

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**ADAPTIVE BACKSTEPPING CONTROL BASED EMEGENCY SCHEME
FOR IMPROVING TRANSIENT STABILITY OF POWER SYSTEMS
WITH RENEWABLE ENERGY SOURCES**



M.Sc. THESIS

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Department of Electrical Engineering

Electrical Engineering Programme

JUNE 2022

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**YENİLENEBİLİR ENERJİ KAYNAKLARIYLA ENTEGRE GÜÇ
SİSTEMLERİNDE GEÇİCİ KARARLILIĞI KONTROLU İÇİN
UYARLANABİLİR GERİ ADIM KONTROLÜ TABANLI ACİL DURUM
DÜZENİ**

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To my family and friends,





FOREWORD

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ABBREVIATIONS

DAE	: Differential Algebraic Equations
ABC	: Adaptive Backstepping Controller
TSEC	: Transient Stability Excitation Control
MPC	: Model Predictive Control
AVR	: Automatic Voltage Regulator
AEs	: Algebraic Equations
DEs	: Differential Equations
PSS	: Power System Stabilizer
PSO	: Particle Swarm Optimization
GA	: Genetic Algorithm
RES	: Renewable Energy Sources
PV	: Solar Photovoltaic
WSCC	: Western System Coordinating Council
ISE	: Integral Square Error
ITSE	: Integral Time Square Error
IAE	: Integral Absolute Error
ITAE	: Integral Time Absolute Error



SYMBOLS

E'_q	: q-axis transient internal voltage
δ	: Rotor angle of synchronous generator
ω	: Angular speed of synchronous generator
ω_s	: Synchronous speed
P_m	: Mechanical power
P_e	: Electrical power
P_D	: Damping power
X_d	: d-axis synchronous reactance
X'_d	: d-axis synchronous transient reactance
D	: Damping coefficient
H	: Inertia constant
T'_{d0}	: Open Circuit Time Constant on the d-axis
E_{fd}	: Excitation field voltage
T_A	: Exciter time constant
K_A	: Exciter regulator gain
V_{ref}	: Reference voltage input to exciter
V	: Bus terminal voltage magnitude
θ	: Bus terminal voltage angle
T_{SR}	: Speed Relay Time Constant
K_G	: Governor's Proportional Gain
R	: Speed Droop Coefficient
P_{ref}	: Reference Mechanical Power
P_A	: Mechanical Actuation Output Power
P_{HP}	: High Pressure Output Power
P_{RT}	: Reheat Output Power
P_{CO}	: Crossover Output Power
T_{HP}	: High Pressure Time Constant
T_{RT}	: Reheat Time Constant
T_{CO}	: Crossover Time Constant
T_{SM}	: Servo Motor Time Constant
R_s	: Stator resistance
I_d	: d-axis current of stator
I_q	: q-axis current of stator
P_L	: active load power
Q_L	: reactive load power
$Y_{(i,k)}$	: Magnitude of the reduced admittance matrix
$\alpha_{(i,k)}$	: angle of the reduced admittance matrix
P_G	: Active generator power
Q_G	: Reactive load power
V_G	: Complex generator voltage

I_G	: Complex generator current
V_L	: Complex load voltage
Y_{red}	: Reduced admittance matrix
$T_1, T_2, T_3,$	: Compansator time constants
T_4	
T_w	: Washout time constant
K_{pss}	: Power system stabilizer gain
ω_{ref}	: Reference rotor speed
V_G	: Generator's Complex Voltage Phasor
I_G	: Generator's Complex current Phasor
Ω	: Particle in PSO
J	: Objective Function
$\phi_{j,jj}$	: admissible Range For Controller Parameters
$V_{j,jj}$	: admissible Range of Velocity
μ	: Number of Interval
K_{ANG}	: TSEC Regulator Gain
T_{ANG}	: TSEC Time Constant
P_{cmd}	: Active Power Command
Q_{cmd}	: Reactive Power Command
I_{pcmd}	: Active Command Current
I_{qcmd}	: Reactive Command current
Q_{ref}	: Reference Reactive Power
P_{RES}	: Active Power of RES
Q_{RES}	: Reactive Power of RES
V_{dRES}	: d-axis terminal voltage
V_{qRES}	: q-axis terminal voltage
I_p	: d-axis RES Current
I_q	: q-axis RES Current
u_f	: Adaptive Backstepping Controller Input signal
u_{TS}	: TSEC Input Signal
u_{PSS}	: PSS Input Signal

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ADAPTIVE BACKSTEPPING CONTROL BASED EMERGENCY SCHEME FOR IMPROVING TRANSIENT STABILITY OF POWER SYSTEMS WITH RENEWABLE ENERGY SOURCES

SUMMARY

Due to the high demand for electrical energy, operation of modern power systems under stressed loading conditions have become more common. Renewable energy sources are incorporated into modern power systems (RES) that include solar photovoltaics (PV), wind turbines, etc., and complex loads that can considerably alter the electrical system's dynamics. The power system comprises synchronous generators and other energy sources linked together to generate electrical power. When a severe disturbance on the electrical grid occurs, the supply of electrical power may be endangered, and this must be ensured by selecting the corrective action. Transient instabilities occur after extreme contingencies, which are a significant threat to the dynamic security of systems. In this condition, the generator's rotor speeds and rotor angles change suddenly, which causes quick altering of electrical power, and therefore, maintaining system security in tricky conditions is one of the crucial tasks in electrical engineering. The corrective control is applied after disturbance. Emergency control schemes, such as transient stability excitation control (TSEC), can improve the system's stability. TSEC enhances transient stability by controlling excitation system of generators. This control is one of the conventional excitation control techniques that is compared with other methods in this thesis. Besides the emergency control schemes, Power System Stabilizer (PSS) can be a proper solution to decrease the oscillations in a power system in the transient period.

A multi-machine power system consists of generators, turbines, transformers, transmission lines, and loads. To design the dynamics of a power system, the set of differential-algebraic equations (DAEs) should be solved with numerical methods. Differential equations include synchronous generator and turbine inter-area equations, and algebraic equations include stator algebraic equations and network equations. In this study, a tandem-compound single-reheat steam turbine controlled by a speed governor is considered, and it produces the related mechanical power for inputting to synchronous generators. Synchronous generators can be designed with different degrees of accuracy to make the related electrical power. In this study, the 3th order (flux-decay) model synchronous generator with the first-order excitation system (static exciter) is regarded. The network side consists of transmission lines, loads, and other components. This study replaces RES with the related synchronous generator with equal injected real and reactive power.

In this thesis, Adaptive backstepping control (ABC) is proposed to improve the transient stability of power systems during emergency conditions. The thesis problem and the modeling studies are aligned with the studies of collaboration in the

TUBITAK project no. 118E184 and in our published paper, whereas the development of ABC-based controller is the main contribution of this thesis. The control acts on the excitation system of synchronous generators. ABC is a nonlinear feedback excitation control with uncertainties. The control law can be constructed in a recursive manner using the adaptive backstepping approach without linearization to improve transient stability. When a severe fault occurs, the Lyapunov function approach is used to analyze the convergence of the rotor angle and relative speed of the generator, as well as the active electrical power provided by the generator with the intended controller. In this work, the parameters of ABC are successfully tuned using Particle Swarm Optimization (PSO), which is one of the reliable meta-heuristic optimization algorithms. PSO is a bio-inspired algorithm that discovers the best solution in the solution space. It differs from other optimization approaches in that it just requires the objective function and does not rely on the gradient or any differential form of the objective. Therefore, it is an appropriate choice for searching the best parameters for the ABC. First of all, the design of a multimachine power system is discussed in a detailed manner. In this part, the related equations about generators and turbines are elaborated. The construction of the network admittance matrix and the reduced admittance matrix that shows the inside network data are discussed. In addition, PSS and its tuning methods are considered with clarification of PSO. At the end of this section, the injection of RES into the power system with related block diagrams is shown. In the rest of the thesis, the design procedure of ABC is explained in four steps comprehensively.

YENİLENEBİLİR ENERJİ KAYNAKLARIYLA ENTEGRE GÜÇ SİSTEMLERİNDE GEÇİCİ KARARLILIĞI KONTROLU İÇİN UYARLANABİLİR GERİ ADIM KONTROLÜ TABANLI ACİL DURUM DÜZENİ

ÖZET

Elektrik enerjisine olan yüksek talep nedeniyle, modern güç sistemlerinin stresli yükleme koşulları altında çalışması daha yaygın hale geldi. Yenilenebilir enerji kaynakları (RES), güneş fotovoltaikleri (PV), rüzgar türbinleri vb. ve elektrik sisteminin dinamiklerini önemli ölçüde değiştirebilen karmaşık yükleri içeren modern güç sistemlerine dahil edilmiştir. Güç sistemi, elektrik gücü üretmek için birbirine bağlı senkron jeneratörler ve diğer enerji kaynaklarından oluşur. Elektrik şebekesinde ciddi bir arıza meydana geldiğinde, elektrik gücü beslemesi tehlikeye girebilir ve bu, düzeltici eylem seçilerek sağlanmalıdır. Geçici Durum Kararlılığı, güç sisteminin büyük bir arızadan sonra normal koşullarına dönme yeteneği olarak tanımlanır. Yükün aniden kaldırılması, hat değiştirme işlemleri nedeniyle sistemde meydana gelen büyük bozulmalar; sistemde arıza meydana gelmesi, bir hattın aniden kesilmesi vb. Geçici kararsızlıklar, sistemlerin dinamik güvenliği için önemli bir tehdit olan aşırı beklenmedik durumlardan sonra ortaya çıkar. Bu durumda jeneratörün rotor hızları ve rotor açıları aniden değişir, bu da elektrik gücünün hızlı değişmesine neden olur ve bu nedenle zor koşullarda sistem güvenliğini sağlamak elektrik mühendisliğinin en önemli görevlerinden biridir. Düzeltici kontrol, arızadan sonra uygulanır. Geçici kararlılık gibi acil durum kontrol şemaları uyarma kontrolü (TSEC), sistemin kararlılığını artırabilir. TSEC, jeneratörlerin uyarma sistemini kontrol ederek geçici kararlılığı artırır. Bu kontrol, bu tezde diğer yöntemlerle karşılaştırılan geleneksel uyarma kontrol tekniklerinden biridir. Acil durum kontrol şemalarının yanı sıra, Güç Sistemi Stabilizatörü (PSS), bir güç sistemindeki geçici rejimdeki salınımları azaltmak için uygun bir çözüm olabilir.

Birbirine bağlı güç sisteminin kararlılığı, bir tür bozulmaya maruz kaldıktan sonra normal veya kararlı çalışmaya geri dönebilme yeteneğidir. Sürekli şekilde boyut olarak büyüyen ve geniş coğrafi bölgelere yayılan birbirine bağlı sistemlerle, güç sisteminin çeşitli bölümleri arasında senkronizasyonu sürdürmek giderek daha zor hale geliyor. Bu tezde, MATLAB/Simulink ile çok makineli sistemlerin geçici rejim kararlılığını inceleyeceğiz. Modern güç sistemlerinde, her biri birkaç jeneratör ve birçok yük içeren birçok birbirine bağlı üretim istasyonu bulunur. Bu yüzden çok makineli sistemi sunduk ve stabilitesi illüstrasyon ve çeşitli arızalar kullanılarak analiz edilecek ve arızaya da çözüm sağlanacaktır. Çok makineli bir güç sistemi, jeneratörler, türbinler, transformatörler, iletim hatları ve yüklerden oluşur. Bir güç sisteminin dinamiklerini tasarlamak için, diferansiyel cebirsel denklemler (DAE'ler) kümesi sayısal yöntemlerle çözülmelidir. Genel veya özel formdaki DAE'ler, çok gövdeli ve

esnek gövde mekaniği, elektrik güç tasarımı, optimal kontrol, sıkıştırılmaz akışkanlar gibi mühendislik ve bilimden kaynaklanan çok çeşitli problemlerin matematiksel modellenmesinde ortaya çıkar. Newton-Raphson, Runge-Kutta gibi farklı sayısal yöntemlerle çözülebilir. Diferansiyel denklemler, senkron jeneratör ve türbin alanlar arası denklemleri içerir ve cebirsel denklemler, stator cebirsel denklemlerini ve şebeke denklemlerini içerir. Bu çalışmada, bir hız regülatörü tarafından kontrol edilen ve senkron jeneratörlere giriş için ilgili mekanik gücü üreten tandem bileşenli tek tekrar ısıtılmalı bir buhar türbini ele alınmıştır. Senkron jeneratörler, ilgili elektrik gücünü yapmak için farklı doğruluk derecelerinde tasarlanabilir. Bu çalışmada, birinci dereceden uyarma sistemli (statik uyarıcı) ve üçüncü dereceden (akı-azalımlı) model senkron jeneratör ele alınmıştır. Şebeke tarafı, iletim hatları, yükler ve diğer bileşenlerden oluşur. Bu çalışma, yenilenebilir enerji kaynaklarını eşit enjekte edilen gerçek ve reaktif güce sahip ilgili senkron jeneratör ile değiştirmektedir.

Bu tezde, acil durumlarda güç sistemlerinin geçici kararlılığını iyileştirmek için Adaptif geri adım kontrolü (ABC) önerilmiştir. No. 118E184 TÜBİTAK projesinde ve yayınlanan makalemiz işbirliği çalışmaları ile tez problemi ve modelleme çalışmaları hizalanmıştır, oysa ABC tabanlı denetleyicinin geliştirilmesi bu tezin ana katkısıdır. Kontrol, senkron jeneratörlerin uyarma sistemine etki eder. ABC, belirsizlikleri olan doğrusal olmayan bir geri besleme uyarım kontrolüdür. Kontrol yasası, geçici kararlılığı iyileştirmek için doğrusallaştırma olmadan uyarlanabilir geri adım atma yaklaşımı kullanılarak özyinelemeli bir şekilde oluşturulabilir. Ciddi bir arıza meydana geldiğinde, Lyapunov fonksiyonu yaklaşımı, rotor açısının ve jeneratörün bağıl hızının yakınsamasını ve ayrıca jeneratör tarafından amaçlanan kontrolör ile sağlanan aktif elektrik gücünü analiz etmek için kullanılır. Bu çalışmada, güvenilir meta-sezgisel optimizasyon algoritmalarından biri olan Particle Swarm Optimization (PSO) kullanılarak ABC'nin parametreleri başarıyla ayarlanmıştır. Parçacık sürüsü optimizasyonu (PSO), ilk olarak 1995'te tanıtılan devrim niteliğindeki popülasyon tabanlı bir optimizasyon metodolojisidir. Bu stratejinin birçok faydası vardır. Basit, hızlı ve az depolama gereksinimi ile birkaç satırda programlanabilir. Hesaplamalı bilimde, parçacık sürüsü optimizasyonu (PSO), belirli bir kalite ölçüsüne göre aday bir çözümü yinelemeli olarak iyileştirmeye çalışarak bir sorunu optimize eden bir hesaplama yöntemidir. Bir problemi, burada parçacıklar olarak adlandırılan bir aday çözümler popülasyonuna sahip olarak ve bu parçacıkları arama uzayında basit matematiksel formüle göre parçacığın konumu ve hızı üzerinde hareket ettirerek çözer. Her parçacığın hareketi, yerel olarak en iyi bilinen konumundan etkilenir, ancak aynı zamanda, diğer parçacıklar tarafından daha iyi konumlar bulunduğunda güncellenen arama uzayındaki en iyi bilinen konumlara doğru yönlendirilir. Bunun sürüyü en iyi çözümlere doğru hareket ettirmesi bekleniyor. PSO, çözüm uzayında en iyi çözümü arayan biyo-ilhamlı bir algoritmadır. Diğer optimizasyon tekniklerinden, sadece amaç fonksiyonu gerektirmesi ve amacın gradyanına veya herhangi bir diferansiyel formuna bağlı olmaması bakımından farklıdır. Bu nedenle, ABC için en iyi parametreleri aramak için uygun bir seçimdir.

Öncelikle çok makineli bir güç sisteminin tasarımı detaylı bir şekilde ele alınmıştır. Bu bölümde jeneratörler ve türbinler ile ilgili denklemler detaylandırılmıştır. Şebeke kabul matrisinin yapısı ve şebeke içindeki verileri gösteren indirgenmiş kabul matrisi tartışılmıştır. Ek olarak, PSS ve onun ayarlama yöntemleri, PSO'nun netleştirilmesiyle birlikte ele alınmaktadır. Bu bölümün sonunda ilgili blok diyagramları ile RES'in

güç sistemine enjeksiyonu gösterilmektedir. Tezin geri kalanında, ABC'nin tasarım prosedürü dört adımda kapsamlı bir şekilde açıklanmaktadır.





1. INTRODUCTION

The power system is one of the most intrinsically complicated systems that persistently change formation due to load changes, disturbances, and adding devices and instruments. Nowadays, in developed countries supply of electricity plays a significant role in the nation's life quality. Thus, the reliability and stability of electrical systems should be guaranteed. A power system is viewed as a massive multiple-input multiple-output system comprised of subsystems dispersed across a huge geographical location due to its increasing complexity. As a result, the goal of stabilizing the entire system becomes a problematic endeavor. Furthermore, most electrical grid components are forced to run at or near their stability limitations due to increasing load. Because of the reasons mentioned above, keeping power system stability is one of the essential tasks in electrical engineering [1].

Renewable energy sources (RES) are considered green power sources, and their efficient usage of these resources have a low environmental impact, generate little additional waste, and are long-term based on long - term economic and societal demands. [2]. RES systems can negatively affect the electrical system. In this thesis, the impact of RES systems on power systems' dynamics is analyzed and their adverse effects on transient stability are mitigated.

According to the definition, the capacity of a power grid to recover or reestablish after being subjected to a physical disruption, a condition of operational equilibrium, with the majority of system variables being constrained such that the whole system remains intact, is referred to as power system stability [3]. Power systems can lose their stability due to line switching, transmission line tripping, load shedding, generator tripping, etc... [4]. The capacity of a power system to maintain its stability after facing a severe disturbance is referred to as transient stability. To analyze the transient stability of a power system, the set of differential and algebraic equations (DAE) should be considered. Transient stability analyses depend on examining the dynamics of electrical systems, consisting of synchronous generators connected to an electrical

grid. Synchronous generators are electromechanical systems that must perform in unison. An electrical power system is close equilibrium under normal operating conditions, with only negligible deviations from true-steady-state stress created by minor changes in loads. At this condition, these generators operate synchronously. The problem arises when the electrical system is disturbed. At this condition, the generators are subjected to out of synchronism, so that it can cause instability of the power system.

When an electrical grid experiences a substantial disruption, such as a short circuit, the rotor speed of certain generators varies (usually the generators which are close to the occurrence fault place). Consequently, this mode produces oscillations on voltages and currents of the system that can lead to damage on monitoring devices if the disturbance is so large. Therefore, these oscillations must be reduced urgently by various appropriate techniques.

Control is a vital element for the enhancement of transient stability. Control can decrease the fluctuations of rotor speeds and electrical powers considerably. Therefore, different control techniques can be applied to achieve the best result. Control devices can be connected to generators, transmission lines, and distribution sides. In this thesis, the controllers are connected to generators to obtain transient stability. In [5], when the system is exposed to severe contingencies, it is necessary to deploy a centralized emergency controller in order to maintain synchronism. The suggested control approach is based on non-local measures, which makes it more accurate. The downsides of centralized control systems, on the other hand, are their high computing complexity as well as the possibility of losing connection between the controller and the generators that are being controlled. In addition, due to physical distance between various components of the system, it may result in an unjustified rise in the cost of power transmission. A decentralized emergency control approach is used throughout this thesis in an effort to best control the excitation of the available synchronous generators in order to maintain the transient stability of the power system after it has been subjected to a severe contingency, which is discussed in detail later. When compared to earlier methodologies, the proposed control structure is based only on local feedback signals, making it ideal for large-scale systems without the requirement for a wide-area measurement system to be implemented.

Power system analysis and control have been a popular topic during the last times, especially because of growing renewable energy sources (RES). RES adds additional damping on power system oscillations and modifies power system dynamics significantly. There are various control approaches for attaining transient stability in the literature. The use of power system stabilizers [6], FACTS devices [7], braking resistors [8], [9], generator trip-ping [10], fast valving [11], and controlled islanding [12] are among the most effective methods that could prevent transient instabilities as they improve the systems' dynamic response under critical contingencies.

