approach is proposed to simulate the uncertainties associated with power systems in transient stability assessments. The Monte Carlo methods used in the research described in this thesis is the crude Monte Carlo technique and the simulation process is facilitated by parallel computing, The Monte Carlo process can also be facilitated using other techniques for example the variance reduction technique. Further research on employing other approaches for improving the efficiency of the Monte Carlo algorithm would be extremely useful.

- The main simulation engine used in the studies described in this thesis is the *PSCAD/ EMTDC*. The *PSCAD/EMTDC* engine requires relatively detailed models and therefore needs extensive computational time. Very detailed models are, however, not always required in power system transient stability assessments. A simpler one phase representation of power systems is often enough to examine the transient performance of power systems using simulation engines such as *PSS/E*. Extension of the research using *PSS/E* as a stability simulation engine would be very useful and provides a wide range of reliability assessment particularly for large and complex power systems.

- In this thesis, the number of *DGs* and their name plate capacities as well as connection points to the network were predefined. Other planning may reveal different probabilistic transient stability results. Hence, in order to find the optimum penetration level, point of connection and size of *DGs* for transient stability performance of the selected test system, sensitivity analysis may be performed.

- A protection system can be designed for the active distribution network and the effect on the protection system on the transient stability results can be studied.

- The well-being analysis is focused on the single objective of transient stability performance in this thesis. However, true "well-being" should include other factors such as power quality. The other objectives could be included in well being analysis in the future.

- Probabilistic evaluation of the power quality of power systems (especially transient and steady state voltage performance) and well-being studies on the power quality assessment can be considered as two major extensions of this research.

Appendix A

Stability Analysis Using Linearized Models

Linearized models of synchronous machines are widely used in small-signal analysis. Their attractiveness is that for finding the dynamic performance of the system, the time-based simulation is not required and parametric behavior can be analytically derived. For this reason, the feasibility of assessing transient stability analysis using linearized models approach is investigated in this thesis.

The linear model of a *SMIB* system is developed using *Model 2.2* of a synchronous generator. A detailed explanation for the linearization process can be found in [4]. Basically, the linearization of a *SMIB* system entails:

- Solving the machine and network equations to find the steady state operating point

- Linearization of the resultant equation
- Linearization of the differential equations of the machine
- Representation of the system in state space model

To analyze the stability of the system using state space representation, the system should be modeled as [139]:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{A.1}$$

Where, x, y, u, A, B, C, and D are state vector, output vector, input vector, state matrix, input matrix, output matrix, and feed-froward matrix, respectively.

Using this representation the transfer function of the system can be found as:

$$G(s) = C(sI - A)^{-1}B + D \tag{A.2}$$

Since the transfer function representation of a system gives the opportunity to perform frequency domain analysis, frequency domain methods such as Root-locus, Bode and Nyquist can be used for stability studies [139].

By using Model 2.2 of SG and application of the linearization of *SMIB* system of Figure 3.1, state and input matrices of the system can be derived as follows [4]:

$$x = \begin{bmatrix} \Delta\omega_r & \Delta\delta & \Delta\Psi_{fd} & \Delta\Psi_{1d} & \Delta\Psi_{1q} & \Delta\Psi_{2q} \end{bmatrix}^{-1} \tag{A.3}$$

$$u = \begin{bmatrix} \Delta T_m \\ \Delta E_{fd} \end{bmatrix} \tag{A.4}$$

Considering the parameters of the *SMIB* system (Table 3.1), matrices A and B are calculated as follows:

$$A = \begin{bmatrix} 0 & -0.1582 & -0.0833 & -0.0802 & -0.0204 & -0.1181 \\ 376.9911 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.1327 & -0.7885 & 0.5976 & 0.0001 & 0.0005 \\ 0 & -5.9967 & 26.8739 & -35.4994 & 0.0040 & 0.0235 \\ 0 & -0.1376 & -0.0009 & -0.0009 & -2.9289 & 2.2229 \\ 0 & -3.0512 & -0.0203 & -0.0196 & 8.4971 & -22.1808 \end{bmatrix} \tag{A.5}$$

$$B = \begin{bmatrix} 0.1418 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1374 & 0 & 0 & 0 \end{bmatrix}^{-1} \tag{A.6}$$

The eigenvalues of the matrix A are shown in Table A.1.

Table A.1: Eigenvalues of the *SMIB* system

-35.8282
-22.8983
-0.0407
-1.7958
-0.4173 ± 7.0560j

As can be seen, all of the eigenvalues have negative real part and hence the system is stable. If δ is considered as the output of the system, transfer function can be calculated using Equation (A.1):

$$T(s) = \frac{1}{s^6 + 61.4s^5 + 1029s^4 + 5312s^3 + 4.77 \times 10^4 s^2 + 7.554 \times 10^4 s + 2996} \tag{A.7}$$

Root-locus and Bode diagrams of the *SMIB* system are shown in Figures A.1 and A.2, respectively.

