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GENERATION TRIPPING FOR TRANSIENT STABILITY CONTROL USING THE EMERGENCY SINGLE MACHINE EQUIVALENT METHOD

THESIS

REQUIREMENT FOR THE DEGREE OF:
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BY

LAURA LETICIA JUÁREZ CALTZONTZIN

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"GENERATION TRIPPING FOR TRANSIENT STABILITY CONTROL USING THE EMERGENCY SINGLE MACHINE EQUIVALENT METHOD "

Presentada por el alumno:

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En la Ciudad de México D. F., el día 8 del mes de Diciembre del año 2010, la que suscribe Laura Leticia Juárez Caltzontzin, alumna del Programa de Maestría en Ciencias en Ingeniería Eléctrica con número de registro B081664, adscrito a la Sección de Estudios de Posgrado e Investigación de la ESIME-Zacatenco del IPN, manifiesta que es autor (a) intelectual del presente trabajo de Tesis bajo la dirección del Dr. Daniel Ruiz Vega y cede los derechos del trabajo intitulado Generation Tripping for Transient Stability Control Using the Emergency Single Machine Equivalent Method, al Instituto Politécnico Nacional para su difusión, con fines académicos y de investigación.

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ABSTRACT

System Protection Schemes (SPS) like generation tripping, load shedding and other stability controls apply emergency control actions in order to stabilize the electric power system when a severe contingency, causing a large unbalance between generation and load powers, occurs.

Most practical generation tripping schemes for controlling transient stability problems, commonly used these days, are based on the occurrence of a specific event and are designed and adjusted by means of off-line studies; however, inaccuracies in the system dynamic model and unpredicted operating conditions that may appear in actual system operation, could make the SPS fail. In order to avoid these problems, measurement-based SPS have been proposed, which use real-time measurements in order to assess the severity of the problem and to adapt the size and location of the control action needed to stabilize the system when an actual contingency occurs.

This work describes the emergency single machine equivalent method (E-SIME for short), which has been developed for controlling transient stability problems using real-time measurements. The following aspects of E-SIME are developed and described in detail:

- Basics of the SIngle Machine Equivalent (SIME) method.
- The main steps of the Emergency SIME method:
  - Predictive transient stability assessment using power and rotor angle measurements.
  - Determination of the size and location of the control action to stabilize the system.
- Structure and development of a new computer program able to apply the method.
- Application and performance testing of E-SIME in systems having different structures, sizes and operating conditions.
- Discussion of the method practical implementation issues and cases where the method needs improvements.

In this stage of the research, real-time measurements are simulated using the TRANSTAB transient stability program. Results of this initial work in the E-SIME method, reported in this thesis, are very encouraging and show that this method could provide in a near future an approach to implement a measurement based SPS.

RESUMEN

Los esquemas de protección a nivel del sistema como el disparo de generación, el tiro de carga y otros controles de estabilidad aplican acciones de control de emergencia para estabilizar al sistema eléctrico de potencia cuando una contingencia severa, que causa un gran desbalance entre las potencias de generación y carga, ocurre.

La gran mayoría de los esquemas prácticos de disparo de generación para controlar problemas de estabilidad transitoria, utilizados comúnmente estos días, están basados en la ocurrencia de un evento específico y son diseñados y ajustados por medio de estudios realizados fuera de línea; sin embargo, inexactitudes en el modelo dinámico del sistema y condiciones de operación imprevistas que pueden aparecer en la operación real del sistema de potencia, pueden hacer que falle el esquema de protección a nivel del sistema. Para evitar estos problemas, se han propuesto esquemas de protección a nivel del sistema basados en mediciones, lo cuales utilizan mediciones en tiempo real para evaluar la severidad del problema y para adaptar la magnitud y la localización de la acción de control necesaria para estabilizar el sistema de potencia cuando ocurre una contingencia.

Este trabajo describe el método de emergencia de la máquina equivalente, que ha sido desarrollado para controlar problemas de estabilidad transitoria utilizando mediciones en tiempo real. Los siguientes aspectos de este método son desarrollados y descritos en detalle:

- Los conceptos básicos del método de la máquina equivalente.
- Los dos pasos principales del método de emergencia de la máquina equivalente:
  - Evaluación predictiva de la estabilidad transitoria utilizando mediciones de potencias y ángulos de carga.
  - Determinación de la magnitud y localización de la acción de control para estabilizar al sistema.
- La estructura y el desarrollo de un nuevo programa de computadora que aplica el método.
- La aplicación y prueba del desempeño del método en sistemas con diferentes estructuras, tamaños y condiciones de operación.
- La discusión de los aspectos de implementación práctica del método y casos en los que el método necesita ser mejorado.

En esta etapa de la investigación, las mediciones en tiempo real son simuladas utilizando el programa TRANSTAB de estabilidad transitoria. Los resultados de este trabajo inicial en el método de emergencia de la máquina equivalente, reportados en esta tesis, son muy alentadores y muestran que este método puede proveer, en un futuro cercano, una solución para implementar un esquema de protección a nivel del sistema basado en mediciones.

DEDICATORIA

Dedicado a la memoria de Antonio Munguía y González Castillo, su recuerdo siempre será inspiración para todos los que tuvimos la fortuna de conocerlo.

A mis familiares, por su apoyo incondicional, especialmente por comprender estos años de continuas ausencias y motivarme en todo momento.

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GLOSSARY

CCT:	Critical clearing time.
CIGRE:	Conseil International des Grands Réseaux Électriques.
CM's:	Critical Machines.
COA:	Center Of Angle.
DSA:	Dynamic Security Assessment.
EAC:	Equal Area Criterion.
EEAC:	Extended Equal Area Criterion.
DEEAC:	Dynamic Extended Equal Area Criterion.
E-SIME:	Emergency SIngle Machine Equivalent Method.
GPS:	Global Position System.
HEEAC:	Hybrid Extended Equal Area Criterion.
IEEE:	Institute of Electrical and Electronics Engineers.
MIPS:	Mexican Interconnected Power System.
NM's:	Non-Critical Machines.
OLEC:	Open Loop Emergency Control.
OMIB:	One-Machine Infinite Bus.
PMU:	Phasor Measurement Unit
SIME:	SIngle Machine Equivalent Method.
SPS:	System Protection Scheme.
T-D method:	Time Domain methods.
TRANSTAB:	TRANsient STABility time domain program.
WAMS:	Wide Area Measurements System.
WECC:	Western Electricity Coordinating Council.

NOMENCLATURE

A_{acc}:	Accelerating area.
A_{dec}:	Decelerating area.
δ:	Rotor angle position.
δ_{ct}:	OMIB angle at control time.
$\delta_i = \delta(t_i)$:	OMIB angle at the current processing time.
δ_m:	Maximum angular value.
δ_{OMIB}:	OIMIB angle.
δ_u:	Unstable angle.
δ_r:	Return angle.
Δt:	Sample time.
M:	Inertia coefficient.
η:	Transient stability margin.
P_m:	Mechanical power.
P_e:	Electrical power.
P_a:	Accelerating power.
P_{ep}:	Post-fault electrical power.
t_0:	Is the beginning of the during-fault period of the time.
t_e:	Is the beginning of the post-fault period of the time.
t_f:	Time at what the predictive TSA starts.
t_i:	Current processing time.
t_{ct}:	Is the passed by time between the occurrence of the contingency and the control action; it is also called "the control time".
t_d:	Is the total time of the program to acquire the data, transmit the control order to the power plant and to apply the control action.
t_u:	Time to instability of the system.
ω:	Rotor speed.
$\omega_i = \omega(t_i)$:	OMIB speed at the current processing time.

CHAPTER 1:

INTRODUCTION

1.1 INTRODUCTION

The electricity supply is one of the basic and most important resources that countries have, it has a very important role in modern economies since they have a strongly dependence on reliable and secure services [Knight, 2001, CIGRE, 2001].

Electric power systems must be designed to supply an electric energy service at minimum cost with the least impact to the environment. They must maintain the level of reliability, quality and security of the system, and simultaneously find a new balance of energy flows while optimizing the generation and coordinate control actions of the control areas involved in the system [Fink and Carlsen, 1978, Kundur, 1994]. To achieve this, systems must operate in an efficient way at normal operating conditions, and after the occurrence of any disturbance, they must be capable of absorbing these stresses without further damage. When disturbances take place, the operating conditions change, and it is necessary to carry out control measures in order to successfully bring the system back to its normal operation state, depending on the security level.

It has been recognized since the 80's that power systems are growing in complexity. One of the main reasons for this increasing complexity is the current difficulty of expanding the transmission system due to environmental and economic restrictions. In addition to the facts mentioned above, these days, electric power systems around the world operate nearest their physical and security limits than before, due to economical pressure and intensified power transactions imposed by the electricity markets developed in some countries. At the same time, the problem is aggravated given the trend to merge existing systems into much larger entities and to monitor them in shorter and shorter time horizons. This still true for analysis aspects and even more for control, given that control actions must deal with considerably more restrictive market requirements than in the past [Ruiz-Vega and Pavella, 2003a].

Historically, power systems have been widely interconnected in order to supply electricity to the customers in a reliable and secure way, or to interchange power in emergencies [Fortesque, 1925, Elgerd, 1982, Kundur, 1994]. Over the years, operation of power systems has changed according to the necessities of the electric industry, from the isolated operation to supply individual loads, till the interconnection of wide areas forming pools in one system or between systems. This latter was achieved with the development of the alternating current transmission of power and the parallel operation of generators started approximately in 1890 [AIEE, 1937] and has been largely developed until these days.

Apart from the inherent problems of the system operation, in some systems in which electric utilities have been restructured, creating electric markets [Hunt y Shuttleworth, 1996], [Pérez-Arrillaga, 1982], new problems related to the specific characteristics of these markets have been emerged such as the problem of transmission system expansion, which in turn additionally decreases the power transmission capacity. In these very limited conditions, it is necessary to implement discrete stability controls; without which power systems could not operate at the current transmission levels required nowadays.

The most common transient stability protection schemes used in these days are based on the occurrence of a specific event and are designed and adjusted by means of off-line studies. However, in the real operation of the system, operators may find unpredicted operating conditions that were not taking into account in the design studies; in consequence it is possible that in some occasions protection devices would fail.

Due to this fact, it has been proposed to use more intensely system protection schemes employing real time measurements. This trend has been reinforced by the growing development of systems that provide fast synchronized measurements in real time. This is the reason this work studies the Emergency SIngle Machine Equivalent (E-SIME) Method, an approach which allows implementing system protection schemes to solve transient stability problems using real time measurements.

1.2 OBJECTIVE OF THE THESIS

The aim of this work is to describe the basic concepts and to implement the Emergency SIngle Machine Equivalent (E-SIME) Method, presenting its structure, testing the performance of its assessment and control techniques, and describing its important potential for developing a transient stability emergency control function of electric power systems using real time measurements.

1.3 HISTORICAL BACKGROUND AND MOTIVATION

This section presents a literature review related to the main subject of this work, the Single-Machine Equivalent method (SIME) and its two variants: the "preventive SIME" and the "emergency SIME". This method, and in particular E-SIME are described in chapter 3.

1.3.1 The SIME method

SIME is a hybrid direct-temporal transient stability method. It is based in the combination of time domain simulations with the Equal Area Criterion (EAC), which has been widely studied and strengthened over the time.

In [Skilling and Yamakawa, 1940] the EAC was used to determine the transient stability limits and to reduce the complete system to a One Machine Infinite Bus (OMIB) equivalent system. In this paper, a graphic method is proposed as an extension of the EAC developed before in [Dahl, 1938] and permits it to be applied to analyze power system stability under disturbances in which time is an important factor. Its main advantage is that it allows determining the angular position of the synchronous machine as a function of time; i. e., that the swing curve can be plotted from these results. From that time on, EAC was considered as a method that could only be applied in small systems that could be simplified to a two-machine system represented with the classical model.

In [Xue, 1988, Xue et al., 1988] authors proposed an uncomplicated direct method for power system on-line transient stability assessment based on the combination of the OMIB equivalent with the EAC and combining it with Taylor series expansions and corrective factors in order to amplify the advantages of Liapunov's direct approaches. The proposed method was called the Extended Equal Area Criterion (EEAC) and consisted of decomposing of the multimachine system into two groups: the "candidate critical machines" and the remaining machines, and to aggregate them into an equivalent OMIB system; then the "pre-filter" candidate critical machines are tested in a sequence to identify the critical ones. With this method, the analysis of transient stability was performed free from step-by-step calculations or trial and error procedures, and stability margins are calculated in an analytical fashion.

The EEAC continued to be studied and improved in several works; in [Xue et al., 1989], as a continuation, this criterion was used to study first-swing and second-swing stability and to find two transient stability limits: the critical clearing time (CCT) and the transient stability margin (η) with simple algebraic expressions thanks to the conjunction of the OMIB system with the Taylor series expansion. Additionally, in this article they clarify the assumption that the system's separation depends on the angular deviation between the two (and only these two) equivalent clusters: the critical one and that comprising the remaining machines.

Latter, in a subsequent work [Xue et al., 1993] the EEAC is presented as a new direct method to adapt the EAC to multimachine fast transient stability assessment by decomposing the system machines into two re-named groups: the critical cluster (CC[1]) and the one that comprises the rest of the machines, then aggregate each group into an equivalent machine and replace the resulting two equivalents by an OMIB system in order to apply the EAC to this OMIB.

At the beginning of the EEAC development, the CC's selection was based on the "initial accelerations criterion", in other words: machines likely to be critical are considered those with the largest initial accelerations, but these variables do not reflect the actual degree of machines' criticalness. This first version of the EEAC proposed in [Xue et al., 1993] gave very good results with a large variety of power systems (for instance, the Chinese EMS and the French EHV systems). However, some difficulties were revealed and they introduced two changes: the individual angles were refreshed during and after the fault (Dynamic OMIB) and the critical machines are classified in the proper order they should be combined. Then the EEAC evolved into the Dynamic EEAC (DEEAC) [Xue et al., 1993] which gradually gave rise to the Hybrid EEAC (HEEAC) [Zhang, 1995], which was subsequently renamed as the SIME method [Zhang et al., 1997, Pavella et al., 2000].

The main assets that SIME provides are: an early termination stopping criterion (which consequently reduces of the length of the required time domain simulations), the assessment of stability margins and the possibility of identifying the group of critical system machines. In [Zhang et al., 1996] the most important rules and steps to implement SIME method were presented. These five rules are the fundamentals of SIME and state the general approach to formulate the OMIB system in an appropriate fashion and to calculate the stability margins (positive for stable scenario, zero for the borderline stability case and negative for unstable scenario) then the aggregation of the relevant machines (CC) and the remaining ones into the relevant OMIB system.

In [Zhang et al., 1996] it was also presented the application of the SIME method to the Hydro-Québec System for first swing and multi-swing stability assessment. The SIME method has been also tested on the Brazilian network that is a system that required an accurate method to screen contingencies in order to identify only the relevant ones and, at the same time, provide accurate results for the secure operation of the system [Bettiol et al., 1997] and proved to be a successful method that is computationally efficient and has the ability to handle any power system with all kinds of modeling.

In [Bettiol et al., 1997] it was also proposed a variant of SIME method: "filtering SIME" that deals with the selection of contingencies that would provoke instability.

[1] The CC contains the critical machines that are responsible for the separation of the system whenever instability occurs. The actual CC is that candidate which yields the minimum candidate critical clearing time [Xue et al., 1988].

Filtering SIME consists basically in the selection of the "potentially harmful" contingencies and the rejection of the "harmless" ones; the purpose of this latter is to become faster but preserve the reliability of the method and these conditions can only be reached by relaxing the strict accuracy requirements of SIME while selecting the contingencies. The final procedure is integrated by a sequence of the filtering phase (consisting in two filtering steps) and the contingency assessment phase. In the Brazilian South-Southeast power system of 56 generators, the filtering SIME was carried out using simple and detailed modeling and a list of 192 contingencies. In the filtering phase, the first step rejected 127 contingencies and "sent" 65 to the second filtering step where filtering SIME discarded other 55 contingencies and selected only 10 feasible contingencies to be assessed by regular SIME.

Gradually, SIME has been divided into two types of transient stability assessment: preventive and predictive transient stability assessment. In general, preventive control aims at assessing "what to do" in order to avoid loss of synchronism if an a priori harmful contingency would occur while the emergency control aims at triggering a countermeasure in real time after a contingency has actually occurred [Ernst et al., 2000, Ernst and Pavella, 2000]. This latter type of control has been implemented in two fashions: "open-loop emergency control" and "closed-loop emergency control".

SIME was initially developed to improve the performance of the conventional time-domain (T-D) techniques for transient stability assessment and was extended to embrace preventive and emergency control and originated two types of SIME method: "**Preventive SIME**" that goes on the traditional way of assessing transient stability and "**Emergency SIME** (E-SIME)" that uses real time measurements to assess transient stability [Ernst et al., 2000].

1.3.2 The E-SIME method

In [Ernst et al., 2000] an approach to the preventive and emergency transient stability control schemes using SIME was presented.

Latter on, the emergency SIME method has been studied in different fashions and has been modified and strengthened. In [Ruiz-Vega et al., 2003] it was proposed a combination of two powerful techniques for emergency control: the closed-loop emergency control (E-SIME) and the open-loop emergency control (OLEC) in different horizons of time to combine preventive with emergency actions. In a more recent work the main purpose is to use the same general SIME-based method and combine their desirable features: the quickness of the OLEC action and the closed-loop capability of E-SIME [Ruiz-Vega et al., 2003].
The most recent work on the main topic of this thesis is presented in [Glavic et al., 2007] where the authors presented the achievements and prospects of the E-SIME

method. They use a generation shedding scheme as a control action to avoid instability that has been tested in various real-life power systems like the South-Southeast Brazilian system, the EPRI test system, the WECC system and Hydro-Québec system using the ST-600 and ETMSP programs as TD simulations as a base for E-SIME just for want of real-life measurements. Providing the emergency scheme would become strongly system dependent, they also recommend the evaluation of various different types of control actions instead of using the generation tripping only. Some conclusions and observations are presented in order to enable the reader to take into consideration the system conditions like the angle reference and external conditions like noise and the number of measurements.

The Single Machine Equivalent method has been the subject of large research and some books are concentrated on the power systems security assessment and deals with the crux of SIME: The Book [Pavella et al., 2000] presents a comprehensive approach to transient stability assessment and control. Here is presented the development of SIME method and its variants over the time and the techniques to implement the procedure. The two different methods are the “Preventive SIME” and the “Emergency SIME” so this book is mainly divided into these two approaches. Some other books or chapters of books devoted to this topic are: [Wehenkel et al., 2006] [Ruiz-Vega and Pavella, 2008] and [Pavella et al., 2009].

1.4 JUSTIFICATION

The growing competition in the electric power utility environment has resulted in an augment of stress in transmission systems [Karady and Gu, 2002]. In the current power systems, especially those in which an electric market has been established and where the active power is viewed as a product to commercialize, the preventive control schemes for the security of power systems, mainly consisted in the security constrained re-dispatch, are every time less accepted and as a consequence there have been proposed system protection schemes consisted in executing emergency controls when a large disturbance affects the system [CIGRE, 2001].

Using real time measurements to activate the operation of the system protection schemes is nowadays one of the most investigated areas in power systems research due to the availability of fast synchronized real time measurements: the wide area measurement systems (WAMS). However, until now, most of the methods that have been developed to process synchronized phasor measurements have been used to analyze power system blackouts post mortem, or to only detect abnormal system conditions and display alarms, and very few methods, really able to assess the severity of the problem and design control actions in real time, have been proposed.
In the specific case of transient stability, as the phenomena are very fast, there are additional difficulties to develop the control schemes mentioned. However, as shown

in this work, the emergency- single machine equivalent method (E-SIME), provides the basis for developing a measurement-based system protection scheme, which is able to stabilize the system using a generation tripping control action.

1.5 SCOPE

At this stage of the research, this thesis work deals exclusively with the description and performance evaluation of the emergency SIME method in predicting transient stability and designing control actions early enough to be able to stabilize the system using generation tripping schemes.

The practical application of the method is limited by the current development of the communication systems and the PMU's installed in the network, because these units can not provide the measurements at the required sampling and speed. Moreover, PMU's only measure voltage and current phasors at the transmission system level, while the necessary variables to develop the method (load angles, machine speeds, mechanical powers and electrical powers) can not be provided yet.

As a consequence, in this work the results of a computational program are used to simulate the real time measurements. However, as described in the following section, important contributions have been made in this work in order to arrive towards the method practical implementation.

1.6 CONTRIBUTIONS

The main contributions of this work can be briefly described as follows:

- A detailed description of the emergency SIME method and of its two main steps: the predictive transient stability assessment and the design of control actions using generation tripping schemes, is presented.

- The development of a new computer program to automatically apply the E-SIME method. The program was coupled with the TRANSTAB time-domain simulator, but it was developed as an independent module that in a near future can be used with more powerful time-domain simulators in the testing phase of the method, and as the basis for a future program using real-time measurements.

- The program was tested with power systems of different sizes and configurations, showing the good performance of E-SIME in transient stability control. One important aspect of this testing phase is that it demonstrated that the method is able to work in cases where the contingencies affect meshed power systems where the critical machines cannot be easily known in advance.

- A new equivalent test power system was developed in order to use a more realistic system to test the E-SIME method. This power system was derived from the Oriental Control Area of the Mexican Interconnected Power System of 2001, and was selected because various power plants in this system are equipped with event-based automatic tripping schemes.

1.7 PUBLICATIONS DERIVED FROM THE THESIS

- Laura. L. Juárez Caltzontzin, Daniel Ruiz Vega (2010). "Predictive Evaluation of Transient Stability Using the Emergency SIngle-Machine Equivalent Method" (in Spanish). *Memorias de la Reunión de Verano de Potencia del IEEE*, July 11 to 17, 2010. Acapulco, Gro., MEXICO.

1.8 THESIS ORGANIZATION

This section outlines the main structure of the thesis, as follows:

- Chapter 1 presents an introduction to the topic of research, the objective and scope of this thesis, and the reasons for the developing of this work and its contributions.

- Chapter 2 outlines and discusses the main methods for controlling transient stability problems, including generation tripping schemes.

- Chapter 3 describes in detail the Emergency SIngle-Machine Equivalent E-SIME method and its two main steps: predictive transient stability assessment and control design. The structure of the developed program and its coupling with the time-domain simulator are outlined. Some requirements for its future practical application are also mentioned.

- Chapter 4 shows the application of the methodology to different power systems, showing cases in which the method is able to control transient stability by itself and where it needs to be combined with an automatic system protection scheme.

- Chapter 5 finally provides the conclusions and suggestions for further research work in this topic.

CHAPTER 2:

TRANSIENT STABILITY CONTROL

2.1 INTRODUCTION

Security is the robustness of the power system in terms of its ability to withstand a wide variety of disturbances (programmed or not) and to operate in equilibrium under normal and distressed conditions, while reducing the risk of outages [Dy Liacco, 1978, Knight, 2001, Kundur, 1994, Pavella et al., 2000, IEA,2005].

For the purpose of security, the power system is planned and operated to maintain the following conditions [Ruiz-Vega, 2002b, Kundur, 2000]:

- After any disturbance, any element of the system is overloaded (static condition).
- After any disturbance, all bus voltages are within their permissible limits.
- After any disturbance, the system must be stable and during the transient period it must have an acceptable voltage drop and damping.

The first two conditions are studied in static security; the third condition is the main concern in this work and belongs to the field of dynamic security assessment and control.

Security must be quantitatively evaluated by means of security margins for each one of the different problems. These margins can be defined in terms on the main variable that drives system static or dynamic problem of interest or, in order to improve its practical implementation and interpretation, it can be "translated" in terms of a variable associated with system operation that can be easily monitored by the planning engineer or the system operator. In this way, a commonly accepted practice is to define the security margins of most dynamic and static problems as functions of the power transfer limit of the system tie lines. In this way, different kinds of margins can be compared to each other, and the final operational limit is usually chosen as the minimum limit allowed by all security studies.

In addition to the conditions described above, the power system planner and operator must take into consideration some other aspects for instance: the constant change of the global economy, the growing awareness of natural environment and the restructuring of electric utilities where economic aspects must be taken into account to minimize looses and augment the earnings. The horizon is not flexible at all: the majority of the decisions are made in a context of uncertainty (the demand, the availability of the resources to produce energy, the prices, the fuel, the regulatory legislation, etc.) [Expósito, 2009]. Thus, in the widest framework, the power system must be able to maintain the load demand of power and should supply quality environmentally friendly energy at the lowest prize within its permissible limits.

To achieve all those functions, the power system requires the employment of a coordinated hierarchical control system [Dy Liacco, 1978] flexible enough to avoid wrong interactions that could cause adverse situations such as power system oscillations or instabilities. However, these control systems are very complicated because they are based on a great quantity of measurements that are continually monitored and actualized. As a consequence, the majority of these control schemes are performed by powerful computers in energy management centers [Expósito, 2009].

Power system operation and control has been unfolded over the years, its development is predominantly the result of the study of the blackouts occurred worldwide. In Fig. 2.1 it is shown the evolution of power system control technology over the years.

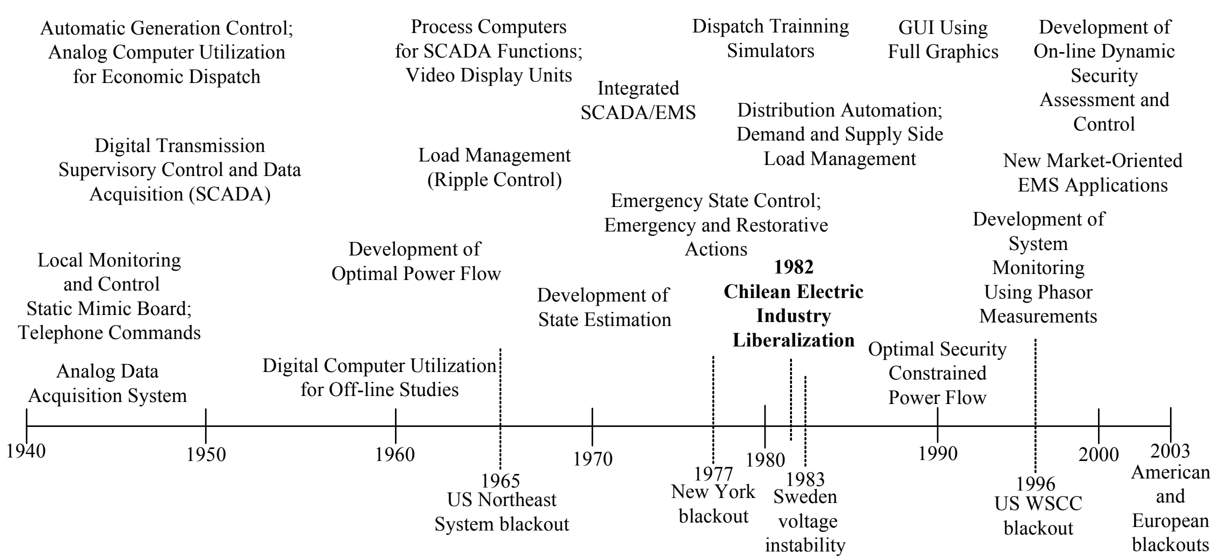


Figure 2.1 Significant events in the evolution of power system control technology [Ruiz-Vega, 2009]. Adapted from [Handschin and Petroianu, 1991] and Updated from [Ruiz-Vega, 2002a].

In the forties (and until about the sixties) the monitoring and control of the power system was performed in a power station or a substation via the dispatch office and using the telephone to send commands to the field system operators. The automatic generation control was made in an analogue fashion. In general, the progress in power system monitoring and control is the result of the improvement in other fields like: computation, electronics, signals processing, measurement devices, etc. With the development of the acquisition data systems, the monitoring and control of the power system evolved and computers were used for off-line power system planning studies [Handschin and Petroianu, 1991].

With the occurrence of the New York blackout in 1965, the concern about the importance of the security assessment started to grow, and during the seventies, the State Estimator and optimal power flow theory had their main improvement. Later, in the eighties, after a new series of blackouts and with the advent of computer hardware able to manage with the system, the necessity of trained operators was evident and training simulators were carried out [Handschin and Petroianu, 1991].

In this context, the security assessment of power systems becomes an important challenge for power system's planners and operators since any power system (even if it is designed to withstand any "plausible" contingency) is a potential candidate to be threatened by a disturbance (whatever its nature) that may led to a partial or total collapse of the interconnected system.

This problem has not been caused by isolated conditions, it may be seen as the consequence of several factors: as power systems have growth in interconnections, new technologies and controls have emerged, in addition, power systems operate every time more stressed and nearest their stability limits. In some industries, were the electric utilities have been reformed, it has been demonstrated that the security of the transmission network is vital in the operation of electricity markets and recent 2003 disruptions in America and Europe (see [IEA, 2005]) have created concern that electricity reform had reduced electricity system reliability [IEA, 2005], all these conditions have also provoked the emerging of different forms of system instabilities [CIGRE, 2000] that will be introduced in § 2.2.

2.2 POWER SYSTEM STABILITY

As mentioned before, the electric power system is a dynamic nonlinear time-varying system in which their main parameters and variables vary with time; those sudden variations are commonly known as disturbances and are due to the daily load variation or programmed actions in the system operation (such as transmission network and generating plants maintenance). For instance, fig. 2.2 depicts the daily load demand in the Mexican Interconnected Power System power system (SIN as in Spanish), it can be observed that the load demand changes with time during the 24 hours of the day and has different behavior for the different seasons of the year.

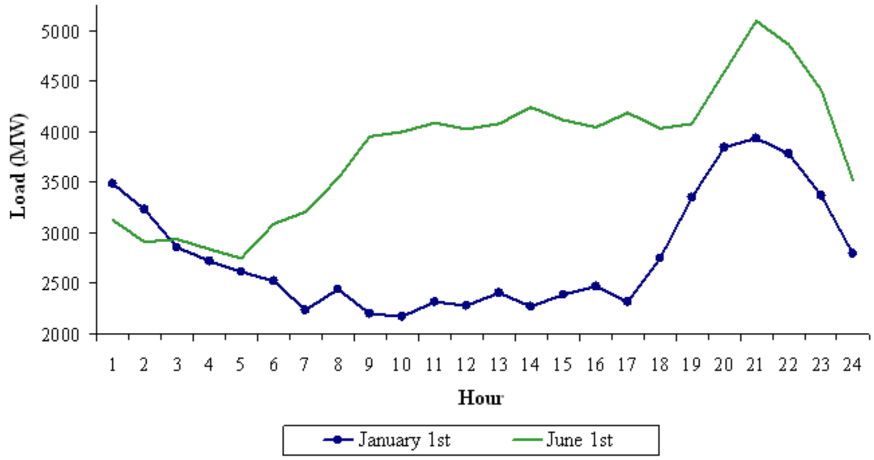


Figure 2.2 Measured values of the Mexican National interconnected power system during two different days in two different seasons in 1995 (Adapted from [Ruiz-Vega, 2002a]).

Power system stability has been widely studied over the years and has been recognized as an important problem for secure system operation since the 1920s [IEEE, 2004]. Historically, it started giving cause for concern with the parallel operation of synchronous machines around 1890 [AIEE, 1937] where first stability problems were spontaneous oscillations or "hunting" due to inefficient damping that were solved by introducing damping windings and turbine-type prime movers [Concordia, 1985]. However, it was up to the latest fifties when the majority of the problems were encountered to be transient instabilities [Ruiz-Vega, 2002b].

With the interconnection of power systems, new types of instability such as voltage instabilities, frequency instabilities, etc., started being studied what made necessary the punctual definition and classification of power system stability. In [IEEE, 2004] power system stability is defined as the *ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.* This definition is valid for the entire system, which means that if a single generator or group of generators losses synchronism[2] the system as a hole would remain stable.

This definition assumes that during the transient period, between the initial stationary state (pre-disturbance) and the final stationary state, the damping and the main variables of the power system are within their admissible limits and have little impact on the quality of the electric service. The final operation state of the system must be acceptable so that their frequency and voltage values remain within their normal limits and all the generators operate in synchronism [Ruiz-Vega, 2002b].

[2] The terms synchronism, equilibrium and stable will be use interchangeably in the following.

2.2.1 Power system stability classification

The classification of power system stability is shown in figure 2.3 and is based on different aspects of the power system [IEEE/CIGRE, 2002]:

- The physical nature of the instability that is indicated by the main variable affected by instability (rotor angle, frequency or voltage).
- The size of the disturbance (large or small).
- The devices, processes and times that must be taken into account to assess stability

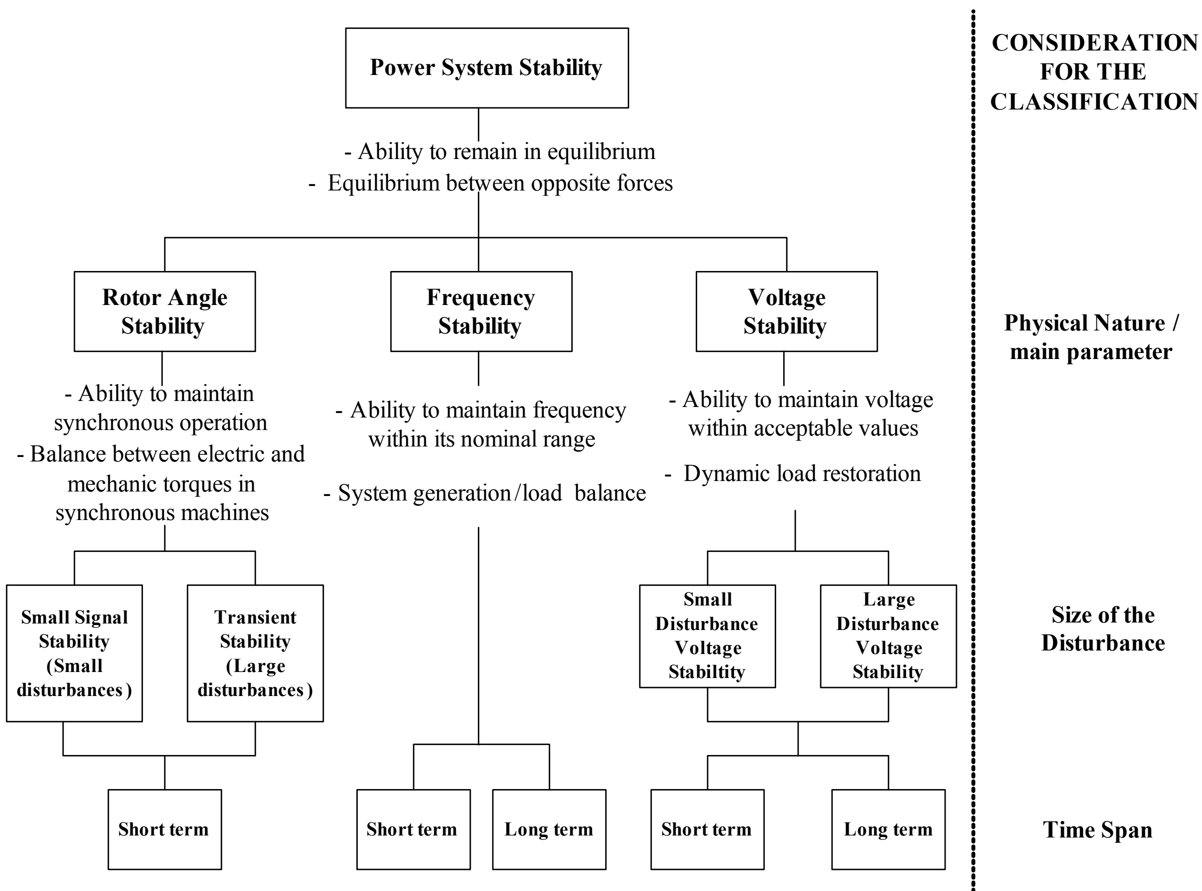


Figure 2.3 Power Systems Transient Stability Classification (Adapted from [IEEE, 2004]).

Here there are presented the definitions of the different types of stability based on the physical nature of the instability:

Rotor angle stability: is the ability of the synchronous machines of an interconnected power system, to remain in synchronism when the system is subjected to a disturbance. Rotor angle stability depends on the ability of the system to maintain or restore the equilibrium between mechanic and electro mechanic torque in all the machines connected to the power system [Kundur and Morrison, 1997].

Frequency stability: is the ability of the power system to maintain the frequency within a normal range after being subjected to any disturbance resulting in a significant imbalance between generation and load that could (or not) lead to the separation of the interconnected power system in isolated subsystems.

Frequency stability depends on the ability of the power system to restore the total of the generating power and the load power balance in the different subsystems with minimum loss of load [Kundur and Morrison, 1997].

Voltage Stability: is the ability of the power system to maintain steady voltages at all buses in the system after being subjected to a disturbance [IEEE, 2004]. This stability type depends on the ability of the generation and transmission power subsystems to restore the load power and reach acceptable voltage values in all the nodes of the system after a disturbance. The voltage instability is the result of the load effort to restore the energy consumption to a greatest value that is the combined capacity of the generation and transmission subsystems [Van Cutsem and Vournas, 1998].

Based on the size of the disturbance, stability is classified as follows:

Small disturbance or small signal stability: is the ability of the power system to remain in synchronism after being subjected to a small disturbance.
A disturbance is considered small if its consequences could be examined by a linear model of the system, otherwise the disturbance can be classified as a large disturbance [IEEE, 2004]. What defines the size of a disturbance are the techniques employed to solve the mathematical problem, the results of an analysis using the linear model of the system must be valid for the real system (non-linear system).
Analysis techniques using linear and non-linear models are supplementary and the identification of the causes and their possible solutions require a coordinated usage of both. Despite the fact that linear techniques are highly attractive because of their advantages (like the availability of sensitivity techniques able to identify the elements that provoke the instability and those which have an important influence in the phenomena) their results are not always valid for the real system [Ruiz-Vega, 2005].

Large disturbance or transient stability: is the ability of the power system to maintain synchronism when it is subjected to a large disturbance (for instance a short circuit), the response of the system has to do with large excursions of generator angles. This thesis is devoted to transient stability and a deep analysis on it is made in § 2.2.2 and chapter 3.
Based on the time span the classification of stability is:

Long term stability: the phenomena of interest are in the period of time from milliseconds to 15 or 20 seconds (very fast phenomena).

Short term stability: the phenomena of interest are in a period of time from tens of seconds to tens of minutes (slower phenomena).

In figure 2.4 it is shown the time span of the different types of instabilities that occur in the power system. It can be noticed that the different kinds of instabilities defined above have different and specific periods of time. Thus, transient instabilities are developed in periods of time up to 20 seconds (short term stability) while frequency and voltage instabilities can be classified in both short and long term stability for any size of the disturbance.

2.2.2 Power system instability classification

Depending on the network topology, system operating conditions and the form of disturbance, different sets of opposing forces may experience sustained imbalance leading to different forms of instability [CIGRE, 2007]. In this context, transient instability can be also classified as follows [Ruiz-Vega, 2002b]:

First swing stability: is the result of the lack of synchronizing torque and results in an aperiodic change of direction in the rotor angle of the group of machines that loses synchronism.

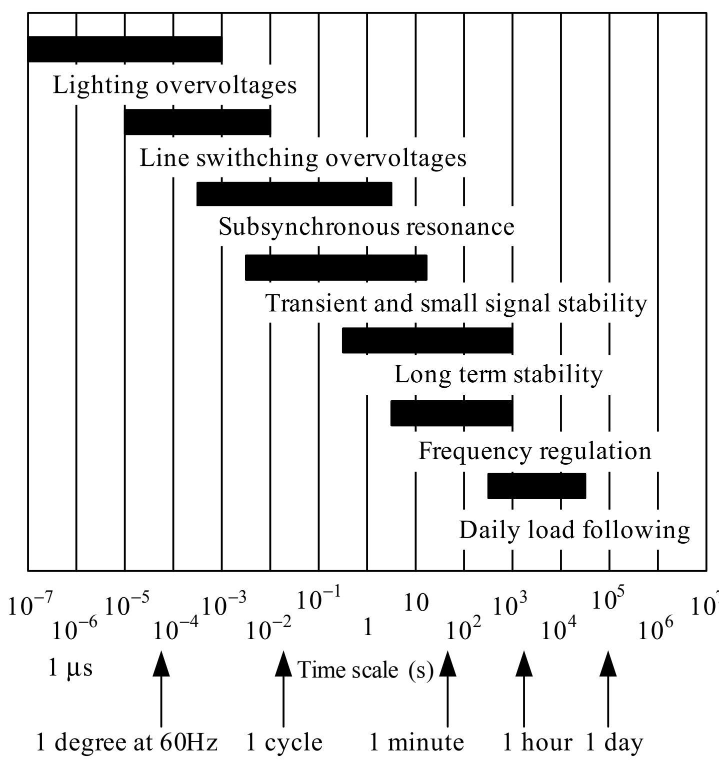


Figure 2.4 Frequency bands of dynamics phenomena.

Multi-swing stability: is the result of the lack of damping in the system and results in an oscillatory instability.

The second classification of transient instability is made in terms of the group of machines that loses synchronism [Ruiz-Vega, 2002b].

Up-swing stability: this kind of instability occurs when the accelerating machines' group loses synchronism.

Back-swing stability: this kind of instability occurs when the decelerating machines' group loses synchronism with respect to the others.

The third classification of transient instability is made as a function of the number of machines that lose synchronism [Ruiz-Vega, 2002b].

Plant mode instability: this phenomenon is presented when one or more machines of the same power plant lose synchronism.

Inter-area mode instability: Is presented when an important group of machines loses synchronism with respect to the rest of the system.

2.3 TRANSIENT STABILITY

Transient stability may be defined as the ability of a power system to maintain the synchronous operation of synchronous machines when it is subjected to a large disturbance (physical approach). However, power system transient stability is similar to the stability of any dynamic system which has a mathematical description so that power system transient stability is a strongly nonlinear high dimensional problem (system theory approach) [Pavella et al., 2000].

The transient stability problem analyzes the way in which the electrical output power of a synchronous machine connected to a large system vary when its rotor angle change and how it affects the stability of the entire system. The generation-load power relation is always changing as a result of any kind of disturbance (small or large), however, under steady-state conditions, there exists equilibrium between the input mechanical torque and the output electrical torque of each machine of the system and the speed of the synchronous machine can be considered constant [Kundur, 1994, Kimbark, 1948]. If the system is perturbed, this equilibrium is disturbed and leads to the acceleration or deceleration of the rotors of the synchronous machines. If the mechanical torque is larger than the electrical torque, then the machine tends to accelerate and its rotor angular position tends to increase, in the opposite case, the machine tends to decelerate and its rotor angular position deceases.

If one generator of the power system goes faster than another, the angular position of its rotor relative to that of the slower machine will advance. These angular difference shifts part of the load from the slower machine to the faster machine to reduce the speed deviation and the angular separation. In spite of the fact that the power-angle relationship is strongly nonlinear, after a certain limit, this angular difference causes the power transfer to decrease and the angular separation to increase. If the system restoring forces are capable of maintaining the machines in synchronism absorbing the kinetic energy corresponding to these rotor speed differences after the fault time clearance then the system will be stable, otherwise the system will lose synchronism. [Kundur, 1994, Kimbark, 1948].

Loss of synchronism would occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group after separating from each other [IEEE, 2004].

The torque deviation of a synchronous machine after being subjected to a disturbance can be separated in two components (equation 2.1) [Kundur, 1994] and system stability depends on the existence of both of them [IEEE, 2004].

$$\Delta T_e = T_S \Delta \delta + T_D \Delta \omega \tag{2.1}$$

Where:

$\Delta\delta$ is the synchronizing torque component and T_S is the synchronizing torque coefficient, then $T_S\Delta\delta$ is the component torque in phase with the rotor angle deviation. And $\Delta\omega$ is the damping torque component and T_D is the damping torque coefficient, then $T_D\Delta\omega$ is the component torque in phase with the speed deviation.

In the absence of sufficient synchronizing torque aperiodic or nonoscillatory instabilities would occur and lack of damping torque leads to oscillatory instabilities [IEEE, 2004].

Transient stability deals with large disturbances and involves numerical integration for its solution; its effects have been widely studied over the years because it is one of the most challenging problems for the security appraisal of the system. At the beginning, the assessment of power system transient stability was carried out by using graphical methods (for instance the Equal Area Criterion) and swing curves; the integration of the swing equations of the machines was made by hand, these was possible because power systems could be well represented by a one-machine infinite bus (OMIB) system or by a two machine system (see figure 2.5).

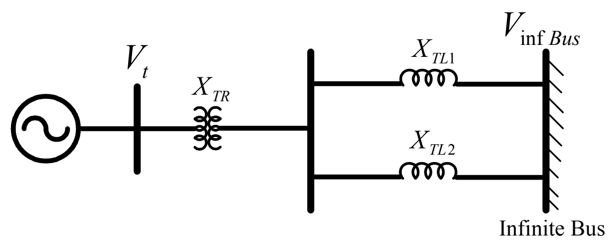


Figure 2.5 One-machine infinite bus system (Adapted from [Kundur, 1994]).

The dynamic model of this OMIB system consists in a single equation (2.2): the swing equation.

$$M\frac{d^2\delta}{dt} = P_m - P_e = P_a \tag{2.2}$$

That is usually divided into two differential equations:

$$M\frac{d\omega}{dt} = P_m - P_e = P_a \tag{2.3}$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \tag{2.4}$$

Where:
M= the inertia coefficient
δ= the rotor angle position
ω =the Rotor speed
P_m = the mechanical power
P_e = the electric power
P_a = the accelerating power

The system can be represented by the "classical model" which is adequate to analyze first swing stability and is the simplest representation of it. Classical model dynamics are described by equation (2.2) and other considerations for modelling are [Kundur, 1994, Kimbark, 1948, Anderson and Fouad, 1977]:

- Machines are represented by an mmf behind the direct axis transient reactance.
- Loads are represented by a constant impedance model.
- The mechanical power is constant and damping is neglected.

