IMPLEMENTATION OF PROBABILISTIC TECHNIQUES

IN

TRANSIENT STABILITY STUDIES

A Thesis

Submitted to the College of Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in the
Department of Electrical Engineering
University of Saskatchewan

by

KELVIN CHI-HUNG CHU
Saskatoon, Saskatchewan
March 1985

COPYRIGHT

ACKNOWLEDGEMENTS

The author would like to express his sincere thanks and appreciation to his supervisor, Dr. Roy Billinton who has expedited this research with substantial advice, discussion and encouragement. He has guided this work with a wise and balanced mix of direction and latitude.

Sincere thanks are also extended to Dr. R.J. Fleming and Dr. M.S. Sachdev for their help and advice on numerous occasions. The author would also like to acknowledge and thank Mr. Lorry Wilson and Mr. Charles Shih of the Saskatchewan Power Corporation for their assistance in supplying the necessary data for the study carried out in this work.

Special thanks are due to his wife, Ellen, for her patience and constant encouragement throughout the period of this research.

This work was financed by the University of Saskatchewan in the form of Graduate Scholarship and by the Natural Sciences and Engineering Research Council of Canada.

Electrical Engineering Abstract 85A248

"IMPLEMENTATION OF PROBABILISTIC TECHNIQUES IN TRANSIENT STABILITY STUDIES"

Student: Kelvin Chi-Hung Chu Supervisor: Dr. Roy Billinton

M. Sc. Thesis Presented to the College of Graduate Studies

March 1985

Abstract

Stability studies have become an essential part of power system planning, design, control and operation. Two types of stability studies are generally considered, namely, steady-state stability studies and transient stability studies. This thesis deals with transient stability only. A transient stability study is concerned with the effect of a large or sudden disturbance on a system and the ability of the system to handle such perturbations. It has been observed that factors such as fault types, fault locations, fault clearing schemes, system parameters and initial operating conditions greatly affect the transient performance of a system. A number of these factors are probabilistic in nature. The probabilities of the occurrence of these factors vary from one system to another and depend on the weather condition. Transient stability studies are presently normally conducted in a deterministic manner. A "worst-case" contingency is introduced to the system and the system is investigated for its transient performance. The result obtained using this approach is generally conservative and ignores the probabilistic aspects of the problem. It is therefore necessary to include the probabilities associated with these factors in order to obtain a more realistic appraisal of system security. An index, called the "Probability of Stability" was proposed by Billinton and Kuruganty which illustrates the margin and profile of the system stability. This is the probability that the system disturbance will be removed within the critical clearing time.

This thesis describes the implementation of the concept proposed by Billinton and Kuruganty into a compact framework. The digital computer program developed is a self-contained, integrated program which takes into account different possible contingencies and their corresponding probabilities. The results are displayed in both tabular and graphical forms. Some of the system parameters can be changed interactively to perform sensitivity studies. The system can be investigated in part or entirely. The result is a set of indices which indicate the transient performance of a system. The program was tested by investigating two multi-machine systems, one an 8-bus system and the other a 42-bus Saskatchewan Power Corporation equivalent system. The sentivities of these indices to some of the factors are investigated and are presented in this thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

The demand for energy has been increasing steadily since the beginning of the industrial revolution. The invention of the induction motor by Nikola Tesla in 1888 marked the growing importance of electrical energy in the industrial world. It has been estimated that the demand for electrical energy in North America has doubled every ten years [1].

Electrical energy has become the core of modern development. Industrial societies are so highly dependent on the supply of electrical energy that a major system black-out may involve damages in the order of billions of dollars and affect society tremendously.

A loss of electrical power supply will stop production and may cause damage to equipment and products. A prolonged loss of electrical power will result in the spoilage of food, inconvenience to human living and comfort and may even invoke instability in the community due to riots or increases in crime, etc. The stability of the power system cannot be ignored in modern societies which are so highly dependent on electrical energy supply.