Power system stability may be improved with the use of excitation controllers, which provide additional damping to make power systems stable and minimize low frequency oscillations like as those caused by [13]. The literature contains a number of different excitation control methods that improve transient stability. These include feedback linearizing model predictive excitation control [14], nonlinear adaptive excitation control [15], switching excitation control between a bang-bang funnel excitation controller and a conventional excitation controller [16], and transient stability excitation control (TSEC) [17]. TSEC is a conventional discontinues excitation control that improves transient stability by controlling excitation system of synchronous generators. This control uses rotor angle, and rotor speeds signal to maintain stability of the system. Further, TSEC is applied only in the transient period approximately 2 seconds depends on the severity of disturbance. In [18], it is proposed to improve transient stability by coordinating the control loops for the excitation and governor, it use a decentralized model reference adaptive control approach, and [19], which employs two switching bang-bang controllers for both excitation and governor, both of which are implemented in [19].

The linear control theory-based procedures [20] are only practical for small signal stability. When the post-fault region undergoes tiny oscillations, small signal stability arises. Linearization around the operational point is necessary in this case. Thus, linear control techniques are not appropriate to guarantee a power system when a severe disturbance has occurred. Several nonlinear excitation control approaches have been suggested to improve the transient stability of power systems subjected to large disturbances. Feedback linearizing model predictive excitation controller [14] and Partial feedback linearizing excitation controller [21] are the nonlinear control

techniques that can preserve the system's security in the severe condition. The backstepping controller is implemented on a single machine infinite bus system in [22, 23]. In addition, this approach is used on a large power system in [24]. All of the above-mentioned controllers are constructed with the premise that all of the power system's dynamic characteristics are determined. Some characteristics in natural power systems are unknown because they are difficult to measure, such as the damping coefficient, reactance, and transient reactance of synchronous generators. The uncertainty in the precise values of the aforementioned factors may have a substantial influence on the overall stability of the system.

This thesis aims to design a controller that can guarantee the power system's stability when some parameters are unknown. In this thesis, we propose an ABC-based control method that enhances the methodology and improves the results of our work in [25] where an emergency control scheme based on Model Predictive Control (MPC) is introduced to prevent transient instabilities. The ABC control scheme is an appropriate technique to damp oscillations and improve transient stability even when the system is subjected to different disturbances [15, 26, 27]. In addition, this technique is implemented on the power system integrated with renewable energy sources (RES) that shows the robustness of the proposed controller. The proposed controller is based on a nonlinear 4th order model that includes automatic voltage regulator (AVR) and 3th order synchronous generator model (flux-decay). The unknown parameters are approximated and fed into the controller design scheme. Then, the Lyapunov function is used to verify the system's stability. Particle swarm optimization (PSO) is used to fine-tune the parameters of controllers [28, 29]. PSO is a metaheuristic algorithm because it makes little or no assumptions about the optimized problem and may seek enormous areas of alternative solutions. Optimizing the nonlinear function by PSO is appropriate because it can search in the vast area to select the best condition.

In this thesis, the simulations are organized in MATLAB/Simulink. In addition, Western System Coordinated Council System (WSCC - IEEE 9 bus - 3 machines) and (IEEE 68 bus - 14 machines - 2 RES) are used to test the performance of the controllers.

The rest of the thesis is organized as follows: Multi-machine power system dynamics in chapter 2. In this chapter the design of power system dynamics is discussed,

comprehensively. The design process of decentralized adaptive backstepping controller is illustrated in chapter 3. Simulation results are shown in chapter 4. First of all, the simulation part related to IEEE 9 bus- 3 machines is discussed comprehensively. Firstly, the PSS, TSEC, and ABC parameters given from the PSO algorithm are shown. In this part, it can be seen that generator no.1 has not participated in control actions due to demonstrating the efficacy of controllers. As a further comparison, we look at the five error signals produced when a symmetrical three-phase fault arises in two test cases, firstly the fault arises on bus no. 8 and is cleared beyond its critical period by tripping the line connecting buses no. 8 and 9, and after that the contingency occurs on bus no.4 at the critical time by tripping the line connecting buses no. 4 and 5. The rest of this section includes the generator's rotor speeds and rotor angles figures related to the system when it implemented with: normal condition (without controller), PSS, TSEC, ABC, and ABC with PSS.

Moreover, the same control schemes are tested on IEEE 68 bus - (14 machines - 2 RESs) system. This section aims to test the larger and more critical system, so two of the most critical faults is selected (fault on buses no.19 and no.28), and integrating RES on the power system becomes more crucial. All of the synchronous generators that participated in control actions, all individuals, with the exception of those numbered 14, 15, and 16, are presumed to be taking part in an emergency control operation similar to the IEEE 9 bus-3 machines system, the results are discussed. The results of the simulation demonstrate the efficacy of the control technique even when few generators are selected to participate in the emergency control procedure. The thesis is then concluded in chapter 5.

2. MULTI MACHINE POWER SYSTEMS DYNAMICS

This chapter will elaborate on the dynamics of synchronous generators interconnected to the electrical network, which consists of loads and transmission lines. For simulating electrical systems, a set of differential and algebraic equations (DAE) must be solved. Synchronous generators can be modeled by different degrees of accuracy [30]. In our manuscript [25], we modeled the synchronous generators in high order model (6^{th} -order). Also, the (second-order) and (3^{th} -order) model is available in [31]. Due to the goal of the thesis, ((3^{th} -order) - flux decay,) generator model including transient analysis of the electrical system will be solved in the following sections. m denotes the number of machines in the next parts, and n indicates the number of buses in the electrical grid. (Fig. 2.1 shows the electrical grid)

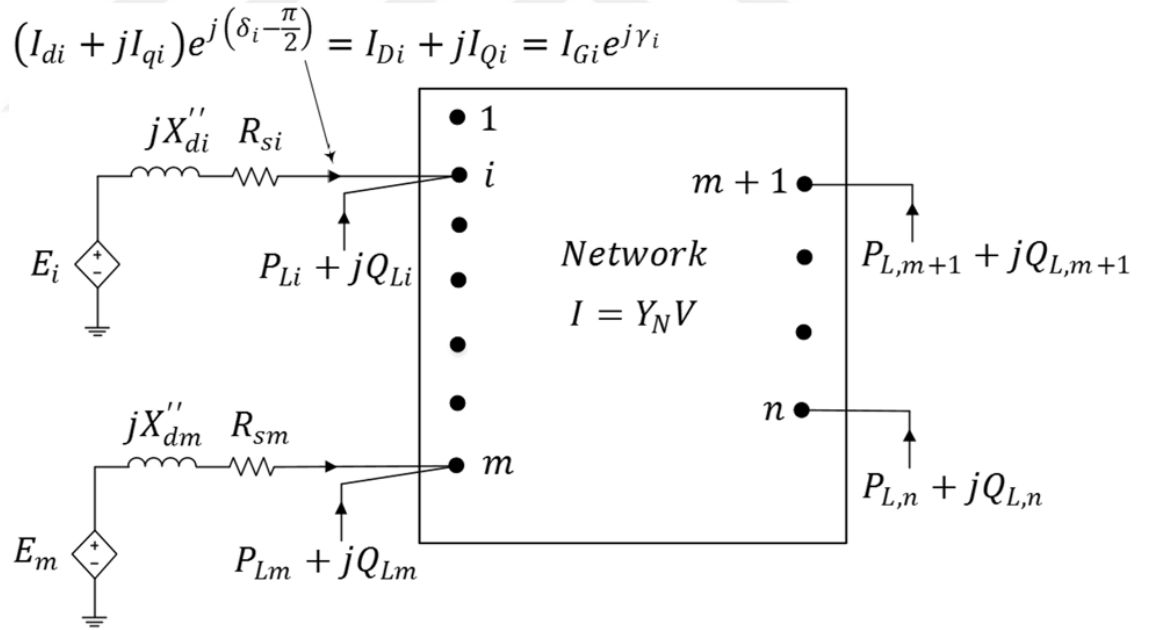


Figure 2.1 : Multimachine Interconnected Network Dynamics.

2.1 Differential Equations

2.1.1 Synchronous Generator

Differential equations subjected to synchronous generator can be written blow:

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad i = 1, \dots, m \quad (2.1)$$

$$\frac{d\omega_i}{dt} = \frac{P_{mi} - P_{ei} - D_i(\omega_i - \omega_s)}{2H_i} \quad i = 1, \dots, m \quad (2.2)$$

$$\frac{dE'_{qi}}{dt} = \frac{-E'_{qi} - (X_{di} - X'_{di})I_{di} + E_{fdi}}{T'_{d0i}} \quad i = 1, \dots, m \quad (2.3)$$

Where E'_{qi} , δ_i , and ω_i denotes the q-axis transient internal voltage, rotor angle, angular speed of a synchronous generator, respectively. In addition P_{mi} and P_{ei} are the mechanical power input and electrical power, respectively. P_{Di} is the damping power that is written in equation 2.4 (D_i is the damping coefficient).

$$P_{Di} = D_i(\omega_i - \omega_s) \quad i = 1, \dots, m \quad (2.4)$$

2.1.2 Excitation System (Static Exciter)

In order to design the excitation system, static exciter is chosen witch includes Automatic Voltage Regulator (AVR).

$$\frac{dE_{fdi}}{dt} = \frac{-E_{fdi} + K_{Ai}(V_{refi} - V_i)}{T_{Ai}} \quad i = 1, \dots, m \quad (2.5)$$

In the equations, 2.5, E_{fd} is the Field voltage that is injected to the synchronous generator from exciter, and T_{Ai} is the time constant of the exciter. Furthermore, K_{Ai} denotes the exciter regulator gain, and V_{refi} , V_i are Reference voltage input and magnitude of bus voltage, respectively.

2.1.3 Turbine and Governor

We analyze a tandem-compound single-reheat steam turbine [13, 32] power that operates under the control of a speed governor in the present study. The configuration of the turbine and its control system is shown in Fig. 2.2. An example of a speed

relay is shown in Fig. 2.2, where the relay has a first-order transfer function and a time constant TSR , as well as a gain $KG = 1/R$, where R denotes the rate of change of the speed. Throughout this demonstration, we'll refer to P_{ref} and P_A as the constant mechanical power delivered to the relay and the output of mechanical actuation by the servo motor applied to the intercept valve, respectively; this is to make the diagram more straightforward. The outputs of the high-pressure steam chest, reheat, and crossover are denoted by the variables P_{HP} , P_{RT} , and P_{CO} , respectively. The high-pressure steam chest, reheat, and crossover phases are represented by first-order transfer functions with the time constants T_{HP} , T_{RT} , and T_{CO} , respectively, corresponding to their respective time constants. There are three scales for their contributions to the total produced power: α , β , and γ . The sum of these three scales equals one. The positions of the control valve (CV) and the intercept valve (IV) are changed by the servo-motors, which are described by first-order transfer functions with time constants T_{SM} and T_{SI} , respectively, and are controlled by the control valve (CV) and the intercept valve (IV). The mechanical actuation of the valves is provided by the servo-motor and speed relay, whose dynamics are slower than the electromechanical dynamics of the generators. Their dynamics must be taken into consideration since failing to do so might result in a considerable degradation of control performance, or possibly the occurrence of instability, as a result of the failure to account for temporal delays in control operations caused by the actuator dynamics. A general speed-governing system is used as a main frequency regulator for slight variations in the speed of the system [13]. We used this type of turbine and speed governing system in our work [25] to control intercept valves of steam turbines with model predictive controller (MPC). Additionally, the detail characteristics of this model is available in [31].

2.2 Algebraic Equations

The sections 2.2.1 and 2.2.2 describe Algebraic equations (AEs) in the detailed model. In the section 2.2.1, Stator algebraic equations are solved. R_{si} , I_{di} , I_{qi} , θ_i represent Stator resistance, d-axis current of stator, q-axis current of stator, and angle of bus voltage respectively. In the section 2.2.2, Network algebraic equations will be elaborated. Where, P_{Li} is the active load power and Q_{Li} is the reactive load

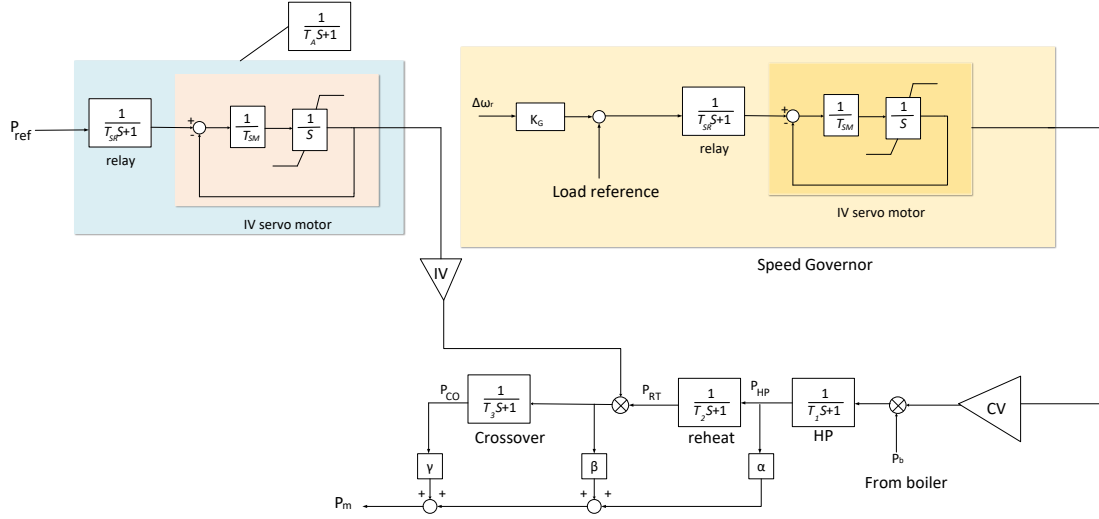


Figure 2.2 : Turbine and speed governing system [32].

power. Finally, $Y_{(i,k)}$ and $\alpha_{(i,k)}$ denote magnitude and angle of i^{th} and k^{th} the reduced admittance matrix that will be described in section 2.4.

2.2.1 Stator Algebraic Equations

$$V_i \sin(\delta_i - \theta_i) + R_{si} I_{di} - X_{qi} I_{qi} = 0 \quad i = 1, \dots, m \quad (2.6)$$

$$E'_{qi} - V_i \cos(\delta_i - \theta_i) - R_{si} I_{qi} - X'_{di} I_{di} = 0 \quad i = 1, \dots, m \quad (2.7)$$

2.2.2 Network Algebraic Equations

$$I_{di} V_i \sin(\delta_i - \theta_i) + I_{qi} V_i \cos(\delta_i - \theta_i) + P_{Li}(V_i) + \sum_{k=1}^n V_i V_k Y_{(i,k)} \sin(\theta_i - \theta_k - \alpha_{(i,k)}) = 0 \quad i = 1, \dots, m \quad (2.8)$$

$$I_{di} V_i \cos(\delta_i - \theta_i) - I_{qi} V_i \sin(\delta_i - \theta_i) + Q_{Li}(V_i) - \sum_{k=1}^n V_i V_k Y_{(i,k)} \cos(\theta_i - \theta_k - \alpha_{(i,k)}) = 0 \quad i = 1, \dots, m \quad (2.9)$$

$$P_{Li}(V_i) - \sum_{k=1}^n V_i V_k Y_{(i,k)} \cos(\theta_i - \theta_k - \alpha_{(i,k)}) = 0 \quad i = 1, \dots, m \quad (2.10)$$

$$Q_{Li}(V_i) - \sum_{k=1}^n V_i V_k Y_{(i,k)} \sin(\theta_i - \theta_k - \alpha_{(i,k)}) = 0 \quad i = 1, \dots, m \quad (2.11)$$

2.3 Initial values Calculation

The electrical test system has three different conditions in stability analysis: before disturbance, during the disturbance, and after disturbance. To simulate the before disturbance condition, It is typical to presume that the system is in a steady-state state. By equalizing zero value to all the derivatives of differential equations, the below equations are extracted. MATPOWER does load flow analysis in this section [33]. By referring to the load flow analysis, it is assumed that bus voltages and generator output powers for $(i = 1, \dots, m)$ can be written $(\bar{V}_i = V_i e^{j\theta})$ and $(P_{Gi} + jQ_{Gi})$, respectively.

- Calculating generator output current: $\bar{I}_{Gi} = I_{Gi} e^{j\gamma_i} = \frac{(P_{Gi} - jQ_{Gi})}{\bar{V}_i^*} = (I_{di} + jI_{qi}) e^{j(\delta_i - \frac{\pi}{2})}$
- Calculating rotor angle (δ_i) : $\delta_i = \text{Phase}(V_i e^{j\theta} + (R_{si} + jX_{qi}) \bar{I}_{Gi})$
- Calculating I_{di} and I_{qi} : $\begin{cases} I_{di} = \Re(\bar{I}_{Gi} e^{-j(\delta_i - \frac{\pi}{2})}) \\ I_{qi} = \Im(\bar{I}_{Gi} e^{-j(\delta_i - \frac{\pi}{2})}) \end{cases}$
- Calculating q-axis transient internal voltage: $E'_{qi} = V_i \cos(\delta_i - \theta_i) + X'_{di} I_{di}$
- Calculating field voltage: $E_{fdi} = E'_{qi} + (X_{di} - X'_{di}) I_{di}$
- Calculating reference voltage: $V_{refi} = \frac{E_{fdi}}{K_{Ai}} + V_i$
- Calculating mechanical power: $P_{mi} = E'_{qi} I_{qi} + (X_{qi} - X'_{di}) I_{di} I_{qi}$

2.4 Admittance Matrix With Constant Impedance Load

To analyze power system stability, calculating the admittance matrix from line data is required. The dynamics model described by DAES may be transformed to an explicit version without algebraic equations by integrating constant impedance load into the bus admittance matrix horizontal entries [30] where m indicates the number of synchronous generators and n denotes the number of network buses. The current balance form of the network is given below:

$$\begin{bmatrix} I_G \\ 0 \end{bmatrix} = \begin{matrix} m & n-m \\ n-m & \end{matrix} \begin{pmatrix} Y_A & Y_B \\ Y_C & Y_D \end{pmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (2.12)$$

$$\begin{cases} I_G = Y_A V_G + Y_B V_L \\ 0 = Y_C V_G + Y_D V_L \end{cases} \quad (2.13)$$

so,

$$V_L = -Y_D^{-1}Y_C V_G \quad (2.14)$$

The submatrices of the augmented admittance matrix are defined by Y_A , Y_B , Y_C , and Y_D in the preceding equations. Furthermore, V_G and I_G indicate the complex voltage and current phasors of generators, respectively, while V_L denotes the complex voltage phasor of load buses.. By substituting equation 2.14 into 2.13 the following equations are achieved:

$$I_G = Y_A V_G + Y_B (-Y_D^{-1}Y_C) V_G = (Y_A - Y_B Y_D^{-1}Y_C) V_G = Y_{red} V_G \quad (2.15)$$

$$Y_{red} = (Y_A - Y_B Y_D^{-1}Y_C) \quad (2.16)$$

Y_{red} is the reduced admittance matrix which contains only generator bus nodes. Further, Y_{red} is utilized for solving algebraic equations that is described in section 2.2.2. Here, the mentioned submatrices are defined in detail. In order to calculate Y_A the following procedure is considered. In the block matrix, Y_g is the augmented matrix where $Z_{gi} = R_{si} + X'_{di} I_{di}$ for $i = 1, \dots, m$.

$$Y_g = \begin{bmatrix} \frac{1}{Z_{g1}} & 0 & \cdots & 0 \\ 0 & \frac{1}{Z_{g2}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{Z_{gm}} \end{bmatrix}$$

$$Y_A = Y_g \quad (2.17)$$

Y_B and Y_C are shown in below. It should be noted that Y_B is $m \times n$ matrix and Y_C is $n \times m$ matrix.

$$\left\{ \begin{array}{l} Y_B = m \begin{pmatrix} m & n-m \\ \begin{pmatrix} -Y_g \end{pmatrix} & \dots & 0 \end{pmatrix} \\ Y_C = \begin{pmatrix} m \\ n-m \end{pmatrix} \begin{pmatrix} \begin{pmatrix} -Y_g \end{pmatrix} \\ \vdots \\ 0 \end{pmatrix} \end{array} \right.$$

Finally, the Y_D is produced with Y_{bus} and Y_L that both of them has $n \times n$ size. Y_{bus} is the overall admittance matrix of electrical grid that is described in [34]. Y_L is the load matrix that is given below.

$$Y_{Li} = \frac{-(P_{Li} + jQ_{Li})^*}{V_{0i}^2} \quad i = 1, \dots, n \quad (2.18)$$

Where P_{Li} , Q_{Li} , and V_{0i} are the load active power, load reactive power and bus terminal

$$Y_L = \begin{bmatrix} Y_{L1} & 0 & \dots & 0 \\ 0 & Y_{L2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Y_{Ln} \end{bmatrix}$$

voltage bus, respectively.

$$Y_D = Y_{bus} + Y_L \quad (2.19)$$

2.5 Power System Stabilizer

Excitation devices with high gain and quick response time are very beneficial for transient stability (synchronizing torque), but they may also compromise tiny signal stability when used in combination (damping torque). By decreasing generator rotor angle swings, which occur throughout a broad frequency range in the power system, power system stabilizer (PSS) management offers a positive contribution to the power system's stability. Low frequency modes, also known as inter-area modes, are formed by coherent groups of generators swinging against other coherent groups of generators in an interconnected system at low frequencies. These modes are present in all linked

systems, and the damping of these modes is dictated by the strength of the tie lines and the loading factors of the individual units. Because of weak linkages produced by line breaks and high system loads, it is possible for inter-area modes to be poorly damped. PSS control can often give considerable increases in inter- area mode dampening by providing stabilizers to the majority of units that engage in power swing modes. PSS provides dampening torque to the excitation system in response to rotor speed variation [30]. The elements of a standard PSS are depicted in fig.2.3. The model consists of two phase-lead compensator $(\frac{T_1s+1}{T_2s+1}, \frac{T_3s+1}{T_4s+1})$, a washout high pass-filter $(\frac{T_ws}{T_ws+1})$, and a gain (K_{pss}) . Where $T_1, \dots, T_4$ are the compensator time constants and T_w is the washout time constant. For tuning the parameters of a PSS, Optimization algorithms can be applied. I used particle swarm optimization (PSO) [28] algorithm for tuning the related parametrs. The optimization aims to reduce the objective function (equation 2.20) concerning the following constraints:

$$Objective \ function = \int_0^{t_{sim}} |\omega_i - \omega_{ref}| dt \quad i = 1, \dots, m \quad (2.20)$$

$$\begin{cases} K_{Pss(min)} < K_{Pss} < K_{Pss(max)} \\ T_{1(min)} < T_1 < T_{1(max)} \\ T_{2(min)} < T_2 < T_{2(max)} \\ T_{3(min)} < T_3 < T_{3(max)} \\ T_{4(min)} < T_4 < T_{4(max)} \end{cases}$$

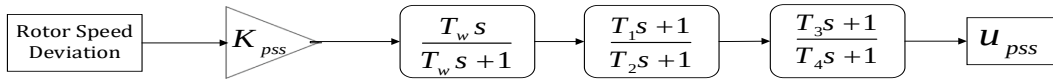


Figure 2.3 : Convetional PSS Structure.