Then the equivalent system is depicted in figure 2.6 where the equivalent reactance is composed by the direct axis transient reactance of the machine and the equivalent reactance of the transmission network.

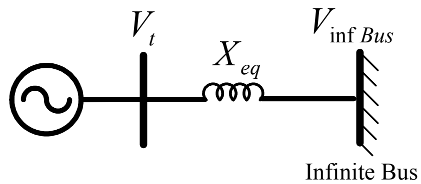


Figure 2.6 Basic one-machine infinite bus system.

The transient stability problem can be solved in different fashions and in the following section there will be presented two approaches to deal with transient stability.

2.3.1 Transient stability approaches.

TD-Approaches

As power system grew in size and interconnections, they could no longer be represented by an OMIB system; with the interconnection of power systems, new stability problems emerged and the modelling requirements to represent the system evolved too, generators and excitation systems' mathematical representation rose in detail and complexity and new methods to assess stability were employed: the time-domain (TD) methods of integration; TD methods started being popular with the advent of computers because they allow the representation of the dynamic behaviour of the system closer to its real functioning making possible to include detailed models of the elements involved in the system (generators, loads, the transmission network and some other dynamic devices) and to represent the non-linearity of the system.
TD methods have two main features [Ruiz-Vega, 2009]:

- The time-domain simulation results are able to accurately predict the dynamic behaviour of the system but it depends on the precision of the parameters employed.
- They are not capable of providing sensitivity techniques to determine the causes of the stability problem and design adequate control measures.

In consequence most of the investigations and researching efforts are devoted to develop some aspects of the TD methods.

In TD methods, the model of a multi-machine system is divided into two sets of equations:

$$\dot{x} = f(x, y) \tag{2.5}$$

$$0 = g(x, y) \tag{2.6}$$

The set of equations (2.5) corresponds to the differential equations of the system that correspond to the dynamic equations of all machine rotors and controls and the differential equations that represent other dynamic elements and their controls. The set (2.6) represent the algebraic equations of the machines' stator, the network, and loads.

The TD approach simulates the system dynamics in the during-fault period and post-fault configurations. The during-fault period of simulation is very short while the post-fault period of simulation is longer [Pavella, et al., 2000].

The sets of equations (2.5) and (2.6) must be co-ordinately solved, for that purpose, different schemes of solution have been proposed that depend on the integrating method chosen, the two main methods are:

- Alternate-Explicit method
- Simultaneous-Implicit method

The Alternate-explicit method was the first method proposed for time simulation. The use of an integration method allowed solving equation systems (2.5) and (2.6) in an alternate fashion. The values of the state variables of the system are found by an explicit integration method (for instance: a Runge-Kutta method) in a single step without interacting with the network solution. This latter is due to the fact that in the moment of computing the differential equations, the network variables are considered constant and vice versa: during the network equations solution, the state variables of the system are considered constant.

When a disturbed is applied to a power system, the set of equations (2.6) has to be resolved again to obtain the new values of the algebraic variables. The state variables do not need to be recalculated because the have no discontinuities [Ruiz-Vega, 2009].

In spite of its simplicity, the Alternate-explicit methods were preferred at the beginning of the development of digital computer programs, this was possible because the power system could be represented by a classic model and the first-swing stability studies were the most common.

Nevertheless, approximately in the sixties, the usage of excitation controls of fast responses started to be generalized and the interconnection of power systems caused the appearing of poor damped low frequency oscillations or instable oscillations. In order to avoid this situation the representation of the system had to be improved and the level of modeling augmented to reproduce the system behavior in a wide time horizon (say 20sec.) for the purpose of proving the effectiveness damping of the system oscillations.

With the augment of the modeling detail, the stiffness of the equations system enlarged as well, this provoked the use of smaller integration steps to avoid numeric instabilities [Arrillaga and Arnold, 1990] and caused the method to become impractical. This lead to the development of new kinds of methods, mainly those that use implicit integration methods (for example: trapecial rule) and in the latest of the sixties and during the seventies the simultaneous-implicit methods emerged. Nowadays, these TD methods continue being the most accepted for TSA.

TD methods have many advantages and disadvantages, some of them are [Pavella et al., 2000]:

Pros of TD methods:

- They give the dynamic description of the system's behavior in the time domain.
- Any power system with different degree of modeling can be studied.
- Is very accurate when the parameters are precise enough.

Cons of TD methods:

- Do not provide tools to throw away the harmless disturbances for the system under study.
- They can not provide stability and security margins.
- They are helpless in the design of control actions to improve stability.

Direct approaches

Another way to attempt TSA is using direct methods that started being developed in the sixties. Its main features are: the restriction of the TD simulation only for the during-fault period (what avoids the repetition of TD simulations and computer effort) and the possibility of obtaining stability margins [Pavella et al., 2000].

One of the most difficult tasks to apply direct methods is the construction of good Lyapunov functions for multimachine power systems what is only possible if very simplified models of the system are used. Another difficult is the assessment of a practical stability domain. These difficulties were overcome by combining theoretical approaches with practical engineering solutions.

Two examples of this approach are the Lyapunov criterion and the Equal Area Criterion (EAC), this latter will be presented in the following section.

2.3.2 Transient stability assessment using the EAC.

The EAC is a powerful technique to assess power system transient stability. As it was mentioned in chapter 1, their origins are not clear but first proposals were made in [Dahl, 1938, Crary, 1947, Kimbark, 1948]. This method allows the study of the behaviour of a one-machine system connected to an infinite bus without solving differential equations.

Considering the OMIB system in figure 2.5 with the features mentioned before, and which is governed by equation (2.2) we can multiply both sides this equation by *dδ/dt* [Pavella et al., 2000]:

$$M\frac{d^2\delta}{dt}\frac{d\delta}{dt} = P_a\frac{d\delta}{dt} \tag{2.7}$$

Therefore.

$$\frac{M}{2}\frac{d\left(\frac{d\delta}{dt}\right)^2}{dt} = P_a\frac{d\delta}{dt} \tag{2.8}$$

Multiplying by *dt* to have differentials:

$$\frac{M}{2}d\left(\frac{d\delta}{dt}\right)^2 = P_a d\delta \tag{2.9}$$

Integrating (2.9) between δ_0 (the pre-fault equilibrium angle) to δ (any post-fault angle):

$$\frac{M}{2}\left(\frac{d\delta}{dt}\right)^2 = \int_{\delta_0}^{\delta} P_a d\delta \tag{2.10}$$

Or in terms of equation (2.4):

$$\frac{M}{2}(\omega - \omega_0)^2 = \int_{\delta_0}^{\delta} P_a d\delta \tag{2.11}$$

Thus.

$$\omega - \omega_0 = \sqrt{\frac{2}{M}\int_{\delta_0}^{\delta} P_a d\delta} \tag{2.12}$$

Here ω - ω_0 is the relative speed of the machine respect to the infinite bus. Providing this speed return to zero the system will be first-swing stable then the speed will return to zero if the accelerating power is either zero or opposite sign to the rotor speed. An increasing in rotor angle δ implies that the difference ω - ω_0 is greater than zero, when the rotor angle δ reaches its maximum value (δ_m) then the difference ω - ω_0 equals zero. This happens when a negative accelerating power P_a damps the speed form ω-ω_0 > 0 to zero. This process is expressed as:

$$\omega - \omega_0 = \int_{\delta_0}^{\delta} P_a d\delta > 0; \delta_0 < \delta < \delta_m \tag{2.13}$$

$$\omega - \omega_0 = \int_{\delta_0}^{\delta_m} P_a d\delta = 0; P_a(\delta_m) \leq 0 \tag{2.14}$$

In order to assess transient stability by means of the EAC to a multimachine power system it is necessary to simplify it to a two-machine equivalent system and then replace it by an equivalent OMIB (see § 3.2.2) that represents the dynamics of the entire system. The application of this criterion to assess transient stability of a power system will be done in chapter 3.

To illustrate the EAC, let us consider that in a system like the one displayed in figure in figure 2.5 has been subjected to a three-phase fault at bus A, the initial operating point of the system is the intersection of mechanical and electric power (point *1* in figure 2.7). Due to the disturbance, the electric power transfer falls to zero (point *2*) at this point the electric power is smaller than the mechanical power and the machine gains kinetic energy until the fault is cleared at point *3*, the system reaches point *4* the area *1,2,3,4* represents the accelerating area of the system. When the fault is cleared, the system reaches δ_u and the system conditions changes to curve P_{ep}. EAC states that the system will be stable if the decelerating area is at least equal to accelerating area. In order to achieve this latter there are a wide variety of control actions to stabilize the system and become the decelerating area greater then the accelerating one. These control schemes will be fully described in § 2.4.

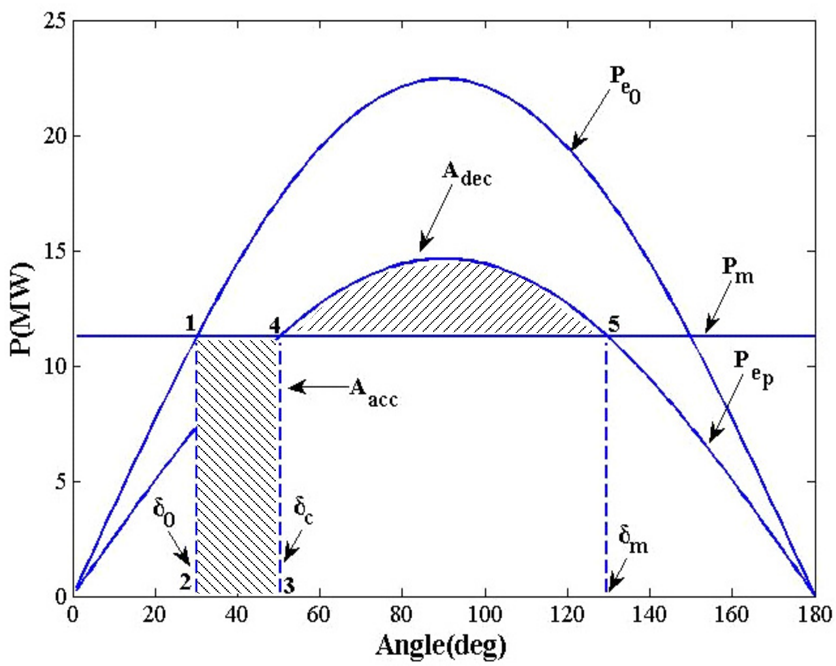


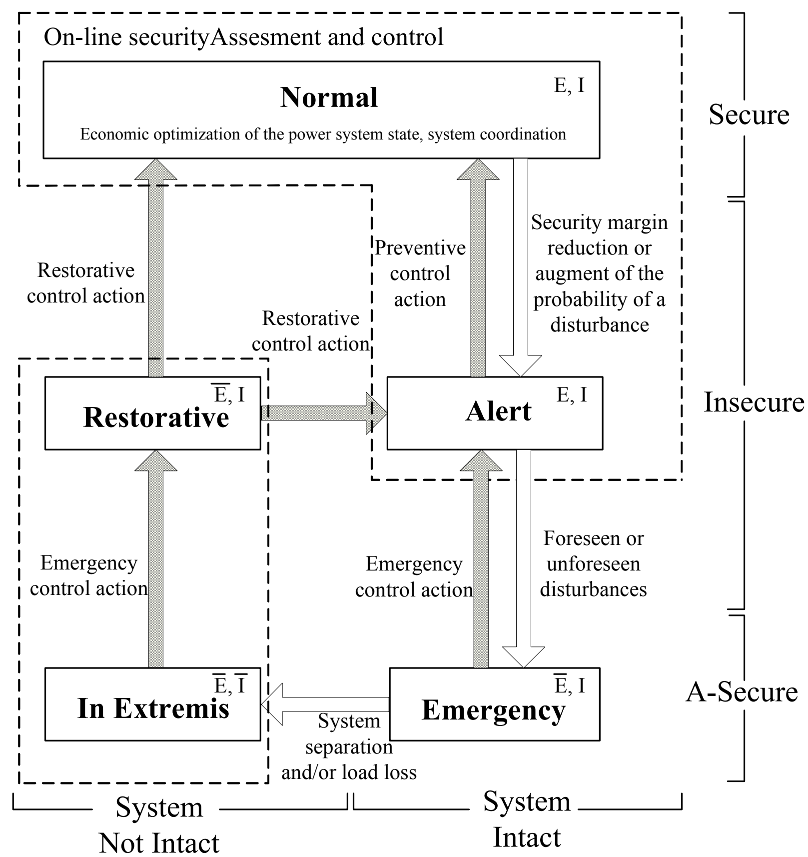
Figure 2.7 EAC of an infinite bus machine equivalent.

2.4 CONTROL OF TRANSIENT STABILITY

Power systems are described by five operating states [Fink and Carlsen, 1978] that must be born in mind to make an adequate design of the control scheme [Ruiz-Vega, 2009]; there are specific characteristics that define each one of the operating states depending on the security conditions and restrictions, Fig. 2.8 shows a Dy Liacco's diagram or transition states diagram.

Basically, the behaviour of the system is described by two sets of equations: algebraic and differential equations; without being very descriptive in modelling, by the moment, it will be mentioned that the set of differential equations represent the physical laws of the dynamic behaviour of the components of the system while the two sets of algebraic equations represent the equality and inequality restrictions of the system.

The equality restrictions are related to the total load of the system and the total generation supplied to that load, the purpose of those restrictions is to maintain the balance between load an generation (load flow). The inequality restrictions represent the fact that specific variables (like currents or voltages) must not exceed maximum values which represent the physical limits of the equipment [Fink and Carlsen, 1978].



E: Equality constraints, I: Inequality constraints, -: Negation

Figure 2.8 Dy Liacco's diagram. As adapted by [Fink and Carlsen, 1978].

In the **normal** operating state, all the variables must be within their own limits which means that all the restrictions are satisfied and the generation is adequate to satisfy the total of the load in the system [Fink and Carlsen, 1978, Kundur, 1994], in this operating state the reserve margins must be large enough to maintain an adequate security level respect to the strains so that the system would be subjected and, in case of the occurrence of a fault, the system has to be able to stand the disturbance without violating the mentioned restrictions.

If the security level is diminished or the probability of a disturbance augments, then the system enters into an **alert** operating state, in spite of the fact that in this state all the restrictions are satisfied and within specific margins, the reserve margin would be such that a disturbance would result in a violation of the equality or inequality restrictions so that preventive actions must be applied to restore the security level of the system.

If the fault is hard enough and no preventive measures are taken, the system enters into an **emergency** operating state, here the inequality restrictions are violated and the security margin is practically zero, at this point, the system would still intact only if "heroic measures" are adopted otherwise the system enters into an **in extremis** operating state; in this state both, the equality and inequality restrictions are violated, the system can not hold on intact what would result in the lose of parts of the system (brownouts) unless emergency actions are carried out to save as many parts of the system as possible from the total collapse (blackout).

When the collapse is conclusive the system enters into a **restorative** state, in this state control actions are taken to reconnect the system and picking up load again. From the restorative state the system would enter into a normal or alert operating state depending on the circumstances.

In table 2.1 the transition nature between operating states and their possible causes are presented [Fink and Carlsen, 1978]. When the system's operating state changes from normal to any other, the operator must carry out pertinent countermeasures to restore the security level of the system. The hierarchical order of those control measures is vertical so that each of the operating state has specific control measures to maintain adequate operating conditions.

Table 2.1 Transitions between Operating States.

Operating state	Nature of the transition	Probable causes
Normal to Alert	Reduction of the system's security level.	• Reduction of the security margin due to: an unusual load augment, the loss of a generating unit, fuel reduction, reduction of the capability of electric devices due to environmental conditions or maintenance. • Reduction of the energy delivered due to: loss of transformers or transmission lines, unusual distribution of the industrial load, reduction of the capability of electric devices due to high temperatures. • Increase in the possibility of a disturbance due to severe storms, natural disasters, social phenomena or accidents.
Alert to Emergency	Violation of inequality restrictions.	Erroneous functioning or temporal loss of an extremely important element due to internal electric faults or to unpredictable external events such as lighting.
Emergency to In extremis	Violation of the equality restrictions (loss of the systems' integrity).	Loss of a large number of tie-lines what leads to a system islanding due to lighting in critical tie-lines or the improper functioning of protection equipment during the emergency state.

In table 2.2 [Fink and Carlsen, 1978, Ruiz-Vega, 2002a] the measures for each of the operating states are presented.

Table 2.2 Control Measures.

Operating state	Control measure
Alert	Economic dispatch or security re-dispatch, network re-configuration, voltage reduction, etc. The purpose is to restore the reserve margins of the system.
Emergency	Immediate control measures to eliminate the equipment overloaded like: fast fault-clearing (automatic) , fast valving (automatic), dynamic braking (automatic), modulation of the excitation system (automatic), capacitors switching (manual), HVDC lines modulation, load modulation, generation tripping (automatic) and all measures for the alert operating state.
In extremis	Heroic actions to avoid the system's breakthrough: load shedding (manual), controlled islanding of some areas of the system and all measures mentioned for the alert and emergency operating state.
Restorative	Corrective control actions to restore the optimal functioning of the system, such actions are: the units restarting, load restoration, re-synchronizing the isolated areas of the system, etc.

The control systems currently used can be classified into different ways, depending on various factors such as [Ruiz-Vega, 2009]:

- The operating state of the power system.
- The functioning of the control system (open-loop or closed-loop).
- The geographic area covered by the control system (distributed or centralized).

Depending on the operating state of the system, two kinds of controls can be used:

- Preventive Controls (on-line controls).
- Corrective controls (real time or emergency controls).

The *preventive controls* are applicable to the system when the operating state is classified as **normal** or **alert**. When the system is faced to a possible contingency the vulnerability of the system must be determined in order to design and apply a control action before the occurrence of the disturbance and, in consequence, to enlarge the security level of the system. In the normal operating state, the control systems commonly employed are those which its main objective is to improve the economic efficiency of the system.

The control system in normal operating state is hierarchically organised in three main levels:

- Primary control system: it is a distributed system that acts in a fast fashion (seconds) using local measurements to regulate the value of a variable. Commonly, in this level, the controls used are proportional type.

- Secondary control system: is a centralized system that analyses the behaviour of the system as a whole using measurements of the overall system from a control centre. The devices that constitute these system act slower than the primary control (tens of seconds) to avoid wrong interactions or instabilities in the control system. In this control level, the controls employed are integrated and they correct the steady state mistakes that remain after the control action performed by the primary control.

- Tertiary control system: its purpose is to economically optimize the operation of the system. To carry out its functions, this control system requires the utilization of an economic dispatch or optimal power flow (OPF) program in addition to the different kinds of measurements. The economic dispatch program is performed approximately every 15 minutes and the OPF program is performed every 30 minutes.

The *corrective* or *emergency controls* act when the contingency has actually occurred. There are two basic schemes of emergency control [CIGRE, 2001, Ruiz-Vega, 2009]:

- Response-based (or Measurement-based) emergency controls.
- Event-based emergency controls.

Response-based emergency controls are based on measured electric variables (such as voltage, frequency, etc.) and initiate their protective actions when the contingency has caused the measured value to hit the trigger level of the corresponding variable [CIGRE, 2001]. These emergency controls are used to adjust the control action magnitude in accordance with the severity of the contingency.

The event-based are designed to operate upon the recognition of a particular combination of events (like the loss of several lines in a substation) controls act automatically by the appliance of a fixed control action (previously determined) when the occurrence of the event has been detected. The event-based emergency control is faster than measurement- based control since it does not have to wait for the system response to a specific event [CIGRE, 2001]. However, these kinds of controls must be designed for all relevant events, while a response-based control operates even for the events that were not planned.

2.4.1 Preventive control of transient stability problems

The preventive controls are applicable to the system when the operating state is classified as normal or alert. When the system is faced to a possible contingency the vulnerability of the system must be determined in order to design and apply a control action before the occurrence of the disturbance and, in consequence, to enlarge the security level of the system.

In the normal operating state, the control systems commonly employed are those which its main objective is to improve the economic efficiency of the system. The control system in normal operating state is hierarchically organized in three main levels:

- Primary control system: it is a distributed system that acts in a fast fashion (seconds) using local measurements to regulate the value of a variable. Commonly, in this level, the controls used are of proportional type.

- Secondary control system: is a centralized system that analyses the behavior of the system as a whole using measurements of the overall system from a control centre. The devices that constitute these system act slower than the primary control (tens of seconds) to avoid wrong interactions or instabilities in the control system. In this control level, the controls employed are integrated and they correct the steady state mistakes that remain after the control action performed by the primary control.

- Tertiary control system: its purpose is to economically optimize the operation of the system. To carry out its functions, this control system requires the utilization of an economic dispatch or optimal power flow (OPF) program in addition to the different kinds of measurements. The economic dispatch program is performed approximately every 15 minutes and the OPF program is performed every 30 minutes.

The hierarchical control systems described above has been developed in the majority of the systems around the world (at least until the secondary control system for the purpose of controlling the frequency) and in some systems for the secondary voltage control system [Ruiz-Vega, 2009]. Both control loops has been importantly modified in restructured utilities in which it is pretended to create a large amount of reactive power, and frequency regulation markets complicate the control system operation. One of the main investigation areas consists in the development of hierarchical control systems for alert and emergency operating states analogous to those used in normal operating state; using dynamic security techniques for the secondary control and programs that combine the dynamic security with economic optimization techniques for the tertiary level.

Some of the preventive control actions applicable to normal operating state are [Ruiz-Vega, 2002, Fink and Carlsen, 1978]: economic dispatch or security re-dispatch, network re-configuration, voltage reduction, etc.

2.4.2 Emergency control of transient stability problems

The concept of emergency control is associated with prevention of system-wide faults so that a failure of one element does not affect the operating conditions of other interrelated or independent elements. Emergency tools such as excitation boost and frequency load shedding devices appeared in the thirties [Vénikov, 1985].

Most of the emergency schemes consider the entire power system as an equivalent two-machine system comprising two generators with an interconnecting transmission system.

Emergency control involves additional controllers to those usually included in the main controller, but out of operation under normal situations, that handle the operation in abnormal situations [CIGRE, 2001]. Shift of control mode from normal operation to emergency control can be classified as a Special Protection Scheme (SPS).

System Protection Scheme (SPS) is the common name used when the focus for the protection is on the power system supply capability rather than on specific equipment [CIGRE, 2001]. A SPS is designed to detect abnormal system conditions and to take measures (other than the isolation of faulted elements) to preserve system integrity and to improve the system performance. SPS actions include: changes in load, generation, or system configuration to maintain the synchronism of the system. The majorities of the SPS rely on communication and are used as a means to operate power systems closer to their limits (given the context of restrained possibility of network development because of economic and regulatory problems) or to increase the power system security [CIGRE, 2001].

One of the main features that distinguish SPS from the single protection of the power system and its elements is that SPS are designed based on specific necessities by users and its implementation is not yet standard.

In order to improve transient stability SPS imposes special demands on system and equipment and must be based on a prudent assessment of the benefits and costs. Currently, there exists a wide variety of SPS and the majority of them are based on the following actions [CIGRE, 2001]:

- Generation tripping.
- Steam turbine fast valving or generator runback.
- Gas turbine or pumping storage start-up.
- Actions on the AGC such as set point changes.
- Under frequency load shedding (UFLS).
- Under voltage load shedding (UVLS).
- Remote load shedding.
- Dynamic braking or braking resistor.
- Controlled system separation or controlled opening of interconnection or area islanding.
- Tap changers blocking and set point adjustment.
- Quick increase of generator voltage set point or high speed excitation systems.

The actions above contribute to transient stability enhancement; there are some system parameters that have a significant effect in transient stability [Padiyar, 2002]:

- The inertia of the machines
- Reactances of the machines
- Reactances of the transmission network (pre-fault and post-fault network).
- The speed of the operation of switching devices
- The fault clearing-time (that is clearly related to the speed of the switching a protective devices).

Thus, stability should improve by using different methods that modify the characteristics of the system. Methods for improving transient stability have been highly studied since the sixties [Kundur, 1994]. Power System transient stability can be enhanced and its dynamic response improved if the system is properly designed and operated [Machowski, 2008]. However, for a given system any method for improving transient stability may not be adequate, this is due to the fact that transient stability enhancement methods must be prudently chosen so that the system would maintain stability for different system conditions and contingencies [Kundur, 1994]. The targets of the methods of improving transient stability are [Kundur, 1994]:

- Minimizing the severity and duration of the fault.
- Increasing the restoring forces.
- Reducing the accelerating torque (controlling the mechanical power or applying artificial load).

Most of the methods for improving stability are options available for economic system design and they must contribute to the system operation flexibility without compromising security aspects of the system.
For instance, from the design viewpoint, the following actions help to improve stability [Machowski, 2008]:

- The adequate design of protective equipment and circuit-breakers that ensure the fastest possible fault clearing;
- The use of single-pole circuit-breakers so that during single-phase faults only the faulted phase is cleared and the un-faulted phases remain intact;
- The right design of a system configuration that is suitable for the particular operating conditions (e.g. avoiding long, heavily loaded transmission links).

From the operating viewpoint, the following actions help to improve stability [Machowski, 2008]:

- Ensuring an appropriate transmission capability reserve;
- Avoiding operation of the system at low frequency and/or voltage;
- Avoiding weakening the network by the simultaneous outage of a large number of lines and transformers.

Of course those actions are not continuous but they start following a disturbance and are temporary in nature [Padiyar, 2002]. In this section, a quick review of some actions to enhance transient stability of power systems is presented.

High-Speed Fault Clearing.

The kinetic energy that the machine gains during a fault is directly proportional to its duration [Kundur, 1994]. Currently, two-cycle breakers with high-speed relays are used to quickly clear the fault [Kundur, 1994].

Reduction of Transmission System Reactance.

The transmission network reactances are determinant parameters for transient stability so that the reduction of the reactance of some elements of the transmission network system improves transient stability by increasing post-fault synchronizing power transfers [Kundur, 1994]. These can be achieved by using transformers with lower reactances and series capacitors in the transmission lines (the maximum power transfer capability of a transmission line can be increased by using series capacitor banks), however, this can contribute to transient stability enhancement depending on the facilities provided for bypassing the capacitor during faults and reinsertion after fault clearing, in general, the series compensation is used for long overloaded lines.

Regulated shunt compensation.

The use of shunt compensators able to maintain specific bus voltages at adequate levels is a common practice to improve transient stability since it can augment the flow of the synchronizing power in the interconnected system. Shunt compensation also increases the maximum power transfer capability of long transmission lines [Kundur, 1994].

Dynamic braking.

Consist in the appliance of artificial electrical load during a disturbance with the objective of diminish the rotor acceleration by augmenting the electrical power output of the machines. This can be achieved by switching in shunt resistors for a period of time after the fault in order to reduce the accelerating power of closer machines to dissipate the kinetic energy gained during the fault. This action can be applied to remote hydraulic machines because they are more robust than thermal units and can bare the sudden in switching of shunt resistors. The switching time must be carefully determined because if the resistors remain connected for a long period of time it may result in back swing instability [Kundur, 1994].

Reactor switching.

Shunt reactors may improve transient stability because the reactor is normally connected to the network and the reactive load increases the generator internal voltage which helps stability [Kundur, 1994].

Independent-pole operation.

When every phase of the circuit breaker is opened with an independent pole and they can be close or open independently, it is call independent-pole operation. Thus, a failure that affects one pole will not restrict the operation of the other two poles. Whit this kind of circuit breakers it is really improbable that a failure of the three poles would occur because the operating mechanism guarantees that at least two of the poles will be open what considerably reduces the risk of a three-phase fault on the system [Kundur, 1994].

Single pole switching.

This scheme uses separate operating mechanisms for each phase and the relay is designed to trip different number of lines depending on the fault type and the duration. Since the majority of the transmission line's faults are line-to-ground type, only one line must be opened and re-close instead of the three of them. This scheme is particularly attractive where a single line connects two systems or when an important line connects the generating station to the rest of the system; however, there are some disadvantages that must be bear in mind: the secondary-arc extinction, the fatigue of the turbine-generator shafts and the negative-sequence currents in thermal units [Kundur, 1994].

Steam turbine fast-valving.

This technique consists in the quick closing and opening of steam valves in order to reduce the accelerating power of the machine after the occurrence of a severe transmission system fault [Kundur, 1994]. This scheme is usually applied to thermal generators. The control action can be divided into two categories: the momentary fast-valving and the sustained fast-valving. Fast-valving helps the system to keep in synchronism by means of reduce the turbine mechanical power, despite the fact that it is also an effective and economical method to improve transient stability because the implementation cost is low, it may have adverse effects on the turbine and boiler/steam generator.

Using fast-valving has the advantage that the mechanical power is reduced but all the units persist connected to the system, on the contrary of what happens with generation tripping, and the total inertia remains intact.

Controlled system separation.

The controlled system separation initiates by opening tie lines before the complete system collapses and is used to prevent a major disturbance that would be the consequence of a disturbance in a part of the system that would propagate to the entire system. In some cases it may be necessary to shed some loads to maintain the balance of load and generation in the system that was separated from the main part of the system [Kundur, 1994].

Once that the system is controlled the reconnection of the isolated parts would be done.

High-speed excitation systems.

The use of high-speed excitation systems is the most economical and effective method to improve transient stability [Kundur, 1994]. After the occurrence of a fault and its clearance the voltage at the generator terminals is low and with the increase of generator field voltage the internal voltage of the machine increases too, as a consequence the synchronizing power increases.

The effectiveness of high-speed excitation system depends on the ability of the excitation system to increase the field voltage to the highest possible value [Kundur, 1994].

Discontinuous excitation control.

This type of control action controls the generator excitation so that the terminal voltage is maintained near the maximum permissible value over the entire positive swing of the rotor angle [Kundur, 1994]. This can be achieved by keeping the excitation at ceiling until the highest point of the swing is reached.

The discontinuous excitation controls are commonly used to improve stability in generating units that have inter-area swings, particularly those with low-frequency inter-area swings. This control scheme must be combines with other protection schemes because it is necessary to make sure that the increased magnetizing current does not cause protections operation [Kundur, 1994].

Control of HVDC transmission links.

HVDC transmission links are really controllable and this asset helps transient stability enhancement. During the occurrence of a disturbance, the dc power can be ramped down very fast in order to minimize the balance between load and generation of the altern current system, thus the effectiveness of fast control of dc power is comparable to the effects that have load shedding or generation tripping [Kundur, 1994].

Generation tripping.

This control scheme has been widely used. It consists in the selective tripping of generators when a harmful contingency occurs; most of them are event-based (based on the direct detection of events such as line trips [CIGRE, 2001]) and its main purpose is to ensure that the effects of faults and disturbances are restricted to local areas [IEEE, 1995].

As generating units can be rapidly tripped, this is a very effective means of improving transient stability by reducing the accelerating torque on the machines that remain in service after any disturbance [Kundur, 1994, CIGRE, 2001]. As fast as the machines are be tripped, they can be re-connected when the disturbance has been cleared. The use of generator tripping subjects the unit to up to a full-load rejection with the associated impact on the generator, prime mover, and energy supply system, this impact is usually of more concern for thermal units than for hydro units and some providence must be taken into account in order to allow the fast re-synchronization of the machine to the system (say 15 to 30 minutes); otherwise the machine would not be available for some hours [IEEE, 1978].

At the beginning, this practice was confined to hydro units because they are remote from load centers and there is no risk for the machine from a spontaneous trip. Later on, this practice has been extended to certain thermal, fossil-fuel and nuclear units [IEEE, 1978, Kundur, 1994].

In general, generator tripping falls into two categories [Karady and Gu, 2002]:

- On line-generation tripping: if the unit to be tripped is selected by means of on-line calculations.
- Off-line generation tripping: when the unit to be tripped is determined by using off-line methods (like offline-developed look-up tables to match fault locations and system status with generator tripping information).

Generator tripping can be initiated from a transfer trip scheme or by arranging the breakers at the power plant [IEEE, 1978]. The system operator can sing contracts with companies that own the generating plants in which system protection schemes like this one are installed, in fact this kind of contracts have been implemented in some electricity markets [Ruiz-Vega and Pavella, 2003b].

There are specific industry recommended practices for generation tripping in case of abnormal operating conditions or severe faults. Since tripping practice subjects generators to hard changes in load that may damage the machine, the prime mover or the energy supply system [Kundur, 1994], some important aspects must be carefully considered when evaluating this form of discrete control. The most important aspects to consider when tripping a machine are [Kundur, 1994]:

- The over speed that results from the tripping generator: the controls must be able to fully reject the load without tripping the turbine because it is essential for the unit to maintain its auxiliary load before it is re-connected to the system. When this control scheme is used very often, it is advisable to emphasize the preventive maintenance and periodic testing of the turbine valves and protective systems because they must be in optimum conditions to ensure the safe and reliable operation of the speed controls.

- The thermal stresses that are provoked by the load changes: when a generating unit is tripped it is subjected to high thermal stresses because the range of the variation of the unit output is so wide. As mentioned before, when the machine is tripped, it operates for a while with an auxiliary load or without load what leads the machine to diminish the temperature of the turbine metals and it continues in this way till the machine is reloaded, thus the load starts heating the metals again in the critical areas. This stresses must be limited to acceptable levels by appropriate operating procedures.

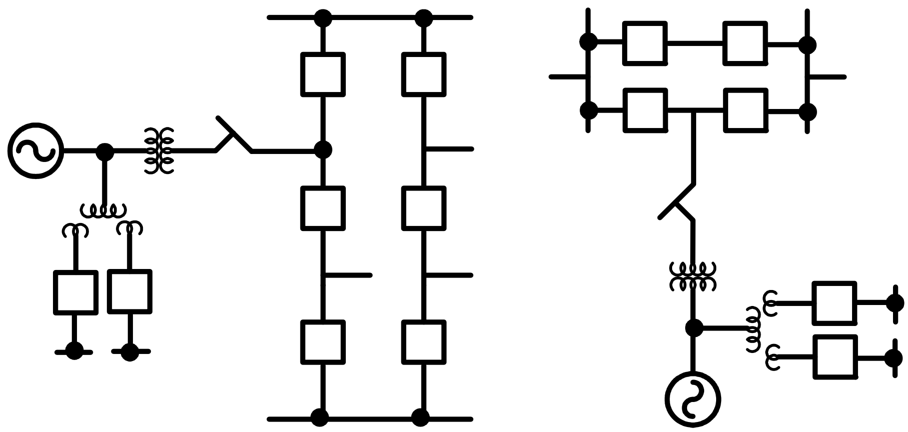
- The high levels of shaft torques due to successive disturbances. When a generating unit is rejected in a power station that has multiple units, all the units experience consecutive disturbances that may result in high levels of shaft torques.

When tripping a machine, there exist some specific modes to isolate a generating unit: simultaneous tripping, generator tripping, unit separation and sequential tripping [IEEE, 1995], selecting one of them directly depends on the purpose of the generation tripping. In this work it is pretended to allow the fast re-synchronization of the machine to the system, this requires specific design of the unit and its controls for this mode of operation. There are two modes of machine isolation that fulfill these purpose: generator tripping and unit separation:

Generation tripping: This mode of isolation trips the generator and field breakers. The scheme does not shut down the prime mover and is used where it may be possible to correct the abnormality quickly and thereby permitting the reconnection of the machine to the system in a short period of time. The protection which trips the generator of power system disturbance, can trip though this mode if permitted by the type of prime mover and boiler steam [IEEE, 1995].

Unit separation: This tripping scheme is similar to generator tripping but initiates only the opening of the generator breakers. The scheme is recommended for application when it is desirable to maintain the unit auxiliary loads connected to the generator. The advantage of this scheme is that the unit can be re-connected to system with minimum delay. This trip mode requires that the unit be capable of a runback operation following a full load rejection trip [IEEE, 1995].

In large power plants, it is common to use a breaker and a half or ring bus yard layout with a disconnect on the generator feed (see figure 2.9). This allows the generator to be taken off-line, the disconnect opened, and the breakers closed to maintain another tie between the main buses. In the early phases of plant construction, it is common to have a ring bus configuration which will later be expanded to a breaker and a half. The ring configuration requires a disconnect switch on the generator feed that can be opened so that the ring can be closed when the generator is off-line. Some engineers have used auxiliary contacts in the motor operator of these disconnect switches to disable some or all the generator protection when the generator is off-line. While this appears to be a convenient indication of the status of the machine, it can be fooled by abnormal conditions.



(a) (b)

Figure 2.9 (a)Typical breaker-and-a-half station.
(b)Typical ring bus station.

For the generator tripping to be effective, the unit must be tripped within the first few cycles after the fault clearing [Karady and Gu, 2002]. Considering that the loss of synchronism of the power system occurs 1 s after the fault clearance the required time to complete the trip must be within the 250 ms after the fault inception [Matsuzawa et al., 1995].

After the generation tripping the events that happen are in the following order [Kundur, 1994].

- Tripping the boiler
- As the turbine is not tripped, its controls limit the over speed and then the speed is set to a near-rated speed.
- The unit operates with no load or with an auxiliary load, sometimes the machine is used to supply the unit auxiliary load.
- The boiler is purged and re-fired to be ready for the re-connection.
- The unit is re-synchronized to the system
- The unit is reloaded at a predetermined rate.

The main negative aspect of generation rejection is that it subjects the rejected unit to sudden changes in electrical and mechanical loading, which may result in over-speed, thermal stresses and a reduction in shaft life due to shock-initiated fatigue [IEEE, 1978].

The most reliable techniques to stabilize the system are: fast valving, generation tripping load shedding and controlled system separation [Taylor, 1994]. The most common SPS are probably under-frequency controlled load shedding and generation tripping [Machowski, 2008, CIGRE, 2001, Karady and Gu, 2002].

In this work, generation tripping will be used as a means of control action for the E-SIME method (considered as a SPS in [CIGRE, 2001]) to predict and improve transient stability; the methodology and the techniques used for this purpose will be described in chapter 3.

2.4.3 Preventive vs Emergency control

Given that in this work the control scheme used is generation tripping, in this section is presented the application of the EAC to illustrate the difference between preventive and emergency control and the influence of the generation tripping on the power system.

The EAC was applied to an unstable case of a test system named MMT equivalent system described in appendix A. A three-phase fault is applied at node 7, when the fault is cleared the 1 - 7 line is disconnected. The behavior of the system is depicted in figure 2.10 where P_{e0} is the electrical power of pre-fault scenario and P_{ep} is the electrical power of the post-fault scenario, the mechanical power of the system is P_{m0}. Before the fault, the operating point is "*1*" (stable equilibrium point), when the fault occurs the system reaches point "*2*", during the fault the system changes to the operating point "*3*" and at the clearing time the systems reaches point "*4*", the system losses synchronism and reaches point "*5*" (unstable point). The system is clearly unstable since accelerating area is bigger than the decelerating area. In order to stabilize the system two different control actions were carried out: generation re-schedule and generation tripping, the main differences between these two schemes are presented below.

Preventive control (Generation re-scheduling)

In order to stabilize the system, the power plant was re-scheduled by reducing the plant capacity in 20% permanently. In figure 2.11 is shown the effect of tripping generation re-schedule, the mechanical power P_{m0} is modified and becomes P_{m1}, the electric power remains the same, however when the mechanical power is reduced, the decelerating area becomes equal to the accelerating area and the system is stabilized.

Emergency control (Generation tripping)

In order to stabilize the system, 2 machines (1 and 2 of the system) were tripped. In figure 2.12 is shown the effect of tripping those units, the mechanical power P_{m0} is modified and becomes P_{m1}, the electric power also changes in magnitude since two machines were tripped and are no longer connected to the system; in this way the decelerating area becomes bigger than the accelerating area and the system is stabilized.

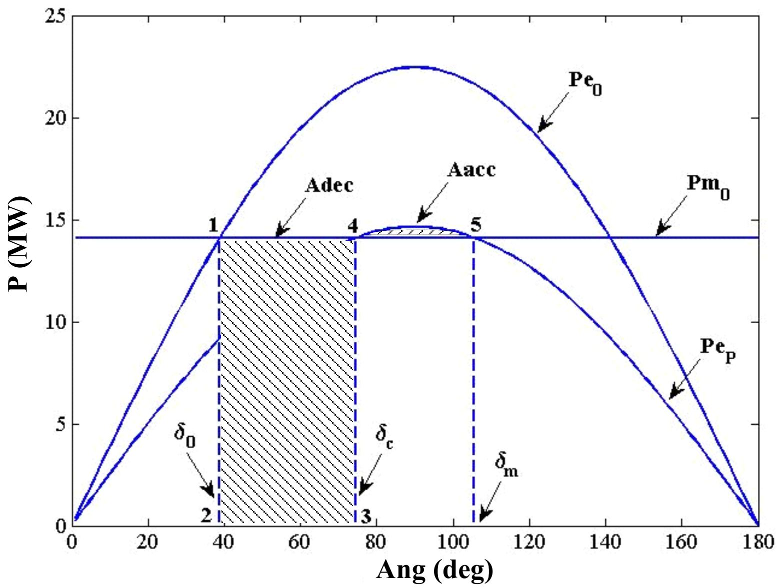


Figure 2.10 Unstable case for the MMT power system.

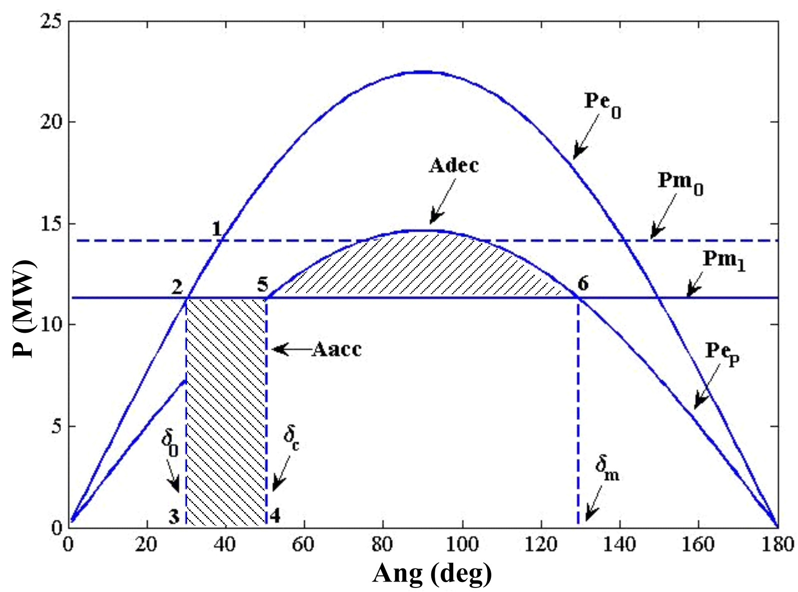


Figure 2.11 Stabilized case for the MMT power system using preventive control.

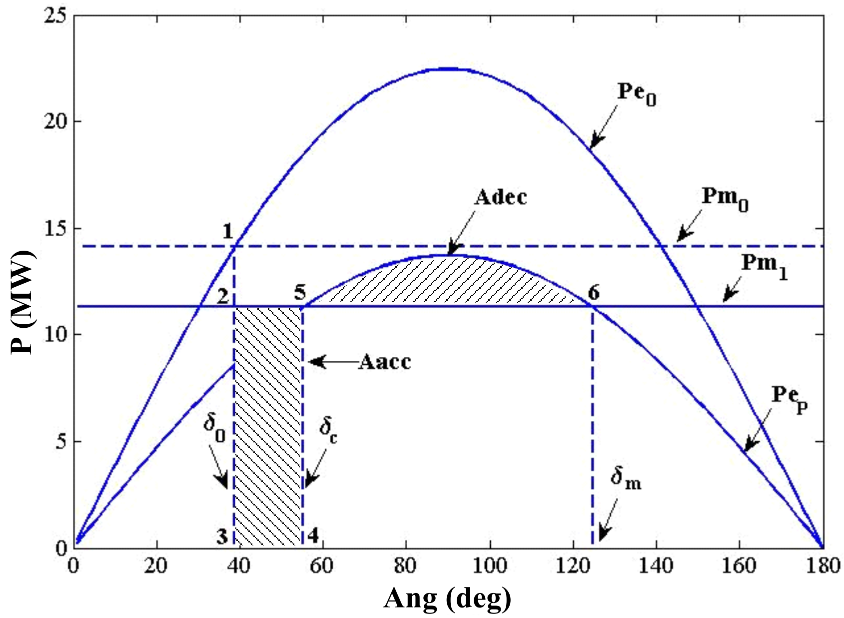


Figure 2.12 Stabilized case for the MMT power system using emergency control.

There are important differences between preventive and emergency control actions: while preventive control actions are planned using off-line studies and are armed when the system is faced to a plausible contingency, emergency actions are triggered when the contingency has actually occurred. Re-schedule generation implies the reduction of the entire plant capacity for a long period of time while tripping machines implies to disconnect the machine from the system and re-connect around 30 minutes later.

2.4.2 On-line and real time control of transient stability

Historically, security assessment has been performed by off-line planning studies (using tools like power flows and TD simulations) in spite of the fact that computation efforts to evaluate a single condition of a system are technically rigorous [CIGRE, 2007].

System operators depend on the results of operational planning studies (off-line studies) to control the system operation. However, these off-line techniques are not practical in today's power systems because the operating limits computed off-line for a given operating point are not necessary true for other operating condition of the system. In consequence, on-line TSA techniques that enable the operator to know the actual condition of the system and perform the security assessment in near-real time have emerged; they are also speed enough to allow the operator to take control measures to maintain the security level.