1.1 Importance of Power System Stability to Engineers and System Scientists

Increases in system load demand requires more system components, such as generators and transmission lines etc., to be added to the system. As communities expand due to the growth in population, the area served becomes wider, and larger generators and longer transmission lines are often required. Systems tend to become larger, more complex and sophisticated. They are also interconnected to other systems for better reliability and operating economics.

As the system grows bigger, more components are installed. The characteristics of these components are mostly non-linear in nature, therefore a power system is a large non-linear system. Like any other non-linear system, stability becomes a definite problem for power system engineers. The performance of such complex systems must be predicted by the system designers. This task provides a challenge which requires powerful tools of analysis and synthesis. This challenge requires intellect, knowledge and experience. Stability evaluation is an important aspect of both system planning and operation.

A power system is a large scale non-linear system. It therefore provides a classical vehicle for the application of available stability analysis techniques and for the testing of new ones that may be developed. Considerable work has been done and is continuing to be done in this important area by power system engineers, scientists, research workers and others.

1.2 A Brief History of Power System Stability Evaluation

Stability in a power system is a problem associated with the parallel operation of synchronous machines. Edward Kimbark [2] suggested that the problem might have appeared when synchronous machines were first operated in parallel and that the first serious problem of parallel operation, however, was not stability, but "hunting".

Hunting in synchronous machines was initially due to pulsating torque delivered by direct-connected steam engines. This was aggravated by the resonance between the period of pulsation of the prime-mover torque and the electromechanical period of the power system. Other factors such as improper design of the machine or even too high a line resistance could also cause "hunting" of synchronous machines operating in parallel.

The seriousness of hunting among synchronous machines operating in parallel was reduced with the addition of machine damper windings as suggested by LeBlanc in France and Lamme in America. The problem generally disappeared with the introduction of steam turbines.

Stability of generating machines was not a general problem during the first twenty years of this century. The stability limits were well above the normally transmitted power due to the lower reactances in the circuits because of the short length of transmission lines and in the machines for good inherent voltage regulation. With the introduction of automatic voltage controlling devices such as generator-voltage regulators, induction feeder-voltage regulators and synchronous condensers, it was possible to increase generator reactances and line impedances. This results in a more economical design and has the advantage of limiting the short-circuit currents. These modifications, however, led to a decrease in the inherent stability of the power system.

Stability soon became an important problem especially in systems with long-distance transmission. An example is that of a remote hydro station feeding into a densely populated center. Economics would dictate a tendency to transmit power which approaches the steady state stability limit, leading to a more serious stability problem particularly when a short circuit occurred on the lines.

Stability problems became the object of thorough investigation from about 1920 onward. Many tests were made and different methods of analysis were developed. Some of the analytical methods commonly used will be discussed later.

Ever since that time, stability consideration has been recognized as an essential part of power system design, operation and control [3,4]. Many fundamental papers on this subject have been published. Some of them were edited in Reference 5. A considerable number of texts have also been written which are devoted, in part or entirely to stability analysis [1,6-10].

1.3 Steady-State and Transient Stability

Generally, two types of stability problems are considered, namely, steady-state stability (sometimes called dynamic stability) and transient stability. The types are distinguished by the nature of the disturbance.

Steady-state stability studies consider the ability of the system to operate under stable conditions at some particular load point and the effect of an incrementally small change in system loading upon the ability to operate.

Transient stability studies consider the effect of a large or sudden perturbation on the system and its ability to operate. The disturbances can be a line fault, a loss of load, a loss in capacity, or due to line switching, etc.

This thesis deals only with transient stability and steady-state stability is not discussed further.

In summary, transient stability analysis considers the performance of the system when it is subjected to a large or sudden disturbance.

1.3.1 General Definition for Power System Stability

Edward Kimbark [2] suggested the following definition:

> " Power system stability is a term applied to alternating current electric power systems, denoting a condition in which the various synchronous machines of the system remain in synchronism, or 'in-step', with each other."