Where, ω_{ref} is the reference rotor speed and ω_i is the angular rotor speed. Further, t_{sim} is the simulation time. The top and lower boundaries of the constraints may be found in [30].

2.5.1 Particle Swarm Optimization

Particle swarm optimization (PSO) is a revolutionary population-based optimization methodology that was first introduced in 1995. This strategy has a lot of benefits. [28] It is simple, quick, and can be programmed in a few lines, with little storage requirements.

A PSO-based approach alters each particle's trajectory in the search space by

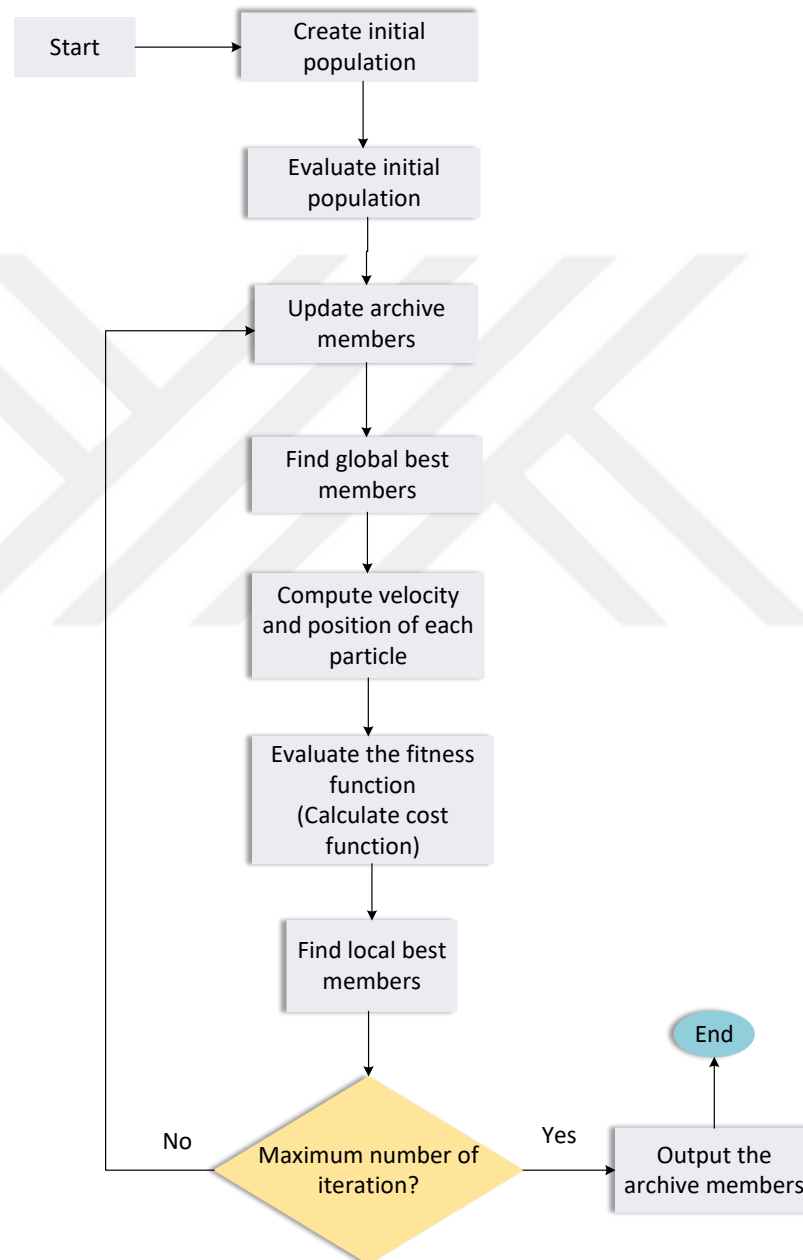


Figure 2.4 : Flowchart of PSO.

dynamically adjusting its velocity in response to its own flight experience and that of other particles in the search space. Fig. 2.4 demonstrates the flowchart of PSO. In

contrast to other evolutionary algorithms such as the Genetic Algorithm (GA), PSO offers a well-balanced and adaptable method for improving the capacity to find the optimum local and global locations [35]. The following are some of the benefits of PSO over other optimization approaches: [36]:

- It is more adaptable, resilient, and simple to deploy.
- It has less parameters to customize.
- It can solve the problem of late convergence and increase search capabilities.
- It is less prone to become entangled in local minimal.
- It features a more efficient memory capacity (local and neighboring best).
- When using this strategy, the starting population has no effect on the quality of the solution that is provided by it.

PSO is used to a power grid throughout this study to discover the best value for the PSS, ABC, and TSEC parameters.

2.5.1.1 definitions of the PSO terminology

Particle $\Omega_i(t)$

At iteration t, a candidate solution (controller parameters). The size of each particle is the total of the parameters of the controllers.

Population

A collection of m particles $\{\Omega_1(t), \Omega_2(t), \dots, \Omega_m(t)\}$, where m denotes the number of candidate solutions.

Objective function $J_i(t)$

This function is used to determine the fitness of the i^{th} controller at the t^{th} iteration.

Local best $\Omega_i^*(t)$

It is the best fitness value that this particle has obtained up to this iteration.

$$\begin{cases} \Omega_i^*(t) = \{\Omega_i(t) : J_i(\Omega_i^*(t)) \leq J_i(\Omega_i(t))\} \\ J_i^*(t) = J_i(\Omega_i^*(t)) \end{cases}$$

Global best $\Omega^{**}(t)$

All particles' best position (or fitness) between all individual local best positions.

Where n is the numbers of controllers.

$$\Omega^{**}(t) = \{\Omega_i^*(t) : J(\Omega^{**}(t)) \leq J_i(\Omega_i^*(t))\}, \quad i = 1, \dots, n$$

2.5.2 The steps of the PSO technique

Initialization

Define the time counter (t), and the performance evaluation counter (c), as well as their maximum values t_{max} , and c_{max} .

Create an arbitrary number of particles and assign a velocity to each of these particles. These values are derived based on the following information: the size of each particle (p), the population size (m), the admissible range for controller parameters ($\phi_{j,jj}^{min}$, and $\phi_{j,jj}^{max}$), and admissible range of velocity ($V_{j,jj}^{min}$, and $V_{j,jj}^{max}$).

$$V_{j,jj}^{max} = \frac{\phi_{j,jj}^{max} - \phi_{j,jj}^{min}}{\mu} \quad (2.21)$$

Where, μ is the number of interval in jj^{th} dimension.

Update archive members and find global best members

For each particle, determine the fitness, then search for the best values among all the fitness values and set this value as the global best fitness ($J^{**}(t)$) and the particle that gives this fitness value as the global best position ($\Omega^{**}(t)$), After that set $t = t + 1$, and $c = c + 1$.

$$\begin{cases} J_i^*(t) = J_i(t) \\ \Omega_i^*(t) = \Omega_i(t) \\ J^{**}(t) = \min\{J_1^*(t), \dots, J_n^*(t)\} \end{cases}$$

Compute velocity and position of each particle

$$V_{j,jj}(t) = \Psi(V_{j,jj}(t-1)) + c_1 r_1 (\phi_{j,jj}^*(t-1) - \phi_{j,jj}(t-1)) + c_2 r_2 (\phi_{j,jj}^{**}(t-1) - \phi_{j,jj}(t-1)) \quad (2.22)$$

$$\Psi = \frac{2}{|2 - X - \sqrt{X^2 - 4X}|} \quad (2.23)$$

Where,

$X = c_1 + c_2$, $X > 4$, $\phi_{j,jj}^*(t)$, and $\phi_{j,jj}^{**}(t)$ are controller's local and global best parameters. Each particle's location changes as a consequence of the velocities update, as shown in the following equation.

$$\phi_{j,jj}(t) = \phi_{j,jj}(t-1) + V_{j,jj}(t) \quad (2.24)$$

$$\Omega_i(t) = [\phi_{j,1}(t), \phi_{j,2}(t), \dots, \phi_{j,m}(t)] j = 1, \dots, p \quad (2.25)$$

Update local and global bests

Each particle evaluates its objective function using the changed location, and new individual best $J_i^*(t)$ and associated $\Omega_i^*(t)$ to find global best ($J^{**}(t, c) = J(\Omega^{**}(t, c))$) if $J^{**}(t, c) \leq J^{**}(t-1, c-1)$. After the fitness has increased and the parameters have been updated, set $c = c + 1$ and move on to the next step. Meanwhile, update $J^{**}(t, c)$ and $\Omega^{**}(t)$ and proceed to the next step.

Stopping criteria

The search process will terminate if the maximum allowable iteration is reached, $t = t_{max}$.

2.6 Transient Stability Excitation Control (TSEC)

In some severe conditions, normal continuous excitation control does not guarantee system security. This is especially true when the transmission system fault affects the system via a slow inter area mode rather than a local machine system mode. The power system can achieve stability by adding a discontinuous stabilizing signal to the excitation system in transient conditions.

TSEC improves transient stability by adjusting generator excitation such that the

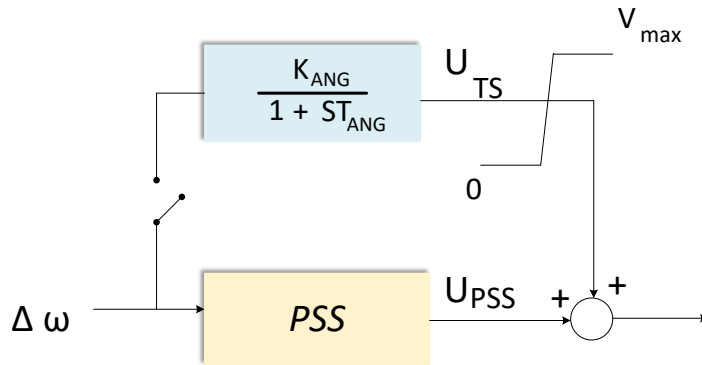


Figure 2.5 : block diagram of TSEC control scheme [17].

terminal voltage maintains near the maximum allowable limit during the positive swing

of the rotor angle. The controller uses rotor speed deviations as an input during the transient period of around 2 seconds following a severe disturbance, because it may induce instability in the steady-state situation if used continually. The usage of a terminal voltage limiter prevents excessive terminal voltage.

Figure 2.5 represents the block diagram of TSEC. The relay is constructed to make the controller discontinuous. TSEC has a transfer function that consists of a gain (K_{ANG}) and a time constant (T_{ANG}) that are tuned depends on the disturbance condition.

2.7 Renewable energy resources

Due to the decreased emission of greenhouse gases in the world, using renewable energy resources (RES) instead of traditional power supplies can be a good choice [37]. Among various RESs, solar photovoltaic (PV) generation popularity is being increased in the developed countries because the surplus electricity from a grid-connected PV system may be sent into the utility grid, the grid is utilized as a backup, it is quite simple to set up, and there are no storage expenses and losses. In this chapter, the impact of integrated RES units on the stability of power grids will be analyzed comprehensively. Despite conventional power generation units, the inertia of RESs can be ignored because some of them don't have inertia or have minimal inertia, so they can negatively influence the stability of power systems. In the following parts, the generic model of RES will be discussed. Fig. 2.6 has four blocks that will be elaborated in the following claims.

2.7.1 repc_a

This block represents the plant controller where one or two PI controller produce the active power command (P_{cmd}) and reactive power command (Q_{cmd}) [37]. repc_a denotes the inputs of the block are the reference signals which are obtained from the grid($P_{ref}, Q_{ref}, V_{ref}$), and depending of the main objective of the control are utilized [39].

2.7.2 reec_a

The electrical control of the RES plant is indicated by reec_a. The block has two inputs (P_{cmd}, Q_{cmd}) and two outputs (I_{pcmd}, I_{qcmd}) which are active and reactive command

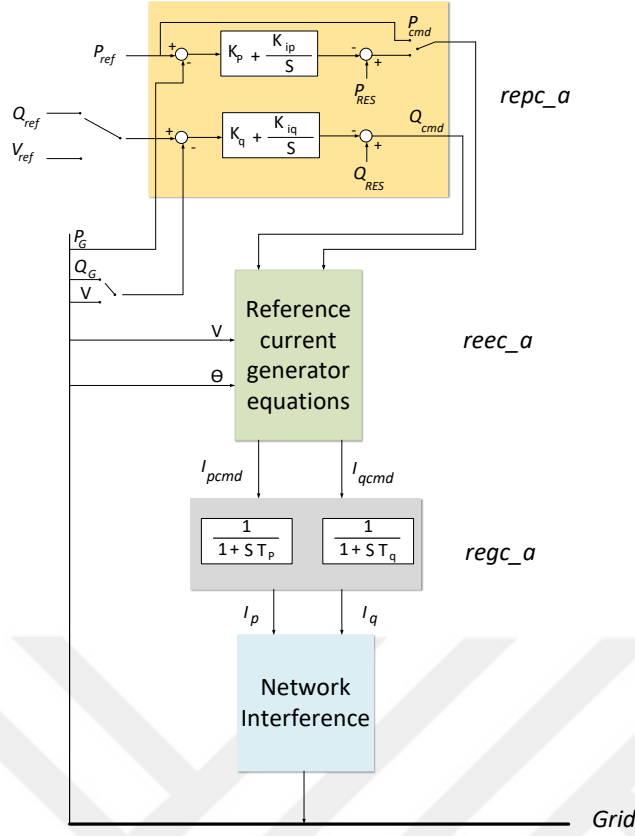


Figure 2.6 : The generic model of RES [38].

currents, respectively. The equation 2.26 denotes the calculation of command currents.

$$\begin{bmatrix} I_{pcmd} \\ I_{qcmd} \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix}^{-1} \begin{bmatrix} P_{cmd} \\ Q_{cmd} \end{bmatrix} \quad (2.26)$$

where V_d and V_q are the dq components of the RES terminal voltages.

2.7.3 regc_a

The inputs are I_{pcmd} and I_{qcmd} , and the outputs are I_p and I_q , which represent the injection currents into the network, respectively. Two low-pass filters with short time constants ($T_p = 0.02$ s, $T_q = 0.02$ s) were used to represent the converter.

2.7.4 Network Interference

In the network interference block at Fig. 2.6, the aim is to generate new admittance matrix of the network which integrated with RESs. The following equations denote the mentioned procedure.

$$\begin{cases} P_{RES} = \Re((V_{dRES} + jV_{qRES})(I_p + jI_q)^*) \\ Q_{RES} = \Im((V_{dRES} + jV_{qRES})(I_p + jI_q)^*) \end{cases} \quad (2.27)$$

Where in the equation 2.27, P_{RES} and Q_{RES} represent the active and reactive power of RES. Further, V_{dRES} and V_{qRES} are the d-q axis terminal voltages of the connected bus to RES. The P_{RES} and Q_{RES} should be injected to the network admittance matrix as follows:

$$Y_{Li} = \frac{-(P_{Li} + jQ_{Li})^*}{V^2} - \frac{(P_{RESi} + jQ_{RESi})^*}{V^2} \quad i = 1, \dots, n \quad (2.28)$$

In the equation 2.28, n denotes the number of buses and V_i is the bus terminal voltage. Y_L is constructed as the process that mentioned in the section 2.4. By adding RESs into the system, the admittance matrix of the network will be modified. RESs are modeled as negative loads and they have been modeled as above [40], for more details, refer to [30].

It is clear that the admittance matrix of the system is changed at each time step during the simulation because P_{RES} and Q_{RES} are not consistent in the transient condition.



3. DECENTRALIZED ADAPTIVE BACKSTEPPING CONTROLLER

According to the suggested Nonlinear System Control presented in this chapter, low-frequency oscillations and transient stability of synchronous generators in a multimachine power system will be reduced, while transient stability will be increased. The suggested design of the i th synchronous generator makes only use of local information and is compatible with other generators that do not need the use of distant signals [26]. The design processes are consistently designed for the creation of both the Control Law and related Lyapunov functions. The procedure of creating the mentioned controller will be discussed in the following sections. It is created utilizing the third-order model of synchronous generator and static exciter as the basis for the controller.

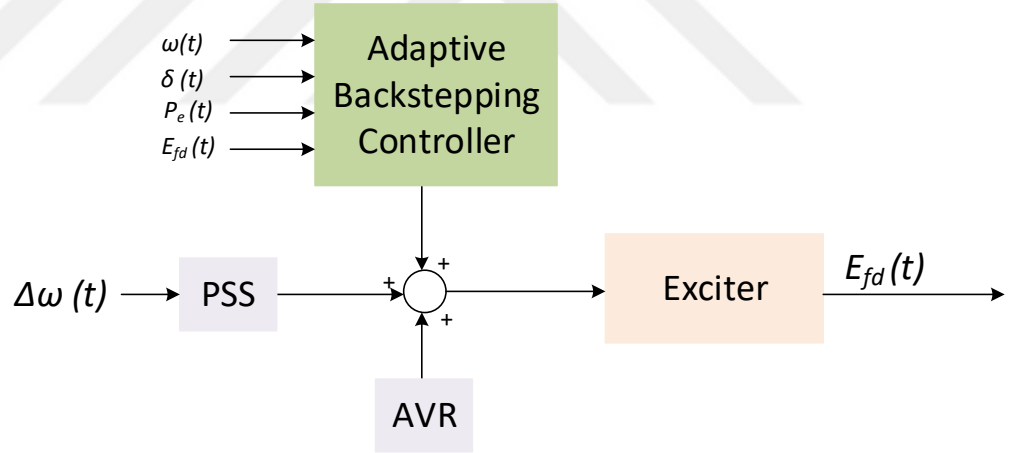


Figure 3.1 : Excitation system connected with backstepping controller.