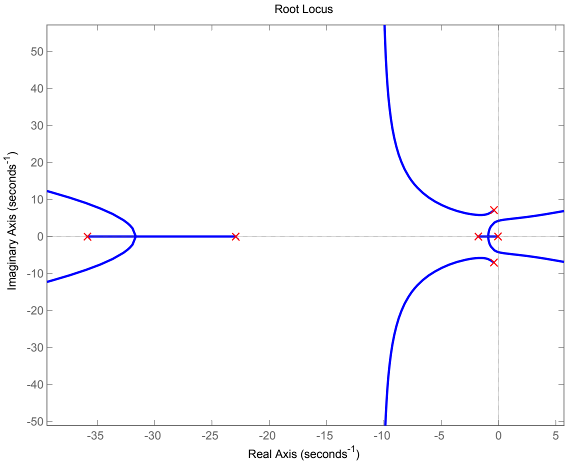


FIGURE A.1: Root Locus plot of the *SMIB* system

Note that all of previous linearized analyses are performed for the steady state operation of the system.

Phase margin and gain margin are two candidates to be selected as stability index and they can be used for relative stability analysis.

In order to use the linearized model (frequency domain method) for transient stability analysis, a large disturbance should be applied to the system under study. The problem

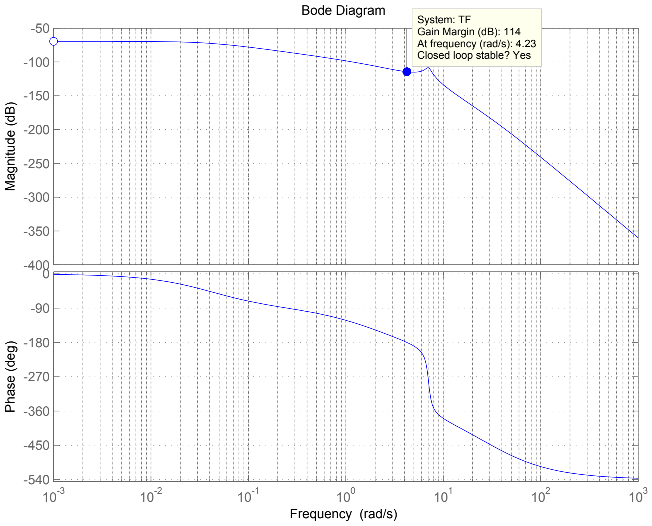


Figure A.2: Bode diagram of the *SMIB* system

which emerges here in using linearized models for transient stability analysis is that the disturbance duration can not be considered anywhere in this analysis. The reason is that linearized model needs initial condition for linearization and hence the matrix 'A' will be determined using initial conditions and will not change during the frequency analysis. The steady state operation of the system is initial condition and the duration of the disturbance which is a very important parameter in transient stability analysis does not have any influence on the results of the study. In other words, there is no difference between linearized models for two cases with the same fault impedances and different fault durations.

Note that, linearization for operation of a system with a large disturbance is not valid, since the changes of the variables of the system is too much to be considered as linear. Considering the reasons provided above, the linearized model approach is not used in this thesis for transient stability assessment.

Appendix B

Derivation of Critical Clearing Time of an Induction Generator

Using the steady-state equivalent circuit of IG shown in Figure B.1, this proposed approach of Reference [115] is demonstrated in the following equations:

$$V_{TH} = \frac{Z_M}{Z_M + Z_S} V_T \tag{B.1}$$

$$Z_{TH} = R_{TH} + jX_{TH} = \frac{Z_M Z_S}{Z_M + Z_S} \tag{B.2}$$

Where, $Z_M = jX_M$, $Z_S = R_S + jX_S$. The magnitude of the rotor current and the electrical torque can be found as follows:

$$|I_R| = \frac{V_{TH}}{\sqrt{(R_{TH} + R_R/s)^2 + (X_{TH} + X_R)^2}} \tag{B.3}$$

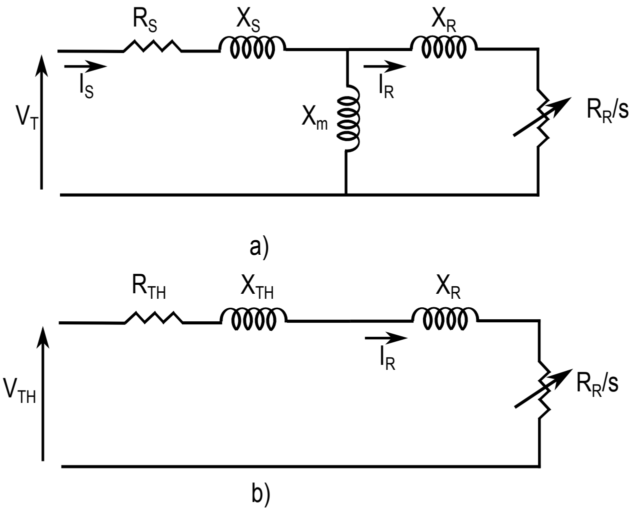


FIGURE B.1: Steady-state equivalent circuits of an IG; a) Complete circuit. b) Reduced circuit

$$T_E = \frac{R_R}{s}|I_R|^2 = \frac{V_{TH}^2}{(R_{TH} + R_R/s)^2 + (X_{TH} + X_R)^2} \tag{B.4}$$

