DESIGN OF AN ENERGY FUNCTION BASED ONLINE SYSTEM STABILITY MONITORING AND INTEGRITY PROTECTION SCHEME

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÖZGÜR TANIDIR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

FEBRUARY 2025

Approval of the thesis:

DESIGN OF AN ENERGY FUNCTION BASED ONLINE SYSTEM STABILITY MONITORING AND INTEGRITY PROTECTION SCHEME

submitted by **ÖZGÜR TANIDIR** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Naci Emre Altun
Dean, Graduate School of **Natural and Applied Sciences** ______________

Prof. Dr. İlkay Ulusoy
Head of Department, **Electrical and Electronics Engineering** ______________

Prof. Dr. Ali Nezih Güven
Supervisor, **Electrical and Electronics Engineering, METU** ______________

Examining Committee Members:

Prof. Dr. Murat Göl
Electrical and Electronics Engineering, METU ______________

Prof. Dr. Ali Nezih Güven
Electrical and Electronics Engineering, METU ______________

Prof. Dr. Saffet Ayasun
Electrical and Electronics Engineering, Gazi University ______________

Prof. Dr. Cengiz Taplamacıoğlu
Electrical and Electronics Engineering, Gazi University ______________

Assist. Prof. Dr. Keyvan Firuzi
Electrical and Electronics Engineering, METU ______________

Date:11.02.2025

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: ÖZGÜR TANIDIR

Signature :

ABSTRACT

DESIGN OF AN ENERGY FUNCTION BASED ONLINE SYSTEM STABILITY MONITORING AND INTEGRITY PROTECTION SCHEME

TANIDIR, ÖZGÜR
Ph.D., Department of Electrical and Electronics Engineering
Supervisor: Prof. Dr. Ali Nezih Güven

February 2025, 111 pages

Renewables, markets and growth induced complexity, challenges todays modern power systems to operate at lower security margins. System operation becomes much more vulnerable to fast shifts in the generation, less controllable due to the reducing inertia and more prone to cascading failures. Hence transient stability will become the major concern and the need for better situational awareness has become evident. In this regard, system operation immensely needs online tools for monitoring, analyzing and controlling the grid in case of disturbances. The main motivation of this study stems from a question: Is it possible to form and tune a remedial action scheme via energy function based online dynamical stability assessment for changing operating conditions?. On this point, this study aims to deal with development of an online system wide monitoring and control scheme in order to ensure system stability at all operating conditions. In this regard, first energy function based contingency ranking and transient stability assessment method that can be utilized to determine stability margins among the grid clusters and sensitivities has been developed. Then coherent grid clusters in the sense of stability, specifically margin sensitivity, are determined to form a basis for mitigating actions. Building a correct and robust set of mitigating actions for a wide possibility of operating conditions and contingencies is a cumbersome task. This study offers a new approach to this task by taking advantage of coherent grid clusters in the sense of margin sensitivities. Hence, an online adaptive remedial action scheme structure that gathers reliable actions is formed in an automatized manner which surely relieve the grid operations. In this sense, considering online forming and adaptation via margin sensitivity approach, the energy function based centralized online system integrity scheme proposed in this study is significantly different from active remedial action schemes.

Keywords: transient stability, remedial action scheme, energy function

ÖZ

ENERJİ FONKSİYONU TABANLI ANLIK SİSTEM KARARLILIK İZLEME VE KORUMA ŞEMASININ TASARIMI

TANIDIR, ÖZGÜR
Doktora, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Ali Nezih Güven

Şubat 2025 , 111 sayfa

Modern güç sistemleri, yenilenebilir enerji entegrasyonu, şebeke genişlemesi, market etkisiyle daha da karmaşıklaşmaktadır. Yenilenebilir kaynaklı hızlı üretim değişimleri ve azalan atalet, sistem işletiminde kontrol edilebilirliği ve güvenlik marjını azaltmaktadır. Bu durum şebekenin kararlı ve güvenli işletimi için durum farkındalığı analizi yapan anlık izleme, analiz ve kontrol araçların önemini ortaya çıkarmaktadır.

Bu çalışmanın ana motivasyonu şu soruyla özetlenebilir: Değişen işletim koşulları için enerji fonksiyonu tabanlı anlık dinamik kararlılık değerlendirmesi aracılığıyla bir önleyici ve düzeltici özel koruma şeması oluşturmak ve ayarlamak mümkün müdür?. Bu noktada çalışma, tüm işletim koşullarında sistem kararlılığını sağlamak amacıyla anlık bir sistem izleme ve kontrol şeması geliştirmeyi amaçlamaktadır. Çalışmada, ilk olarak enerji fonksiyonu tabanlı kısıt önceliklendirme ve geçici rejim kararlılık değerlendirme yöntemi geliştirilecektir. Bu yaklaşım ile kararlılık marjları ve aksiyonlarının kararlılık üzerinde duyarlılığını belirlenecektir. Elde edilen sonuçlar ışığında önleyici/düzeltici eylemler, duyarlılıkların gruplandırılması ve efektif birleşimi dikkate alınarak belirlenebilecektir. İşletim koşullarının ve kısıtların çeşitliliği göz önüne alındığında güvenilir düzeltici/koruyucu eylemler seti oluşturmak zorlu bir görevdir. Bu çalışma, kararlılık marjı duyarlılığı bakış açısıyla belirlediği anlık aksiyon kümeleri ile bu göreve yeni bir yaklaşım sunmaktadır. Bu sayede, güvenilir düzeltici/önleyici eylemleri bir araya getiren anlık uyarlanabilir bir eylem düzeni yapısı, otomatikleştirilmiş bir şekilde oluşturulmaktadır. Çalışmada önerilen enerji fonksiyonu tabanlı merkezi sistem bütünlük şemasının, kararlılık marjına dayalı eylem şeması belirleme ve durum bazlı uyarlama yaklaşımı ile mevcut düzeltici eylem şemalarından (RAS veya SPS) önemli ölçüde farklılaşmaktadır.

Anahtar Kelimeler: geçici rejim kararlılığı, özel koruma sistemi, enerji fonksiyonu

To My Beloved One

whose love, vision and humor reshaped my perspective on life

To our wonderful children Kemal and Güneş

whose laughter and boundless energy persuaded me that impossible is ok, too.

ACKNOWLEDGMENTS

First of all, I would like to express my deepest gratitude to my supervisor Prof. Dr. Ali Nezih Güven for his trust, guidance, advice, encouragement and support throughout the research. He is the one who shaped and nurtured my academic life and it was an honor to have opportunity to work with him. I also want to thank each of my committee members for their understanding, helpful comments and intellectual guidance.

I also would like to thank the to my father who gave me the desire to have this title. His vision, encouragement and support is with me whenever I need and I will be proud to fulfill our ambition.

I owe a debt of gratitude to my wife for her endless support and patience through this research. After all the things we faced together in the last couple of years, I am sure that I simply couldn't have done this without you.

Finally, my special gratitude goes to my family for their unconditional support, love and encouragement throughout my life.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

With the effects of the climate crisis and global warming, transforming the global energy system from fossil fuels to low-carbon energy sources has become one of the most critical challenges of today. Rising global temperatures and increasing environmental concerns have placed significant pressure on countries to transition towards cleaner and more sustainable energy sources. Many governments worldwide are now focusing on shifting their energy supply to renewable alternatives [1]. Electricity is expected to become the backbone of the energy system, requiring power grids to become greener, more advanced, and highly flexible.

In this regard, most investments in the past decade have been directed toward renewable energy technologies such as solar and wind, which are considered key to reducing emissions in the electricity sector [2]. While relying on renewable energy sources is a crucial step toward achieving a sustainable future, it also introduces challenges related to supply security and the stable operation of the electricity grid due to the intermittent nature of these sources.

Grid operators, in response, are seeking solutions to maintain grid reliability and stability while adapting to these changes. Today, most of the European grid is interconnected to enhance overall system balance and strength. Load dispatch centers continuously determine load planning and dispatching while ensuring that system constraints are not violated. Additionally, interconnected grids require cooperative operation, which brings further precautions and planning to reduce risks. Despite the significant benefits of interconnection, such as improved reliability and economic efficiency, it also increases operational complexity.

Moreover, the increasing share of distributed generation across power networks further complicates grid operations. Controlling such generation is inherently more challenging as it reduces grid observability. Additionally, voltage and frequency control become more difficult because distributed generation is connected at the distribution level rather than the transmission system. Consequently, a coordination framework between distribution and transmission system operators is required, adding another layer of complexity to grid management.

With the growing size of power systems, increasing renewable energy penetration, and rising complexity, modern grids are now operating with lower security margins. System operations have become more vulnerable to sudden shifts in generation, less controllable due to decreasing inertia, and more prone to cascading failures. As a result, ensuring grid security and stability has become a major concern, making the need for better situational awareness more evident than ever.

Situational awareness tools play a vital role in enabling efficient real-time grid monitoring, providing predictive insights, and enhancing operators' decision-making capabilities. These tools continuously collect and analyze data from various sources such as SCADA, Phasor Measurement Units (PMUs), and Advanced Metering Infrastructures (AMIs). When this data is processed and transformed into actionable information, system assessments become faster and more accurate. This allows operators to anticipate potential threats and take proactive measures before disturbances escalate into serious stability risks. In other words, these tools help reduce the risk of instability and blackouts. The ability to visualize, interpret, and respond to grid conditions in real time is now a fundamental necessity in modern power system operation.

On the other hand, system stability and security assessments still heavily rely on extensive offline studies conducted well in advance. While this approach is effective for conventional power systems, where generation planning is relatively predictable, it may not be sufficient for modern grids with variable renewable energy sources and rapidly changing consumption patterns. Additionally, growing system complexity requires situational awareness tools that can provide real-time visualization of system stability. Past blackout incidents have demonstrated that the absence of effective situational awareness tools was one of the major causes of system failures [3].

Furthermore, fast-acting automated control mechanisms, such as remedial action schemes (RAS), are becoming essential for ensuring system stability. These solutions dynamically adjust power flows, redistribute generation resources, and respond to grid disturbances in real time. Coordinated control actions that consider various system constraints and interdependencies are crucial for maintaining operational security and preventing cascading failures.

In conclusion, the rapidly evolving structure of modern power grids, driven by increasing renewable energy integration and rising operational complexity, requires advanced situational awareness and decision-support tools to ensure secure and reliable operation. The integration of enhanced real-time monitoring, visualization tools, and automated grid control mechanisms will be key to addressing these challenges. Additionally, adaptive control solutions that respond to real-time grid conditions will improve control accuracy. Since various control actions can interact with one another, coordinated control is essential for maintaining system security. Therefore, the implementation of online, coordinated, and adaptable situational awareness and grid control strategies is necessary to enhance system resilience.

1.2 Motivation of the Research

Modern power systems require advanced online tools for real-time monitoring, analysis, and control, particularly during disturbances. This requirement will be much more significant than that of today as the grids are expanding and evolving with new technologies and renewables. Also considering the todays data availability and processing speed, power systems automatized controls and decision support tools possess huge possibility of development.

Traditional power system stability analysis relies on comprehensive system modeling and analysis, which is both time-consuming and highly dependent on operating conditions. Analysis part in general contducted offline and based on either extensive scenario possibilities or max/min level operating conditions. However, as the penetration of renewables increase, grid conditions are changing so rapidly that grid may face conditons that is not covered by the beforehand studies. In this regard, online analysis requirement gain importance. These limitations make real-time computational tools essential for online monitoring and dynamic stability enhancement.

This research emphasizes online dynamic stability assessment (DSA) and, more specifically, transient stability assessment (TSA). A fast online DSA framework can provide supervisory input to the transmission system operator (TSO), ensuring system security by identifying and executing necessary countermeasures based on acceptable security levels. Such countermeasures may include adjusting network configurations, implementing generator tripping, load shedding, or modifying generation schedules. Properly designed actions are crucial for preventing cascading failures caused by overloaded electrical equipment, necessitating a comprehensive online analysis strategy that spans from steady-state to dynamic-state operations.

To mitigate the impact of contingencies, necessary control actions should be preplanned, and system operators must utilize rapid online monitoring tools to initiate immediate corrective measures during abnormal system conditions. However, due to the inherent uncertainty of large-scale power system operations, pre-defined control strategies alone may not be sufficient to address all critical contingencies affecting transient stability. Furthermore, continuously changing power flows make it impractical to design power system stabilizers that accommodate all possible operating scenarios.

To address these challenges, this study proposes an online transient stability assessment framework tailored for large power grids. It systematically examines generator rotor angle dynamics in multi-machine systems using Lyapunov-based methodologies. Additionally, the information gathered through the energy functions considering contingencies will be utilized for developing a remedial action scheme in order to assist grid operators with automatized controls in case of any instability conditions. By integrating contingency-based energy function analyses, the research aims to develop an effective online updated remedial action scheme that enhances grid resilience through automated and intelligent control mechanisms.

1.3 Research Objectives, Challenges and Contributions

With the increasing complexity, growing size, and higher penetration of renewable energy sources, modern power systems are increasingly operating at lower security margins. System operation has become more vulnerable to rapid changes in generation, less controllable due to declining inertia, and more prone to cascading failures. Consequently, transient instability has emerged as a critical concern, necessitating enhanced situational awareness and real-time control mechanisms.

In this regard, power system operation requires advanced online tools for real-time monitoring, analysis, and control to ensure stability under dynamic and uncertain conditions. The primary motivation of this Ph.D. study arises from the fundamental question: Is it possible to develop and dynamically tune a System Integrity Protection Scheme (SIPS) using an energy function-based online dynamic stability assessment framework for evolving operating conditions? To address this challenge, the study aims to develop a comprehensive online system-wide monitoring and control scheme that ensures power system stability across all operating scenarios. More specifically, the study sets out the following objectives:

- Develop an energy function-based contingency ranking and transient stability assessment method to evaluate stability margins across grid clusters and determine critical sensitivities
- Determine coherent grid clusters in the sense of stability observation and control via forming a bridge between model based and measurement based clustering algorithms
- Design an online adaptive remedial action scheme (RAS) that dynamically updates its parameters based on real-time stability assessments.
- Optimize algorithm performance in terms of speed, accuracy, and security to ensure reliable and efficient execution of online stability assessments and control actions.

The problem dealt in the study, is crucial for the next generation of the power systems in terms of maintaining power supply reliability, security and quality. It can also be expressed that energy (Hybrid TEF) based centralized system integrity scheme proposed in this study significantly different from any active remedial action scheme (RAS or SPS).

However, several key challenges must be overcome to develop such a scheme:

- **Robustness of analysis:** As the stability assessment is the core of the aimed tool, the used stability/security assessment and screening methods have to generate robust and reliable assessment results.
- **Adaptibility of scheme to changing operating conditions:** Security concerns which need to be resolved via aimed scheme can be diversified for changing operating conditions. In this regard, online adaptation of the controls needed.
- **Optimal remedial measures:** Mitigation actions may change among operating conditons and contingencies. It is important to gather both reliable and robust mitigating/preventive actions in online manner and form a minimum redundant set of actions to reduce vulnerability to malfunction.
- **Speed of analysis:** Since the scheme requires real-time calculations to accommodate rapidly changing grid conditions, performance improvements are essential to achieve fast and accurate decision-making.

In the following, the main contributions of the presented work are listed:

- In todays electrical grids, with the penetration of renewables, grid operating conditions hence the system dynamics are changing faster than it used to be. So determination of critical contingencies, stability conditions together with the mitigating actions need to be conducted online. Online adaptive RAS approach is one of the main contributions of this study. In the study online stability assessment is conducted to form and adapt the RAS scheme. Considering the conventional RAS applications which rely on offline studies, offered scheme is substantially different.
- Currently deployed systems focuses on local security concerns rather than a global view. In this study, grid wise view on this subject is considered.

- Online determination of mitigating actions based on coherent grid clusters in the sense of stability control is one of the novelties introduced with this study. The mitigating actions formed, grouped and adapted based on energy function sensitivity.

By integrating real-time stability assessment with an adaptive control framework, this research aims to contribute to the development of next-generation power system security tools, ensuring grid resilience under increasingly complex and uncertain operating conditions.

1.4 The Outline of the Thesis

This thesis is structured to systematically explore the assessment and enhancement of transient stability in power systems, with a particular focus on direct methods and the application of transient energy functions (TEF). The proposed remedial action scheme is developed and validated through extensive simulations.

In the first chapter research topic, highlighting the motivation behind the study and the challenges associated with power system stability assessment is given. This chapter defines the research objectives and contributions, providing a roadmap for the rest of the thesis.

Second chapter provides an overview of power system stability, including its classification and key influencing factors. It explores various stability control approaches, online dynamic security assessment (DSA) methods, and computational techniques used in stability analysis. Additionally, remedial action schemes (RAS) are discussed, outlining their functional structure and design requirements.

Theoretical foundation of transient stability assessment is introduced in the third chapter. It discusses key properties of energy functions and examines different direct methods, including the Closest Unstable Equilibrium Point (CUEP), Controlling Unstable Equilibrium Point (CUEP), and the Potential Energy Boundary Surface (PEBS) method. The applicability of these methods in transient stability analysis is also explored.

Modeling and development of energy functions for transient stability assessment is the main target in chapter 4. After introducing power system model utilized in the study, limitations and assumptions are discussed. This chapter also covers the development of energy functions and the computation of transient energy, forming the basis for stability evaluation.

Chapter 5 explains the proposed remedial action scheme based on transient energy function method. It describes the contingency ranking and screening process, stability assessment and energy margin determination method, and the use of energy margins for identifying critical cases. Additionally, it explains the sensitivity analysis of energy margins and the methodology for determining the optimal remedial action set.

Application of the proposed scheme on IEEE 39 and 118 bus test cases are given in the Chapter 6. This chapter presents the implementation and validation of the proposed scheme. The results of contingency ranking, stability assessment, and energy margin sensitivity analysis are provided to evaluate the scheme's effectiveness.

Finally, Chapter 7 provides a comprehensive summary of the key findings and contributions of this dissertation. It highlights the main conclusions drawn from the proposed framework for dynamic stability assessment and enhancement, emphasizing its effectiveness and potential impact on power system operation. The chapter also discusses the implications of the research in the broader context of transient stability analysis.

Additionally, a brief overview of suggested future research directions is presented. These include potential extensions of the proposed methodology, integration with modern grid technologies, and the application of emerging computational techniques.

CHAPTER 2

POWER SYSTEM STABILITY ASSESSMENT AND CONTROL

2.1 Definition and Classification of Power System Stability

The main requirement of system stability is to keep the synchronous operation of power system with adequate capacity and fast reaction to meet the fluctuations in electric demand and changes in system topology. Power system stability refers to the capability of an electric power system, under a given initial operating condition, to restore a state of equilibrium following a disturbance, ensuring that system variables remain within acceptable limits so that the system as a whole remains operational [4]. The stability phenomenon represents a singular issue encompassing various forms of instability, which arise due to the high dimensionality and complexity of power system structures and dynamic behaviors. To facilitate a comprehensive understanding of stability, proper classification is crucial for conducting a meaningful power system stability analysis.

Stability is categorized based on different criteria, including the nature of the instability (such as voltage instability and frequency instability), the magnitude of the disturbance (small disturbance or large disturbance), and the timescale of stability (short-term or long-term). Furthermore, stability is broadly classified into steady-state stability and dynamic stability. Steady-state stability refers to the system's ability to transition from one operating point to another in response to minor load variations. On the other hand, power system dynamic stability, often discussed in the literature as a subset of rotor angle stability, assesses whether the system can sustain stable operation following various disturbances. Figure 2.1 illustrates the classification of power system stability as defined by the IEEE/CIGRE joint task force on stability terms and definitions [4].

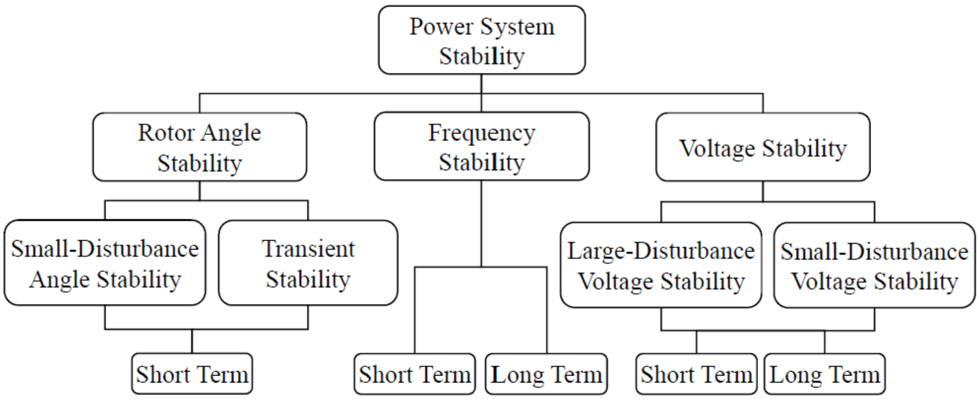


Figure 2.1: Classification of stability based on IEEE/CIGRE joint task force on stability [4]

For the each individual stability phenomenon shown in Figure 2.1 , brief descriptions is as follows;

1. **Rotor Angle Instability** occurs when the synchronous machines in an interconnected power system lose their ability to remain in synchronism following a disturbance.

    - Small-disturbance (or small-signal) rotor angle instability arises when the power system fails to maintain synchronism under minor disturbances.
    - Large-disturbance rotor angle instability, commonly known as transient instability, occurs when the system loses synchronism due to a major disturbance, such as a short circuit on a transmission line.

2. **Frequency Instability** refers to deviations in system frequency beyond predefined limits, which specify both the maximum allowable magnitude and the duration of frequency excursions. This type of instability results from a significant unresolved imbalance between active power generation and demand, leading to either overfrequency or underfrequency conditions.

3. **Voltage Instability** is characterized by the system's inability to sustain steady voltages at all buses following a disturbance from a given initial operating state.

Voltage deviations from normal levels can be triggered by factors such as system faults, sudden load increases, or other operational disruptions.

- Small-disturbance voltage instability occurs when the system is unable to maintain stable voltages in response to minor perturbations, such as gradual changes in load.
- Large-disturbance voltage instability arises when the system fails to sustain voltage stability following major events, including system faults, generator outages, or circuit contingencies.

Additionally, there are conditions not acceptable by the power system operation and can be classified as conditions lead to loss of stable operation. These include overloading and cascading. Overloads occur when the current flowing through power system components exceed their rated capacity. This typically results from the redistribution of power through operational facilities following the sudden unavailability of other system elements, such as transmission lines or transformers, which may have been isolated due to a fault. Cascading on the other hand, refers to the uncontrolled, successive failure of power system components initiated by an incident at any location. This phenomenon leads to widespread power outages, as the failures propagate beyond the initially affected area in an unrestrained manner, exceeding the boundaries anticipated in system studies.

The effect on the grid part and timescale of above instability conditions are visualized in Figure 2.2.It is shown in the Figure 2.2 that transient stability is the phenomenon that occur really quick and effect large portion of the system.. Hence, the thread that possess can be stated as really large. Transient instability phenomenon is usually in the form of uncontrollable significant increase and separation of the relative angles between two or more generators due to insufficient synchronizing torque. With non-linear power angle in mind, the resulting system response forces generators to move rotor angles to largely from steady state operation point. In this regard, this study mainly focuses on assessment of transient stability and relieving the effects.

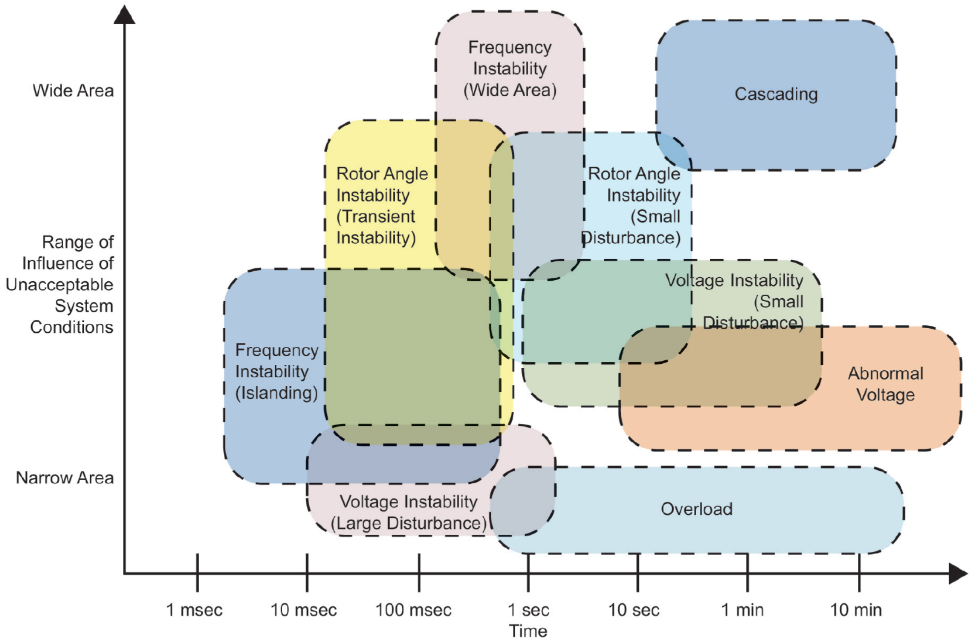


Figure 2.2: Time scale and area of affected area in instability types [5]

2.2 Factors Affecting Stability

The stability of a grid is mainly influenced by the type and magnitude of disturbance and the operating condition. There are also numerous factors including the dynamic behavior of system components, control strategies and settings, and protection mechanisms. The key factors affecting power system stability can be summarized as follows:

- **Pre- and Post-Disturbance System Conditions:** The operating state of generators before and during a fault plays a crucial role in stability. Higher generator loading before a fault increases the likelihood of instability during disturbances.
- **Fault Characteristics:** The duration, location, and type of fault determine the amount of kinetic energy accumulated by the system. Faults that last longer durations lead generator rotors to gain more kinetic energy, which, beyond a certain threshold, may not be dissipated after fault clearance, leading to instability.
- **Synchronous Machine Parameters:** Factors such as the inertia constant (H),

which represents the stored kinetic energy per unit rated power, and the generator terminal voltage significantly affect stability. A higher inertia constant reduces rotor angle swings, thereby enhancing stability, while generator bus voltages shape the power angle curve, influencing power delivery across the system.

- **Excitation and Governor System Characteristics:** The excitation system and governor dynamics play a critical role in damping power oscillations. The automatic voltage regulator (AVR) continuously monitors terminal voltage and regulates it through the excitation system. Additionally, fast valving, which rapidly modulates steam valve operation, helps manage generator acceleration during faults.

- **Transmission Reliability Margin:** Transmission system robustness is essential for maintaining stability. A transmission outage due to overloading in abnormal system conditions can lead to uncontrolled cascading failures by triggering the sequential loss of additional network components.

- **System Protection and Relaying**: Protection schemes play a vital role in maintaining stability. Since power systems have a limited capacity to absorb disturbances, the rapid detection and isolation of faulty components enhance stability. Special protection schemes, such as controlled system islanding, can be implemented to split the grid at predetermined points, preventing large-scale cascading failures.

2.3 Power System Stability Control

2.3.1 Objective and Control Structures

The objective of security and stability control of electric power systems is to maintain synchronous operation and security of power supply even in a disturbed state of the system. This objective can be fulfilled by various stages and types of systems starting from generating unit to grid operator. In Table 2.1 general control structures are given.

Table 2.1: Stability controls in electricity grid

Control Point	**Stability Control**	**Control Applied or Coordinated By**
Generator	Excitation systems Frequency regulator Generator protection	grid regulations (codes), load frequency controls, automatic generation controls
Lines & Transformers	Element Protection	Protection Scheme of the grid (defense plan)
Loads	Element Protection, Under Frequency Load Shedding	Protection Scheme of the grid (defense plan)
FACTS Devices	POD and Protection	Operator Designed settings, SCADA (or explict control structure)
Power Plant	Power Park Controls	Grid regulations (codes), load frequency controls, automatic generation controls
SCADA	Automatic Generation Control	
SPS	Selected control relays	SPS Scheme Designed by grid operator
Controlled Islanding	Selected control relays	Scheme Designed by grid operator

2.3.2 Control Approaches

Coordination and interaction planning among these control options needs a careful analysis and planning studies. Control point selection, timing selection, amount determination are the important points that define control strategy. In [6], four distinctive control types are described namely, preventive control, event-based control, response based control and restorative control.

Preventive control mainly focuses on satisfying security criteria for credible contingencies before the contingency occur. Restorative controls can even be active in a normal state of operation where all grid variables stand in the normal operation conditions. The important point is to ensure system security and reliability for N and N-1 cases. Hence this control is usually operated by the grid operator by the generation and re dispatching and topological maneuvers like switching.

The main objective of event based control type is to prevent the loss of system stability or limit violation of key operating parameters due to contingency occurrences. Hence in this type of control, a contingency immediately provokes degined control structures such as generator tripping, fast valving, load shedding, capacitor/reactor switching or line tripping.