3.1 Power System Model

The modeling of differential equations (DEs) of a power system may be characterized as follows, as mentioned in the section 2.

$$\frac{d\delta_i}{dt} = \omega_0(\omega_i - \omega_{ref}) \quad i = 1, \dots, m \quad (3.1)$$

$$\frac{d\omega_i}{dt} = \frac{P_{mi} - P_{ei} - D_i(\omega_i - \omega_{ref})}{2H_i} \quad i = 1, \dots, m \quad (3.2)$$

$$\frac{dE'_{qi}}{dt} = \frac{-E'_{qi} - (X_{di} - X'_{di})I_{di} + E_{fdi}}{T'_{d0i}} \quad i = 1, \dots, m \quad (3.3)$$

$$\frac{dE_{fdi}}{dt} = \frac{-E_{fdi} + K_{Ai}(V_{refi} - V_i + u_{fi})}{T_{Ai}} \quad i = 1, \dots, m \quad (3.4)$$

All of the above parameters are explained in the section 2. In addition, u_f is the adaptation control law that will be described in the following parts.

In addition, The following equations are algebraic equations (AEs) of a system.

$$I_{di} = \sum_{j=1}^n E'_{qj}(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \quad i = 1, \dots, m \quad (3.5)$$

$$I_{qi} = \sum_{j=1}^n E'_{qj}(B_{ij}\sin\delta_{ij} + G_{ij}\cos\delta_{ij}) \quad i = 1, \dots, m \quad (3.6)$$

$$V_{di} = I_{qi}X_{qi} \quad i = 1, \dots, m \quad (3.7)$$

$$V_{qi} = E'_{qi} - I_{di}X'_{di} \quad i = 1, \dots, m \quad (3.8)$$

$$V_{ti} = \sqrt{V_{di}^2 + V_{qi}^2} \quad i = 1, \dots, m \quad (3.9)$$

$$P_{ei} = E'_{qi}I_{qi} \quad i = 1, \dots, m \quad (3.10)$$

$$Q_{ei} = E'_{qi}I_{di} \quad i = 1, \dots, m \quad (3.11)$$

The above parameters are explained in section 2.

Furthermore, the controller has two unknown parameters that make it parametric uncertainties. The unknown parameters are D_i and differences between X_{di} and X'_{di} that are defined as:

$$\theta_i = [\theta_{i1} \quad \theta_{i2}] = [D_i \quad X_{di} - X'_{di}] \quad (3.12)$$

$$\tilde{\theta}_i = \theta_i - \hat{\theta}_i \quad (3.13)$$

In the equation (3.13) $\tilde{\theta}_i$ and $\hat{\theta}_i$ are parameter estimation error and dynamic estimation of θ_i , respectively.

3.2 Converted Power System Dynamic Model

To use the adaptive backstepping method, the power system model should be changed suitably. At first, the derivative of the currents I_{qi} and I_{di} are considered.

$$\begin{aligned} \dot{I}_{qi} = & \sum_{j=1}^n \dot{E}'_{qj}(B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij}) + \sum_{j=1}^n E'_{qj}(B_{ij} \cos\delta_{ij} - G_{ij} \sin\delta_{ij})(\dot{\delta}_i - \dot{\delta}_j) = \\ & \sum_{j=1}^n \dot{E}'_{qj}(B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij}) + \sum_{j=1}^n E'_{qj}(B_{ij} \cos\delta_{ij} - G_{ij} \sin\delta_{ij})\omega_0(\Delta\omega_i - \Delta\omega_j) = \\ & \sum_{j=1, j \neq i}^n \dot{E}'_{qj}(B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij}) - E'_{qi}B_{ii}\omega_0\Delta\omega_i + \sum_{j=1}^n E'_{qj}(B_{ij} \cos\delta_{ij} - G_{ij} \sin\delta_{ij})\omega_0\Delta\omega_j \\ & + \dot{E}'_{qi}G_{ii} \sum_{j=1, j \neq i}^n E'_{qj}(B_{ij} \cos\delta_{ij} - G_{ij} \sin\delta_{ij})\omega_0\Delta\omega_j \end{aligned} \quad (3.14)$$

Suppose that when the i^{th} generator is taken into account, the j^{th} ($j \neq i$) has constant rated speed and generator excitation [41]. By this assumption $\dot{I}_{qi}$ will be:

$$\begin{aligned} \dot{I}_{qi} = & \dot{E}'_{qi}G_{ii} - E'_{qi}B_{ii}\omega_0\Delta\omega_i + \sum_{j=1}^n E'_{qj}(B_{ij} \cos\delta_{ij} - G_{ij} \sin\delta_{ij})\omega_0\Delta\omega_j \\ = & \dot{E}'_{qi}G_{ii} - E'_{qi}B_{ii}\omega_0\Delta\omega_i - I_{di}\omega_0\Delta\omega_i \end{aligned} \quad (3.15)$$

By the same procedure $\dot{I}_{di}$ is the following equation :

$$\dot{I}_{di} = -\dot{E}'_{qi}B_{ii} + \omega_0\Delta\omega_i(I_{qi} - E'_{qi}G_{ii}) \quad (3.16)$$

The power system model equations should be updated to a new set of equations in order to extend the adaptive backstepping controller design procedure to a nonlinear system.

$$\begin{cases} \Delta\dot{\delta}_i = \omega_0\Delta\omega_i \\ \Delta\dot{\omega}_i = \frac{(-\Delta P_{ei} - \theta_{i1}\Delta\omega_i)}{2H_i} \\ \Delta\dot{P}_{ei} = f_{i3} + g_{i3}\Delta E_{fdi} - I_{di}g_{i3}\theta_{i2} \\ \Delta\dot{E}_{fdi} = \frac{f_{i4} + K_{Ai}u_{fi}}{T_{Ai}} \end{cases} \quad i = 1, \dots, m \quad (3.17)$$

Where,

$$\begin{cases} g_{i3} = \frac{(I_{qi} + E'_{qi} G_{ii})}{T'_{d0i}} \\ g_{i4} = \frac{(I_{di} + E'_{qi} B_{ii})}{T'_{d0i}} \\ f_{i3} = (-E'_{qi} + E_{fd0i})g_{i3} - T'_{d0i}E'_{qi}\omega_0\Delta\omega_i g_{i4} \\ f_{i4} = \frac{(K_{Ai}(V_{refi} - V_i) - E_{fd0i} - \Delta E_{fdi})}{T_{Ai}} \end{cases} \quad i = 1, \dots, m \quad (3.18)$$

In the equations 3.17 and 3.18, $\Delta\delta_i = \delta_i - \delta_{0i}$, $\Delta\omega_i = \omega_i - \omega_{0i}$, $\Delta P_{ei} = P_{ei} - P_{mi}$, and $\Delta E_{fdi} = E_{fdi} - E_{fd0i}$, where δ_{0i} , ω_{0i} , E_{fd0i} denote the initial condition of rotor angle, rotor angular speed and excitation field voltage of the i^{th} synchronous generator that are calculated in the steady state condition.

3.3 Design of Adaptive Backstepping Controller

In this instance, the nonlinear adaptive backstepping approach will be used to construct the nonlinear controller, and it will be done in a step-by-step approach. Consider the scenario in Fig. 3.2 for an illustration of how the stabilizing function and single control rule for each step are especially meant to stabilize the augmented system for $i = 1, \dots, m$ synchronous generators. After that, in the last stage, the actual control law, the parameter update laws, and the complete Lyapunov function are all generated in the same time frame. The proposed controller has six positive parameters ($c_{1i}, c_{2i}, c_{3i}, c_{4i}, \gamma_{1i}, \gamma_{2i}$) for each controlled synchronous generator that should be tuned in order to have the best performance. The design procedure has four steps that will be explained in detail.

3.3.1 Step 1

We assume that $e_{1i} = \Delta\delta_i$ which is the first error variable, the stabilizing function for $\Delta\omega_i$ and the Lyapunov function and derivative of it will be:

$$\alpha_{1i} = \frac{-c_{1i}e_{1i}}{\omega_0} \quad (3.19)$$

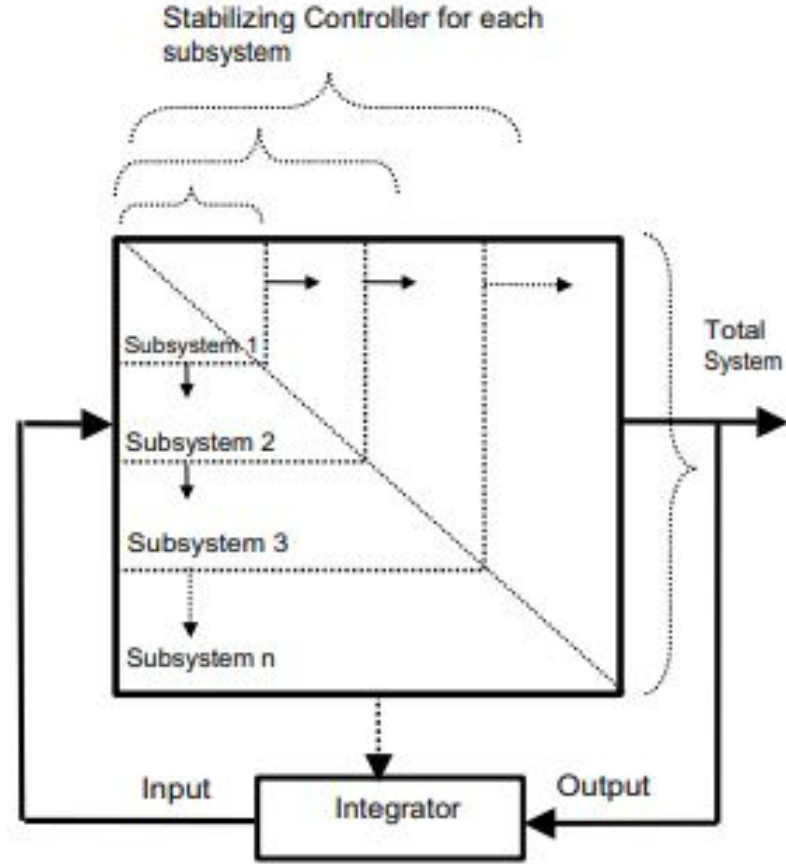


Figure 3.2 : Block diagram of backstepping controller [24].

$$W_{1i} = \frac{1}{2}e_{1i}^2 \quad (3.20)$$

$$\dot{W}_{1i} = -c_{1i}e_{1i}^2 + \omega_0 e_{1i}e_{2i} \quad (3.21)$$

Where $e_{2i} = \Delta\omega_i - \alpha_{1i}$ is the second error variable. The below equation is the derivative of e_{1i} that will be utilized in the next steps.

$$\dot{e}_{1i} = -c_{1i}e_{1i} + \omega_0 e_{2i} \quad (3.22)$$

3.3.2 Step 2

In this step similar to step 1 a new Lyapunov function is created. The new Lyapunov function includes θ_1 estimation error.

$$W_{2i} = W_{1i} + \frac{1}{2}e_{2i}^2 + \frac{1}{2\gamma_{1i}}\tilde{\theta}_{1i}^2 \quad (3.23)$$

$$\dot{W}_{2i} = -c_{1i}e_{1i}^2 - c_{2i}e_{2i}^2 + \frac{\tilde{\theta}_{1i}}{\gamma_{1i}}(\dot{\tilde{\theta}}_{1i} - \frac{\gamma_{1i}e_{2i}\Delta\omega_i}{2H_i}) - \frac{e_{2i}(\Delta P_{ei} - \alpha_{2i})}{2H_i} \quad (3.24)$$

Here, α_{2i} is the second stabilizing function.

$$\alpha_{2i} = k_{1i}e_{1i} + k_{2i}e_{2i} \quad (3.25)$$

in the equation (3.25) k_{1i} and k_{2i} are:

$$\begin{cases} k_{1i} = 2H_i(\omega_0 - \frac{-c_{1i}^2}{\omega_0} + \frac{c_{1i}\hat{\theta}_{1i}}{2H_i\omega_0}) \\ k_{2i} = 2H_i(c_{1i} + c_{2i}) - \hat{\theta}_{1i} \end{cases}$$

The third error variable is $e_{3i} = \Delta P_{ei} - \alpha_{2i}$ and the derivative of e_{2i} is:

$$\dot{e}_{2i} = -\omega_0 e_{1i} - c_{2i}e_{2i} - \frac{e_{3i}}{2H_i} - \frac{\Delta\omega_i\tilde{\theta}_{1i}}{2H_i} \quad (3.26)$$

3.4 Step 3

Similar to the previous steps the third Lyapunov function is defined:

$$W_{3i} = W_{2i} + \frac{1}{2}e_{3i}^2 + \frac{1}{2\gamma_{2i}}\tilde{\theta}_{2i}^2 \quad (3.27)$$

$$\dot{W}_{3i} = -c_{1i}e_{1i}^2 - c_{2i}e_{2i}^2 - c_{3i}e_{3i}^2 + \frac{\tilde{\theta}_{1i}}{\gamma_{1i}}(\dot{\tilde{\theta}}_{1i} - \frac{\gamma_{1i}e_{2i}\Delta\omega_i}{2H_i}) + \frac{\tilde{\theta}_{2i}\dot{\tilde{\theta}}_{2i}}{\gamma_{2i}} + e_{3i}(c_{3i}e_{3i} - \frac{e_{2i}}{2H_i} + \Delta\dot{P}_{ei} - \dot{\alpha}_{2i}) \quad (3.28)$$

The above equation can be written in the simple form:

$$\begin{aligned} \dot{W}_{3i} = & -c_{1i}e_{1i}^2 - c_{2i}e_{2i}^2 - c_{3i}e_{3i}^2 + \frac{\tilde{\theta}_{1i}}{\gamma_{1i}}(\dot{\tilde{\theta}}_{1i} - \frac{\gamma_{1i}e_{2i}\Delta\omega_i}{2H_i} + \frac{\gamma_{1i}k_{2i}e_{3i}\Delta\omega_i}{2H_i}) + \frac{\tilde{\theta}_{2i}}{\gamma_{2i}}(\dot{\tilde{\theta}}_{2i} - \gamma_{2i}I_{di}g_{3i}e_{3i}) \\ & + g_{3i}e_{3i}(\Delta E_{fdi} - \alpha_{3i}) \end{aligned} \quad (3.29)$$

The third stabilizing function is defined as:

$$\alpha_{3i} = \frac{-(k_{3i}e_{1i} + k_{4i}e_{2i} + k_{5i}e_{3i} + f_{3i})}{g_{3i}} + I_{di}\hat{\theta}_{2i} \quad (3.30)$$

Where,

$$\begin{cases} k_{3i} = c_{1i}k_{1i} + \omega_0 k_{2i} - \frac{c_{1i}\dot{\theta}_{1i}}{\omega_0} \\ k_{4i} = k_{2i}(\frac{\hat{\theta}_{1i}}{2H_i} - c_{3i}) - k_{1i}\omega_0 - \frac{1}{2H_i} + \dot{\hat{\theta}}_{1i} \\ k_{5i} = (c_{3i} + \frac{k_{2i}}{2H_i}) \end{cases}$$

Here, the forth error variable is $e_{4i} = \Delta E_{fdi} - \alpha_{3i}$ and derivative of third error variable is written in the following form:

$$\dot{e}_{3i} = \frac{e_{2i}}{2H_i} - c_{3i}e_{3i} + e_{4i}g_{3i} + \frac{k_{2i}\Delta\omega_i\tilde{\theta}_{1i}}{2H_i} - \tilde{\theta}_{2i}g_{3i}I_{di} \quad (3.31)$$

3.4.1 Step 4

In the last step, the Lyapunov function and derivative of it can be written as follows:

$$W_{4i} = W_{3i} + \frac{1}{2}e_{4i}^2 \quad (3.32)$$

$$\begin{aligned} \dot{W}_{4i} = & -c_{1i}e_{1i}^2 - c_{2i}e_{2i}^2 - c_{3i}e_{3i}^2 - c_{4i}e_{4i}^2 + \frac{\tilde{\theta}_{1i}}{\gamma_{1i}}(\dot{\tilde{\theta}}_{1i} - \frac{\gamma_{1i}e_{2i}\Delta\omega_i}{2H_i} + \frac{\gamma_{1i}k_{2i}e_{3i}\Delta\omega_i}{2H_i}) \\ & + \frac{\tilde{\theta}_{2i}}{\gamma_{2i}}(\dot{\tilde{\theta}}_{2i} - \gamma_{2i}I_{di}g_{3i}e_{3i}) + e_{4i}(c_{4i}e_{4i} + g_{3i}e_{3i} + f_{4i} + \frac{K_{Ai}u_{fi}}{T_{Ai}} - \dot{\alpha}_{3i}) \end{aligned} \quad (3.33)$$

By defining the control law and adaptation law the below equations are extracted:

$$\hat{\theta}_{1i} = -\tilde{\theta}_{1i} = -\frac{\gamma_{1i}e_{2i}\Delta\omega_i}{2H_i} + \frac{\gamma_{1i}k_{2i}e_{3i}\Delta\omega_i}{2H_i} \quad (3.34)$$

$$\hat{\theta}_{2i} = -\tilde{\theta}_{2i} = -\gamma_{2i}I_{di}g_{3i}e_{3i} \quad (3.35)$$

$$u_{fi} = \frac{-T_{Ai}(c_{4i}e_{4i} + g_{3i}e_{3i} + f_{4i} - \dot{\alpha}_{3i})}{K_{Ai}} \quad (3.36)$$

By making derivative from the equation (3.30) the derivative of $\dot{\alpha}_{3i}$ can be written in the below equation:

$$\begin{aligned} \dot{\alpha}_{3i} = & \frac{-(\dot{f}_{3i} + k_{3i}\dot{e}_{1i} + k_{4i}\dot{e}_{2i} + k_{5i}\dot{e}_{3i} + \dot{k}_{3i}e_{1i} + \dot{k}_{4i}e_{2i} + \dot{k}_{5i}e_{3i})}{g_{3i}} \\ & + \frac{(k_{3i}e_{1i} + k_{4i}e_{2i} + k_{5i}e_{3i} + f_{3i})\dot{g}_{3i}}{g_{3i}^2} + I_{di}\hat{\theta}_{2i} + I_{di}\dot{\hat{\theta}}_{2i} \end{aligned} \quad (3.37)$$

At the end, we can see that the fourth Lyapunov function is:

$$\dot{W}_{4i} = -c_{1i}e_{1i}^2 - c_{2i}e_{2i}^2 - c_{3i}e_{3i}^2 - c_{4i}e_{4i}^2 \quad (3.38)$$

It is obvious that the above function is negative semidefinite that in this condition the stability of the system is satisfied.

3.5 Tuning of Adaptive Backstepping Controller by PSO Algorithm

The section that follows addresses utilizing PSO to discover the best configuration of electric power system controllers. It enables a more resilient controller design by accounting for disturbances using nonlinear simulations rather than linearization [24]. The problem can be formulated with the following cost function and the related constraints.

$$J = \int_0^t K_1 |\omega_i - \omega_0| + K_2 |\delta_i - \delta_0| + K_3 |P_{ei} - P_{mi}| \quad (3.39)$$

The constraints are defined as:

$$\left\{ \begin{array}{l} c_{iMin} < c_i < c_{iMax} \\ \gamma_{iMin} < \gamma_i < \gamma_{iMax} \\ |\omega_i - \omega_0|_{Min} < |\omega_i - \omega_0| < |\omega_i - \omega_0|_{Max} \\ |\delta_i - \delta_0|_{Min} < |\delta_i - \delta_0| < |\delta_i - \delta_0|_{Max} \\ |P_{ei} - P_{mi}|_{Min} < |P_{ei} - P_{mi}| < |P_{ei} - P_{mi}|_{Max} \end{array} \right.$$

In the equation (3.39) ($K_1 = 0.4, K_2 = 0.3, K_3 = 0.3$) are the weight parameters and t is the simulation time. The optimization procedure aims to reduce the frequency, rotor angle, and electrical power oscillations to improve transient stability. The upper bound and lower bound of the constraints are written in the result section.

4. Simulation Results

On two different test systems, the suggested method has been evaluated: (a) an IEEE WSCC 9-bus system, and (b) a modified IEEE 68-bus system (14 machines - 2 RESs), all of which operate at 60 Hz. As shown in Fig. 4.1, the control system configuration for each generating unit that will be participating in the emergency control scheme is provided in these systems. Section 3 contains the technical information on adaptive backstepping control, which is followed by the findings acquired from simulations for test systems. AVR and PSSs are implemented as described in Section 2 for the synchronous generators and associated AVR. The MATLAB-Simulink software is used to simulate the dynamic model of the power system, which includes these generating units [42]. In order to show the performance of the controllers 2 critical contingencies are selected. The first contingency which involves on bus no.8, and the second contingency is occurred on bus no.4.