Briefly speaking, the stability problem concerns the behaviour or performance of synchronous machines after they have been perturbed. If the disturbance does not involve any net change in power, the machines should return to their original state. If an unbalance between the supply and demand is created by a change in load, in generation, or in network conditions or configuration, a new operating state is necessary.

Following this disturbance, power flow in the system will try to readjust itself to the new condition. This fluctuation in power flows is oscillatory and will be damped toward a new quiescent operating condition if the system is stable. If the oscillation is excessive, it may trip protective equipment and therefore create a major system interruption.

When a power system operating under a steady load condition is perturbed, a readjustment of the voltage angles of the synchronous machines will occur. If such an occurrence creates an unbalance between the system generation and load, it will result in the establishment of a new steady-state operating conditions, with the subsequent adjustment of the voltage angles.

This adjustment period is called the transient period. The system behaviour during this time is called the dynamic system performance. This is important in defining system stability. The main criterion for stability is that the synchronous machines remain in synchronism, that is, all remain operating in parallel and at the same speed at the end of the transient period.

Another definition can now be stated [1]:

> " If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition, we say the system is stable. If it does not, it is considered unstable."

1.3.2 Causes of Power System Instability

There are many events which may lead to the instability of a power system. Some of these are:

1. One or more generators fall out of step or synchronism with respect to the rest of the system, or
2. Inter- or intra-connected areas trip due to large oscillations or fluctuations in power flows with possible cascade tripping in a large network.

The most common perturbing influences on the system are:

1. line faults, especially on a heavily loaded line.
2. a sudden loss of load.
3. a sudden loss in generating capacity.
4. line switching.

It is impossible to prevent the loss of synchronism for all possible system incidents. A basic and practical approach for the system engineer is to ensure that synchronism is maintained under certain specified basic contingencies. Some examples are :

1. the tripping of interconnections.
2. a sudden increase in load,
3. the loss of a large generator or group of generators, and
4. a three, two or single phase fault at or near a generating or main terminal station with or without successful line reclosing.

1.4 Available Analytical Methods Used in Transient Stability Evaluation

The analysis of transient stability is generally speaking essentially a study of a set of non-linear differential equations, known as the "Swing Equations". Since there is no single method of solving general simultaneous non-linear differential equations, several special methods which are applicable especially to the power system stability problem have been developed. Transient stability analysis is done generally by checking that the system is stable for each contingency chosen from a selected list.

Engineers have been seriously searching for and developing analytical methods for the prediction and study of power system stability [11] since 1920. Several methods which were proposed and tested prior to 1937 are documented in Reference 12. Since that time there has been a steady increase in the number of publications in this area [13,14].

The many methods developed can generally be classified into one of two categories, Classical methods and Direct Methods.

1.4.1 Classical Methods

This can also be divided into two subcategories as follows:

A) Methods for simple two-machine or lower order systems.

B) Methods for multi-machine systems - numerical methods.

A) Methods for simple two-machine or lower order systems

i) Equal area criterion method:

The equal area criterion is a classical method often used to study the simple two-machine problem. The method is described in many text books [2,15]. Its value lies more in the conceptual insight it provides rather than its practical value for quantitative evaluation. This method is based on the comparison of system energies before and after a fault. If the acceleration energy, gained during the fault and represented by an area on the power angle diagram, is less than or equal to the post-fault deceleration system energy, which is represented by another area on the power angle diagram, then the system is stable. The fault clearing time at which these two areas are equal is called the "Critical Clearing Time". The drawback of this method is that it cannot handle systems with more than two machines. It is, therefore, of limited value other than for illustrative purposes.

ii) Graphical method :

In this method, the techniques of using phase planes, e.g., the isocline method and the acceleration plane method, are introduced to take care of some types of non-linearities [16,17]. These techniques require very skillful and lengthy drafting work, so they are impractical for general use. Another problem of this method is that it cannot handle systems of higher order.