On the other hand, response based controls are formed to arrest the propagation of disturbance impacts and prevent system collapse due to extremely severe contingencies. These control typically activated after the violation of key operating thresholds defined by the grid operators based on either experience or the detailed analysis.Under frequency load shedding scheme implemented in the transmission grid is a typical example for sych control type.

Finally, restorative controls used for turning the grid to the normal operating state after a blackout or an emergency case. Main point is to restore power system as quickly as possible and reach a secure and reliable operating point.

2.3.3 Stability Enhancement Approaches

A wide range of measures can be implemented to enhance power system stability. These measures aim to improve the resilience of the grid under both normal and abnormal operating conditions, ensuring secure and reliable operation. The key strategies for improving system stability are as follows:

- **Optimized System Configuration and Maintenance Scheduling:** The system layout and maintenance activities should be planned in a way that ensures the power system remains within its secure operating limits, even during abnormal conditions. Proper system planning helps prevent excessive loading and enhances overall system reliability.
- **Reduction of Transmission System Reactance:** Lowering the reactance of the transmission network enhances system stability by improving power transfer capability. This can be achieved through the addition of parallel transmission circuits and the application of series compensation on existing lines.
- **Deployment of Advanced Generation Technologies for Voltage and Stability Control:** Power system stability can be reinforced through the integration of new generation units that provide reactive power support and voltage control

services. Technologies such as power system stabilizers, Flexible AC Transmission Systems (FACTS), rapid-response thermal units with fast-valving capabilities, and high-speed automatic excitation systems significantly contribute to stability enhancement.

- **Integration of Dynamic Braking Resistors:** The installation of dynamic braking resistors at generator and substation terminals helps mitigate excessive rotor acceleration during fault conditions. These resistors introduce an artificial load following a disturbance, thereby improving damping characteristics and restoring system stability.

- **Enhancement of Protective Systems and Coordination Among System Operators:** The deployment of high-speed protection devices and effective coordination among interconnected system operators facilitate faster fault clearance and the implementation of appropriate corrective measures. Well-coordinated protection schemes are crucial for preventing cascading failures and minimizing system disturbances.

- **Implementation of Online Remedial and Preventive Measures:** In modern power systems, which operate within a competitive market-driven framework, offline preventive actions alone are insufficient to maintain stability margins. Consequently, online Dynamic Security Assessment (DSA) tools play a critical role in ensuring that the power system operates within secure stability limits. Various online measures can be utilized to safeguard system stability, including:

  - **System Topology Adjustments:** Selective tripping of critical generators, when necessary, can ensure that the remaining units maintain synchronism. Additionally, generation rescheduling and re dispatch strategies can be employed to optimize power generation allocation, thereby alleviating transmission constraints and preventing overloads.
  - **High-Speed Protection Schemes:** The adoption of advanced transmission line protection techniques, such as single-pole tripping and adaptive reclosing, minimizes the impact of disturbances on the power system. High-speed automatic reclosing mechanisms provide an effective means of restoring power continuity following fault clearance.

- **Utilization of Online Transformer Tap Changers and Phase-Shifting Transformers:** Real-time adjustment of transformer tap settings and phase angles enables precise control of power flows across the transmission network. Continuous regulation of voltage setpoints and phase angles ensures optimal system performance and prevents excessive loading of transmission corridors.

- **Automatic Load Shedding for Frequency Control:** Under-frequency load shedding (UFLS) is a critical corrective measure that helps maintain system frequency within acceptable limits during severe disturbances. Traditional under frequency load shedding (UFLS) schemes based on fixed settings can be enhanced by adaptive load shedding strategies that dynamically adjust shedding locations and magnitudes based on real-time power flow and voltage conditions.

- **Control of Reactive Power and HVDC Link Utilization:** Effective management of reactive power generation and absorption enhances voltage stability and supports system reliability. Additionally, the implementation of specialized HVDC link control strategies can facilitate dynamic power flow adjustments, ensuring generation-load balance in interconnected AC networks during system disturbances.

- **Deployment of High-Speed Excitation Systems:** Fast-response excitation control systems play a crucial role in transient stability improvement. Rapid boosting of generator field voltage during disturbances enhances synchronizing torque, reducing the risk of rotor angle instability.

By implementing these stability-enhancing measures, power system operators can maintain the integrity of the grid while adapting to evolving operational challenges. The combination of preventive and corrective strategies ensures a robust and resilient power system capable of withstanding disturbances and maintaining secure operation.

2.4 Online DSA and Control

Dynamic security assessment (DSA) tools are addressing the need to improve situation awareness of the system operator, specifically for the grid transient stability in case of credible contingencies. DSA is defined in [7] as follows: "DSA refers to the analysis required to determine whether or not a power system can meet specified reliability and security criteria in both transient and steady-state time frames for all credible contingencies."

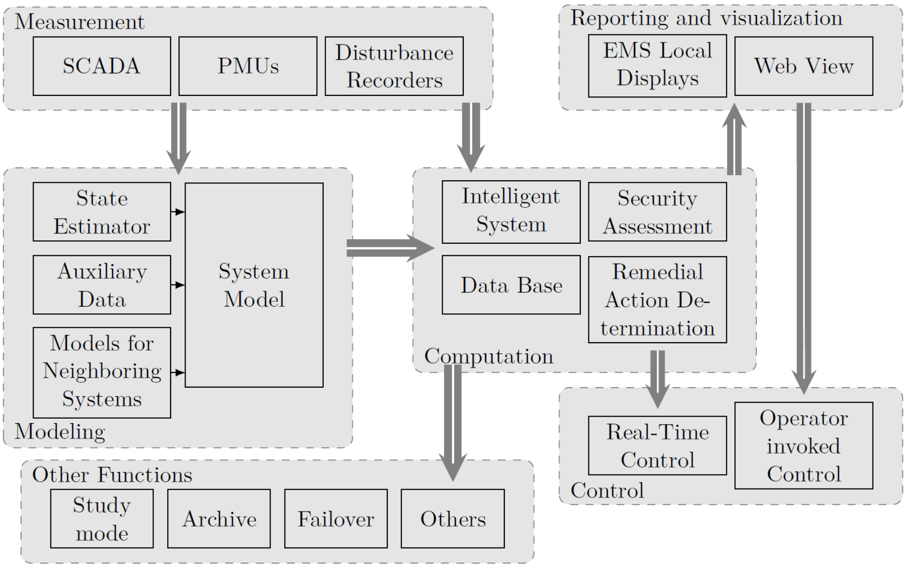


Figure 2.3: DSA General Structure [8]

A proposed structure for online DSAs is depicted in figure 2.3.It is clear from the figure that main components of a DSA includes observable system with a robust measurements, updated and accurate power system model whose size and complexity properly adjusted, visualization and computational core. The control part which can also be stated as the action scheme may or may not be the automatized depending on the automation approach.

In traditional power systems, operators heavily relied on offline security assessments to ensure daily operations were secure and reliable. However, modern power systems have become more complex due to open markets and the integration of renewable energies, making operations less predictable. As a result, depending solely on offline dynamic security assessments (DSAs) is no longer practical or feasible. On the other hand, online DSA relies only on current operating scenario and assesses the ongoing real-time (or near real-time) dynamic security status, thus is able to give timely control actions to maintain system stability. Consequently, the global demand for online DSAs is increasing [9].An extensive review of on-line dynamic security assessment tools and techniques is given in Cigre Report [9]. The report details the current installations of online dynamic security assessment (DSA) and ongoing research in the field. A list of online DSA installations worldwide, including information on the assessment methods used is given in Table 2.2.

It is clear from the table that transient stability assessment and voltage stability assessment are the most commonly utilized computations. More information on the transient stability assessment modules in stated DSAs are given in Table 2.3.The table shows that time domain simulation technique is utilized in the computational core of almost all of the installations. There are also several techniques and approaches that are introduced in the next chapter.

Table 2.2: A list of online DSA installations and functions [9]

Country	Location/ Company/Proj.	SCOPE			
		TSA	**VSA**	**SSSA**	**FSA**
Australia	NEMMCO	x		x (MB)	x
Bosnia	NOS	x	x		
Brazil	ONS	x	x	x	x
Canada	BCTC	x	x		
Canada	Hydro-Quebec	x	x		
China	Beijing Elect. Power Corp	x			
China	CEPRI	x			
China	Guangxi Elect. Power Co.	x		x	x
Finland	Fingrid		x	x (MB)	
Greece	Hellenic Power System		x		
Ireland	ESB	x	x		
Italy & Greece	Omases Project	x	x		
Japan	TEPCO	x	x		
Malaysia	Tenaga Nasional Berhad	x	x		
New Zealand	Transpower	x	x		x
Panama	ETESA	x	x		
Romania	Transelectrica	x	x		
Russia	Unif . Elect. Power System	x	x		
Saudi Arabia	SEC	x	x		
South Africa	ESKOM	x	x		
USA	PJM	x	x	x	
USA	Southern Company	x			
USA	Northern States Power	x			
USA	MidWest ISO		x		
USA	Entergy		x		
USA	ERCOT	x	x		
USA	FirstEnergy		x		
USA	BPA		x		
USA	Southern Cal Edison		x		

* TSA: Transient security assessment, VSA: voltage security assessment, SSA: small signal security assessment, FSA: frequency security assessment.

Table 2.3: State-of-the-art TSA approaches [9]

Country – Company/Proj.	**Type**	**Description**
Australia – NEMMCO	TDS	Extensive off-line studies to determine operating limits
Bosnia – NOS	SSSL	Max. power transfer margin using Dimo's method security margin: large enough to ensure TSA
Brazil – ONS	TDS DM	DM Simulation in combination with SIME method
Canada – Hydro-Quebec	TDS	Power transfer limits are determined off-line and are employed during on_line opearation
China – CEPRI	TDS	Extensive time-domain simulation utilizing parallel processing
China – Guangxi Elect. Power Co.	TDS	Simulation of a limited selection of contingencies.
Italy & Greece – Omases Project	TDS DM	Simulation in combination with SIME method
Japan – TEPCO	TDS	Simulation in combination with TEPCO-BCU method DM and BCU classifiers
Malaysia – Tenaga Nasional Berhad	TDS	Simulations of a set of contingencies
New Zealand – Transpower	TDS	Operating limits are determined from off-line studies
Panama – ETESA	SSSL TDS	Dimo's method to determine max. loading Off-line TDS to determine necessary security margin
Romania – Transelectrica	SSSL TDS	Dimo's method to determine max. loading Off-line TDS to determine necessary security margin
TDS Off-line TDS to determine necessary security margin		
USA – PJM	TDS DM	TDS to compute non-linear system response TSA margin determined using SUME based approach
USA – Southern Company	TDS DM	TDS to compute non-linear system response TSA margin determined using SUME based approach

* TDS: Time domain simulation, SSSL: Steady-state stability limit, DM: Direct methods

2.5 Computational Approaches in DSA

2.5.1 Time Domain Simulation

Time domain simulation (TDS) is a widely used technique for transient stability analysis in power systems. This method involves numerically solving the differential equations that describe the dynamic behavior of the power system over a specified period. In this approach power system is modeled in detail covering generator dynamics, generator control dynamics (AVR, PSS, Governor etc.).

The simulation process is divided into three main periods: pre-fault, during-fault, and post-fault, each representing a different network configuration in order to assess the system's capability to withstand the disturbance under investigation. This approach ensures a comprehensive evaluation of system dynamics under transient conditions.

Time domain simulation starts with solving the load flow problem to establish the system's pre-disturbance operating condition. The obtained load flow solution provides essential data, including initial bus voltages, power flows, and system operating conditions, which serve as the foundation for dynamic simulations. Once the pre-fault state is determined, the system's dynamic response is analyzed through the numerical integration of differential equations representing power system behavior.

At each simulation time step, system state variables are updated by solving algebraic and differential equations. The integration techniques utilized enable precise computation of system evolution over time. At the instant of disturbance, system parameters are modified to reflect the new operating condition, and the simulation continues iteratively until the required simulation time is reached.

One of the key outputs of transient stability analysis is the swing curve, which illustrates the evolution of rotor angles for each generator. These curves are further examined to determine whether the angular deviation between any two machines exceeds the predefined stability threshold. If the angular difference surpasses this limit, the system is considered unstable, and the iterative process is terminated. Otherwise, calculations continue for the total simulation period.

To accurately represent system behavior under transient conditions, derivatives of state variables are computed at each time step. The future state of the system is determined based on the present state variables and their rates of change, ensuring a realistic dynamic representation. This iterative approach provides valuable insights into the power systems ability to maintain synchronism following disturbances, which is critical for ensuring secure and stable operation.

In this regard, system response, including oscillations, damping effects, and potential instabilities of each of the components can be observed. TDS gives detailed and accurate representation of system dynamics. However, this approach can be computationally demanding, especially for large power systems and require several accurate parameters from all the detailed models.

2.5.2 Direct Methods

Direct methods in transient stability analysis provide an alternative to time domain simulations by assessing system stability without explicitly solving the differential equations over time. These methods offer a faster and often more insightful way to determine system stability margins and critical conditions.

The direct methods of Lyapunov theory provide a framework for evaluating the transient stability of a power system subjected to a disturbance. These methods operate by defining a suitable Lyapunov function for the post-fault system and applying stability theorems to determine the region of asymptotic stability around the post-fault stable equilibrium point.

In transient stability assessment using Lyapunov's direct method, the post-fault system's stability is determined by analyzing whether the system's initial state at fault clearing falls within the established stability region. This assessment is conducted by comparing the system energy at the moment of fault clearing against a critical energy threshold. If the total energy accumulated during the fault remains below this critical value, the system is deemed stable.

The Lyapunov function commonly utilized in power system stability studies is directly associated with the transient energy function (TEF) of the post-fault system, incorporating both kinetic and potential energy components. The kinetic energy term represents the relative motion of generator rotors and is formally independent of the power network, while the potential energy term accounts for the stored energy in network elements and machine rotors. This potential energy is influenced by network parameters such as transfer conductances and system topology, which play a crucial role in post-fault stability behavior.

There are several approaches in direct methods:

- **Transient Energy Function Approach [10] [11] [12] [13] [14]:** The sum of the potential and the kinetic energy during disturbance is taken as the Lyapunov function, and the evaluation result in determination of stability boundaries.

- **Equal Area Criterion Approach [15] [16] [17] [18] [19]:** This approach is a graphical method specifically applicable to single-machine infinite bus (SMIB) systems. It compares the areas under the power-angle curve to determine stability. When the principles extended for the multimachine case it called as extended equal area creiterion approach.

Direct methods are generally faster than time domain simulations as they do not require solving differential equations over time. They also provide a clearer understanding of stability margins and critical conditions.

2.5.3 Hybrid Methods

Hybrid approaches in transient energy functions (TEF) integrate energy function methods with time-domain simulations to enhance the accuracy and efficiency of dynamic stability assessments in power systems [20]. Compared to traditional methods that rely solely on time-domain simulations or direct energy function analyses, hybrid approaches offer a balanced trade-off between speed and accuracy. While time-domain simulations provide detailed dynamic behavior, they are computationally intensive when applied to all possible contingencies. Direct energy function methods offer rapid assessments but may lack precision in complex scenarios. Hybrid approaches mitigate these limitations by using energy function methods for quick screening and reserving time-domain simulations for critical cases, thereby optimizing both performance and reliability in transient stability assessments.

Modern dynamic stability assessment tools are increasingly incorporating hybrid approaches to balance computational efficiency with analytical accuracy. Energy function methods, such as the Potential Energy Boundary Surface (PEBS) or Equal Area Criterion (EAC), are employed to quickly evaluate the system's stability under various contingencies [20] [21] [22] [23]. These methods provide a rapid assessment by estimating the system's potential energy and identifying critical scenarios that may lead to instability.

Studies have demonstrated that hybrid approaches can significantly enhance the performance of transient stability assessments. In [24], hybrid approach is considered in the core of real-time transient stability assessment tool for the national grid company of UK. The approach utilized in transient stability indexing and clustering. In [25], performance indices for contingency screening process is formed using hybrid approach. In [26], the two-stage parallel hybrid method has shown effectiveness in fast contingency screening and detailed analysis of critical contingencies, leading to improved dynamic security assessment.

2.5.4 AI Based Methods

Proliferation of PMUs increases quality and quantity of the measurements in modern grids. In the presence of the measurements, AI methods generally preferred when the data exist for training and validation. Models are trained on historical data to predict the stability of power systems under different operating conditions. Several AI approaches can be stated to determine grid transient stability such as decision tree [27], fuzzy systems [28] [29], neural network based [30] [31] [32] [33] [34] [35] [36], SVM based [37] [38], ELM based [39].

2.6 Remedial Action Scheme(RAS)

The primary function of an online Dynamic Security Assessment (DSA) system is to determine if the power system is at risk of a security threat, either in its current state or a future state. When a security alarm is triggered, operators need clear guidance on the appropriate actions to take. Besides, there is a possibility that the grid may face an emergency state after a contingency or cascade events. This type of situations require emergency or preventive control strategies. Hence, control part of the DSA, which can be named as remedial action, is an inevitable part.

Current state-of-the-art DSA installations offer methods for determining remedial measures such as load shedding or generation adjustments. However, there is a need to broaden the scope of these measures, providing operators with multiple options for optimal control actions. Further research is required to implement automated control actions, where DSA tools not only assess security but also determine and automatically execute remedial measures. In [40], RAS is defined as "A scheme designed to detect predetermined system conditions and automatically take corrective actions that may include, but are not limited to, adjusting or tripping generation (MW and Mvar), tripping load, or re-configuring a System(s). RAS accomplish objectives such as maintaining grid stability, maintaining acceptable voltages and flows in the grid and limit the impact of cascading or extreme events.". Remedial Action Schemes (RAS), also known as Special Protection Systems (SPS), detect abnormal conditions and take corrective actions to preserve system integrity.

2.6.1 Functional Structure

The functional structure of online RAS framework is comprised of four high-level modules.

1. Wide area data acquisition and information processing is the first part any monitoring and control structure. Today modern systems utilize PMU's and SCADA measurements for that structure. Dedicated measurement units for RAS can be implemented based on project necessities.

2. Real-time monitoring, online estimation and online stability analysis part: The main objective of this layer is to determine accurate grid condition and conduct analysis. Based on the inputs gathered and the topology information, contingency ranking, screening and security assessment is conducted at this level. Qualitative analysis results are obtained to determine system state and margin to stability.

3. Adaptive and coordinated decision planning of stability control: In this layer stability control decisions are determined. Any specific condition or contingency that may cause instability is further processed in terms of stability mar-

gins and sensitivities. This processing either rely on offline or online studies. In offline study, the area that is aimed to be preserved is analyzed by extensive scenario studies. Arming conditions and countermeasures for the instability is carefully determined. On the other hand, online decision planning relies on automated computation techniques for time-domain simulations, TEF, EEAC, AI, quantitative stability indices, sensitivity analyses and optimal control decisions. The main challenge to implement the adaptive control decision planning is the development of reliable and robust software for automatic searching of control decisions using time-domain simulations or TEF methods or EEAC, based on the near-to-real-time steady-state conditions.

4. Automatic activation of event-based and response-based controls: In the final layer, decision tables based on the results of the upper layer is constructed and logic is complemented by the required action signals.

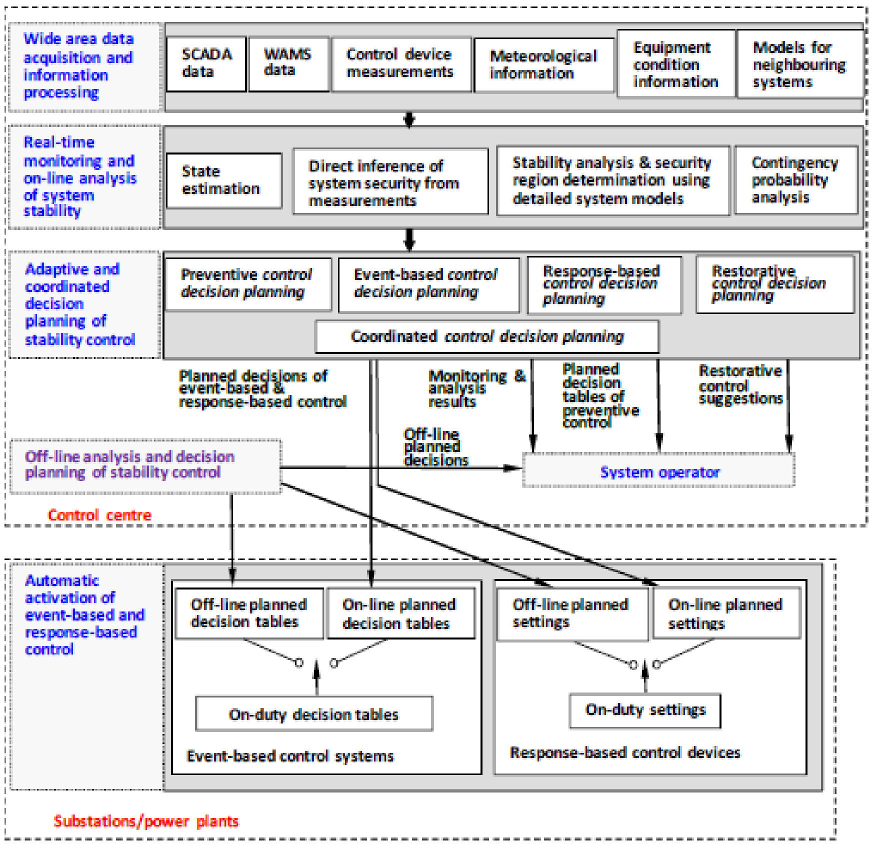


Figure 2.4: General architecture in online RAS approach [6]

The measurement and monitoring stages in the above structure are already well established however; the remaining is not yet maturated as there are significant challenges exist. These challenges can be expressed as time requirement, modeling and simulation accuracy, correct determination of stability margins and controls.

2.6.2 Key Design Requirements

General design requirements for a RAS can be summarized as follows;

- **Selectivity:** the most effective measures should be selected to mitigate the impact of a given contingency for the current system conditions and avoid unnecessary loss of power supply.
- **Rapidness:** control actions should be activated as fast as needed, so the power system may satisfactorily recover from the ongoing disturbance.
- **Dependability and security:** the control should not fail to operate when required and its unintended operation (when action is not required) should be prevented.
- **Accuracy:** the power or energy removed, injected or shifted in the system by the stability control should be applied at the right time and be of the right amount, not a Watt/Var more and not a Watt/Var less.
- **Adaptability:** the control decision set should be adjusted to the current operating condition and the contingencies should be correctly identified, so that the most cost-effective control actions are always carried out.
- **Coordination:** multiple automatic control schemes implemented in a region should be coordinated to avoid undesirable control actions.

2.6.3 Countermeasures or Remedial Actions

Utilities use RAS for problems ranging from single contingency protection to complete network stability assessment and protection. Figure 2.5 shows the system problems that can be addressed effectively and economically using SPS, and corresponding countermeasure to relief the system stress.

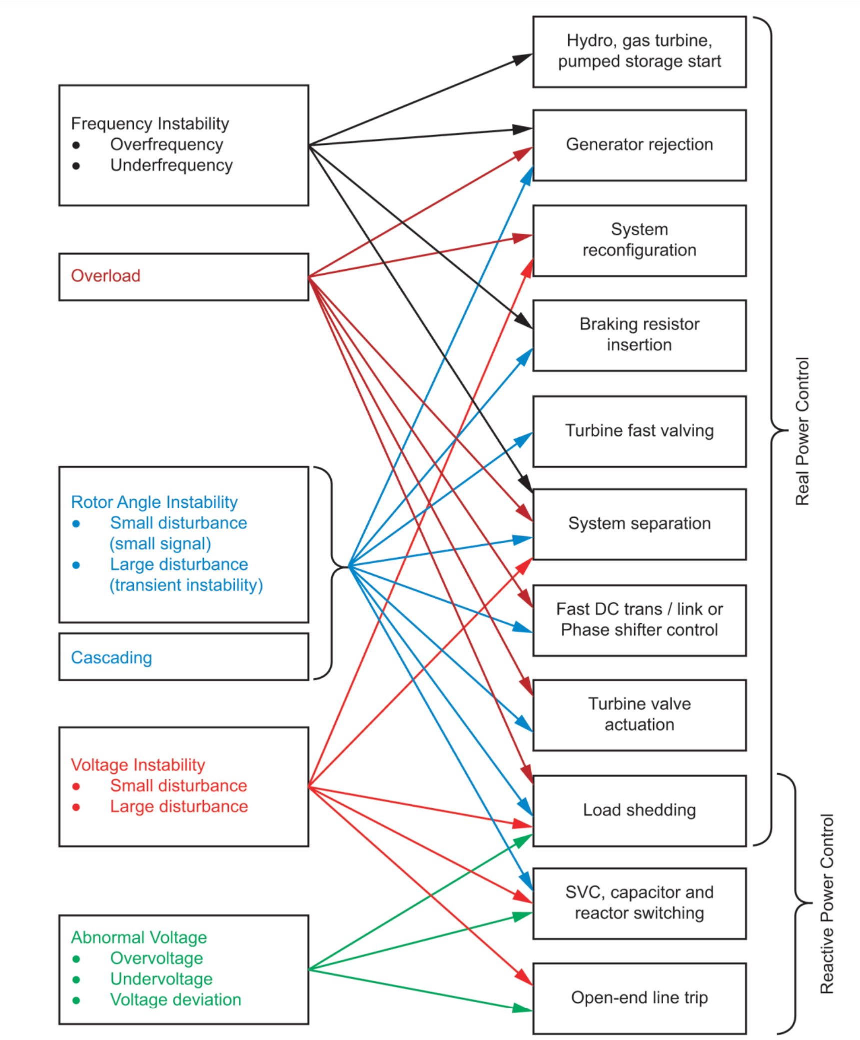


Figure 2.5: Critical power system conditions and common System Integrity Protection Scheme mitigation actions [5]

2.6.4 General Design Approach

The measurement and monitoring stages in the above structure are already well established however; the remaining is not yet maturated as there are significant challenges exist. These challenges can be expressed as time requirement, modeling and simulation accuracy, correct determination of stability margins and controls. It should be noted that RAS applications carefully designed and tailored to the system needs.

Hence, extensive system studies required to create such a scheme. Definition of the problem that necessitates RAS and solution with RAS implementation are obtained through system planning studies such as power flow, stability, and/or other modeling of the power system as part of the transmission operations function. The general objectives of this planning process are as follows:

- Identification of the contingencies that result in unacceptable system conditions. Usually these involve loss of one or more elements in the grid resulting in instability which the system may not be able to recover.
- Identification of the power system operating scenarios in which defined contingency lead violations on the grid elements (ie. Overloading, breaker operation, over/under voltage etc.).
- Among the set of operating conditions, observe grid variables (ie. Voltage, frequency, flows etc.) to define arming conditions for the RAS. If there is no clear set of variables, that define arming conditions, then design system as always armed.
- Identify sequence of actions to resolve and mitigate problems. Among several operating conditions several mitigation actions may exist. Try to obtain intersection of mitigation actions which resolve the related problem in almost all of the operating conditions.
- Order the mitigating actions in terms of solution effectiveness. To reduce the complexity and to increase redundancy, try to obtain minimum set of action. If it is possible adapt volume of mitigating actions with the pre-fault conditions.
- Crosscheck the design with the existing grid RAS applications. Avoid operations that arm or operate other RAS applications. It should be emphasized that cascaded RAS operations may lead to unintended unstable conditions.

CHAPTER 3

THEORETICAL FOUNDATION OF DIRECT METHODS ON TRANSIENT STABILITY

3.1 Transient Stability

Power system stability analysis examines how a power system responds to disturbances. It can be defined as the property of a power system that enables it to remain in steady-state operating condition under normal operating conditions and to regain an acceptable-state of equilibrium after being subjected to a disturbance. The power system stability problem includes three aspects which are: transient stability, voltage stability and frequency stability. Transient stability is a major concern in power system security and reliability because it is the most common type of instability and its impacts can cause greatest economic losses.

The goal of transient stability analysis is to study the stability of grid angles following a major disturbance. Analysis specifically looks at transient changes in the rotor angles of interconnected synchronous machines within the power system. It assesses the system's ability to maintain synchronism for the case of a disturbance that accelerate one or more machines relative to the group of coherent machines

Transient stability analysis can be done in two major ways. The most popular and traditional approach entails using system equations to solve for the system variables in the time domain given a particular disturbance scenario. This approach can be applied to any detailed power system model and provides comprehensive information on state variables. However, the time-domain method has significant drawbacks. It comes with a computational burden as the algebraic and differential equations needs to be solved for each time step, which is particularly challenging for modern power systems with thousands of machines and buses that increases the number of equations. Additionally, time domain simulation method does not produce any information regarding the degree of stability, that is to say how much the case is close to the stability or even how much operation necessary to make it stable, nor does it offer preventive control strategies when the system is unstable, meaning it lacks sensitivity information.

