POWER SYSTEM STABILIZER FOR MULTIMACHINE POWER SYSTEMS BASED ON FUZZY LOGIC CONTROL AND ARTIFICIAL BEE COLONY ALGORITHM

BY

ABDULLAH MOHAMMED BARAEAN

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This thesis, written by **ABDULLAH MOHAMMED BARAEAN** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.**

H. Duwaish

Dr. Hussain N. AL-Duwaish
(Advisor)

Dr. ALI AHMED AL-Shaikhi
Department Chairman

Dr. Salim Ibrir
(Member)

Dr. Salam A. Zummo
Dean of Graduate Studies

Dr. Mohammad Khalid
(Member)

7/5/18
Date

This Thesis is dedicated to my supportive father,

my loving mother, my brothers, my wife

and all my friends

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony Optimization Algorithm.
FLPSS	Fuzzy Logic Power System stabilizer.
ABC-FLPSS	Artificial Bee Colony based Fuzzy Logic Power System Stabilizer.
CPSS	Conventional Power System Stabilizer.
WSCC	Western System Coordinated Council.
HVDC	High Voltage Direct Current.
AVR	Automatic Voltage Regulator.
PSS	Power System Stabilizer.
MMPS	Multi-Machine Power System.
SMIB	Single-Machine Infinite Bus power systems.
PID-PSS	Proportional-Integral-Derivative Power System Stabilizer.
PI-PSS	Proportional-Integral Power System Stabilizer.
TCSC	Thyristor Controlled Series Capacitor.
FACTS	Flexible AC Transmission Systems.
SVC	Static VAR Compensator.
PSO	Particle Swarm Optimization.

HSA	Harmony Search Algorithm.
GA	Genetic Algorithm.
ISE	Integral of Squared Error.
IAE	Integral of the Absolut value of Error
ITAE	Integral of the Time weighed Absolut Error

ABSTRACT

Full Name : ABDULLAH MOHAMMED BARAEAN

Thesis Title : POWER SYSTEM STABILIZER FOR MULTIMACHINE POWER SYSTEMS BASED ON FUZZY LOGIC CONTROL AND ARTIFICIAL BEE COLONY ALGORITHM

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In recent years, Fuzzy Logic systems have become a hot spot in the field of designing a robust controller for enhancing the transient stability of power systems with a superior performance compared to classical controllers. This work proposes an Artificial Bee Colony Optimization Algorithm (ABC) to optimize the input-output scaling factors of a Fuzzy Logic Power System stabilizer (FLPSS) which leads to damp local and inter-area oscillations following disturbances in power systems. The test system considered is a two-area 4-machine 11-bus multi-machine power system for evaluating the performance of an Artificial Bee Colony based Fuzzy Logic Power System Stabilizer (ABC-FLPSS) under variable disturbances and load conditions. The Integral Squared Error (ISE) of the rotor speed deviation is formulated as an objective function for optimizing the fuzzy logic PSS scaling factors. To evaluate the effectiveness of the proposed controller, the system is simulated under different conditions which vary from small disturbances such as a small signal change in one of the system parameters to a large disturbance such as the removal of one of the main transmission lines. Simulation results show the superiority of the *proposed ABC-FLPSS controller compared to the FLPSS and the Conventional Power System Stabilizer (CPSS).*

Keywords: *Artificial Bee Colony Optimization Algorithm, Fuzzy Logic Power System Stabilizer, Power System Transient Stability, Power System stabilizers.*

ملخص الرسالة

الاسم الكامل : عبدالله محمد باريان.

عنوان الرسالة : مثبت نظام القدرة لأنظمة القدرة متعددة الآلات إعتمادا على التحكم الضبابي المنطقي و خوارزمية مستعمرة النحل الذكية.

التخصص : هندسة كهربائية.