Solving $T_M = T_E$ will result in a quadratic equation:

$$(R_{TH}^2 + (X_{TH} + X_R)^2)s^2 + (2R_R R_{TH} - R_R V_{TH}^2/T_M)s + R_R^2 = 0 \tag{B.5}$$

If the resultant quadratic equation is solved, the steady-state speed and critical speed can be calculated as follows:

$$\begin{aligned} \omega_0 &= 1 - \tfrac{b+\sqrt{\Delta}}{2a} \\ \omega_{critical} &= 1 - \tfrac{b-\sqrt{\Delta}}{2a} \end{aligned} \tag{B.6}$$

Where, $a = R_{TH}^2 + (X_{TH} + X_R)^2$, $b = 2R_R R_{TH} - R_R V_{TH}^2/T_M$, $c = R_R^2$, $\Delta = b^2 - 4ac$.

Critical clearing time of the IG can be found by solving Equation (3.8) and substitution of Equations (B.6):

$$CCT = (\frac{-2H}{T_M}\frac{1}{R_{TH}^2+(X_{TH}+X_R)^2})\sqrt{\frac{R_R^2}{T_M^2}(-4(X_{TH}+X_R)^2T_M^2-4R_{TH}V_{TH}^2T_M+V_{TH}^4)} \tag{B.7}$$

Appendix C

Test System Data

Table C.1: Shunt capacitors

Node	Ph-A kVAr	Ph-B kVAr	Ph-C kVAr
844	100	100	100
848	150	150	150
Total	250	250	250

Table C.2: Overhead line configurations

Config.	Phasing	Phase ACSR	Neutral ACSR	Spacing ID
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

Table C.3: Distributed loads

Config.	Phasing	Phase ACSR	Neutral ACSR	Spacing ID				
Node A	Node B	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
802	806	Y-PQ	0	0	30	15	25	14
808	810	Y-I	0	0	16	8	0	0
818	820	Y-Z	34	17	0	0	0	0
820	822	Y-PQ	135	70	0	0	0	0
816	824	D-I	0	0	5	2	0	0
824	826	Y-I	0	0	40	20	0	0
824	828	Y-PQ	0	0	0	0	4	2
828	830	Y-PQ	7	3	0	0	0	0
854	856	Y-PQ	0	0	4	2	0	0
832	858	D-Z	7	3	2	1	6	3
858	864	Y-PQ	2	1	0	0	0	0
858	834	D-PQ	4	2	15	8	13	7
834	860	D-Z	16	8	20	10	110	55
860	836	D-PQ	30	15	10	6	42	22
836	840	D-I	18	9	22	11	0	0
862	838	Y-PQ	0	0	28	14	0	0
842	844	Y-PQ	9	5	0	0	0	0
844	846	Y-PQ	0	0	25	12	20	11
846	848	Y-PQ	0	0	23	11	0	0
Total			262	133	240	120	220	114

Table C.4: Line Segment data

Node A	Node B	Length(ft.)	Configuration
800	802	2580	300
802	806	1730	300
806	808	32230	300
808	810	5804	303
808	812	37500	300
812	814	29730	300
814	850	10	301
816	818	1710	302
816	824	10210	301
818	820	48150	302
820	822	13740	302
824	826	3030	303
824	828	840	301
828	830	20440	301
830	854	520	301
832	858	4900	301
832	888	0	XFM-1
834	860	2020	301
834	842	280	301
836	840	860	301
836	862	280	301
842	844	1350	301
844	846	3640	301
846	848	530	301
850	816	310	301
852	832	10	301
854	856	23330	303
854	852	36830	301
858	864	1620	302
858	834	5830	301
860	836	2680	301
862	838	4860	304
888	890	10560	300

Table C.5: Regulators data

Regulator ID:	1		
Line Segment:	814 - 850		
Location:	814		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2.7	2.7	2.7
X - Setting:	1.6	1.6	1.6
Volltage Level:	122	122	122

Regulator ID:	2		
Line Segment:	852 - 832		
Location:	852		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2.5	2.5	2.5
X - Setting:	1.5	1.5	1.5
Volltage Level:	124	124	124

Table C.6: Spot loads

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-4 kVAr
860	Y-PQ	20	16	20	16	20	16
840	Y-I	9	7	9	7	9	7
844	Y-Z	135	105	135	105	135	105
848	D-PQ	20	16	20	16	20	16
890	D-I	150	75	150	75	150	75
830	D-Z	10	5	10	5	25	10
Total		344	224	344	224	359	229

Table C.7: Regulators data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2500	69 - D	24.9 -Gr. W	1	8
XFM -1	500	24.9 - Gr.W	4.16 - Gr. W	1.9	4.08

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