Alternative to the time domain simulations, direct methods to analyze transient stability utilizing energy functions was developed by several researchers in the history [10] [40] [41] [42]. Based on the second rule of the Lyapunov, direct methods give a quantitative measure of system stability without the time - consuming numerical integration of a (post-fault) power system. The assessment time compared the conventional time domain simulations increases the value offered by this approach. In addition, a bunch of information comes with the utilization of direct methods which indeed provide invaluable data when forming a preventive control structure.

3.2 Properties of the Energy Functions

In transient analysis of power systems, energy functions are used to evaluate the stability region surrounding stable equilibrium points. For direct techniques, it is important to construct an energy function for a transient stability model. An energy function extends the concept of a Lyapunov function and must meet three specific conditions as described below. For a general nonlinear autonomous dynamical system V :R”-> R is an energy function for this system if the following three conditions are satisfied [43]:

i) The derivative of the energy function V(x) along any system trajectory, x(t), is non-positive,

ii) V (x) = 0 only if x is an equilibrium point,

iii) V (x(t)) is bounded means x(t) is also bounded.

For the power systems, classical model neglecting losses only include generator motion dynamics with power transfers. Hence the model can be presented as

$$\dot{\delta}_i = \omega_i \tag{3.1}$$

$$\dot{\omega}_i M_i = P_i - D_i\omega_i - \sum_{j=1, j\neq i}^{n} P_i(\delta_i - \delta_i) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} E_i E_j B_{ij} \sin \delta_i - \delta_j \tag{3.2}$$

There exists an energy function for this classical model

$$\mathbf{V}(\delta,\omega) = \frac{1}{2}\sum_{i=1}^{n} M_i\omega_i^2 - \sum_{i=1}^{n} P_i(\delta_i - \delta_i^s) - \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} E_i E_j B_{ij}[\cos(\delta_i - \delta_j) - \cos(\delta_i^s - \delta_j^s)] \tag{3.3}$$

where $x^s = (\delta^s, 0)$ is the stable equilibrium point. It is shown in [44] that the three conditions of energy function stated above are satisfied. As can be seen from equation 2.3 the transient energy function contains both kinetic and potential terms. The system kinetic energy related with the motion of the rotors, hence the first term, relating inertia with the rotor speed constitute system kinetic energy. The potential energy is related with the change in energy flow from initial state to the final state by considering the trajectory.

3.3 Direct Methods

Given pre-fault, faulted and post fault network, direct methods for transient stability follows similar procedures which can be summarized as follows:

- **Step 1.** Simulation of fault-on grid to gather the trajectory.
- **Step 2.** Determine the starting point of the post-fault grid conditions. This can be named as the initial condition of post-fault.
- **Step 3.** Form an applicable energy function.
- **Step 4.** Based on chosen approach, calculate energy value with the trajectory obtained in the first step.
- **Step 5.** Compare system energy described in the 4th step with the critical energy value. If it is smaller than the critical energy, then the system is considered as stable; or vice versa.

In this regard, several methods which were presented in the literature are investigated and the details regarding the approaches will be expressed in detail in the following chapters

3.3.1 Closest Unstable Equilibrium Method

This approach is a conventional method that approximates the stability region boundary by using a certain level set of the energy function passing though the closest UEP [61], [62]. The approach is simple and gives an estimate of the entire stability boundary. This method uses the constant energy surface $(\delta, \omega) : V(\delta, \omega) = U(\delta_1)$, passing through the closest UEP $(\delta_1, 0)$ to approximate the stability boundary $\delta A(\delta_s, 0)$. If a state with its energy function value lower than the assumed constant energy surface, than the state is counted as stable and its trajectory will converge to the UEP point as shown in Figure 3.1.

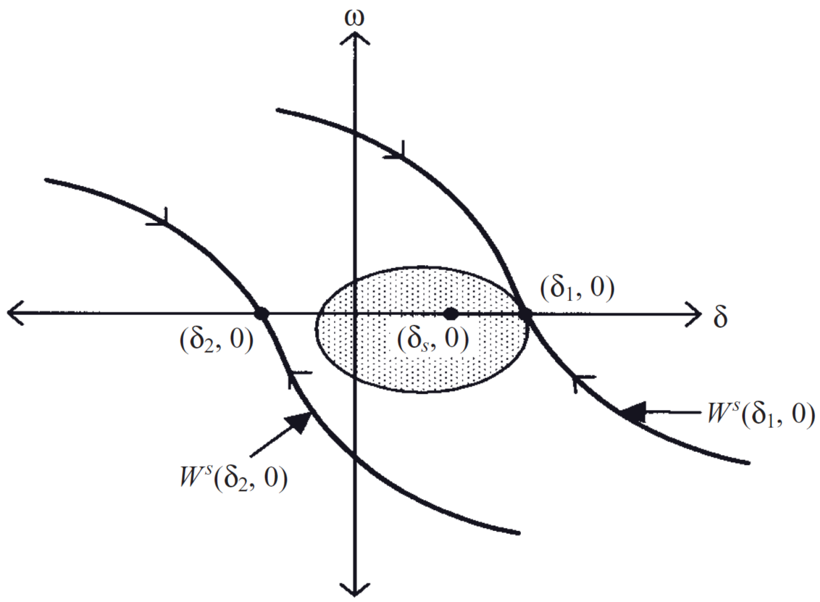


Figure 3.1: Constant energy surface defined by closest UEP method [45]

However, the method is an conservative approach as the energy function surface does not cover all the stability region in general. In this regard, a state whose post-fault trajectory starting outside of the energy function surface but in the stability region may be counted as unstable although it is stable and converging as shown in Figure 3.2.

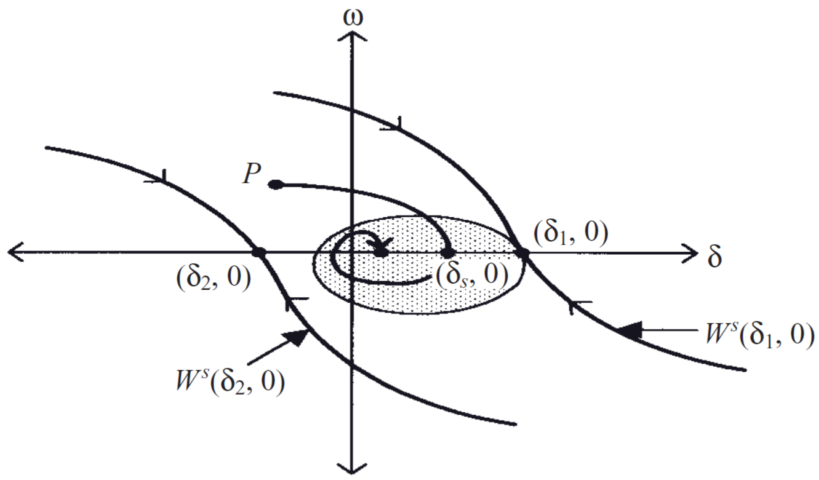


Figure 3.2: Example of conservative evaluation by closest UEP method [45]

In practical applications, the nearest UEP approach is not a preferred direct method due to its strong conservativeness. Hence this technique is not popular.

3.3.2 Controlling Unstable Equilibrium Method

The concept behind the controlling UEP method is that the constant energy surface passing through the controlling UEP can be employed to accurately approximate the relevant part of the stability boundary. For each fault - on trajectory, there exists a unique corresponding UEP, named as controlling UEP, whose stable manifold constitutes the relevant stability boundary.

It is possible to precisely estimate the relevant portion of the stability boundary that the fault-on trajectory is traveling towards by using the constant energy surface that passes through the controlling UEP. In essence, a state is said to lie inside the stability region as defined by the controlling UEP technique if its energy function value is less than that of the controlling UEP. This allows for the assertion, without the need for numerical integration, that the resulting trajectory will converge to the Stable Equilibrium Point (SEP). One of the key advantages of the controlling UEP method is its ability to provide more precise and less conservative stability assessments compared

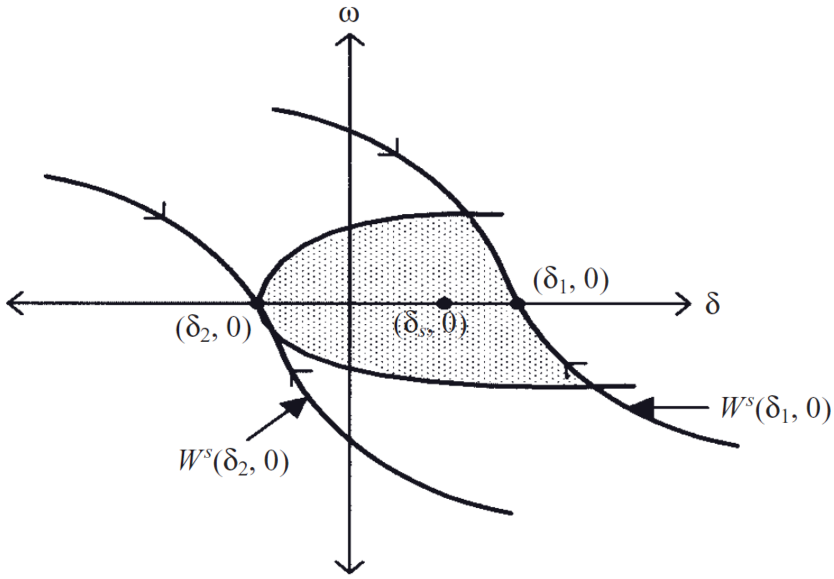


Figure 3.3: Example of conservative evaluation by closest UEP method [45]

to the closest UEP method. The closest UEP method simply uses the UEP closest to the initial condition to approximate the stability boundary, which can lead to overly conservative estimates. In contrast, the controlling UEP method takes into account the specific trajectory of the system following a disturbance, leading to more accurate results.

However, controlling UEP points is hard to find. Identifying the controlling UEP points requires significant computational effort and sophisticated algorithms. The process involves determining the UEPs and their associated stable manifolds, which can be complex, especially for large-scale power systems with numerous generators and buses. The inherent complexity of power system dynamics means that finding these controlling UEP points is not straightforward and often requires iterative methods and advanced techniques. Given the computational intensity involved in identifying controlling UEPs, it can be challenging to apply this method in a real-time operational context. Despite these challenges, the controlling UEP method remains a powerful tool for transient stability assessment. It offers a more refined approach to determining stability boundaries and can significantly enhance the reliability of stability assessments in power systems.

3.3.3 PEBS Method

Potential Energy Boundary Surface (PEBS) method [44] has been introduced in order to avoid challenging identification of unstable equilibrium point (UEP) of interest. PEBS observes the stability region problem in the subspace of rotor angles where it provides an estimate of an exit point. Given the fact that both stable and unstable equilibrium points lie in the subspaces of rotor angle zero, PEBS approach searches the gradient system in (12) and determines the stability boundary

$$\omega_i = 0 = \frac{dV_p(\delta)}{d\delta_i} fori = 1, 2, ..., n \tag{3.4}$$

At the point of maximum potential energy, following steps are carried out to find the critical clearing time and the critical energy. The graphical illustration in Figure 3.4 also describe the steps. 1) The first maximum point of the potential energy V_p identified during fault on trajectory and assumed as the critical energy V_{cr}. 2) Critical clearing time is found via calculation of energy function of the system. t_{cc} is the time when the system energy equals to the critical energy found in step 1. That is $V_k(\omega(t_{cc})) + V_p(\omega(t_{cc})) = V_{cr}$.

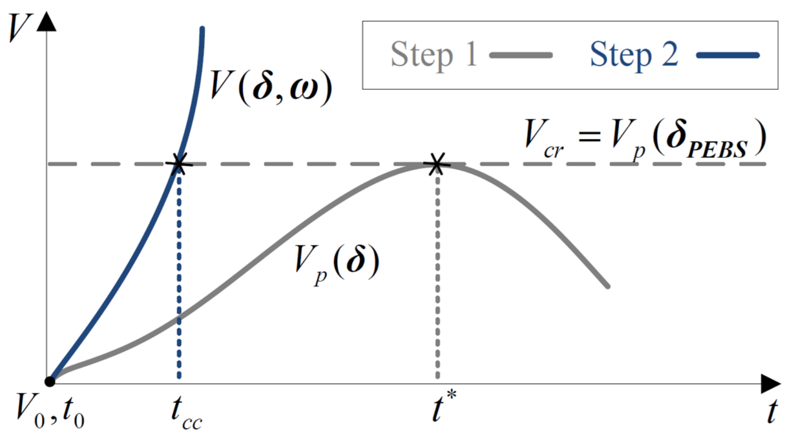


Figure 3.4: Graphical description of PEBS method [46]

PEBS method searches stability boundary on the angle space and does not account the kinetic energy of the exit point. In this illustration, it can be said that PEBS method performs well when the unstable equilibrium point stays close to the exit point. The accuracy may degrade when the exit point has some kinetic energy remaining.

3.4 Possible Application of Direct Methods

Direct methods can be implemented in a grid monitoring applications by providing real-time insights into system stability. These methods allow operators to continuously track transient stability margins and detect early warning signs of instability. By leveraging direct methods, monitoring systems can offer near-instantaneous assessments of disturbances, enabling operators to take corrective actions before stability issues escalate. This real-time capability enhances situational awareness and supports proactive decision-making to maintain grid reliability.

Direct methods are also valuable as a screening tool for power system stability studies. Before performing detailed numerical simulations, system planners can use direct methods to quickly identify potentially unstable operating conditions. This prescreening approach helps reduce computational effort by narrowing down the number of cases that require extensive time-domain analysis. By filtering out stable scenarios early, direct methods improve the efficiency of stability studies and streamline contingency analysis for power system operations.

Beyond their use in screening and monitoring, direct methods offer promising applications for power system transient stability assessment. They can be employed to enhance decision-making during contingency analysis by quickly identifying scenarios that may lead to instability. This allows system operators to take preventive actions before disturbances escalate.

Moreover, direct methods can facilitate stability-constrained economic dispatch, ensuring that power generation schedules consider transient stability limits. This integration can improve both reliability and efficiency by preventing operating conditions that could lead to system instability.

Furthermore, direct methods can be used in special protection schemes. Information gathered from close real-time stability assessments can be utilized to determine settings and control actions. This application enhances grid stability, reducing the likelihood of cascading failures and widespread outages.

In summary, direct methods offer versatile applications for power system transient stability assessment. Their ability to provide fast and insightful stability evaluations makes them valuable tools for improving system resilience, operational efficiency, and stability.

CHAPTER 4

TRANSIENT STABILITY ASSESSMENT USING TEF

4.1 Transient Stability Assessment and the Role of Transient Energy Function

In conventional transient stability analysis, state equations are solved using step-by-step numerical integration. When a disturbance occurs, the system undergoes three main stages: pre-fault, fault-on, and post-fault. First, the initial conditions are determined under pre-fault operating conditions. Then, during the fault-on stage, the system dynamics are governed by modified equations reflecting the disturbance. Once the fault is cleared, post-fault equations model the system's recovery trajectory. These simulations generate rotor angle trajectories over time—if the angles remain bounded, the system is considered stable; otherwise, instability occurs.

A key limitation of conventional transient stability assessments is their scenario-specific nature. Any variation in initial conditions, network configuration, power flows, or fault characteristics necessitates a separate analysis. Factors such as fault location, duration, load levels, and system parameters significantly impact stability, requiring multiple simulations to determine stability limits. This process is not only computationally intensive but also time-consuming, making real-time assessment impractical for modern power systems.

With the increasing penetration of renewable energy, power systems are experiencing rapid changes in operating conditions, making stability assessments even more complex. Traditional numerical integration methods struggle to keep pace with these evolving challenges. Consequently, faster and more efficient techniques are required. The Transient Energy Function (TEF) method has emerged as a promising solution to this problem. Unlike conventional time-domain simulations, which rely on iterative numerical integration, TEF provides an analytical approach to transient stability assessment. It enables direct computation of stability limits, significantly reducing computational effort while enhancing real-time decision-making capabilities.

Ensuring transient stability remains a fundamental challenge in power system operation. The TEF method provides a fast, effective, and computationally feasible approach for real-time transient stability assessment. Furthermore, its capability to quantify stability margins offers valuable insights for system operators, enabling proactive decision-making and preventive control strategies.

In this study, the TEF method is selected as the core framework for transient stability assessment. TEF possesses the potential to meet the requirements for online determination of transient stability limits. By integrating stability assessment with sensitivity analysis, the proposed approach aims to compute stability limits directly, enhancing situational awareness and system security in real time.

4.2 Power System Modeling for Transient Stability Assessment

A power system is described mathematically by a set of non-linear differential equations and a set of algebraic equations as follows:

$$
\begin{aligned}
\dot{x} &= f(x, y) \\
0 &= g(x, y)
\end{aligned}
\tag{4.1}
$$

where

- $f(x, y)$ differential part of the function representing generator modeling .
- $g(x, y)$ algebraic equations
- x and y are the state vector and algebraic variable vector

Short-term transient stability focuses on preservation of synchronism (rotor angle dynamics), this type of stability studies generally consider the classical model of the generator. Hence, the generator is represented as a voltage source behind transient reactance. The generator dynamic equations given in (2.3) define the differential part of the DAE. The set of the differential equations for the n-machine model is given as;

$$\begin{aligned} \dot{\delta}_i &= \omega_i \\ \dot{\omega}_i &= \frac{1}{M_i}(P_{mi} - P_{ei} - D_i\omega_i) \end{aligned} \tag{4.2}$$

where

- δ_i is the rotor angle with respect to synchronous frame
- ω_i is the deviation of the rotor angular speed from synchronous speed ω_s
- P_{ei} is the active electrical power output of the ith machine
- P_{mi} is the mechanical power of the ith generator
- M_i is the constant reflecting inertia of the ith generator

On the other hand, active and reactive mismatch equations are forming the algebraic equations of the system. For an N bus system these equations can be written as;

For generator busses:

$$\begin{gathered} \sum_{k=1}^{n} V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) \\ -V_i[I_{di} \sin(\delta_i - \theta_i) + I_{qi} \cos(\delta_i - \theta_i)] - P_{Li} = 0 \\ \sum_{k=1}^{n} V_i V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) \\ -V_i[I_{di} \cos(\delta_i - \theta_i) - I_{qi} \sin(\delta_i - \theta_i)] - Q_{Li} = 0 \\ i = 1, ..., n \end{gathered} \tag{4.3}$$

For load busses:

$$\begin{gathered} \sum_{k=1}^{n} V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) - P_{Li} = 0 \\ \sum_{k=1}^{n} V_i V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) - Q_{Li} = 0 \\ i = n+1, ..., N \end{gathered} \tag{4.4}$$

In this regard, vectors of the state and algebraic variables of the multi machine power system DAE model in (4.1) can be stated as

$$
\begin{aligned}
\mathbf{x} &= \begin{bmatrix} \delta_1 & \delta_2 & \dots & \delta_n & \omega_1 & \omega_2 & \dots & \omega_n \end{bmatrix}^T \\
\mathbf{y} &= \begin{bmatrix} U_1 & U_2 & \dots & U_N & \theta_1 & \theta_2 & \dots & \theta_N \end{bmatrix}^T
\end{aligned}
\tag{4.5}
$$

A simplified version of the model, called the "reduced network model," can be created by focusing solely on the generator buses. To achieve this simplification, the loads are represented as fixed impedances, and the transient reactances of the generators are incorporated into a modified admittance matrix. This resulting reduced power system model is illustrated in the Figure 4.1.

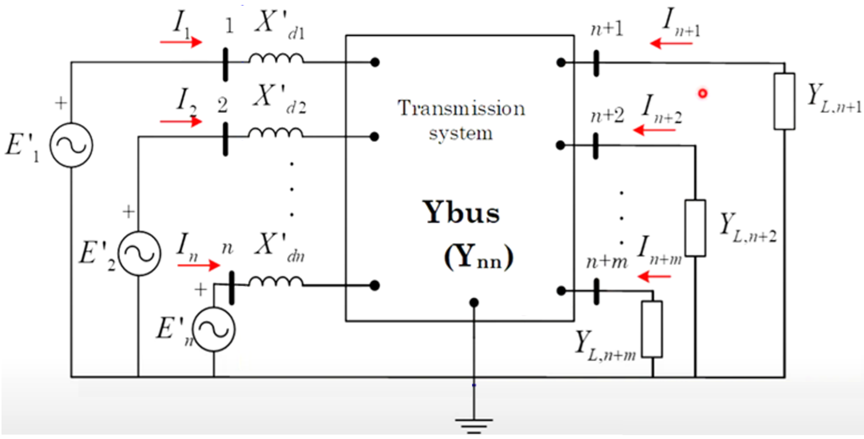


Figure 4.1: Reduced network model presentation

The steps to accomplish this reduction are the following [47]:

- Use the prefault load-flow, $Y_l = (P_{load}{}^{-}jQ_{load})/V^2$, to obtain the admittance value of the loads. These values are included in the diagonal of the admittance matrix Y_{bus}. Then form $Y_{bus}^{new}(i,i) = Y_{bus}(i,i) + Y_l(i)$
- Update Y_{bus}^{new} to include transient reactances. Create the $Y_{12}, Y_{21}, and Y_{22}$ matrices. These three matrices are part of the extended matrix, Y_{ext}, which includes all of the original buses plus the internal nodes. The partition of Y_{ext} is the following matrix:

$$
\begin{bmatrix} Y_{bus}^{new} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}
$$

with n being the number of generators and N being the number of buses.

- For the extended system following hold and elimination can be conducted as shown:

$$\begin{bmatrix} 0 \\ I \end{bmatrix} = \begin{bmatrix} Y_{bus}^{new} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V \\ E \end{bmatrix}$$
$$Y_{red} = Y_{22} - Y_{21}[Y_{bus}^{new}]^{-1}Y_{12} \tag{4.6}$$

Combining of the information gathered through the section, it can be said that only generator internal buses remained in the the reduced network model. By doing so, algebraic equations are dropped and the problem becomes an ODE solution.The dynamic equations for each generator can be expressed as;

$$\begin{aligned} \dot{\delta}_i &= \omega_i \\ M_i\dot{\omega}_i &= P_i - P_{ei} - D_i\omega_i \\ P_{ei} &= \sum_{j=1, j\neq i}^{n} [C_{ij}sin(\delta_i - \delta_j) + D_{ij}cos(\delta_i - \delta_j)] \end{aligned} \tag{4.7}$$

where

$C_{ij} = E_iE_jB_{ij}$ and $D_{ij} = E_iE_jG_{ij}$

δ_i, ω_i rotor angle and speed with respect to synchronous frame

M_i moment of inertia of the ith generator

D_i damping factor

E_i internal voltage magnitude behind transient reactance

G_{ij}, B_{ij} transfer conductance and susceptance for reduced network

$P_i = P_m - E_i^2G_{ii}$ and P_{mi} is the mechanical input

The above equations are valid for pre-fault, fault-on and post-fault systems except the transfer conductance and suseptance terms. Only the electrical powers are changing.

4.3 Classical Model Assumptions

Although the classical model has the ability to show multi-machine system dynamics, there are a bunch of assumptions and limitations exist in such type of a model. The main assumptions behind the classical model are;

i) Mechanical power is fixed to prefault value .(ie, no governor dynamics)

ii) Damping is neglected.

iii) Generators represented as constant EMF behind the transient reactance.

iv) Generator mechanical rotor angle assumed to coincide with the phase angle of the voltage behind transient reactance.

v) Loads are constant taken as impedances which calculated based on the prefault voltage conditions (ie. network is reduced to generator internal buses.)

The classical model is useful for the study of the transient response during the first swing of disturbance. It is wise to assume that motion of the machine are determined primarily by the electrical synchronizing forces and the inertial forces. Limitations of the classical model can be summarized as;

i) Model produce reliable results for first swing stability as the governor dynamics not presented.

ii) Reduction of the network leads to loss of network topology. In this regard it is not possible to observe transient energy changes in different components of the network.

4.4 Center of Inertia Model

The classical model equations are written with respect to any arbitrary synchronous frame. Center of inertia formulation captures the mean motion of the system by referencing all the angles to a motional center. In this sense,it is easier to express the transient behavior of the generator which differentiates from the mean motion. Center of inertia frame can be define utilizing;

$$\delta_0 = \frac{1}{M_T}\sum_{i=1}^{n} M_i\delta_i$$
$$\omega_0 = \frac{1}{M_T}\sum_{i=1}^{n} M_i\omega_i \tag{4.8}$$

where $M_T = \sum_{i=1}^{n} M_i$

then motion equation become

$$\dot{\delta}_0 = \omega_0$$
$$M_T\dot{\omega}_0 = \sum_{i=1}^{n}(P_{mi} - P_{ei}) = \sum_{i=1}^{n} P_i - 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} D_{ij}cos\delta_{ij} = P_{COI} \tag{4.9}$$

Transform also the variable δ_i and ω_i to the COI variables as:

$$\theta_i = \delta_i - \delta_0$$
$$\tilde{\omega}_i = \dot{\delta}_i - \dot{\delta}_0 \tag{4.10}$$

In this illumination system equations can be written as:

$$\dot{\theta}_i = \tilde{\omega}_i$$
$$M_i\tilde{\omega}_i = P_{mi} - P_{ei} - \frac{M_i}{M_T}P_{COI} \tag{4.11}$$

Notice that the center of angle variables satisfy the constraints

$$\sum_{i=1}^{n} M_i\theta_i = \sum_{i=1}^{n} M_i\tilde{\omega}_i = 0 \tag{4.12}$$

4.5 Energy Function Development

System equations considering COI is given in (4.11).Assume this equation will be solved to find post-fault behavior of the ith generator. Multiply equation with $\dot{\theta}_i$ from both sides.

$$M_i\,\tilde{\omega}_i\dot{\theta}_i = (P_i - P_{ei} - \frac{M_i}{M_T}P_{COI})\dot{\theta}_i \tag{4.13}$$

Then integrate (4.13) with respect to time until reaching a stable operating point. In that point $\tilde{\omega}(t_s) = 0$ and $\theta(t_s) = \theta^s$.

$$\int M_i\,\tilde{\omega}_i\dot{\theta}_i dt = \int (P_i - P_{ei} - \frac{M_i}{M_T}P_{COI})\dot{\theta}_i dt + V_i \tag{4.14}$$

Since $\dot{\theta}_i dt = d\theta_i$, (4.14) can be re-written as:

$$V_i = \int_{\theta_i^s}^{\theta_i} [M_i\,\tilde{\omega}_i - P_i - P_{ei} - \frac{M_i}{M_T}P_{COI}]d\theta_i \tag{4.15}$$

The system energy function is the sum of all generators as given in (4.16)

$$V = \int_{\theta_i^s}^{\theta_i} \sum i = 1n[M_i\,\tilde{\omega}_i - P_i - P_{ei} - \frac{M_i}{M_T}P_{COI}]d\theta_i \tag{4.16}$$

Use P_{ei} in equation (4.7) in the energy function and the energy function becomes;

$$\begin{aligned} V|_{\theta_s}^{\theta_i} = (1/2)\sum_{i=1}^{n} M_i\tilde{\omega_i}^2 - \sum_{i=1}^{n} P_i(\theta_i - \theta_s) \\ -\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}[C_{ij}(cos\theta_{ij} - cos\theta_{ij}^s) \\ -\int_{\theta_i^s+\theta_j^s}^{\theta_i+\theta_j} D_{ij}cos\theta_{ij}d(\theta_i+\theta_j)] \end{aligned} \tag{4.17}$$

It should also be noted that $\sum_{i=1}^{n}\frac{M_i}{M_T}P_{COI}\dot{\theta}_i = 0$

This is the general form of the transient energy function. The terms in this function can be interpreted as follows:

- The first term $(1/2)\sum_{i=1}^{n} M_i\tilde{\omega_i}^2$ represents the total kinetic energy change relative to COI.

- The second term $\sum_{i=1}^{n} P_i(\theta_i - \theta_s)$ represents the the change in potential energy in rotors relative to the COI.

- The third term $C_{ij}(cos\theta_{ij} - cos\theta_{ij}^s)$ represents the magnetic energy stored in the branch ij.

- The fourth term $\int_{\theta_i^s+\theta_j^s}^{\theta_i+\theta_j} D_{ij}cos\theta_{ij}d(\theta_i + \theta_j)$ represents the change in dissipated energy of branch ij.

The fourth term,representing the dissipated energy, is in the form of integral and path dependent. Several approaches aim to approximate this term hence to reduce integral. A linear trajectory approach suggested by Athay et. al. in [48] is as follows:

$$I_{ij} = D_{ij}\frac{(\theta_i - \theta_i^s + \theta_j - \theta_j^s)}{(\theta_{ij} - \theta_{ij}^s)sin(\theta_{ij} - \theta_{ij}^s)} \tag{4.18}$$

This approach consist of using linear angle space path approximation for evaluating the contribution of the transfer conductance terms in the energy function by evaluating numerically the integral in (4.17) using the trapezoidal rule. And finally transient energy function can be written as:

$$V(\theta,\omega) = \frac{1}{2}\sum_{i=1}^{n} M_i\tilde{\omega}_i^2 - \sum_{i=1}^{n} P_i(\theta_i - \theta_i^s) - \sum_{i=1}^{n-1}\sum_{j=1}^{n}[C_{ij}(cos\theta_{ij} - cos\theta_{ij}^s) - I_{ij} \tag{4.19}$$

where $I_{ij} = D_{ij}\frac{(\theta_i - \theta_i^s + \theta_j - \theta_j^s)}{(\theta_{ij} - \theta_{ij}^s)sin(\theta_{ij} - \theta_{ij}^s)}$

4.6 Transient Energy Computation

The procedure for computing the transient energy function, and its application to assess the system transient stability, consists of the following steps.