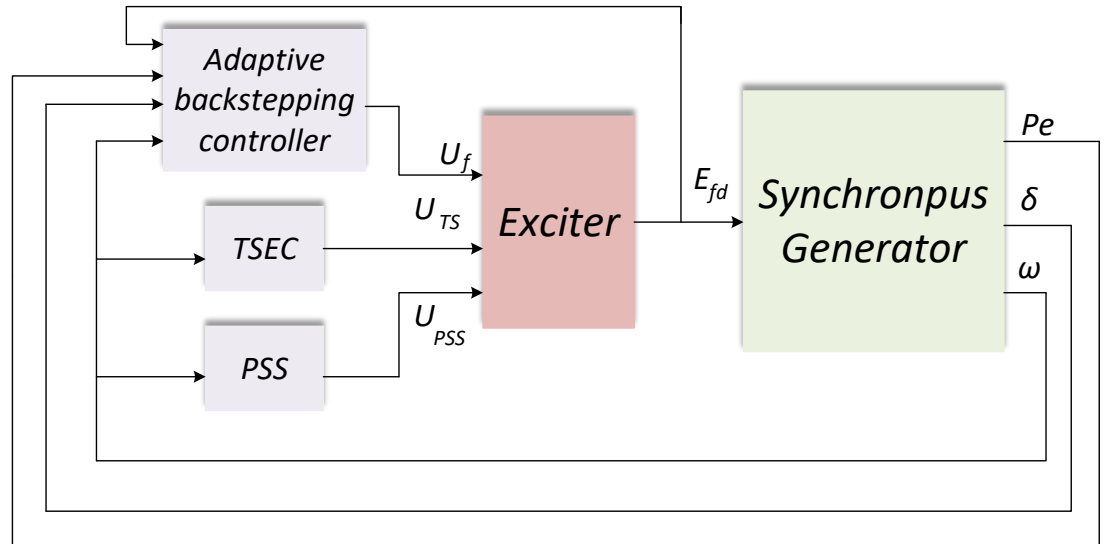


Figure 4.1 : Overall System Configuration.

4.1 IEEE WSCC 9-Bus System

Fig. 4.2 shows a single-line diagram for the IEEE WSCC 9-bus test system [43], and it is assumed that all of the units are capable of participating in the emergency control scheme.

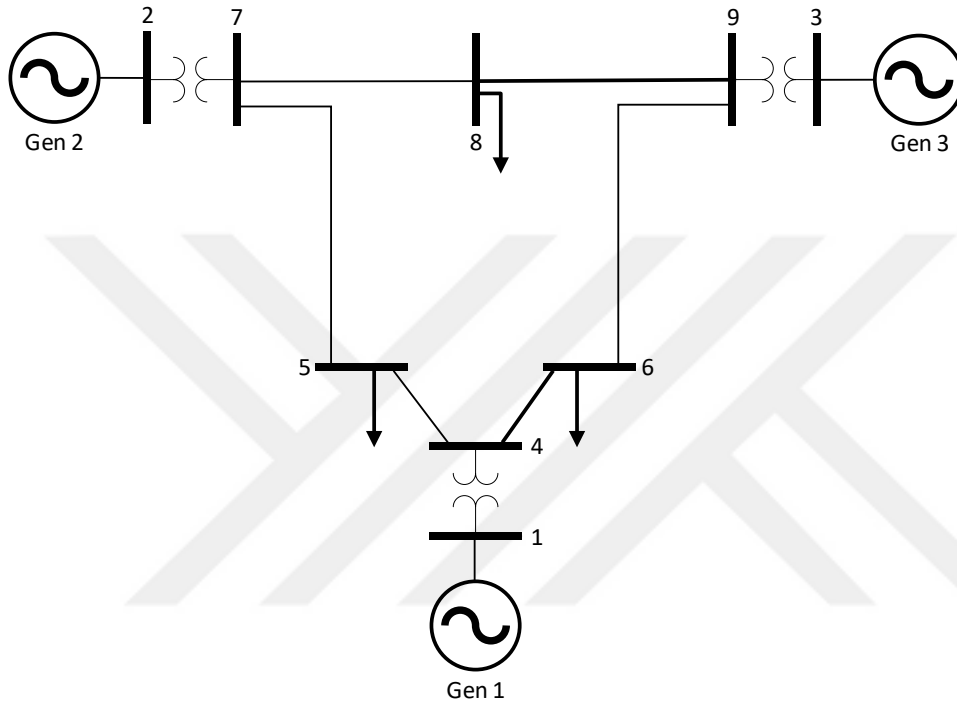


Figure 4.2 : WSCC Nine Bus-Three Machine System.

4.2 Test case I

Take, for illustrate, a severe contingency in which there is a three-phase fault on bus no. 8. The critical clearance periods for the system under normal conditions (i.e., without a controller) have been determined to be $0.37s$ in length. In this case, we suppose that the fault arises at time $t = 1s$ and that it is cleared at time $0.37s$ by tripping the line connecting buses no.8 and 9, and time-domain simulations confirm that the system loses its stability and a corrective control action is needed. It is assumed that the generator no.1 is not implemented with controller. It is estimated that D_m and $(X_d - X'_d)$ have 70 percents of their real values.

First of all, The PSS parameters are tuned which is described in section 2. In order to achieve the acceptable and better results, the PSO algorithm is considered, and the optimization is performed in 100 iterations.

The following parameters are selected to tuned the PSS, TSEC, and ABC parameters in test case I and test case II :

$$\begin{cases} m = 10 \\ c_1 = 2.05 \\ c_2 = 2.05 \\ \mu = 10 \\ \text{Number of iteration} = 100 \end{cases}$$

Further, tables 4.1, and 4.2 show the PSS, and TSEC parameters. After tuning the parameters of PSS, the parameters of the adaptive backstepping controller must be tuned that was described in section 3.5 with respect to the following constraints: (Table 4.3 shows the ABC parameters)

$$\begin{cases} 0 \leq c_{1i} \leq 30 \\ 0 \leq c_{2i} \leq 30 \\ 0 \leq c_{3i} \leq 0.2 \\ 0 \leq c_{4i} \leq 30 \\ 0 \leq \gamma_{1i} \leq 2 \\ 0 \leq \gamma_{2i} \leq 2 \end{cases}$$

Table 4.1 : Tuned PSS parameters by PSO.

Gen no.	G_2	G_3
K_{pss}	2.624	3.706
T_1	0.0278	0.0759
T_2	0.101	0.115
T_3	1.173	0.567
T_4	0.592	1.219

Table 4.2 : TSEC parameters.

Gen No.	G_2	G_3
K_{ang}	58.5938	39.514
T_{ang}	1.52	1.49

Table 4.3 : Adaptive backstepping controller parameters tuned by PSO.

Generator Parameters	G ₂	G ₃
C ₁	9.4296	8.1611
C ₂	8.6198	13.7775
C ₃	0.0656	0.0746
C ₄	23.5989	8.1985
γ_1	1.01	0.95
γ_2	0.92	1.05

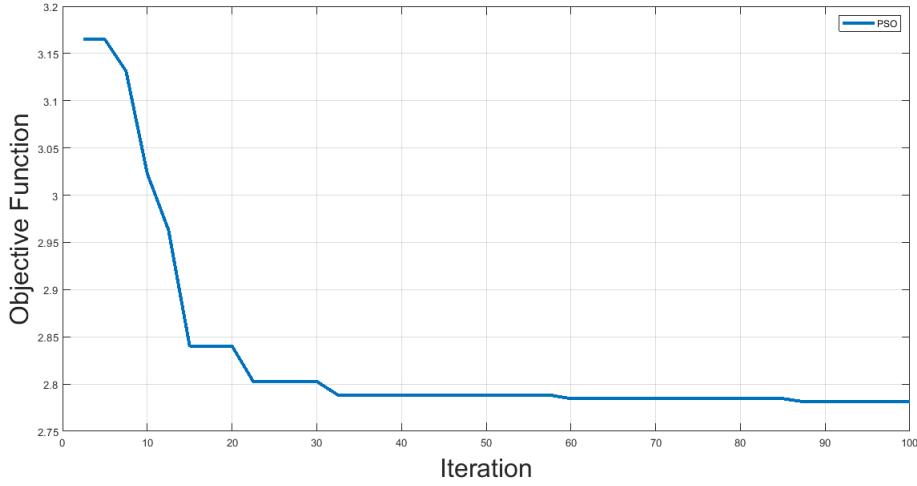
**Figure 4.3 :** The optimization process of ABC parameters with PSO.

Figure 4.3 shows the optimization process of ABC parameters by using PSO.

A total of four performance indicators that indicate the settling time and oscillation are introduced in order to show the performance of controllers and PSS. (Integral square error(ISE),Integral time square error (ITSE), Integral absolute error (IAE), and Integral time absolute error (ITAE)) [44].

$$ISE = 10^5 \times \int_0^{t_{sim}} \sum_{i=1}^m (\omega_i - \omega_1)^2 \cdot dt \quad (4.1)$$

$$ITSE = 10^5 \times \int_0^{t_{sim}} \sum_{i=1}^m t \cdot (\omega_i - \omega_1)^2 \cdot dt \quad (4.2)$$

$$IAE = 10^5 \times \int_0^{t_{sim}} \sum_{i=1}^m |\omega_i - \omega_1| \cdot dt \quad (4.3)$$

$$ITAE = 10^5 \times \int_0^{t_{sim}} \sum_{i=1}^m t \cdot |\omega_i - \omega_1| \cdot dt \quad (4.4)$$

he ΔCCT is defined as the enhancement in critical clearing time offered by the PSS or other control operations, and it is measured in seconds.

$$\Delta\text{CCT} = \text{CCT}_c - \text{CCT}_o \quad (4.5)$$

where CCT_o is the CCT when there is no supplemental control (i.e., when there is no PSS) and CCT_c is the CCT that is acquired when an extra control has been implemented.

By referring to the four performance indices (ISE, ITSE, IAE, ITAE) in the table 4.4, it is obtained that PSS has an effective performance in decreasing oscillations of rotor speeds, rotor angles, and electrical powers in the disturbance condition. On the other hand, as described above, PSS is not a proper control action to improve transient stability in critical situations. ΔCCT is an effective index that can realize the efficacy of the controllers in enhancing transient stability, so we can see that PSS has the lowest value of ΔCCT in contrast with other control actions. Also, TSEC has the highest ΔCCT value in contrast with PSS, but it is seen that the other performance indices don't have the satisfying value. Then, it is concluded that the adaptive backstepping controller and PSS have the best performance against other actions. In this condition, ΔCCT has the highest value, and other performance indices have the lowest values. Furthermore, Figure 4.4, 4.5, 4.6, 4.7 and 4.8 shows the performance of the controllers. These figures show the 3 synchronous generators simulation when the power system is reacted with the symmetric three phase fault, and the rotor angles and rotor speeds time domain simulations are the good selection between other variables to show the performance because by referring to these figures, the Diagnosis of system's behaviour will be so easy. By referring to the Figure 4.4, it can be seen that system losses its stability in the normal condition when synchronous generators are not controlled with PSS, TSEC, and ABC. In the figure 4.5, it is obvious that power system obtain its stability in the critical time and oscillations of rotor angles and rotor speeds are diminished. In addition, figure 4.6 shows the time domain simulation of the system when it is controlled by TSEC. In this scenario, we can see that the system is stable in its critical time and its ΔCCT are improved compared with the condition that system is controlled by PSS. Furthermore, figure 4.7 shows the performance of the power system when it is controlled by ABC. It is clear that, this scenario has a better results against of the previous scenarios. Finally, the best performance is reached when the power

system is controlled by ABC and PSS, simultaneously. It can be seen that system has the minimum oscillations in rotor speed and rotor angle deviations.

Table 4.4 : Performance of the controllers when disturbance occurs on bus 8.

Controllers	$\Delta CCT(ms)$	ISE	ITSE	IAE	ITAE
Only PSS	41	241.8	6439	1.503×10^4	3.986×10^5
TSEC + PSS	51	301.8	8066	1.687×10^4	4.505×10^5
Only Adaptive backstepping	400	141.9	3944	1.518×10^4	4.136×10^5
Adaptive backstepping + PSS	510	53.26	1317	5817	1.399×10^5

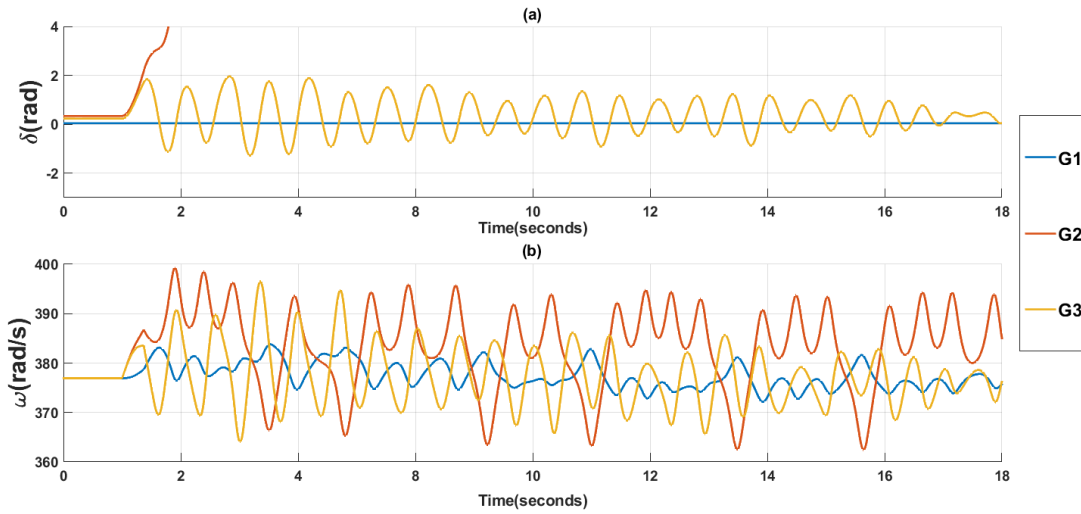


Figure 4.4 : When the system is in normal condition (without controller), the evolution of (a) rotor angles (b) rotor speeds.

In addition, figure 4.9 shows the control inputs of PSS (U_{PSS}), TSEC (U_{TSEC}), and ABC (U_f).

4.3 Test case II

In order to show the another test case, the contingency which is occurred on bus no.4 at time $t = 1s$ is assumed. This fault is cleared at the critical time $t = 0.325s$ after disturbance by tripping the line between bus no.4 and no.5. Tables 4.5,4.6, and 4.7 show the tuned PSS, TSEC, and ABC parameters, respectively. Additionally, table 4.8 demonstrates the mentioned performance indices values when the power system is controlled with the controllers. By referring to the table 4.8, we can see that by selecting a better control action (Adaptive Backstepping Controller) with PSS, the best

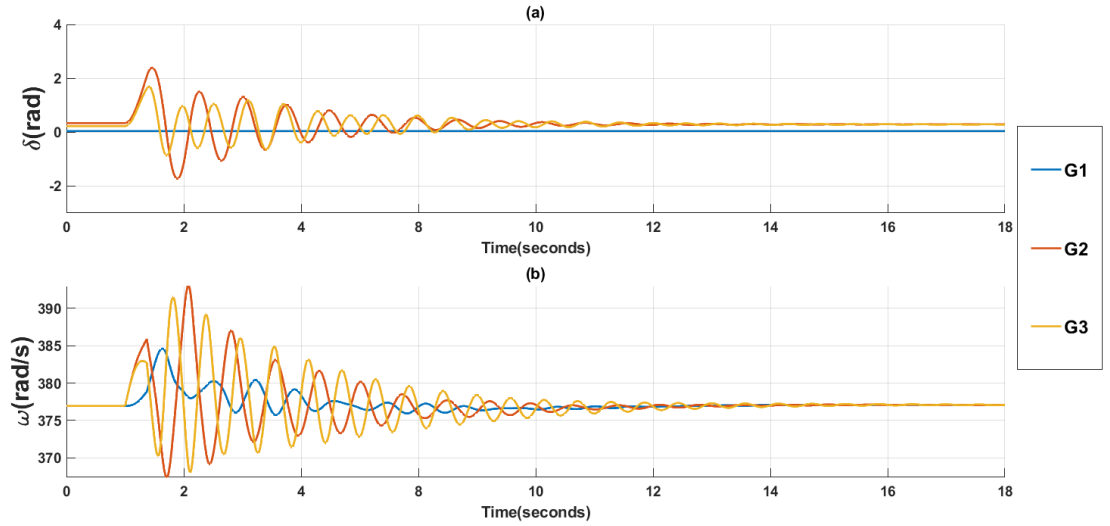


Figure 4.5 : When the system is regulated by PSS, the evolution of (a) rotor angles (b) rotor speeds.

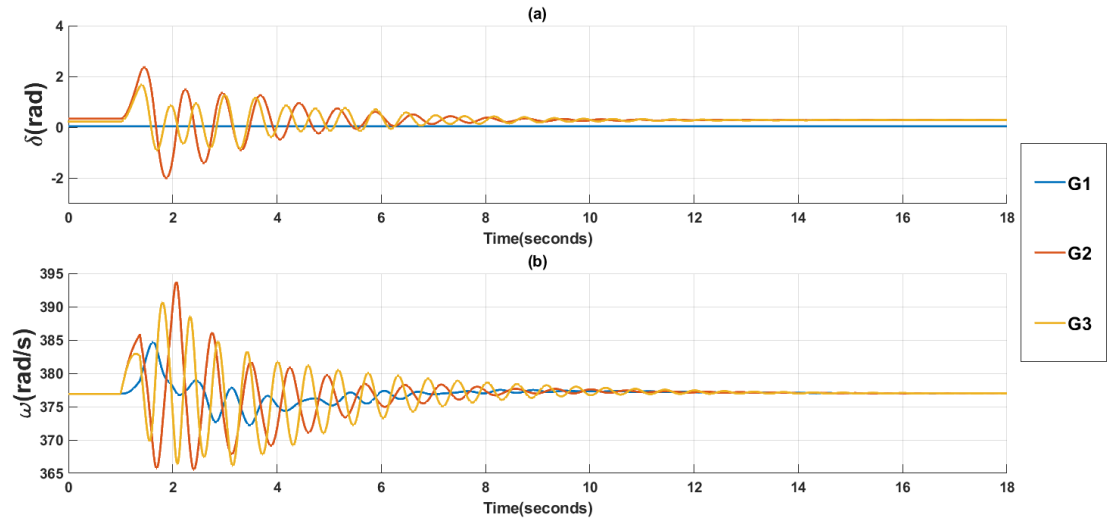


Figure 4.6 : When the system is regulated by TSEC, the evolution of (a) rotor angles (b) rotor speeds.

performance is reached. Furthermore, Figures 4.10, 4.11, 4.12, 4.13, and 4.14 are the good demonstration to see the power system's performance when it is controlled in different conditions. By referring to figure 4.10, it can be seen that system loses its stability when it is in the normal condition (without PSS, TSEC, and ABC). In addition, figure 4.11 shows the system performance with PSS, the oscillations of rotor speeds and rotor angles are decreased but it has not been a proper choice for improving

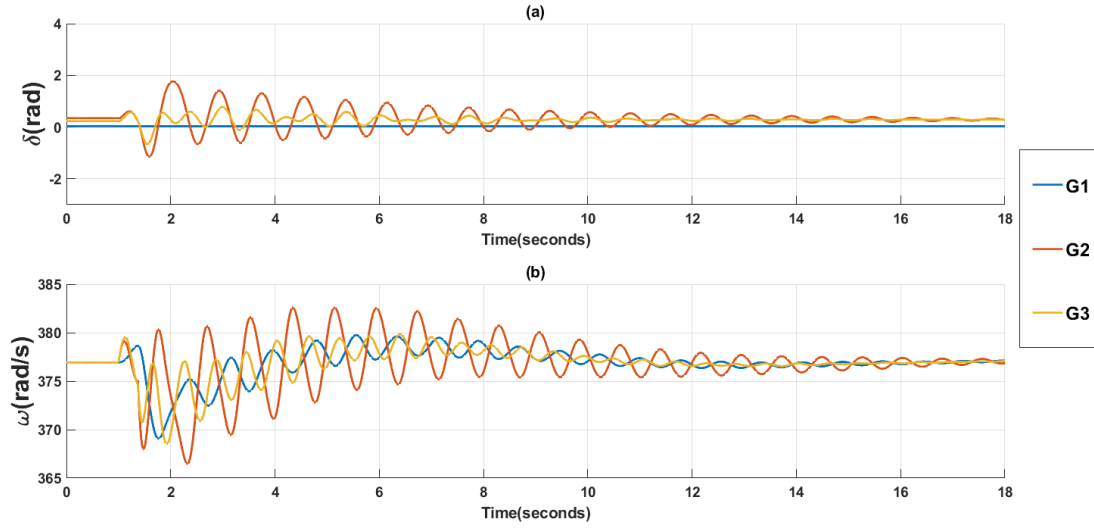


Figure 4.7 : When the system is regulated by ABC, the evolution of (a) rotor angles (b) rotor speeds.