B) Methods for Multimachine Systems - Numerical Methods

Many numerical methods have been developed to solve the non-linear differential equation problem and many texts have been published. The "point-by-point" or "step-by-step" method [2] is the most widely used technique for solving the swing equations. It was particularly useful at the time when computations were done by hand or by network analyzers instead of by digital computers. The installation of digital computers and the tremendous increase in computation power make other numerical methods more feasible and permit more accurate results.

In general, the time specific solution for the machine angles of the swing equations is obtained numerically by a step-by-step integration procedure for a period extending from after the inception of the fault up to the clearing of that particular fault. The swing (power angle) curves are calculated by directly integrating the velocity changes with respect to time. If the angles of all machines are converging to an equilibrium condition at the end of the integration period, then a stable condition is indicated.

1.4.2 Direct Methods

These include the direct method of Lyapunov and the subsequent improvements on the method.

A) Energy Integral method

This was first proposed and applied by Aylett in 1958 [18] to a multimachine system. It is an application of the concept of acceleration and deceleration energy, used in the "Equal area" criterion, to a multimachine environment. The critical switching time for the system is the instant when the system energy integral, which is the difference of the kinetic energy and the potential energy, changes from a negative to a positive sign. This is the simplest form of the more general direct method of Lyapunov.

B) Direct method of Lyapunov

Lyapunov's method was first proposed as a solution to the power system stability problem by Gless [19] and El-Abiad and Nagappan [20]. This method determines the stability behaviour of a system of simultaneous, first order, ordinary differential equations without obtaining the time domain solution. Stability information is obtained from the general properties of a function which describes the state of the system in the neighbourhood of the equilibrium point. It is based on the generalized energy idea that if a system has an asymptotically stable equilibrium state, the stored energy of such a system displaced within the domain of attraction (or the region of asymptotic stability) decays naturally with increasing time until it finally reaches its minimum value at the equilibrium state. This method requires the determination of a suitable function, called the Lyapunov function. This function itself is a generalization of the energy function. Its first time derivative gives information on asymptotic stability, stability, or instability of the equilibrium state in the sense of Lyapunov. This method had its drawbacks in terms of not giving consistent results for the critical clearing time for a wide range of fault conditions and the difficulty in developing a satifactory energy function for the system. As a result the application of this method was not widespread.

In the early 70's, researchers such as Willems [21], Ribbens-Pavella [22], Saccomanno [23], Fouad [24], Pai, Mohan and Rao [25,26] largely focussed on the theoretical aspects of the problem. By the end of the 70's, a significant breakthrough in obtaining excellent practical results had been achieved by Athay, Podmore and Virmani in U.S.A. [27], Ribbens-Pavella et al. in Europe [28], and Kakimoto, Ohsama and Hayashi in Japan [29]. Hence, what once appeared to be a mere academic exercise and viewed with skepticism by the power industry because of its conservative results is again gaining acceptance both as an off-line tool for planning purposes as well as for on-line security assessment schemes.

The numerical "step-by-step" method is generally preferred and has been widely used because of its simplicity. This classical method, however, is valid for the first swing only, the system behaviour beyond that period is not normally predicted. Many assumptions were made to simplify the problem. Some of these are :

1. Mechanical power input is constant.
2. Damping or asynchronous power is negligible.
3. Constant-voltage-behind-transient-reactance model for the synchronous machine is valid.
4. The mechanical rotor angle of a machine coincides with the angle of the voltage behind the transient reactance.
5. Loads are represented by passive impedances.

In order to extend the validity of the analysis for the subsequent period, more detailed modelling of the system elements such as governors, exciters, generators and loads are required. This greatly increases the computational time and demands more computational power to achieve a solution. Although significant improvements in the application of numerical and computational methods to the stability analysis problem have been made [30,31] and more powerful, faster and cheaper computers have been developed, these factors have been counteracted by the increasing complexity of systems and the rapidly rising computational demands of stability studies. The more accurately the system is modelled, the more computational time is required. The more simplications are introduced, the less accurate the results will be. In practical system analysis, compromises must be made between accuracy and computer time [4,32].