In addition, using on-line data allows the acquisition of relevant information about the current system status that off-line techniques do not provide. In the new competitive environment, especially in the reformed utilities, the uncertainty of predicting future operating conditions has created the necessity of new approaches to security assessment: On-line Dynamic Security Assessment (DSA) where the system security is computed near real-time [CIGRE, 2007].

Despite the fact that on-line control systems are growing in use, detailed and exhaustive off-line studies are still used in the operation planning to give general guidelines for system operators.
The functions of an On-line DSA system are the following [CIGRE, 2007]:

- Knowing the exact actual power system condition.
- Developing of an appropriate network model.
- Combining dynamic and contingency data to perform a suitable TSA.
- Performing the analysis and report the results.
- Raising alarms when security issues are detected.
- Identifying security issues and making recommendations to relieve them.

The Architecture of an on-line DSA system is depicted in figure 2.13. In this horizon, real-time operation means that the input data reflect the actual system conditions. Real-time controls use measures from devices that capture analogue values and status indications; they are also stored into the real-time database [CIGRE 2007]. The operator has only few seconds to: analyze the situation and screen a large number of contingencies to identify the harmful ones and examine them to design adequate control actions in case the contingency occurs. The operator must also decide if preventive action should be taken or to rely on emergency controls (emergency action once that the contingency has actually occurred) [Pavella et al., 2000].

Real-time and online TSA are not necessarily complement contributes. On line implies that the calculations are available to the operator in the Energy Management System itself, however, there is no guarantee that the online computational process will be fast enough to produce results that can be labeled real-time [CIGRE 2007].

Experience indicates that effective real-time management of electricity systems can only be achieved through centralized, or centrally coordinated, system operation. System operators are also responsible for executing emergency procedures to manage extreme events in a manner that minimizes the impact on supply while protecting critical electricity infrastructure.

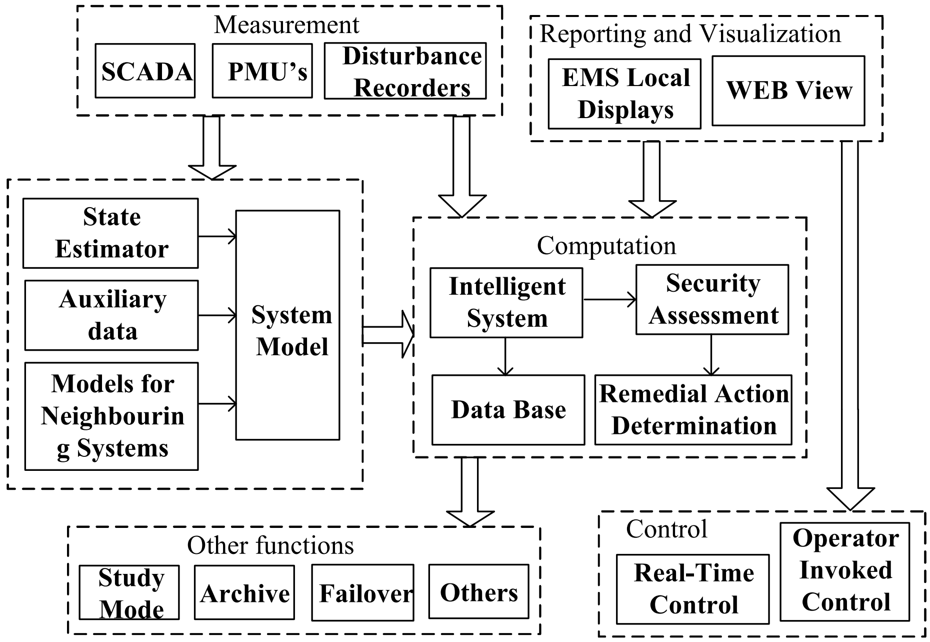


Figure 2.13 Components of an on-line dynamic security assessment system (Adapted from [CIGRE, 2007]).

CHAPTER 3:

THE EMERGENCY SIME METHOD

3.1 INTRODUCTION

SIME is a mature and powerful transient stability method which provides very valuable information about the power system dynamic performance that can be used to develop transient stability security assessment and control functions. It has two main variants: preventive SIME and emergency SIME (E-SIME). The main difference between both methods lie in the source of the information about the power system dynamic performance they process: while the first one uses the results of time-domain simulations, the latter uses real time measurements to assess transient stability.

Nevertheless, the preventive SIME and the E-SIME methods have their inceptions in the same principles and they both use the Equal Area Criterion (EAC) to determine the stability of the system. For the sake of simplicity, in this chapter a brief general description of the preventive SIME method and its formulation is elaborated in order to present the basic concepts of the method. In the second phase, the E-SIME method and its main characteristics and conceptualization are described in detail and, the last part of this chapter describes the structure of the E-SIME simulation program developed in this work.

3.2 THE SIME METHOD

The equivalent system most often considered to study the power system in emergency conditions is a two-machine system comprising two generators with an interconnecting transmission system between them [Vénikov, 1982]. That system configuration can be achieved by reducing the original multi-machine power system into a One Machine-Infinite Bus (OMIB) equivalent system; this latter is valid since the behavior of the machines of a real power system is similar to that of a two-machine system when the system looses synchronism [Kimbark, 1948]. This fact was known for a long time (almost 80 years) in power system transient stability assessment, but it was considered that the equivalent OMIB could only be properly obtained in two machine systems represented by the classical model. One of the most important achievements of SIME is that during its development it was fully demonstrated that the OMIB equivalent could be derived for large scale multi machine systems, and considering any modeling level detail in both, system components and contingencies [Pavella et al., 2000].

3.2.1 Foundations of the SIME method

SIME is a hybrid method that combines the time-domain simulation method with the equal area criterion. It is based on the following two principles (taken with permission from [Ruiz-Vega, 2002a]):

Proposition 1: *However complex, the mechanism of a power system loss of synchronism originates from the irrevocable separation of its machines into two groups. Hence, the multi-machine system transient stability may be inferred from that of a One-Machine Infinite Bus (OMIB) system properly selected (the critical OMIB).*

Proposition 2: *The transient stability of an OMIB may be assessed in terms of its transient stability margin* η*, defined as the excess of its decelerating over its accelerating energy.*

SIME combines the benefits of time-domain and direct methods, while avoiding their disadvantages. The use of the time-domain simulation method has the advantage of providing the most accurate system dynamic response available, while the essential advantage of the application of the equal area criterion is that it provides stability margins in order to assess the severity of the instability. Combination of both methods provides a very important "emergent" advantage: the identification of the machines responsible for the system separation.

SIME's main information: stability margin and identification of the set of critical machines, is importantly complemented with very useful simplified representations of the multi machine large scale system dynamic response by means of three OMIB system representations in the time-domain, in the P-δ plane and the phase plane which have been used to derive very important assessment and control techniques that could be implemented either on-line and in real-time. As an example, as it is presented in this chapter, E-SIME predictive transient stability assessment is mainly based in the OMIB P-δ plane representation of the system.

Apart from the differences in the source of the data they process, preventive SIME and emergency SIME have important conceptual differences from the transient stability control point of view:

- Preventive SIME: aims at assessing and designing "what to do" in order to avoid the system loss of synchronism if an a priori harmful contingency would occur [Ernst et al., 2000, Ernst and Pavella, 2000].
- Emergency SIME: aims at assessing, designing and triggering a countermeasure in real-time after a contingency has actually occurred "what to do" in order to stabilize the system [Ernst et al., 2000, Ernst and Pavella, 2000, Ruiz-Vega, 2002a].

3.2.2 Overall formulation of the SIME method

SIME concentrates on the post-fault configuration of a system after being subjected to a large disturbance that may drive the system to instability. Then, based on the proposition 1 in § 3.1, the two groups of machines (the critical one and the non-critical machines' group) are identified and replaced by a two-machine system and then by an OMIB; transient stability is assessed by means of the EAC in this latter OMIB.

The identification of the critical machines is done in the following fashion [Pavella, et al., 2000]:

- SIME method drives the T-D simulation first in the during-fault and then in the post-fault configuration.
- Immediately after the system enters into a post-fault state, SIME method begins to sort the rotor angles of all the machines at each time step of the T-D simulation.
- SIME identifies the larger rotor angle deviation between adjacent machines and two groups are conformed: the critical group (those machines whose rotor angle deviation is one of the largest) and the non-critical group (the rest of the machines).
- These two machine groups are first reduced to a two-machine system, then to a candidate OMIB whose parameters are computed as in § 3.2.1 and the procedure is repeated until the candidate OMIB reaches the instability conditions (given by the EAC and shown in § 3.2.3) then the OMIB is considered the critical OMIB.

The derivation of the OMIB time-varying parameters is accomplished as follows [Pavella, et al., 2000]:

- For the application of the EAC the system must be transformed into a two-machine equivalent system, these latter are aggregated into their corresponding centre of angle (COA) and replaced by an OMIB. All these changes are made using the parameter values of the system refreshed by the T-D program.

- The following formulas correspond to the pattern which decomposes the machines into critical (subscript *C*) and non-critical machines (subscript *NC*). The expressions to calculate the corresponding OMIB parameters are:

  i) COA of the group of the critical machines (*CM's*) and the non-critical machines (*NM's*)

$$\delta_C(t) \triangleq \frac{1}{M_C}\sum_{k\in C} M_k \delta_k(t) \tag{3.1}$$

$$\delta_{NC}(t) = \frac{1}{M_{NC}}\sum_{j\in NC} M_j \delta_j(t) \tag{3.2}$$

  Where

$$M_C = \sum_{k\in C} M_k \; ; \qquad M_{NC} = \sum_{j\in NC} M_j \tag{3.3}$$

  ii) Rotor angle of the corresponding OMIB

$$\delta(t) \triangleq \delta_C(t) - \delta_{NC}(t) \tag{3.4}$$

  iii) Rotor speed of the corresponding OMIB

$$\omega(t) = \omega_C(t) - \omega_{NC}(t) \tag{3.5}$$

  Where

$$\omega_C(t) = \frac{1}{M_C}\sum_{k\in C} M_k \omega_k(t) \; ; \qquad \omega_{NC}(t) = \frac{1}{M_{NC}}\sum_{j\in NC} M_j \omega_j(t) \tag{3.6}$$

  iv) Mechanical power of the corresponding OMIB

$$P_m(t) = M\left(\frac{1}{M_C}\sum_{k\in C} P_{mk}(t) - \frac{1}{M_{NC}}\sum_{j\in NC} P_{mj}(t)\right) \tag{3.7}$$

  v) Electric power of the of the corresponding OMIB

$$P_e(t) = M\left(\frac{1}{M_C}\sum_{k\in C} P_{ek}(t) - \frac{1}{M_{NC}}\sum_{j\in NC} P_{ej}(t)\right) \tag{3.8}$$

  vi) Accelerating power of the corresponding OMIB

$$P_a(t) = P_m(t) - P_e(t) \tag{3.9}$$

  vii) Equivalent OMIB inertia coefficient

$$M = \frac{M_C M_{NC}}{M_C + M_{NC}} \tag{3.10}$$

3.2.3 Transient stability assessment

Transient stability assessment is performed by means of the EAC, described in chapter 2. Despite the fact that T-D simulations are very useful methods that can provide a very detailed analysis of the transient stability problem, the EAC has demonstrated to be a powerful and unique tool for sensitivity analysis and control issues [Pavella, et al., 2000].

The EAC states that the stability of a system in faulted conditions may be assessed by means of a stability margin, which is the excess of the decelerating area (that represents the maximum potential energy that the system can dissipate in post-fault conditions) over the accelerating area (that represents the kinetic energy gained during the fault) of the *P*-δ curve of the equivalent OMIB; this margin is written as follows:

$$\eta = A_{dec} - A_{acc} \tag{3.11}$$

Expression (3.11) establishes the energy conservation: the energy gained during the fault must be released as potential energy in the post-fault period for the system to be stable, and otherwise the system is unstable [Pavella, et al., 2000].

In this context SIME uses the EAC to assess transient stability; however, what makes it attractive is that SIME calculates the P_m-δ and the P_e-δ curves using the results of a T-D program (or real-time measurements depending upon the case) only for the period of time EAC requires to assess stability (that is usually quite short). The duration of the computation is upper bounded by the time the OMIB takes to reach angles δ_u or δ_r. Angle δ_u is the "unstable angle" and can be found at the unstable equilibrium of the P_e and the P_m curves at which the system becomes unstable. Angle δ_r is the "return angle" and represents the maximum angular deviation before the system reaches its maximum angular deviation and starts decreasing, what means that the system remains stable.

In general, for during-fault and post-fault scenarios the stability margin can be expressed as:

$$\eta = -\int_{\delta_0}^{\delta_{ch}} P_a d\delta - \int_{\delta_{ch}}^{\delta_u} P_a d\delta = -\int_{\delta_0}^{\delta_u} P_a d\delta \tag{3.12}$$

Where: δ_{ch} represents the angle where the accelerating power changes sign (from positive to negative). The conditions (criteria) for the system to be declared stable or unstable are described below (As in [Pavella, et al., 2000]).

Unstable conditions: In this case, the stability margin is negative, $\eta < 0$, what means that the accelerating area is greater than the decelerating area ($A_{dec} < A_{acc}$). The P_e

curve crosses P_m and P_a passes by zero and continues increasing, then the OMIB losses synchronism. An OMIB reaches the unstable angle at the time t_u when:

$$P_a(t_u) = 0\,, \qquad \dot{P}_a(t_u) = \left.\frac{dP_a}{dt}\right|_{t=t_u} > 0 \tag{3.13}$$

Where: $\omega > 0$ for $t > t_0$. The conditions expressed in (3.13) equations are used to determine the critical OMIB of the system.

Stable conditions: In this case the stability margin is positive, $\eta > 0$, what means that the decelerating area is greater than the accelerating area ($A_{dec} > A_{acc}$). The system kinetic energy is less than the potential energy and P_e curve stops al $\delta = \delta_r$ before crossing P_m and then the rotor angle starts decreasing. An OMIB is stable when the return angle δ_r is reached at t_r:

$$\omega(t_r) = 0\,, \qquad \text{with } P_a(t_r) < 0 \tag{3.14}$$

As soon as these conditions are reached, the T-D simulations can be stopped and the system is considered fist-swing stable.

3.2.4 Stability margins

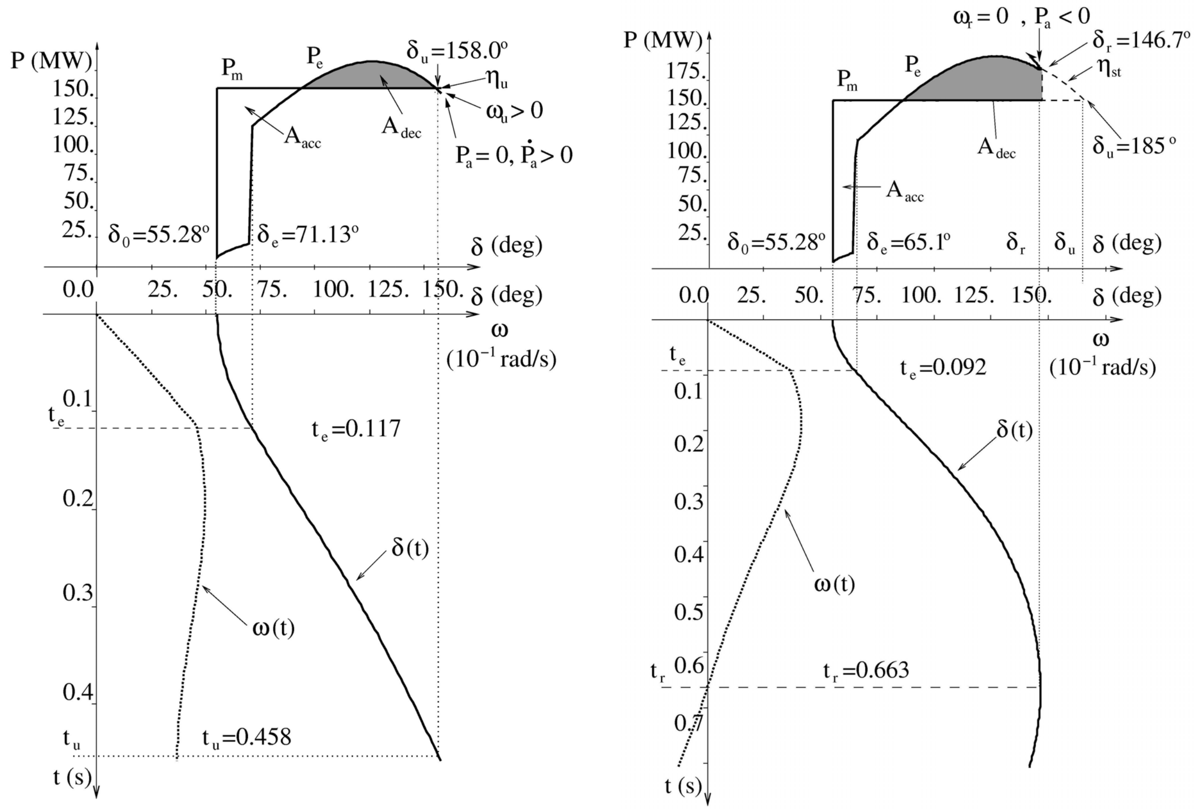
The unstable margin is written as follows:

$$\eta_u = -\frac{1}{2} M \omega_u^2 \tag{3.15}$$

Computation of this margin is simple and closed, and avoids the calculation of the accelerating and decelerating areas of the *P*-δ curve by numerical integration. The stable margin is defined as follows:

$$\eta_s = \int_{\delta_r}^{\delta_u} |P_a|\, d\delta \tag{3.16}$$

The stable margin only can be approximated because δ_u and $P_e(\delta)$ ($\delta_u > \delta > \delta_r$) can not be computed in a direct way since the *P*-δ curve returns before reaching them at δ=δ_r . To calculate this margin we can only use an approximation. Figure 3.1 schematically shows the computation of the stability margins from simulations performed in the three-machine test system (see appendix A). In this work, the approximation of the stability margin was performed by means of the least squares technique, as described in section 3.7.



a) Unstable case illustrating transient instability conditions and negative (unstable) margin.

b) Stable case illustrating transient stability conditions and positive (stable) margin.

Fig. 3.1 SIME: stability and instability conditions and computation of their corresponding stability margins. Simulations performed on the three-machine test system. Application of the EAC to the rotor angle-power curve of the OMIB equivalent. Corresponding OMIB rotor angle and speed curves ([Ruiz-Vega, 2002a]).

3.3 THE EMERGENCY SIME METHOD

As pointed out before, the emergency SIME method employs real-time measurements instead of T-D simulations in order to control system transient stability just after a contingency has actually occurred [Pavella et al., 2000]; even though, this is difficult to achieve since real-time measurements directly depend on the technological advances and the availability of equipment that can provide them. The general principle and description of the Emergency SIngle-Machine Equivalent (E-SIME) is performed in this section.

3.3.1 Principle

The main purpose of E-SIME is to predict the behavior of the system and design countermeasures to control the system and to prevent it from losing synchronism in real-time. E-SIME also continues monitoring the system to evaluate if the triggered action was effective or if it is necessary to take new control actions. E-SIME predicts the system behavior once that it has entered in its post-fault configuration and uses the multimachine-system data available at consecutive sample times.

The main structure of the E-SIME method can be described by the following steps [Pavella et al., 2000]:

Predictive stability assessment

Predictive stability assessment tries determining, in a horizon of time ahead enough from the system unstable time, if the system will lose stability by performing, in sequence:

- The prediction of the OMIB structure.
- The prediction of the *P-δ* curve of the OMIB by means of weighted leas-squares (WLS).
- Transient instability is predicted by verifying whether the projected *P-δ* curve meets SIME's instability conditions or not.
- If the system does not reach instability, measurements must be refreshed and the stability must be assessed again; on the contrary, if the system is unstable, and the method computes the corresponding margin and the time to instability, and goes to the control design phase.

Control design and application phase

In case system instability is predicted, E-SIME designs an emergency control action by performing the following steps:

- Determination of the size and location of the control action that must be applied to avoid system instability by means of E-SIME predictive stability assessment of the system after the control action has been taken.
- Triggering the corresponding action.

E-SIME continues monitoring the system using the predictive stability assessment in order to verify if the control actions were properly triggered and effective. In case system is found to become unstable, E-SIME would design and trigger additional control actions. In general, E-SIME is organized as shown in figure 3.2.

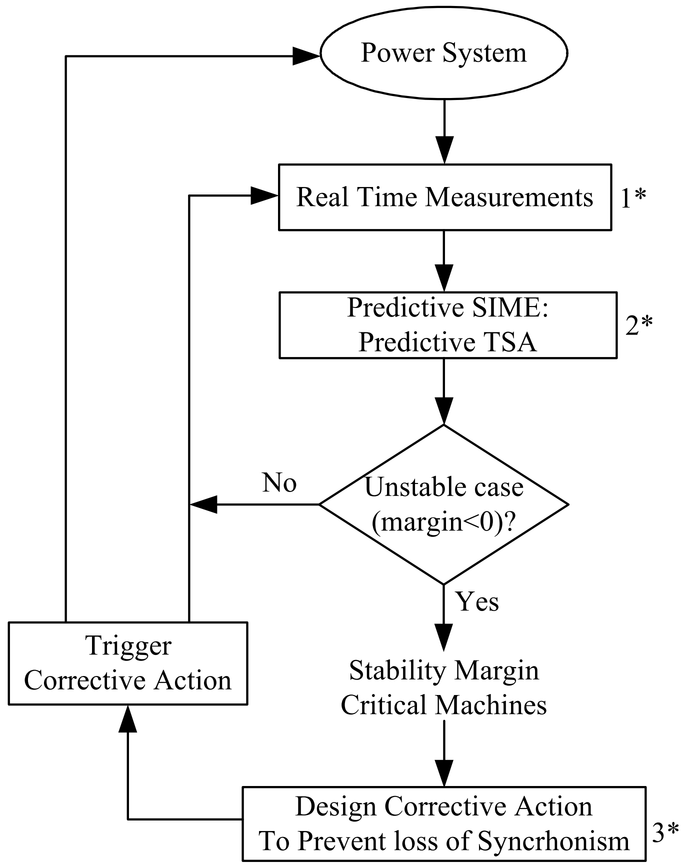


Figure 3.2 General organization of E-SIME (Adapted from [Pavella et al., 2000]).

Timing of the method

The activities involved in the method and depicted at fig. 3.2 have the following estimated time durations (in brackets) [Pavella et al., 2000]:

- Acquiring the data at power plants and transmitting them to the control room [50 ms].
- Processing the data at the control room (Blocks 2* and 3* of fig. 3.2) [between 60 and 200 ms].
- Delivering control actions from the control room to the power plant [50ms].
- Applying control actions [50 ms].

On average, the time to carry out a complete and effective emergency control scheme (ECS) goes from 210 ms to 350 ms after the contingency has been cleared. Therefore, if the contingency time to instability (t_u) is smaller than 450 ms (considering an average fault clearing time of 100 ms), the method is not going to have enough time to act and is not going to be able to work.

3.3.2 Description of the predictive assessment method

The E-SIME method predicts transient stability in real-time using the available data of the system at consecutive sample times in which the OMIB is analyzed to know whether it will remain stable or will be driven to instability.

The essential point of the method is the accurate prediction of the P_a-δ curve, because this is crucial in determining both, the unstable angle δ_u and the unstable margin η, as mentioned in § 3.2.3. A detailed description of the E-SIME method is developed in this section.

The specific notation of the E-SIME method (in addition to the general notation of the preventive SIME method that was defined in § 3.2) is written below [Pavella et al., 2000]:

$t_0=0$	is the beginning of the during-fault period of the time.
te	is the beginning of the post-fault period of the time.
Δt	is the sample time.
tf	is the time at what the predictive TSA starts.
ti	is the current processing time.
tct	is the passed by time between the occurrence of the contingency and the control action; it is also called "the control time".
td	is the total time of the program to acquire the data, transmit the control order to the power plant and to apply the control action.
$\delta i= \delta(ti)$	is the OMIB angle at the current processing time.
$\omega i=\omega(ti)$	is the OMIB speed at the current processing time.

This section illustrates the E-SIME method using an application case performed in the IEEE three-machine test system (described in appendix A) which is particularly attractive because of its simplicity. It is used to present every step of the method, from the prediction to the control action. The simulations presented below were made using a detailed model of the system. Test conditions are: a three-phase fault was applied at node 5 at t = 0.0 s and cleared at $t_e = 0.2$ s by tripping the line connecting nodes 5 and 7 (contingency 3 of Table A.6 presented in Appendix A). To avoid repetition, the mentioned case will be called example case in the remaining sections of the chapter.

The scheme of E-SIME is:

- Starting at time t_i, just after the disturbance has been cleared ($t_i \geq t_e + 2\Delta t$) it must be considered the incoming of measurements at times $t_i - 2\Delta t$, $t_i - \Delta t$ and t_i; using these measurements the individual machine rotor angles are predicted by means of Taylor series expansion in an horizon of some time ahead (say 100 ms). To illustrate the prediction of the individual machines' angles, an example of the

Taylor series expansion of these angles is presented. In figure 3.3, where the prediction of the individual machines of the example case is performed until the system becomes unstable. The prediction is done every time step immediately after the fault clearance. The real behavior of the system is drawn in dotted line. As it can be seen, the prediction at the very first instants of the clearing time is not accurate enough; however, it improves as more additional measurements are acquired.

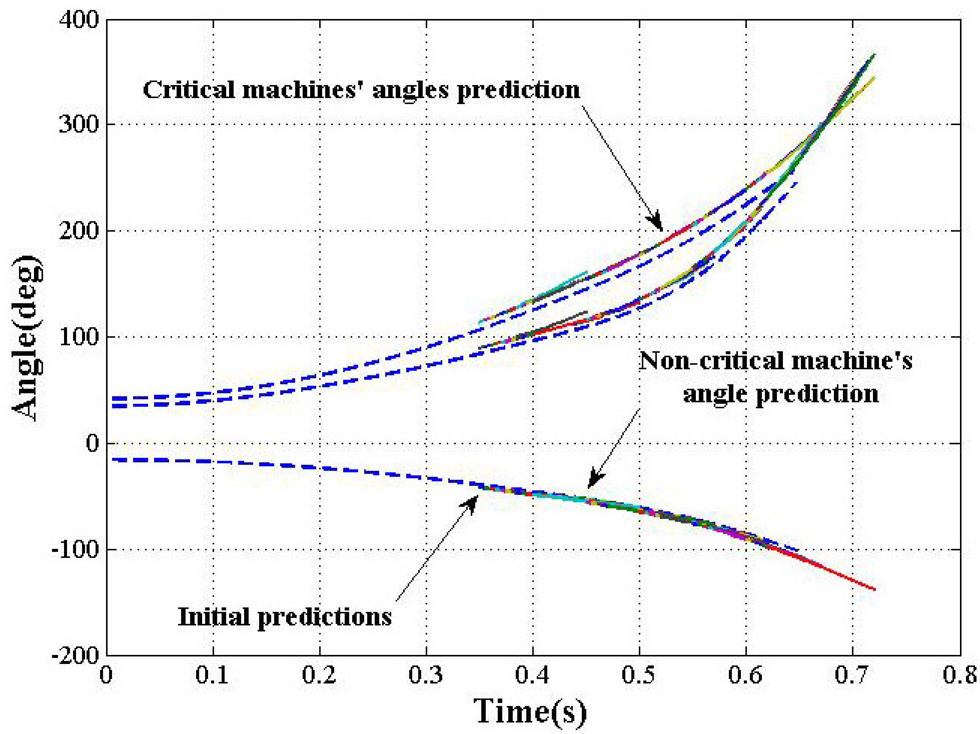


Figure 3.3 Taylor Series prediction of the three-machine test system for the example case.

- The individual machines' rotor angles are sorted in decreasing order to form the candidate group of *CM's* with those advanced machines over the largest angular distance between two successive machines.

- The corresponding OMIB is constructed, and their parameters are determined as described in § 3.2.2, using data from the individual machines at t_i - $2\Delta t$, t_i -Δt and t_i times.

- The P_a - δ curve is approximated by expression (3.17) for the t_i - $2\Delta t$, t_i - Δt and t_i times. An example of the approximation of the P_a - δ curve of the example case is shown in figure 3.4, where it can be seen that, during the first time steps after the fault inception, the prediction is not accurate enough; however, at time step 14 the prediction converges to a nearly constant value: δ_u = 65.48°.

$$\hat{P}_a(\delta) = a\delta^2 + b\delta + c \tag{3.17}$$

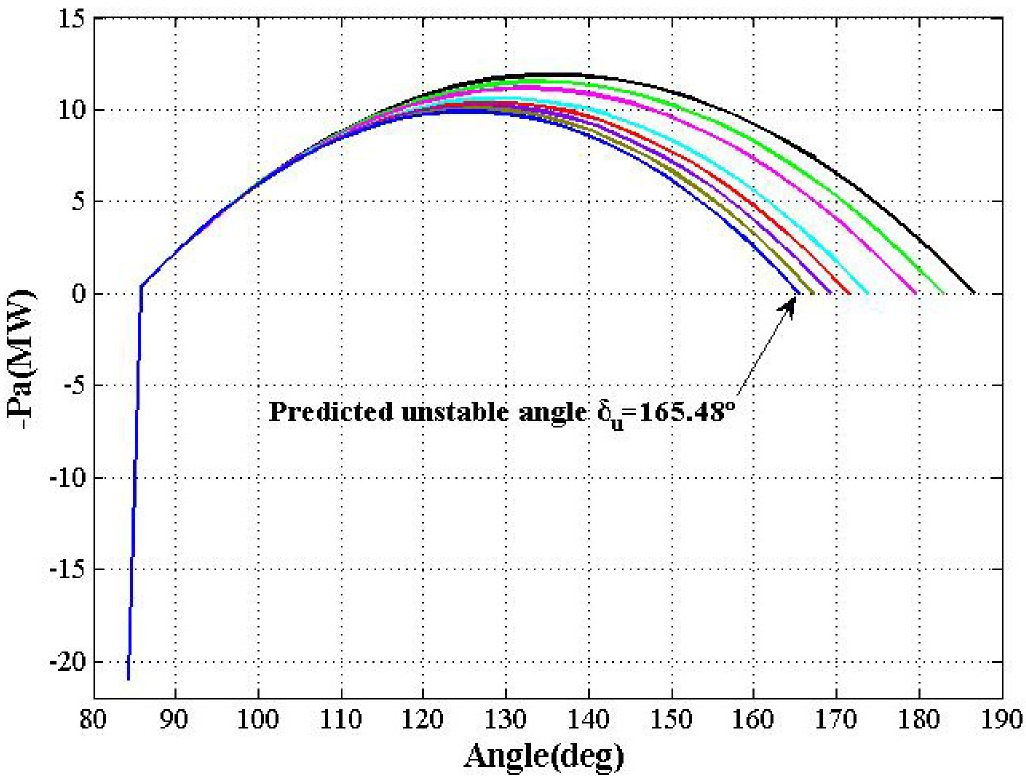


Figure 3.4 Prediction of the Pa-δ curve of the three-machine test system for the example case.

- Equation (3.17) is solved in order to find an approximation to the δ_u OMIB angle $\delta_u > \delta(t_i)$ and verify the stable condition of equation (3.13).

- The stability margin is calculated according to (3.12) and (3.15):

$$\eta = -\int_{\delta_i}^{\delta_u} P_a d\delta - \frac{1}{2} M \omega_i^2 \tag{3.18}$$

- If η is negative or very near to zero, the system is declared unstable and control actions must be triggered.

- The time to instability (t_u), which is the time that takes the OMIB to reach the unstable rotor angle δ_u, is computed with the equation (3.19).

$$t_u = t_i + \int_{\delta_i}^{\delta_u} \frac{d\delta}{\sqrt{\frac{2}{M} \int_{\delta_i}^{\delta} -P_a d\delta + \omega_i^2}} \tag{3.19}$$

- Finally, a new set of measurements is acquired to continue monitoring the system.

E-SIME requires only fractions of mili-seconds to be carried out since it involves inexpensive and fast steps; it predicts if the system is going be unstable and determines very helpful information: stability margins, the identification of the set of critical machines and the time at which the system will lose synchronism. This information is very valuable since it can be successfully used to design control actions in real-time, whose magnitude and location are adapted to the current operating conditions and the severity of the actual contingency, and that are applied early enough to be effective. This method does not identify the location and type of contingency because, as mentioned above, it better concentrates in finding the place to apply the control action to stabilize the system.

Table 3.1 summarizes the prediction of the E-SIME method for the example case. It displays in column 1 the measurement number, in column 2 the time of the measurement, in column 3 the predicted OMIB unstable angle, in column 4 the predicted unstable time, in column 5 the predicted unstable margin and in column 6 the predicted stability margin after the control action has been applied.

Fault was cleared at $t_e = 200$ ms and measurements are received each 5 ms, so prediction of stability starts after the third incoming measurement, at t = 210 ms. At t = 260 ms, the method predicts system instability with a time to instability around 540 ms, and decides to trip machine 2. It is important to notice that, at this time, the method can also predict the effect of the selected control action, as shown in column 6 of Table 3.1. This control action, that is finally applied at t = 360 ms, stabilizes the system and is described in detail in next section.

3.3.3 Description of the emergency control design method

The aim of the E-SIME method is to design and trigger control actions to stabilize the system after a contingency has actually occurred. In order to do that, the control scheme must be developed in a closed loop fashion to follow-up the system evolution so as to know if the control actions are adequate or to make proper re-adjustments if necessary [Ruiz-Vega et al., 2003].

Stabilizing an unstable case consists of cancelling out the negative margin by increasing the decelerating area or decreasing the accelerating area of the P-δ curve of the equivalent OMIB [Pavella et al., 2000]. This may be achieved either by reducing the mechanical power of the OMIB (and as a consequence decreasing the mechanical power of the CM’S) using fast valving or generation tripping; or by increasing the electrical power of the OMIB by using dynamic braking, HVDC links or FACTS devices (all those schemes were detailed in chapter 2).

The negative margin means that the integral term in (3.18) is not large enough and a proper action to stabilize the system should be increasing this area by increasing the decelerating power [Pavella et al., 2000]. In this work the control scheme chosen is generation tripping and its influence on the system stability is described below.

Table 3.1 Closed-loop emergency control of the example case.

1	2	3	4	5	6
Measurement	**t_i(s)**	**δ_u(rad)**	**t_u(s)**	**η/M (rad/s)^2**	**η/M (rad/s)^2 after shedding**
3	0.2100	87.3686	0.2105	-11.9	---
4	0.2150	190.8694	0.5823	-7.6	---
5	0.2200	186.6421	0.5726	-7.9	---
6	0.2250	182.8720	0.5644	-8.2	---
7	0.2300	179.5036	0.5576	-8.4	---
8	0.2350	176.4899	0.5520	-8.6	---
9	0.2400	173.7889	0.5476	-8.8	---
10	0.2450	171.3670	0.5440	-9.0	---
11	0.2500	169.1921	0.5414	-9.1	---
12	0.2550	167.2389	0.5395	-9.2	---
13	0.2600	165.4839	0.5383	-9.3	---
It is decided to trip machine 2 at t=0.360s					
14	0.2650	163.9060	0.5378	-9.4	0.06
15	0.2700	162.4885	0.5378	-9.4	0.4
16	0.2750	161.2148	0.5383	-9.5	0.07
17	0.2800	160.0718	0.5392	-9.6	0.1
18	0.2850	159.0462	0.5406	-9.6	0.04
19	0.2900	158.1283	0.5424	-9.6	19.6
20	0.2950	157.3078	0.5445	-9.7	41.7
21	0.3000	156.5761	0.5469	-9.7	42.8
22	0.3050	155.9253	0.5496	-9.7	28.2
23	0.3100	155.3483	0.5525	-9.8	37.1
24	0.3150	154.8389	0.5557	-9.8	-0.1
25	0.3200	154.3914	0.5591	-9.8	53.8
26	0.3250	154.0001	0.5628	-9.8	51.5
27	0.3300	153.6604	0.5666	-9.9	26.9
28	0.3350	153.3681	0.5705	-9.9	83.2
29	0.3400	153.1183	0.5746	-9.9	62.2
30	0.3450	152.9081	0.5789	-9.9	66.9
31	0.3500	152.7333	0.5833	-9.9	75.0
32	0.3550	152.5906	0.5878	-9.9	171.8
Machine 2 is tripped					
33	0.3600	---	---	0.22	---

To computationally implement generation tripping it is necessary to consider the shedding of one critical machine (m_j), x seconds after the current time t_i. It can be assumed that at t_i, n sets of measurements corresponding to the post-fault scenario have been already acquired.

These sets correspond to t_i, $t_i - \Delta t$, ... , $t_i - (n-1)\Delta t$ times and the critical OMIB relies on the values of parameters (δ, ω, γ, P_a) computed form the n sets of measurements.

Shedding the m_j machine x seconds after the last set of measurements acquisition, results in modifying OMIB's structure because the number of *CM's* decreases by one.

First of all, the angle and the speed of this new OMIB (denoted as OMIB$^{(1)}$) after the actual shedding of machine m_j must be predicted. To this end we first compute the new OMIB$^{(1)}$ variables from the n sets of measurements using (3.1) to (3.10) where C is replaced by $C/\{j\}$ to indicate that machine m_j does not belong to the group of *CM's* any longer. Superscript $^{(1)}$ identifies the parameters of this new OMIB$^{(1)}$.

The $P^{(1)}$-$\delta^{(1)}$ curve is approximated by solving:

$$P_a^{(1)} = a^{(1)}\delta^2 + b^{(1)}\delta + c^{(1)} \tag{3.20}$$

The angle that OMIB$^{(1)}$ reaches at the control time, x seconds after the current time, is denoted $\delta_{ct}^{(1)}$ and is computed using:

$$x = \int_{\delta_i^{(1)}}^{\delta_{ct}^{(1)}} \frac{d\delta^{(1)}}{\sqrt{\frac{2}{M^{(1)}}\int_{\delta_i^{(1)}}^{\delta^{(1)}} -P_a^{(1)} d\delta^{(1)} + \left(\omega_i^{(1)}\right)^2}} \tag{3.21}$$

Note that solving this equation for $\delta_{ct}^{(1)}$ can only be done numerically.

Once $\delta_{ct}^{(1)}$ is computed, the value of the OMIB$^{(1)}$ speed at the control time can be determined by solving (3.22) for $\omega_{ct}^{(1)}$.

$$-\frac{1}{2}M^{(1)}\left(\omega_{ct}^{(1)}\right)^2 = -\int_{\delta_i^{(1)}}^{\delta_{ct}^{(1)}} P_a^{(1)} d\delta^{(1)} - \frac{1}{2}M^{(1)}\left(\omega_i^{(1)}\right)^2 \tag{3.22}$$

The only approximation to compute $\delta_{ct}^{(1)}$ and $\omega_{ct}^{(1)}$ is the extrapolation of the $P_a^{(1)}$ curve. To compute the stability margin of the corrected system, the shape of the accelerating power of OMIB$^{(1)}$ will be needed. However, the $P^{(1)}$- $\delta^{(1)}$ curve computed before is no longer appropriate for this purpose. In fact, is valid under the assumption that machine m_j is still in activity. But, while the shedding of machine m_j does not influence $P_m^{(1)}$(at least at the very first moments after this shedding), it does influence $P_e^{(1)}$. This influence will be approximated by considering that the electrical power produced by the *CM's* is a function of the angle of the OMIB of concern, no matter how many machines are still in activity. And the same assumption is made for the *NM's*. It can be supposed that the electrical output produced by the machines of group $C/\{j\}$ just after t_{ct} equals the electrical output produced by the machines of group C just before t_{ct}.

Then, the shape of the accelerating power of OMIB$^{(1)}$ after the corrective time can be computed by:

$$\delta^{(2)} = \delta^{(1)} \text{ and } P_a^{(2)} = P_a^{(1)} - M^{(1)} \frac{P_{e_j}}{M_C^{(1)}} \tag{3.23}$$

And the n set of parameters is used to compute $a^{(2)}$, $b^{(2)}$ and $c^{(2)}$ by:

$$P_a^{(2)} = a^{(2)}\delta^2 + b^{(2)}\delta + c^{(2)} \tag{3.24}$$

Finally, using $a^{(2)}$, $b^{(2)}$ and $c^{(2)}$ the stability margin is evaluated by using (3.25) to find the value of the unstable angle of the controlled system $\delta_u^{(2)}$.

$$\eta = -\int_{\delta_{ct}^{(2)}}^{\delta_u^{(2)}} P_a^{(2)} d\delta^{(2)} - \frac{1}{2} M^{(1)} \left(\omega_{ct}^{(1)}\right)^2 \tag{3.25}$$

The machines to shed are the most advanced ones. The procedure to identify how many machines to shed is simple: from the predicted critical group of machines, shed the most advanced one and compute the stability margin; if it is still negative, shed another machine and continue until the margin becomes positive [Pavella et al., 2000].

To show the application of generation tripping and the prediction of the system's behavior in order to know if the corrective action is enough to stabilize the system, in this section it will be presented the application of generation tripping to the "example case".

Figure 3.5 presents the individual machines angles for the example case, where the fault is cleared at t = 200 ms and machine two is tripped at t_{ct} = 0.36 s. In Fig. 3.6 the P - δ curve of the system is presented for the E-SIME predicted OMIB structure, including the indication of the angles at which each step of the E-SIME method is performed. It is important to remember that in Fig. 3.6 time is not a variable, but the times at which assessment and decisions were taken are indicated at the value of the OMIB angle they were performed.

Curve of Fig. 3.6 starts with E-SIME predictive assessment, three measurements after the fault was cleared, in point A (all observations can be checked in Table 3.1). Predictive stability assessment is performed, and at t = 260 ms, it is decided to trip machine 2. This happens in Fig. 3.6 at the point labeled $t_{decision}$, where the OMIB angle is around 108^o. Some time later, at t = 360 ms, machine 2 is tripped. This point is indicated by the label t_{action}, at the maximum OMIB angle, around δ = 125^o (point B). When the machine is tripped, the structure of both, the OMIB and the center of angle (COA) reference change (see equation (3.1)), and this can be observed as a jump in individual machines of Fig. 3.5 and in the OMIB powers, angle and phase plane shown in Figs. 3.6 to 3.9.

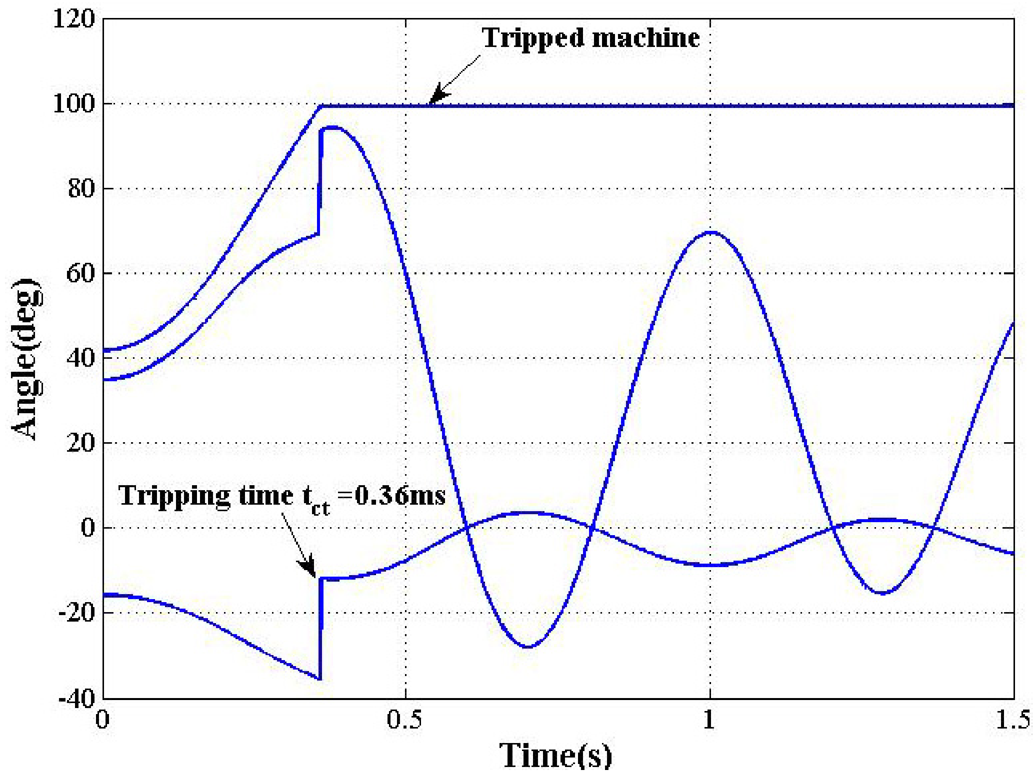


Figure 3.5 Swing curves of the individual machines of the example case showing the action of E-SIME to stabilize the system. After tripping machine 2 its angle value remains constant.