1. Compute prefault period. First, read the input data and performs a load flow analysis on the system before any fault occurs. This analysis yields the power, voltage

magnitude, and voltage angle at each bus. These results are then used to calculate the internal voltage magnitude and angle of every generator in the system.

$$E_i \angle \delta_i = \overline{V_i} + j \acute{x}_{di} \frac{P_i - jQ_i}{V_i^2} for i = 1, 2, ..., n \tag{4.20}$$

2. Form the augmented admittance matrix that represents the network nodes, with two key modifications: all loads are represented as constant admittances connected to ground, and the internal nodes of the generators are added to the matrix.

3. Similarly compute fault on and post fault admittance matrices.

4. Compute the fault on trajectory by solving system ordinary diffential equations shown in (4.11) and search for $\frac{dV_{potentialP}}{d\delta} = 0$. At that point sysetm potential energy is maximum and kinetic energy is minimum.

5. Find unstable equilibrium point and compute critical energy. Details of the PEBS method are given in chapter 3.

CHAPTER 5

PROPOSED REMEDIAL ACTION SCHEME

5.1 Overview of the Scheme

The main motivation of this study is to develop an online system wide monitoring and control scheme in order to ensure system stability at all operating conditions. In this regard, energy function based online stability assessment and margin based RAS is formed as seen in Figure 5.1.

As shown in the figure online tool start with the data collection from PMU and SCADA and topology processors. Although this is not the topic of this study it is an important part of the tool as the data quality is the first necessity for the accurate assessment. Hence a reliable data flow from mentioned data sources and a robust state estimation is seen as a must have.

The first part of the proposed structure in this study is the contingency screening and ranking part. In this part, contingency ranking based on dot product of rotor acceleration relative to the center of inertia (COI)is utilized. Critical contingencies is filtered out via this process hence the number of cases that further assessed for stability will be reduced.

The stability assessment for the critical contingencies will be conducted via energy functions. Margins for critical cases calculated together with the margin sensitivities.

The arming conditions and the countermeasures for remedial action scheme is defined based on the results for margins and margin sensitivities. Coherent grid clusters in the sense of margin sensitivities is determined in order to form remedial action scheme in an online manner.

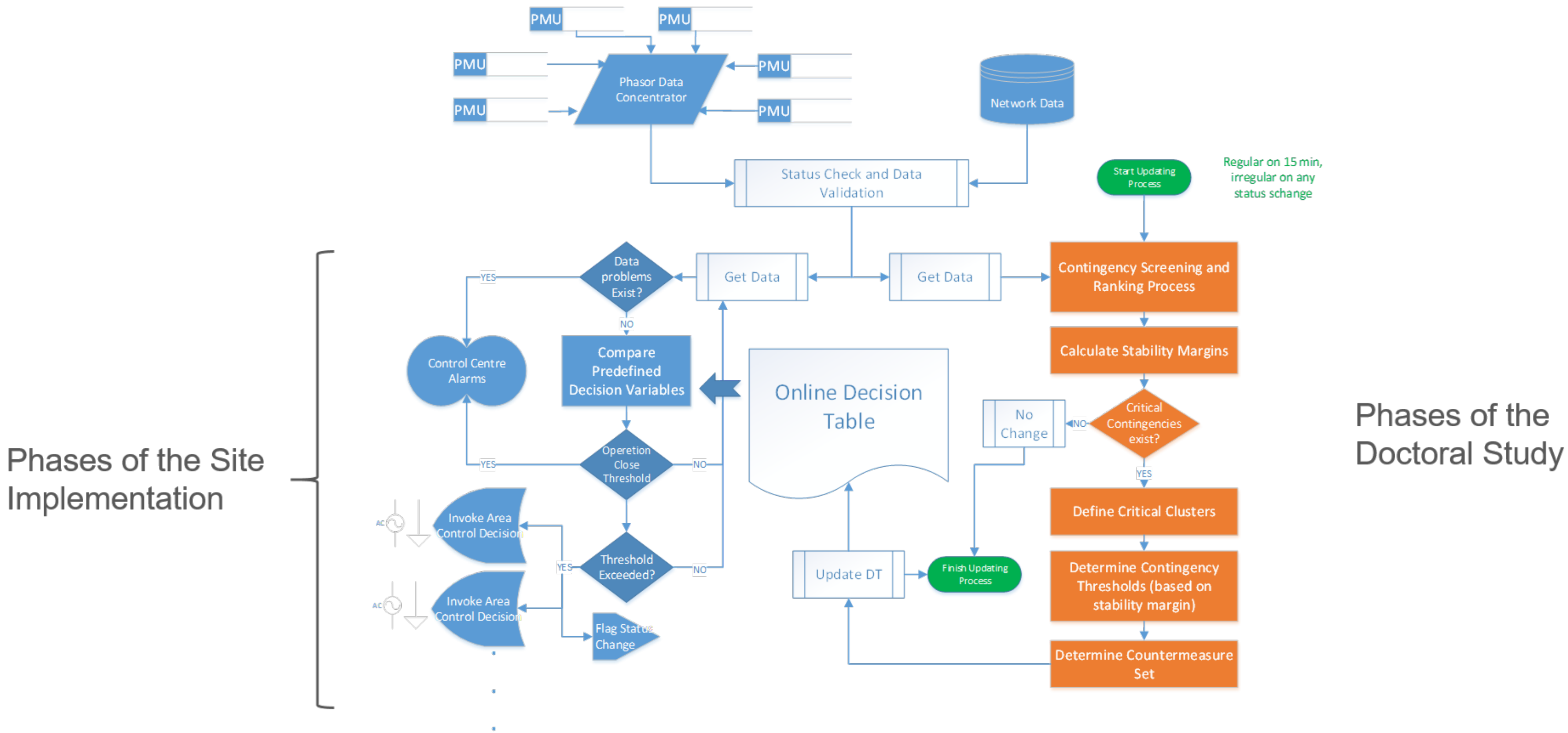


Figure 5.1: Proposed system integrity protection scheme

In the following sections details for each part of the proposed structure is given.

5.2 Contingency Ranking and Screening

For large and complex power systems, analyzing every possible contingency in full detail is both impractical and unnecessary. Instead, engineers use fast and accurate screening methods to manage computations effectively. A good screening method must correctly rank contingencies based on their severity. To do this well, the method should provide a clear measure of how severely the system is affected in a transient state.

Direct methods are widely used because they offer a precise measure of stability. Energy margin and the equivalent equal area criterion have been applied for years. Many approaches exist to approximate Transient Energy Function (TEF) calculations, each balancing speed and accuracy differently. Fu and Bose [49] compared three screening methods based on coherency, transient energy conversion, and dot products of system variables. Additionally, a composite index, which assigns different weights to the prior defined indexes and sums up their contributions was proposed. Chan [25] proposed a method that sorts contingencies into four categories: transiently unstable, oscillatory unstable, stable but poorly damped, and stable and well-damped. This classification helps prioritize critical cases. In [13] , seven BCU classifiers as discussed were improved and were employed to enable a fast screening of a given set of contingencies. The method was tested on a large system with 14,500 buses. It was capable of capturing all unstable cases, 92 to 99.5 percentage of the stable cases and needed approximately 1.356 s per contingency. Another approach, described in [50], uses the Sparse Transient Energy Function (STEF) and applies three filtering steps. The first filter, based on the exit point (EP), provides a fast but conservative ranking by removing most stable cases. The second filter, using the minimum gradient point (MGP), further refines the ranking. The final filter, based on the unstable equilibrium point (UEP), determines the exact energy margin and evaluates the remaining contingencies with high precision. Paper [51] introduced an method called the "Second Kick" approach. This technique combines time simulation with transient energy function analysis. It calculates kinetic and potential energy before applying a "Second Kick," which is a fixed-duration fault after the original fault clearing. This extra step improves accuracy by determining the transient energy margin for both stable and unstable cases. Unlike traditional TEF methods, this approach does not require knowledge of the UEP, making it more flexible.

The key goal of contingency ranking is to compute indices that measure system severity. Effective indices improve screening accuracy while maintaining speed. In this study, a TEF-based approach was used to rank contingencies. A dot product method was applied to detect the exit point, which marks the first peak of transient potential energy in the post-fault system. This was calculated using the dot product of the fault-on power mismatch vector and the fault-on angle vector. Since rotor speed is also crucial, the contingency ranking process incorporated a dot product approach that considered rotor angle, rotor speed, and accelerating power. This method enhances precision and ensures reliable contingency ranking for large-scale power systems.

$$\text{dot} =< \omega, \theta >= \sum_{i=1}^{NG} \omega_i(\theta_i - \theta_i^{cl}) \tag{5.1}$$

where

- δ_i: Rotor angles with respect to COI
- δ_i^{cl}: Rotor angle at fault clearing time for generator i.
- ω: Rotor speed with respect to COI

The dot product can give the measure of total accelerating power and the power system (including generator and network) response to this accelerating power; therefore it could be a good index for ranking dynamic contingencies.

5.3 Stability Assessment and Energy Margins for Critical Cases

For determining the stability limit, the quantitative measure of whether the system is stable or unstable is the key factor. Much research effort has gone into finding a good index to indicate the degree of system stability in on-line DSA. The normalized energy margin in the TEF method is one of them. The transient energy function can be derived directly from the dynamic equations written with respect to the COI as given in eq. 3.19.

In the TEF method, the transient energy margin is defined as

$$EnergyMargin(EM) = V_{cr} - V_{cl}$$

where is the transient energy at the controlling unstable equilibrium point (UEP) and Vcl is the transient energy at fault clearing time. For a given contingency, the system is stable for a positive value of EM and unstable for a negative value of EM .

In terms of transient stability assessment, the main steps are given as follows:

1. Get the critical contingencies list from the ranking results
2. Prepare pre-fault, fault-on and post-fault matrices
3. For each contingency apply a three phase fault and solve for system equations
4. Obtain the exit point and UEP via observing max of the potential energy
5. Calculate critical energy utilizing PEBS approach defined in section 2.3.3.
6. From critical energy also calculate the critical clearing time that is simulation time to reach the critical energy.

5.4 Defining Energy Margin Sensitivities

Energy margin sensitivity measures how the energy margin of generators changes when there is a small shift in power dispatch. Even though changes in grid topology parameters, such as admittance matrices, are minimal, shifting generation affects machine angles and clearing speeds. As a result, the system's unstable equilibrium point shifts, altering the energy margins of critical generators. These margins may increase or decrease depending on the shift. However, finding the optimal generation shift is complex due to the many possible adjustments. To make this process efficient, certain steps must be followed. First, similar to sensitivity analysis, energy margin sensitivity is defined as the change in energy margin caused by a unit change in generation. To maintain balance between generation and load, any increase or decrease in one generator's output must be compensated by adjustments in the remaining generators. Second, system dynamics must be considered. When power generation changes suddenly, the remaining generators naturally adjust based on their inertial response. The generation shift should be conducted in the same way to ensure system stability. Third, the process is refined by focusing on critical generators. The most effective way to influence the energy margin of a critical generator is usually by adjusting its own output. Instead of assessing all generators, the analysis prioritizes those most likely to impact system stability. The followed procedure is shown in Figure 5.2.

Finally, energy margin sensitivities for critical generators are calculated for each contingency within a given operating condition. This is done using the Transient Energy Function (TEF) approach, as explained in Section 2. This method helps identify the most effective generation in terms of energy margin, improving grid stability and reliability.

5.5 Determining Remedial Action Set

In this comprehensive study, we identify and analyze critical and coherent grid clusters based on energy margin sensitivity. These clusters serve as a fundamental basis for developing effective remedial actions, which are essential for maintaining grid stability and operational efficiency. Constructing a robust and well-structured set of remedial measures capable of addressing a wide range of operating conditions and contingencies is a challenging task. This research introduces an innovative approach that leverages coherent grid clusters formed through margin sensitivities, enabling a more systematic and data-driven method for enhancing grid resilience. Hence, an online adaptive remedial action scheme structure that gathers reliable actions can be formed in an automatized manner which surely relieve the grid operations.

In the proposed approach obtained energy margin sensitivities for each generator and contingency is calculated in order to create countermeasure pool in case of critical contingencies. Obtained sensitivity data through analysis are then clustered utilizing

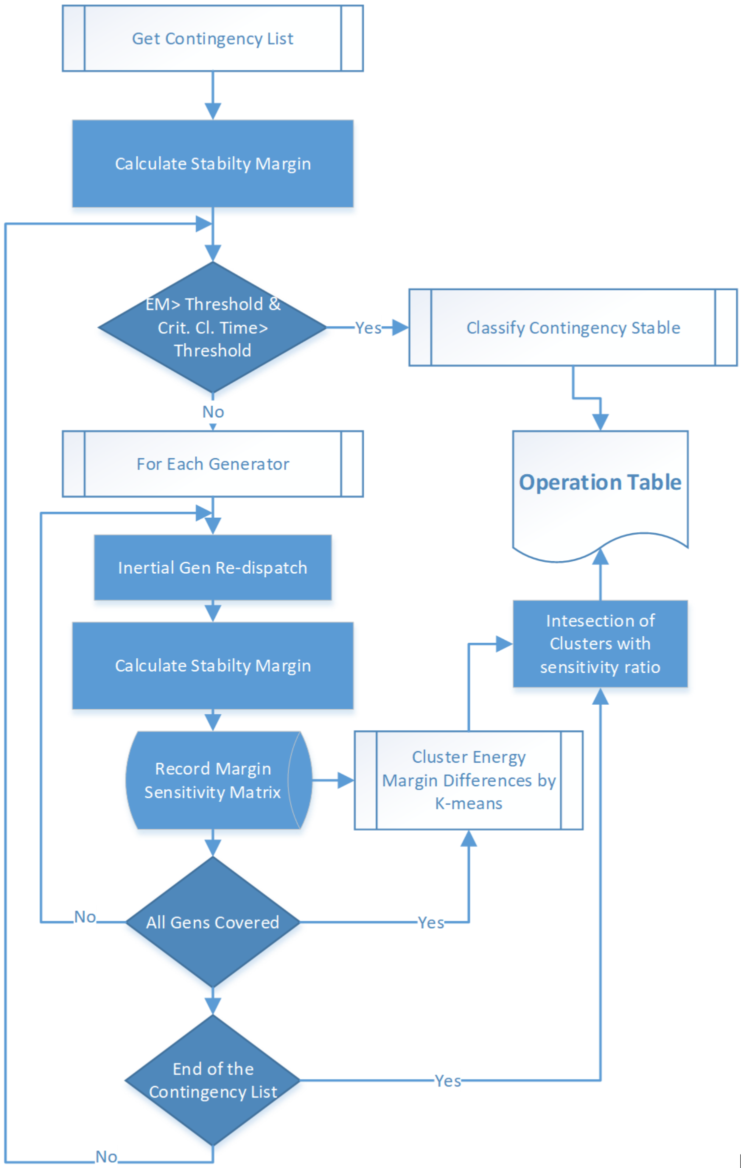


Figure 5.2: Flowchart of the energy margin sensitivity calculation and clustering

K-means approach according to their effectiveness. This grouping automatically sort and screen the countermeasures in order to ease the selection among the possibilities.

The main method in this clustering depends on the K-means algorithm. K-means aims to partition n observations into k clusters with the nearest mean using sum of the squared Euclidean distances between each data point and the cluster center of the subset that contains data point, as shown in (5.2). This process accelerates the identification of coherent grid clusters in terms of energy margin sensitivities. Moreover, the decision-making process for determining remedial actions for each contingency is largely automated through this methodology.

$$E(m_1, ..., m_n) = \sum_{i=1}^{N} \sum_{k=1}^{M} ||x_i - m_k||^2 \tag{5.2}$$

A critical aspect of the K-means algorithm is determining the optimal number of clusters, as it directly impacts the accuracy, interpretability, and effectiveness of the clustering results. To address this challenge, the widely used Elbow Method is employed. This technique involves plotting the within-cluster sum of squares against the number of clusters and identifying the "elbow" point, where increasing the number of clusters beyond this threshold yields diminishing returns. In this study, an advanced automated elbow selection technique [52] is implemented to refine the clustering process based on energy margin sensitivity, ensuring a well-balanced trade-off between granularity and computational efficiency.

The next step is to determine possible remedial actions for the grid for changing operating conditions. This is an crucial step in order to reduce number of countermeasure of the grid, in order to reduce signaling requirements and complexity of the RAS design. In this regard, the change in remedial actions according to the changing operating conditions are investigated. The main aim is to understand whether a global set of remedial actions which satisfy all the problematic cases can be defined or not. The results section provides an in-depth discussion on how the structural properties of the grid topology enable remedial actions to be constrained within a globally defined and limited set. This predefined set remains consistent across various operating scenarios and can be seamlessly integrated into remedial action schemes. Stability margin sensitivity emerges as a promising metric for identifying this robust and efficient set of remedial actions, offering a systematic and data-driven approach to enhancing grid stability and resilience.

This novel approach significantly enhances the identification of coherent grid clusters by leveraging energy margin sensitivities. Additionally, it facilitates the automation of the decision-making process, allowing for rapid and precise determination of remedial actions required to address various contingency scenarios.

CHAPTER 6

ONLINE TEF BASED REMEDIAL ACTION SCHEME DESIGN

This chapter gives details regarding the contingency screening and on-line transient stability assessment results and summarizes the main findings. The chapter begins with a short description of the test cases utilized in the study.Then details and characteristics regarding the developed operating scenarios is introduced. Following chapters presents the results obtained in proposed scheme throughout the operating scenarios.

6.1 Test Cases

6.1.1 IEEE 39 Bus Test Case

The IEEE 39-bus test system, also known as the 10-machine New-England power system, is a widely used benchmark in power system studies for analyzing power flow, stability, control, and optimization. It represents a simplified model of the New England power grid and is commonly used in several research studies. Model consists of 39 Buses of which 10 Buses are generator Buses, 12 transformers, 10 generators, 34 transmission lines, and 19 loads. The system operates at a nominal voltage of 345 kV for the transmission network.The system is shown in Figure 6.1. This test system will be modeled to use for validating the proposed method.

There are 10 generators whose MVA rating ranging from 300 – 10000 MVA, are connected to the system. Generator 1 is modeled as high capacity generator to represent the interconnection. Table 6.1 gives the initial load flow conditions of the 10 generators buses.

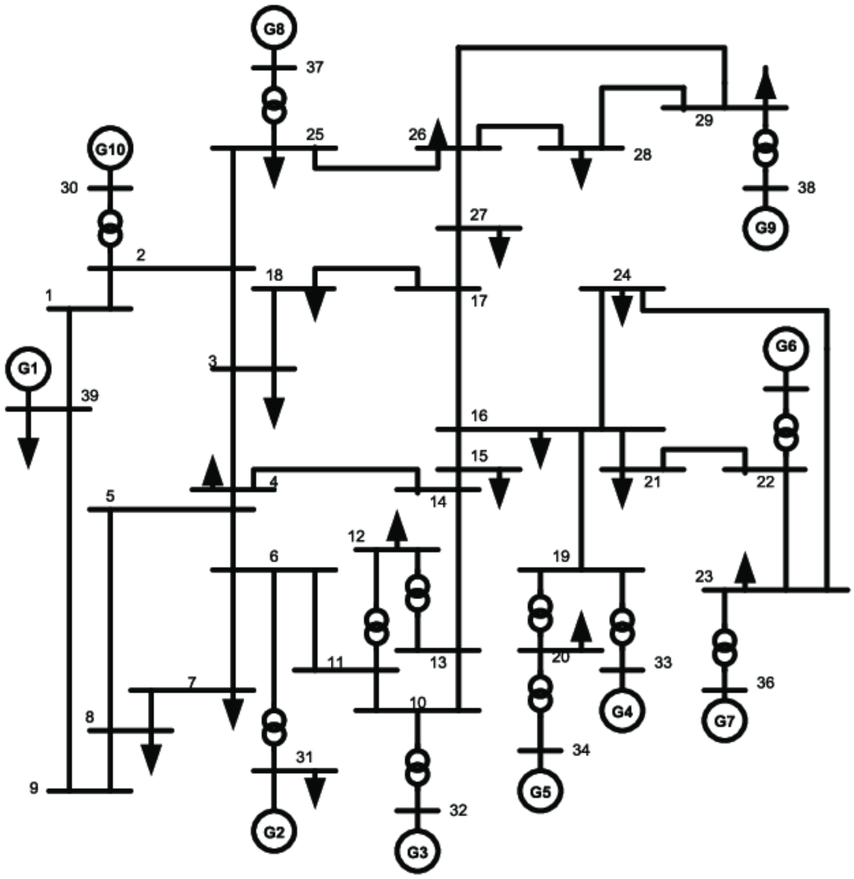


Figure 6.1: IEEE 39 Bus Test System

Table 6.1: IEEE 39 Bus - Loading of the generators (base case)

Name	Active Power	Reactive Power	Loading
	MW	Mvar	%
G 01	1594.08	164.08	16
G 02	489.84	225.2	77.04
G 03	544	224.56	73.6
G 04	544	119.28	69.6
G 05	408	157.36	72.88
G 06	411.76	184.4	56.4
G 07	412.96	90.8	60.4
G 08	399.84	57.28	57.68
G 09	680	57.12	68.24
G 10	410.64	153.84	43.84

6.1.2 IEEE 118 Bus Test Case

he IEEE 118-bus test system is a larger and more complex benchmark power system model used for advanced power system studies. It represents a portion of the American Electric Power System (in the U.S. Midwest) as of December 1962 and is widely used for testing power flow, stability, optimization, and control algorithms. Model consists of 118 buses, 28 transformers, 54 generators, 186 transmission lines, and 91 constant impedance loads. 19 out of 54 generators are synchronous generators, others are synchronous condensers and motors. The system operates at multiple voltage levels, including 138 kV, 161 kV, and 230 kV.The system is shown in Figure 6.2. With 118 buses, 54 generators, and 186 branches, it provides a more realistic and challenging scenario compared to smaller test systems like the IEEE 39-bus system. This test system will be modeled to use for validating the proposed method.

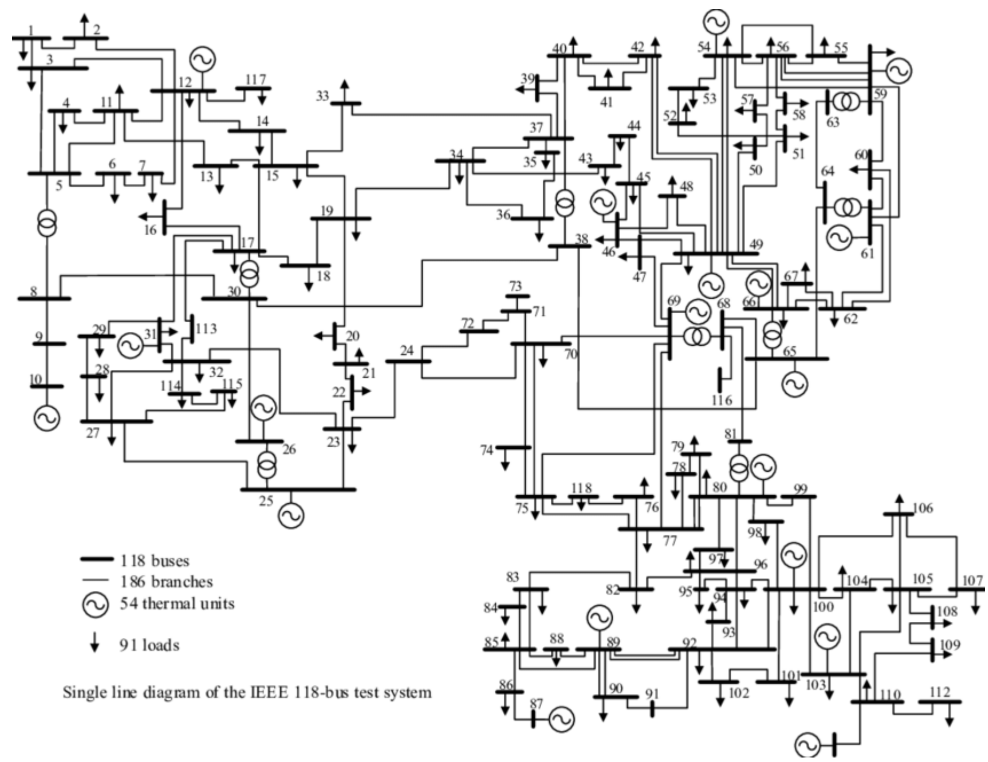


Figure 6.2: IEEE 118 Bus Test System

There are 18 conventional synchronus generators whose MVA rating ranging from 50 – 850 MVA, are connected to the system. Table 6.2 gives the initial load flow conditions of the 19 generators buses.

Table 6.2: IEEE 118 Bus - Loading of the generators (base case)

Name	Active Power	Reactive Power	Loading
	MW	Mvar	%
Gen 10	432.48	-93.28	74.96
Gen 100	240.72	115.12	80.88
Gen 103	50.4	32	59.68
Gen 111	46.72	32	56.64
Gen 12	90.8	48.8	82.48
Gen 25	114.88	38.56	36.72
Gen 26	269.68	14.8	65.92
Gen 31	23.04	24	44.4
Gen 46	34.08	18.88	52
Gen 49	196.24	100.64	66.8
Gen 54	57.84	32	66.08
Gen 59	117.36	74.56	59.68
Gen 61	140.16	28.24	61.36
Gen 65	267.76	17.84	52.4
Gen 66	364	25.44	71.28
Gen 69	431.84	-47.76	73.68
Gen 80	413.76	152.08	74.72
Gen 87	20.24	10.32	30.32
Gen 89	434	27.36	52.08

6.2 Operating Scenarios

To examine the impact of varying operating conditions on stability assessment and remedial action determination, both test cases were subjected to four distinct operating scenarios, as outlined in Table 6.3. These scenarios were designed to simulate real-world grid conditions, including daily load variations (representing day and night load shifts), and changes in generation distribution, such as shifts in generation from loaded to unloaded generators or vice versa.

The first operating condition was simulated to observe behavior of the stressed grid condition,hence the loads of the grid were linearly scaled up by 20 percent. The change in the generation conditions were also given in Table 6.4, respectively for the 39 and 118 test systems.

Table 6.3: Scenarios Covered in the Study

Scenario Name	Test Case	Operating Condition	Total Grid Generation
1A	IEEE 39 Bus	High Load Case	7368 MW
1B	IEEE 118 Bus	High Load Case	4680 MW
2A	IEEE 39 Bus	Low Load Case	4898 MW
2B	IEEE 118 Bus	Low Load Case	3140 MW
3A	IEEE 39 Bus	Increased generation in critical generators	6140 MW
3B	IEEE 118 Bus	Increased generation in critical generators	3740 MW
4A	IEEE 39 Bus	Decreased generation in critical generators	6145 MW
4B	IEEE 118 Bus	Decreased generation in critical generators	3750 MW

Table 6.4: Generator dispatch for cases 1A and 1B

39 Bus Test Case				118 Bus Test Case			
Name	Active Power	Reactive Power	Loading	Name	Active Power	Reactive Power	Loading
	MW	Mvar	%		MW	Mvar	%
G 01	1992.6	205.1	20	Gen 10	540.6	-116.6	93.7
G 02	612.3	281.5	96.3	Gen 100	300.9	143.9	101.1
G 03	680	280.7	92	Gen 103	63	40	74.6
G 04	680	149.1	87	Gen 111	58.4	40	70.8
G 05	510	196.7	91.1	Gen 12	113.5	61	103.1
G 06	514.7	230.5	70.5	Gen 25	143.6	48.2	45.9
G 07	516.2	113.5	75.5	Gen 26	337.1	18.5	82.4
G 08	499.8	71.6	72.1	Gen 31	28.8	30	55.5
G 09	850	71.4	85.3	Gen 46	42.6	23.6	65
G 10	513.3	192.3	54.8	Gen 49	245.3	125.8	83.5
				Gen 54	72.3	40	82.6
				Gen 59	146.7	93.2	74.6
				Gen 61	175.2	35.3	76.7
				Gen 65	334.7	22.3	65.5
				Gen 66	455	31.8	89.1
				Gen 69	539.8	-59.7	92.1
				Gen 80	517.2	190.1	93.4
				Gen 87	25.3	12.9	37.9
				Gen 89	542.5	34.2	65.1

The second operating condition is an inverted version of the first one. In this case a more relaxed grid conditions were simulated to observe behavior during night conditions. Hence the loads of the grid were linearly scaled down by 20 percent. The change in the generation conditions were also given in Table 6.5 , respectively side by side for the 39 and 118 test systems.