Despite the previously mentioned shortcomings of the direct methods using Lyapunov functions, the fact that they do not require the detailed solution of the system differential equations and therefore are faster than the simulation methods makes the direct methods more attractive. Due to the unavailability of higher order Lyapunov functions, direct methods are presently used in deriving first approximations of stability margins. In the light of the recent improvements, there is bound to be further research on these methods to make them more feasible and practical in power system stability assessment.

1.5 Outline of Thesis

This thesis deals with the implementation of the stochastic stability evaluation proposed by Kuruganty and Billinton [40]. The objectives are three-fold:-

A) To select the appropriate modelling and solution techniques to be used in the determination of system indices.

B) To develop a digital computer program which includes the probabilistic aspects of transient stability evaluation.

C) To test the program by investigating some practical power systems and to examine the sensitivity of these indices to the factors that affect the transient stability performance of the system.

In this thesis, the problem of transient instability and the available analytical techniques are briefly reviewed in Chapter 1. In order to appreciate the importance of the probabilistic approach in power system evaluation and the possible application of this technique in power system security assessment, the development of probabilistic techniques in system adequacy evaluation and some of the available methods are explored in Chapter 2. The probabilistic aspects in system security evaluation which include such parameters as type of faults, location of faults, fault clearing phenomena, system parameters and operating conditions are also briefly discussed in Chapter 2. This is followed by a trace of the recent work done in probabilistic transient stability evaluation and the introduction of the stability index, the "Probability of Stability".

Chapter 3 describes the differences between the deterministic approach and the stochastic approach used in system security evaluation. The "swing equation" is also discussed. The models used to represent the different power system elements are presented. The synchronous machine is represented by the "two-axis" model and the equations are derived. The network solution and load flow technique are also briefly reviewed. Finally, the probability indices, the transient stability program and its subroutines are discussed.

The effects of different factors such as the types of faults, location of faults, fault clearing time, system parameters and operating conditions on the system stability are examined in Chapter 4. This is done by considering two practical systems. The system's ability to handle disturbances is illustrated using the developed probability indices.

CHAPTER 2

Reliability Evaluation of Modern Power System

The primary function of a modern electric power system is to satisfy the system load demand as economically as possible and with a reasonable assurance of continuity and quality. However, no matter how much money, time and effort are invested, it is impossible to eliminate the possibility of equipment outages and the need to remove equipment from service to perform preventive maintenance. The consideration of these aspects together with other less tangible elements in the planning, design and operation of a power system is usually designated as "reliability evaluation". The word "reliability" has a very wide range of meaning and is used to indicate concern with the ability of the system to perform its intended function. In other words, the concept of power system reliability covers all aspects of the ability of the system to satisfy the customer requirements and it is most often used in a qualitative rather than a quantitative sense.

Basically, power system reliability can be categorized into two basic and functional aspects. These are :

i. System adequacy.
ii. System security.

System adequacy deals with the ability of the existing facilities in the system to satisfy the customer load demand. Adequacy analyses are carried out on each of its major sub-systems, namely, the generation system, the transmission system and the distribution system. The concept of adequacy, therefore, can be associated with static system conditions which do not include disturbances such as those considered under system security evaluation.

System security concerns the ability of the system to respond to disturbances occurring in the system. It is associated with the dynamic response of the system to whatever perturbations it is subjected to. The regions concerned include both local areas and the whole system and may even spread to other interconnected systems.

Researchers and the utility industry have been trying to develop appropriate criteria for the two areas of adequacy and security. The development and applications have been largely focussed on the area of system adequacy evaluation, and the area of probabilistic system security assessment has received relatively little attention. Widespread disturbances are not a common occurrence. This fact coupled with the lack of satisfactory, universally acceptable and fast methods in system security assessment has resulted in relatively minimal development in this area. Some papers have been published [34-41], however, on this relatively unexplored area. With the improvement in the general transient stability techniques, there will undoubtedly be more research done in this area in the near future.