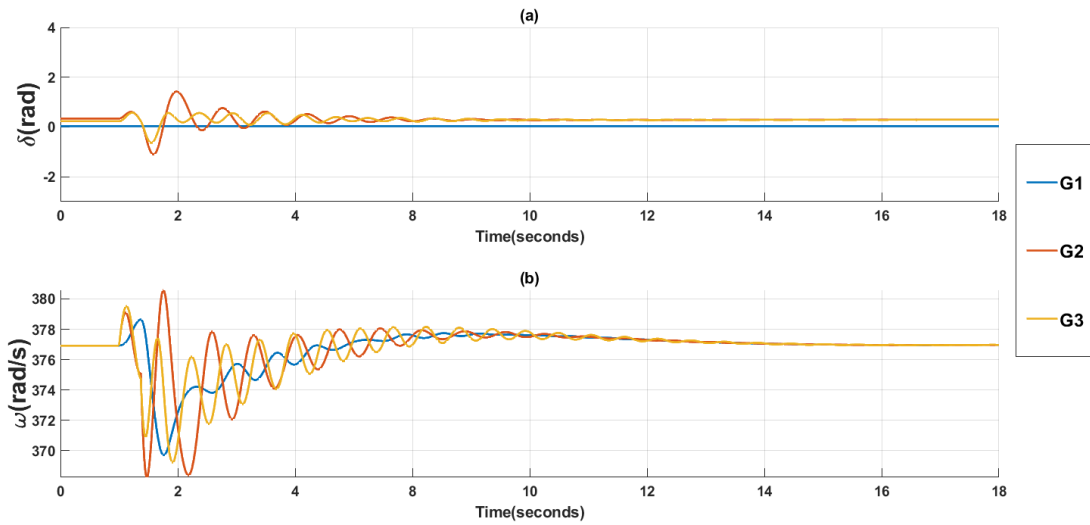


Figure 4.8 : When the system is regulated by ABC and PSS, the evolution of (a) rotor angles (b) rotor speeds.

transient stability. Figure 4.12 is the performance of the system when it is controlled by TSEC. In addition, figure 4.13 depicts the system performance when it is controlled by only ABC. It is obvious that the system has the best performance compared with previous scenarios, so it can be improved by adding PSS to decrease the oscillations of rotor angles and rotor speeds, see figure 4.14.

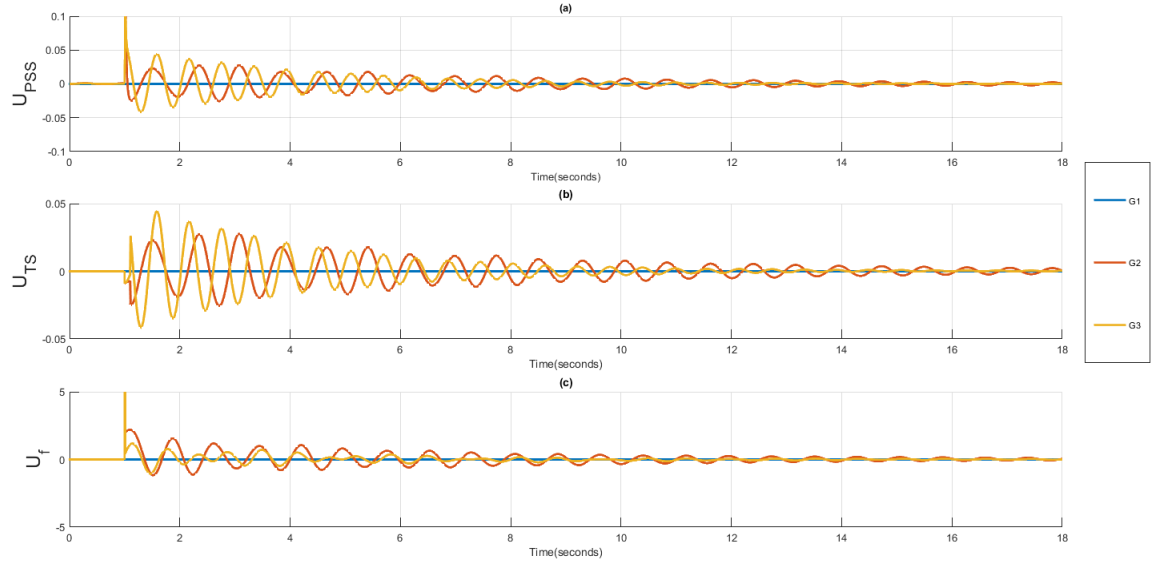


Figure 4.9 : The control inputs of PSS, TSEC, and ABC.

$$\left\{ \begin{array}{l} 0 \leq c_{1i} \leq 30 \\ 0 \leq c_{2i} \leq 30 \\ 0 \leq c_{3i} \leq 0.2 \\ 0 \leq c_{4i} \leq 30 \\ 0 \leq \gamma_{1i} \leq 2 \\ 0 \leq \gamma_{2i} \leq 2 \end{array} \right.$$

Table 4.5 : Tuned PSS parameters by PSO.

Gen no.	G_2	G_3
K_{pss}	3.52	4.56
T_1	0.028	0.0859
T_2	0.121	0.117
T_3	1.129	0.671
T_4	0.521	1.429

Table 4.6 : TSEC parameters.

Gen No.	G_2	G_3
K_{ang}	68.87	35.26
T_{ang}	1.52	1.49

4.4 Modified IEEE 68 Bus System

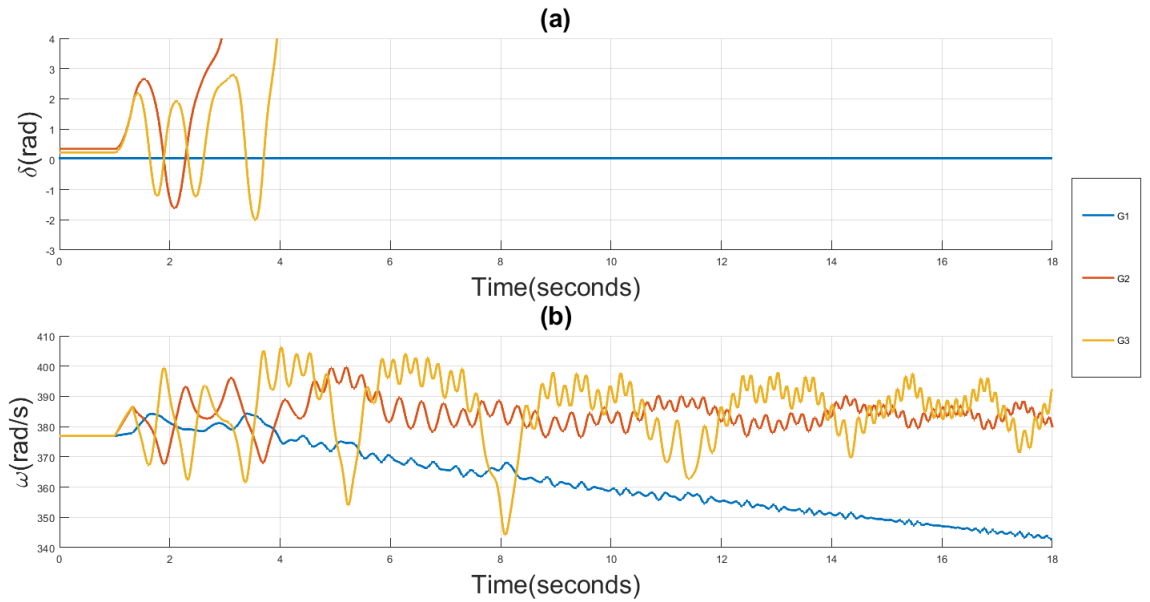
As part of a comprehensive system, the modified IEEE 68-bus system with 14 synchronous generators (SG) and 2 power electronics interfaced RESs system, 68-bus-14-SG-2-RES system, is chosen, see Fig 4.15. The system parameters are

Table 4.7 : Adaptive backstepping controller parameters tuned by PSO.

Generator Parameters	G ₂	G ₃
C ₁	9.8297	7.9651
C ₂	6.7854	15.2387
C ₃	0.08582	0.09444
C ₄	22.6246	10.2155
γ_1	1.04	0.96
γ_2	0.92	1.04

Table 4.8 : Performance of the controllers when disturbance occurs on bus 4.

Controllers	$\Delta CCT(ms)$	ISE	ITSE	IAE	ITAE
Only PSS	45	289.4	7740	1.657×10^4	4.429×10^5
TSEC + PSS	56	335	8968	1.758×10^4	4.786×10^5
Only Adaptive backstepping	461	143.9	4067	1.68×10^4	4.783×10^5
Adaptive backstepping + PSS	526	48.72	1259	6216	1.523×10^5

**Figure 4.10 :** When the system is in normal condition (without controller), the evolution of (a) rotor angles (b) rotor speeds.

obtained from [45]. A modified version of the system Fig4.15 is also being developed, in which the SGs no. 7 and 8 are replaced by two RES units, as shown in the figure, to improve performance. Given that the RES are not a part of the system's overall inertia, the system's dynamic behavior changes significantly as a consequence of this variation in its dynamic behavior. For the purpose of testing the controllers' robustness and demonstrating the usefulness of the suggested technique, we conduct the following case study, in which only the synchronous generator units are supposed to participate in an emergency control action, except for the ones numbered 14, 15, and 16. In order

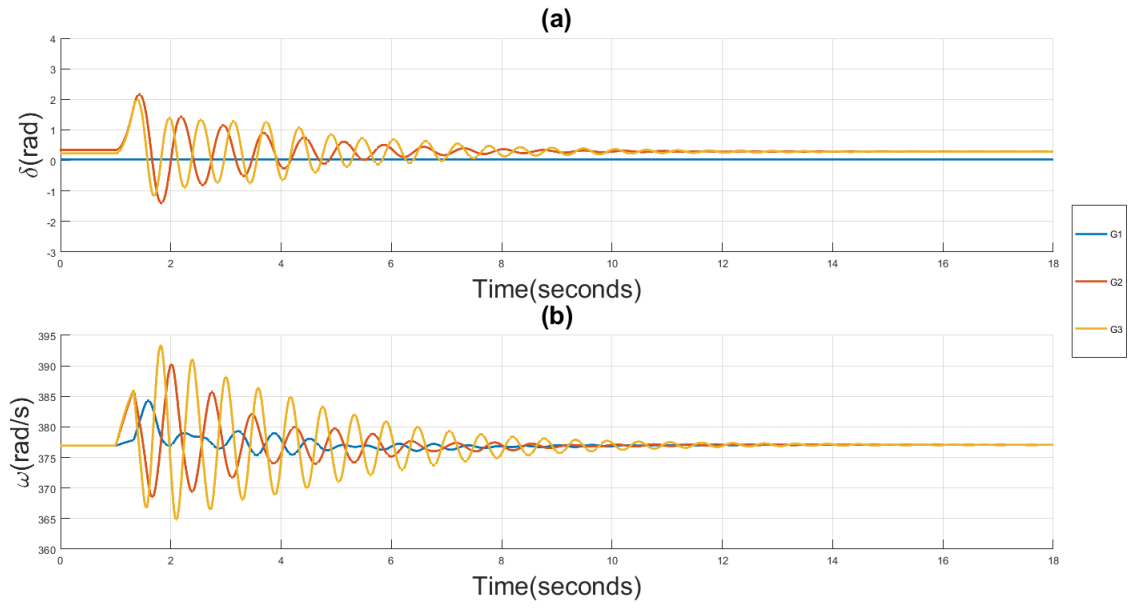


Figure 4.11 : When the system is regulated by PSS, the evolution of (a) rotor angles
(b) rotor speeds.

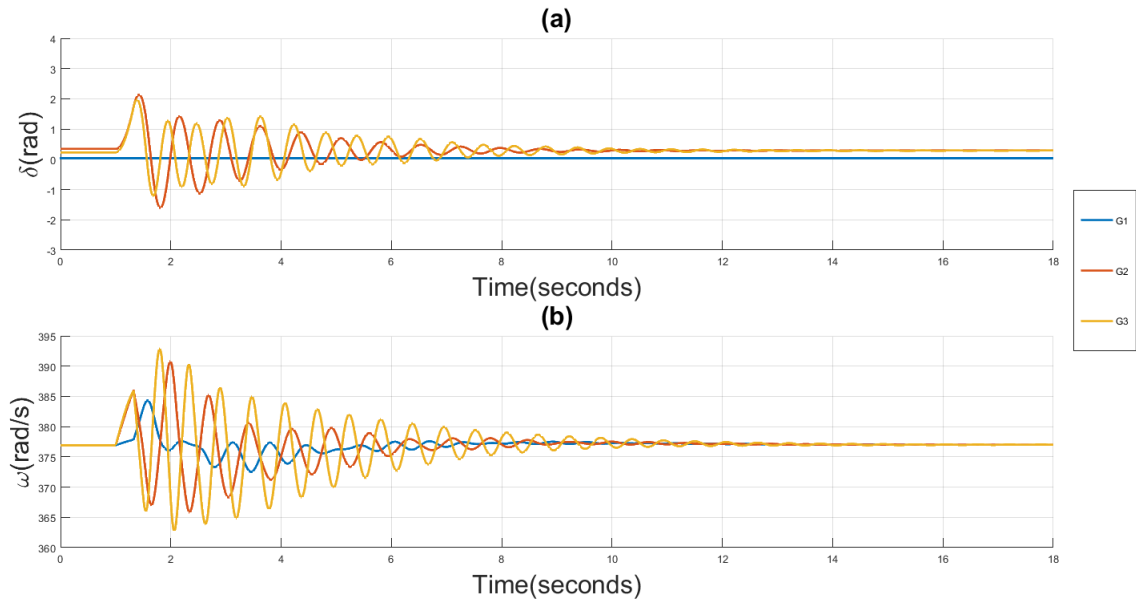


Figure 4.12 : When the system is regulated by TSEC, the evolution of (a) rotor angles
(b) rotor speeds.

to show the performance of the controllers, two test cases (Test case III and Test case IV) that depicts the power system's performance under different control actions are chosen.

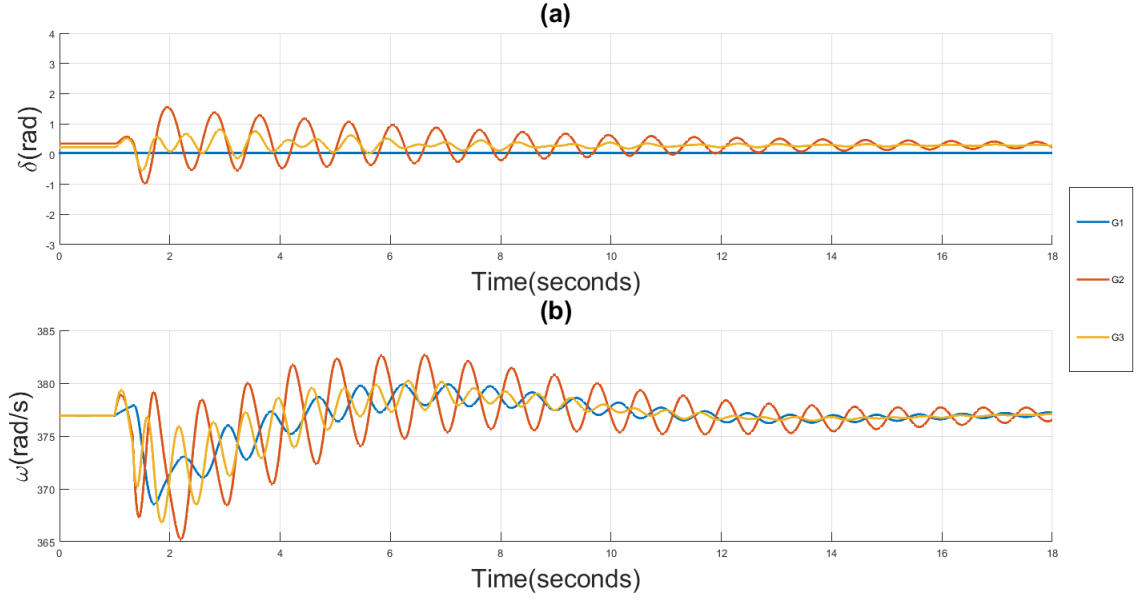


Figure 4.13 : When the system is regulated by ABC, the evolution of (a) rotor angles (b) rotor speeds.

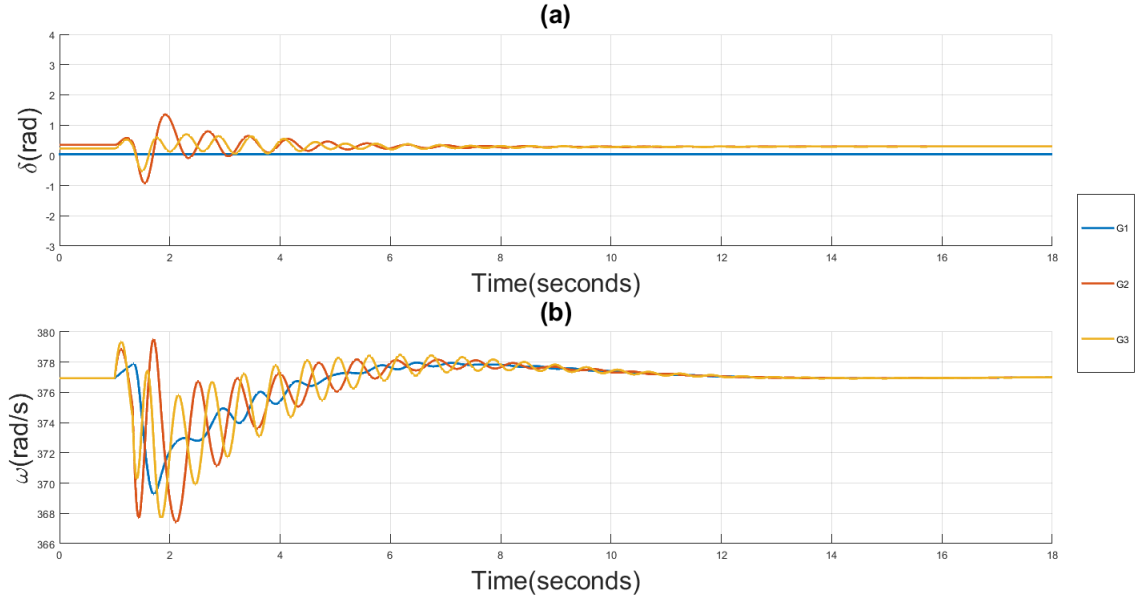


Figure 4.14 : When the system is regulated by ABC and PSS, the evolution of (a) rotor angles (b) rotor speeds.

4.5 Test case III

The contingency which includes a failure at bus no 19, is assumed for the modified test system. The symmetric three phase fault occurs at $t = 0.345s$ that the system loses its stability. The performance of the controllers in stabilizing the system is represented in the table 4.9. In addition, Figures 4.16, 4.17, 4.18, 4.19, and 4.20 demonstrate the system performance when it is subjected to various control actions, respectively. The

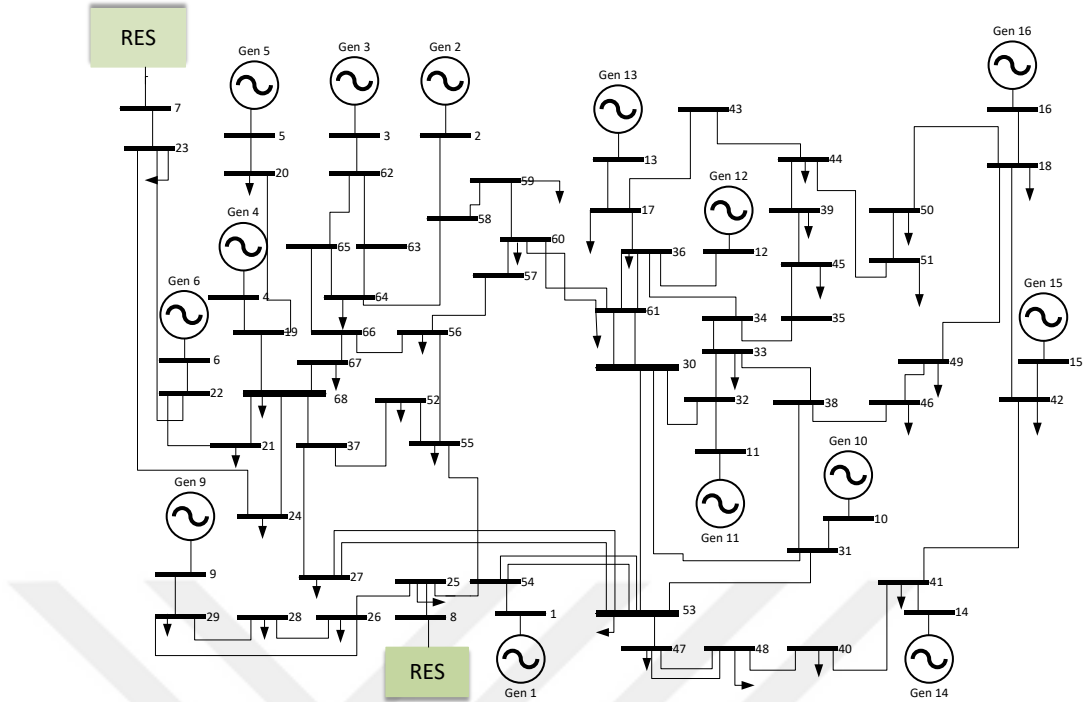


Figure 4.15 : The 68-bus-14-SG-2- RES test systems.