Table 6.5: Generator dispatch for cases 2A and 2B

39 Bus Test Case				118 Bus Test Case			
Name	Active Power	Reactive Power	Loading	Name	Active Power	Reactive Power	Loading
	MW	Mvar	%		MW	Mvar	%
G 01	1275.3	-28.4	12.8	Gen 10	362.4	-131	65.3
G 02	391.9	112.3	58.2	Gen 100	201.7	46.4	62.7
G 03	435.2	103.4	55.9	Gen 103	42.2	24.1	48.6
G 04	435.2	43.6	54.7	Gen 111	39.1	24.5	46.2
G 05	510	125.2	87.5	Gen 12	76.1	22.3	63.4
G 06	329.4	103.6	43.2	Gen 25	96.2	-7.3	29.2
G 07	330.4	27.2	47.4	Gen 26	226	-18.4	55.3
G 08	319.9	-22	45.8	Gen 31	19.3	15.1	32.7
G 09	544	-60.3	54.7	Gen 46	28.6	-2.5	38.3
G 10	328.5	75.5	33.7	Gen 49	164.4	19.9	50.2
				Gen 54	48.5	40	62.9
				Gen 59	98.3	43	46.1
				Gen 61	117.4	-15.3	50.8
				Gen 65	224.4	-37.5	44.4
				Gen 66	305	-3.4	59.6
				Gen 69	361.9	-136.4	65.5
				Gen 80	346.7	95.4	60.9
				Gen 87	17	5.3	23.7
				Gen 89	363.6	-5	43.6

In the third loading scenario, the grid's response to a modified generation distribution was thoroughly investigated. This scenario was specifically designed to increase the generation share of the critical generators identified in the first two loading scenarios. By doing so, the study aimed to evaluate the grid's behavior under a more challenging and stability-risky operating condition. This approach allowed for a deeper analysis of the grid's resilience and the effectiveness of the newly developed special protection scheme (SPS) in addressing potential stability issues. The SPS was rigorously tested for its capabilities in constraint filtering and stability assessment, particularly under stressed conditions where the grid is more vulnerable to disturbances.In this context, the changes made to the generation distribution scenario in the 39-bus test system and the 118-bus test system are shown in Table 6.6.

Table 6.6: Generator dispatch for cases 3A and 3B

39 Bus Test Case				118 Bus Test Case			
Name	Active Power	Reactive Power	Loading	Name	Active Power	Reactive Power	Loading
	MW	Mvar	%		MW	Mvar	%
G 01	1030.1	85.9	10.3	Gen 10	170.6	-134.5	36.8
G 02	646.3	223.9	97.7	Gen 100	252.1	88.6	81
G 03	680	214.9	89.1	Gen 103	84	25.8	87.9
G 04	680	114.3	86.2	Gen 111	84	20.9	86.6
G 05	510	166.9	89.4	Gen 12	31.6	39.8	40.7
G 06	543.3	194.4	72.1	Gen 25	101.1	5.5	30.7
G 07	544.8	94.1	79	Gen 26	126.1	-11.9	30.9
G 08	527.4	-1.9	75.3	Gen 31	20.3	25.4	43.4
G 09	850	27.4	85	Gen 46	30	-11.7	43
G 10	128.8	142.7	19.2	Gen 49	172.8	107	61.6
				Gen 54	50.9	40	64.8
				Gen 59	103.3	44	48.2
				Gen 61	123.4	-13.2	53.2
				Gen 65	235.7	-11.9	46.1
				Gen 66	320.4	-28.1	62.8
				Gen 69	380.2	42	64.8
				Gen 80	364.2	190.1	69.6
				Gen 87	63	6	84.4
				Gen 89	696.5	77.1	83.9

A fundamental challenge in designing special protection schemes (SPS) is ensuring that the system operates with both reliability and selectivity. This means that the SPS should be capable of triggering protective actions precisely when required while avoiding unnecessary or false activations that could disrupt normal grid operations. Achieving this balance is essential for maintaining system stability and preventing unintended consequences.

To rigorously assess the selectivity of the proposed SPS, a fourth loading scenario has been developed. The primary objective of this scenario is to evaluate whether the protection scheme can effectively distinguish between critical and non-critical grid conditions, ensuring that it activates only in response to genuine contingencies. In this scenario, the load on critical generators within the power grid has been deliberately reduced, creating conditions that allow for a thorough examination of the SPS's decision making capabilities.

Within this context, modifications have been made to the generation distribution patterns in standard test systems to simulate realistic operational conditions. Specifically, adjustments in generation dispatch for the 39-bus and 118-bus test systems have been implemented, as detailed in Table 6.7.

Table 6.7: Generator dispatch for cases 4A and 4B

39 Bus Test Case				118 Bus Test Case			
Name	Active Power	Reactive Power	Loading	Name	Active Power	Reactive Power	Loading
	MW	Mvar	%		MW	Mvar	%
G 01	2180.9	211	21.9	Gen 10	383.8	-129.8	68.7
G 02	398	204.7	63.9	Gen 100	260.6	94.1	84
G 03	442.1	195.3	60.4	Gen 103	74.3	34.6	82
G 04	442.1	90.9	56.4	Gen 111	74.3	28.7	79.7
G 05	510	159.6	89.1	Gen 12	92.9	46.4	83.1
G 06	334.6	160.6	46.4	Gen 25	260.6	22.6	79.3
G 07	335.5	61.1	48.7	Gen 26	323.8	9.4	79
G 08	324.8	74.5	47.6	Gen 31	55.8	30	84.4
G 09	552.5	-0.6	55.3	Gen 46	55.8	1.5	74.4
G 10	634.5	174.1	65.8	Gen 49	245.3	41.4	75.4
				Gen 54	74.3	40	84.4
				Gen 59	173.2	64.4	79.3
				Gen 61	173.2	-10.5	74.5
				Gen 65	223	-13.8	43.6
				Gen 66	223	10.8	43.6
				Gen 69	185.8	-85.5	34.7
				Gen 80	185.8	190.1	45.1
				Gen 87	55.8	8.6	75.2
				Gen 89	620.7	17.4	74.4

For each of the test cases, all possible N-1 contingencies over the transmission lines have been studied. In this regard a three phase fault is applied at the middle section of the lines. Critical energies and critical clearing times for the contingency cases are calculated. Further stability classification for designated 0.15 sec lasted fault is also applied. All the classifications were performed according to this clearing time. For example, a contingency having energy margin smaller than this its critical energy case is classified as stable otherwise the contingency is classified unstable.

6.3 Contingency Ranking Results for Scenarios

First process in the proposed TEF based RAS is to conduct contingency ranking. The main aim of contingency ranking and screening in the scheme is to efficiently identify and prioritize the most severe potential contingencies that could threaten the stability.

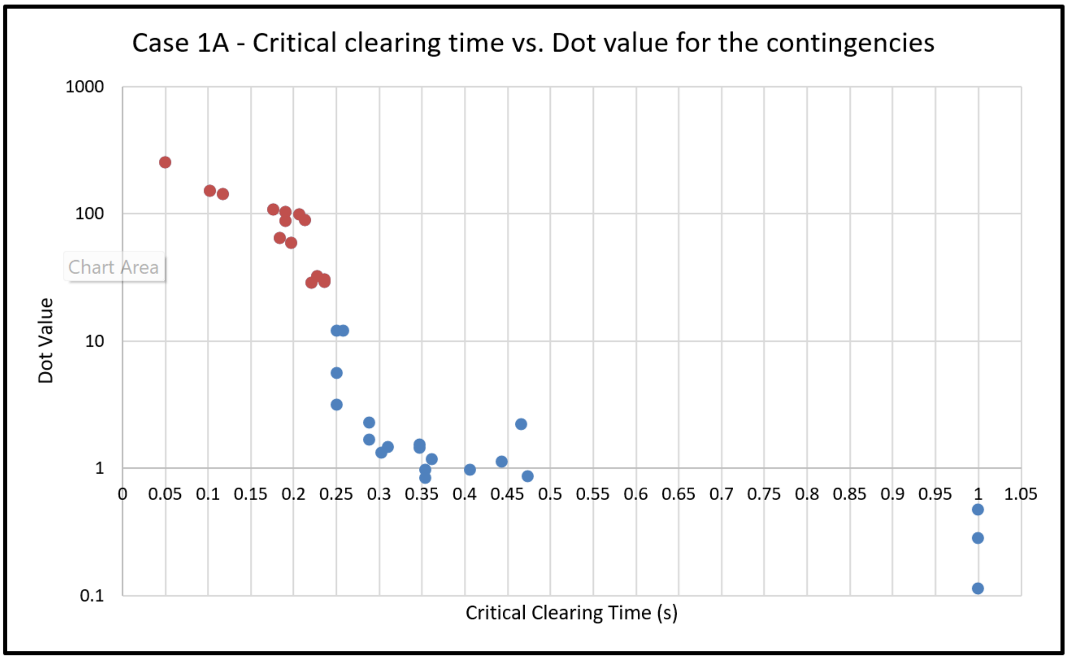
The approach for contingency ranking and screening for the proposed scheme was given in Section 5.2. In this section results obtained through this process are introduced and examined.

Contingency ranking and screening starts with gathering system snapshot and contingency set. For this study, list of contingencies were taken as transmission lines. In each of the contingency, a three phase to ground fault is applied at the middle section of the line for an interval of 0.25 seconds. The system trajectories, which describe the dynamic response of the system to the fault,are obtained from hybrid TEF assessment approach. There are total of 34 contingencies in the IEEE 39 bus test case and 186 case for IEEE 118 bus case.

In order to assess reliability, contingency ranking results results were tested against a reference stability assessment. In the reference assessment method, rotor angle trajectories and critical clearing time for the contingency is calculated using detailed time domain simulations.

6.3.1 Results for IEEE 39 Bus Cases

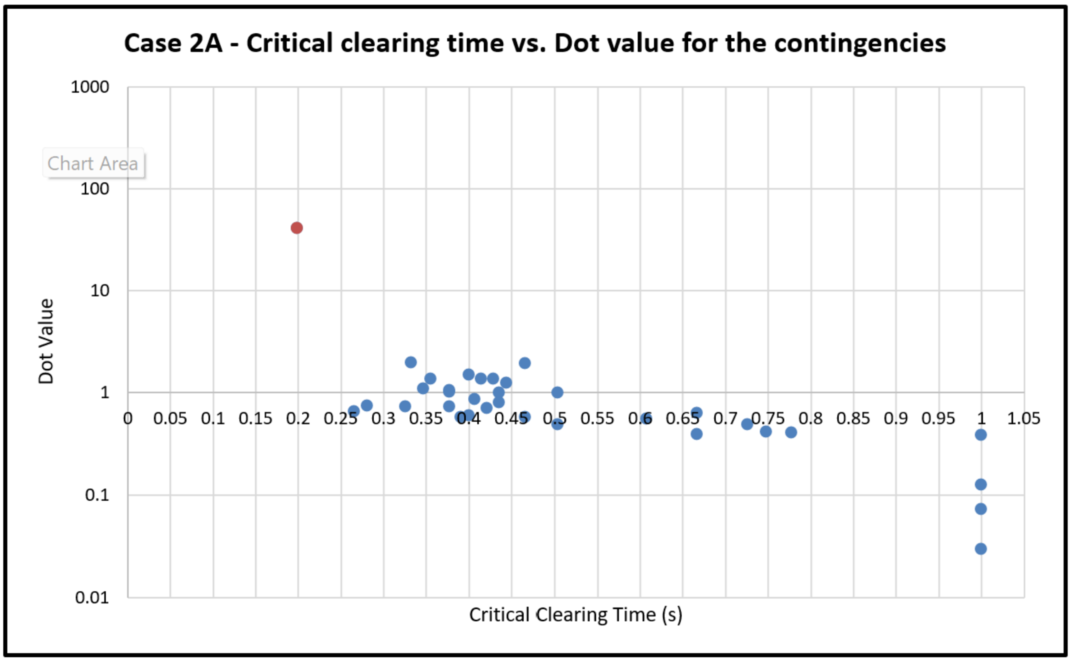
Figure 6.3 presents the results of the contingency ranking and screening process for Case 1A. The findings indicate that the dot product-based ranking effectively distinguishes between stable and unstable cases, demonstrating a clear separation between the two. Contingencies with critical clearing times below 0.25 seconds are prioritized by the ranking function, ensuring that the most vulnerable cases are highlighted. Furthermore, highly critical contingencies exhibit higher dot product values, reinforcing their relative severity among the evaluated cases. When compared to the reference assessment, the implemented contingency ranking method exhibits high reliability and accuracy, validating its effectiveness in ranking evaluation.



Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 28 - 29	0.05	250.4836	Line 04 - 05	0.236	28.75508	Line 14 - 15	0.354	0.96871
Line 26 - 29	0.102	150.8607	Line 06 - 07	0.236	30.41403	Line 23 - 24	0.354	0.831482
Line 26 - 28	0.117	141.2471	Line 17 - 27	0.25	3.181601	Line 02 - 03	0.362	1.172281
Line 26 - 27	0.176	107.9565	Line 05 - 08	0.25	12.06223	Line 17 - 18	0.406	0.979314
Line 25 - 26	0.184	64.39226	Line 22 - 23	0.25	5.603935	Line 08 - 09	0.443	1.127562
Line 02 - 25	0.191	87.48678	Line 07 - 08	0.258	12.02038	Line 16 - 19	0.466	2.200458
Line 05 - 06	0.191	101.9805	Line 16 - 17	0.288	1.665796	Line 03 - 18	0.473	0.858888
Line 10 - 13	0.198	58.95931	Line 04 - 14	0.288	2.286529	Line 01 - 02	1	0.278695
Line 10 - 11	0.206	99.70192	Line 16 - 21	0.302	1.337587	Line 01 - 39	1	0.114996
Line 06 - 11	0.213	88.65762	Line 16 - 24	0.31	1.46705	Line 09 - 39	1	0.471711
Line 13 - 14	0.221	28.53436	Line 15 - 16	0.347	1.536701			
Line 21 - 22	0.228	31.95121	Line 03 - 04	0.347	1.443271			

Figure 6.3: Contingency ranking and screening results for Case 1A

The results of the contingency ranking and screening function for the Case 2A is given in Figure 6.4. In this case the total load hence the strees on the grid is reduced. The results have shown that the critically of the contingencies are reduced similar to the grid condition as expected. There are only one case critical, whose critical clearing time is lower than 0.25 seconds, is shown in the results. Therefore it can be said that implemented method works well to give consistent results based on the changing grid condition.

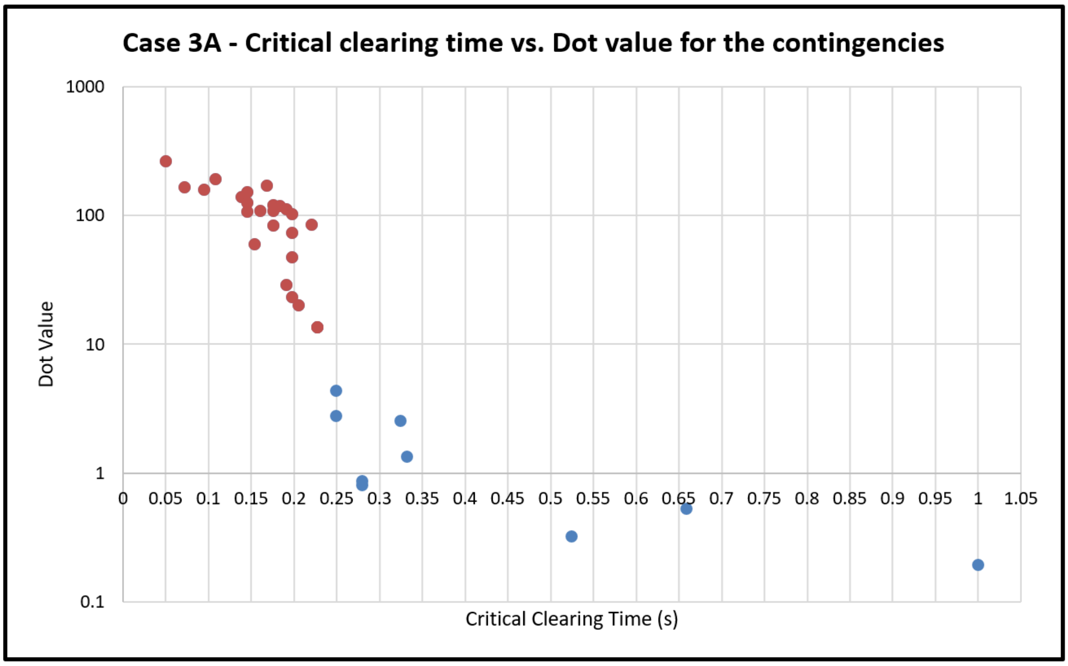


Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 28 - 29	0.198	40.76478	Line 02 - 25	0.399	0.608067	Line 17 - 18	0.607	0.552821
Line 26 - 29	0.265	0.657883	Line 13 - 14	0.406	0.871599	Line 23 - 24	0.666	0.390049
Line 26 - 28	0.28	0.746923	Line 04 - 05	0.414	1.358758	Line 03 - 04	0.666	0.634092
Line 26 - 27	0.325	0.731868	Line 22 - 23	0.421	0.709411	Line 14 - 15	0.725	0.485036
Line 05 - 06	0.332	1.994299	Line 05 - 08	0.429	1.379524	Line 02 - 03	0.748	0.41526
Line 10 - 13	0.347	1.099851	Line 16 - 21	0.436	0.798048	Line 03 - 18	0.777	0.410674
Line 10 - 11	0.354	1.369695	Line 15 - 16	0.436	1.002721	Line 08 - 09	1	0.38391
Line 06 - 11	0.377	0.732386	Line 07 - 08	0.443	1.258002	Line 01 - 02	1	0.073147
Line 16 - 24	0.377	1.012918	Line 16 - 19	0.466	1.957243	Line 01 - 39	1	0.029861
Line 16 - 17	0.377	1.068401	Line 21 - 22	0.466	0.583292	Line 09 - 39	1	0.123171
Line 25 - 26	0.391	0.578182	Line 17 - 27	0.503	0.481381			
Line 06 - 07	0.399	1.511643	Line 04 - 14	0.503	0.989242			

Figure 6.4: Contingency ranking and screening results for Case 2A

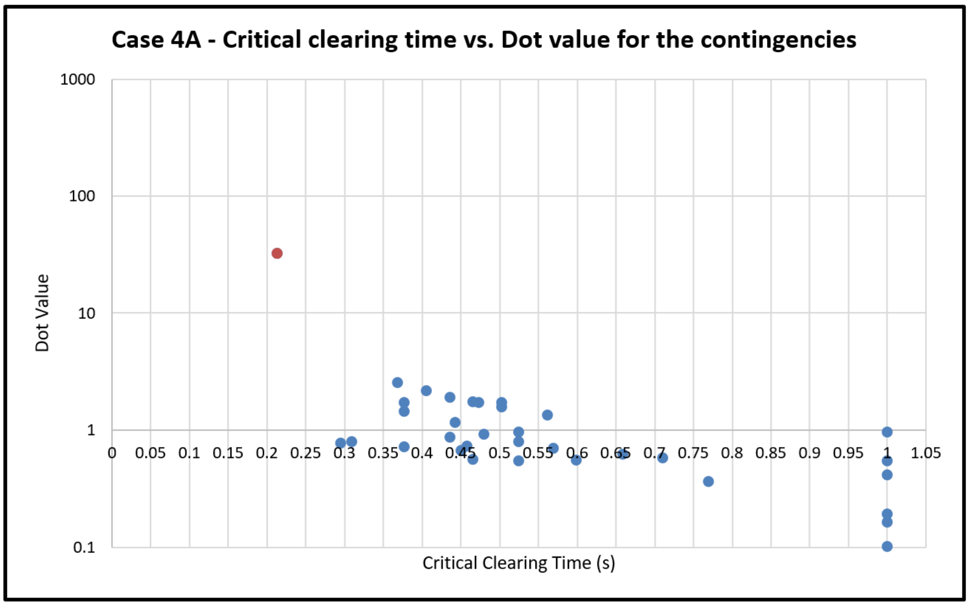
The results of the contingency ranking and screening function for Case 3A are presented in Figure 6.5. In this scenario, the total load—and consequently, the overall stress on the grid—has increased, particularly for the critical generators operating under initial conditions. As expected, this has led to a significant rise in contingency criticality. More than half of the contingencies have been marked as critical, with their respective critical clearing times falling below 0.25 seconds, as indicated in the results.

Conversely, reducing the stress on critical generators leads to a decrease in the number of critical contingencies, which aligns with expectations. This observation is further validated by the results obtained for Case 4A, as illustrated in Figure 6.6. The comparison between these two cases confirms that the implemented method consistently produces reliable and accurate results by adapting to changing grid conditions.



Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 28 - 29	0.05	262.7286	Line 10 - 11	0.176	119.7061	Line 03 - 04	0.228	13.41728
Line 26 - 29	0.072	164.1752	Line 13 - 14	0.176	83.11327	Line 23 - 24	0.25	4.331395
Line 26 - 28	0.095	156.1517	Line 06 - 07	0.184	116.9726	Line 14 - 15	0.25	2.762804
Line 02 - 25	0.109	190.8862	Line 16 - 24	0.191	28.63525	Line 03 - 18	0.28	0.858109
Line 26 - 27	0.139	138.4549	Line 05 - 08	0.191	110.789	Line 02 - 03	0.28	0.805949
Line 21 - 22	0.146	106.4	Line 16 - 21	0.198	22.96235	Line 16 - 19	0.325	2.533975
Line 25 - 26	0.146	124.1239	Line 22 - 23	0.198	72.63867	Line 08 - 09	0.332	1.333525
Line 05 - 06	0.146	150.3772	Line 07 - 08	0.198	101.3894	Line 01 - 02	0.525	0.321371
Line 16 - 17	0.154	59.57499	Line 17 - 27	0.198	47.34898	Line 09 - 39	0.659	0.530162
Line 10 - 13	0.161	108.3696	Line 15 - 16	0.206	19.8712	Line 01 - 39	1	0.19367
Line 06 - 11	0.169	167.7181	Line 04 - 14	0.221	84.45197			
Line 04 - 05	0.176	108.3587	Line 17 - 18	0.228	13.42646			

Figure 6.5: Contingency ranking and screening results for Case 3A

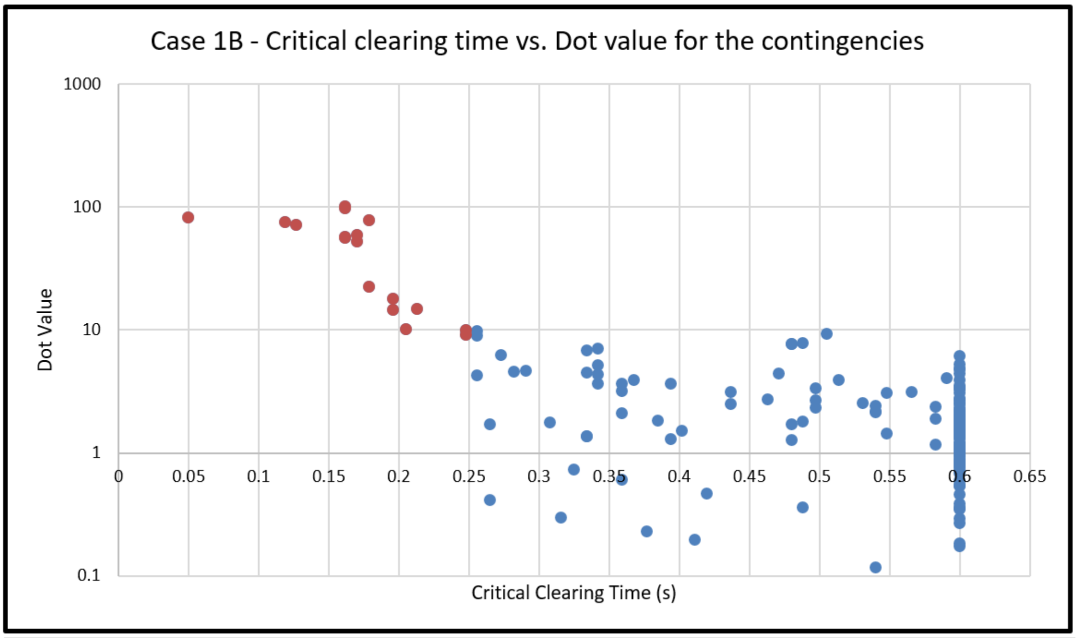


Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 28 - 29	0.213	32.22185	Line 02 - 25	0.458	0.726902	Line 17 - 27	0.599	0.553962
Line 26 - 29	0.295	0.771213	Line 04 - 05	0.466	1.740731	Line 17 - 18	0.659	0.615177
Line 26 - 28	0.31	0.793659	Line 25 - 26	0.466	0.555161	Line 03 - 18	0.711	0.5773
Line 05 - 06	0.369	2.524569	Line 05 - 08	0.473	1.721025	Line 23 - 24	0.77	0.361188
Line 10 - 11	0.377	1.719747	Line 02 - 03	0.48	0.91944	Line 08 - 09	1	0.413606
Line 10 - 13	0.377	1.426729	Line 16 - 19	0.503	1.70036	Line 01 - 02	1	0.193885
Line 26 - 27	0.377	0.716998	Line 07 - 08	0.503	1.566623	Line 14 - 15	1	0.539131
Line 06 - 11	0.406	2.163139	Line 21 - 22	0.525	0.545241	Line 03 - 04	1	0.949424
Line 06 - 07	0.436	1.894704	Line 16 - 17	0.525	0.95642	Line 01 - 39	1	0.101573
Line 16 - 24	0.436	0.86892	Line 15 - 16	0.525	0.794926	Line 09 - 39	1	0.165537
Line 13 - 14	0.443	1.154715	Line 04 - 14	0.562	1.332528			
Line 22 - 23	0.451	0.663169	Line 16 - 21	0.57	0.697309			

Figure 6.6: Contingency ranking and screening results for Case 4A

6.3.2 Results for IEEE 118 Bus Cases

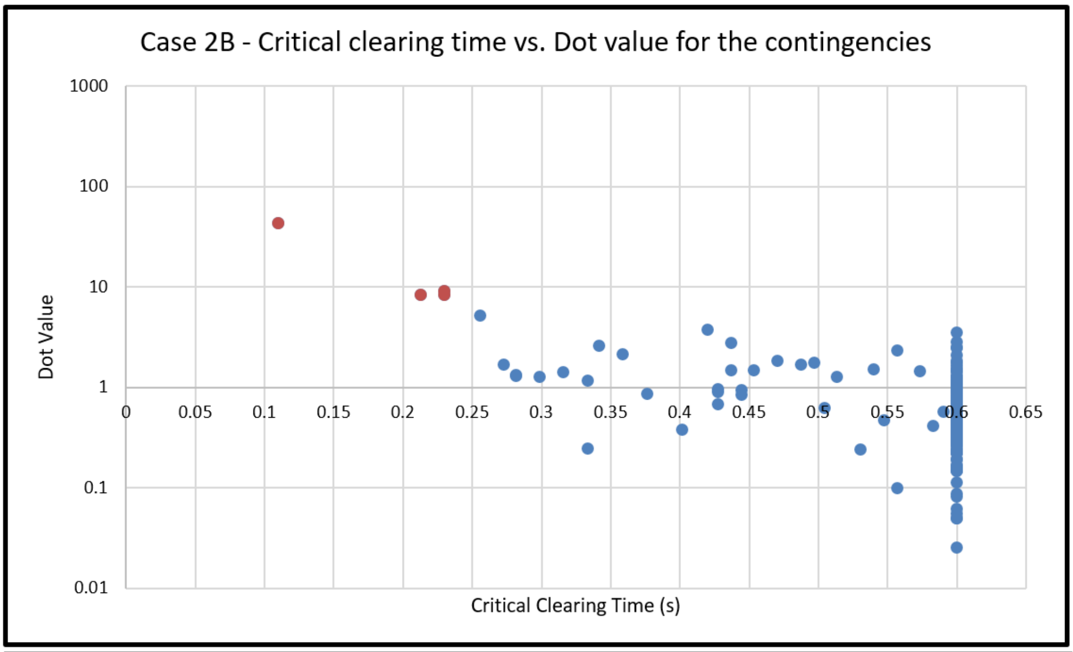
Figure 6.7 presents the results of the contingency ranking and screening process for Case 1B. The findings indicate that the dot product-based ranking effectively distinguishes between stable and unstable cases, demonstrating a clear separation between the two. Contingencies with critical clearing times below 0.25 seconds are prioritized by the ranking function, ensuring that the most vulnerable cases are highlighted. Furthermore, highly critical contingencies exhibit higher dot product values, reinforcing their relative severity among the evaluated cases. When compared to the reference assessment, the implemented contingency ranking method exhibits high reliability and accuracy, validating its effectiveness in ranking evaluation.



Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 8-30	0.05	81.84	Line 12-16	0.256	9.779095	Line 78-79	0.342	6.948237
Line 4-5	0.119	74.90	Line 77-80 C1	0.256	4.217431	Line 94-100	0.342	5.174045
Line 26-30	0.127	71.26	Line 2-12	0.256	8.99315	Line 16-17	0.359	2.100693
Line 5-6	0.162	56.99	Line 88-89	0.265	0.412222	Line 77-80 C2	0.359	0.601896
Line 5-11	0.162	55.87	Line 3-12	0.265	1.701529	Line 92-102	0.359	3.180214
Line 65-68	0.162	97.41	Line 77-78	0.273	6.245198	Line 100-103	0.359	3.636311
Line 68-116	0.162	100.39	Line 69-75	0.282	4.565379	Line 17-18	0.368	3.871393
Line 4-11	0.17	52.26	Line 69-70	0.291	4.629867	Line 89-92 C2	0.377	0.228289
Line 11-12	0.17	59.05	Line 64-65	0.308	1.761824	Line 14-15	0.385	1.804557
Line 68-81	0.179	77.88	Line 89-90 C2	0.316	0.294726	Line 15-19	0.394	3.617645
Line 89-92 C1	0.179	22.41	Line 79-80	0.325	0.727892	Line 38-65	0.394	1.281612
Line 6-7	0.196	14.42	Line 12-117	0.334	1.360758	Line 13-15	0.402	1.512697
Line 7-12	0.196	17.69	Line 15-17	0.334	4.477206	Line 85-89	0.411	0.193643
Line 3-5	0.205	10.08	Line 30-38	0.334	6.785097	Line 80-97	0.42	0.462268
Line 69-77	0.213	14.86	Line 1-3	0.334	1.345767	Line 18-19	0.437	3.089405
Line 11-13	0.248	9.15	Line 17-113	0.342	4.2872	Line 92-93	0.437	2.49407
Line 12-14	0.248	9.95	Line 23-25	0.342	3.616626	Line 99-100	0.463	2.717831

Figure 6.7: Contingency ranking and screening results for Case 1B

The results of the contingency ranking and screening function for the Case 2B is given in Figure 6.8. In this case the total load hence the stress on the grid is reduced. The results have shown that the critically of the contingencies are reduced similar to the grid condition as expected. There are only one case critical, whose critical clearing time is lower than 0.25 seconds, is shown in the results. Therefore it can be said that implemented method works well to give consistent results based on the changing grid condition.

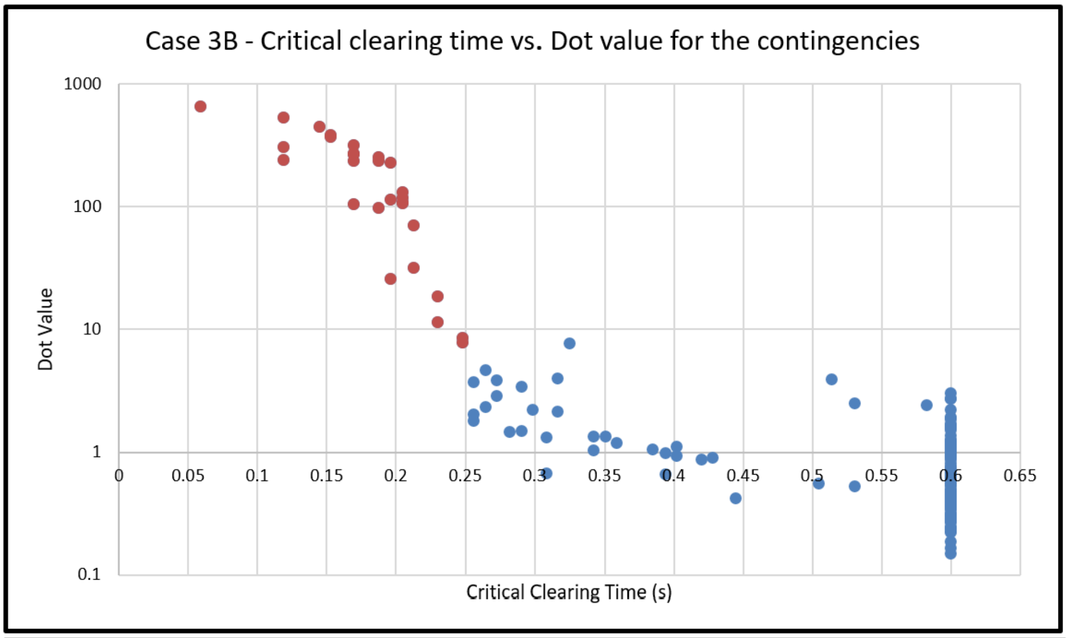


Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 8-30	0.11	43.01	Line 11-13	0.428	0.890855	Line 88-89	0.557	0.097878
Line 4-5	0.213	8.35	Line 12-14	0.428	0.958455	Line 15-19	0.574	1.427332
Line 65-68	0.23	9.01	Line 64-65	0.428	0.679031	Line 9-10	0.583	0.408638
Line 68-116	0.23	8.23	Line 30-38	0.437	2.756512	Line 8-9	0.591	0.569108
Line 68-81	0.256	5.19	Line 69-75	0.437	1.466279	Line 1-3	0.6	0.459481
Line 11-12	0.273	1.69	Line 2-12	0.445	0.842623	Line 12-117	0.6	0.44719
Line 5-6	0.282	1.30	Line 12-16	0.445	0.929308	Line 13-15	0.6	0.488746
Line 5-11	0.282	1.31	Line 69-70	0.454	1.45837	Line 14-15	0.6	0.602785
Line 4-11	0.299	1.25	Line 15-17	0.471	1.827891	Line 15-33	0.6	0.737005
Line 7-12	0.316	1.40	Line 94-100	0.488	1.667214	Line 16-17	0.6	0.717533
Line 6-7	0.334	1.16	Line 17-113	0.497	1.723754	Line 17-31	0.6	0.795553
Line 89-92 C1	0.334	0.24	Line 3-12	0.505	0.615813	Line 18-19	0.6	1.163925
Line 69-77	0.342	2.59	Line 100-103	0.514	1.267914	Line 19-20	0.6	0.573814
Line 26-30	0.359	2.11	Line 79-80	0.531	0.235833	Line 19-34	0.6	0.554217
Line 3-5	0.377	0.86	Line 17-18	0.54	1.509242	Line 20-21	0.6	0.281607
Line 77-80 C1	0.402	0.38	Line 38-65	0.548	0.464193	Line 21-22	0.6	0.236975
Line 77-78	0.42	3.69	Line 78-79	0.557	2.320935	Line 22-23	0.6	0.377033

Figure 6.8: Contingency ranking and screening results for Case 2B

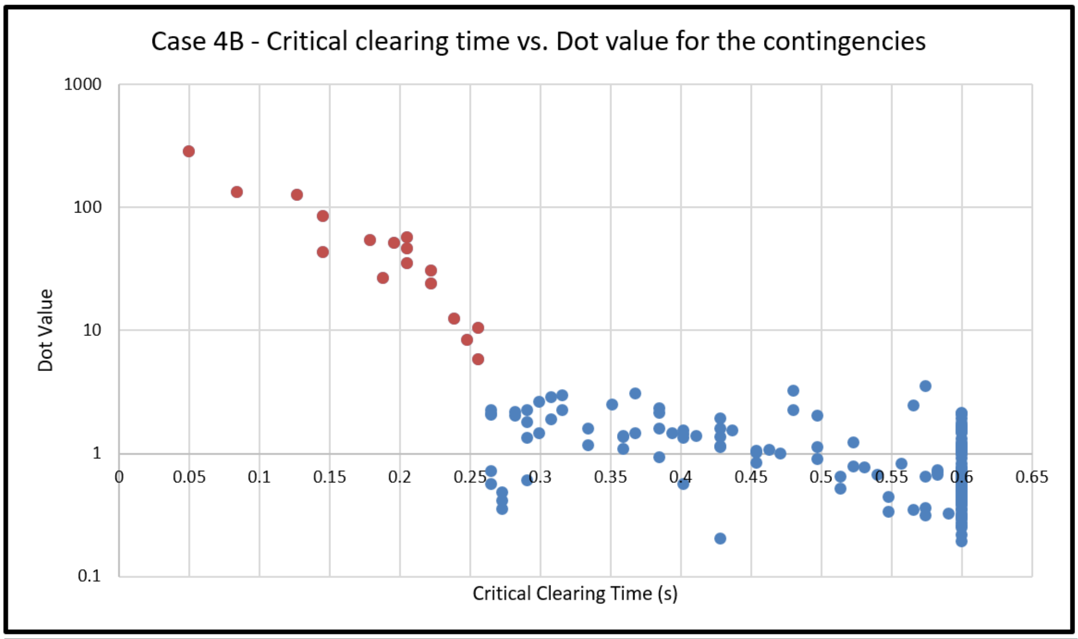
The results of the contingency ranking and screening function for Case 3B are presented in Figure 6.9. In this scenario, the total load—and consequently, the overall stress on the grid—has increased, particularly for the critical generators operating under initial conditions. As expected, this has led to a significant rise in contingency criticality. More than half of the contingencies have been marked as critical, with their respective critical clearing times falling below 0.25 seconds, as indicated in the results.

Conversely, reducing the stress on critical generators leads to a decrease in the number of critical contingencies, which aligns with expectations. This observation is further validated by the results obtained for Case 4A, as illustrated in Figure 6.10. The comparison between these two cases confirms that the implemented method consistently produces reliable and accurate results by adapting to changing grid conditions.



Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 89-92 C1	0.059	654.97	Line 93-94	0.196	224.9941	Line 80-97	0.273	2.845793
Line 88-89	0.119	530.42	Line 77-80 C1	0.205	105.9976	Line 98-100	0.282	1.442214
Line 68-81	0.119	304.16	Line 82-96	0.205	118.2215	Line 77-80 C2	0.291	3.377732
Line 82-83	0.119	240.86	Line 92-94	0.205	130.835	Line 101-102	0.291	1.480827
Line 94-100	0.145	443.27	Line 94-96	0.205	107.3304	Line 80-98	0.299	2.215687
Line 89-90 C2	0.153	381.05	Line 77-78	0.213	70.38304	Line 92-100	0.308	1.29851
Line 92-102	0.153	370.74	Line 95-96	0.213	31.79654	Line 109-110	0.308	0.66177
Line 85-89	0.17	269.25	Line 89-90 C1	0.23	11.28693	Line 69-77	0.316	3.967107
Line 92-93	0.17	316.17	Line 91-92	0.23	18.31821	Line 80-96	0.316	2.112779
Line 100-103	0.17	232.98	Line 84-85	0.248	7.753052	Line 64-65	0.325	7.617157
Line 89-92 C2	0.17	264.15	Line 90-91	0.248	8.407845	Line 83-84	0.342	1.033703
Line 65-68	0.17	104.82	Line 79-80	0.256	3.722076	Line 104-105	0.342	1.320342
Line 85-88	0.188	235.40	Line 83-85	0.256	1.793478	Line 80-99	0.351	1.334514
Line 94-95	0.188	250.14	Line 100-101	0.256	2.02659	Line 100-104	0.359	1.18517
Line 99-100	0.188	96.45	Line 38-65	0.265	4.606585	Line 105-106	0.385	1.049072
Line 68-116	0.196	113.87	Line 96-97	0.265	2.330526	Line 103-104	0.394	0.978446
Line 77-82	0.196	25.73	Line 78-79	0.273	3.812814	Line 108-109	0.394	0.653325

Figure 6.9: Contingency ranking and screening results for Case 3B



Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value	Contingency	CCT(s)	Dot Value
Line 26-30	0.05	283.32	Line 5-6	0.265	2.06425	Line 17-113	0.308	2.85842
Line 89-92 C1	0.084	131.65	Line 5-11	0.265	2.082596	Line 15-17	0.316	2.933534
Line 23-25	0.127	126.61	Line 82-83	0.265	2.240047	Line 95-96	0.316	2.242285
Line 8-30	0.145	43.40	Line 93-94	0.265	0.56309	Line 23-32	0.334	1.585653
Line 88-89	0.145	84.98	Line 94-95	0.265	0.714325	Line 84-85	0.334	1.155404
Line 89-90 C2	0.179	53.61	Line 89-90 C1	0.273	0.352439	Line 17-18	0.351	2.493388
Line 30-38	0.188	26.76	Line 91-92	0.273	0.409194	Line 83-85	0.359	1.084368
Line 92-102	0.196	51.63	Line 92-94	0.273	0.47572	Line 100-101	0.359	1.35057
Line 89-92 C2	0.205	46.21	Line 4-11	0.282	2.004087	Line 3-5	0.359	1.381321
Line 94-100	0.205	57.06	Line 99-100	0.282	2.172537	Line 27-32	0.368	1.456773
Line 4-5	0.205	34.89	Line 7-12	0.291	2.247067	Line 60-61	0.368	3.031757
Line 85-89	0.222	23.91	Line 23-24	0.291	1.779935	Line 12-14	0.385	1.573143
Line 92-93	0.222	30.71	Line 90-91	0.291	1.321283	Line 15-19	0.385	2.317357
Line 100-103	0.239	12.34	Line 94-96	0.291	0.597121	Line 77-82	0.385	2.133059
Line 85-88	0.248	8.36	Line 8-9	0.299	1.454927	Line 101-102	0.385	0.919612
Line 11-12	0.256	10.40	Line 82-96	0.299	2.624708	Line 11-13	0.394	1.447277
Line 25-27	0.256	5.81	Line 6-7	0.308	1.870384	Line 12-16	0.402	1.531498

Figure 6.10: Contingency ranking and screening results for Case 4B

6.3.3 Summary

From analysis of the results, the following observations are made.

- The implemented contingency ranking and screening method effectively discriminates between critical and unstable contingencies across all evaluated cases. This clearly demonstrates that the developed process is both reliable and accurate, providing a robust foundation for the overall transient stability assessment (TSA) scheme.

- Prioritization among critical contingencies is achieved, as the most severe contingencies exhibit higher dot product values, reinforcing their relative severity within the evaluated dataset. These elevated indices not only reinforce the relative severity of these contingencies but also satisfy one of the essential requirements for effective contingency screening in dynamic security assessment.

- Although the threshold value may vary with operating conditions, a clear threshold can be established based on the dot product values generated during the contingency ranking process. This threshold allows for the elimination of contingencies that are not critical for further stability assessment, effectively marking them as stable.Consequently, eliminating these cases reduces computational complexity and enhances efficiency in executing the overall DSA scheme.

- The dot product-based contingency ranking and screening process exhibits high adaptability and can be seamlessly integrated into the rest of the transient stability assessment framework.

  In summary, the implemented contingency ranking and screening approach efficiently identifies and prioritizes the most severe potential contingencies that could jeopardize system stability and reliability. In a real-world power system, the number of potential contingencies may reach the order of hundreds, making efficient ranking essential. This is particularly crucial for online DSA, where the time available to reach stability conclusions is highly constrained. Thus, a reliable contingency ranking mechanism is imperative for the effective execution of online DSA.

6.4 Stability Assessment For the Cases

The next process in the proposed Online TEF Based Remedial Action scheme is to evaluate transient stability assessment. In this regard, stability assessment for the defined operating conditions are conducted via scheme.

The main aim of stability assessment and energy margin determination process in the scheme is to determine stability condition of the grid for the critical contingencies defined in former section. Besides, this process provide quantitative measure for stability which indeed a must have thing in order to determine appropriate control actions.

The approach for stability assessment and energy margin determination for the proposed scheme was given in Section 5.3. In this section results obtained through this process are introduced and examined.

In order to assess reliability, stability assessments of the proposed scheme were tested against a reference stability assessment similar to the contingency ranking process. Critical energies and critical clearing times for the contingency cases are calculated. However for the transient stability assessment and margin calculation, stability classification for designated 0.15 sec lasted fault is considered. In other words, all the classifications were performed according to this clearing time. For example, a contingency having an energy margin smaller than its critical energy is classified as stable otherwise the contingency is classified unstable.

6.4.1 Results for IEEE 39 Bus Cases

Table 6.8, shows the results obtained via proposed transient stability assessment tool for Case 1A. For the sake of simplicity, contingency cases whose critical clearing time is higher than 0.25 seconds are dropped. Detailed results of the transient stability assessment for Case 1A reveal that grid will experience instability in 3 out of 34 contingency cases. These specific contingencies, which exhibit a negative energy margin and are classified as unstable, have a critical clearing time of less than 0.15 seconds. Additionally, the relationship between critical clearing time and critical energy requirements is visually depicted in Figure 6.11, providing further insights into the dynamics of system stability under various contingency cases. These findings suggest a direct correlation between fault clearing times and the critical energy of the system.

Table 6.8: Transient stability assessment results for Case 1A

Case 1A				
Critical Contingencies	Critical Clearing Time	Critical Energy	Energy Margin	Assessment
Line 28 - 29	0.05	0.06794	-0.05206	unstable
Line 26 - 29	0.102	0.08915	-0.03085	unstable
Line 26 - 28	0.117	0.09459	-0.02541	unstable
Line 26 - 27	0.176	0.13242	0.01242	stable
Line 25 - 26	0.184	0.1337	0.01370	stable
Line 02 - 25	0.191	0.1375	0.01750	stable
Line 05 - 06	0.191	0.15323	0.03323	stable
Line 10 - 13	0.198	0.13702	0.01702	stable
Line 10 - 11	0.206	0.14281	0.02281	stable
Line 06 - 11	0.213	0.16095	0.04095	stable
Line 13 - 14	0.221	0.14646	0.02646	stable
Line 21 - 22	0.228	0.15303	0.03303	stable
Line 04 - 05	0.236	0.17366	0.05366	stable
Line 06 - 07	0.236	0.1899	0.06990	stable
Line 17 - 27	0.25	0.18858	0.06858	stable
Line 05 - 08	0.25	0.18151	0.06151	stable
Line 22 - 23	0.25	0.17187	0.05187	stable

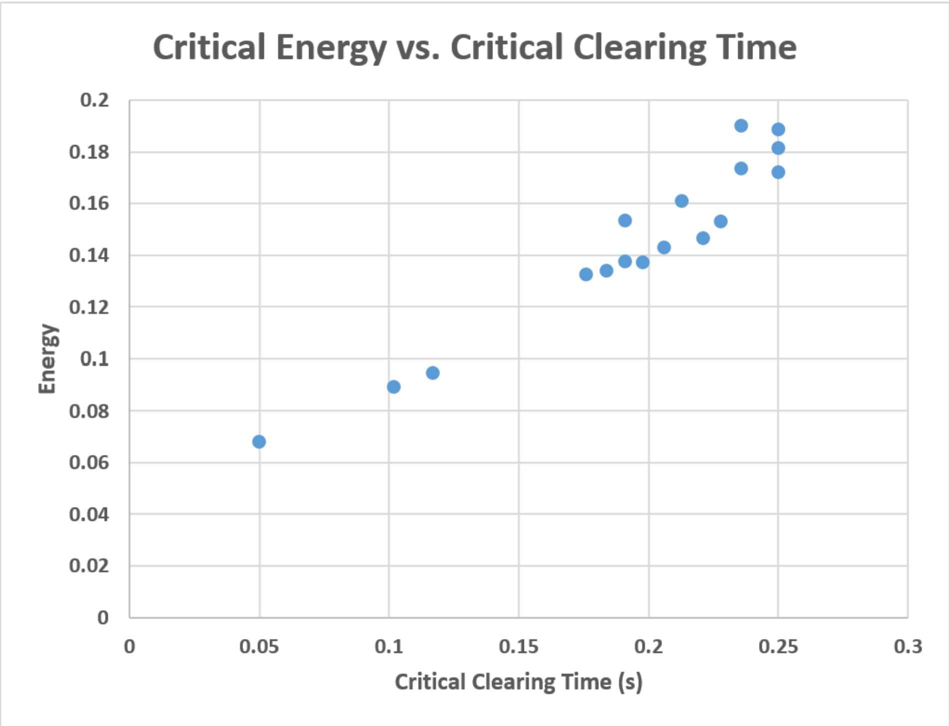


Figure 6.11: Relation Between Energy and Critical Clearing Time - Case 1A

The results of the stability assessment function for the Case 2A is given in Table 6.9. In this case the total load hence the stress on the grid is reduced. The results have shown that none of the cases having negative margin which means all contingencies are stable for 0.15 second lasting faults.

Table 6.9: Transient stability assessment results for Case 2A

Case 2A				
Critical Contingencies	**Critical Clearing Time**	**Critical Energy**	**Energy Margin**	**Assessment**
Line 28 - 29	0.198	0.1535567	0.03356	Stable
Line 26 - 29	0.265	0.16201855	0.04202	Stable
Line 26 - 28	0.28	0.1642423	0.0442423	Stable

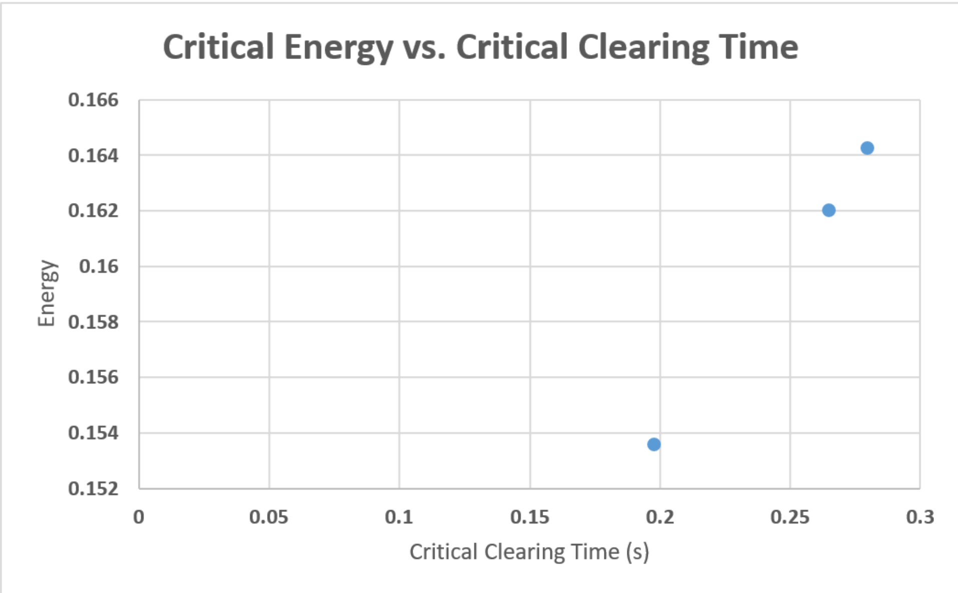


Figure 6.12: Relation Between Energy and Critical Clearing Time - Case 2A

Results obtained for case 3A show that increasing the load on the critical generators by increasing their dispatch level will negatively affect grid stability as expected. Cases with negative stability margin has increased to 8 out of 34. On the other hand, reducing generation on the critical generators has much more positive effect for the grid stability as can be seen from the results of case 4A as shown in . Hence, it can be said that the generation distribution has high impact on the grid stability and can be utilized to strengthen grid stability.

Table 6.10: Transient stability assessment results for Case 3A

Case 3A				
Critical Contingencies	Critical Clearing Time	Critical Energy	Energy Margin	Assessment
Line 28 - 29	0.05	0.0927	-0.03726	unstable
Line 26 - 29	0.072	0.1034	-0.02656	unstable
Line 26 - 28	0.095	0.1172	-0.01278	unstable
Line 02 - 25	0.109	0.1640	0.03401	stable
Line 26 - 27	0.139	0.1676	0.03764	stable
Line 21 - 22	0.146	0.1420	0.01200	stable
Line 25 - 26	0.146	0.1980	0.06800	stable
Line 05 - 06	0.146	0.1909	0.06094	stable
Line 16 - 17	0.154	0.1887	0.05874	stable
Line 10 - 13	0.161	0.1874	0.05738	stable
Line 06 - 11	0.169	0.2113	0.08126	stable
Line 04 - 05	0.176	0.2119	0.08190	stable
Line 10 - 11	0.176	0.2025	0.07253	stable
Line 13 - 14	0.176	0.1981	0.06806	stable
Line 06 - 07	0.184	0.2036	0.07358	stable
Line 16 - 24	0.191	0.2307	0.10074	stable
Line 05 - 08	0.191	0.2085	0.07849	stable
Line 16 - 21	0.198	0.20407294	0.07407	stable
Line 22 - 23	0.198	0.20470139	0.07470	stable
Line 07 - 08	0.198	0.20990413	0.07990	stable
Line 17 - 27	0.198	0.23787514	0.10788	stable
Line 15 - 16	0.206	0.23320863	0.10321	stable
Line 04 - 14	0.221	0.22987039	0.09987	stable
Line 17 - 18	0.228	0.23093708	0.10094	stable
Line 03 - 04	0.228	0.22493697	0.09494	stable
Line 23 - 24	0.25	0.23909554	0.10910	stable
Line 14 - 15	0.25	0.24651667	0.11652	stable

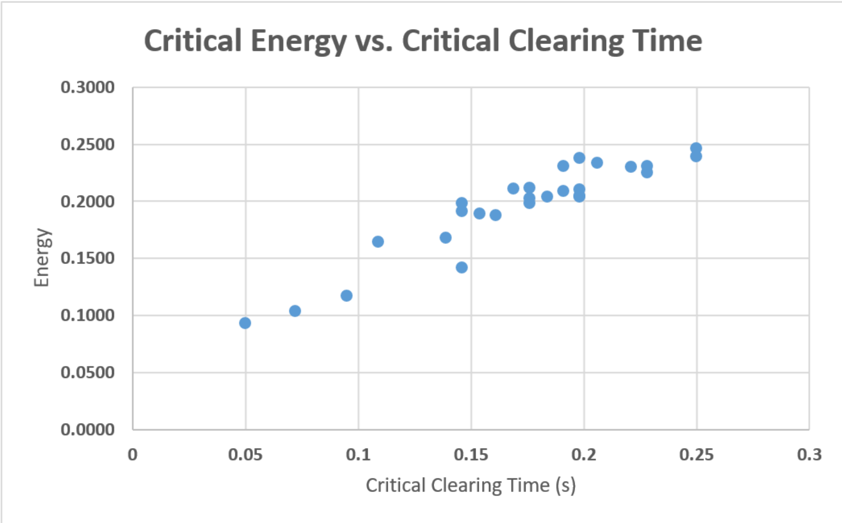


Figure 6.13: Relation Between Energy and Critical Clearing Time - Case 3A

Table 6.11: Transient stability assessment results for Case 4A

Case 4A				
Critical Contingencies	Critical Clearing Time	Critical Energy	Energy Margin	Assessment
Line 28 - 29	0.213	0.1509704	0.03097	Stable
Line 26 - 29	0.295	0.1595629	0.03956	Stable
Line 26 - 28	0.31	0.16347915	0.04347915	Stable

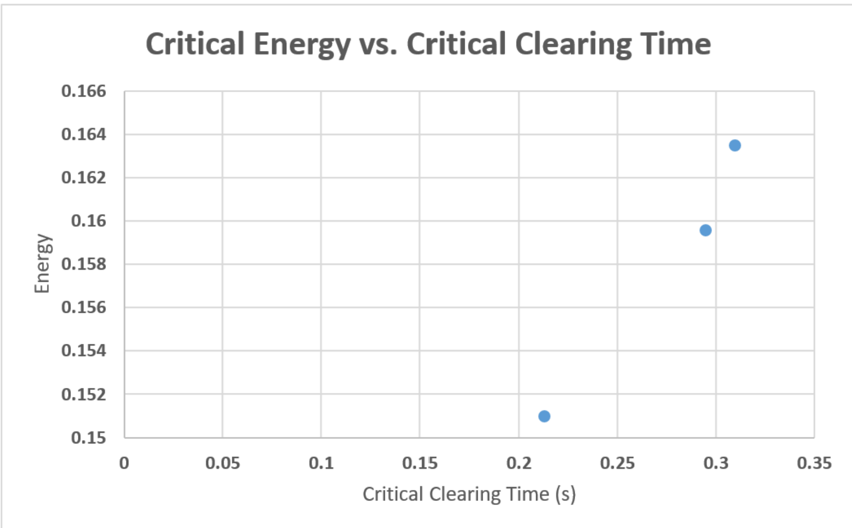


Figure 6.14: Relation Between Energy and Critical Clearing Time - Case 4A

6.4.2 Results for IEEE 118 Bus Cases

Table 6.12, shows the results obtained via proposed transient stability assessment tool for Case 1B. For the sake of simplicity, contingency cases whose critical clearing time is higher than 0.25 seconds are dropped. Detailed results of the transient stability assessment for Case 1B reveal that grid will experience instability in 3 out of 186 contingency cases. These specific contingencies, which exhibit a negative energy margin and are classified as unstable, have a critical clearing time of less than 0.15 seconds. Additionally, the relationship between critical clearing time and critical energy requirements is visually depicted in Figure 6.15, providing further insights into the dynamics of system stability under various contingency cases. These findings suggest a direct correlation between fault clearing times and the critical energy of the system.