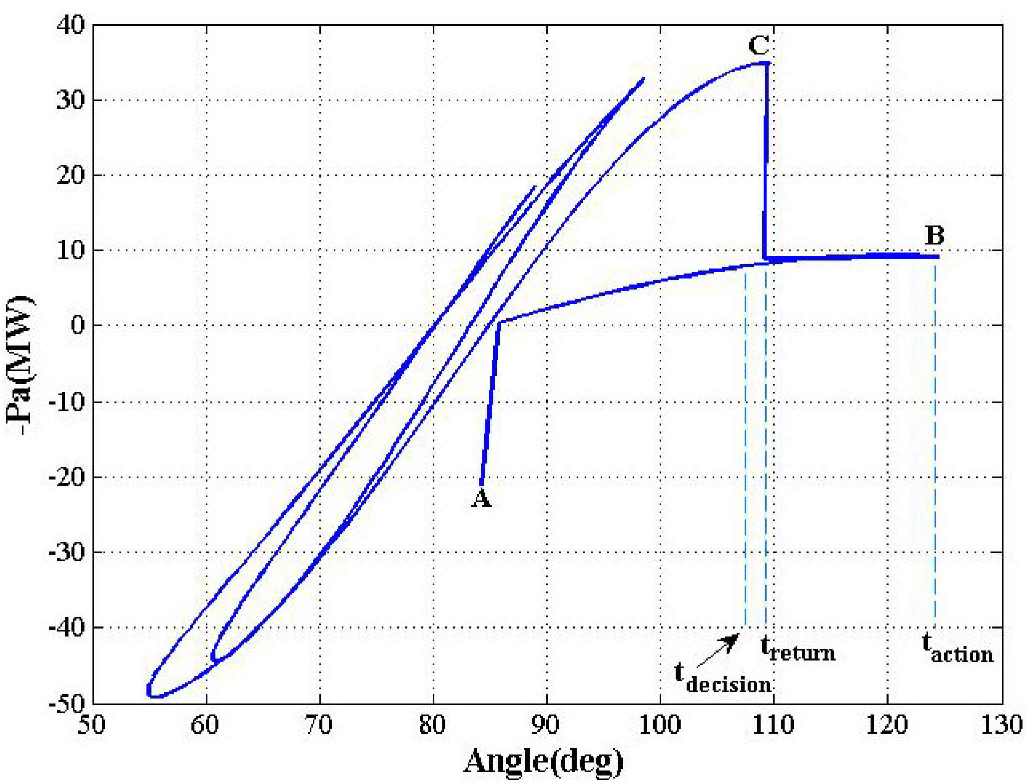


Figure 3.6 P_a-δ curve of the OMIB of the example case showing the action of E-SIME to stabilize the system. Time of the different assessment and control steps of E-SIME are indicated.

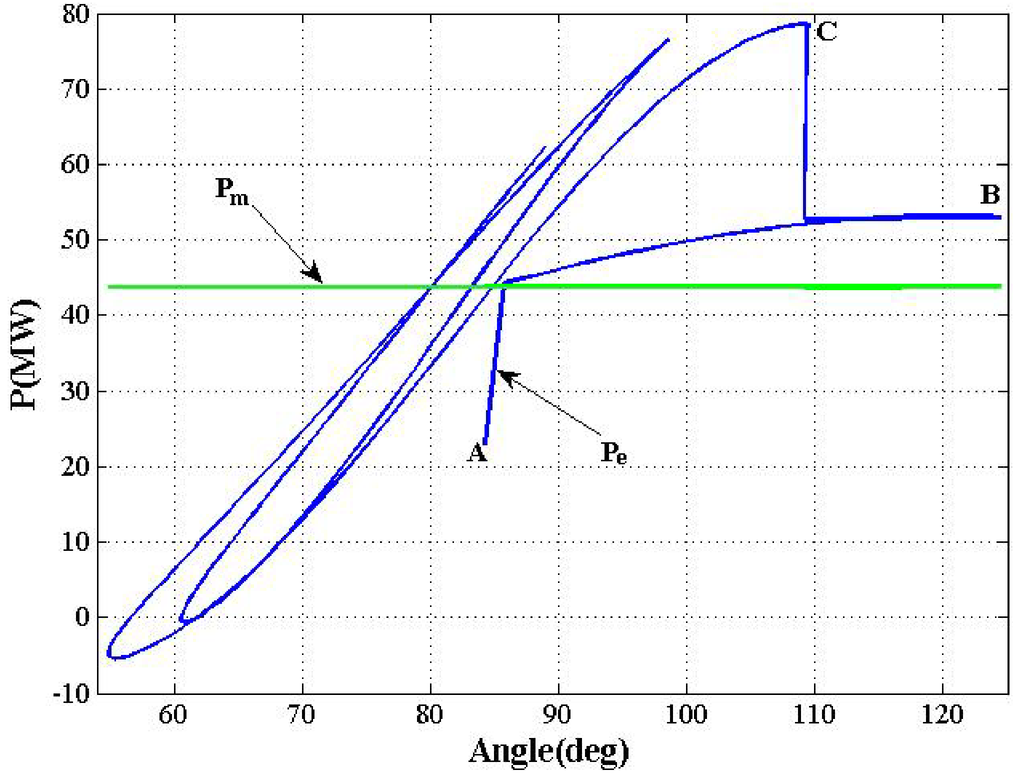


Figure 3.7 OMIB mechanical and electrical powers of the example case showing the action of E-SIME to stabilize the system. Points A, B, and C are included for a straightforward comparison with Fig. 3.5.

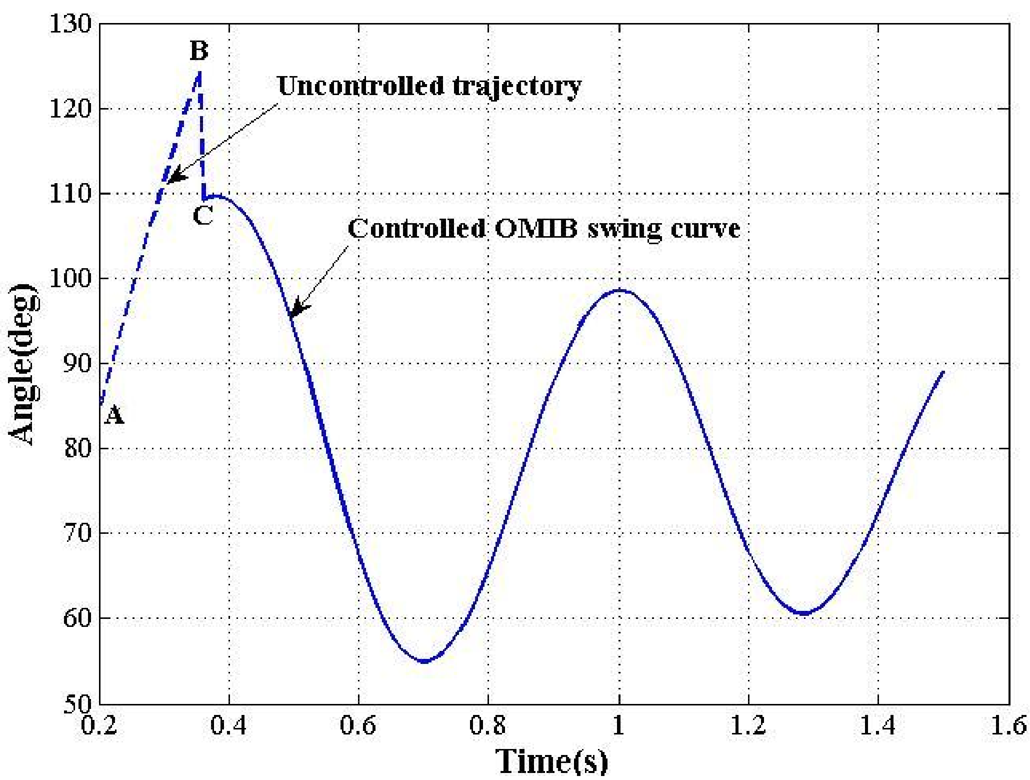


Figure 3.8 OMIB swing curve of the example case showing the action of E-SIME to stabilize the system. Points A, B, and C are included for a straightforward comparison with Fig. 3.5.

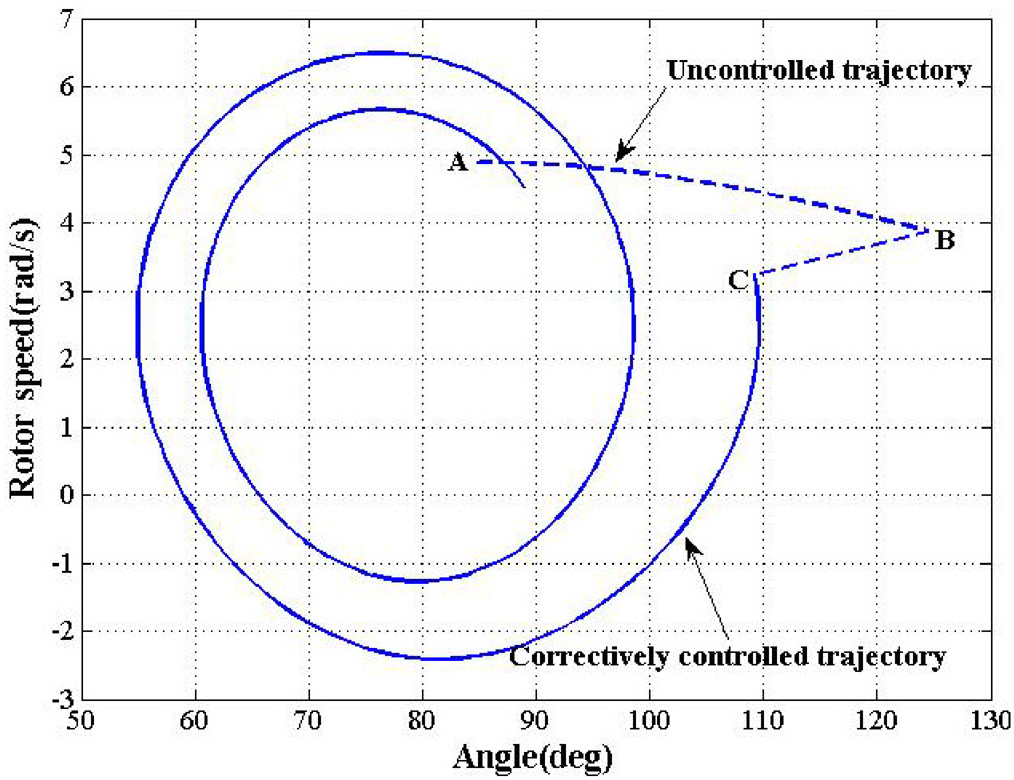


Figure 3.9 OMIB phase plane of the example case showing the action of E-SIME to stabilize the system. Points A, B, and C are included for a straightforward comparison with Fig. 3.5.

The following observations can be derived from results presented in Figs. 3.5 to 3.9:

- The jump in state and algebraic variables of the system, shown in all figures, mainly comes from the change in the COA reference. Tests have been performed using other angle references like the angle of a selected individual machine and in this case the jump does not appear.
- The action of the generation tripping scheme can be very clearly appreciated in all figures, but the ones displaying the P - δ plane show that the effect of this emergency control action is to increase the decelerating area by changing system state from the "post-fault" curve to the "after tripping curve" which has an enlarged decelerating area with a maximum power near point C.
- The effect of power system detailed modeling can also be observed more clearly in P-δ curves: they are not sinusoidal anymore and, after the system has been stabilized by the action of the generation tripping scheme, it oscillates.
- This example is very illustrative of the flexibility of the SIME method: Besides the main information for assessing and control stability (margins, identification of critical machines), OMIB equivalent representations improve the interpretation of system dynamic performance and can be used to implement different on-line and real-time control functions.

3.4 PRACTICAL CONSIDERATIONS FOR THE APLICATION OF THE E-SIME METHOD

As E-SIME is considered and advanced System Protection Scheme (SPS) [CIGRE, 2001] some considerations must take into account for its practical implementation:

Technological and software requirements:

- The action is initiated by information acquired at one or more key buses located elsewhere in the power system and its main purpose is to maintain the integrity of the whole power system. In consequence, this type of control is of a high level of complexity and is strongly dependent on telecommunication facilities [CIGRE, 2001].
- It is of vital importance that the computing tools could cope with the simulation of the system response to the control actions.
- The times that the software must be able to introduce are [CIGRE, 2001]: time delays caused by the real-time communication system (in the case of this work, the time that the PMU's lasts to deliver the measurements), time delays corresponding to data processing and computations in the SPS (for the E-SIME method, blocks 2 and 3 in figure 3.2) and the intentional delays introduced between various steps of action when the SPS has to act repeatedly (in a closed loop fashion).

Installation of the control scheme:

- The installation of the E-SIME method as any other SPS involves the same requirements as other equipment: technical, financial and legal aspects. In this case, what is different from other devices is that in a SPS more than one organization or company can be involved in the same activity (in restructured power systems and electricity markets) This implies possible legal responsibilities for the owners of the SPS, which could directly result in pecuniary penalties [CIGRE, 2001].

Particular considerations of the E-SIME method:

- This method is design for large systems that have a considerable amount of generation in remote power plants with weak links. It is also design to trip hydraulic plants.
- Under very unstable conditions, the stability margin η may not exist because the OMIB P_e and P_m curves do not intersect which means that there's no post-fault equilibrium [Ruiz-Vega, 2009].

- The prediction relies on real time measurements acquired at a regular time steps and refreshed with the same rate.

- At the beginning of the prediction the method may not be accurate enough; however, the predicted OMIB is likely to contain the machines responsible for the instability and approximately at measurement 10 the prediction becomes reliable enough to take the corresponding control actions [Pavella et al., 2000].

- The hardware requirements of emergency control are phasor measurements unit (PMU) devices placed at the main power plant stations and communication systems to transmit this information [Ruiz-Vega et al., 2003]. Phasor measurement main characteristics are described below.

3.5 REAL TIME MEASUREMENTS CURRENTLY AVAILABLE

The synchronization techniques combined with computational methods based on measurements give an opportunity to measure phasors and phase angles in real time [Phadke, 1993]. Real time measurements are currently used to monitor power systems in order to know the operating conditions and to take decisions that directly affect the system in order to augment the security level or to apply control or protective actions to preserve the integrity of the system, moreover, some of the planning and operating decisions are closely related with physical quantities of the system. These quantities must be acquired at different geographical points of the power system and they need to be synchronized; measurements like that are provided by phasor measurement units (PMU's). In this section it will be presented a general description of synchronized fasorial measurements and the units to measure them.

Phasors are basic tools to analyze alternative current circuits that have been introduced to represent sinusoidal waveforms in stationary state with fundamental frequency; even if the system is not totally "static" in stable state, phasors are useful to describe the behavior of the system [Phadke, 1993]. Phasorial representation simplifies the acquisition, concentration and processing of power system data [ABB, 2001].

The first prototypes of modern phasor measurement units were built by Virginia Tech in 1980 [Phadke, 2008]. A generic phasor measurement unit is shown in figure 3.10. One of the most important characteristics of PMU technology is that measurements are given in real time with high accuracy and speed. The IEEE standards that define the structures of the output files of the PMU's allow the interoperability between PMU's manufactured by different companies.

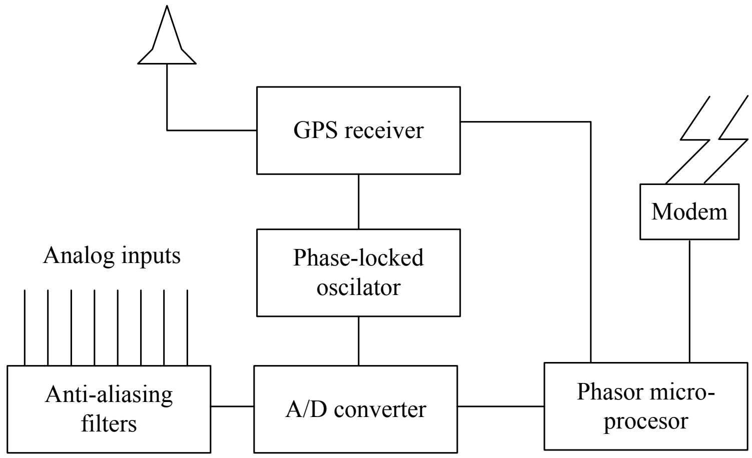


Figure 3.10 Generic PMU (Adapted form [Phadke, 2008]).

The synchronizing source of the measurements is based on a time signal from the Global Position System (GPS) what allows acquiring very accurate data. The PMU receiver provides one pulse per second that is labeled with a time tag (year, day, minute, second) what is really helpful for system operators to analyze post-mortem disturbances or to estimate the state of power systems.

PMU's are situated at power system's substations and provide tagged measurements in time: positive sequence magnitudes of voltages and currents at monitored buses they also provide the sampling frequency and the frequency deviation. These measurements are situated at local storing devices where remote units can have access in order to use the data to analyze the power system.

The potential applications of PMU's are a wide range of schemes, in this work there are mentioned only a few of them [Phadke, 1993, ABB, 2000]:

- Measure frequency and magnitude of phasorial quantities.
- State estimation by using complex power and voltage magnitudes in different points of the power system and computing the state of the system by means of non-linear techniques.
- Stability prediction can be improved using real-time measurements instead of using traditional integration of the equations in time.
- Power systems monitoring: the state of the power system is defined by the positive sequence voltages collection in all buses of the bulk system simultaneously.
- Advanced network protection.
- Advanced control schemes.

Current PMU's can measure system phase angles, voltages, currents and real or reactive power with a rate of 1,2,4,5,10,12,15,20,30 and 60 messages per second for 60Hz nominal data rate [SEL, 2008].

Phasor measurement units have become a mature technology to monitor and control current power systems. The majority of the application field of PMU's are currently under investigation and some research groups are making efforts to develop new techniques to use real-time measurements.

3.6 DIGITAL COMPUTER PROGRAM

The digital computer program of the E-SIME method consists in a set of subroutines written in FORTRAN 77. This computer program is coupled with the time-domain simulation program TRANSTAB [Ruiz-Vega, 1996] that provides artificial real time measurements. In figure 3.11, a general flow diagram of the program is depicted. The following section will shown the coupling between the E-SIME and TRANSTAB programs.

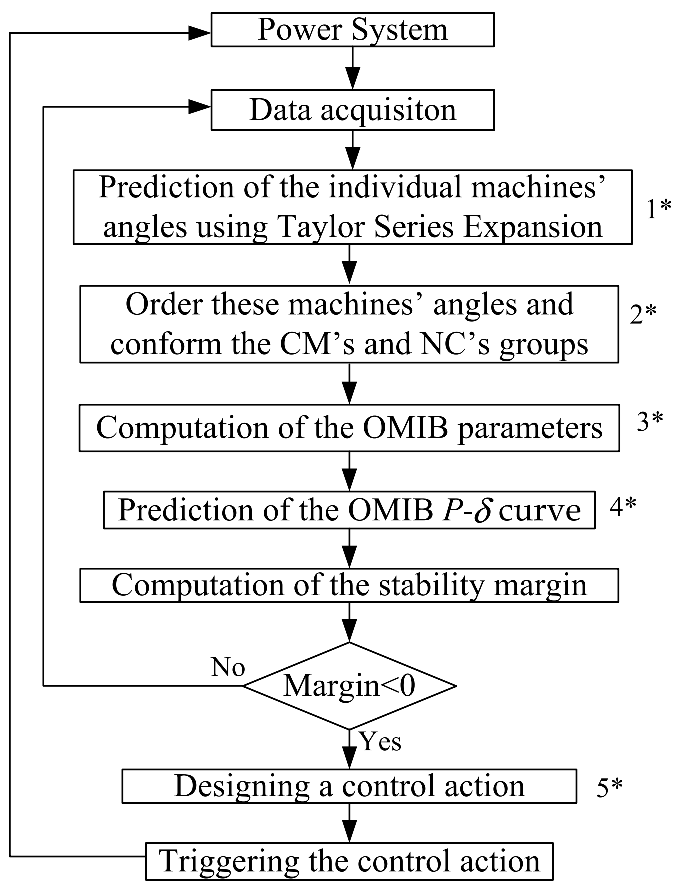


Figure 3.11 General flow diagram of the E-SIME method computational program.

For blocks 1* and 2* of figure 3.11 the individual machines' angles are predicted as in figure 3.12.

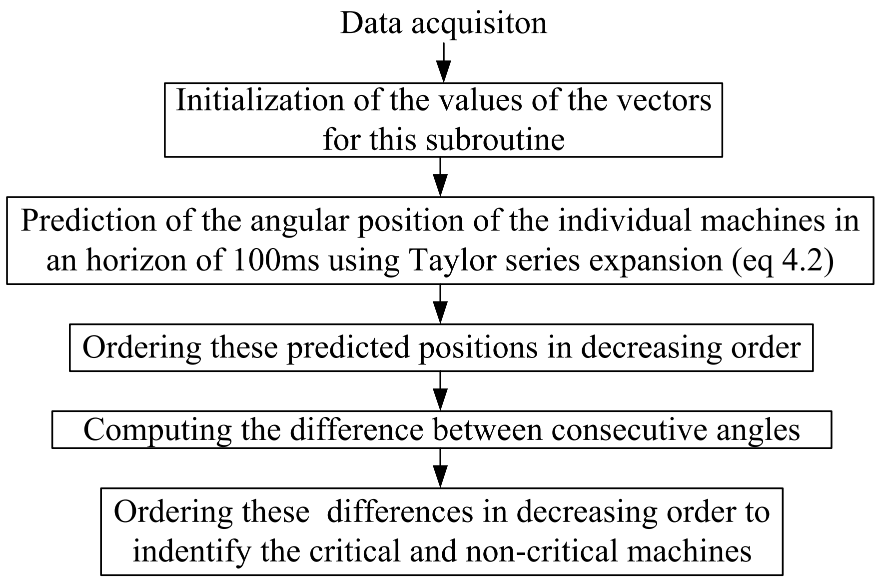


Figure 3.12 Flow diagram of the prediction step of individual machines' angles.

To expand the individual machines' angles of the system, in general, Taylor Series can be expressed using equation (3.26):

$$x(t+\Delta t) = x(t) + x^{(1)}(t)\Delta t + x^{(2)}(t)\frac{\Delta t^2}{2!} + ... \qquad (3.26)$$

Applying (3.26) to δ_i:

$$\delta_i(t+\Delta t) = \delta_i(t) + \delta_i^{(1)}(t)\Delta t + \delta_i^{(2)}(t)\frac{\Delta t^2}{2!}$$

$$\delta_i(t+\Delta t) = \delta_i(t) + \omega_i(t)\Delta t + \left[\frac{1}{M_i}\left(P_{m_i}\right) - \frac{1}{M_i}\left(P_{e_i}\right)\right]\frac{\Delta t^2}{2!} \qquad (3.27)$$

For block 3* of figure 3.10, the OMIB parameters are computed as in figure 3.13.

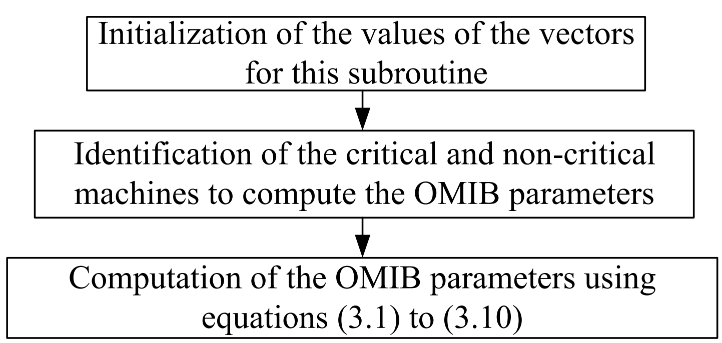


Figure 3.13 Flow diagram of the computation of the OMIB parameters.

To approximate the P_a - δ curve in block 4* of figure 3.11 it is necessary to find the numerical *a*, *b* and *c* coefficients of the equation (3.17) by means of the least squares method as described below.

Taking into account that the method involves *n* measurements, the sum of squared residuals of (3.17) is:

$$q = \sum_{i=1}^{n}\left[P_a(\delta) - \hat{P}_a(\delta)\right] = \sum_{i=1}^{n}\left[P_a(\delta) - \hat{a}\delta^2 + \hat{b}\delta + \hat{c}\right]^2 \qquad (3.28)$$

Where the symbol ^ indicates that these are estimated values.

The necessary condition to make the value of "*q*" minimum is to set the gradient to zero, equation (3.17) has three parameters, thus there are three gradient equations that must be satisfied:

$$\frac{\partial q}{\partial \hat{a}} = 0\ , \quad \frac{\partial q}{\partial \hat{b}} = 0 \quad \text{and} \quad \frac{\partial q}{\partial \hat{c}} = 0 \qquad (3.29)$$

Applying these criteria and rearranging the terms of equation (3.28), a linear equation system is found:

$$\hat{c}\sum_{i=1}^{n}\delta_i^j + \hat{b}\sum_{i=1}^{n}\delta_i^{j+1} + \hat{a}\sum_{i=1}^{n}\delta_i^{j+2} = \sum_{i=1}^{n}P_a(\delta)_i\,\delta_i^j \qquad (3.30)$$

With j=0,1,2.

The linear system equation of (3.30) of the form Ax = B is first built and then solved using a numerical method for determining the *a*, *b* and *c* coefficients of expression (3.17), which is in turn solved to find the unstable angle δ_u. Then the P_a-δ curve is predicted until δ_u. The proposed algorithm is shown in figure 3.14.

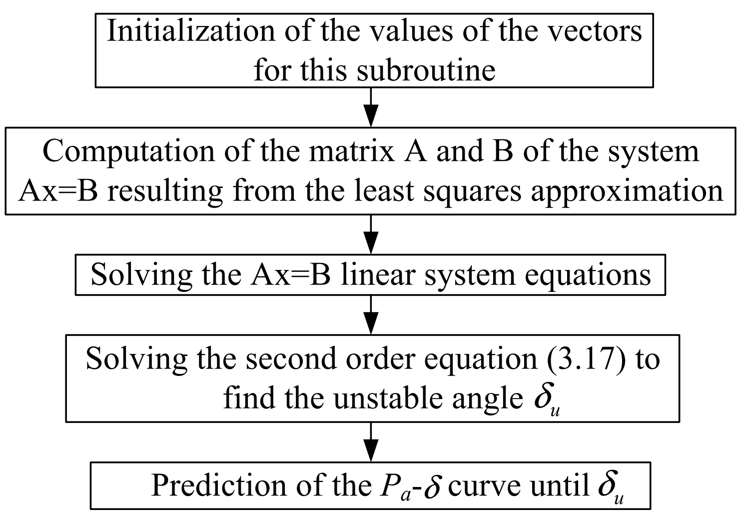


Figure 3.14 Flow diagram of the prediction of the P_a-δ curve.

If the stability margin is found to be negative then control actions must be designed and triggered. For block 5* of figure 3.11 control actions are computed as in figure 3.15:

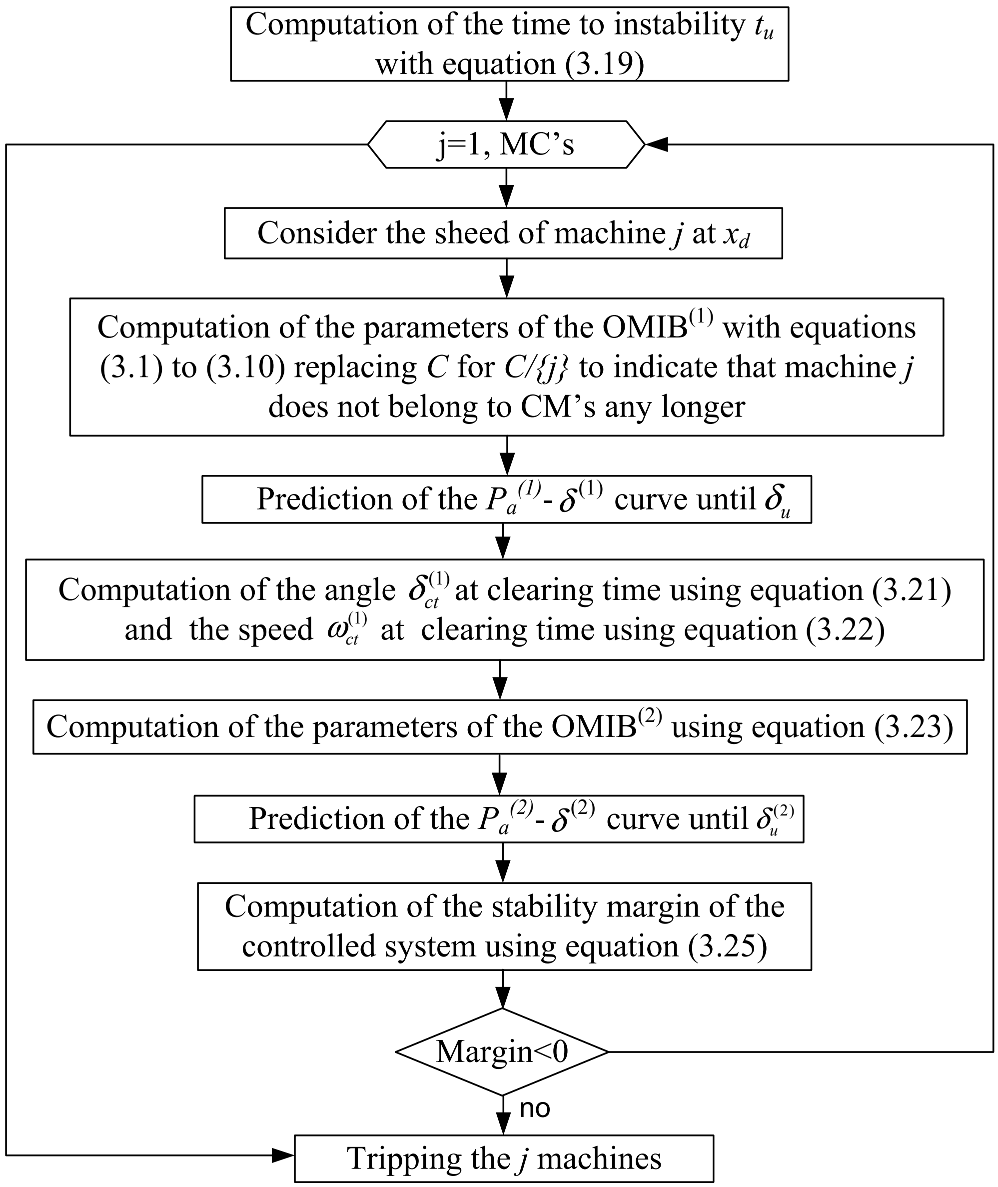


Figure 3.15 Flow diagram of the emergency control action design step.

As already mentioned, selecting the group of machines to be tripped in order to stabilize the system is based on the prediction of system transient stability after the emergency control has been applied.

This predictive transient stability assessment is used before the generation tripping scheme has actually operated, and could be used after this action, in order to assess if the actual control action has been effective or another additional action should be designed and applied.

3.7 COUPLING THE TIME DOMAIN SIMULATION COMPUTER PROGRAM WITH THE E-SIME METHOD COMPUTER PROGRAM

The E-SIME program is directly coupled with the time domain subroutine of the main program TRANSTAB [Ruiz-Vega, 1996] as shown in figure 3.16.

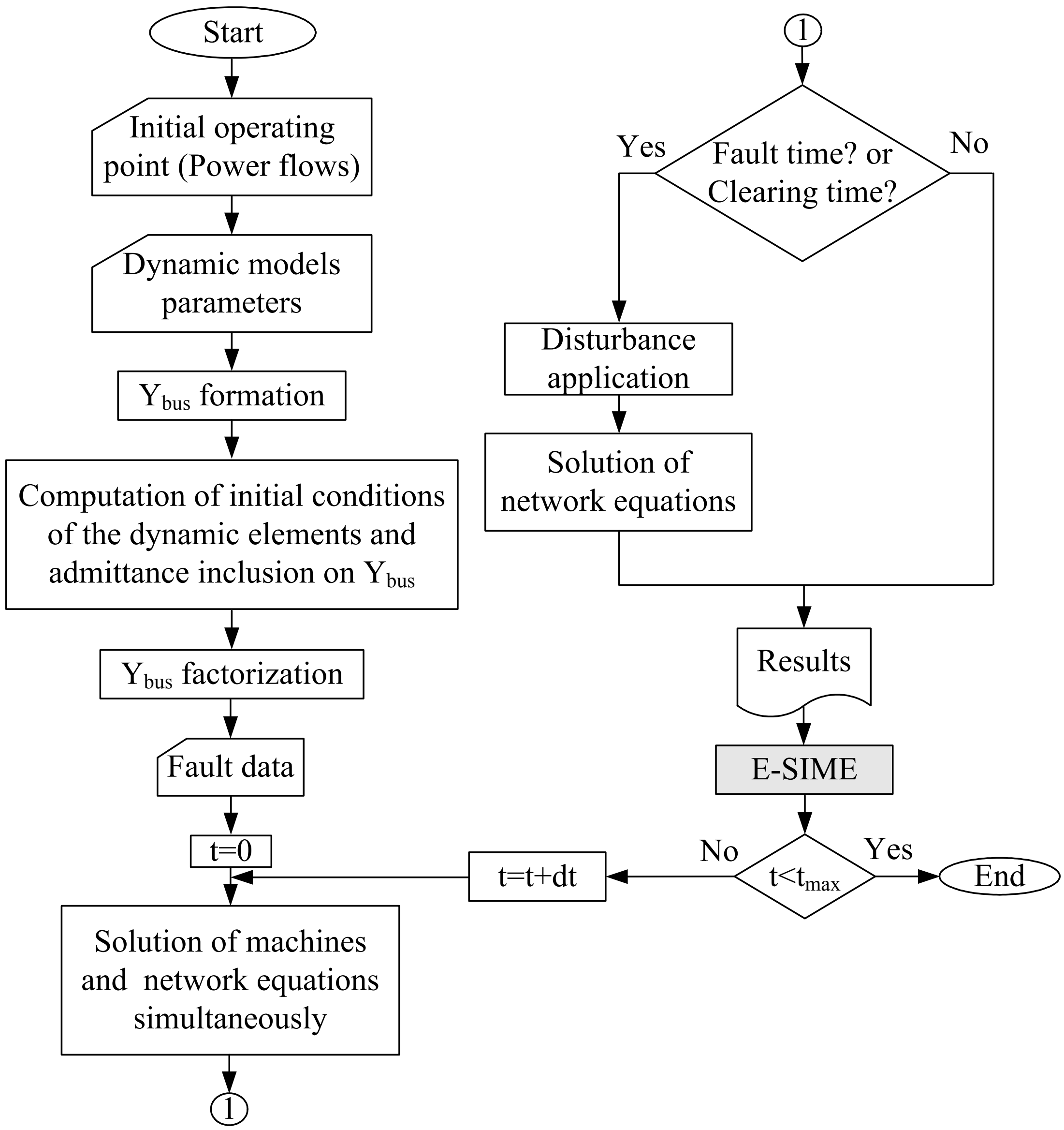


Figure 3.16 Flow diagram of the coupling of TRANSTAB and E-SIME programs.

E-SIME subroutines receive the results of the time domain program as artificial measurements with a regular sample time and assess transient stability using stability margins. If the system is unstable, E-SIME automatically triggers control actions that the T-D program executes and continue monitoring the system using new measurements.

The E-SIME program was written to be completely independent of the TRANSTAB program, so it could be easily coupled with another T-D simulation program. In a near future E-SIME would probably analyze real time measurements.

This version of the TRANSTAB program has subroutines to store and solve sparse systems of linear equations to analyze large dimension systems efficiently. In the next chapter, E-SIME method and program are tested using different power systems.

CHAPTER 4:

APPLICATION OF THE METHODOLOGY AND ANALYSIS OF RESULTS

4.1 INTRODUCTION

This chapter presents the application of the E-SIME method to three different test systems and the analysis of the obtained results. The purpose of this chapter is to analyze as many scenarios as possible in order to show the capabilities of the E-SIME method in controlling transient stability, and also to present some cases in which it is not able to perform an accurate transient stability assessment due to the inherent characteristics of transient instabilities.

4.2 THE IEEE THREE-MACHINE TEST POWER SYSTEM

The E-SIME method was applied to the IEEE three-machine test power system in this section. Simulations were made using the classical and detailed models with the parameters and initial conditions of the system shown in Appendix A. In Table 4.1, the critical clearing times of the contingencies considered for the three-machine test system (see Table A.6 of Appendix A) using classical model are presented. They were assessed and ranked using the TRANSTAB program, developed in [Ruiz, 1996].

Table 4.1 Contingency ranking of the IEEE three-machine test system with classical model.

Contingency number	Critical clearing time
4	0.155
5	0.175
10	0.210
8	0.230
6	0.270
7	0.300
11	0.305
1	0.310
3	0.315
9	0.385
2	0.400
12	0.445

Case 1A: for this case the E-SIME method was applied to the IEEE three-machine test system, using the classical model and considering contingency 3 of Table A.6 with a clearing time t_e = 0.35s. As soon as the system enters in its post-fault conditions, the E-SIME method starts assessing stability. The first set of data is acquired at t = 260ms and the sampling rate of data acquisition is 5ms.

Table 4.2 summarizes the prediction assessment of the E-SIME method for case 1A. Prediction of stability starts at t = 36 ms when at least three measurements have been acquired. Just 25 ms after the assessment started, the system is declared unstable (when the stability margin converges to a nearly constant value) and this gives the possibility to apply control actions to stabilize the system. The predicted time to instability is of approximately 200 ms ahead of the current time, so the method has enough time to design and trigger control actions. The control action designed by E-SIME consisting in tripping the critical machine number two is finally applied at t = 475 ms, and the system is stabilized.

Table 4.2 Closed-loop emergency control for case 1A.

Measurement	t_i(s)	δ_u(rad)	t_u(s)	η/M (rad/s)^2	η/M (rad/s)^2 after shedding
3	0.3600	92.9675	0.3638	-17.4	---
4	0.3650	138.2942	0.5020	-14.5	---
5	0.3700	140.8983	0.5147	-14.3	---
6	0.3750	141.0822	0.5202	-14.3	---
It is decided to trip machine 2 at t = 0.475s					
7	0.3800	141.2742	0.5258	-14.3	18.5
8	0.3850	141.4718	0.5313	-14.3	54.6
9	0.3900	141.6724	0.5369	-14.3	54.2
10	0.3950	141.8752	0.5425	-14.3	18.2
11	0.4000	142.0780	0.5481	-14.2	17.7
12	0.4050	142.2797	0.5537	-14.2	19.4
13	0.4100	142.4785	0.5593	-14.2	15.6
14	0.4150	142.6739	0.5649	-14.2	18.2
15	0.4200	142.8647	0.5704	-14.2	17.0
16	0.4250	143.0497	0.5760	-14.2	38.0
17	0.4300	143.2285	0.5815	-14.2	50.5
18	0.4350	143.3998	0.5870	-14.2	20.8
19	0.4400	143.5637	0.5925	-14.2	16.8
20	0.4450	143.7190	0.5979	-14.2	16.9
21	0.4500	143.8651	0.6033	-14.2	18.6
22	0.4550	144.0020	0.6087	-14.2	57.2
23	0.4600	144.1286	0.6141	-14.1	21.4
24	0.4650	144.2449	0.6195	-14.1	4.6
25	0.4700	144.3504	0.6248	-14.1	17.7
Machine 2 is tripped					
26	0. 4750	---	---	---	6.9

Figure 4.1 shows the predictive transient stability assessment results, in terms of the OMIB P_a - δ curves. It can be observed that the predicted unstable angle is δ_u = 141° of figure 4.1 is calculated at t = 0.375s (see Table 4.1 results). Figure 4.2 presents the OMIB angle trajectory before applying the corrective action; it can be noticed that it indicates that the system will be unstable. At time t = 475 ms (100 ms after the decision is taken) machine 2 is tripped and the OMIB reaches its return angle δ_r. This is shown in figure 4.3, where the swing curves of individual machines of the entire system are shown.

As explained before in chapter 3, when machine 2 is disconnected from the rest of the system its angle remains constant, as can be seen in figure. 4.3. This is only a way to represent that the machine is no longer connected to the system (the TD program disconnects the machine and keeps its last angle value constant). At the moment of the tripping, the rest or the system machines seem to jump to another operation point, and this is due to the fact that the system angular reference, the COA, changes.

When the machine is tripped, the parameters of the OMIB also change since the number of critical machines decreases by one. Figure 4.4 displays the equivalent OMIB accelerating power curve in the P- δ plane, indicating the points at which the main steps of E-SIME are performed. Predictive assessment starts in point *A* when E-SIME method has actually processed at least three measurements of the system variables (see Table 4.2). The decision to trip machine number 2 is taken at t = 375 ms of current time, which correspond to 108 ° as shown in Fig. 4.4 at the point labeled $t_{decision}$. When the OMIB angle has reached around 122.5° (point B) the corrective action is taken; this point is labeled t_{action} and corresponds to a point in time at t = 475ms. Then the OMIB angle returns almost instantly to around 106.6° (point *C*) at the point labeled t_{return} because the OMIB angle "jumps" to a new OMIB, it can be noticed that the OMIB angle does not reach the predicted unstable angle of 141° in Table 4.2 and that the system is stable.

Analogously, figures 4.5, 4.6 and 4.7 present the OMIB equivalent mechanical and electrical powers, swing curve and phase plane, respectively. In all figures, points indicating the execution of each one of E-SIME main steps are: point *A*, where the SIME method starts its calculations, point *B* where the OMIB reaches the maximum angle and the control action is applied, and point *C* at which the system jumps to a new OMIB curve.

SIME representations show again to be very useful in both, the development of assessment and control techniques and the interpretation of system dynamic behavior.

This is an example of a successful stabilization of the system using emergency controls. In the following cases it will be studied some conditions in which the system can not be controlled.

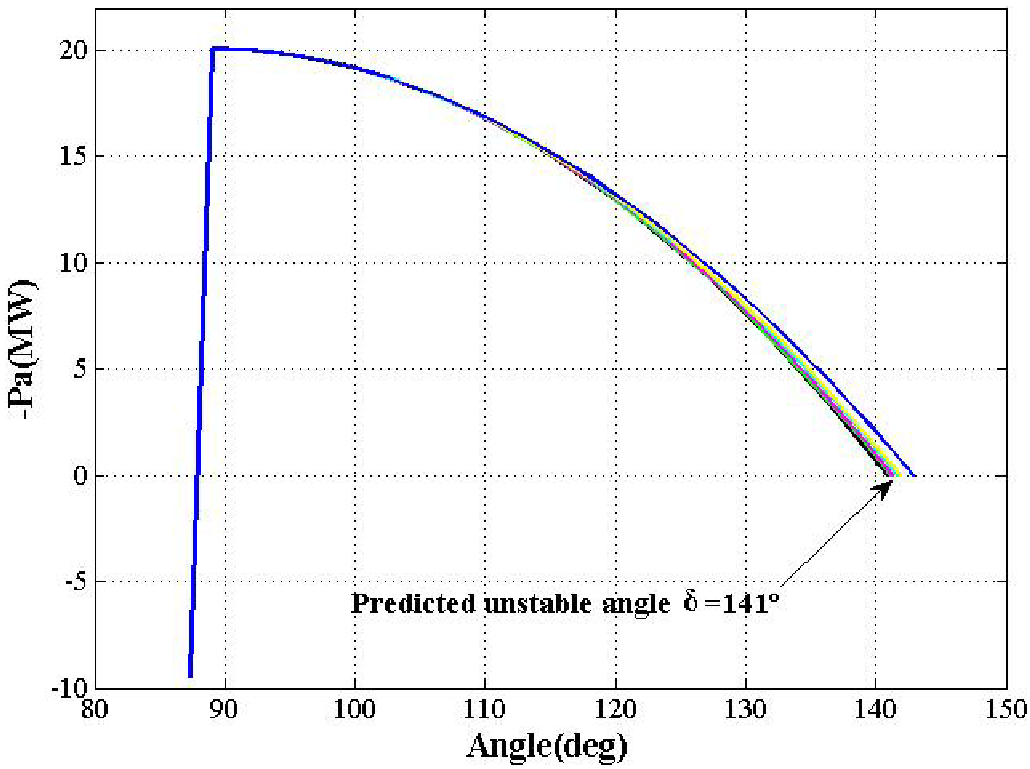


Figure 4.1 E-SIME stability prediction for case 1A.

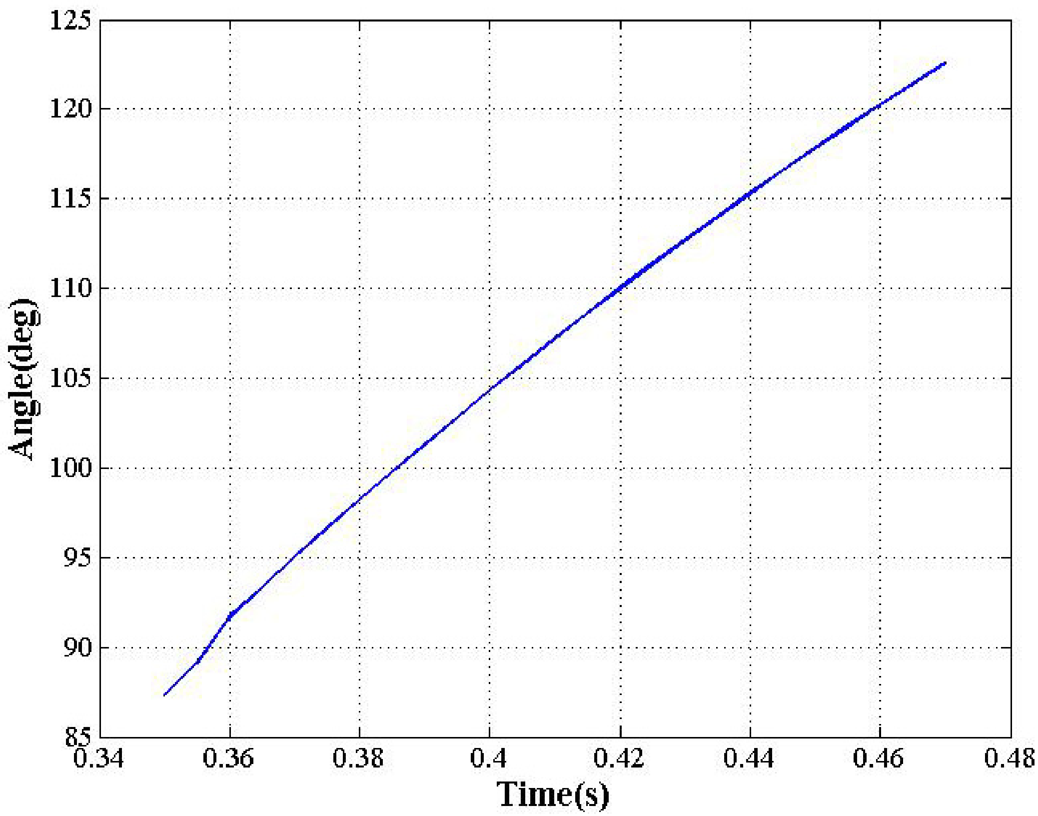


Figure 4.2 OMIB equivalent angle trajectory before the control action is applied for case 1A.