PSO parameters that are chosen to tune constant parameters of the controllers as below:

$$\begin{cases} m = 20 \\ c_1 = 2.05 \\ c_2 = 2.05 \\ \mu = 10 \\ \text{Number of iterations} = 100 \end{cases}$$

Further, tables 4.10, 4.12, and 4.11 show the PSS's, TSEC's, and ABC's parameters, subsequently. By referring to the table 4.9 and the following figures, it is concluded that ABC has the better performance when compared to other control actions. ΔCCT obtained from the ABC + PSS action is the highest value among others. On the other hand, it can be concluded that PSS has the better performance in decreasing fluctuations of rotor speeds because the lowest values about ISE, ITSE, IAE, and ITAE are found when PSS is integrated to the excitation system. Additionally, TSEC has the better performance in improving transient stability but it cannot influence on oscillations of rotor speeds like PSS. Furthermore, the following figures demonstrate the behaviour of the synchronous generators when different control actions are implemented on the system in detailed manner. As mentioned before, PSS cannot

be an appropriate control action for improving transient stability, and TSEC improves the performance of PSS not more. Therefore, ABC is a robust control technique to enhancement transient stability when the power system is subjected to a severe disturbance.

Furthermore, figure 4.16 depicts the system performance when it is not controlled with PSS, TSEC, ABC, and it is obvious that system losses its stability in this condition. Figure 4.17 depicts the rotor angles and rotor speeds of the power system when it is integrated with PSS. It is clear that in this condition the oscillation of the mentioned signals are decreased, significantly, and the system is in the stable condition. Figure 4.18 is the system's performance when excitation system is connected to TSEC. By considering to this figure, it is concluded that system in this condition obtain its stability and the oscillations of rotor speeds and rotor angles are diminished. In addition, Figure 4.19 shows the system when it is connected only to ABC. It can be seen that in this condition, the power system is stable but it needs to other injected signal to decreased the oscillations after disturbance. In order to reach to the mentioned goal, the power system is operated under ABC and PSS when they connected to the power system simultaneously. Figure 4.20 shows the system's performance in the mentioned condition.

Table 4.9 : Performance of the controllers when disturbance occurs on bus 19.

Controllers	$\Delta CCT(ms)$	ISE	ITSE	IAE	ITAE
Only PSS	47	51.91	1291	1.22×10^4	2.385×10^5
TSEC + PSS	55	103.6	2662	1.688×10^4	3.955×10^5
Only Adaptive backstepping	60	541.2	1.48×10^4	7.265×10^4	2.009×10^5
Adaptive backstepping + PSS	595	153.3	3910	1.794×10^4	4.181×10^5

4.6 Test Case IV

Here, for demonstrating the performance of the controllers, the symmetric three phase contingency is used at the bus no.28 by tripping the line between bus no.28 and no.26 at time $t = 1s$. The critical time that the system losses its stability is 0.371 seconds after disturbance. The tables 4.13, 4.14, and 4.15 are the tuned ABC, PSS, and TSEC constant parameters.

In the rest of this section, the performance of the mentioned controllers will be evaluated with the performance indices(ISE,ITSE,IAE,ITAE, and ΔCCT) in the table

Table 4.10 : Adaptive backstepping controller parameters tuned by PSO.

Gen No.	C_1	C_2	C_3	C_4	γ_1	γ_2
G ₁	1.0108	1.0412	0.0095	1.0758	0.0770	0.0650
G ₂	1.1369	1.2000	0.0063	1.074	0.1068	0.0813
G ₃	0.8382	1.1700	0.0068	1.0308	0.1132	0.1310
G ₄	1.1937	0.9267	0.0097	0.8000	0.05981	0.1325
G ₅	1.1994	0.8506	0.0097	1.1138	0.1363	0.1072
G ₆	0.8675	0.8587	0.0076	0.9250	0.0917	0.1237
G ₉	0.9787	0.9585	0.0078	0.9360	0.1303	0.1494
G ₁₀	0.9968	0.9267	0.0098	1.1067	0.1071	0.0663
G ₁₁	1.1389	1.0511	0.0091	1.1740	0.0661	0.0559
G ₁₂	1.1208	1.1372	0.0093	0.9151	0.1210	0.1400
G ₁₃	1.1305	1.0264	0.0072	0.9524	0.1124	0.0974

Table 4.11 : Optimized PSS parameters.

Generators/Parameters	K_{PSS}	T_1	T_2	T_3	T_4
G ₁	20	0.15	0.04	0.15	0.04
G ₂	20	0.15	0.04	0.15	0.04
G ₃	20	0.15	0.04	0.15	0.04
G ₄	20	0.15	0.04	0.15	0.04
G ₅	20	0.15	0.04	0.15	0.04
G ₆	20	0.15	0.04	0.15	0.04
G ₉	12	0.09	0.02	0.09	0.02
G ₁₀	20	0.15	0.04	0.15	0.04
G ₁₁	20	0.15	0.04	0.15	0.04
G ₁₂	20	0.15	0.04	0.15	0.04
G ₁₃	20	0.15	0.04	0.15	0.04

Table 4.12 : 68 bus test system's TSEC parameters.

Gen No.	K_{ang}	T_{ang}
G ₁	71.04	1.46
G ₂	75.07	1.49
G ₃	78.22	1.5
G ₄	78.61	1.51
G ₅	78.54	1.42
G ₆	79.01	1.47
G ₉	80.05	1.5
G ₁₀	74.41	1.5
G ₁₁	76.08	1.49
G ₁₂	72.06	1.46
G ₁₃	79.84	1.47

4.16. Additionally, for better understanding the different scenarios similar to the previous test cases the figures 4.21, 4.22, 4.23, 4.24, and 4.25 will be demonstrated.

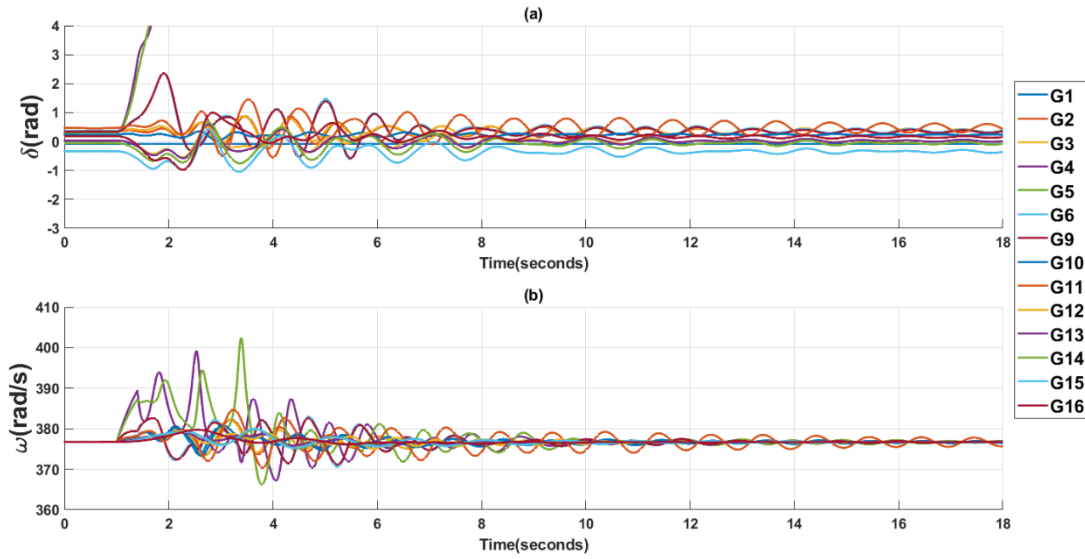


Figure 4.16 : When the system is in normal condition (without controller), the evolution of (a) rotor angles (b) rotor speeds.

Table 4.13 : Adaptive backstepping controller parameters tuned by PSO.

Gen No.	C_1	C_2	C_3	C_4	γ_1	γ_2
G ₁	1.0241	1.0581	0.0082	1.0842	0.0791	0.0760
G ₂	1.1598	1.1870	0.0075	1.0623	0.1076	0.0745
G ₃	0.7965	1.1810	0.0072	1.0694	0.1984	0.1567
G ₄	1.1561	0.8743	0.0094	0.7921	0.06826	0.0127
G ₅	1.1584	0.7806	0.0084	1.1256	0.1476	0.1145
G ₆	0.8348	0.8964	0.0069	0.9465	0.0975	0.1158
G ₉	0.5815	0.8961	0.0087	0.9561	0.1487	0.1578
G ₁₀	0.9657	0.8974	0.0056	1.1057	0.1096	0.0784
G ₁₁	1.1458	1.0698	0.0074	1.1891	0.0684	0.0642
G ₁₂	1.1481	1.1145	0.0085	0.9641	0.1412	0.1512
G ₁₃	1.1547	1.0364	0.0089	0.9687	0.1541	0.0987

By considering to the table 4.16, it is concluded that the power system has a better condition when it is controlled by ABC and PSS, simultaneously similar to the previous scenarios. In addition, it can be seen that system losses its stability when it is not controlled with the mentioned controllers in figure 4.21. Figures 4.22 and 4.23 demonstrates the system's behaviour when it controls under PSS and TSEC, subsequently. In these figures, we see that the synchronous generators are in the stable condition at the critical time, and the fluctuations of rotor speeds and rotor angles are diminished significantly. Finally, by referring to the figures 4.24, and 4.25 that

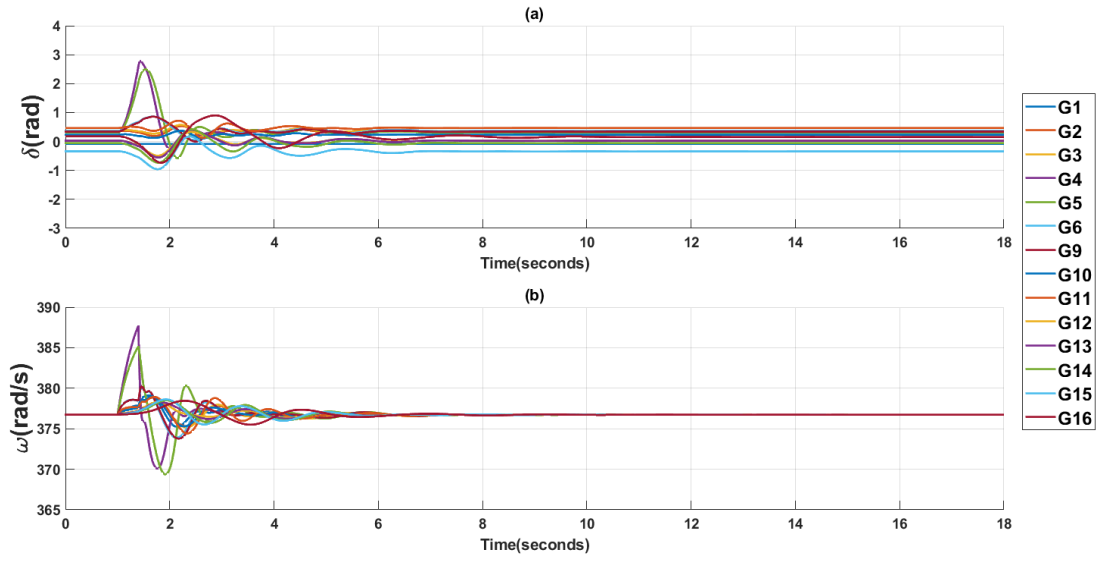


Figure 4.17 : When the system is regulated by PSS, the evolution of (a) rotor angles
(b) rotor speeds.

Table 4.14 : Optimized PSS parameters.

Generators/Parameters	K_{PSS}	T_1	T_2	T_3	T_4
G ₁	19.87	0.14	0.04	0.142	0.038
G ₂	20.04	0.146	0.038	0.142	0.04
G ₃	19.84	0.14	0.038	0.141	0.03
G ₄	19.92	0.151	0.041	0.16	0.028
G ₅	20.12	0.143	0.03	0.148	0.034
G ₆	20.21	0.153	0.039	0.152	0.034
G ₉	11.94	0.084	0.019	0.095	0.021
G ₁₀	19.84	0.141	0.038	0.154	0.032
G ₁₁	20.04	0.148	0.041	0.155	0.038
G ₁₂	19.95	0.154	0.042	0.148	0.038
G ₁₃	20.07	0.148	0.038	0.147	0.037

show the rotor angles and rotor speeds of the synchronous generators when the system is controlled with ABC and ABC+PSS, it is concluded that system gain its stability in both of the scenarios but system has a better performance in the scenario that it controls with ABC+PSS. In this situation, Δ_{CCT} has the maximum value.

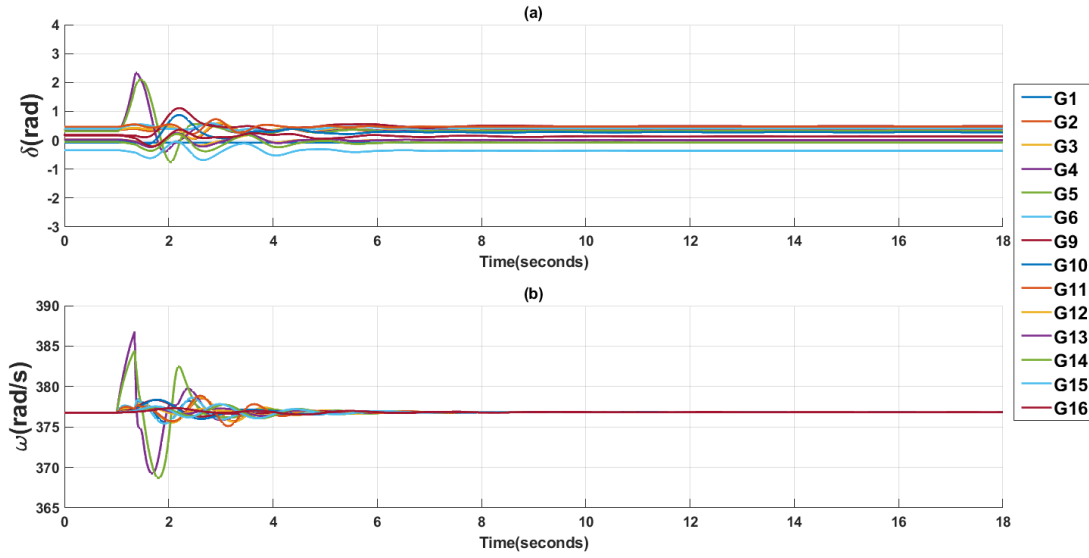


Figure 4.18 : When the system is regulated by TSEC, the evolution of (a) rotor angles
(b) rotor speeds.

Table 4.15 : 68 bus test system's TSEC parameters.

Gen No.	K_{ang}	T_{ang}
G ₁	81.05	1.47
G ₂	78.02	1.49
G ₃	78.26	1.5
G ₄	76.51	1.52
G ₅	81.02	1.44
G ₆	78.08	1.45
G ₉	82.07	1.51
G ₁₀	75.42	1.49
G ₁₁	77.11	1.5
G ₁₂	71.09	1.41
G ₁₃	78.85	1.48

Table 4.16 : Performance of the controllers when disturbance occurs on bus 28.

Controllers	$\Delta CCT(ms)$	ISE	ITSE	IAE	ITAE
Only PSS	41	75.06	1929	1.535×10^4	3.558×10^5
TSEC + PSS	49	101.2	2618	1.817×10^4	4.316×10^5
Only Adaptive backstepping	54	522.2	1.31×10^4	7.021×10^4	1.954×10^5
Adaptive backstepping + PSS	521	158.3	4090	2.092×10^4	5.023×10^5

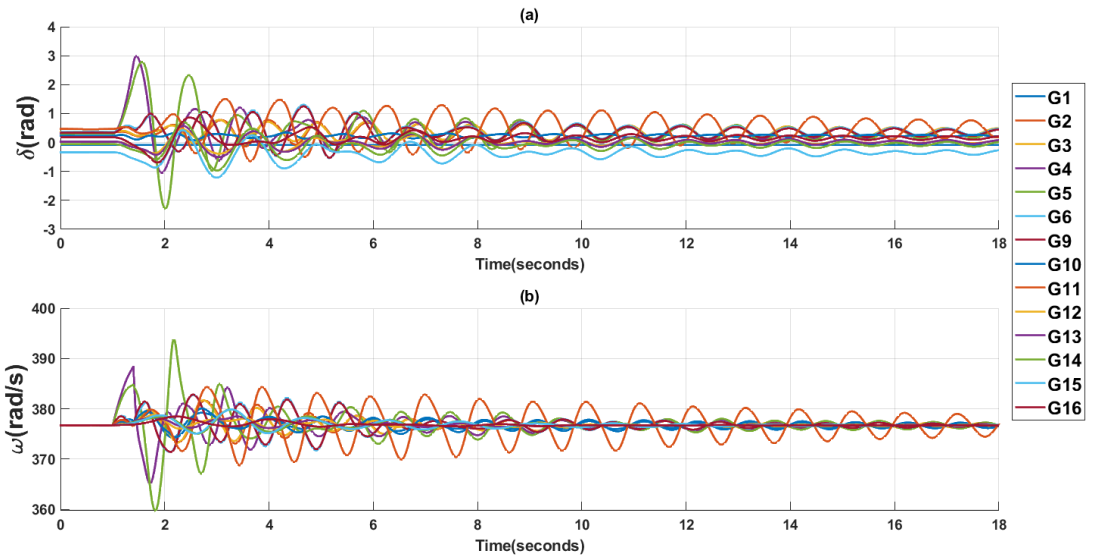


Figure 4.19 : When the system is regulated by ABC, the evolution of (a) rotor angles (b) rotor speeds.

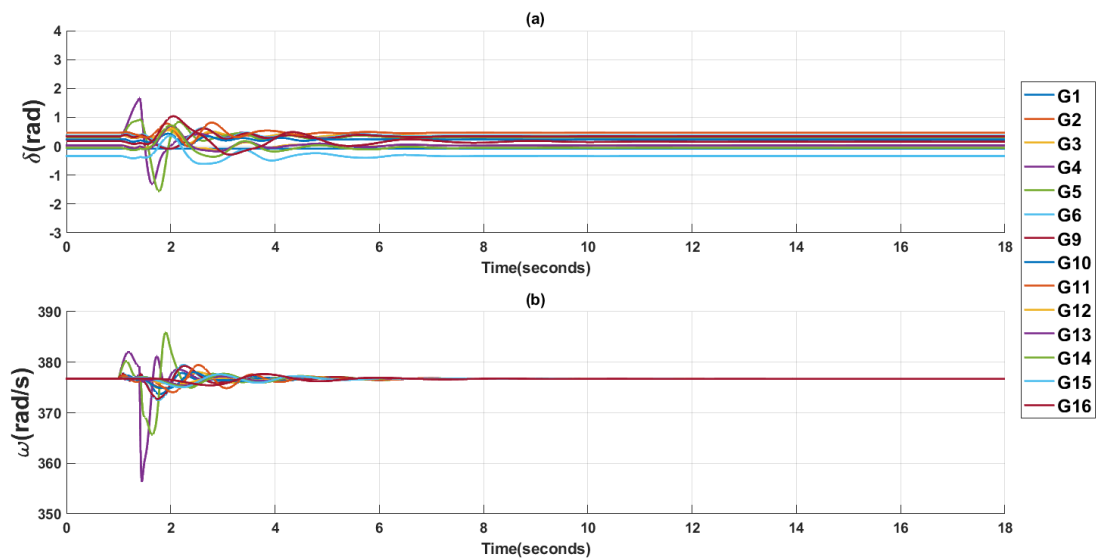


Figure 4.20 : When the system is regulated by ABC and PSS, the evolution of (a) rotor angles (b) rotor speeds.