Table 6.12: Transient stability assessment results for Case 1B

Case 1B				
Critical Contingencies	**Critical Clearing Time**	**Critical Energy**	**Energy Margin**	**Assessment**
Line 8-30	0.05	0.1445	-0.31547	unstable
Line 4-5	0.119	0.4183	-0.04175	unstable
Line 26-30	0.127	0.4194	-0.04064	unstable
Line 5-6	0.162	0.4816	0.02156	stable
Line 5-11	0.162	0.4849	0.02490	stable
Line 65-68	0.162	0.5027	0.04265	stable
Line 68-116	0.162	0.5022	0.04217	stable
Line 4-11	0.17	0.4949	0.03495	stable
Line 11-12	0.17	0.5500	0.09002	stable
Line 68-81	0.179	0.5066	0.04661	stable
Line 89-92 C1	0.179	0.5268	0.06680	stable
Line 6-7	0.196	0.5323	0.07230	stable
Line 7-12	0.196	0.5746	0.11462	stable
Line 3-5	0.205	0.4853	0.02527	stable
Line 69-77	0.213	0.6763	0.21626	stable
Line 11-13	0.248	0.5838	0.12383	stable
Line 12-14	0.248	0.6082	0.14824	stable

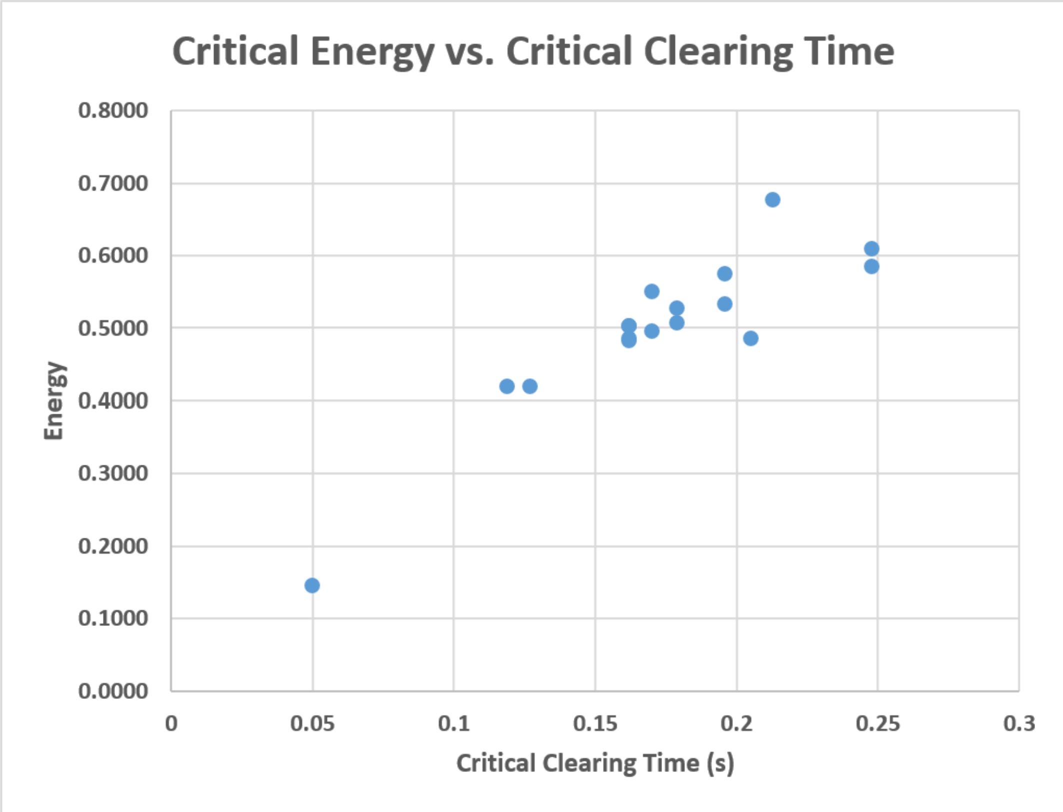


Figure 6.15: Relation Between Energy and Critical Clearing Time - Case 1B

The results of the stability assessment function for the Case 2B is given in Table 6.13. In this case the total load hence the stress on the grid is reduced. The results have shown that only one of the cases having negative margin shows instability.

Table 6.13: Transient stability assessment results for Case 2B

Case 2B				
Critical Contingencies	Critical Clearing Time	Critical Energy	Energy Margin	Assessment
Line 8-30	0.11	0.3624	-0.11757	unstable
Line 4-5	0.213	0.7056	0.22564	unstable
Line 65-68	0.23	0.7536	0.27358	unstable
Line 68-116	0.23	0.7408	0.26082	stable
Line 68-81	0.256	0.8433	0.36332	stable

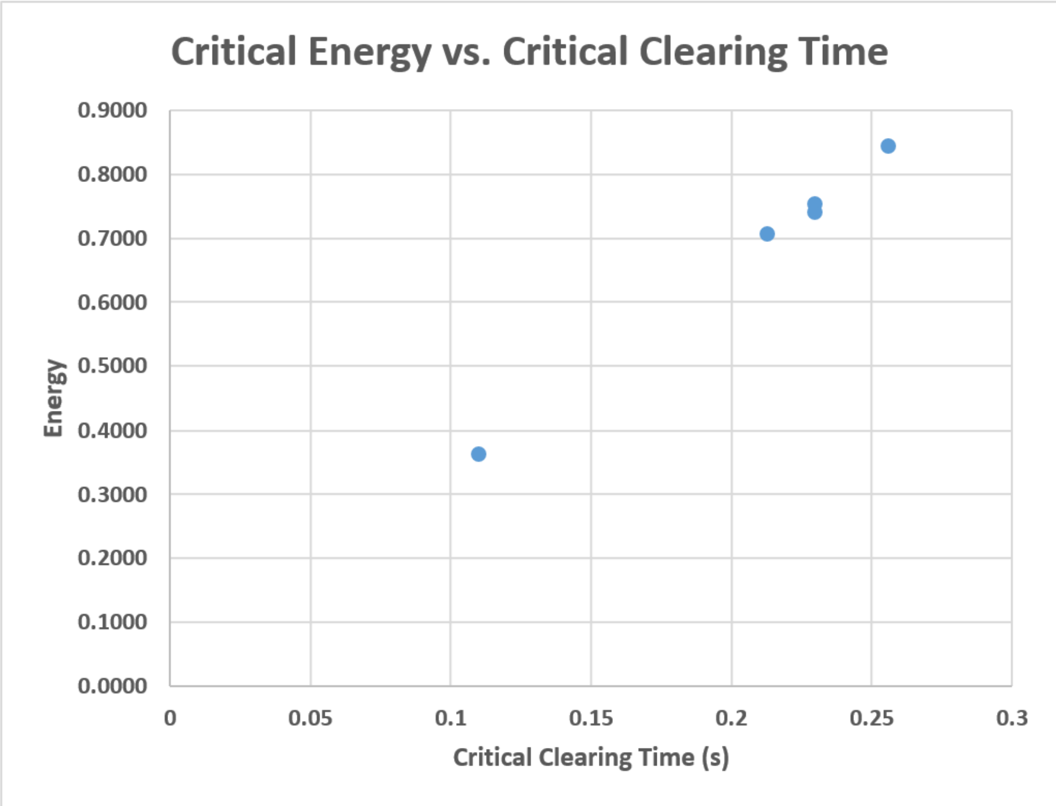


Figure 6.16: Relation Between Energy and Critical Clearing Time - Case 2B

Results obtained for case 3B show that increasing the load on the critical generators by increasing their dispatch level will negatively affect grid stability as expected. Cases with negative stability margin has increased to 5 out of 186. On the other hand, reducing generation on the critical generators has much more positive effect for the grid stability as can be seen from the results of case 4B as shown in 6.15. Hence, it can be said that the generation distribution has high impact on the grid stability and can be utilized to strengthen grid stability.

Table 6.14: Transient stability assessment results for Case 3B

Case 3B				
Critical Contingencies	**Critical Clearing Time**	**Critical Energy**	**Energy Margin**	**Assessment**
Line 89-92 C1	0.059	0.2548	-0.20522	unstable
Line 88-89	0.119	0.4152	-0.04477	unstable
Line 68-81	0.119	0.3960	-0.06399	unstable
Line 82-83	0.119	0.4341	-0.02589	unstable
Line 94-100	0.145	0.4427	-0.01732	unstable
Line 89-90 C2	0.153	0.4770	0.01704	stable
Line 92-102	0.153	0.4840	0.02402	stable
Line 85-89	0.17	0.4722	0.01223	stable
Line 92-93	0.17	0.5055	0.04550	stable
Line 100-103	0.17	0.5673	0.10734	stable
Line 89-92 C2	0.17	0.4876	0.02759	stable
Line 65-68	0.17	0.7261	0.26607	stable
Line 85-88	0.188	0.5039	0.04395	stable
Line 94-95	0.188	0.5976	0.13761	stable
Line 99-100	0.188	0.4957	0.03566	stable
Line 68-116	0.196	1.0273	0.56733	stable
Line 77-82	0.196	0.5282	0.06824	stable
Line 93-94	0.196	0.571563641	0.11156	stable
Line 77-80 C1	0.205	0.7840	0.32399	stable
Line 82-96	0.205	0.6634	0.20336	stable
Line 92-94	0.205	0.5530	0.09301	stable
Line 94-96	0.205	0.6122	0.15220	stable
Line 77-78	0.213	0.7837	0.32371	stable
Line 95-96	0.213	0.6261	0.16612	stable
Line 89-90 C1	0.23	0.5184	0.05843	stable
Line 91-92	0.23	0.5863	0.12632	stable
Line 84-85	0.248	0.5534	0.09342	stable
Line 90-91	0.248	0.5672	0.10722	stable

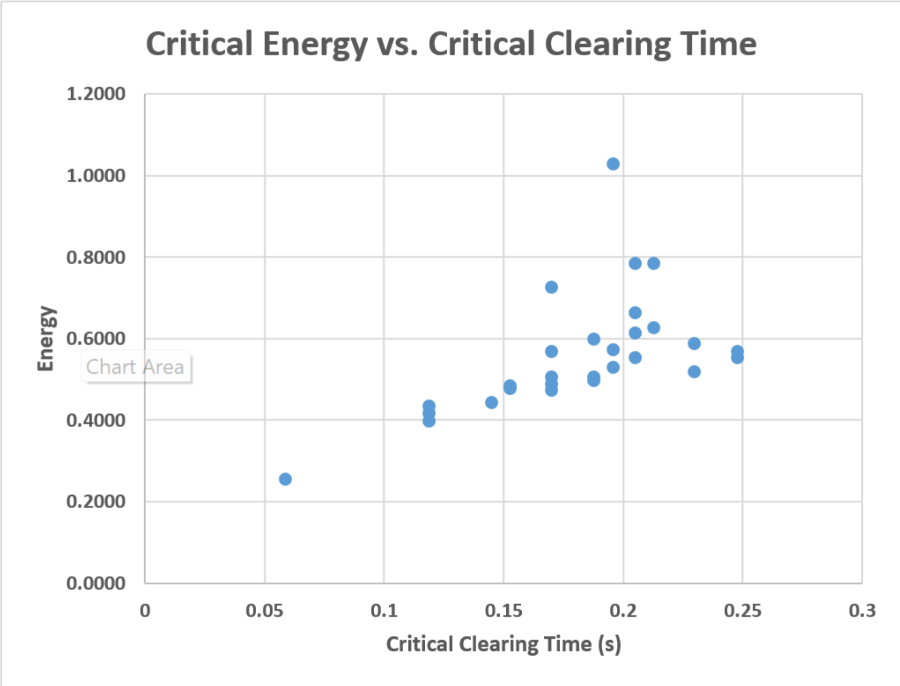


Figure 6.17: Relation Between Energy and Critical Clearing Time - Case 3B

Table 6.15: Transient stability assessment results for Case 4B

Case 4B				
Critical Contingencies	Critical Clearing Time	Critical Energy	Energy Margin	Assessment
Line 89-92 C1	0.084	0.3694	-0.09057	unstable
Line 23-25	0.127	0.2425	-0.21746	unstable
Line 8-30	0.145	0.4053	-0.05471	unstable
Line 88-89	0.145	0.4456	-0.01440	unstable
Line 89-90 C2	0.179	0.5617	0.10167	stable
Line 30-38	0.188	0.5538	0.09382	stable
Line 92-102	0.196	0.6623	0.20232	stable
Line 89-92 C2	0.205	0.6105	0.15047	stable
Line 94-100	0.205	0.8624	0.40238	stable
Line 4-5	0.205	0.4980	0.03798	stable
Line 85-89	0.222	0.5063	0.04628	stable
Line 92-93	0.222	0.6819	0.22189	stable
Line 100-103	0.239	0.6213	0.16128	stable
Line 85-88	0.248	0.7257	0.26575	stable

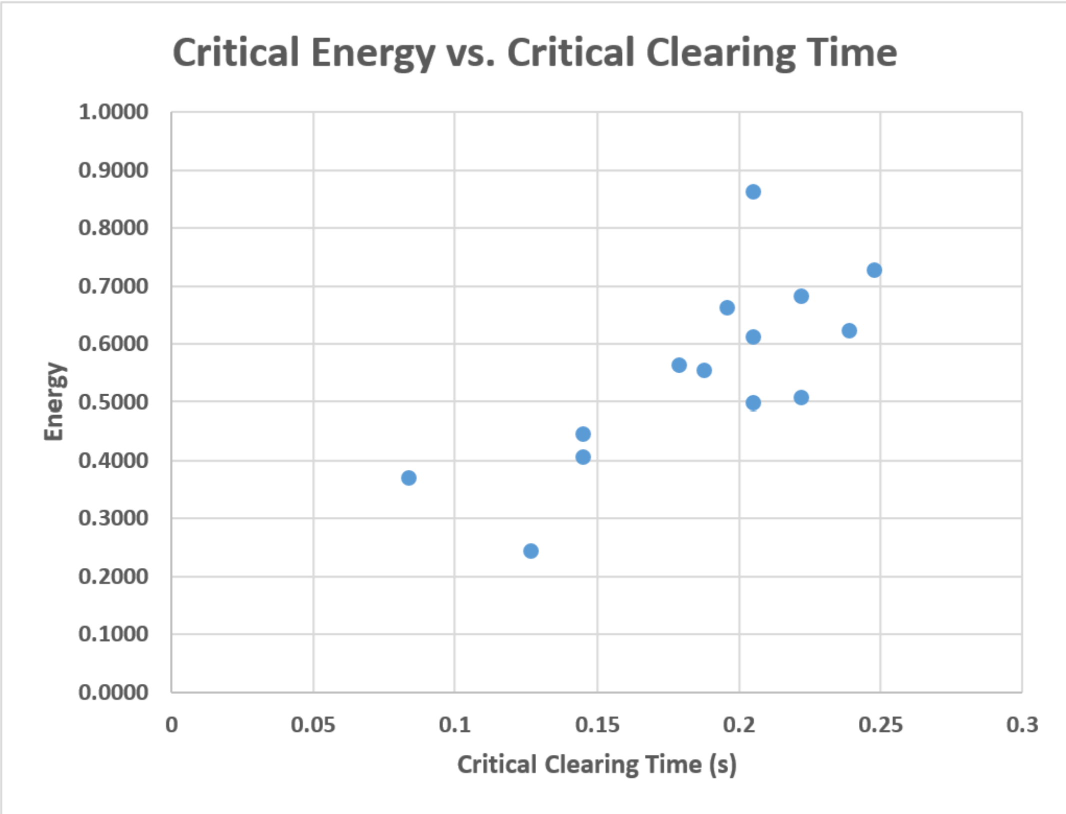


Figure 6.18: Relation Between Energy and Critical Clearing Time - Case 4B

6.4.3 Summary

Transient stability assessment results are obtained for all scenarios defined. Table 6.16 and 6.17 show the effect of the operating condition on the grid stability, respectively for the IEEE 39 and 118 bus cases.

Table 6.16: Transient stability results for IEEE 39 bus cases

Critical Contingencies	Case 1A		Case 2A		Case 3A		Case 4A	
	Tcc(s)	Verdict	Tcc(s)	Verdict	Tcc(s)	Verdict	Tcc(s)	Verdict
Line 28 - 29	0.05	Unstable	0.198	Stable	0.05	Unstable	0.213	Stable
Line 26 - 29	0.102	Unstable	0.25	Stable	0.072	Unstable	>0.25	Stable
Line 26 - 28	0.117	Unstable	>0.25	Stable	0.095	Unstable	>0.25	Stable
Line 02 - 25	0.191	Stable	>0.25	Stable	0.109	Unstable	>0.25	Stable
Line 26 - 27	0.176	Stable	>0.25	Stable	0.139	Unstable	>0.25	Stable
Line 21 - 22	0.228	Stable	>0.25	Stable	0.146	Unstable	>0.25	Stable
Line 25 - 26	0.184	Stable	>0.25	Stable	0.146	Unstable	>0.25	Stable
Line 05 - 06	0.191	Stable	>0.25	Stable	0.146	Unstable	>0.25	Stable
Line 16 - 17	>0.25	Stable	>0.25	Stable	0.154	Stable	>0.25	Stable
Line 10 - 13	0.198	Stable	>0.25	Stable	0.161	Stable	>0.25	Stable
Line 06 - 11	0.213	Stable	>0.25	Stable	0.169	Stable	>0.25	Stable
Line 04 - 05	0.236	Stable	>0.25	Stable	0.176	Stable	>0.25	Stable
Line 10 - 11	0.206	Stable	>0.25	Stable	0.176	Stable	>0.25	Stable
Line 13 - 14	0.221	Stable	>0.25	Stable	0.176	Stable	>0.25	Stable
Line 06 - 07	0.236	Stable	>0.25	Stable	0.184	Stable	>0.25	Stable
Line 16 - 24	>0.25	Stable	>0.25	Stable	0.191	Stable	>0.25	Stable
Line 05 - 08	0.25	Stable	>0.25	Stable	0.191	Stable	>0.25	Stable
Line 16 - 21	>0.25	Stable	>0.25	Stable	0.198	Stable	>0.25	Stable
Line 22 - 23	0.25	Stable	>0.25	Stable	0.198	Stable	>0.25	Stable
Line 07 - 08	>0.25	Stable	>0.25	Stable	0.198	Stable	>0.25	Stable
Line 17 - 27	0.25	Stable	>0.25	Stable	0.198	Stable	>0.25	Stable
Line 15 - 16	>0.25	Stable	>0.25	Stable	0.206	Stable	>0.25	Stable
Line 04 - 14	>0.25	Stable	>0.25	Stable	0.221	Stable	>0.25	Stable
Line 17 - 18	>0.25	Stable	>0.25	Stable	0.228	Stable	>0.25	Stable
Line 03 - 04	>0.25	Stable	>0.25	Stable	0.228	Stable	>0.25	Stable
Line 23 - 24	>0.25	Stable	>0.25	Stable	0.25	Stable	>0.25	Stable
Line 14 - 15	>0.25	Stable	>0.25	Stable	0.25	Stable	>0.25	Stable

Table 6.17: Transient stability results for IEEE 118 bus cases

Critical Contingencies	Case 1B		Critical Contingencies	Case 2B		Critical Contingencies	Case 3B		Critical Contingencies	Case 4B	
	Tcc(s)	Verdict		Tcc(s)	Verdict		Tcc(s)	Verdict		Tcc(s)	Verdict
Line 8-30	0.05	Unstable	Line 8-30	0.11	Unstable	Line 89-92 C1	0.059	Unstable	Line 89-92 C1	0.084	Unstable
Line 4-5	0.119	Unstable	Line 4-5	0.213	Stable	Line 88-89	0.119	Unstable	Line 23-25	0.127	Unstable
Line 26-30	0.127	Unstable	Line 26-30	>0.25	Stable	Line 68-81	0.119	Unstable	Line 8-30	0.145	Unstable
Line 5-6	0.162	Stable	Line 5-6	>0.25	Stable	Line 82-83	0.119	Unstable	Line 88-89	0.145	Unstable
Line 5-11	0.162	Stable	Line 5-11	>0.25	Stable	Line 94-100	0.145	Unstable	Line 89-90 C2	0.179	Stable
Line 65-68	0.162	Stable	Line 65-68	0.23	Stable	Line 89-90 C2	0.153	Stable	Line 30-38	0.188	Stable
Line 68-116	0.162	Stable	Line 68-116	0.23	Stable	Line 92-102	0.153	Stable	Line 92-102	0.196	Stable
Line 4-11	0.17	Stable	Line 4-11	>0.25	Stable	Line 85-89	0.17	Stable	Line 89-92 C2	0.205	Stable
Line 11-12	0.17	Stable	Line 11-12	>0.25	Stable	Line 92-93	0.17	Stable	Line 94-100	0.205	Stable
Line 68-81	0.179	Stable	Line 68-81	0.25	Stable	Line 100-103	0.17	Stable	Line 4-5	0.205	Stable
Line 89-92 C1	0.179	Stable	Line 89-92 C1	>0.25	Stable	Line 89-92 C2	0.17	Stable	Line 85-89	0.222	Stable
Line 6-7	0.196	Stable	Line 6-7	>0.25	Stable	Line 65-68	0.17	Stable	Line 92-93	0.222	Stable
Line 7-12	0.196	Stable	Line 7-12	>0.25	Stable	Line 85-88	0.188	Stable	Line 100-103	0.239	Stable
Line 3-5	0.205	Stable	Line 3-5	>0.25	Stable	Line 94-95	0.188	Stable	Line 85-88	0.248	Stable
Line 69-77	0.213	Stable	Line 69-77	>0.25	Stable	Line 99-100	0.188	Stable			
Line 11-13	0.248	Stable	Line 11-13	>0.25	Stable	Line 68-116	0.196	Stable			
Line 12-14	0.248	Stable	Line 12-14	>0.25	Stable	Line 77-82	0.196	Stable			
						Line 93-94	0.196	Stable			
						Line 77-80 C1	0.205	Stable			
						Line 82-96	0.205	Stable			
						Line 92-94	0.205	Stable			
						Line 94-96	0.205	Stable			
						Line 77-78	0.213	Stable			
						Line 95-96	0.213	Stable			
						Line 89-90 C1	0.23	Stable			
						Line 91-92	0.23	Stable			
						Line 84-85	0.248	Stable			

Results obtained for cases that reducing the load on the grid or dispatch on critical generators, hence the stress, will positively affect grid stability as expected or vice versa. It can be said that the generation distribution has high impact on the grid stability and can be utilized to strengthen grid stability.

It is important to express that a set of critical contingencies for the 39 bus grid remains to be the most critical ones, although the energy margins vary with respect to changing operating scenarios. It implies that the grid topology determines the critical generators and contingencies. In that sense, either an investment or a local RAS is required to resolve those critical contingencies for lines connecting Buses 26, 28, 29. Indeed, grids usually operate in the same manner with the effect of topology and the energy market. Critical conditions for the grid remain same but the criticality varies. In this regard, it can be stated that local RAS solutions are usually sufficient to preserve grid conditions.

On the hand, this reality will change with the increase in the renewable penetration. Future grids will be more challenging as the generation mix and the distribution vastly vary with the availability of the primary energy source. IEEE 118 Bus case is an example for such situation. As can be seen from Table 6.17, critical contingencies vary with the operating conditions. An important question arising here is that it is possible to determine the global and limited countermeasure sets which resolve possible instability in the grid for every reasonable operating condition.

It is clear that due to the signaling, redundancy and complexity requirements, RAS operations are desired to be limited in a smaller set of generators. In this regard, a search for countermeasure set will be conducted within generators in the next section.

6.5 Energy Margin Sensitivities And Remedial Action Set Determination

Energy margin sensitivity is defined as the change in the energy margin with respect to the change in generation. It is clear that the main aim of the grid operator is to increase stability margins as much as possible to maintain the grid stability, However, determination of the action that contributes most to the grid stability is not trivial. With the information obtained during the transient stability assessment process, the proposed tool can also compute sensitivity of the generators on the stability margin. In this regard, sensitivity matrix for generators in the grid for the given contingency is calculated. Additionally, these sensitivities are then automatically grouped in terms of effectiveness to determine the most effective countermeasure.

Representative outputs of the grouping algorithm are given for Case 3A in the Figure 6.19 and 6.20. Results highlight that the most effective generators for increasing the stability margin may vary depending on the contingency, as expected. In some cases, the action that enhances grid stability converges on a single generator, while in others, multiple candidate generators may be identified. It is clear that to maintain system stability, every critical contingency must be addressed. Therefore, generators which are the only viable option for securing system stability must be included in the countermeasure set. For other critical contingencies, a more logical selection process can be employed to reduce and simplify the countermeasure set. In Case 3A, the set of possible generators for countermeasures can be reduced to a group consisting of G02, G03, G07, and G09. This reduced set of generators is sufficient to resolve the critical contingencies and ensure grid stability.

Line 04-05	Line 06-07	Line 06-11	Line 10-11	Line 10-13	Line 13-14	Line 16-21	Line 16-24	Line 26-28	Line 26-29	Line 28-29	Line 23-24	Line 22-23	Line 21-22	gen key
-0.007	-0.008	-0.008	-0.007	0	-0.007	-0.014	0	0	0	0	-0.014	-0.014	-0.022	G 08
0.045	0.037	0.029	0.008	0.015	0.015	-0.014	0	0	0	0	-0.014	-0.014	-0.022	G 02
0.008	0	0.007	0.022	0.03	0.03	-0.014	0	0	0	0	-0.007	-0.007	-0.014	G 03
-0.007	-0.008	-0.008	0	0	-0.007	-0.007	0.015	0	0	0	0	-0.007	-0.007	G 04
0	0	0	0	0	0	-0.007	0	0	0.008	0	0	0	0	G 05
-0.007	-0.008	-0.008	0	0	-0.007	0.023	0.015	0	0	0	0.03	-0.007	0.045	G 06
-0.007	-0.008	-0.008	0	0	-0.007	-0.014	0	0.044	0.052	0.03	-0.007	-0.007	-0.014	G 09
-0.007	-0.008	-0.008	0	0	-0.007	0.023	0.015	0	0	0	0.052	0.052	0.045	G 07
-0.007	-0.015	-0.008	-0.007	-0.007	-0.007	-0.022	-0.007	0	0	0	-0.022	-0.014	-0.022	G 01
-0.007	-0.008	-0.008	-0.007	0	-0.007	-0.022	-0.007	0	0	0	-0.014	-0.014	-0.022	G 10

Line 07-08	Line 02-25	Line 02-25	Line 25-26	Line 17-18	Line 26-27	Line 17-27	Line 16-17	Line 15-16	Line 14-15	Line 04-14	Line 03-04	Line 05-08	Line 05-06	gen key
-0.007	0.045	0.045	0	0	0	0	-0.015	0	-0.007	-0.015	-0.007	-0.007	0	G 08
0.045	-0.007	-0.007	0	0.008	0	0	-0.008	0	0.038	0.029	0.045	0.045	0.038	G 02
0.008	-0.007	-0.007	0	0.008	0	0	0	0	0.03	0.015	0.022	0.007	0.008	G 03
-0.007	-0.007	-0.007	0	0.015	0	0	0.015	0.015	0	-0.008	0	-0.007	0	G 04
0	0	0	0	0	0	0	-0.008	0	0	0	0	0	0	G 05
-0.007	-0.007	-0.007	0	0.015	0	0	0.015	0.015	0	-0.008	0	-0.007	0	G 06
-0.007	0.03	0.03	0.067	0.008	0.052	0.082	-0.015	0	0	-0.008	-0.007	-0.007	0	G 09
-0.007	-0.007	-0.007	0	0.015	0	0	0.015	0.015	0	-0.008	0	-0.007	0	G 07
-0.007	-0.007	-0.007	0	-0.015	0	-0.007	-0.015	-0.015	-0.014	-0.015	-0.015	-0.007	-0.007	G 01
-0.007	-0.007	-0.007	0	-0.007	0	-0.007	-0.015	-0.008	-0.007	-0.015	-0.007	-0.007	-0.007	G 10

Figure 6.19: Energy margin sensitivities for Case 3A

Line 04-05	Line 06-07	Line 06-11	Line 10-11	Line 10-13	Line 13-14	Line 16-21	Line 16-24	Line 26-28	Line 26-29	Line 28-29	Line 23-24	Line 22-23	Line 21-22	gen key
2	2	2	2	0	2	2	0	0	0	0	2	2	2	G 08
1	1	1	0	1	1	2	0	0	0	0	2	2	2	G 02
0	0	0	1	1	1	2	0	0	0	0	2	2	2	G 03
2	2	2	0	0	2	2	1	0	0	0	0	2	2	G 04
0	0	0	0	0	0	2	0	0	0	0	0	0	0	G 05
2	2	2	0	0	2	1	1	0	0	0	1	2	1	G 06
2	2	2	0	0	2	2	0	1	1	1	2	2	2	G 09
2	2	2	0	0	2	1	1	0	0	0	1	1	1	G 07
2	2	2	2	2	2	2	2	0	0	0	2	2	2	G 01
2	2	2	2	0	2	2	2	0	0	0	2	2	2	G 10

Line 07-08	Line 02-25	Line 02-25	Line 25-26	Line 17-18	Line 26-27	Line 17-27	Line 16-17	Line 15-16	Line 14-15	Line 04-14	Line 03-04	Line 05-08	Line 05-06	gen key
2	1	1	0	0	0	0	2	0	2	2	2	0	0	G 08
1	2	2	0	1	0	0	2	0	1	1	1	1	1	G 02
0	2	2	0	1	0	0	0	0	1	1	1	0	0	G 03
2	2	2	0	1	0	0	1	1	0	2	0	0	0	G 04
0	0	0	0	0	0	0	2	0	0	0	0	0	0	G 05
2	2	2	0	1	0	0	1	1	0	2	0	0	0	G 06
2	1	1	1	1	1	1	2	0	0	2	2	0	0	G 09
2	2	2	0	1	0	0	1	1	0	2	0	0	0	G 07
2	2	2	0	2	0	0	2	2	2	2	2	0	0	G 01
2	2	2	0	2	0	0	2	2	2	2	2	0	0	G 10

Figure 6.20: Margin sensitivities grouped by K-means approach for Case 3A

In the same respect, the study for the determination of transient margin sensitivity and remedial action set were performed for all the scenarios defined. In Table 6.18 and 6.19, effective countermeasures for the critical contingencies are given. It is observed that, despite variations in operating conditions, nearly all contingencies are resolved by similar actions. Moreover, the intersection of these actions converges on four specific generators. This finding is significant because it implies that a special protection scheme controlling and coordinating these four generators would be capable of resolving the critical contingencies and ensuring the stable operation of the grid. Results presented in Table VIII also confirms that finding. In 118 bus system, intersection of the remedial actions that secures stable operation are converging to 4 generators.