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في السنوات الأخيرة، أصبحت أنظمة المنطق الضبابي شائعة الإستخدام في مجال تصميم وحدات تحكم فعاله لتحسين أداء أنظمة القدرة الكهربائية مع أفضلية أداء مقارنة بوحدات التحكم التقليدية. في هذا البحث، تم إقتراح خوارزمية التحسين لمستعمرة النحل الذكية لتحسين عوامل التحجيم لمدخلات ومخرجات مثبت نظام القدرة المنطقي الضبابي الذي يؤدي إلى مقاومة الذبذبات المحلية والذبذبات بين المناطق بعد حدوث إضطرابات في أنظمة القدرة. نظام الإختبار في هذه الدراسةهو عبارة عن نظام قدرة متعدد الألات ويتكون من منطقتين و4 آلات و11 توصيلة من أجل تقييم أداء مثبت أنظمة القدرة المنطقي الضبابي على أساس خوارزمية مستعمرة النحل الذكية وذلك تحت إضطرابات وظروف تحميل مختلفة. تم صياغة دالة الخطأ التربيعي المتكامل لإنحراف سرعة العضو الدوار في المولد الكهربائي كدالة الهدف لتحسين عوامل التحجيم لمثبت أنظمة القدرة المنطقي الضبابي. نتائج المحاكاة تظهر أفضلية وحدة التحكم المقترحة (مثبت نظام القدرة المنطقي الضبابي على أساس خوارزمية مستعمرة النحل الذكية) مقارنة بمثبت نظام القدرة المنطقي الضبابي ثابت العوامل و مثبت نظام القدرة التقليدي.

كلمات دلالية: *خوارزمية التحسين لمستعمرة النحل الذكية، مثبت نظام القدرة المنطقي الضبابي،الإسقرار العابر لنظام القدرة،مثبت نظام القدرة.*

CHAPTER 1

INTRODUCTION

The stability phenomenon of electrical power systems has been, and continues to be, a challenging issue in power system operations. Modern electrical power systems are large-scale, interconnected and complex systems. In operation, these systems are often impaired by low frequency oscillations caused by many kinds of external disturbances such as three phase faults, load changing, generator tripping out or others. During these situations, maintaining the system stability becomes more challenging, and the synchronous generator excitation systems should provide additional damping to compensate for these oscillations and stabilize the whole power system.

Interconnected electrical power systems are complex and commonly face the critical problem of dynamic oscillation. The dynamic oscillation problem is divided into two kinds of oscillation. The first type is local mode oscillation between the generators in the same area, while the second type is inter-area mode oscillation between the generators from one area to others in another area, which is more complex and challenging.

This chapter is describing the background of this research, the objectives and the scope of this thesis following by thesis structure.

1.1 Power System Stability

Stability analysis, which evaluates the effects of external disturbances on the electromechanical dynamic behavior of electrical power systems, is divided into two types:

1. Steady State Stability or Small Signal Stability, which is the ability of the system to overcome small disturbances such as small variations in generators or loads.

2. Transient Stability, which is the ability of the power system to handle large disturbances while maintaining the synchronism. Large disturbances include three phase faults on the transmission line, large load changing and the sudden loss of one or more generators etc.

It is critical to mention that: transient stability is a function of the initial state situation and the disturbance while steady state stability is a function of the initial state situation only. This means that transient stability should receive more attention. The dynamic system models used in this type of analysis are nonlinear and very extensive because nowadays power systems are heavily interconnected with hundreds of synchronous machines which can interact through the medium of their extra-high-voltage and ultra-high-voltage networks [1].

The transient stability phenomenon is considered to be a major issue in the control of power systems with multi-synchronous machines that operate in parallel, becoming even more complex in long-distance power transmission.

Power system transient stability is the ability of the power system to maintain the synchronous operation between its machines in the sense of disturbance, or it can be defined as the ability of the power system to remain at a stable equilibrium point under normal conditions and to converge to this equilibrium point under disturbance conditions. consequently, it is a highly nonlinear problem, and that makes it very problematic and difficult to assess or control [2].

Consider Figure 1.1, which depicts a number of weights that are suspended by elastic strings. The weights represent the generators while the electric transmission lines are represented by the strings. Note that in a transmission system, each transmission line is loaded below its static stability limit. Similarly, when the mechanical system is in a static steady state, each string is loaded below its break point. At this point one of the strings is suddenly cut. This will result in transient oscillations in the coupled strings and all the weights will wobble. In the best possible case, this may result in the coupled system settling down to a new steady state. On the other hand, in the worst possible scenario this may result in the breaking of one more additional string, resulting in a chain reaction in which more strings may break forcing a system collapse. In a similar way, in an interconnected electric power network, the tripping of a transmission line may cause a catastrophic failure in which a large number of generators are lost forcing a blackout in a large area [3].