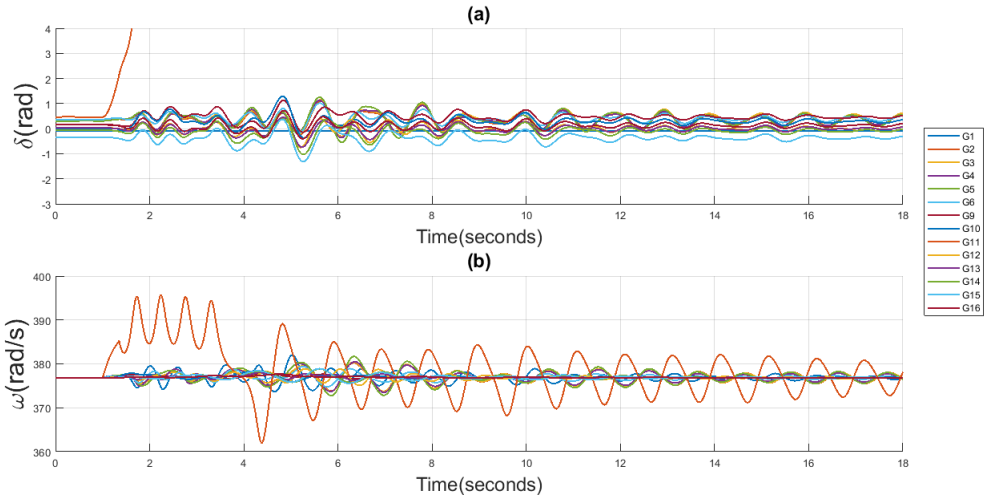


Figure 4.21 : When the system is in normal condition (without controller), the evolution of (a) rotor angles (b) rotor speeds.

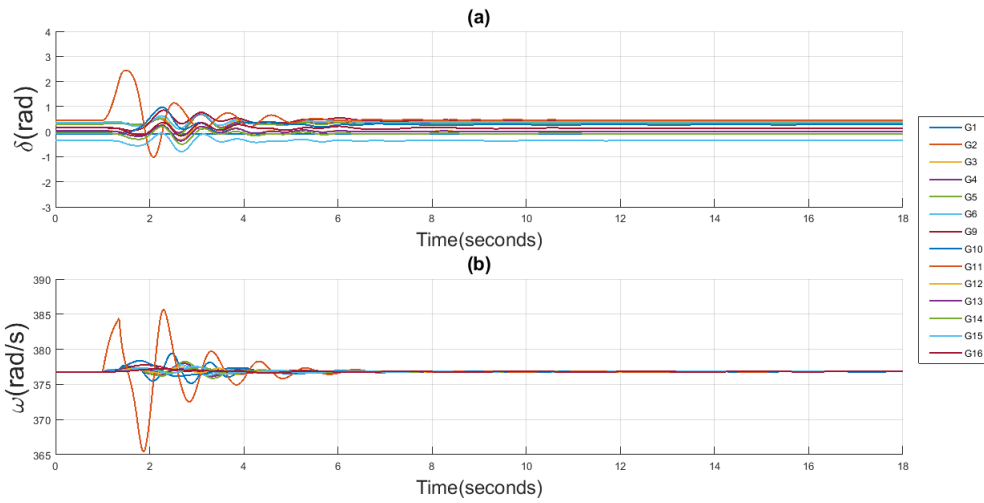


Figure 4.22 : When the system is regulated by PSS, the evolution of (a) rotor angles (b) rotor speeds.

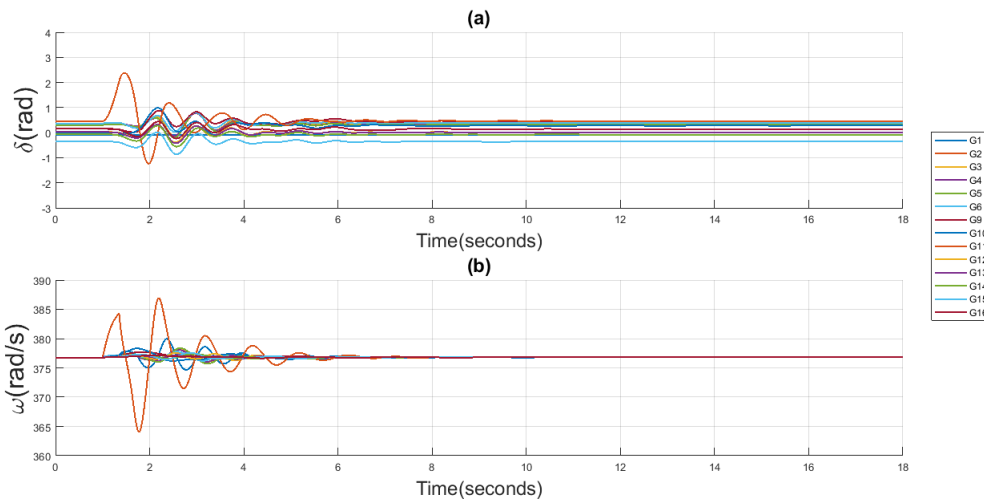


Figure 4.23 : When the system is regulated by TSEC, the evolution of (a) rotor angles (b) rotor speeds.

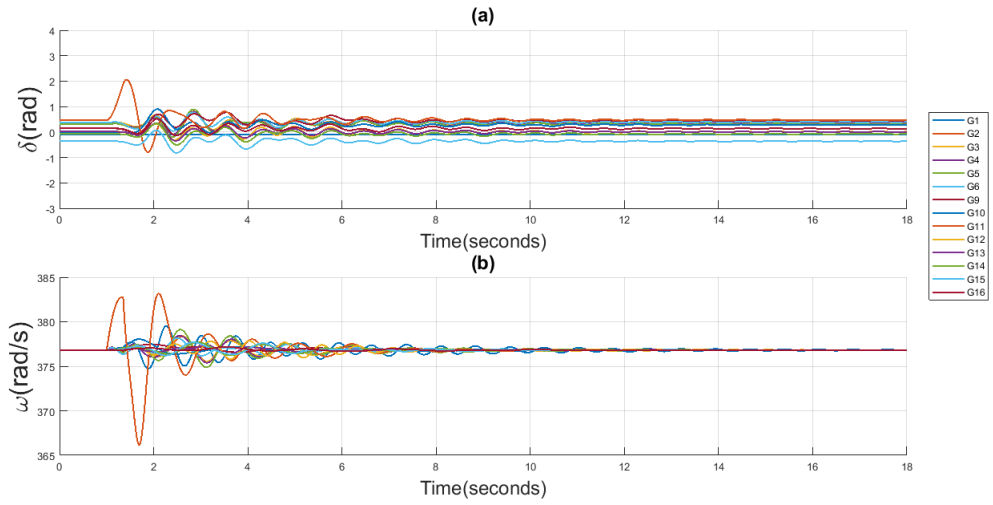


Figure 4.24 : When the system is regulated by ABC, the evolution of (a) rotor angles
(b) rotor speeds.

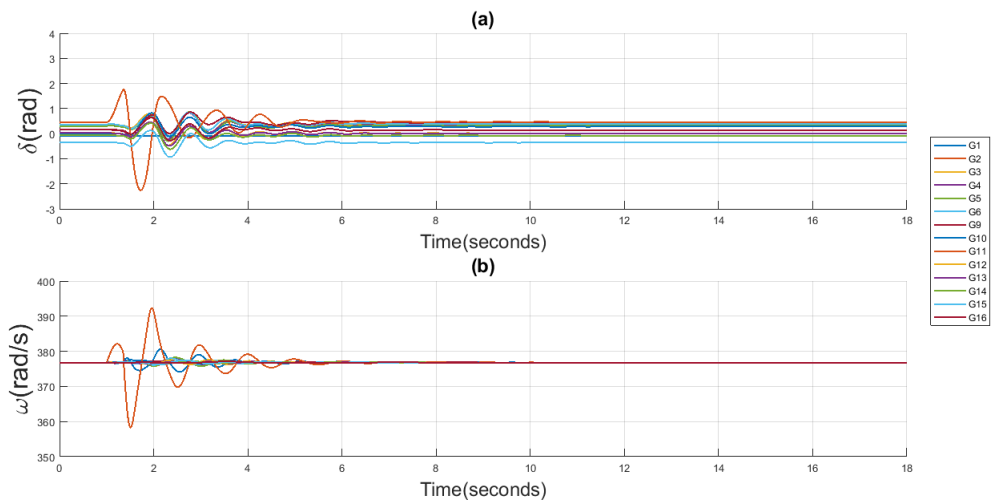


Figure 4.25 : the system is regulated by ABC and PSS, the evolution of (a) rotor angles
(b) rotor speeds.



5. CONCLUSION

In this thesis, an adaptive backstepping control-based emergency scheme for power systems transient stability is proposed. When a critical contingency occurs, the output electrical power rapidly drops (usually), causing an instant acceleration of rotor and could cause an instability in the absence of a remedial action. Unlike the other control actions, the adaptive backstepping controller acts correctly when some parameters of synchronous generators are unknown. Each generator in the system is handled as an independent subsystem, replete with its own nonlinear decentralized adaptive backstepping controller. To attain the best values for the parameters of the given controller, a particle swarm optimization technique is proposed and implemented. In order to show the efficacy of the proposed controller, it is compared with PSS and TSEC control actions. PSS is a supplemental controller that is commonly utilized in an excitation control system. Although the PSS's key role is to offer positive damping torque contributions, experience has shown that it can have an influence on the transient performance of the power system under certain situations. PSS is a control technique that can influence the system's stability when it is threaded to small signal stability. In addition, TSEC is an emergency discontinuous control action that aims to keep the internal voltage at its peak value. Also, PSS and TSEC can guarantee a system's security in small disturbances. Still, they cannot be a considerable control action when a serious fault occurs in the power system.

The adaptive backstepping controllers are designed based on the fourth-order model. Because power systems are constructed up of numerous interconnected synchronous generators, the system must be uncoupled in order to use a decentralized control strategy. Each generator is equipped with a decentralized controller that generates the optimal control law based on the local feedback signals in the proposed method. While the system is operating, the controllers continuously monitor the generator's rotor speed and rotor angle in order to signal an emergency if it surpasses a certain threshold. In addition, since in the existing power systems, some parameters such

as damping coefficients and the difference between reactants and transient reactants of synchronous generators are changed continuously, the controller is performed based on the mentioned uncertainties. The controllers send an optimal signal to the excitation system of synchronous generators. As a result, the objective is to re-synchronize the generator's rotor speeds and angles and maintain the system operating at a level similar to that of the pre-fault situation.

The simulation results test the controllers on the IEEE 9-bus and modified IEEE 68 bus - 14 machines - 2 RESs systems. The set of differential algebraic equations (DAEs) are used to model the systems, which are then simulated in the MATLAB/Simulink environment. Furthermore, insecure contingencies are chosen to make the systems unstable in the absence of corrective action.

First of all, the results related to IEEE 9 bus system are demonstrated. The PSS parameters optimization procedure by using PSO and GWO with results are shown, and after that, the TSEC and ABC parameters obtained with PSO are illustrated. The rest of this section gives the performance of up-mentioned controllers by the related table and the figures. The table consists of some error signals that show the performance of controllers in a detailed manner. Further, each figure includes all of the generator's rotor angles, rotor speeds, and electrical powers.

Secondly, as a larger test system, the modified IEEE - 68 bus is chosen. Two RESs systems are replaced with the two related synchronous generators. Since the inertia of the RESs system is so small, they add extra damping to the power system, so it can significantly change the dynamic behavior of the system. Furthermore, the most critical contingency is chosen to make the crucial condition. In the rest of this section, a process similar to the previous section is demonstrated. By referring to the tables and figures, the differences in performance of the controllers are specified.

In conclusion, the suggested decentralized adaptive backstepping controller is a practical control approach for achieving transient stability in small and large-scale power systems.

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APPENDICES

APPENDIX A : Western System Coordinated Council System Data

APPENDIX B : 68 Bus - 16 Machines Test System Data





APPENDIX A

The data of the Western System Coordinated Council (WSCC) IEEE 3-generators 9-bus system is available in [30]. The load flow, synchronous generators, and exciter data are found in A.1, A.2, and A.3, respectively.

Table A.1 : Load flow Results of WSCC-9bus.

Bus No.	Type	Voltage	Angle	$-P_L$	$-Q_L$	P_G	Q_G
1	Swing	1.04	0	0	0	0.7164	0.2705
2	PV	1.025	9.26	0	0	1.63	0.0665
3	PV	1.025	4.6648	0	0	0.85	-0.1086
4	PQ	1.0258	-2.2168	0	0	0	0
5	PQ	0.9956	-3.9888	1.25	0.5	0	0
6	PQ	1.0127	-3.6874	0.9	0.3	0	0
7	PQ	1.0258	3.7197	0	0	0	0
8	PQ	1.0159	0.7275	1	0.35	0	0
9	PQ	1.0324	1.9667	0	0	0	0

Table A.2 : Generator data.

Generators	G_1	G_2	G_3
H	23.64	6.4	3.01
X_d	0.146	0.8958	1.3125
X'_d	0.0608	0.1198	0.1813
X_q	0.0608	0.1198	0.1813
X'_q	0.0969	0.1969	0.1813
T'_{d0}	8.96	6	5.89
T'_{q0}	0.31	0.535	0.6

Table A.3 : Exciters data.

Exciters	Exciter No.1	Exciter No.2	Exciter No.3
KA	20	20	20
TA	0.2	0.2	0.2



APPENDIX B

The data of the IEEE 68 bus - 16 generators system is found in [45]. The load flow results are found in Table B.2. Further, The generators and exciters data are found in B.3, and B.1, respectively.

Table B.1 : IEEE 68 bus system's exciter data.

Exciter No.	KA	TA
1	40	0.02
2	40	0.02
3	40	0.02
4	40	0.02
5	40	0.02
6	40	0.02
7	40	0.02
8	40	0.02
9	40	0.02
10	40	0.02
11	40	0.02
12	40	0.02
13	40	0.02
14	40	0.02
15	40	0.02
16	40	0.02

Table B.2 : IEEE 68-bus load flow results.

Bus No	Type	Voltage	Angle	$-P_L$	$-Q_L$	P_G	Q_G
1	PV	1.0450	-8.956	0	0	2.50	1.96
2	PV	0.98	-0.9835	0	0	5.45	0.70
3	PV	0.983	1.613	0	0	6.50	0.80
4	PV	0.997	1.668	0	0	6.32	0.0027
5	PV	1.011	-0.6276	0	0	5.05	1.165
6	PV	1.05	3.842	0	0	7.00	2.544
7	PV	1.063	6.031	0	0	5.60	2.908
8	PV	1.03	-2.841	0	0	5.40	0.4907
9	PV	1.025	2.652	0	0	8.00	0.5981
10	PV	1.01	-9.644	0	0	5.00	-0.131
11	PV	1.0	-7.224	0	0	10.00	0.083
12	PV	1.0156	-22.63	0	0	13.50	2.800
13	PV	1.011	-28.65	0	0	35.91	8.850
14	PV	1.0	10.96	0	0	17.85	0.474
15	PV	1.0	0.01683	0	0	10.00	0.767
16	Swing	1.0	0	0	0	33.79	0.936
17	PQ	0.9499	-36.03	60	3.00	0	0
18	PQ	1.0023	-5.805	24.7	1.23	0	0
19	PQ	0.93198	-4.263	0	0	0	0
20	PQ	0.98061	-5.874	6.8	1.03	0	0
21	PQ	0.96024	-7.054	2.74	1.15	0	0
22	PQ	0.99368	-1.801	0	0	0	0
23	PQ	0.99611	-2.161	2.48	0.85	0	0
24	PQ	0.9587	-9.877	3.09	-0.92	0	0
25	PQ	0.9981	-10.0	2.24	0.47	0	0
26	PQ	0.98686	-11.02	1.39	0.17	0	0
27	PQ	0.96789	-12.86	2.81	0.76	0	0
28	PQ	0.98973	-7.497	2.06	0.28	0	0
29	PQ	0.99209	-4.546	2.84	0.27	0	0
30	PQ	0.97618	-19.71	0	0	0	0
31	PQ	0.98381	-17.46	0	0	0	0
32	PQ	0.96988	-15.24	0	0	0	0
33	PQ	0.97381	-19.76	1.12	0	0	0
34	PQ	0.98003	-26.12	0	0	0	0
35	PQ	1.043	-27.09	0	0	0	0
36	PQ	0.96064	-28.83	1.02	-0.1946	0	0
37	PQ	0.95551	-11.79	0	0	0	0
38	PQ	0.98898	-18.76	0	0	0	0
39	PQ	0.99154	-39.29	2.67	0.126	0	0
40	PQ	1.0442	-13.64	0.65	0.235	0	0
41	PQ	0.99965	9.427	10.0	2.50	0	0
42	PQ	0.99896	-0.8435	11.5	2.50	0	0
43	PQ	0.9765	-37.91	0	0	0	0
44	PQ	0.97749	-37.99	2.67	0.048	0	0
45	PQ	1.0471	-29.36	2.08	0.210	0	0

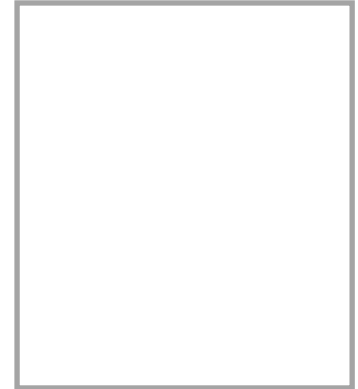
46	PQ	0.99032	-20.53	1.50	0.285	0	0
47	PQ	1.0184	-19.5	2.03	0.325	0	0
48	PQ	1.0337	-18.38	2.41	0.022	0	0
49	PQ	0.99361	-19.82	1.64	0.290	0	0
50	PQ	1.0602	-19.05	1.00	-1.470	0	0
51	PQ	1.0634	-27.29	3.37	-1.220	0	0
52	PQ	0.95454	-12.83	1.58	0.300	0	0
53	PQ	0.98634	-18.94	2.52	1.185	0	0
54	PQ	0.98571	-11.54	0	0	0	0
55	PQ	0.95712	-13.22	3.22	0.020	0	0
56	PQ	0.92084	-11.96	2.00	0.736	0	0
57	PQ	0.9102	-11.21	0	0	0	0
58	PQ	0.90903	-10.4	0	0	0	0
59	PQ	0.90375	-13.31	2.34	0.84	0	0
60	PQ	0.90617	-14.04	2.08	0.708	0	0
61	PQ	0.95565	-23.22	1.04	1.250	0	0
62	PQ	0.91215	-7.312	0	0	0	0
63	PQ	0.90965	-8.37	0	0	0	0
64	PQ	0.83666	-8.377	0.09	0.880	0	0
65	PQ	0.91276	-8.185	0	0	0	0
66	PQ	0.9194	-10.19	0	0	0	0
67	PQ	0.92803	-11.43	3.2	1.530	0	0
68	PQ	0.94829	-10.07	3.29	0.320	0	0

Table B.3 : IEEE 68 bus - 16 machines Generator data.

Gen No.	H	X_d	X'_d	X_q	X'_q	T'_{d0}	T'_{q0}
1	42.00	0.100	0.031	0.031	0.041	10.20	1.50
2	30.20	0.295	0.069	0.069	0.093	6.56	1.50
3	35.80	0.249	0.053	0.053	0.071	5.70	1.50
4	28.60	0.262	0.043	0.043	0.058	5.69	1.50
5	26.00	0.330	0.066	0.066	0.088	5.40	0.44
6	34.80	0.254	0.050	0.050	0.067	7.30	0.40
7	26.40	0.295	0.049	0.049	0.066	5.66	1.50
8	24.30	0.290	0.057	0.057	0.076	6.70	0.41
9	34.50	0.210	0.057	0.057	0.076	4.79	1.96
10	31.00	0.169	0.045	0.045	0.061	9.37	1.50
11	28.20	0.128	0.018	0.018	0.024	4.10	1.50
12	92.30	0.101	0.031	0.031	0.042	7.40	1.50
13	248.00	0.029	0.005	0.005	0.007	5.90	1.50
14	300.00	0.018	0.002	0.002	0.003	4.10	1.50
15	300.00	0.018	0.002	0.002	0.003	4.10	1.50
16	225.00	0.035	0.007	0.007	0.009	7.80	1.50



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