In this context, it becomes apparent that the nature of disturbances leading to instability within the power grid is not static but highly dependent on the prevailing operating conditions, which can vary due to factors such as load changes, generation fluctuations, or network reconfigurations. Despite this variability, the topology of the grid—that is, the physical and electrical configuration of its components — plays a crucial role in limiting the range of potential remedial actions available to counteract instability. These remedial actions, though influenced by the specific nature of the disturbance, are often constrained to a smaller, more manageable set due to the interdependencies and physical limits inherent in the grid's design.

Interestingly, this set of corrective measures remains largely invariant across a wide array of operating scenarios, making it particularly valuable for grid operators who must deal with a variety of dynamic conditions. This invariance means that once identified, these actions can be incorporated into automated or semi-automated remedial action schemes, providing a robust framework for maintaining grid stability under fluctuating conditions.

One promising approach to efficiently identify this set is through the sensitivity of the stability margin, which offers a robust and rapid means of highlighting the most effective corrective actions. By leveraging this sensitivity, grid operators can quickly assess and implement the appropriate remedial strategies, ensuring grid stability under a variety of dynamic conditions.

It should also be emphasized that the invariance mainly exist on the location of the remedial action. The amount of the action may require re-calibration based on operating condition and can be online adjusted by the coordination among measurement and sensitivity results.

In summary, four distinct operating conditions are studied for each of the two test systems to validate the effectiveness of the proposed tool. The results show that while disturbances leading to instability may vary with operating conditions, the remedial actions required to resolve instability can be narrowed down to a smaller, invariant set due to the underlying grid topology. This set of actions remains consistent across different operating scenarios and can be directly applied in remedial action schemes. The stability margin sensitivity approach proves to be a promising method for quickly and reliably identifying this set of actions.

Table 6.18: Countermeasure set for IEEE 39 bus cases

Critical Contingencies	Case 1A Possible Solution Set	Case 2A Possible Solution Set	Case 3A Possible Solution Set	Case 4A Possible Solution Set
Line 28 - 29	G9	G9	G9	G9
Line 26 - 29	G9	-	G9	-
Line 26 - 28	G9	-	G9	-
Line 02 - 25	G8,G9	-	G8,G9	-
Line 26 - 27	G9	-	G9	-
Line 21 - 22	G6,G7	-	G6,G7	-
Line 25 - 26	G9	-	G9	-
Line 05 - 06	G2	-	G2	-
Line 16 - 17	-	-	G4,G7	-
Line 10 - 13	G3	-	G2,G3	-
Line 06 - 11	G2,G4	-	G2	-
Line 04 - 05	G2	-	G2	-
Line 10 - 11	G3	-	G3	-
Line 13 - 14	G3	-	G3	-
Line 06 - 07	G2	-	G2	-
Line 16 - 24	-	-	G4,G6,G7	-
Line 05 - 08	G2	-	G2	-
Line 16 - 21	-	-	G6,G7	-
Line 22 - 23	G7	-	G7	-
Line 07 - 08	-	-	G2	-
Line 17 - 27	G9	-	G9	-
Line 15 - 16	-	-	G4,G7	-
Line 04 - 14	-	-	G2,G3,G6,G7	-
Line 17 - 18	-	-	G2,G3,G4, G8,G10	-
Line 03 - 04	-	-	G2,G3,G6,G7	-
Line 23 - 24	-	-	G7	-
Line 14 - 15	-	-	G2,G3,G6,G7	-

Table 6.19: Countermeasure set for IEEE 118 bus cases

Critical Contingencies	Case 1B Possible Solution Set	Critical Contingencies	Case 2A Possible Solution Set	Critical Contingencies	Case 3A Possible Solution Set	Critical Contingencies	Case 4A Possible Solution Set
Line 8-30	G10	Line 8-30	G10	Line 89-92 C1	G89	Line 89-92 C1	G89
Line 4-5	G10	Line 4-5	G10	Line 88-89	G89	Line 23-25	G25,G26
Line 26-30	G25,G26	Line 65-68	G69	Line 68-81	G80,G100,G103,G111,G87,G89	Line 8-30	G10
Line 5-6	G10	Line 68-116	G69	Line 82-83	G87,G89,G100,G103	Line 88-89	G89
Line 5-11	G10	Line 68-81	G69	Line 94-100	G89	Line 89-90 C2	G89
Line 65-68	G69			Line 89-90 C2	G89	Line 30-38	G10,G12,G25,G26,G31
Line 68-116	G69			Line 92-102	G89	Line 92-102	G89
Line 4-11	G10			Line 85-89	G89	Line 89-92 C2	G89
Line 11-12	G10			Line 92-93	G89	Line 94-100	G89
Line 68-81	G69			Line 100-103	G87,G89,G100,G111	Line 4-5	G10
Line 89-92 C1	G89			Line 89-92 C2	G89	Line 85-89	G89
Line 6-7	G10			Line 65-68	G80,G100,G103,G111,G87,G69,G89	Line 92-93	G89
Line 7-12	G10			Line 85-88	G89	Line 100-103	G89,G100
				Line 94-95	G89	Line 85-88	G89
Line 69-77	G69			Line 99-100	G89		
Line 11-13	G10			Line 68-116	G80,G100,G103,G111,G87, G69,G89		
Line 12-14	G10			Line 77-82	G87,G89		
				Line 93-94	G89		
				Line 77-80 C1	G80,G100,G103,G111,G87,G89		
				Line 82-96	G89		
				Line 92-94	G89		
				Line 94-96	G87,G89,G103		
				Line 77-78	G100,G103,G111,G87,G89		
				Line 95-96	G87,G89,G103		
				Line 89-90 C1	G89		
				Line 91-92	G89		
				Line 84-85	G89		

CHAPTER 7

CONCLUSIONS

With the increasing complexity, size, and renewable energy penetration of modern power systems, ensuring transient stability has become a critical challenge. The evolving nature of power grids, characterized by fluctuating generation patterns, reduced inertia, and increased vulnerability to cascading failures, necessitates a shift from traditional offline stability assessments to adaptive online methodologies. In response to this growing need, this study introduces a novel, energy function-based online transient stability assessment (TSA) and remedial action scheme (RAS) that enhances situational awareness and ensures the stability of the power system in real time.

Unlike conventional RAS approaches that rely on offline studies and predefined corrective measures, the proposed methodology introduces an adaptive, online system integrity scheme. The foundation of this approach lies in the coordination of dynamic security assessment (DSA) tools with remedial action schemes, enabling the automated determination and adaptation of mitigation strategies based on real-time grid conditions. Through the development of an energy function-based contingency ranking and transient stability assessment method, the system's stability margins and sensitivities have been systematically identified. By leveraging these stability margin sensitivities, coherent grid clusters have been determined, facilitating a structured and effective formulation of remedial actions.

A key contribution of this study is the introduction of an online adaptive RAS approach that dynamically selects and updates remedial actions considering changing operating conditions. In contrast to the local SPS solutions, the proposed scheme provides a system-wide perspective, enhancing overall grid resilience. A novel approach of clustering by energy margin sensitivity is proposed and energy function-based margin sensitivity approach has proven effective in classifying stability conditions and clustering generators accordingly. This enables a more structured and automated selection of remedial actions, reducing computational burden while maintaining high accuracy and reliability in transient stability assessments.

The proposed scheme has three main parts namely, contingency ranking and screening part, transient stability assessment and margin determination part and remedial action determination by energy margin sensitivities.

Contingency Ranking and Screening

An efficient and reliable contingency screening method is a fundamental component of online DSA. The developed contingency ranking and screening method effectively identifies and prioritizes severe contingencies that pose a threat to system stability. By employing a dot product-based screening approach, rapid and accurate classification of contingencies can be conducted. The dot product metric quantifies the total accelerating power and the system's response, providing a robust index for ranking dynamic contingencies. The results demonstrate that this approach successfully discriminates between critical and non-critical contingencies across different operating scenarios.

Furthermore, a clear threshold can be established based on the computed dot values, enabling the exclusion of contingencies that do not require further analysis. This significantly reduces computational complexity and enhances the efficiency of the overall TSA scheme. The adaptability of the contingency ranking process ensures that it remains effective across varying grid conditions, reinforcing its reliability for real-time applications.

Transient Stability Assessment and Energy Margin Determination

The second component of the proposed scheme involves transient stability assessment and energy margin determination for contingencies identified as critical during the ranking process. The study employs transient energy function (TEF) methods, specifically utilizing the Potential Energy Boundary Surface (PEBS) approach, to quantify stability margins. TEF provides a direct and computationally efficient means of evaluating system stability without requiring time-domain simulations for every contingency.

The proposed approach was validated through multiple test cases under different operating conditions. The results confirm that the method successfully determines stability conditions with high accuracy and reliability. By quantifying stability margins, this process enables the formulation of effective and targeted remedial actions, which are essential for mitigating instability in real-time.

Adaptive Remedial Action Determination Based on Energy Margin Sensitivities

The final component of the proposed scheme focuses on remedial action determination using energy margin sensitivities.This research introduces an innovative approach that leverages coherent grid clusters formed through margin sensitivities, enabling a more systematic and data-driven method for determining remedial actions. In the proposed approach obtained energy margin sensitivities for each generator and contingency is calculated in order to create countermeasure pool in case of critical contingencies. Obtained sensitivity data through analysis are then clustered utilizing K-means approach according to their effectiveness. This grouping automatically sort and screen the countermeasures in order to ease the selection among the possibilities. in order to reduce signaling requirements and complexity of the RAS a global set of remedial actions which satisfy all the problematic cases is searched.Results obtained through test cases have shown that nature of disturbances leading to instability within the power grid is not static but highly dependent on the prevailing operating conditions, which can vary due to factors such as load changes, generation fluctuations, or network reconfigurations. Despite this variability, the topology of the grid—that is, the physical and electrical configuration of its components — plays a crucial role in limiting the range of potential remedial actions available to counteract instability. The results show that while disturbances leading to instability may vary with operating conditions, the remedial actions required to resolve instability can be narrowed down to a smaller, invariant set due to the underlying grid topology. This set of actions remains consistent across different operating scenarios and can be directly applied in remedial action schemes. Hence, the stability margin sensitivity approach proves to be a promising method for quickly and reliably identifying this set of actions.

In summary, the proposed online transient stability assessment and remedial action scheme significantly advances the state-of-the-art by:

- Introducing an online adaptive RAS framework that ensures real-time mitigation of transient instability.
- Shifting from a localized security focus to a grid-wide approach, providing a more comprehensive stability assessment.
- Implementing an energy function-based methodology for contingency ranking, stability margin analysis, and the formation of coherent grid clusters.
- Automating the identification and adaptation of remedial actions based on real-time grid conditions, reducing computational complexity while maintaining accuracy.

As power systems continue to evolve with increasing renewable integration and reduced security margins, the necessity for real-time, adaptive stability control becomes ever more pressing. The proposed method provides a scalable and effective solution to enhance grid resilience, ensuring secure and reliable power system operation in the face of growing uncertainties and dynamic challenges.

7.1 Future Work

The assessment and enhancement of power system stability remain active areas of research. The ultimate goal of this study is to develop a robust and fast assessment tool for all categories of system stability, along with a comprehensive framework to enhance power system stability under all operating scenarios. The following suggestions outline potential future research directions in this field:

1. The power system model used in this study is a reduced network model that considers only the transient effects of conventional generators. However, inverter-based renewable energy sources are expected to play a crucial role in supporting transient stability through advanced control functions. Grid-forming inverters, anticipated to be integrated into the grid within the next five years, can provide voltage and frequency support, further enhancing system stability.

2. Virtual inertia and oscillation damping capabilities of Flexible AC Transmission System (FACTS) devices can also improve transient stability. Future studies could extend the power system dynamic model to incorporate such control mechanisms for a more comprehensive stability analysis.

3. To validate the proposed scheme, its implementation in a real-time simulation environment could be conducted, allowing for practical testing under realistic operating conditions.

4. Ensuring system security requires more than just assessing rotor angle stability. The screening and assessment method should be extended to include other forms of instability, such as voltage instability, to provide a more holistic evaluation of system security.

5. The hybrid transient energy function (TEF) approach forms the core of the proposed scheme. Although the results have demonstrated good accuracy and reliability, alternative computational methods, such as the Single Machine Equivalent (SIME) method, could be explored. Integrating such approaches may improve accuracy, especially for contingencies close to the instability threshold.

6. The proposed remedial action determination method leverages energy margin sensitivity to effectively group and identify countermeasures. Further research could extend this approach to incorporate additional stability indicators, refining the selection and implementation of corrective actions.

7. Modern power grids are equipped with renewable energy and load forecasting models to estimate short-term system conditions. The proposed scheme could be integrated into grid forecasting models to provide grid operators with invaluable insights for proactive stability management.

8. Machine learning techniques, offer promising applications in this field. Sensitivity measures derived from the proposed scheme could be used as attributes in a machine learning based models for system security assessment, enhancing automation and decision support.

REFERENCES

[1] IRENA, "Dcs and renewable energy targets in 2023: Tripling renewable power by 2030," tech. rep., International Renewable Energy Agency, Abu Dhabi.

[2] IEA, "Renewables 2023," tech. rep., International Energy Agency, Licence: CC BY 4.0.

[3] F. S. Olga P. Veloza, "Analysis of major blackouts from 2003 to 2015: Classification of incidents and review of main causes," *The Electricity Journal*, 2016.

[4] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, "Definition and classification of power system stability ieee/cigre joint task force on stability terms and definitions," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387–1401, 2004.

[5] "Ieee guide for engineering, implementation, and management of system integrity protection schemes," *IEEE Std C37.250-2020*, pp. 1–71, 2020.

[6] J. C2/C4.37, "A proposed framework for coordinated power system stability control," *Cigre Technical Brochure 742*, 2018.

[7] K. Morison, L. Wang, and P. Kundur, "Power system security assessment," *IEEE Power and Energy Magazine*, vol. 2, no. 5, pp. 30–39, 2004.

[8] S. Savulescu, "Real-time stability in power systems," *Springer Verlag*, vol. Springer, p. New York, 2006.

[9] W. G. C. C4.601, "Review of on-line dynamic security assessment tools and techniques," *Cigre*.

[10] A. H. El-abiad and K. Nagappan, "Transient stability regions of multimachine power systems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-85, no. 2, pp. 169–179, 1966.

[11] Y. O. N. Kakimoto and M. Hayashi, “Transient stability analysis of electric power systems via lure type lyapunov functions, parts i and ii,” *Trans. IEE of Japan*, vol. 98, no. 5/6, 1978.

[12] N. Yorino, E. Popov, Y. Zoka, Y. Sasaki, and H. Sugihara, “An application of critical trajectory method to bcu problem for transient stability studies,” *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4237–4244, 2013.

[13] H.-D. Chiang, C.-S. Wang, and H. Li, “Development of bcu classifiers for on-line dynamic contingency screening of electric power systems,” *IEEE Transactions on Power Systems*, vol. 14, no. 2, pp. 660–666, 1999.

[14] Y. Tada, A. Kurita, Y. Zhou, K. Koyanagi, H.-D. Chiang, and Y. Zheng, “Bcu-guided time-domain method for energy margin calculation to improve bcu-dsa system,” *IEEE/PES Transmission and Distribution Conference and Exhibition*, vol. 1, pp. 366–371 vol.1, 2002.

[15] A. A. Fouad and S. E. Stanton, “Transient stability of a multi-machine power system. part ii: Critical transient energy,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 7, pp. 3417–3424, 1981.

[16] Y. Xue, T. Van Custem, and M. Ribbens-Pavella, “Extended equal area criterion justifications, generalizations, applications,” *IEEE Transactions on Power Systems*, vol. 4, no. 1, pp. 44–52, 1989.

[17] K. Chan, Q. Zhou, and T. Chung, “Transient stability margin assessment for large power system using time domain simulation based hybrid extended equal area criterion method,” *2000 International Conference on Advances in Power System Control, Operation and Management, APSCOM-00*, vol. 2, pp. 405–409 vol.2, 2000.

[18] A. Miah, “Simple dynamic equivalent for fast online transient stability assessment,” *IEE Proceedings - Generation, Transmission and Distribution*, vol. 145, pp. 49–55(6), January 1998.

[19] D. Ruiz-Vega, D. Ernst, C. Ferreira, M. Pavella, P. Hirsch, and D. Sobajic, “A contingency filtering, ranking and assessment technique for on-line transient stability studies,” *DRPT2000. International Conference on Electric Util-*

ity Deregulation and Restructuring and Power Technologies. Proceedings (Cat. No.00EX382), pp. 459–464, 2000.

[20] G. Maria, C. Tang, and J. Kim, "Hybrid transient stability analysis (power systems)," *IEEE Transactions on Power Systems*, vol. 5, no. 2, pp. 384–393, 1990.

[21] W. Fangzong, C. Deshu, and H. Yangzan, "An integrated method for transient security assessment of power systems," *Proceedings of TENCON '93. IEEE Region 10 International Conference on Computers, Communications and Automation*, vol. 5, pp. 204–207 vol.5, 1993.

[22] T. Chung and F. Da-Zhong, "A new method of fast assessment of transient stability margins," *1993 2nd International Conference on Advances in Power System Control, Operation and Management, APSCOM-93.*, pp. 521–526 vol.2, 1993.

[23] A. D. D.Z. Fang, T.S. Chung, "Improved techniques for hybrid method in fast-transient stability assessment," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 144, pp. 107–112(5), March 1997.

[24] K. Chan, R. Dunn, and A. Daniels, "Transient and dynamic stability constraint assessment using hybrid tef and clustering analysis," *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.00CH37077)*, vol. 2, pp. 1383–1388 vol.2, 2000.

[25] K. Chan, Q. Zhou, and T. Chung, "Dynamic security contingency ranking and generation reallocation using time domain simulation based severity indices," *PowerCon 2000. 2000 International Conference on Power System Technology. Proceedings (Cat. No.00EX409)*, vol. 3, pp. 1275–1280 vol.3, 2000.

[26] M. Kyesswa, H. K. Çakmak, U. Kühnapfel, and V. Hagenmeyer, "A two-stage parallel hybrid method for power system dynamic security assessment," *at - Automatisierungstechnik*, vol. 71, no. 12, pp. 1002–1017, 2023.

[27] T. Wang, T. Bi, H. Wang, and J. Liu, "Decision tree based online stability assessment scheme for power systems with renewable generations," *CSEE Journal of Power and Energy Systems*, vol. 1, no. 2, pp. 53–61, 2015.

[28] P. K. Ray, S. R. Paital, T. K. Panigrahi, A. Mohanty, and M. Kumar, "Differential evolution-swarm hybrid optimization based svc controller for transient stability

analysis in smib," *2016 International Conference on Information Technology (ICIT)*, pp. 298–303, 2016.

[29] Rekha and A. Singh, "Transient stabilization of smib power system using soft computing technique," pp. 1–6, 11 2015.

[30] S. Kamalasadan, G. D. Swann, and R. Yousefian, "A novel system-centric intelligent adaptive control architecture for power system stabilizer based on adaptive neural networks," *IEEE Systems Journal*, vol. 8, no. 4, pp. 1074–1085, 2014.

[31] B. P. Soni, V. Gupta, R. Kumar, A. Saxena, and S. Surana, "Application of ann for stability assessment of large power system by post-fault rotor angle measurements," *2018 IEEMA Engineer Infinite Conference (eTechNxT)*, pp. 1–6, 2018.

[32] S. A. Siddiqui, K. Verma, K. R. Niazi, and M. Fozdar, "Real-time monitoring of post-fault scenario for determining generator coherency and transient stability through ann," *IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 685–692, 2018.

[33] A. Gupta, G. Gurrala, and P. S. Sastry, "An online power system stability monitoring system using convolutional neural networks," *IEEE Transactions on Power Systems*, vol. 34, no. 2, pp. 864–872, 2019.

[34] E. A. Frimpong, P. Y. Okyere, and J. Asumadu, "On-line determination of transient stability status using mlpnn," *2017 IEEE PES PowerAfrica*, pp. 23–27, 2017.

[35] N. I. Abdul Wahab, A. Mohamed, and A. Hussain, "Fast transient stability assessment of large power system using probabilistic neural network with feature reduction techniques," *Expert Syst. Appl.*, vol. 38, pp. 11112–11119, 09 2011.

[36] M. Mahdi and V. M. I. Genc, "Artificial neural network based algorithm for early prediction of transient stability using wide area measurements," pp. 17–21, 2017.

[37] D. You, K. Wang, L. Ye, J. Wu, and R. Huang, "Transient stability assessment of power system using support vector machine with generator combinatorial tra-

jectories inputs," *International Journal of Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 318–325, 2013.

[38] W. Hu, Z. Lu, S. Wu, W. Zhang, Y. Dong, R. Yu, and B. Liu, "Real-time transient stability assessment in power system based on improved svm," *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 1, pp. 26–37, 2019.

[39] Q. Wang, F. Li, Y. Tang, and Y. Xu, "Integrating model-driven and data-driven methods for power system frequency stability assessment and control," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4557–4568, 2019.

[40] P. C. Magnusson, "The transient-energy method of calculating stability," *Transactions of the American Institute of Electrical Engineers*, vol. 66, no. 1, pp. 747–755, 1947.

[41] P. Aylett, "The energy-integral criterion of transient stability limits of power systems," *Proceedings of the IEE - Part C: Monographs*, vol. 105, pp. 527–536(9), September 1958.

[42] G. E. Gless, "Direct method of liapunov applied to transient power system stability," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-85, no. 2, pp. 159–168, 1966.

[43] H.-D. Chiang and C.-C. Chu, "Theoretical foundation of the bcu method for direct stability analysis of network-reduction power system. models with small transfer conductances," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 42, no. 5, pp. 252–265, 1995.

[44] H.-D. Chiang, F. Wu, and P. Varaiya, "Foundations of direct methods for power system transient stability analysis," *IEEE Transactions on Circuits and Systems*, vol. 34, no. 2, pp. 160–173, 1987.

[45] *Direct Methods for Stability Analysis of Electric Power Systems*, ch. 9-"Foundation of the Closest UEP Method", pp. 129–147. aJohn Wiley and Sons, Ltd, 2010.

[46] M. Oluic, *Dynamic Security Region Assessment*. PhD thesis, KTH, Electric Power and Energy Systems, 2019. The doctoral research has been carried out

in the context of an agreement on joint doctoral supervision between Comillas Pontifical University, Madrid, Spain, KTH Royal Institute of Technology, Stockholm, Sweden, and Delft University of Technology, the Netherlands.QC 20190508.

[47] M. Pai, *Power System Stability: Analysis by the Direct Method of Lyapunov*. North-Holland Mathematical Library, North-Holland Publishing Company, 1981.

[48] T. Athay, R. Podmore, and S. Virmani, “A practical method for the direct analysis of transient stability,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 2, pp. 573–584, 1979.

[49] C. Fu and A. Bose, “Contingency ranking based on severity indices in dynamic security analysis,” *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 980–985, 1999.

[50] V. Chadalavada, V. Vittal, G. C. Ejebe, G. D. Irisarri, J. Tong, G. Pieper, and M. McMullen, “Contingency ranking based on severity indices in dynamic security analysis,” *IEEE Transactions on Power Systems*, vol. 12, no. 1, pp. 153–161, 1997.

[51] Y. Mansour, E. Vaahedi, A. Chang, B. Corns, B. Garrett, K. Demaree, T. Athay, and K. Cheung, “Bc hydro’s on-line transient stability assessment (TSA) model development, analysis and post-processing,” *IEEE Transactions on Power Systems*, vol. 10, no. 1, pp. 241–253, 1995.

[52] A. J. Onumanyi, D. N. Molokomme, S. J. Isaac, and A. M. Abu-Mahfouz, “Autoelbow: An automatic elbow detection method for estimating the number of clusters in a dataset,” *Applied Sciences*, vol. 12, no. 15, 2022.

CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: TANIDIR, Özgür
Research Interests: Power system analysis, power system stability, renewable integration, power system optimization

EDUCATION

Degree	Institution	Year of Graduation
Ph.D.	METU Electrical and Electronics Engineering	2025
M.S.	METU Electrical and Electronics Engineering	2014
B.S.	METU Electrical and Electronics Engineering	2010
High School	Süleyman Demirel Anadolu High School, Anlara	2005

Master Thesis Title: Design Of a Special Protection Scheme and Supplementary Controls Regarding HVDC Back-to- Back Interconnection Between Turkey and Georgia
Supervisor: Prof. Dr. Ali Nezih Güven

FOREIGN LANGUAGES

Turkish (Native)
English (Advanced)

PROFESSIONAL EXPERIENCE

Year	**Place**	**Enrollment**
2010 - Present	TÜBİTAK MAM Energy Technologies	Senior Chief Researcher/Group Leader

PUBLICATIONS

1. S. Eren, D. Küçük, C. Ünlüer, M. Demircioğlu, Y. Yanık, Y. Arslan, B. Özsoy, A. Güverçinci, İ. Elma, Ö. Tanıdır, Y. C. Ölmez, S. Sönmez, "Ubiquitous Web-based Dispatcher Information System for Effective Monitoring and Analysis of the Electricity Transmission Grid". International Journal of Electrical Power Energy Systems, vol: 86, pp. 93-103, March 2017.

2. E. Partal, H. F. Bilgin, E. Altıntaş, T. Avcı, E. B. Özmen, Ö. Tanıdır, "Harmonic Performance Requirements and Mitigation for Back-to-Back HVDC in Turkish Transmission System", Cigre Session 2016, Paris, August 2016.

3. A. Güverçinci, S.Eren, Y. Yanık, Ö. Tanıdır, "Determination of Regional Transmission Connection Capacities in a Deregulated Environment", ELECO 2015, Bursa, Turkey, Nov. 2015.

4. Ö. Tanıdır, O. B. Tör, "Accuracy of ANN based day-ahead load forecasting in Turkish power system: degrading and improving factors," Neural Network World, 4/15, pp. 443-456, 2015.

5. Ö. Tanıdır, M.E. Cebeci, "Investigation of SSR Risk in Akkuyu NEPP", ELECO 2013, Bursa, Turkey, Nov. 2013.

6. Ö. Tanıdır, M.E. Cebeci, C. Gençoğlu and O. B. Tör, "A strategy to enhance AGC performance of power systems that suffer inter-area oscillations and a case study for Turkish power system" International Journal of Electrical Power and Energy Systems, Elsevier, vol. 43, pp. 941-953, June 2012

7. C. Gencoglu, O. B. Tor, O. Tanidir, "Technical Feasibility Analysis of the Proposed 2x350 MW HVDC Substation Between Georgia and Turkey," 43rd North American Power Symposium, Northeastern University, Boston, USA, August 4-6, 2011.

8. O.B. Tör, C. Gençoğlu, Ö. Tanidir, M.E. Cebeci and N. Güven, “Investigation of Necessary Transmission Enforcements at the Balkan Region of ENTSO/E in the sense of Inter-area Oscillations after Interconnection of Turkey”, ELECO 2011, Bursa, Turkey, Dec 2011.

9. C. Gencoglu, O. B. Tor, O. Tanidir, “Türbin Hız Regülatörü Parametre Optimizasyonu ile Hidrolik Santrallerin Kararlı İşletim Kriterlerinin Sağlanması - 2x150 MW Borçka Hidrolik Santrali Örneği -" (Satisfying Stability Criteria of Hydraulic Power Plants by Parameter Optimisation of Turbine Governors - 2x150 MW Borcka HPP Practice-“ ELECO 2010, Bursa, Turkey, Dec. 2010. (The best paper award.)

AWARDS - ACHIEVEMENTS

TÜBİTAK Marmara Research Center, Best Research Group Award of 2015