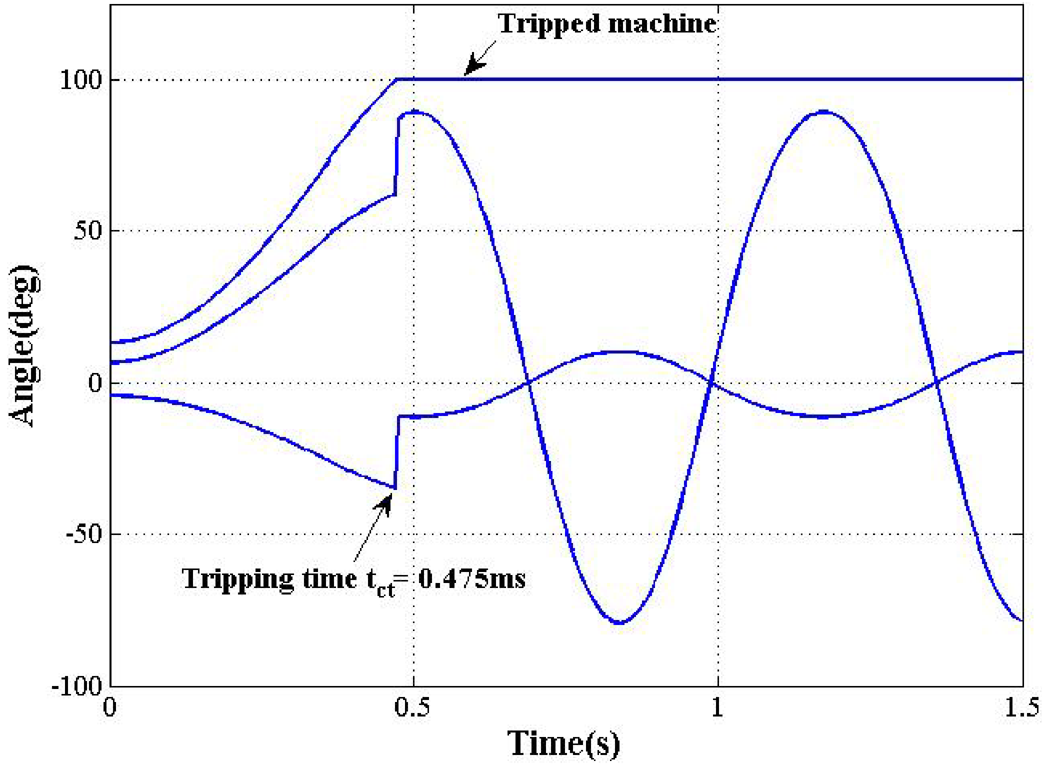


Figure 4.3 Individual machines swing curves for case 1A.

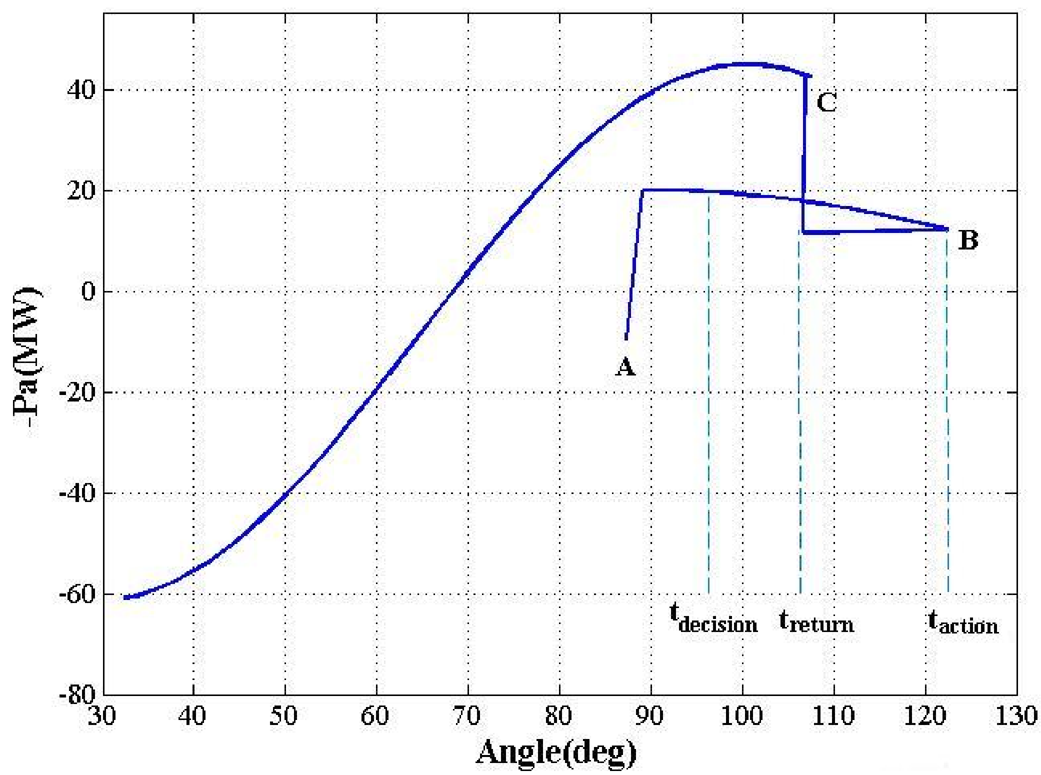


Figure 4.4 OMIB equivalent *P*-*δ* curve for case 1A.

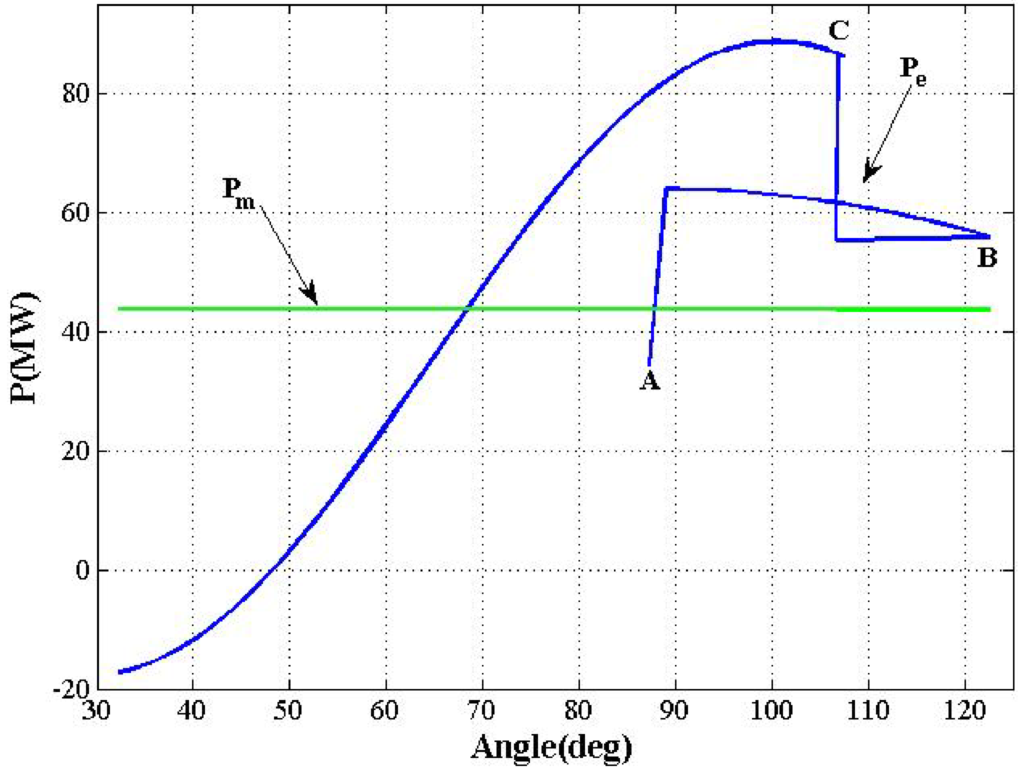


Figure 4.5 OMIB equivalent mechanical and electrical powers for case 1A.

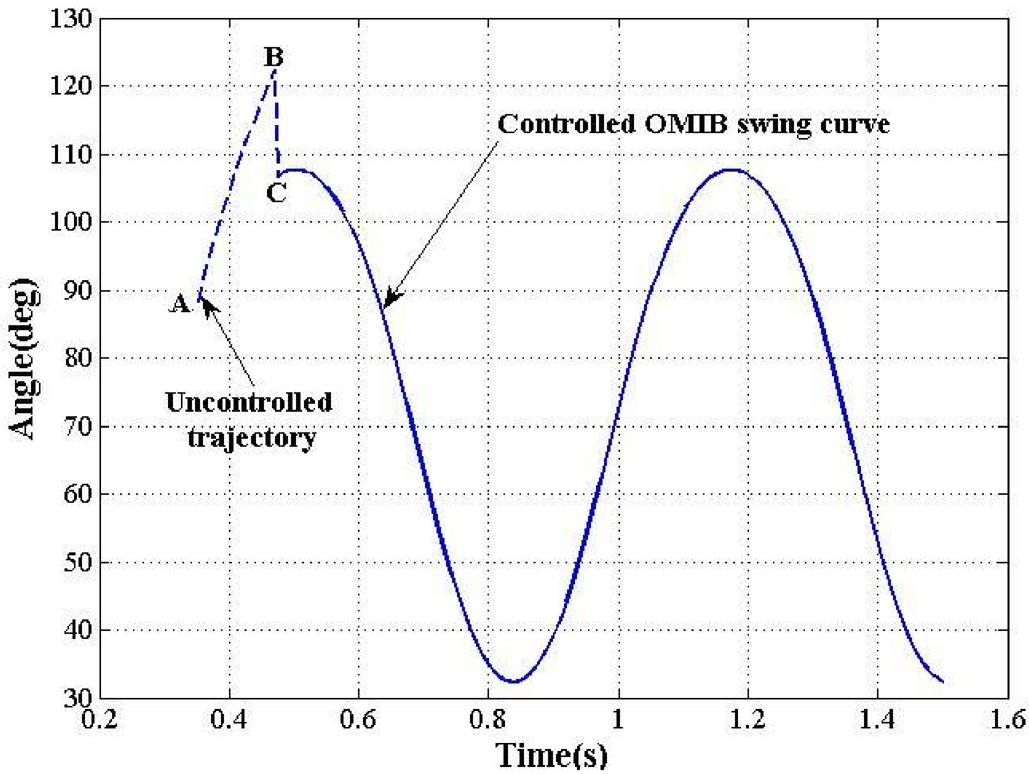


Figure 4.6 OMIB equivalent swing curve for the case 1A: Stabilized system.

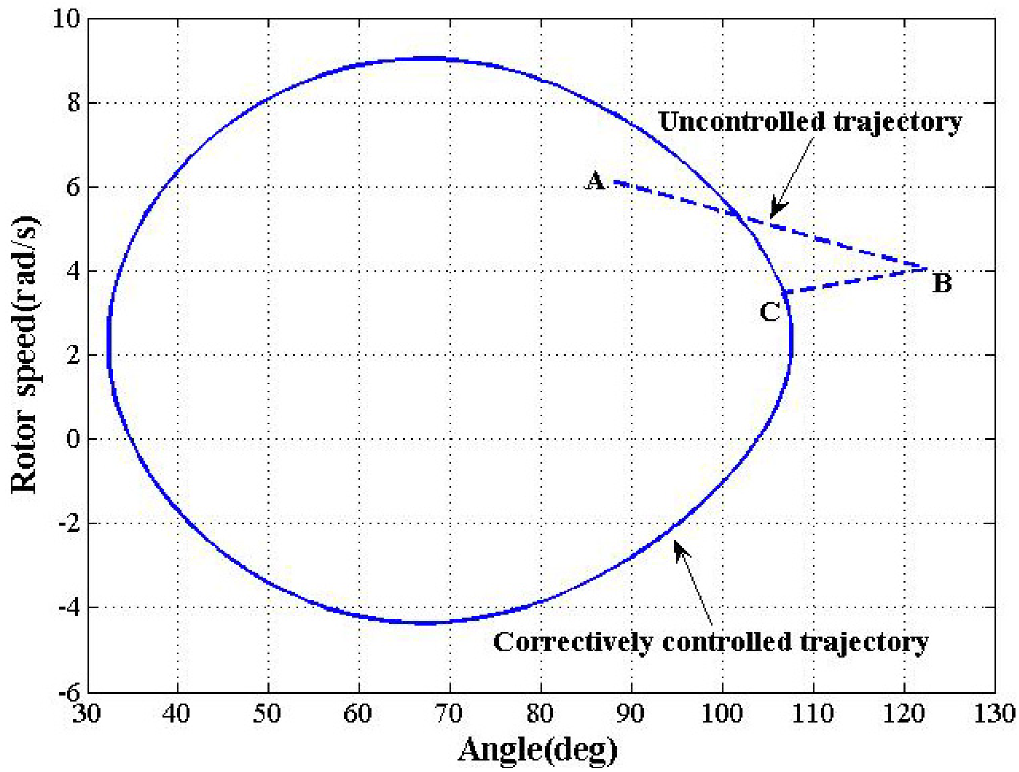


Figure 4.7 OMIB equivalent phase plane for case 1A: Stabilized system.

Case 2A: In this case the E-SIME method was applied to the IEEE three-machine test system, using the classical model and considering contingency 3 of Table A.6 with a long clearing time t_e = 450 ms. This case is a good example of the behavior of the method for a very unstable system; in those cases, E-SIME method can not provide accurate transient stability assessment.

Table 4.3 summarizes the transient stability assessment of E-SIME method for case 2A. It is evident that the system is so unstable that at $t = 0.5$ s the calculations are totally erroneous. Prediction of stability starts at $t = 460$ ms. Despite the fact that instability is accurately predicted only 10 ms after, the system can not be properly stabilized because the predicted time to instability is of around 500 ms, very close to the current time, only 30 ms ahead (see Table 4.3), so the method does not have enough time to design and trigger control actions. This explains results of figures 4.10 and 4.11 where tripping a machine does not stabilize the system as shown in Fig. 4.9.

In this case system had post fault equilibrium and decelerating area, but fault was cleared so late that attraction to the stable equilibrium was lost.

Table 4.3 Closed-loop emergency control for case 2A.

Measurement	t_i(s)	δ_u(rad)	t_u(s)	η/M $(rad/s)^2$	η/M $(rad/s)^2$ after shedding
3	0.4600	131.2508	0.4622	-24.8	---
4	0.4650	144.5457	0.5005	-24.5	---
5	0.4700	144.8878	0.5060	-24.5	---
It is decided to trip machine 2 at t=0.570s					
6	0.4750	144.9159	0.5111	-24.5	26.3
7	0.4800	144.9342	0.5161	-24.5	47.4
8	0.4850	144.9457	0.5211	-24.5	14.5
9	0.4900	144.9520	0.5262	-24.5	34.6
10	0.4950	144.9543	0.5312	-24.5	29.9
11	0.5000	0.00000	0.1734	-36.7	22.9
12	0.5050	0.00000	0.1782	-37.3	1.5
13	0.5100	0.00000	0.1830	-37.9	-0.3
14	0.5150	0.00000	0.1877	-38.5	-0.4
15	0.5200	0.00000	0.1925	-39.2	-1.2
16	0.5250	0.00000	0.1973	-39.8	-0.1
17	0.5300	0.00000	0.2021	-40.4	-3.0
18	0.5350	0.00000	0.2069	-41.1	-2.1
19	0.5400	0.00000	0.2116	-41.9	37.0
20	0.5450	0.00000	0.2163	-42.6	-1.6
21	0.5500	0.00000	0.2211	-43.5	-2.4
22	0.5550	0.00000	0.2257	-44.4	-3.0
23	0.5600	0.00000	0.2304	-45.4	-1.5
24	0.5650	0.00000	0.2350	-46.6	-1.1
Machine 2 is tripped					
26	0.5700	---	---	-31.1	---

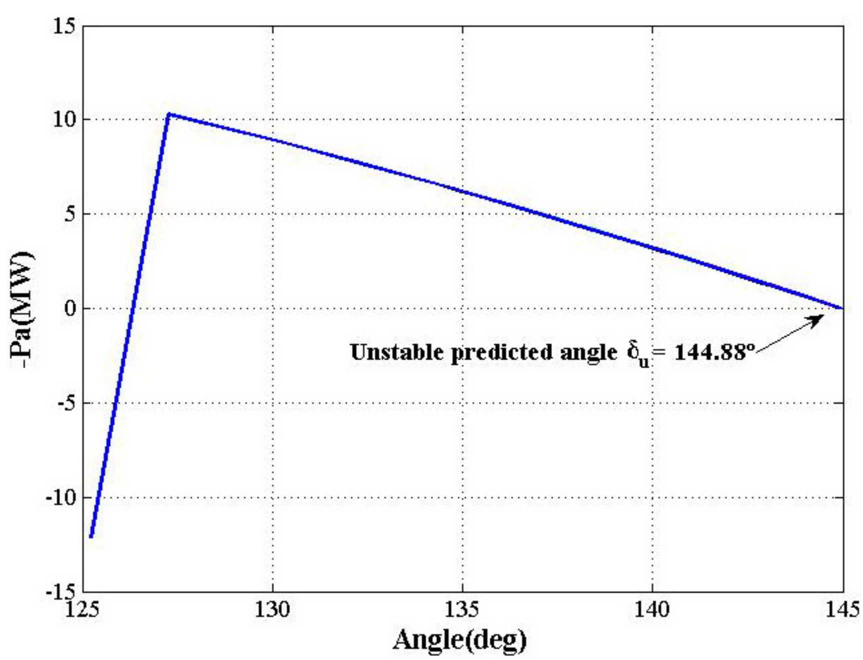


Figure 4.8 E-SIME stability prediction for case 2A.

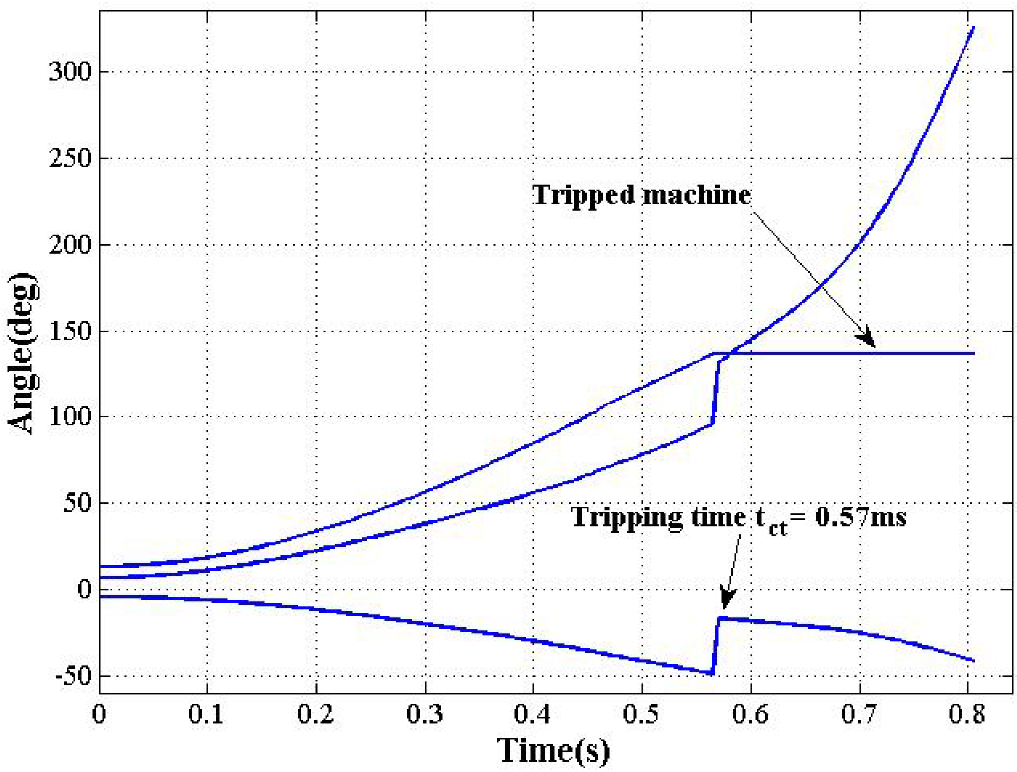


Figure 4.9 Individual machines swing curves for case 2A.

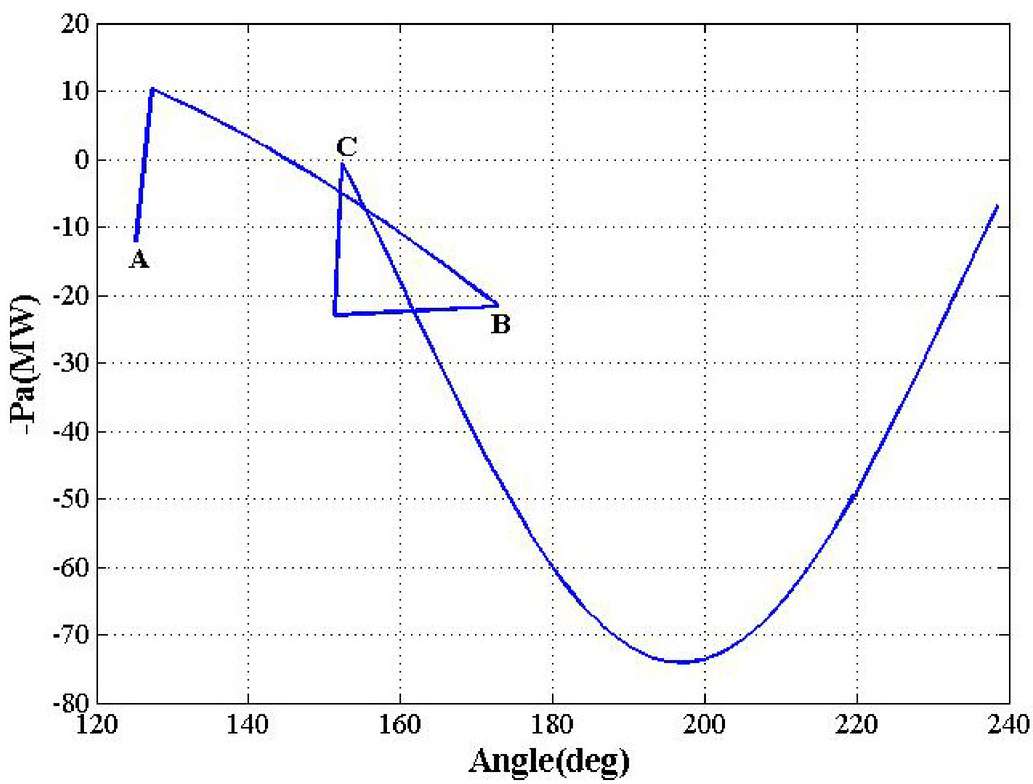


Figure 4.10 OMIB equivalent *P*-*δ* curve for case 2A.

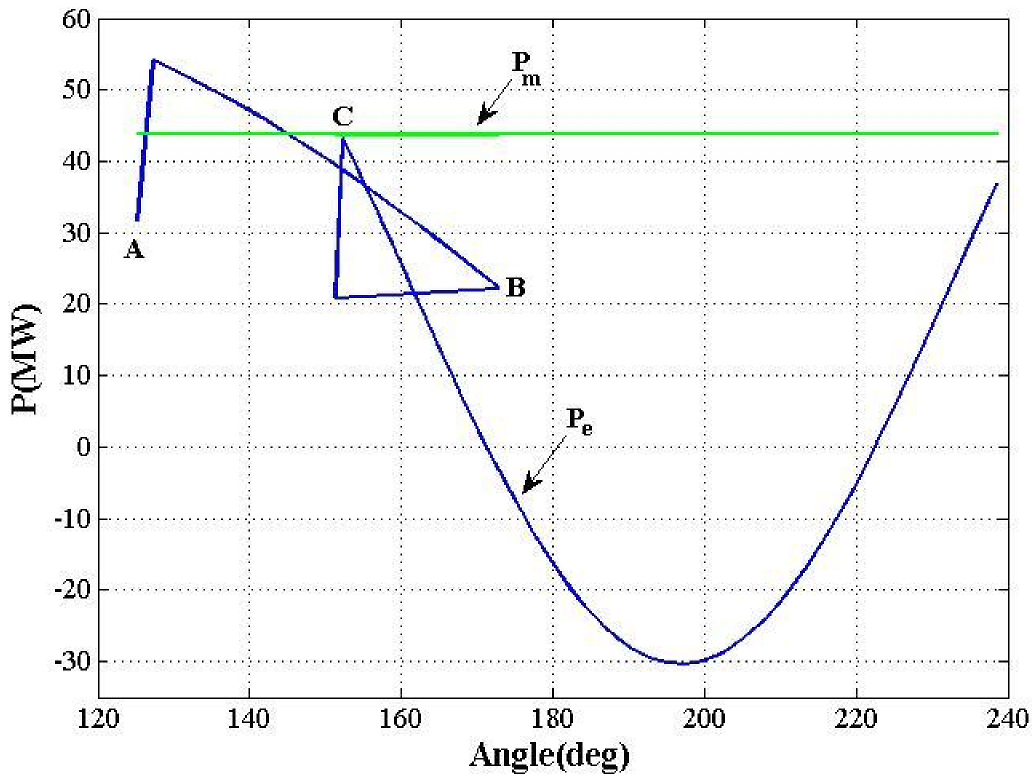


Figure 4.11 OMIB equivalent mechanical and electrical powers for case 2A.

In order to assess the influence of system modeling on the method results, some simulations where made using detailed models, as presented in chapter 3, to describe E-SIME method. The clearing times for the contingencies considered in Table A.6 of the Appendix A are presented in Table 4.4 in increasing order of its critical clearing time. Next section describes a stability case using detailed modeling.

Table 4.4 Contingencies ranking of the three-machine test system with detailed model.

Contingency number	Critical clearing time
4	0.084
5	0.130
10	0.141
3	0.163
8	0.192
6	0.197
1	0.217
11	0.218
7	0.221
9	0.231
2	0.267
12	0.292

Case 3A: for this case the E-SIME method was applied to the IEEE three-machine test system, using the detailed model and considering contingency 3 of Table A.6 with a clearing time t_e = 350 ms. As soon as the system enters in its post-fault conditions, the E-SIME method starts assessing stability. The first set of data is acquired at t = 350ms and the sampling rate of data acquisition is 5ms.

The system is very unstable and the prediction is totally erroneous from the beginning as it can be observed in figure 4.11 where the angular prediction is presented. In those conditions, E-SIME is unable to calculate stability margins and to design and trigger control actions.

Figure 4.12 presents the individual system machine angles. The system does not have post-disturbance equilibrium as it can be observed in figure 4.13, where the $P - \delta$ curve of the OMIB starts at point A, then reaches point B and does not returns to any δ_r; figure 4.14 makes it clear that the system does not reach an equilibrium point after the fault clearance since the equivalent OMIB mechanical and electrical powers do not intersect anymore. This instability problem mechanism corresponds to a case lacking post disturbance equilibrium.

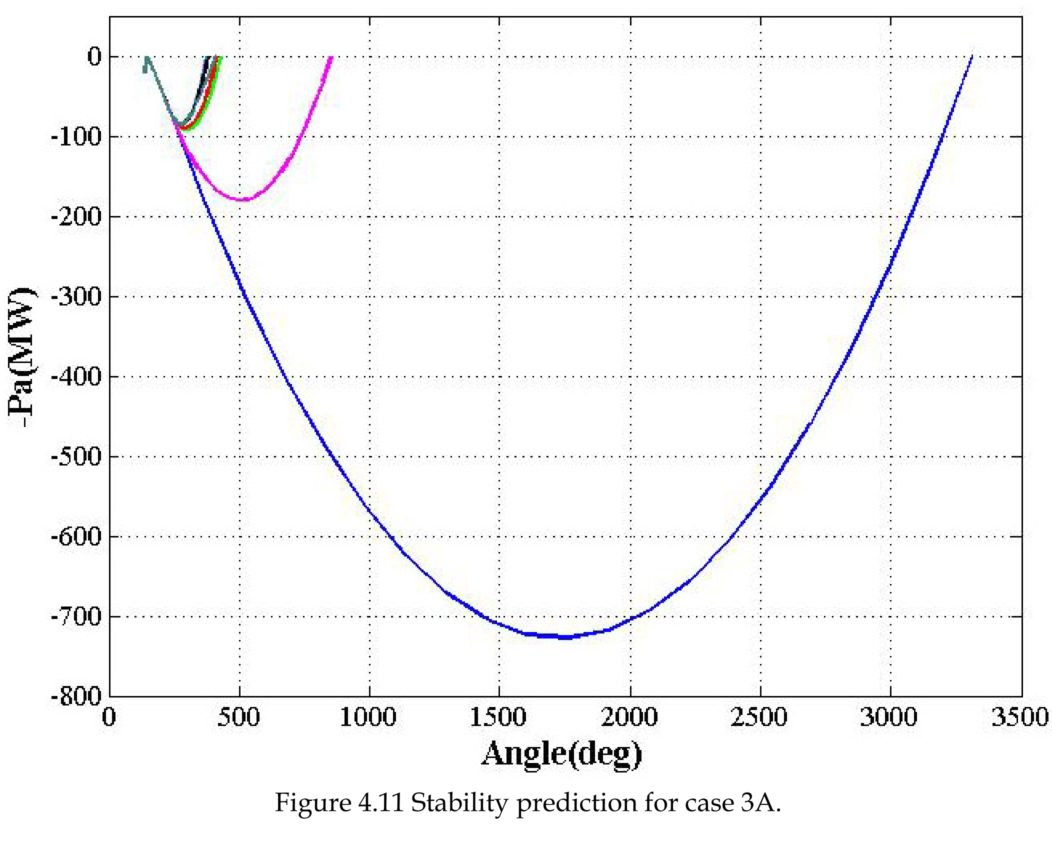


Figure 4.11 Stability prediction for case 3A.

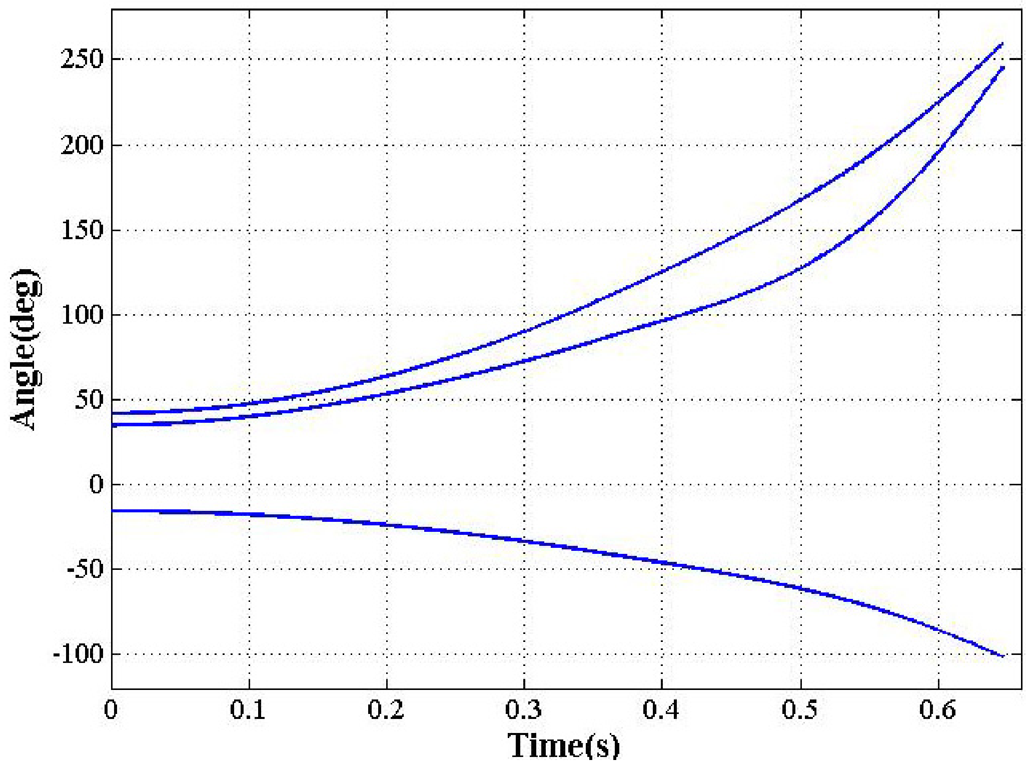


Figure 4.12 δ–t curve of the individual machines after the corrective action for case 3A.

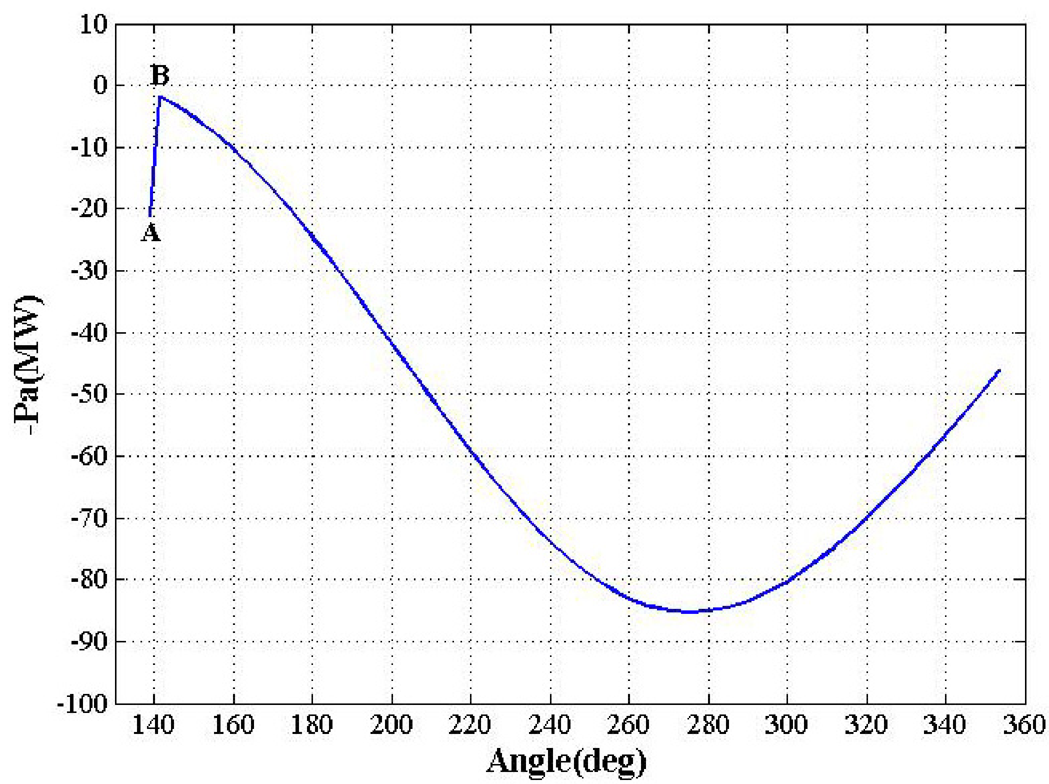


Figure 4.13 P-δ curve of the OMIB for the case 3A.

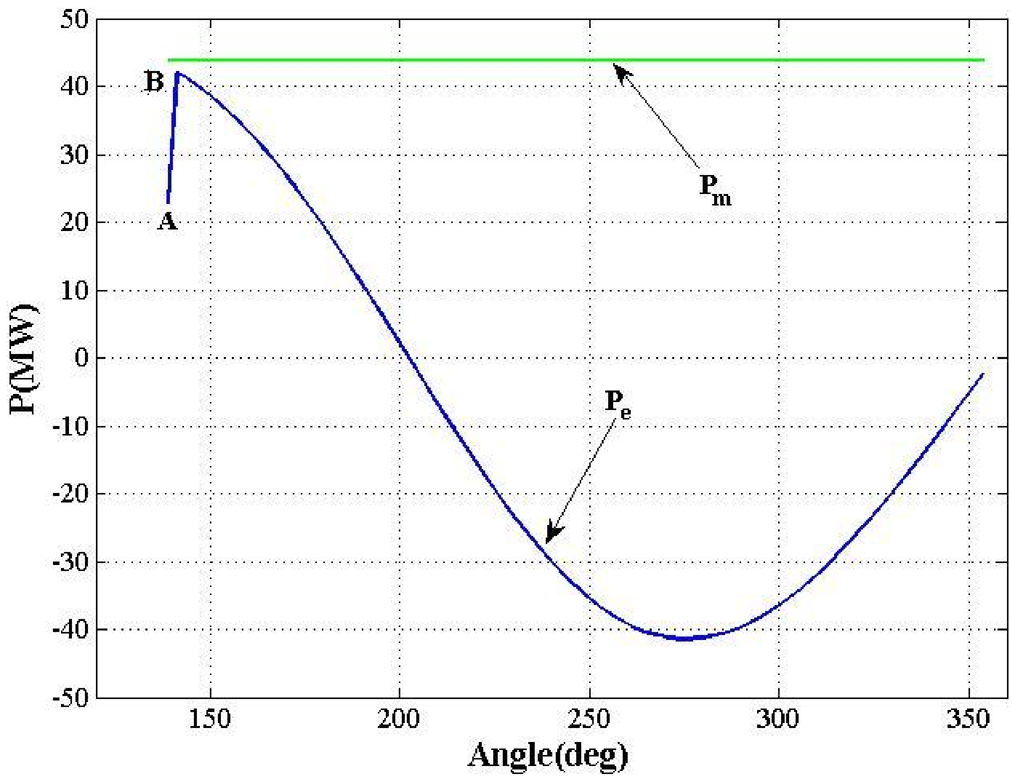


Figure 4.14 Mechanical and electrical powers of the OMIB for the case 3A.

4.3 NEW ENGLAND TEST SYSTEM

The E-SIME method was applied to the IEEE New England test power system in this section. Simulations were made using the classical and detailed models with the parameters and initial conditions of the system shown in Appendix A. In Table 4.5, the critical clearing times of the contingencies considered for the New England test system (see Table A.8 of Appendix A), using detailed model, are presented. They were assessed and ranked using the TRANSTAB program, developed in [Ruiz, 1996].

Case 1NE: for this case the E-SIME method was applied to the IEEE New England test system, using the detailed model and considering contingency 68 of Table A.8 with a clearing time $t_e = 0.1$s. As soon as the system enters in its post-fault conditions, the E-SIME method starts assessing stability. The first set of data is acquired at $t = 100$ms and the sampling rate of data acquisition is 5ms. Table 4.6 summarizes the prediction assessment of the E-SIME method for case 1NE. Prediction of stability starts at $t = 110$ ms when at least three measurements have been acquired.

E-SIME method predicts instability at $t_u = 160$ ms. In spite of this fact, the method has enough time to design and trigger control actions, so it decides to trip machine 10 at t = 220 ms.

Table 4.5 Contingencies ranking of the New England test system with detailed model.

Contingency number	Critical clearing time	Contingency number	Critical clearing time	Contingency number	Critical clearing time
5, 7, 10, 12, 13, 15, 18, 21, 23, 30, 38-41, 45, 47, 48, 50, 52, 53, 54, 58, 62	0.0	60	0.097	26	0.140
42	0.028	31	0.106	25	0.143
8	0.032	19	0.107	72	0.146
67	0.039	37	0.109	74	0.148
49, 51, 59	0.043	321	0.110	14	0.149
6, 9,11, 68	0.05	27	0.113	36	0.150
55	0.057	16	0.114	33, 71, 73	0.151
66	0.067	61	0.120	35	0.157
65	0.076	22	0.125	34	0.158
63	0.082	20	0.126	28	0.208
57	0.093	56	0.131	29	0.211
24, 64	0.096	17	0.133		

Table 4.6 Closed-loop emergency control for case 1NE.

Measurement	t_i(s)	δ_u(rad)	t_u(s)	η/M $(rad/s)^2$	η/M $(rad/s)^2$ after shedding
3	0.1100	87.3686	0.0000	702.0	---
4	0.1150	67.3580	0.1539	-0.7	---
5	0.1200	67.3838	0.1593	-0.7	---
It is decided to trip machine 10 at t=0.220s					
6	0.1250	67.3987	0.1645	-0.7	2.5
7	0.1300	67.4067	0.1696	-0.7	1.3
8	0.1350	67.4113	0.1747	-0.7	2.3
9	0.1400	67.4130	0.1797	-0.7	3.2
10	0.1450	67.4136	0.1847	-0.7	2.1
11	0.1500	78.5038	0.3504	-0.7	1.8
12	0.1550	78.4740	0.3549	-0.7	2.7
13	0.1600	78.4728	0.3599	-0.7	1.9
14	0.1650	78.4940	0.3652	-0.7	2.7
15	0.1700	78.5307	0.3708	-0.7	1.4
16	0.1750	78.5800	0.3765	-0.7	1.1
17	0.1800	78.6373	0.3823	-0.7	8.7
18	0.1850	78.7014	0.3882	-0.7	2.4
19	0.1900	74.3292	0.3299	-0.7	2.2
20	0.1950	0.0000	-0.7452	-0.8	4.0
21	0.2000	78.8836	0.4059	-0.7	5.7
22	0.2050	78.9598	0.4120	-0.7	2.1
23	0.2100	79.0337	0.4180	-0.7	3.8
24	0.2150	78.4900	0.4241	-0.7	3.0
Machine 10 is tripped					
33	0.3600	---	---	2.1	---

The control action is applied at t = 220 ms and the system is stabilized.

The predictive transient stability assessment results, in terms of the OMIB P_a - δ curves can be observed in figure 4.14 where the angle of the OMIB when the stability margin converges is $\delta_u = 78.49^o$. Figure 4.15 shows the OMIB angle before applying the corrective action; it can be noticed that it indicates that the system will be unstable. Figure 4.16 presents the swing curves of individual machines and figure 4.17 displays the predicted P - δ curve with the main steps of E-SIME indicated: point A where the E-SIME method starts its predictions, the point labeled $t_{decision}$, at which control decision is taken, point B (approximately when $\delta_{OMIB} = 73^o$) where the maximum OMIB angle is reached and finally "jumps" to another OMIB at point C.

Figures 4.18, 4.19 and 4.20 present the OMIB equivalent mechanical and electrical powers, swing curve and phase plane, respectively. In all figures, points indicating the execution of each one of E-SIME main steps are: point A, where the SIME method starts its calculations, point B where the OMIB reaches the maximum angle and the control action is applied, and point C at which the system jumps to a new OMIB curve.

Three more cases where the method successfully stabilizes the system under contingency 68 are briefly described below and summarized in Table 4.7. They were selected to show the effect of different measurement sampling times in the results of E-SIME.

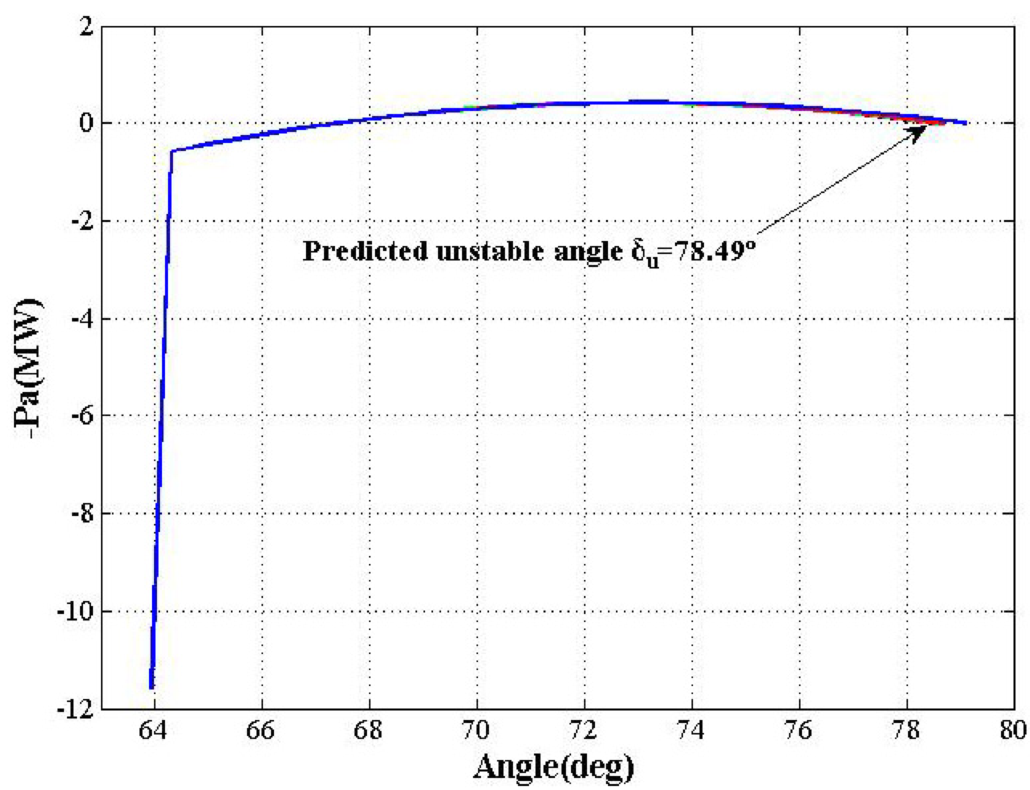


Figure 4.14 E-SIME stability prediction for case 1NE.

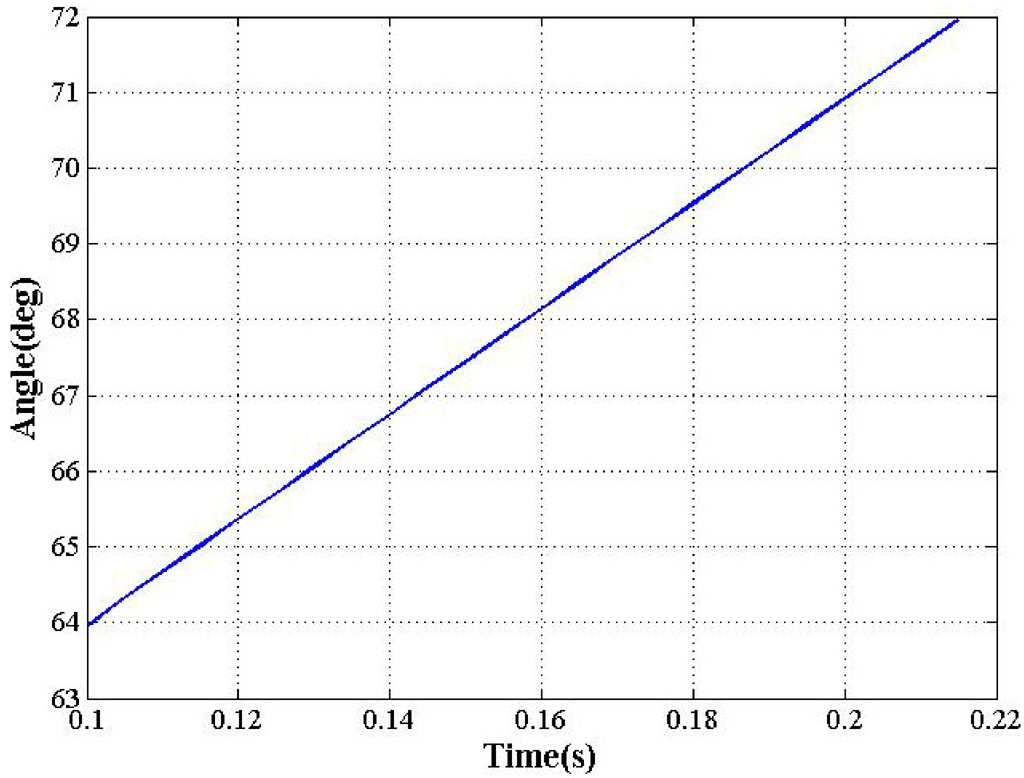


Figure 4.15 OMIB equivalent angle trajectory before the control action is applied for case 1NE.

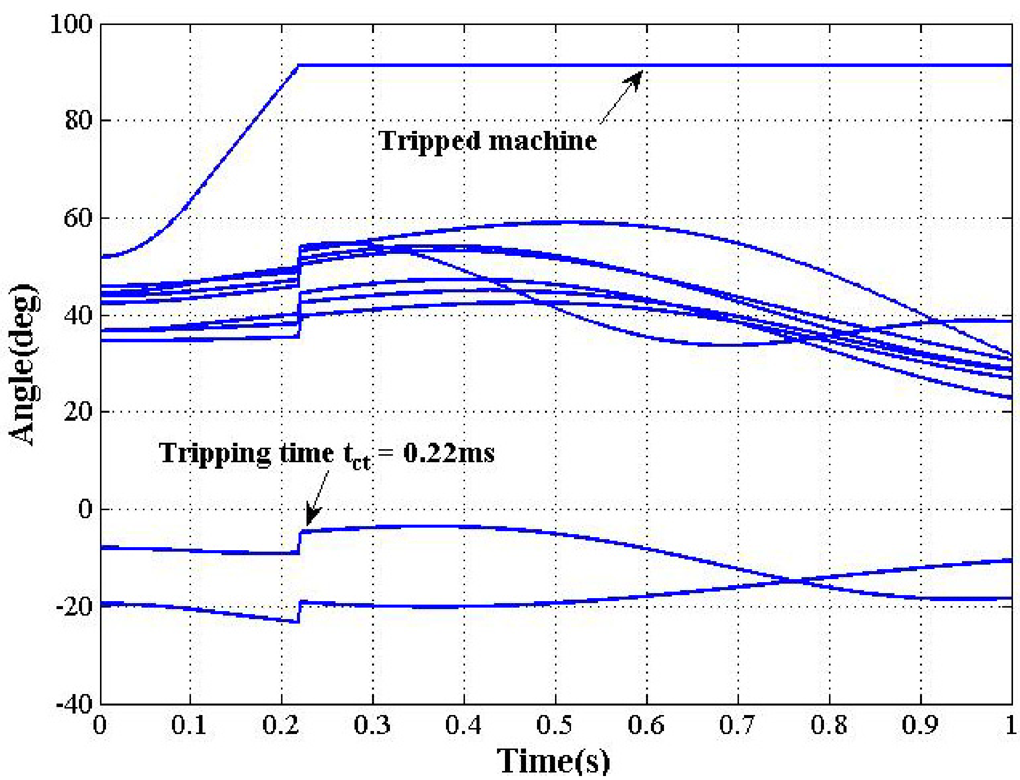


Figure 4.16 Individual machines swing curves for case 1NE.

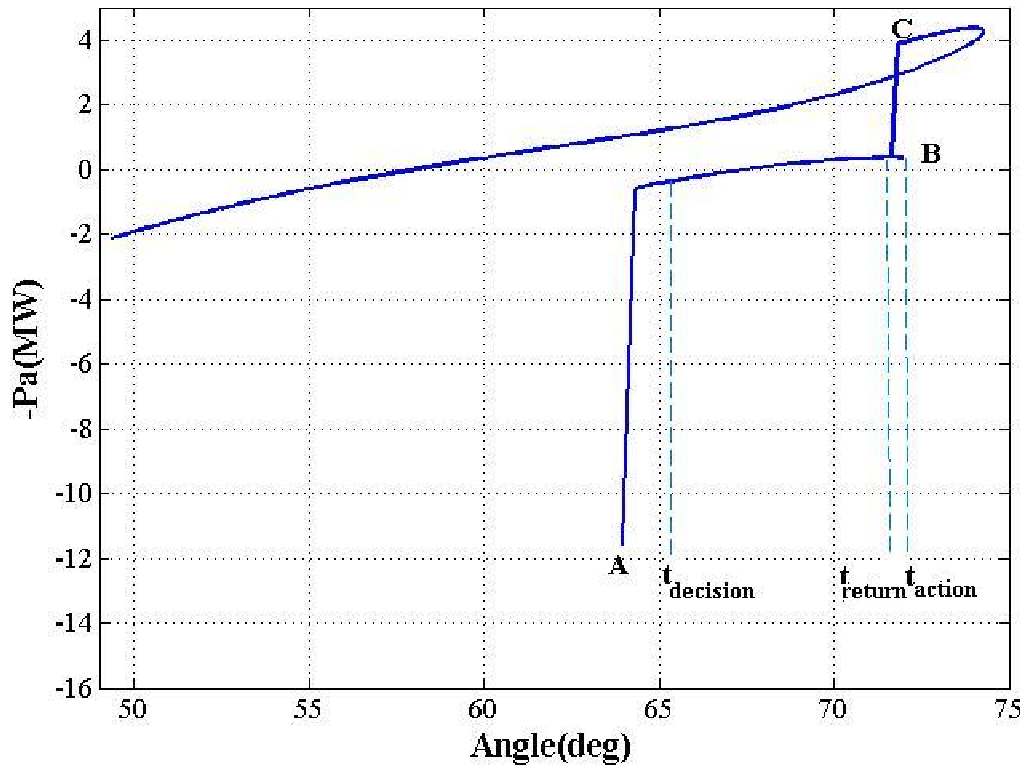


Figure 4.17 OMIB equivalent P-δ curve for case 1NE.

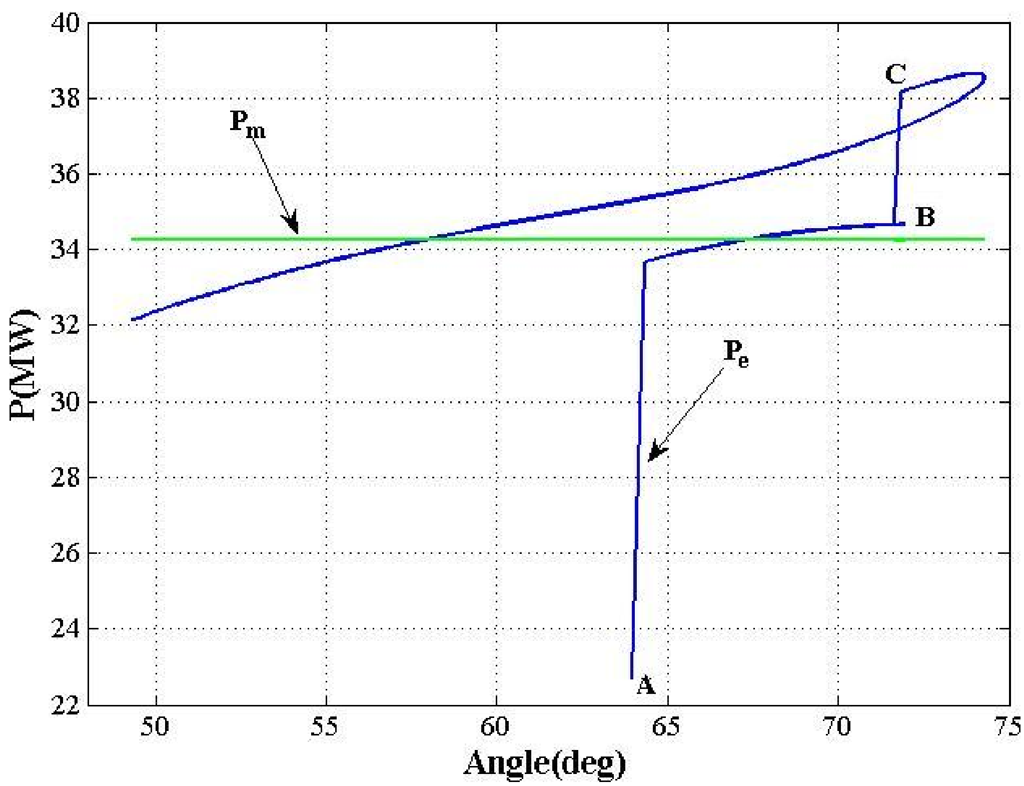


Figure 4.18 OMIB equivalent mechanical and electrical powers for case 1NE.

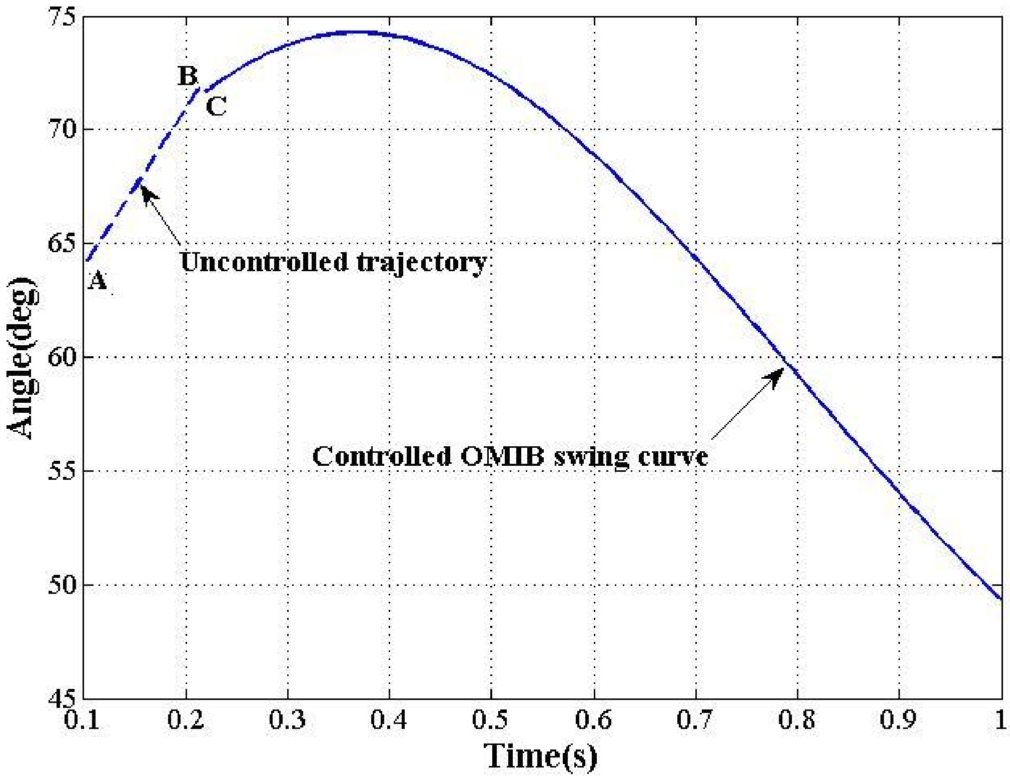


Figure 4.19 OMIB equivalent swing curve for the case 1NE: Stabilized system.

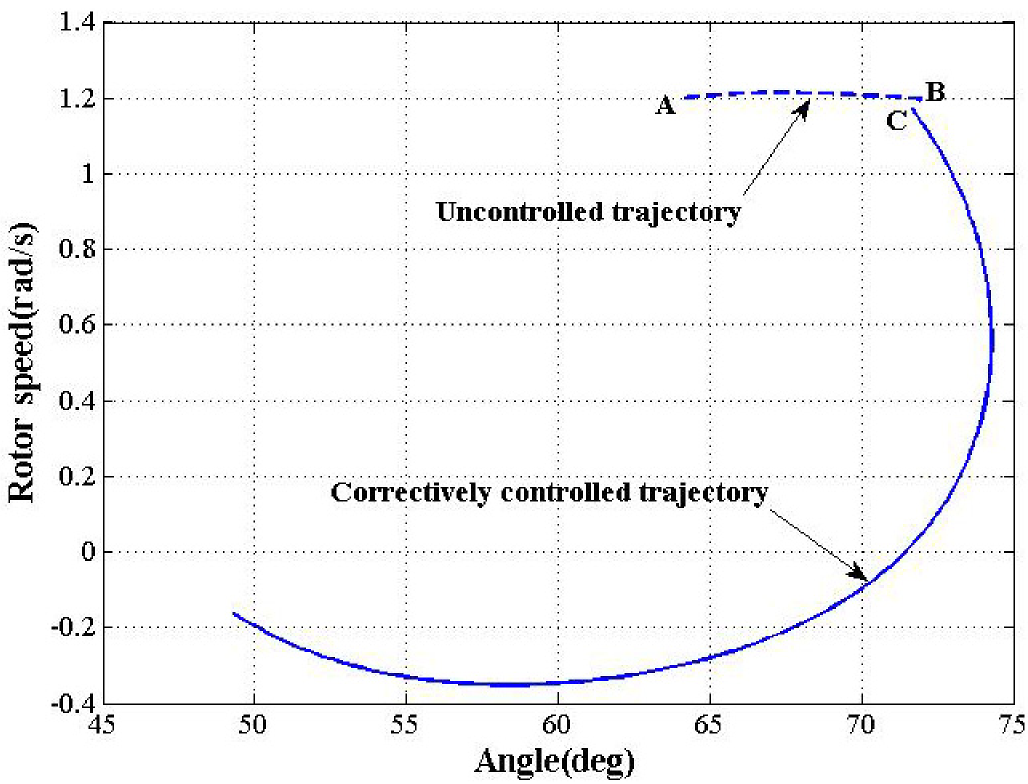


Figure 4.20 OMIB equivalent phase plane for case 1NE: Stabilized system.

Case 2 NE: E-SIME method was applied using classical model, the clearing time was $t_e = 100$ms. E-SIME method starts assessing stability and the first measurements is acquired at t = 100 ms. The sampling rate of data acquisition is 5ms. Table 4.7 summarizes the main assets of this case.

Case 3 NE: E-SIME method was applied using classical model, the clearing time was $t_e = 100$ ms. E-SIME method starts assessing stability and the first measurements is acquired at $t = 100$ ms and the rate of data acquisition is 20ms. Table 4.7 summarizes the main assets of this case.

Case 4 NE: for this case the E-SIME method was applied using the test conditions of the base case NE with detailed model, the clearing time was $t_e = 100$ ms. E-SIME starts assessing stability and the first measurements is acquired at $t = 100$ms. The rate of data acquisition is 20 ms. Table 4.7 summarizes the main assets of this case.

Table 4.7 Closed-loop emergency control for cases 2NE, 3NE and 4NE.

1	2	3	4
Parameter	**Case 2NE**	**Case 3NE**	**Case 4NE**
Measurement when the margin converges	5	5	5
t_i(s) when the margin converges	0.1200	0.1800	0.1800
δ_u(rad) when the margin converges	49.50	109.42	133.21
t_u(s) when the margin converges	0.1354	0.4047	0.4111
η/M (rad/s)^2 when the margin converges	-9.5	-9.3	-9.0
Number of tripped machines	1	1	1
Time tripping t_{ct}	0.2200	0.2800	0.2800
η/M (rad/s)^2 after shedding	253.9	0.1	0.2

Some comments about Table 4.7 results can be summarized as follows:

- Cases 2NE and 3NE (columns 2 and 3) only differ in the measurement sampling rate: first one uses 5 ms while the second one uses 20 ms. Both of them stabilize the system but the longer sampling rate makes E-SIME converge later.

- It is interesting to observe that the predicted instability margin value is practically the same, and this indicates that in this case the measurement sampling rate variation did not affect the stability margin value.

- Time to instability t_u and unstable angle values δ_u are much more affected by changes in the measurement sampling rate. This is due to the fact that with longer sampling rates less measurements are received and processed, and this deteriorates the accuracy of the least squares method approximation of the predictive transient stability assessment.

4.4 PROPOSED SOUTH-EASTERN EQUIVALENT MEXICAN TEST SYSTEM SIEQ

In this section it is presented the performance of the E-SIME method in a new proposed South-Eastern equivalent Mexican test system SIEQ. The simulations were made using only classical model, the parameters and initial conditions of the system are shown in appendix A.

The E-SIME method was applied to the SIEQ test power system. Simulations were made using the classical model with the parameters and initial conditions of the system shown in Appendix A. In Table 4.8, the critical clearing times of the contingencies considered for the SIEQ test system are shown (see Table A.15 of Appendix A for the detailed contingency description). Contingencies were assessed and ranked using the TRANSTAB program, developed in [Ruiz, 1996].

Table 4.8 Contingencies ranking of the New England test system with detailed model.

Contingency number	Critical clearing time
1, 2, 3, 5, 6, 25, 26, 27, 28, 29, 30, 37, 38, 39, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 64, 65, 66, 67, 68, 69	0.0
4, 12, 22, 23, 24, 31, 32, 33, 34, 35, 36, 40, 41, 63	0.05
11	0.02
10	0.025
7, 8, 9	0.03
18	0.06
17	0.075
13, 14, 15, 16,	0.08
19, 20, 21	0.260

Case SIEQ: for this case the E-SIME method was applied to the SIEQ test system, using the classical model and considering contingency 19 of Table A.15 with a clearing time t_e = 0.39 s. As soon as the system enters in its post-fault conditions, the E-SIME method starts assessing stability.

Table 4.9 summarizes the prediction of the E-SIME method for the case SIEQ. Prediction of stability starts at t = 410ms when at least three measurements have been acquired. The group of critical machines is composed of two nuclear machines (machines 19 and 20) and five hydroelectric machines (machines 6, 7, 8, 9 and 10).

The predicted time to instability is of approximately 550 ms, so the method has enough time (about 300 ms) to design and trigger control actions. The control action, consisting in tripping three machines from the critical group (hydro machine number nine, and two nuclear units nineteen and twenty), is applied at t = 520 ms and the system is stabilized.

The prediction of instability is depicted in figure 4.21, where $\delta_u = 126.14^o$ is the unstable angle of the OMIB when the stability margin converges. Figure 4.22 shows the swing curves of individual machines and figure 4.23 depicts the predicted P - δ curve indicating the points at which the main steps of E-SIME are performed: point *A* where the E-SIME method starts its predictions, point *B* where the control action is applied and the maximum angular deviation is reached (at approximately $\delta_{OMIB} = 103^o$) and the final jump to another OMIB curve at point *C*.

The mechanical and electrical powers of the OMIB can be seen at figure 4.24. The OMIB angle of figure 4.25 starts at point *A* and is likely to be unstable, however when the control action is applied at point *B* the system returns to point *C* and the OMIB angle becomes stable. The phase-plane of this case is in figure 4.26 where the stabilized trajectory is shown.

Table 4.9 Closed-loop emergency control for base case SIEQ.

Measurement	t_i(s)	δ_u(rad)	t_u(s)	η/M (rad/s)²	η/M (rad/s)² after shedding
3	0.4100	146.50	0.4143	-42.4	---
4	0.4150	215.44	0.5430	-34.4	---
5	0.4200	216.14	0.5493	-34.3	---
It is decided to trip machines 9, 19 and 20 at t=0.520s					
6	0.4250	166.86	0.4660	-39.6	2.5
7	0.4300	0.000	---	---	1.36
8	0.4350	166.56	0.4754	-39.4	2.3
9	0.4400	219.38	0.5750	-33.2	3.2
10	0.4450	219.71	0.5806	-33.2	2.1
11	0.4500	219.88	0.5859	-33.2	1.8
12	0.4550	219.96	0.5910	-33.1	2.7
13	0.4600	219.94	0.5960	-33.1	1.9
14	0.4650	219.79	0.6007	-33.2	2.7
15	0.4700	219.47	0.6051	-33.2	1.4
16	0.4750	218.91	0.6091	-33.2	1.1
17	0.4800	218.04	0.6126	-33.3	8.7
18	0.4850	216.69	0.6152	-33.4	2.4
19	0.4900	214.66	0.6165	-33.6	2.2
20	0.4950	211.61	0.6161	-33.9	4.0
21	0.5000	207.12	0.6131	-34.4	5.7
22	0.5050	200.74	0.6067	-35.2	2.1
23	0.5100	192.36	0.5967	-36.8	3.8
24	0.5150	182.70	0.5846	-42.9	3.0
Machines 9, 19 and 20 are tripped					
25	0.5200	173.77	0.5830	1.7	---

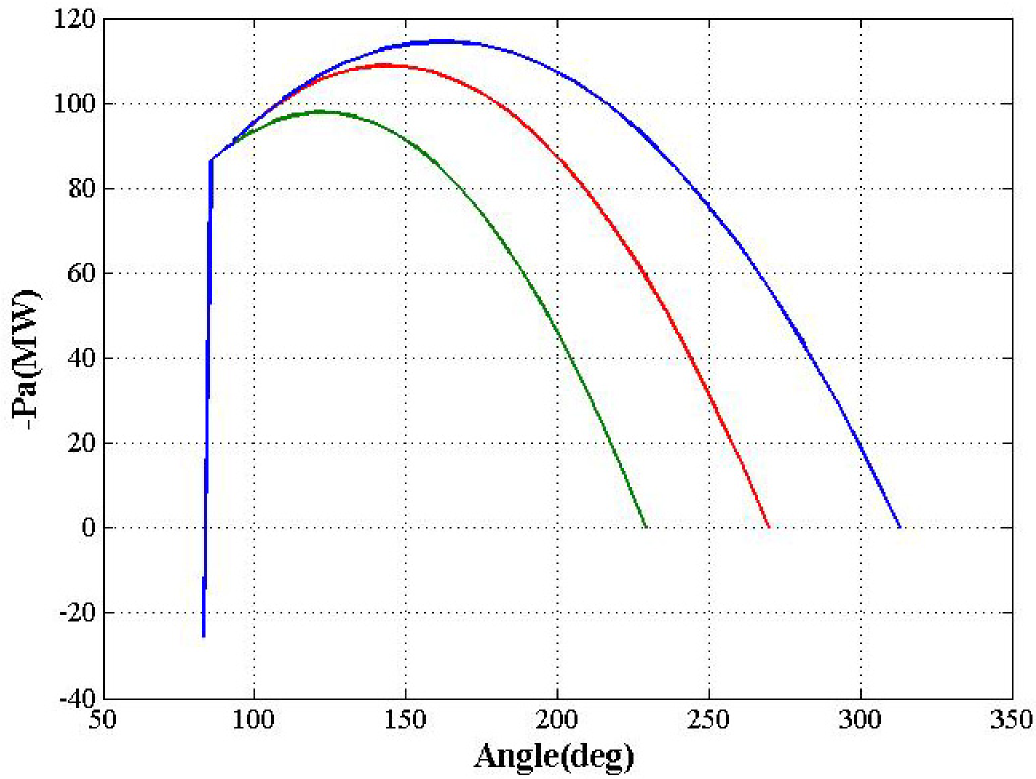


Figure 4.21 E-SIME stability prediction for case SIEQ.

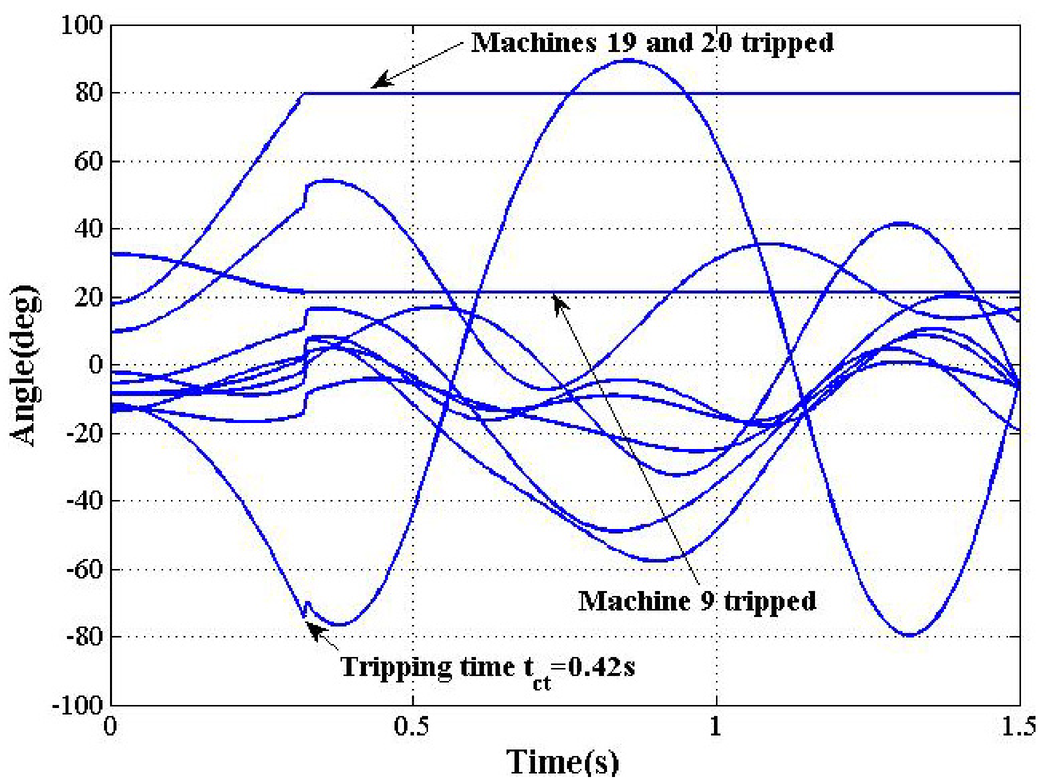


Figure 4.22 Individual machines swing curves for case SIEQ.

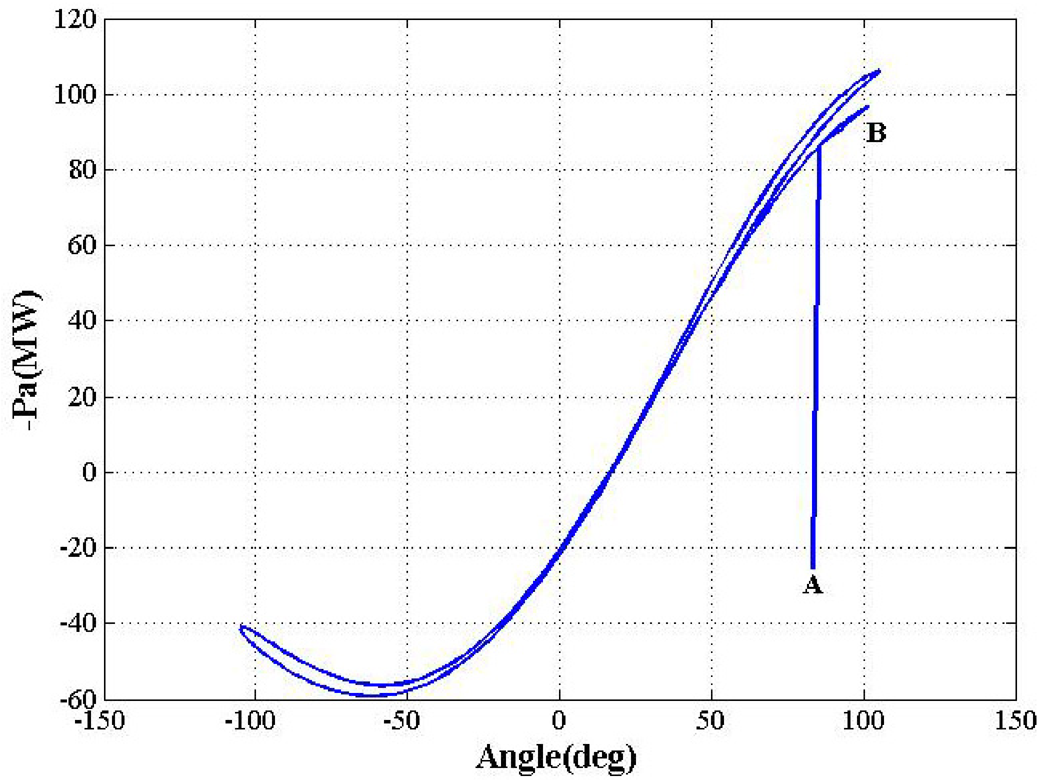


Figure 4.23 OMIB equivalent *P*-*δ* curve for case SIEQ.

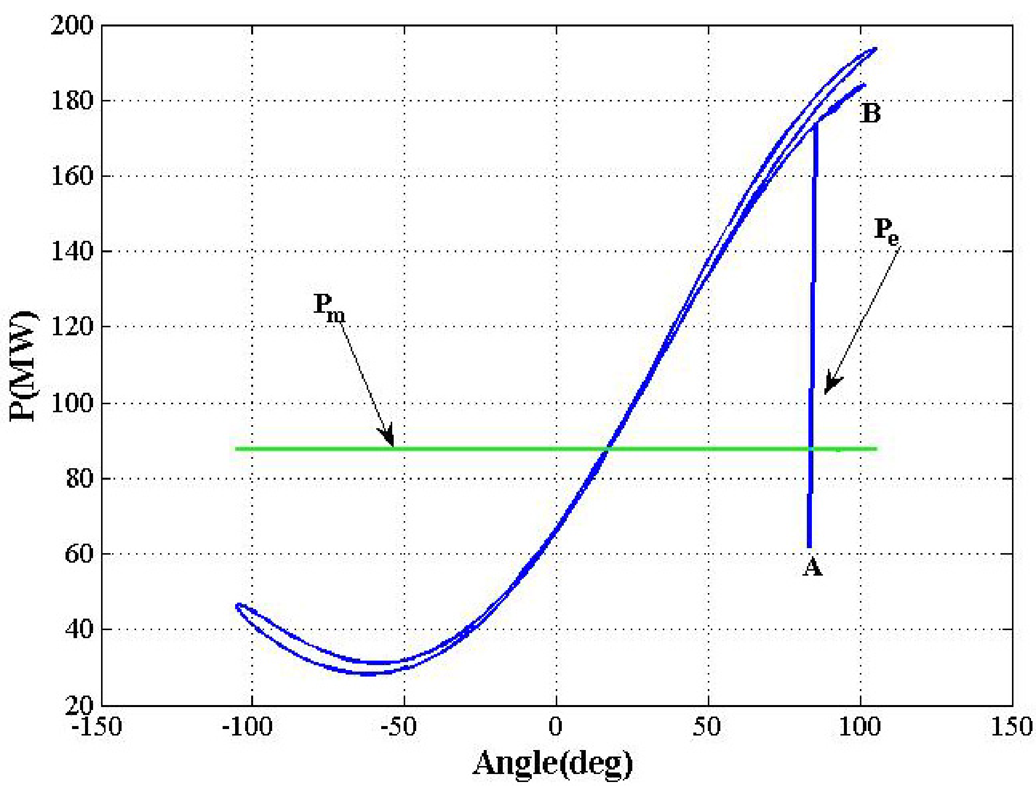


Figure 4.24 OMIB equivalent mechanical and electrical powersfor case SIEQ.

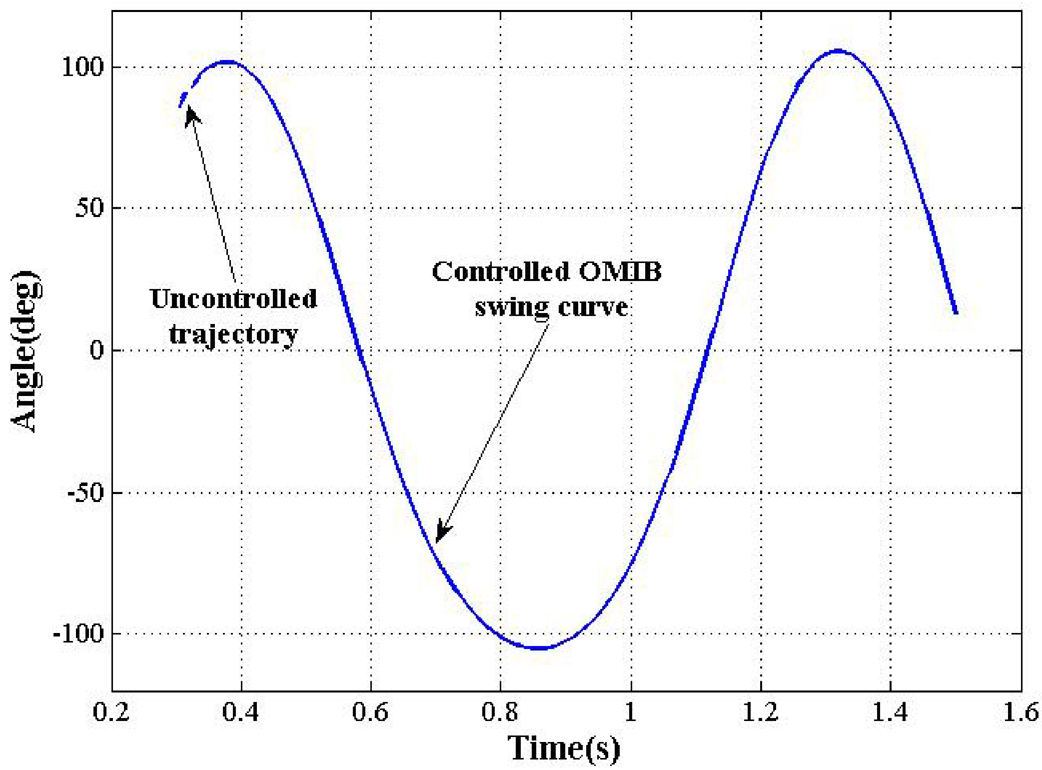


Figure 4.25 OMIB equivalent swing curve for case SIEQ: Stabilized system.

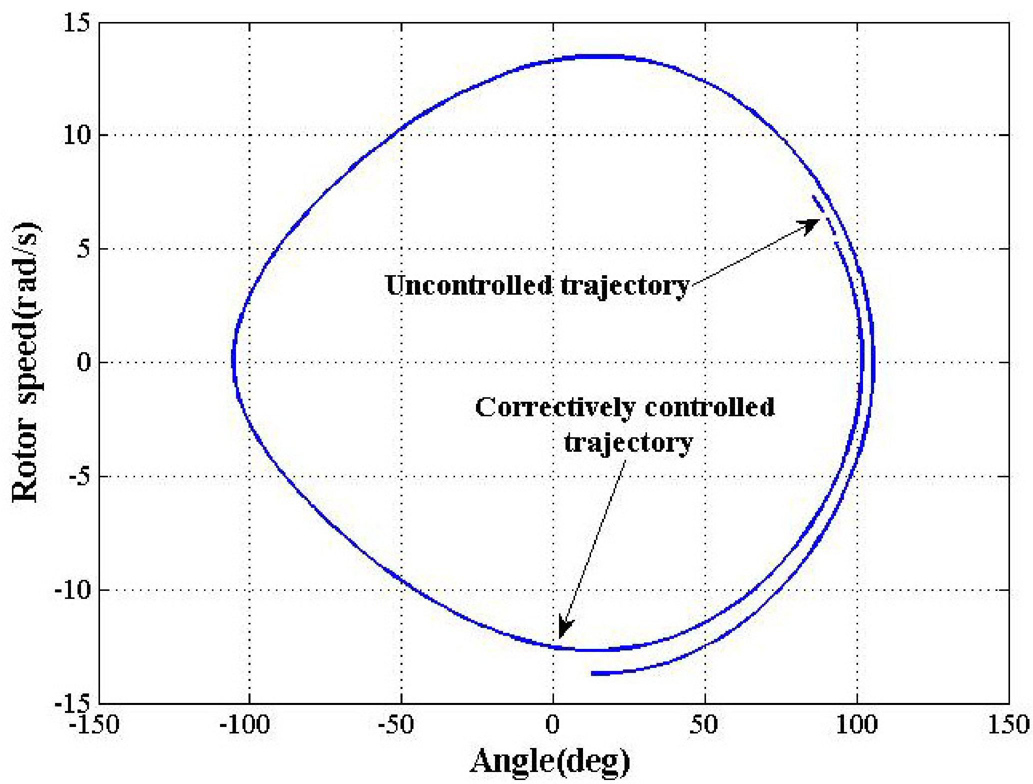


Figure 4.26 OMIB equivalent phase plane for case SIEQ: Stabilized system.

The presented case for the SIEQ system is a very good example of the application of the E-SIME method to a large power system. As is can be seen in figure 4.27 the three - phase fault is applied at bus 32 and a line is tripped between buses 32 and 31 that are near a hydro power plant. However, E-SIME decides to trip three of the most advanced machines, which are located at different power system points: two nuclear machines (20 and 21) connected to node 48 and one hydro unit connected to node 29.

Traditional control schemes detect abnormal operating conditions or dangerous faults and trigger predetermined control actions using off - line contingency studies. The results obtained with the SIEQ test system are very encouraging because it is demonstrated that E-SIME method is not dependent of the fault location and adapts the control action to trip the more disturbed machines. These machines can be located at any place of the meshed power system and E-SIME is able to correctly identify them in order to stabilize the system. These geographical characteristics are shown in figures 4.27 and 4.28.

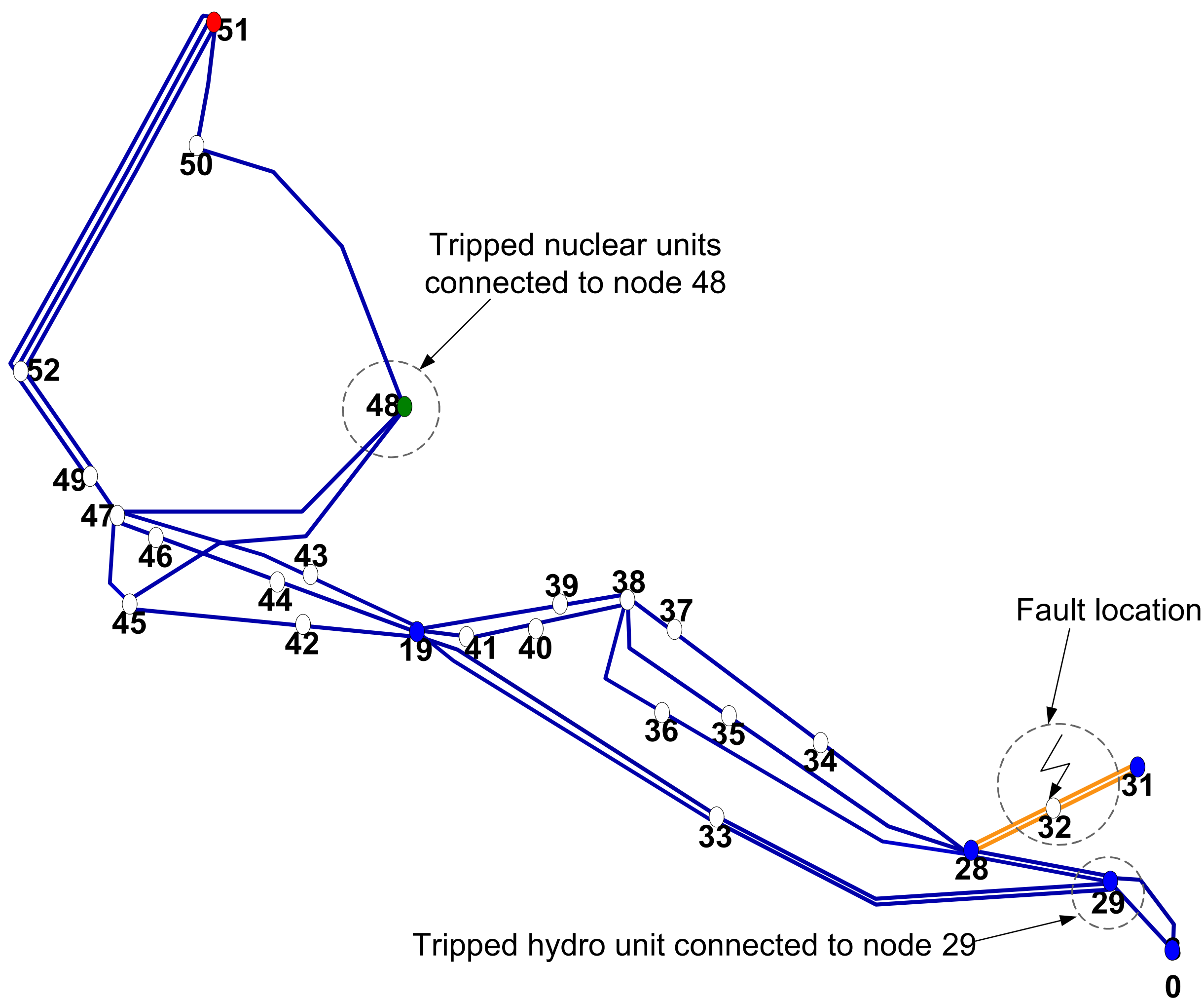


Figure 4.27 Application of the E-SIME method to the SIEQ test system.

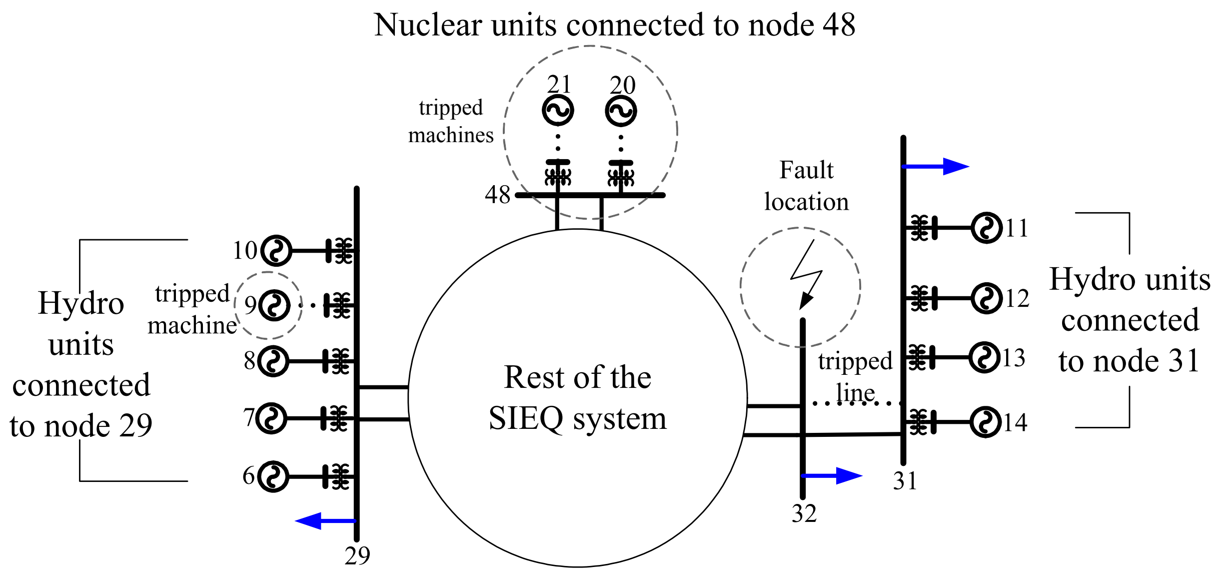


Figure 4.28 Application of the E-SIME method to the SIEQ test system.

CHAPTER 5:

CONCLUSIONS

5.1 CONCLUSIONS

In this work, a transient stability emergency control tool based on the E-SIME method was studied and developed in a digital computer program written in FORTRAN, so the main objectives of the work were successfully met.

The conclusions that can be derived from the results presented in chapter 4, are written below; they are properly divided to illustrate every step of the process.

5.1.1 Real-time measurements

E-SIME is based on the processing of real-time measurements. This thesis is an initial work which describes the structure and assesses the performance of the theoretical method in controlling transient stability. For this task, the real time measurements were artificially created coupling the E-SIME method with a time domain transient stability program TRANSTAB, and they were enough to demonstrate that the method works properly at this stage of the research.

For a future practical implementation of the E-SIME method, it is necessary to test its performance using more realistic conditions. Regarding phasor measurement units (PMU's), this is going to present some difficulties: first of all, current PMU's are unable to provide measurements of the variables required by the E-SIME method; however, it is highly probable that in a near future these quantities will be provided by this kind of units, so it is important to develop new techniques to maximize the opportunities to use the measurements mentioned. A second difficulty is that the requirements of speed and sampling of variables in order to control transient stability are very demanding. It is also very probable that, in a near future, the performance of the wide area measurement system is going to comply with these stringent requirements. A third and final difficulty is found when the system is subjected to a very severe contingency. As it has been demonstrated again in this work, in very severe transient stability problems, E-SIME is not able to control the security problem. However, it is usually for this kind of contingencies that the conventional event-based system protection schemes are designed. For these cases, the contingency is therefore fully known. This fact can be taken as an advantage to coordinate the use of the event-based scheme as the primary transient stability control function with the E-SIME one as the secondary or backup protection.

Location and number of the required PMU's are not currently a problem because the number of PMU's installed all around the world and in the Mexican Interconnected System are increasingly growing. It is expected that, in a near future, all interesting points in the system are going to be monitored and even that the measurement system is going to be redundant.

5.1.2 Stability prediction

The crux of E-SIME method is the stability prediction, which must be accurate enough because it directly influences the decision of activating the system protection scheme. This is why some aspects were bore in mind:

- The Taylor series expansions of the individual system machines are valid in a short horizon of time (say 100 ms), because angular trajectories change with time, and the composition of the OMIB must be refreshed until necessary.

- Providing that the first OMIB calculations may not be accurate enough at the beginning of the assessment, this OMIB surely contains the effects of the machines that may cause instability of the system and proper control actions would hopefully stabilize the system.

- As it can be noticed in results of chapter 4, the P-δ curve prediction during the first instants of the method could be absolutely unreliable and therefore it can conduct to an erroneous assessment, unless a convergence criterion is properly set and used, because in some cases it may seem that a system is likely to be stable while it is not.

- The accuracy of the prediction depends on the order of the function chosen to solve equation 3.17. In this work, a second order function was used to calculate the a, b and c coefficients of expression 3.17, and consequently to find the unstable angle δ_u. This was found to be a good option to predict the behavior of the P-δ curve. However, some additional research about other functions could be performed in order to improve the method's accuracy.

- The stability margin is a strongly useful parameter to assess stability of the system. It is used also in the E-SIME method in the convergence criterion of the predictive stability assessment: it must converge to a nearly constant value to declare a system to be unstable.

5.1.3 Corrective actions

When a system is declared unstable, the E-SIME method designs and triggers proper control actions to stabilize the system. In this work the control action used is the generation tripping scheme, and the most important task of designing it, is to decide the amount and location of generation to be shed.

The implemented tool chooses the generators to be tripped among the most disturbed ones: they are the more advanced critical machines of the OMIB. The method, at the time the predictive assessment converges, can assess the behavior of the system when a critical machine is tripped before it is actually done, and can determine if the control action is sufficient to stabilize the system, or if it is necessary to trip another machine to control the instability. The number of tripped machines is determined as the one that finally provides a stable assessment of the post disturbance operating conditions.

What makes E-SIME method attractive is its capability to continue supervising the system in order to know whether the control action was adequate to stabilize the system or an additional control action is required. This closed loop transient stability control feature is a main advantage of the method.

5.1.4 Behavior of the method

The E-SIME method was used in four test systems with evident differences in size, modeling and response. The results of this evaluation showed that E-SIME method has the following advantages and disadvantages.

Advantages:

- The modeling detail of the power system does not directly influence the behavior of the method, since it uses only few machine variables and one constant parameter to assess stability. System modeling level in this theoretical stage of the research helps improving the realistic conditions the method is tested in, because, in the case of using detailed model the final result of the stabilized system consider the actions of the machines' controls.

- Given that the E-SIME method reduces any system into an OMIB equivalent system, the size of the power system does not affects considerably the time of stability assessment per se. In a practical implementation, the size of the system would impose an additional difficulty for the application of the method by increasing the time delay and complexity of the required communication system.

- The "size" of the control action depends on the actual dynamic behavior of the system after an actual fault inception. This avoids using expensive preventive control actions to protect the system against a contingency that may not occur. It also allows adapting the size of the emergency control action to the minimum one required to control the system avoiding either, over stabilizing the contingency by a too large control action, or failing to stabilize the system because the magnitude of the control action is not large enough.

- Despite the fact that the E-SIME method does not identify the nature and location of the fault, it is able to compute the correct amount of generation to trip after its inception.

- In this stage of the research, the possibility of stabilizing the system with the E-SIME method relies in the fact that all power plants are equipped with an emergency generation tripping scheme. This is not a realistic condition, but in order to improve its applicability, the method could be used to implement systematic procedure to select the set of minimum set of power plants in which a generation tripping scheme should be installed for E-SIME to work.

Disadvantages:

- For very unstable systems the prediction of instability is totally erroneous because of the lack of post-disturbance equilibrium. This is due to the fact that the E-SIME method evaluates stability by means of the EAC and, faced to a system that does not reach a post fault equilibrium point, it simply conducts to erroneous stability assessment. Even in some cases having post-fault unstable equilibrium, if they are so severe that instability occurs very fast, the method does not have enough time to work.

  These very severe cases, as mentioned above in § 5.1.1, are usually identified in the planning phase, since they are the candidate ones for which an event-based system protection scheme are designed and installed. This fact can be advantageously used to coordinate the existing event-based scheme, as the primary transient stability control function, with the E-SIME one as the secondary or backup protection. Better results could be obtained if the automatic event-based generation tripping scheme is adapted on-line using the open loop emergency control (OLEC) approach [Ruiz-Vega and Pavella, 2003b, Ruiz et al., 2003].

5.2 FUTURE WORKS

There exist a wide number of tasks to develop in order to improve the E-SIME method. Some of them have already been proposed in the references consulted in this work. In this section, only improvements and recommendations considered pertinent by the author are presented:

- Testing the performance of the predictive stability assessment phase of E-SIME using higher order Taylor series expansions, in order to verify if accuracy and convergence of the instability prediction improves in a degree that justifies the corresponding increase in the processing complexity.

- Implementing and testing another method to approximate the P-δ curve apart from the least squares method, and using higher order functions for expression (3.17).

- Developing a new convergence criterion for the stability margin that could ensure that instability has been properly assessed.

- Implementing and testing other transient stability control actions like controlled system separation, or load shedding to be triggered by E-SIME to stabilize the system.

- The test system proposed in this work, SIEQ, must be improved including detailed models in order to have system response closer to the one of a real system.

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APPENDIX A

TEST SYSTEMS DATA

A.1 EQUIVALENT MMT TEST SYSTEM

In this section, the main characteristics and parameters of the equivalent MMT system are described. This is an equivalent of the Manuel Moreno Torres (Chicoasén) power plant of the Mexican Interconnected Power System (MIPS), it has seven buses, five machines and four equivalent loads. The initial conditions of the system are presented in the one-line diagram shown in figure A.1. Transmission network parameters and the dynamic parameters of the machines are presented in tables A.1 and A.2 respectively.

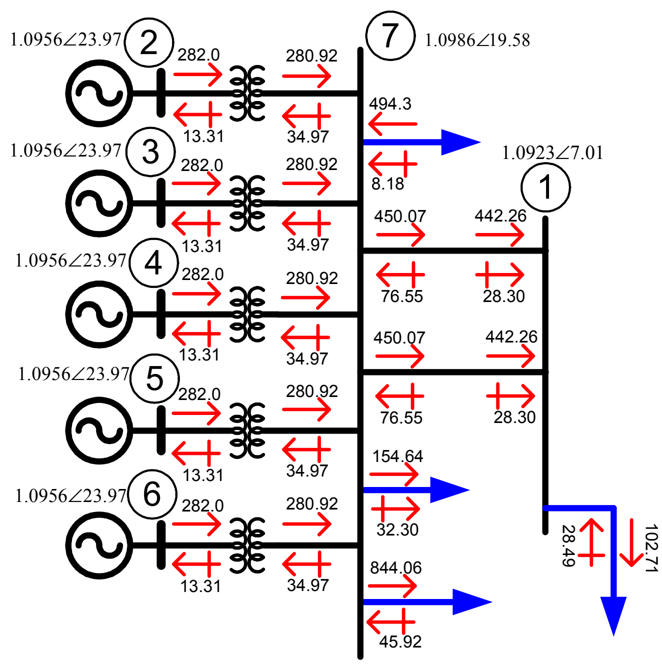

Figure A.1 One-line diagram of equivalent MMT test system

Table A.1 Transmission network data of the MMT equivalent test system.

Buses		Series impedance		Tap		Circuit number	B/2	Element
i node	j node	R_l	X_l	Magnitude	Angular			
1	7	0.00464	0.05832	0.0	0.0	1	0.0	Line 1
1	7	0.00464	0.05832	0.0	0.0	2	0.0	Line 2
2	7	0.00163	0.0326	1.0	0.0	1	0.0	Transf. 1
3	7	0.00163	0.0326	1.0	0.0	1	0.0	Transf. 2
4	7	0.00163	0.0326	1.0	0.0	1	0.0	Transf. 3
5	7	0.00163	0.0326	1.0	0.0	1	0.0	Transf. 4
6	7	0.00163	0.0326	1.0	0.0	1	0.0	Transf. 5

Table A.2 Dynamic parameters of the synchronous machines of the MMT equivalent.

Parameter	Machine number				
	1	2	3	4	5
H(s)	4.0	4.0	4.0	3.2	4.0
X'_d(p.u.)	0.29	0.29	0.29	0.385	0.29

A.2 THREE-MACHINE TEST SYSTEM

In this section, the main characteristics and parameters of the three-machine test system are described. This system has nine buses, three machine and three loads [Anderson and Fouad, 1993]. The initial conditions of the system are presented in the one-line diagram shown in figure A.2. Transmission network parameters and the dynamic parameters of the machines and their excitation control systems are presented in tables A.3 and A.4 respectively. The excitation system considered for this system is the type 1 model Automatic Voltage Regulator displayed in figure A.3.

The simulation data of the contingencies are shown in table A.5. Contingency analysis is performed by the preventive SIME program coupled with TRANSTAB [Ruiz-Vega, 1996]. The description of the contingencies is presented in table A.6.

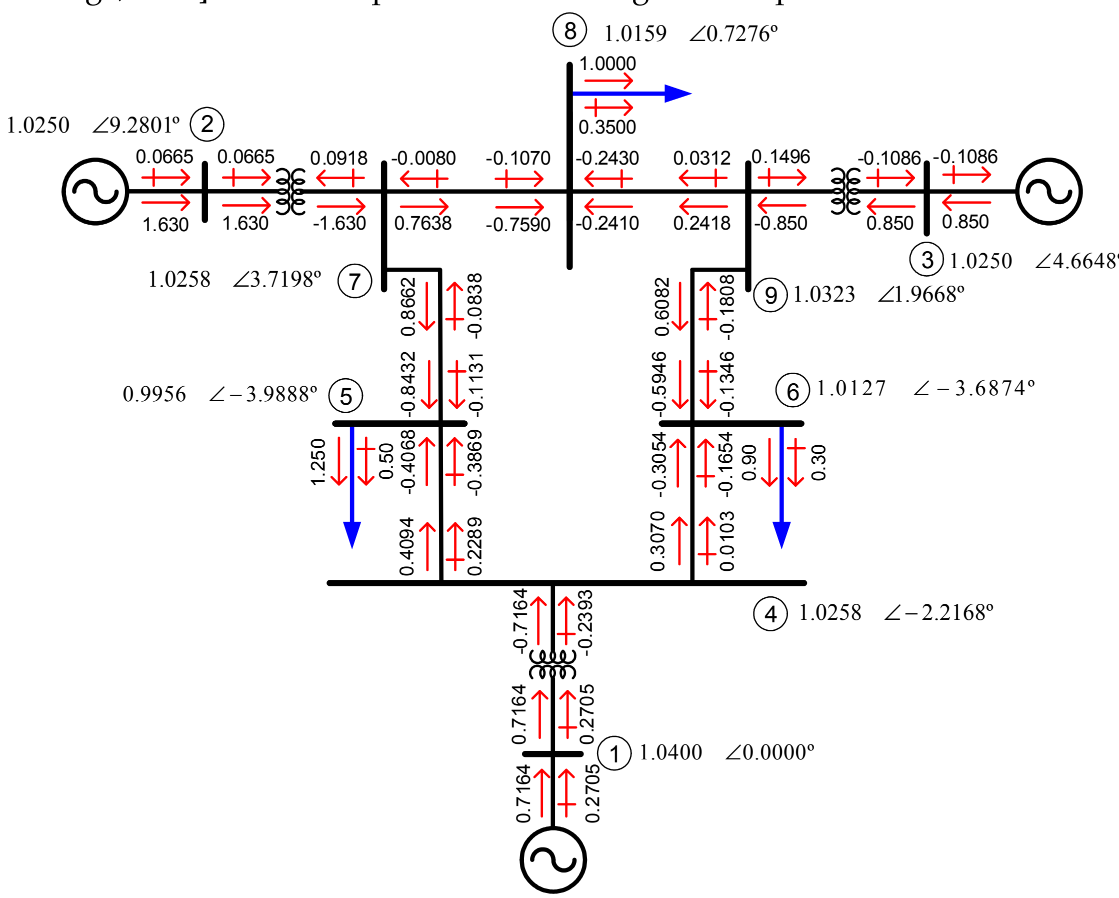

Figure A.2 One-line diagram of the three-machine test system
(Adapted from [Anderson and Fouad, 1993]).

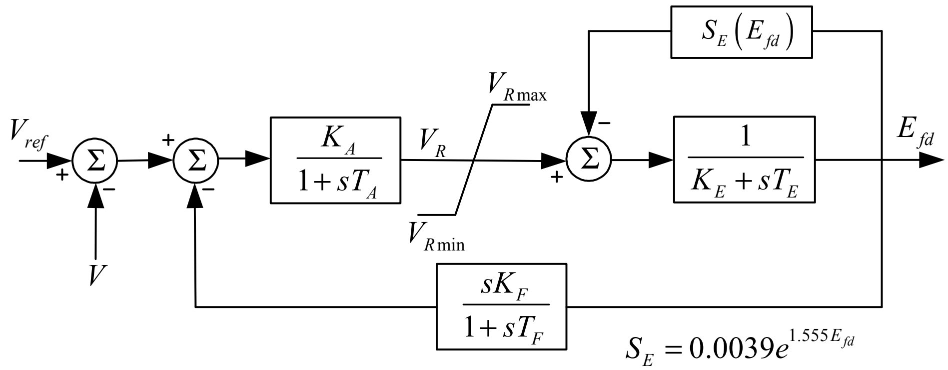

Figure A.3 Automatic Voltage Regulator type 1 model
(Adapted from [Pavella et al., 2000]).

Table A.3 Transmission network data of the three-machine test system.

Buses		Series impedance		Tap		Circuit number	B/2	Element
i node	j node	R_l	X_l	Magnitude	Angular			
4	1	0.0	0.0576	1.0	0.0	1	0.0	Transf. 1
4	5	0.010	0.0850	0.0	0.0	1	0.088	Line 1
5	7	0.032	0.1610	0.0	0.0	1	0.153	Line 2
7	2	0.0	0.0625	1.0	0.0	1	0.0	Transf. 2
7	8	0.0085	0.0720	0.0	0.0	1	0.0745	Line 3
8	9	0.0119	0.1008	0.0	0.0	1	0.1045	Line 4
9	3	0.0	0.0586	1.0	0.0	1	0.0	Transf. 3
6	9	0.039	0.1700	0.0	0.0	1	0.179	Line 5
4	6	0.017	0.0920	0.0	0.0	1	0.079	Line 6

Table A.4 Dynamic parameters of the synchronous machines and exciters dataof the three-machine test system.

.Machine dynamic data				Excitation system	
Parameter	Machine 1	Machine 2	Machine 3	Parameter	All machines
H (s)	23.64	6.4	3.01	K_A	20
M (s^2/rad)	12.54	3.39	1.59	T_A (s)	0.2
X_d (p.u.)	0.1460	0.8958	1.3125	K_E	1.0
X_q (p.u.)	0.0969	0.8645	1.2578	T_E (s)	0.314
X'_d (p.u.)	0.0608	0.1198	0.1813	K_F	0.063
X'_q (p.u.)	0.0969	0.1969	0.2500	T_F (s)	0.35
T'_{d0} (s)	8.96	6.0	5.89		
T'_{q0} (s)	0.31	0.535	0.6		

Table A.5 Simulations using the three-machine test system.

Number of pre-contingency operating states	1
Number of contingencies	12
Type of contingencies	Three-phase short circuit applied at a bus and cleared by tripping a line.
Simulation time	1.5s

Table A.6 Contingencies of the three-machine test system.

Contingency number	Faulted bus	Line tripped	Number of tripped circuit	Contingency number	Faulted bus	Line tripped	Number of tripped circuit
1	4	4-5	1	7	8	8-9	1
2	5	4-5	1	8	9	8-9	1
3	5	5-7	1	9	6	6-9	1
4	7	5-7	1	10	9	6-9	1
5	7	7-8	1	11	4	4-6	1
6	8	7-8	1	12	6	4-6	1

A.3 NEW ENGLAND TEST SYSTEM

This section presents the data values of the New England test system, which has thirty-nine buses and ten machines [Pai, 1981]. The initial conditions of the system are presented in the one-line diagram shown in figure A.4. The transmission network parameters are presented in table A.7 and the description of the contingencies is presented, for space reasons, in table A.8.

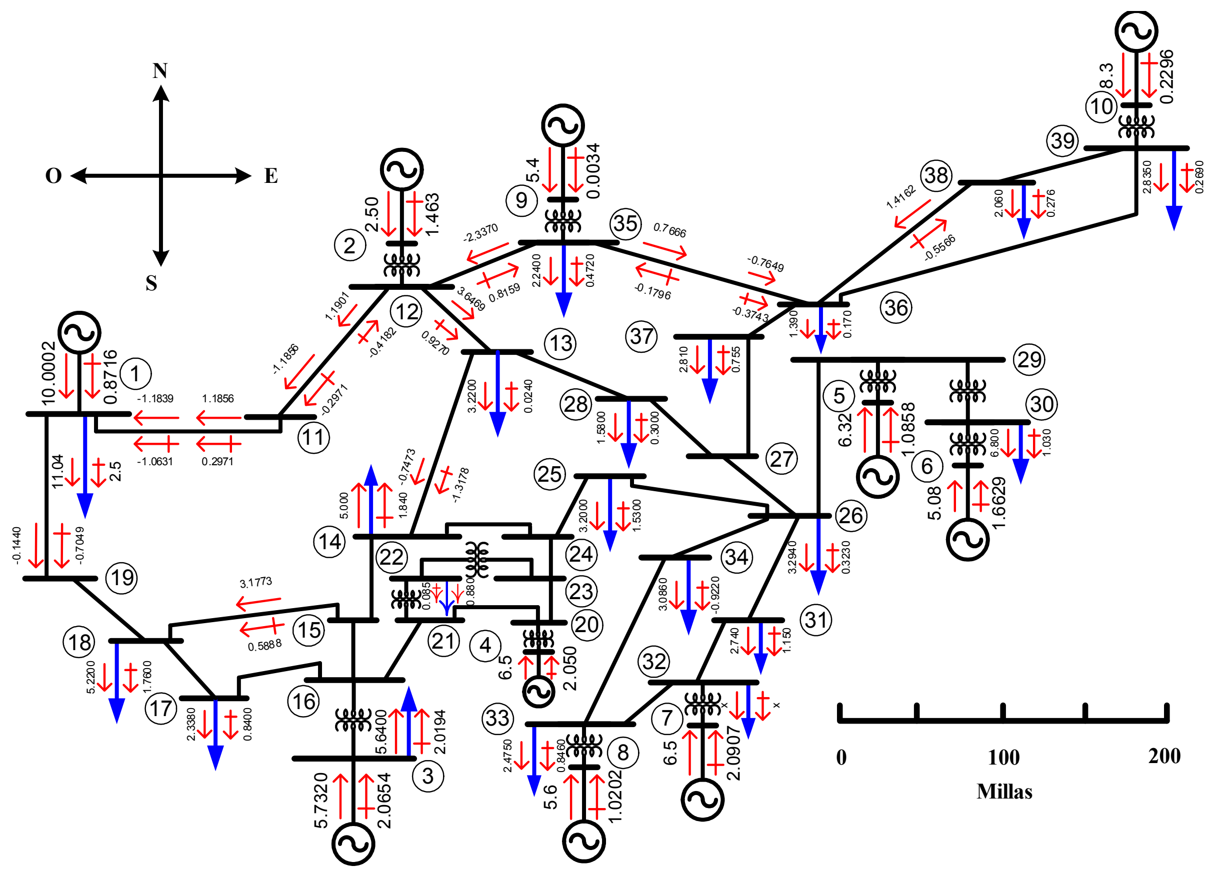

Figure A.4 One-line diagram of the New England test system
(Adapted from [Pai, 1981]).

Table A.7 Transmission network data of the New England test system.

Buses		Series impedance		Tap		Circuit number	B/2	Element
i node	j node	R_l	X_l	Magnitude	Angular			
11	12	0.00350	0.04110	0.0	0.0	1	0.3494	Line 1
11	1	0.00100	0.02500	0.0	0.0	1	0.3750	Line 2
12	13	0.00130	0.01510	0.0	0.0	1	0.1286	Line 3
12	35	0.00700	0.00860	0.0	0.0	1	0.0730	Line 4
13	14	0.00130	0.02130	0.0	0.0	1	0.1107	Line 5
13	28	0.00110	0.01330	0.0	0.0	1	0.1069	Line 6
14	15	0.00080	0.01280	0.0	0.0	1	0.0691	Line 7
14	24	0.00080	0.01290	0.0	0.0	1	0.0738	Line 8
15	16	0.00020	0.00260	0.0	0.0	1	0.0217	Line 9
15	18	0.00080	0.01120	0.0	0.0	1	0.0738	Line 10
16	17	0.00060	0.00920	0.0	0.0	1	0.0565	Line 11
16	21	0.00070	0.00820	0.0	0.0	1	0.0695	Line 12
17	18	0.00040	0.00460	0.0	0.0	1	0.0390	Line 13
18	19	0.00230	0.03630	0.0	0.0	1	0.1902	Line 14
19	1	0.00100	0.02500	0.0	0.0	1	0.600	Line 15
20	21	0.00040	0.00430	0.0	0.0	1	0.0365	Line 16
20	23	0.00040	0.00430	0.0	0.0	1	0.0365	Line 17
23	24	0.00090	0.01010	0.0	0.0	1	0.0862	Line 18
24	25	0.00180	0.02170	0.0	0.0	1	0.1830	Line 19
25	26	0.00090	0.00940	0.0	0.0	1	0.0855	Line 20
26	27	0.00070	0.00890	0.0	0.0	1	0.0671	Line 21
26	29	0.00160	0.01950	0.0	0.0	1	0.1520	Line 22
26	31	0.00080	0.01350	0.0	0.0	1	0.1274	Line 23
26	34	0.00030	0.00590	0.0	0.0	1	0.0340	Line 24
27	28	0.00070	0.00820	0.0	0.0	1	0.0660	Line 25
27	37	0.00130	0.01730	0.0	0.0	1	0.1608	Line 26
31	32	0.00080	0.01400	0.0	0.0	1	0.1283	Line 27
32	33	0.00060	0.00960	0.0	0.0	1	0.0923	Line 28
33	34	0.00220	0.03500	0.0	0.0	1	0.1805	Line 29
35	36	0.00320	0.03230	0.0	0.0	1	0.2565	Line 30
36	37	0.00140	0.01470	0.0	0.0	1	0.1198	Line 31
36	38	0.00430	0.04740	0.0	0.0	1	0.3901	Line 32
36	39	0.00570	0.06250	0.0	0.0	1	0.5145	Line 33
38	39	0.00140	0.01510	0.0	0.0	1	0.1245	Line 34
12	2	0.00000	0.01810	1.025	0.0	1	0.0	Transf. 1
16	3	0.00000	0.02500	1.070	0.0	1	0.0	Transf. 2
20	4	0.00000	0.02000	1.070	0.0	1	0.0	Transf. 3
22	21	0.00160	0.04350	1.006	0.0	1	0.0	Transf. 4
22	23	0.00160	0.04350	1.006	0.0	1	0.0	Transf. 5
29	5	0.00070	0.01420	1.070	0.0	1	0.0	Transf. 6
29	30	0.00070	0.01380	1.060	0.0	1	0.0	Transf. 7
30	6	0.00090	0.01800	1.009	0.0	1	0.0	Transf. 8
32	7	0.00000	0.01430	1.025	0.0	1	0.0	Transf. 9
33	8	0.00050	0.02720	1.000	0.0	1	0.0	Transf. 10
35	9	0.00060	0.02320	1.025	0.0	1	0.0	Transf. 11
39	10	0.00080	0.01560	1.025	0.0	1	0.0	Transf. 12

Table A.8 Contingencies of the New-England test system.

Contingency number	Faulted bus	Line tripped	Number of tripped circuit	Contingency number	Faulted bus	Line tripped	Number of tripped circuit
1	11	11-12	1	39	25	25-26	1
2	12	11-12	1	40	26	25-26	1
3	11	11-40	1	41	26	26-27	1
4	40	11-40	1	42	27	26-27	1
5	12	12-13	1	43	26	26-29	1
6	13	12-13	1	44	29	26-29	1
7	12	12-35	1	45	26	26-31	1
8	35	12-35	1	46	31	26-31	1
9	13	13-14	1	47	26	26-34	1
10	14	13-14	1	48	34	26-34	1
11	13	13-28	1	49	27	27-28	1
12	28	13-28	1	50	28	27-28	1
13	14	14-15	1	51	27	27-37	1
14	15	14-15	1	52	37	27-37	1
15	14	14-24	1	53	31	31-32	1
16	24	14-24	1	54	32	31-32	1
17	15	15-16	1	55	32	32-33	1
18	16	15-16	1	56	33	32-33	1
19	15	15-18	1	57	33	33-34	1
20	18	15-18	1	58	34	33-34	1
21	16	16-17	1	59	35	35-36	1
22	17	16-17	1	60	36	35-36	1
23	16	16-21	1	61	36	36-37	1
24	21	16-21	1	62	37	36-37	1
25	17	17-18	1	63	36	36-38	1
26	18	17-18	1	64	38	36-38	1
27	18	18-19	1	65	36	36-39	1
28	19	18-19	1	66	39	36-39	1
29	19	19-40	1	67	38	38-39	1
30	40	19-40	1	68	39	38-39	1
31	20	20-21	1	69	16	16-41	1
32	21	20-21	1	70	41	41-16	1
33	20	20-23	1	71	22	22-21	1
34	23	20-23	1	72	21	22-21	1
35	23	23-24	1	73	22	22-23	1
36	24	23-24	1	74	23	22-23	1
37	24	24-25	1	75	29	29-30	1
38	25	24-25	1	76	30	29-30	1

The dynamic parameters of the machines and the excitation systems are shown in tables A.9 and A.10 respectively. The automatic voltage regulator is a type 1 excitation control system, presented in figure A.2.

Finally, the simulation data of the contingencies is displayed in table A.11.

Table A.9 Dynamic parameters of the synchronous machines of the New England test system.

Parameter	Machine number									
	1	2	3	4	5	6	7	8	9	10
H(s)	500.0	42.0	30.3	35.8	28.6	26.0	34.8	26.4	24.3	34.5
R_a (p.u.)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X_d (p.u.)	0.02	0.100	0.295	0.2495	0.262	0.670	0.254	0.295	0.290	0.2106
X_q (p.u.)	0.019	0.069	0.282	0.237	0.258	0.620	0.241	0.292	0.280	0.205
X'_d(p.u.)	0.006	0.031	0.0697	0.0531	0.0436	0.132	0.050	0.049	0.057	0.057
X'_q(p.u.)	0.008	0.069	0.170	0.0876	0.166	0.166	0.0814	0.186	0.0911	0.0587
T'_{d0} (s)	7.000	10.200	6.560	5.700	5.690	5.400	7.300	5.660	6.700	4.790
T'_{q0} (s)	0.700	0.000	1.500	1.500	1.500	0.440	0.400	1.500	0.410	1.960

Table A.10 Dynamic parameters exciters of the New England test system.

Parameter	Machine number									
	1	2	3	4	5	6	7	8	9	10
K_A	0.0	5.00	6.000	5.000	5.000	40.000	5.000	40.000	5.000	40.000
T_A (s)	0.0	0.060	0.050	0.060	0.060	0.020	0.020	0.020	0.020	0.020
K_E	0.0	-0.05	-0.06	-0.02	-0.05	1.000	-0.04	1.000	-0.05	1.000
T_E (s)	0.0	0.250	0.410	0.500	0.500	0.790	0.470	0.730	0.530	1.400
K_F	0.0	0.040	0.057	0.080	0.080	0.030	0.075	0.030	0.085	0.030
T_F (s)	0.0	1.000	0.500	1.000	1.000	1.000	1.250	1.000	1.260	1.000

Table A.11 Simulations using the New-England test system.

Number of pre-contingency operating states	1
Number of contingencies	76
Type of contingencies	Three-phase short circuit applied at a bus and cleared by tripping a line.
Simulation time	1.5s

A.4 PROPOSED SOUTH-EASTERN EQUIVALENT MEXICAN TEST SYSTEM SIEQ

In this section, the data of a new test power system is presented. It was developed in this thesis from the data of the Mexican Interconnected Power System (MIPS) of 2001 in order to obtain a modified equivalent system of the bulk transmission system, comprising the main transmission elements in the voltage levels of 400kV and 230 kV.

The system has fifty-two buses and twenty-seven machines. The initial conditions of the system are presented in the one-line diagram shown in figure A.7 at the end of this appendix. For the sake of simplicity the geographic on-line diagram of this system is presented in figure A.5.

The transmission network parameters are presented in table A.12. Synchronous generators are represented by the classical model and the dynamic parameters of the machines are presented in table A.13. Figure A.7 presents the SVC connected to node 19, which was simulated using the basic 1 model of the IEEE [Castro, 2007].

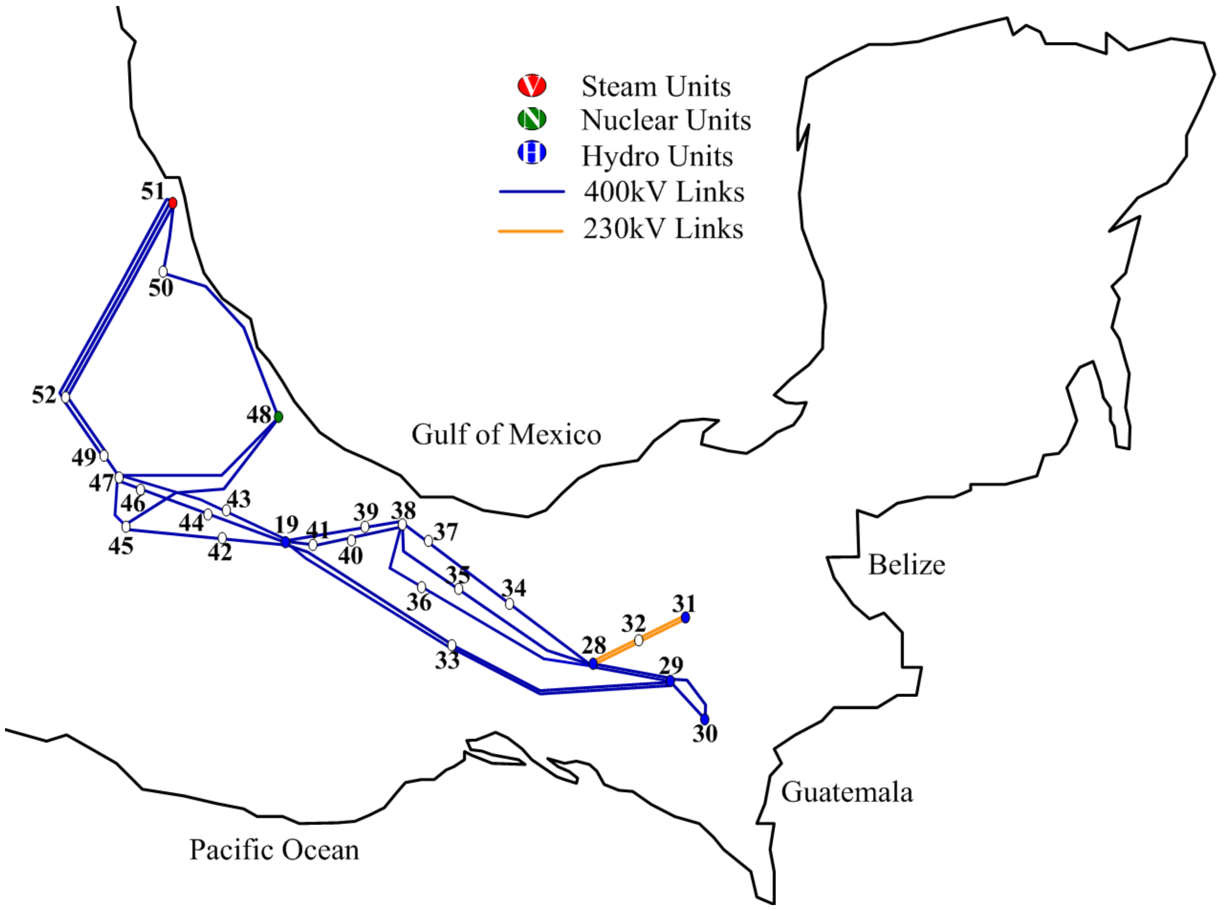

Figure A.5 Geographic diagram of the SIEQ test system.

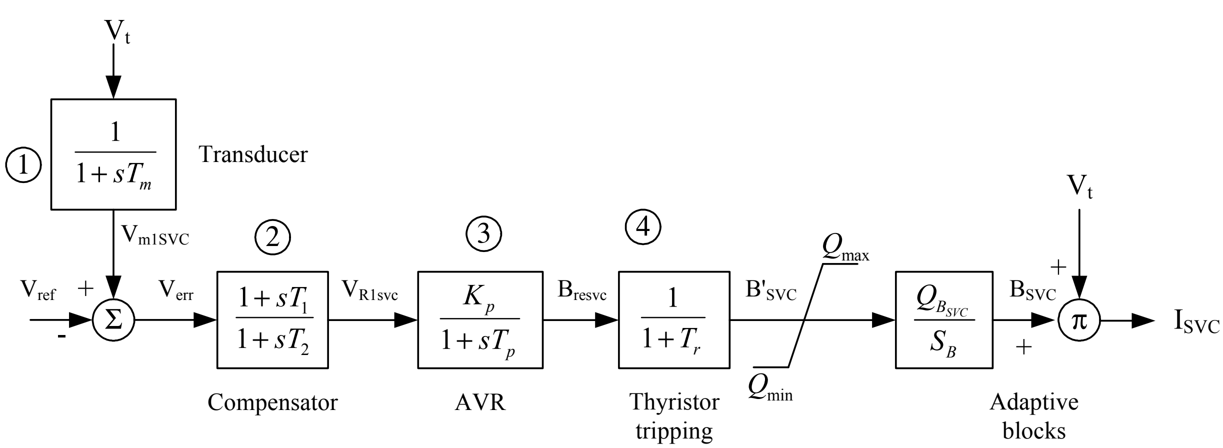

Figure A.6 SVC basic 1 model (Adapted from [Castro, 2007]).

Table A.12 Transmission network data of the SIEQ test system.

Buses		Series impedance		Tap		Circuit number	B/2	Element
i node	j node	R_l	X_l	Magnitude	Angular			
1	28	0.00126	0.0252	1.0	0.0	1	0.0	Transf. 1
2	28	0.00126	0.0252	1.0	0.0	1	0.0	Transf 2
3	28	0.00126	0.0252	1.0	0.0	1	0.0	Transf 3
4	28	0.00126	0.0252	1.0	0.0	1	0.0	Transf 4
5	28	0.00126	0.0252	1.0	0.0	1	0.0	Transf 5
6	29	0.00163	0.0326	1.0	0.0	1	0.0	Transf 6
7	29	0.00163	0.0326	1.0	0.0	1	0.0	Transf 7
8	29	0.00163	0.0326	1.0	0.0	1	0.0	Transf 8
9	29	0.00163	0.0326	1.0	0.0	1	0.0	Transf 9
10	29	0.00163	0.0326	1.0	0.0	1	0.0	Transf 10
11	31	0.00478	0.09565	1.0	0.0	1	0.0	Transf 11
12	31	0.00478	0.09565	1.0	0.0	1	0.0	Transf 12
13	31	0.00478	0.09565	1.0	0.0	1	0.0	Transf 13
14	31	0.00478	0.09565	1.0	0.0	1	0.0	Transf 14
15	30	0.00141	0.0283	1.0	0.0	1	0.0	Transf 15
16	30	0.00141	0.0283	1.0	0.0	1	0.0	Transf 16
17	30	0.00141	0.0283	1.0	0.0	1	0.0	Transf 17
18	30	0.00141	0.0283	1.0	0.0	1	0.0	Transf 18
19	33	0.00296	0.0372	0.0	0.0	1	0.5357	Line 1
19	33	0.00296	0.0372	0.0	0.0	2	0.5357	Line 2
19	39	0.00000	-0.0252	0.0	0.0	1	0.0	Line 3
19	41	0.00000	-0.0251	0.0	0.0	1	0.0	Line 4
19	42	0.00363	0.0448	0.0	0.0	1	0.66146	Line 5
19	43	0.0043	0.05308	0.0	0.0	1	0.78332	Line 6
19	44	0.00191	0.02359	0.0	0.0	1	0.34814	Line 7
20	48	0.00074	0.00943	1.0	0.0	1	0.0	Transf 19
21	48	0.00074	0.00943	1.0	0.0	1	0.0	Transf 20
22	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 21
23	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 22
24	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 23
25	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 24
26	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 25
27	51	0.00144	0.0288	1.0	0.0	1	0.0	Transf 26
28	29	0.00152	0.0192	0.0	0.0	1	0.27851	Line 8
28	29	0.00152	0.0192	0.0	0.0	2	0.27851	Line 9
28	32	0.00016	0.0352	1.0	0.0	1	0.0	Transf 27
28	32	0.00016	0.0352	1.0	0.0	2	0.0	Transf 28
28	34	0.00265	0.0328	0.0	0.0	1	0.48391	Line 10
28	35	0.00277	0.0342	0.0	0.0	1	0.5048	Line 10
28	36	0.00277	0.0342	0.0	0.0	1	0.5048	Line 12
29	30	0.00175	0.02208	0.0	0.0	1	0.32029	Line 13
29	30	0.00175	0.02208	0.0	0.0	2	0.32029	Line 14
29	33	0.00464	0.05832	0.0	0.0	1	0.84598	Line 15
29	33	0.00464	0.05832	0.0	0.0	2	0.84598	Line 16
31	32	0.00518	0.03447	0.0	0.0	1	0.03275	Line 17
31	32	0.00518	0.03447	0.0	0.0	2	0.03275	Line 18
34	37	0.00000	-0.0095	0.0	0.0	1	0.0	Line 19
37	38	0.00013	0.00168	0.0	0.0	1	0.02437	Line 20

Table A.12 (Continuation) Transmission network data of the SIEQ test system.

Buses		Series impedance		Tap		Circuit number	B/2	Element
i node	j node	R_l	X_l	Magnitude	Angular			
38	35	0.00000	-0.0099	0.0	0.0	1	0.0	Line 21
38	36	0.00000	-0.0099	0.0	0.0	1	0.0	Line 22
38	39	0.00434	0.00536	0.0	0.0	1	0.79028	Line 23
38	40	0.00009	0.00117	0.0	0.0	1	0.01740	Line 24
40	41	0.00433	0.05355	0.0	0.0	1	0.79028	Line 25
42	45	0.00000	-0.0237	0.0	0.0	1	0.0	Line 26
43	47	0.00000	-0.0244	0.0	0.0	1	0.0	Line 27
44	46	0.00238	0.0295	0.0	0.0	1	0.43517	Line 28
45	47	0.0007	0.00888	0.0	0.0	1	0.12881	Line 29
45	48	0.00405	0.05088	0.0	0.0	1	0.73806	Line 30
46	47	0.00000	-0.0182	0.0	0.0	1	0.0	Line 31
47	48	0.00431	0.0542	0.0	0.0	1	0.7868	Line 32
47	49	0.00024	0.00235	0.0	0.0	1	0.0452	Line 33
47	49	0.00024	0.00235	0.0	0.0	2	0.0452	Line 34
48	50	0.00292	0.03538	0.0	0.0	1	0.52221	Line 35
49	52	0.00152	0.01887	0.0	0.0	1	0.27851	Line 36
49	52	0.00152	0.01887	0.0	0.0	2	0.27851	Line 37
50	51	0.0013	0.01604	0.0	0.0	1	0.23673	Line 38
51	52	0.0049	0.06062	0.0	0.0	1	0.89471	Line 39
51	52	0.0049	0.06062	0.0	0.0	2	0.89471	Line 40
51	52	0.00309	0.05067	0.0	0.0	3	0.92392	Line 41

Table A.13 Dynamic parameters of the synchronous machines of the SIEQ test system.

Parameter	Machine number									
	1	2	3	4	5	6	7	8	9	10
H(s)	4.05	4.05	4.05	4.05	4.22	4.0	4.0	4.0	3.2	4.0
X'_d(p.u.)	0.28	0.28	0.28	0.28	0.28	0.29	0.29	0.29	0.385	0.29
Parameter	**Machine number**									
	11	12	13	14	15	16	17	18	19	20
H(s)	4.2	4.2	4.2	4.2	4.3	4.3	4.3	4.3	4.3	5.87
X'_d(p.u.)	0.25	0.25	0.25	0.25	0.27	0.27	0.27	0.27	0.27	0.363
Parameter	**Machine number**									
	21	22	23	24	25	26	27			
H(s)	5.87	3.44	3.44	3.1	3.11	3.11	3.11			
X'_d(p.u.)	0.363	0.218	0.218	0.304	0.304	0.304	0.304			

The simulation data of the contingencies is presented in table A.14, while the description of the contingencies is shown in table A.15.

Table A.14 Simulations using the SIEQ test system.

Number of pre-contingency operating states	1
Number of contingencies	69
Type of contingencies	Three-phase short circuit applied at a bus and cleared by tripping a line.
Simulation time	1.5s

Table A.15 Contingencies of the SIEQ test system.

Contingency number	Faulted bus	Line tripped	Number of tripped circuit	Contingency number	Faulted bus	Line tripped	Number of tripped circuit
1	19	19-43	1	36	38	38-39	1
2	19	19-44	1	37	38	38-40	1
3	19	19-42	1	38	39	38-39	1
4	19	19-33	1	39	39	19-39	1
5	19	19-41	1	40	40	38-40	1
6	19	19-39	1	41	40	40-41	1
7	28	28-39	1	42	41	40-41	1
8	28	28-35	1	43	41	19-41	1
9	28	28-36	1	44	42	19-42	1
10	28	28-39	1	45	42	42-45	1
11	28	28-39	1	46	43	19-43	1
12	28	28-32	1	47	43	43-47	1
13	29	29-33	1	48	44	19-44	1
14	29	29-28	1	49	44	44-46	1
15	29	29-28	1	50	45	42-45	1
16	29	29-30	1	51	45	45-48	1
17	30	29-30	1	52	45	45-47	1
18	31	31-32	1	53	46	44-46	1
19	32	31-32	1	54	46	46-47	1
20	32	28-32	1	55	47	45-47	1
21	32	28-32	2	56	47	46-47	1
22	32	28-32	1	57	47	47-48	1
23	33	33-29	1	58	47	47-49	1
24	33	19-33	1	59	48	48-45	1
25	34	28-34	1	60	48	48-47	1
26	34	34-37	1	61	48	48-50	1
27	35	28-35	1	62	49	49-47	1
28	35	35-38	1	63	49	49-52	1
29	36	28-36	1	64	50	48-50	1
30	36	36-38	1	65	50	50-51	1
31	37	34-37	1	66	51	51-50	1
32	37	37-38	1	67	51	51-52	1
33	38	37-38	1	68	52	49-52	1
34	38	38-35	1	69	52	51-52	1
35	38	36-38	1				

It is important to notice that the equivalent SIEQ system provided in this section of Appendix A gives exactly the same initial operating condition that the full Mexican Interconnected Power System (MIPS) case (see Fig. A.7).

Since machine dynamics is only represented by the classical model, the dynamic behavior of the SIEQ system does not represent the actual MIPS dynamic behavior. This is really not a problem since this was done on purpose for confidentiality reasons. This system is only intended to test the performance of E-SIME in more realistic power system in terms of size and topology.

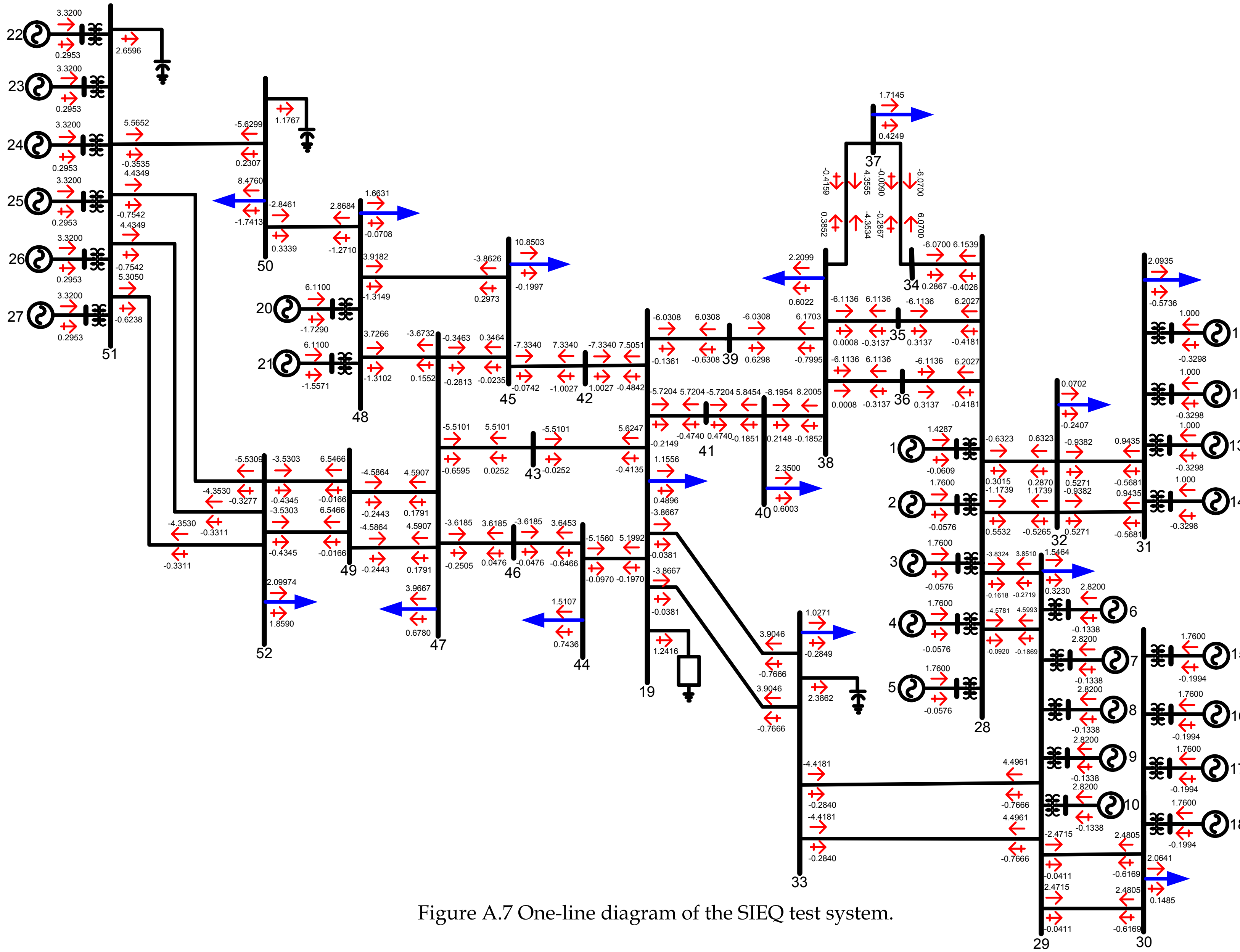

Figure A.7 One-line diagram of the SIEQ test system.

APPENDIX B:

GENERATION TRIPPING VALIDATION

In §3.3.3 it was mentioned that when the machine is tripped, the structure of the OMIB and the center of angle (COA) reference change; this is observed as a jump in individual machines (see figure 3.5). In order to demonstrate that the jump in state variables is mainly due to the angle reference, this appendix presents in figures B.1 and B.2 the results of the same "example case" of chapter 3, using a selected individual machine as the angle reference.

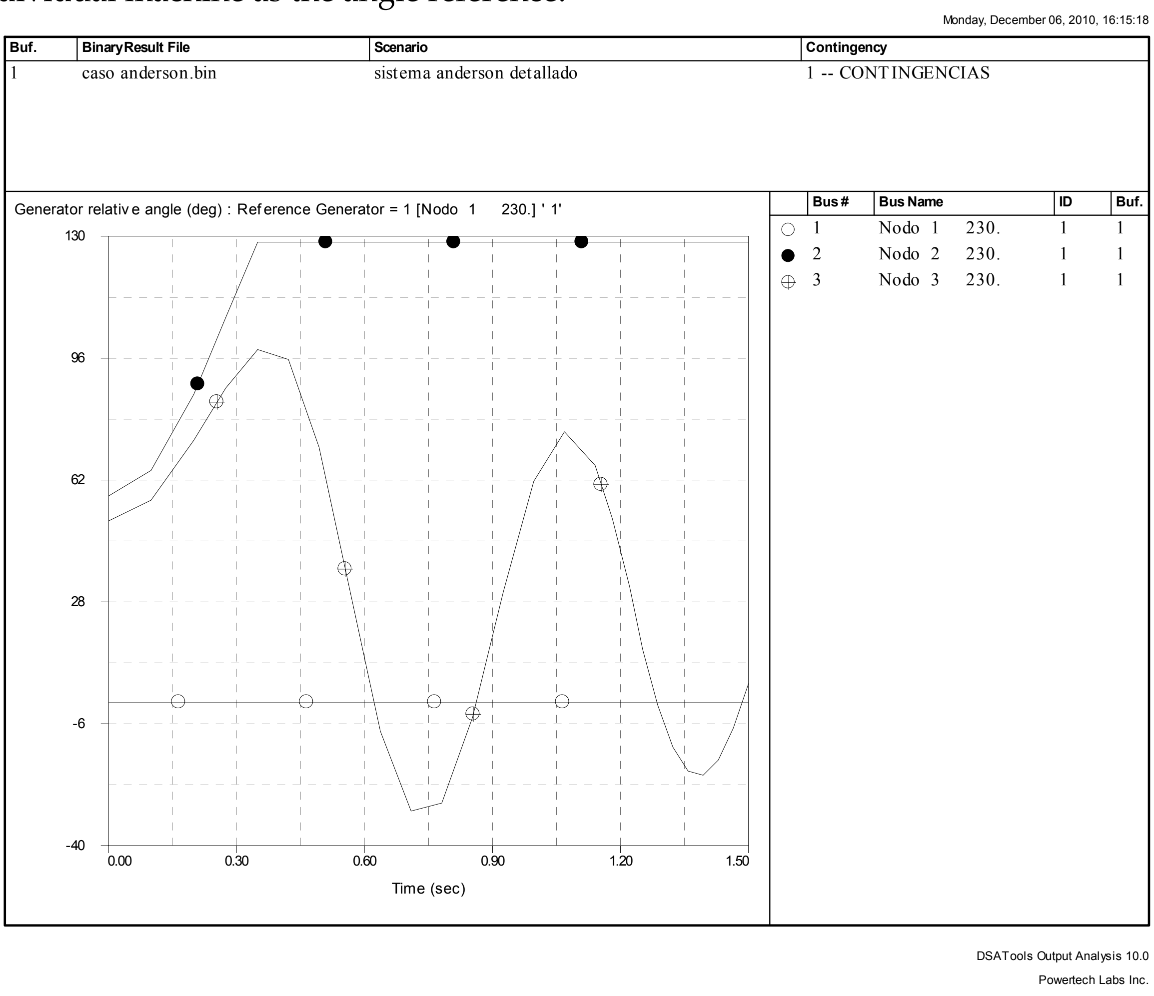

Figure B.1 Individual machines swing curves for the example case using DSATools.

Figure B.1 presents the individual machines swing curves of the "example case" presented in chapter 3 for the three-machine test system. The curves were obtained using DSATools© 10.0. Machine number one is used as reference and machine number 2 was tripped at t = 360 ms. It can be observed that when tripping machine 2 its angle remains constant, and that this simulation validates the generation tripping algorithm implemented in this work for the E-SIME method in the TRANSTAB program.

Figure B.2 shows the individual machines swing curves of the "example case" presented in chapter 3 using both TRANSTAB (in solid line) and DSATools © 10.0 (in dashed line) simulation programs. It can be observed that they are very close to each other; this provides additional means of validation for the tripping algorithm and for the simulation tool.

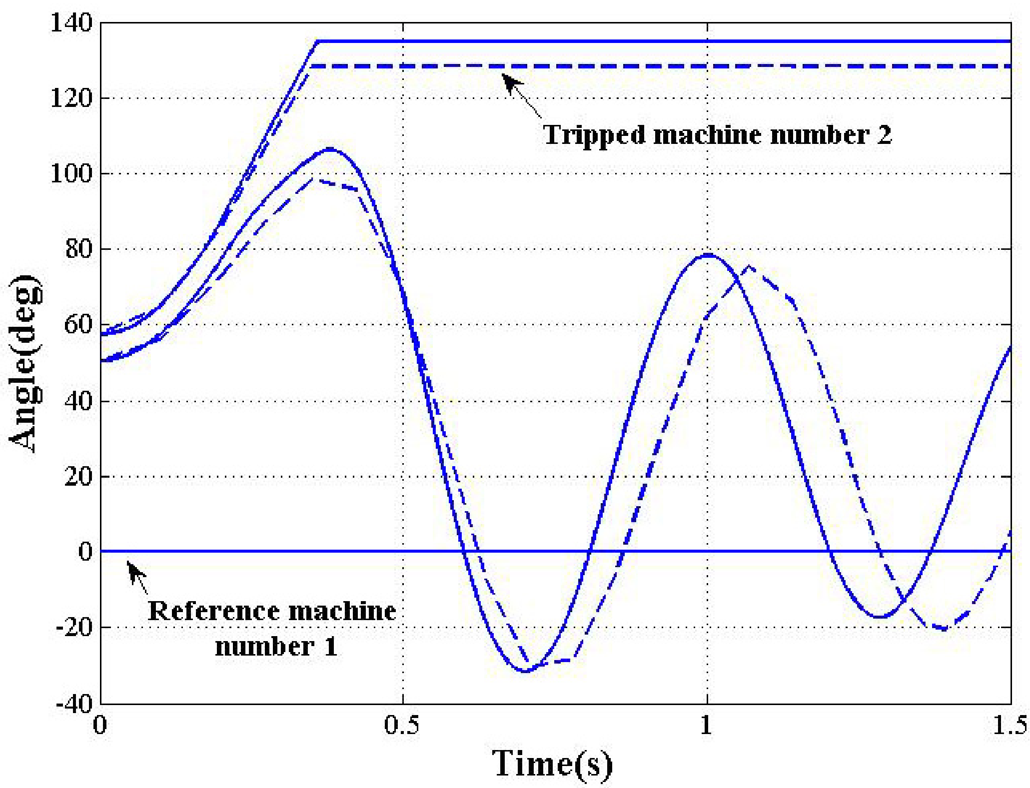

Figure B.2 Individual machines swing curves for the example case.
___ TRANSTAB program (solid line).
--- DSATools program (dotted line).

In figure B.2 it can be observed, that both programs give the same trend for system dynamic behavior. The small differences found in figure B.2 between DSATools© and TRANSTAB results are due to various reasons: differences in the implementation of the trapezoidal rule of integration, in the implementation of the implicit-simultaneous method to solve the system model, in the way excitation control systems are represented and the possibility that DSATools© only stores some values of the system response. This latter characteristic explains the straight line behavior of DSATools© curve near the first maximum angular deviation of machine 3 in Fig. B.2.

One specific simulation condition in DSATools© version 10 is that it only accepts times specified in cycles. This could be another source of the small difference between the results of simulation programs. As it can be seen in Fig. B.2, machine number two is not tripped at exactly the same time in both programs. However, the main point in this section was met: it has been demonstrated that the jumps in system angles and powers after tripping one or more machines are mainly caused by the system angle reference.

APPENDIX C

E-SIME COMPUTER PROGRAM

The computer algorithms to apply the E-SIME method are presented in this appendix. The main module of E-SIME method is presented first, and then the secondary subroutines are numbered.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C       TRANSIENT STABILITY ASSESSMENT USING
C       E-SIME METHOD.
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
      IF(NCONTIN.EQ.1.AND.NSMAX.EQ.1.AND.NTIMET.EQ.1)THEN
        IF(T.GT.(TSAMPLE-DT/2.).AND.T.LT.(TSAMPLE+DT/2.))THEN
          TITAY=T
          TTAY=T
          TIESIME=TL
          TFESIME=TE
          TESIME=T
          NIMAQ=NI
          NMAQS=NG
          REFANG=REFER
          REFVEL=REFERW
          SB=SBASE
C
          DO I=1,NMAQS
C
          NAME(I)=NOMBRE(I)
          HMAQ(IMED,I)=H(I)
          SDMAQ(IMED,I)=SDGEN(I)
          SWMAQ(IMED,I)=SWGEN(I)
          PEMAQ(IMED,I)=PEGEN(I)*SB
          PMMAQ(IMED,I)=PMGEN(I)*SB
          MI(IMED,I)=(2*HMAQ(IMED,I)*SB)/WOT
          MINV(IMED,I)=1/MI(IMED,I)
C
          DELTAY(I)=SDMAQ(IMED,I)
          VELTAY(I)=SWMAQ(IMED,I)
          PETAY(I)=PEMAQ(IMED,I)
          PMTAY(I)=PMMAQ(IMED,I)
C
          END DO
C
          IF(IMED.LE.3)THEN
            CALL TAYLORP(IMED,NTVISIT)
          END IF
C
          INIMED=1
C
          DO I=INIMED,IMED
            ANGOMIB(I)=0.0
            VELOMIB(I)=0.0
            PEOMIB(I)=0.0
            PMOMIB(I)=0.0
          END DO
C
          TOMIB(INIMED)=TIESIME
          DO I=INIMED,IMED
            CALL FOMIB(I,IORDER,IGAP,ANGOMIB(I),VELOMIB(I),
   *             PEOMIB(I),PMOMIB(I),PAOMIB(I),MOMIB(I),
   *             PEMC(I),MMC(I))
            TOMIB(I+1)=TOMIB(I)+DTSAMPLE
          END DO
C
          CALL ESCSALOMIB(INIMED,IMED)
C
          IF(IMED.GE.2)THEN
            IF(ANGOMIB(IMED).LT.ANGOMIB(IMED-1))THEN
              WRITE(60,33)'Tactual=',T,
   *           'El sistema alcanzo el angulo de retorno'
              WRITE(101,33)'Tactual=',T,
   *           'El sistema alcanzo el angulo de retorno'
   33         FORMAT(A8,F8.5,4X,A39)
              BANESTOMIB=1
            END IF
          END IF
C
          IF(IMED.GE.3.AND.BANESTOMIB.EQ.0)THEN
            CALL
MINCUAD(T,INIMED,INDI,IMED,ANGOMIB,PAOMIB,VELOMIB,
     *                 MOMIB,APD,BPD,CPD,DELU,MARGENEST)
            INDI=INDI+1
C
            IF(MARGENEST.GT.0.0)THEN
              WRITE(60,33)'Tactual=',T,
   *                        'El sistema es estable por margen'
              WRITE(101,33)'Tactual=',T,
   *                         'El sistema es estable por margen'
 34           FORMAT(A8,F8.5,4X,A32)
              BANESTMAR=1
            END IF
C
            IF(BANESTMAR.EQ.0)THEN
              CALL
TINEST(T,IMED,ANGOMIB,VELOMIB,MOMIB,APD,BPD,CPD,
   *                    DELU,TINST)
            END IF
C
```

```
            CONVEST=ABS(ABS(MARGENEST)-ABS(MARGENOLD))
            IF(CONVEST.GE.0.1)THEN
              BANCONTROL=0
            ELSE IF(BANNEWACTION.EQ.1)THEN
              BANCONTROL=1
              TF=T+DISPDELAY
              TDISP=TF
              WRITE(*,100)'T=',T,
   *          'Se prepara el esquema de emergencia'
100           FORMAT(/,5X,A2,F10.5,/,5X,A35,/)
C
              IF(T.GT.(TDISP-
DT/2.).AND.T.LT.(TDISP+DT/2.))THEN
                BANNEWACTION=1
              ELSE
                BANNEWACTION=0
              END IF
C
            ELSE IF(BANNEWACTION.EQ.0)THEN
              BANCONTROL=0
            END IF
C
            IF(IMED.EQ.3)THEN
              OPEN(101,FILE="INDICES.SAL")
              WRITE(101,31)'MED','DELTAU','MARGEN',
   *               'TACTUAL','TINEST','CTRL'
              FORMAT(2X,A3,7X,A6,8X,A6,6X,A7,5X,A6,5X,A4)
            END IF
C
WRITE(101,32)IMED,DELU*180/PIT,MARGENEST,T,TINST,
   *                   BANCONTROL
 32 FORMAT(1X,I4,4X,F10.5,4X,F10.5,4X,F8.6,4X,F8.6,5X,I1)
C
            IF(BANCONTROL.EQ.1)THEN
              DO 60 WHILE(MARGENESTCT.LE.0.0.AND.
   *                     NMAQTRIP.LT.IGAP(1))
                BANIMP=1
C
                DO K=NMAQTRIP+1,NMAQS
                  IORDERNEW(K-NMAQTRIP)=IORDER(K)
                END DO
                IGAPNEW(1)=IGAP(1)-NMAQTRIP
C
                TOMIB(INIMED)=T
                DO I=INIMED,IMED
                  CALL FOMIB(I,IORDERNEW,IGAPNEW,ANGOMIB(I),
   *              VELOMIB(I),PEOMIB(I),PMOMIB(I),PAOMIB(I),
   *                 MOMIB(I),PEMC(I),MMC(I))
                  TOMIB(I+1)=TOMIB(I)+DTSAMPLE
               END DO
C
                CALL
MINCUAD(T,INIMED,INDI,IMED,ANGOMIB,PAOMIB,
   *                     VELOMIB,MOMIB,APD,BPD,CPD,DELU1,
   *                     MARGENEST1)
C
                CALL
DELTACT(IMED,ANGOMIB,VELOMIB,MOMIB,APD,BPD,
   *                       CPD,DELCT,VELCT)

C
                DO I=INIMED,IMED
                  ANGOMIB(I)=ANGOMIB(I)
                  PAOMIB(I)=PAOMIB(I)-MOMIB(I)
                END DO
                BANIMP=2
                CALL
MINCUAD(T,INIMED,INDI,IMED,ANGOMIB,PAOMIB,VELCT,
   *
MOMIB,APD,BPD,CPD,DELUCT,MARGENESTCT)
C
                NMAQTRIP=NMAQTRIP+1
 60           END DO
C
              NGRSAL=NMAQTRIP
              DO I=1,NGRSAL
                GENISAL(I)=IORDER(I)
              END DO
              BANIMP=0
C
            END IF
C
          END IF
C
          TSAMPLE=TSAMPLE+DTSAMPLE
          NTVISIT=1
          TESIME=TESIME+DTSAMPLE
          IMED=IMED+1
          BANESTMAR=0
          MARGENOLD=MARGENEST
          NMAQTRIP=0
          BANIMP=0
        END IF
```

```
      END IF
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

C       Finish the E-SIME cycle.
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

1) Subroutine TAYLOR: this subroutine expands the individual machine angles using Taylor Series.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C Subroutine TAYLORP.
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C-------------------------------------------------------------
C
      SUBROUTINE TAYLORP(NMED,NTVISIT)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMTAY.FOR'
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER   I,K,J,NTVISIT,NMED
C
C-------------------------------------------------------------
C
      TFTAY=TITAY+0.1
      DTTAY=0.005
C
      DO 10 WHILE(TTAY.LE.TFTAY)
        DO I=NIMAQ,NMAQS

          SDT(I)=VELTAY(I)*DTTAY
          SDTAY1(I)=DELTAY(I)+SDT(I)
          SDTAY2(I)=(((MINV(NMED,I)*PMTAY(I))-
     *   (MINV(NMED,I)*PETAY(I)))*((DTTAY**2)/2.))
          SDTAY(I)=SDTAY1(I)+SDTAY2(I)
C
          SWT(I)=(((MINV(NMED,I)*PMTAY(I))-
     *    (MINV(NMED,I)*PETAY(I)))*(DTTAY))
          SWTAY(I)=VELTAY(I)+SWT(I)
        END DO
C
        CALL ESCSALTAY(NTVISIT,NMED)
C
        TTAY=TTAY+DTTAY
C
        DO I=NIMAQ,NMAQS
          DELTAY(I)=SDTAY(I)
          VELTAY(I)=SWTAY(I)
        END DO
   10   END DO
C
      CALL ORDENA(SDTAY,NMAQS,IORDER)
C
      DO I=1,NMAQS-1
        GAP(I)=SDTAY(IORDER(I))-SDTAY(IORDER(I+1))
      END DO
C
      CALL ORDENA(GAP,NMAQS-1,IGAP)
C
      OPEN(37,FILE="ANGTAYORD.M")
      WRITE(37,*)'T= ',TITAY
      DO I=1,NMAQS
        WRITE(37,11)SDTAY(IORDER(I)),NAME(IORDER(I)),
     *             GAP(I),IGAP(I)
   11   FORMAT(1X,F10.5,3X,A8,1X,F10.5,1X,I5)
      END DO
      WRITE(37,*)
C
      RETURN
      END
```

2) Subroutine ESCSALTAY: this subroutine writes the Taylor Series expansion results.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C Subroutine ESCSALTAY.
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C------------------------------------------------------------
C
      SUBROUTINE ESCSALTAY(NTVISIT,NMED)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMTAY.FOR'
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER K,NTVISIT,NK,NMED,I,J
C
C -----------------------------------------------------------
C
      IF(NTVISIT.EQ.0)THEN
        OPEN(89,FILE="ANGTAYLOR.M")
        OPEN(88,FILE="VELTAYLOR.M")
        NK=1
      END IF
C
      IF(TTAY.GT.(TITAY-
DTTAY/2.).AND.TTAY.LT.(TITAY+DTTAY/2.))THEN
        WRITE(89,*)'% T = ',TITAY
        WRITE(88,*)'% T = ',TITAY
C
        IF(NK.LT.10)THEN
          WRITE(89,10)NK
   10     FORMAT('ang',I1,'=[')
          WRITE(88,11)NK
   11     FORMAT('vel',I1,'=[')
C
        ELSE IF(NK.LT.100)THEN
          WRITE(89,13)NK
   13     FORMAT('ang',I2,'=[')
          WRITE(88,14)NK
   14     FORMAT('vel',I2,'=[')
C
        ELSE IF(NK.LT.1000)THEN
            WRITE(89,17)NK
   17     FORMAT('ang',I3,'=[')
          WRITE(88,18)NK
   18     FORMAT('vel',I3,'=[')
        END IF
      END IF
C

WRITE(89,16)TTAY,REFANG*180/PIT,(SDTAY(K)*180/PIT,K=1,NMAQS)
      WRITE(88,16)TTAY,REFVEL,(SWTAY(K),K=1,NMAQS)
C
      IF(TTAY.GT.(TFTAY-
DTTAY/2.).AND.TTAY.LT.(TFTAY+DTTAY/2.))THEN
        WRITE(89,"('];')")
        WRITE(88,"('];')")
        NK=NK+1
      END IF
C
   15 FORMAT(1X,51(1X,F10.5))
   16 FORMAT(1X,51(1X,F10.5))
C
      RETURN
      END
```

3) Subroutine FOMIB: this subroutine computes the OMIB parameters.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C
C Subroutine FOMIB
C
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C-------------------------------------------------------------
C
      SUBROUTINE
FOMIB(NMED,MAQ,CMS,ANGOM,VELOM,PEOM,PMOM,PAOM,MEQ,
     *                 PEMAQC,MC)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER  I,J,K,ULMC,PMNC,CMS(NMAQS),MAQ(NMAQS),NMED
      REAL*8
ANGOM,VELOM,PEOM,PMOM,PAOM,MEQ,NMAQUI,PEMAQC,MC
C
C
C-------------------------------------------------------------
C
      MC=0.0
      MNC=0.0
      PRODANGC=0.0
      PRODVELC=0.0
      PRODANGNC=0.0
      PRODVELNC=0.0
      PMMAQC=0.0
      PEMAQC=0.0
      PMMAQNC=0.0
      PEMAQNC=0.0
```

```
      NMAQUI=NMAQS-NMAQTRIP
C
      ULMC=CMS(1)
      PMNC=CMS(1)+1
C
      DO K=1,ULMC
        MC=MC+MI(NMED,MAQ(K))
       PRODANGC=PRODANGC+(MI(NMED,MAQ(K))*SDMAQ(NMED,MAQ(K)))
       PRODVELC=PRODVELC+(MI(NMED,MAQ(K))*SWMAQ(NMED,MAQ(K)))
       PMMAQC=PMMAQC+PMMAQ(NMED,MAQ(K))
       PEMAQC=PEMAQC+PEMAQ(NMED,MAQ(K))
      END DO
C
      ANGMAQC=(1/MC)*PRODANGC
      VELMAQC=(1/MC)*PRODVELC
C
      DO J=PMNC,NMAQUI
        MNC=MNC+MI(NMED,MAQ(J))
     PRODANGNC=PRODANGNC+(MI(NMED,MAQ(J))*SDMAQ(NMED,MAQ(J)))
     PRODVELNC=PRODVELNC+(MI(NMED,MAQ(J))*SWMAQ(NMED,MAQ(J)))
      PMMAQNC=PMMAQNC+PMMAQ(NMED,MAQ(J))
      PEMAQNC=PEMAQNC+PEMAQ(NMED,MAQ(J))
    END DO
C
      ANGMAQNC=(1/MNC)*PRODANGNC
      VELMAQNC=(1/MNC)*PRODVELNC
C
      MEQ=(MC*MNC)/(MC+MNC)
      ANGOM=ANGMAQC-ANGMAQNC
      VELOM=VELMAQC-VELMAQNC
      PMOM=((1/MC)*PMMAQC)-((1/MNC)*PMMAQNC)
      PEOM=((1/MC)*PEMAQC)-((1/MNC)*PEMAQNC)
      PAOM=PMOM-PEOM
C
      RETURN
      END
```

4) Subroutine ESCSALOMIB: this subroutine writes the OMIB parameters.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C Subroutine ESCSALOMIB
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C------------------------------------------------------------
C
      SUBROUTINE ESCSALOMIB(INI,NMED)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMTAY.FOR'
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER I,INI,NMED
C
C ----------------------------------------------------------
C
      IF(BANIMP.EQ.1)THEN
        OPEN(41,FILE="PARAOMIB1.M")
C
        IF(NMED.LT.10)THEN
        WRITE(41,12)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *             'PMOMIB','PAOMIB','OMIB',NMED,'=['
        END IF
C
        IF(NMED.GE.10.AND.NMED.LT.100)THEN
        WRITE(41,14)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *             'PMOMIB','PAOMIB','OMIB',NMED,'=['
        END IF
C
        IF(NMED.GE.100.AND.NMED.LT.1000)THEN
        WRITE(41,15)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *             'PMOMIB','PAOMIB','OMIB',NMED,'=['
        END IF
C
        DO I=1,NMED

WRITE(41,13)TOMIB(I),ANGOMIB(I)*180/PIT,VELOMIB(I),PEOMIB(I),
     *             PMOMIB(I),PAOMIB(I)
        END DO
C
        WRITE(41,*)'];'
      ELSE IF(BANIMP.EQ.0)THEN
C
        OPEN(40,FILE="PARAOMIB.M")
C
        IF(NMED.LT.10)THEN

WRITE(40,12)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *              'PMOMIB','PAOMIB','OMIB',NMED,'=['
   12
FORMAT(A1,2X,A7,4X,A7,5X,A7,4X,A6,5X,A6,5X,A6,/,A4,I1,A2)
        END IF
C
        IF(NMED.GE.10.AND.NMED.LT.100)THEN

WRITE(40,14)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *              'PMOMIB','PAOMIB','OMIB',NMED,'=['
   14
FORMAT(A1,2X,A7,4X,A7,5X,A7,4X,A6,5X,A6,5X,A6,/,A4,I2,A2)
        END IF
C
        IF(NMED.GE.100.AND.NMED.LT.1000)THEN

WRITE(40,15)'%','TIEMPO','DELOMIB','VELOMIB','PEOMIB',
     *              'PMOMIB','PAOMIB','OMIB',NMED,'=['
   15
FORMAT(A1,2X,A7,4X,A7,5X,A7,4X,A6,5X,A6,5X,A6,/,A4,I3,A2)
        END IF
C
        DO I=1,NMED

WRITE(40,13)TOMIB(I),ANGOMIB(I)*180/PIT,VELOMIB(I),PEOMIB(I),
     *             PMOMIB(I),PAOMIB(I)
   13
FORMAT(F10.5,1X,F10.5,1X,F10.5,1X,F10.5,1X,F10.5,1X,
     *          F10.5,1X,I4)
        END DO
C
        WRITE(40,*)'];'
C
        END IF
      RETURN
      END
```

5) Subroutine MINCUAD: this subroutine computes the *a*, *b* and *c* coefficients of the p - δ curve.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C
C Subroutine MINCUAD
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C------------------------------------------------------------
-
C
      SUBROUTINE
MINCUAD(TI,INIC,INI,NMED,X,Y,VEL,MOM,A,B,C,DELTAU,NEST)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER  I,J,K,INI,NMED,NUM,INIC
      REAL*8
X(10000),Y(400),VEL(400),MOM(400),AMC(400,400),
     *         BMC(400),A,B,C,Z(2),DISC,DELTAU,PAE(10000),
     *         DANGLE,NEST,TI
      COMPLEX*16 ZC(2)
C
      OPEN(60,FILE="MATRIZ.SAL")
      OPEN(90,FILE="POTAC.M")
      OPEN(61,FILE="MATRIZ1.SAL")
      OPEN(91,FILE="POTAC1.M")
      OPEN(62,FILE="MATRIZ2.SAL")
      OPEN(92,FILE="POTAC2.M")
C
      NUM=20
      DO I=1,3
        DO J=1,3
          AMC(I,J)=0.0
        END DO
      END DO
C
      DO I=1,3
        BMC(I)=0.0
      END DO
C
      Z(1)=0.0
      Z(2)=0.0
      ZC(1)=(0.0,0.0)
      ZC(2)=(0.0,0.0)
      DELTAU=0.0
C
      DO I=1,NMED+20
        PAE(I)=0.0
      END DO
C
      DO I=INI,NMED
        AMC(1,1)=AMC(1,1)+1
      END DO
C
```

```
      DO I=INI,NMED
        AMC(1,2)=AMC(1,2)+X(I)
      END DO
      AMC(2,1)=AMC(1,2)
C
      DO I=INI,NMED
        AMC(2,2)=AMC(2,2)+(X(I)**2.)
      END DO
      AMC(1,3)=AMC(2,2)
      AMC(3,1)=AMC(2,2)
C
      DO I=INI,NMED
        AMC(2,3)=AMC(2,3)+(X(I)**3.)
      END DO
      AMC(3,2)=AMC(2,3)
C
      DO I=INI,NMED
        AMC(3,3)=AMC(3,3)+(X(I)**4.)
      END DO
C
      DO I=INI,NMED
        BMC(1)=BMC(1)+Y(I)
      END DO
C
      DO I=INI,NMED
        BMC(2)=BMC(2)+(Y(I)*X(I))
      END DO
C
      DO I=INI,NMED
        BMC(3)=BMC(3)+(Y(I)*(X(I)**2.))
      END DO
C
      IF(BANIMP.EQ.1.)THEN
        WRITE(61,10)'-----------------------------------------
---------'
        WRITE(61,12)'MATRIZ A',NMED,'TIEMPO= ',TI
        DO I=1,3
          WRITE(61,13)(AMC(I,J),J=1,3)
        END DO
C
        WRITE(61,11)'MATRIZ B'
        DO I=1,3
          WRITE(61,14)BMC(I)
        END DO
C
      ELSE IF(BANIMP.EQ.0)THEN
C
        WRITE(60,10)'-----------------------------------------
---------'
   10   FORMAT(A50)
        WRITE(60,12)'MATRIZ A',NMED,'TIEMPO= ',TI
   12   FORMAT(/,A9,I3,2X,A8,F10.5)
        DO I=1,3
          WRITE(60,13)(AMC(I,J),J=1,3)
   13     FORMAT(50(1X,F15.6))
        END DO
C
        WRITE(60,11)'MATRIZ B'
   11   FORMAT(/,A8)
        DO I=1,3
          WRITE(60,14)BMC(I)
   14     FORMAT(F15.6)
        END DO
C
      ELSE IF(BANIMP.EQ.2)THEN
        WRITE(62,10)'-----------------------------------------
---------'
        WRITE(62,12)'MATRIZ A',NMED,'TIEMPO= ',TI
        DO I=1,3
          WRITE(62,13)(AMC(I,J),J=1,3)
        END DO
C
        WRITE(62,11)'MATRIZ B'
        DO I=1,3
          WRITE(62,14)BMC(I)
        END DO
C
      END IF
C
      CALL FTRI(3,AMC,BMC)
C
      A=BMC(3)
      B=BMC(2)
      C=BMC(1)
C
      IF(BANIMP.EQ.1.)THEN
        WRITE(61,9)'COEFICIENTES'
        DO I=3,1,-1
          WRITE(61,14)BMC(I)
        END DO
C
      ELSE IF(BANIMP.EQ.0)THEN
C
        WRITE(60,9)'COEFICIENTES'
    9   FORMAT(/,A12)
        DO I=3,1,-1
          WRITE(60,14)BMC(I)
        END DO
C
      ELSE IF(BANIMP.EQ.2)THEN
        WRITE(62,9)'COEFICIENTES'
        DO I=3,1,-1
          WRITE(61,14)BMC(I)
        END DO
C
      END IF
C
      DISC=(B**2)-(4*A*C)
C
      IF(A.NE.0.0)THEN
        IF(DISC.LT.0.0)THEN
          ZC(1)=DCMPLX(-B/(2*A),DSQRT(-DISC)/(2*A))
          ZC(2)=DCMPLX(-B/(2*A),-DSQRT(-DISC)/(2*A))
        ELSE
          Z(1)=(-B+DSQRT(DISC))/(2*A)
          Z(2)=(-B-DSQRT(DISC))/(2*A)
        END IF
C
        IF(Z(1).LE.X(NMED))THEN
          IF(Z(2).GT.X(NMED))THEN
            DELTAU=Z(2)
          END IF
        ELSE
          IF(Z(2).LE.X(NMED))THEN
            DELTAU=Z(1)
          ELSE
            IF((Z(1)-X(NMED)).LT.(Z(2)-X(NMED)))THEN
              DELTAU=Z(1)
            ELSE
              DELTAU=Z(2)
            END IF
          END IF
        END IF
C
        IF(BANIMP.EQ.1.)THEN
          IF(DISC.LT.0.0)THEN
            WRITE(61,15)'X1=',ZC(1),'X2=',ZC(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
          ELSE
            WRITE(61,16)'X1=',Z(1),'X2=',Z(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
          END IF
C
        ELSE IF(BANIMP.EQ.0)THEN
C
          IF(DISC.LT.0.0)THEN
            WRITE(60,15)'X1=',ZC(1),'X2=',ZC(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
   15             FORMAT(/,A3,F10.5,'  j',F10.5,/,A3,F10.5,'
j',F10.5,/,A7,
     *            F10.5,/,A7,F10.5)
          ELSE
            WRITE(60,16)'X1=',Z(1),'X2=',Z(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
   16
FORMAT(/,A3,F10.5,/,A3,F10.5,//,A7,F10.5,/A7,F10.5)
C
          END IF
C
        ELSE IF(BANIMP.EQ.0)THEN
C
          IF(DISC.LT.0.0)THEN
            WRITE(62,15)'X1=',ZC(1),'X2=',ZC(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
          ELSE
            WRITE(62,16)'X1=',Z(1),'X2=',Z(2),'DELTAI=',
     *
X(NMED)*180/PIT,'DELTAU=',DELTAU*180/PIT
          END IF
        END IF
C
        DO I=1,NMED
          PAE(I)=Y(I)
        END DO
C
        IF((DISC.GE.0.).AND.(DELTAU.NE.0.0))THEN

          DANGLE=(DELTAU-X(NMED))/NUM
C
          DO I=NMED+1,NMED+NUM
            X(I)=X(I-1)+DANGLE
            PAE(I)=(A*X(I)**2.)+(B*X(I))+C
          END DO
C
          IF(BANIMP.EQ.1.)THEN
```

```
            IF(NMED.LT.10)THEN
              WRITE(91,17)'POT',NMED,'=['
            END IF
C
              IF (NMED.GE.10.AND.NMED.LT.100)THEN
              WRITE(91,18)'POT',NMED,'=['
            END IF
C
              IF (NMED.GE.100.AND.NMED.LT.1000)THEN
              WRITE(91,23)'POT',NMED,'=['
            END IF
C
            DO J=INIC,NMED+NUM
              WRITE(91,19)X(J)*180/PIT,PAE(J)
            END DO
C
            WRITE(91,20)'];','% '
C
          ELSE IF(BANIMP.EQ.0)THEN
C
            IF(NMED.LT.10)THEN
              WRITE(90,17)'POT',NMED,'=['
   17         FORMAT(A3,I1,A2)
            END IF
C
            IF (NMED.GE.10.AND.NMED.LT.100)THEN
              WRITE(90,18)'POT',NMED,'=['
   18         FORMAT(A3,I2,A2)
            END IF
C
              IF (NMED.GE.100.AND.NMED.LT.1000)THEN
              WRITE(90,23)'POT',NMED,'=['
   23         FORMAT(A3,I3,A2)
            END IF
C
            DO J=INIC,NMED+NUM
              WRITE(90,19)X(J)*180/PIT,PAE(J)
   19         FORMAT(1X,F10.5,1X,F10.5,1X,F10.5)
            END DO
C
            WRITE(90,20)'];','% '
   20       FORMAT(A2,/,A1)
C
          ELSE IF(BANIMP.EQ.2)THEN
            IF(NMED.LT.10)THEN
              WRITE(92,17)'POT',NMED,'=['
            END IF
C
              IF (NMED.GE.10.AND.NMED.LT.100)THEN
              WRITE(92,18)'POT',NMED,'=['
            END IF
C
              IF (NMED.GE.100.AND.NMED.LT.1000)THEN
              WRITE(92,23)'POT',NMED,'=['
            END IF
C
            DO J=INIC,NMED+NUM
              WRITE(92,19)X(J)*180/PIT,PAE(J)
            END DO
C
            WRITE(92,20)'];','% '
C
          END IF
        END IF
C
        IF(BANIMP.EQ.0)THEN

NEST=((A*(X(3)**3.))/3.)+((B*(X(3)**2.))/2.)+(C*X(3))
     *            -((A*(DELTAU**3.))/3.)-((B*(DELTAU**2.))/2.)-
(C*DELTAU)
     *        -((MOM(3)*(VEL(3)**2.))/2.)

c
NEST=((A*(X(NMED)**3.))/3.)+((B*(X(NMED)**2.))/2.)+(C*X(NMED))
c      *            -((A*(DELTAU**3.))/3.)-((B*(DELTAU**2.))/2.)-
(C*DELTAU)
c     *         -((MOM(NMED)*(VEL(NMED)**2.))/2.)
C
          NEST=NEST/MOM(3)
c         NEST=NEST/MOM(NMED)
C
        ELSE IF(BANIMP.EQ.2)THEN

NEST=((A*(DELCT**3.))/3.)+((B*(DELCT**2.))/2.)+(C*DELCT)
     *            -((A*(DELTAU**3.))/3.)-((B*(DELTAU**2.))/2.)-
(C*DELTAU)
     *        -((MOM(3)*(VEL(3)**2.))/2.)
          NEST=NEST/MOM(NMED)
        END IF

C
        IF(BANIMP.EQ.1.)THEN
          WRITE(61,25)'MARGEN PENDIENTE'
   25     FORMAT(A16)
C
          ELSE IF(BANIMP.EQ.0)THEN
            WRITE(60,22)'MARGEN= ',NEST
   22       FORMAT(/,A8,F20.10)
C
          ELSE IF(BANIMP.EQ.2)THEN
            WRITE(62,22)'MARGEN= ',NEST
          END IF
C
        ELSE
          WRITE(90,21)'Division por cero'
   21     FORMAT(A17)
          END IF
C
      RETURN
      END
```

6) Subroutine TINEST: this subroutine computes the time to instability of the system.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C
C Subroutine TINEST
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
C------------------------------------------------------------
-
C
      SUBROUTINE
TINEST(TI,NMED,ANG,VEL,MOM,A,B,C,DELTAU,TINES)
C
      IMPLICIT NONE
C
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER  I,NMED,NUM,BANRAIZ
      REAL*8
TI,ANG(10000),VEL(400),MOM(400),A,B,C,DELTAU,INT,DELTAI,
     *         DELTA,DANGLE,TINES,RAIZ
C
      TINES=0.0
      INT=0.0
      NUM=20
      BANRAIZ=0
C
      DELTAI=ANG(NMED)
      DELTA=ANG(NMED)
      DANGLE=(DELTAU-DELTAI)/NUM
C
      DO I=1,NUM
        DELTA=DELTA+DANGLE
        RAIZ=((2./MOM(NMED))*(((A*DELTAI**3.)/3.)+
     *                    ((B*DELTAI**2.)/2.)+(C*DELTAI)-
((A*DELTA**3.)/3.)-
     *       ((B*DELTA**2.)/2.)-(C*DELTA)))+(VEL(NMED)**2.)
        IF(RAIZ.LE.0.0)THEN
          BANRAIZ=1
        ELSE
         INT=INT+(DANGLE/(SQRT(RAIZ)))
        END IF
        DELTAI=DELTAI+DANGLE
      END DO
C
      TINES=TI+INT
C
      IF(BANRAIZ.EQ.0)THEN
        WRITE(60,10)'TINESTABLE= ',TINES
   10   FORMAT(A12,F10.5)
C
      ELSE
        WRITE(60,11)'TINESTABLE= ','RAIZ NEGATIVA'
   11   FORMAT(A12,A13)
      END IF
C
      RETURN
      END
```

7) Subroutine DELTACT: this subroutine computes the OMIB angle at control time.

```
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C Subroutine DELTACT.
C
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C------------------------------------------------------------
C
      SUBROUTINE DELTACT(NMED,ANG,VEL,MOM,A,B,C,ANGCT,OMGCT)
C
      IMPLICIT NONE
C
```

```
      INCLUDE 'COMMLNK.FOR'
C
      INTEGER  I,NMED,BANRAIZ,BANRAIZOMG
      REAL*8
ANG(10000),VEL(400),MOM(400),A,B,C,DANGLE,CT,DELTA,
     *          DELTCT,RAIZ,RAIZOMG,ANGCT,OMGCT
C
C------------------------------------------------------------
C
C     Se inicializan las variables.
C
      BANRAIZ=0
      BANRAIZOMG=0
      DANGLE=0.001
      CT=0.0
      OMGCT=0.0
      DELTA=ANG(NMED)
      DELTCT=ANG(NMED)
C
      DO 20 WHILE(DISPDELAY.GE.CT)
        DELTCT=DELTCT+DANGLE
          RAIZ=((2./MOM(NMED))*(((A*DELTA**3.)/3.)+
     *       ((B*DELTA**2.)/2.)+(C*DELTA)-((A*DELTCT**3.)/3.)-
     *       ((B*DELTCT**2.)/2.)-(C*DELTCT)))+(VEL(NMED)**2.)
        IF(RAIZ.LE.0.0)THEN
          BANRAIZ=1
        ELSE
          CT=CT+(DANGLE/(SQRT(RAIZ)))
        END IF
        DELTA=DELTA+DANGLE
   20 END DO
C
      ANGCT=CT
C
      RAIZOMG=((2./MOM(NMED))*(((A*ANGCT**3.)/3.)+
     *                           ((B*ANGCT**2.)/2.)+(C*ANGCT)-
((A*ANG(NMED)**3.)/3.)-
     *                                 ((B*ANG(NMED)**2.)/2.)-
(C*ANG(NMED))))+(VEL(NMED)**2.)
      IF(RAIZOMG.LE.0.0)THEN
        BANRAIZOMG=1
      ELSE
        OMGCT=SQRT(RAIZOMG)
      END IF
C
      IF(BANRAIZ.EQ.0)THEN
        WRITE(61,10)'DELTACT= ',ANGCT
   10   FORMAT(/,A9,F10.5)
C
      ELSE
        WRITE(61,11)'DELTACT= ','RAIZ NEGATIVA'
   11   FORMAT(A9,A13)
      END IF
C
      IF(BANRAIZOMG.EQ.0)THEN
        WRITE(61,12)'VELCT= ',OMGCT
   12   FORMAT(/A7,F10.5)
C
      ELSE
        WRITE(61,13)'VELACT= ','RAIZ NEGATIVA'
   13   FORMAT(A7,A13)
      END IF
C
      RETURN
      END
```