Inter-area oscillations manifest wherever the power system is heavily interconnected. The oscillations, unless damped, can lead to grid failure and total system collapse. Low frequency oscillations in the range of 0.04 Hz to 0.06 Hz were observed in the Pacific North West region as early as 1950. The improper speed governor control of hydro units created these oscillations. The Northern and Southern regions of the Western System Coordinated Council (WSCC) were interconnected by a 230-kV line in 1964. Immediately the system experienced a 0.1 Hz oscillation resulting in over 100 instances of the opening of the tie line in the first nine months of operation, while some system damping was provided through the modification in the hydro turbine governors [3].

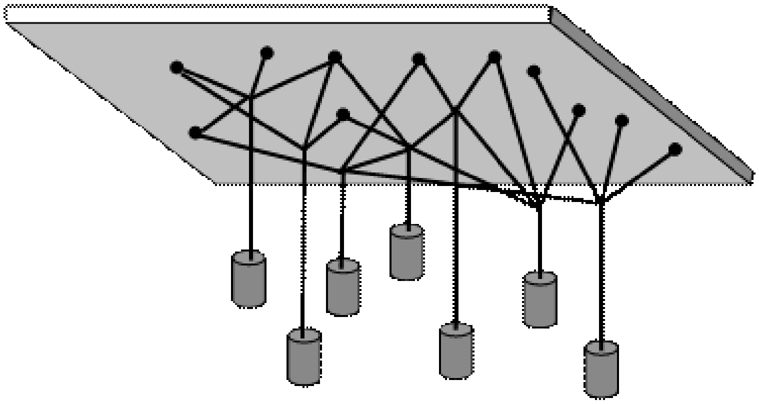


Figure 1.1: Example of an Interconnected Electric Power System Transient Stability

A 500-kV pacific intertie and another ± 400-kV High Voltage Direct Current (HVDC) system was commissioned in 1968. This raised the frequency of oscillation from 0.1 Hz to 0.33 Hz and as a result these oscillations could no longer be controlled through governor action alone. In the late 1980's a new intertie joined the WSCC system to Alberta and British Columbia in Canada. As a result of this interconnection, the two different oscillation frequencies manifested, one at 0.29 Hz and the other at 0.45 Hz [3].

Ontario Hydro is one of the largest utilities in North America. Due to the vast and sparsely populated topology of Canada, the operating span of Ontario hydro is over 1000 km from East to West and from North to South. The Ontario Hydro system is connected to the neighboring Canadian provinces and the North Western region of the United States. In

1959 Ontario Hydro was connected to Michigan in the South and Quebec Hydro in the East. As a result of this connection, a 0.25 Hz oscillation was observed and as a result of this it was decided to remove the tie with Quebec and retain the tie to Michigan. The Western portion of Ontario was connected with neighboring Manitoba in 1956 and then Manitoba was connected to its neighbor Saskatchewan in 1960. This resulted in oscillation in the frequency range 0.35 Hz to 0.45 Hz, often tripping the tie. As a result of this, Ontario Hydro decided to commission power system stabilizers for all of their generating units in the early 1960's. It has also sponsored extensive research in this area [3].

As the result of this research it was established that the action of automatic voltage regulators caused these oscillations. An Automatic Voltage Regulator (AVR) regulates the generator terminal voltage and also helps in the enhancement of transient stability by reducing the peak of the first swing following any disturbance. However, its high gain contributed to negative damping to the system. The knowledge of this relation resulted in the commissioning of power system stabilizers. It was observed that these oscillations were the result of the periodic interchange of kinetic energy between the generator rotors. A Power System Stabilizer (PSS) provides negative feedback from the changes in rotor kinetic energy when it is connected to the excitation system, thereby providing damping to these small oscillations. The PSS has been a subject of extensive research. The team of Dr. P. Kundur, then with Ontario Hydro, and his co-workers has done extensive research in the area of PSS tuning and its characteristics. Through their vast experience and extensive research, they reported the enhancement of inter-area and local modes through PSS. Since a power system is piece-wise linear, its system characteristics change with the operating point. Therefore, an adaptive controller that can attune with to the changes in the system has been developed. It was shown that the adaptive PSS is effective in damping large, as well as small disturbances.

To control transient stability, the synchronous machines must be equipped with an excitation control system to restore the synchronism and facilitate the proper dynamic performance of the system. Time domain analysis is widely used to solve the nonlinear differential equation of the plant dynamic model. In all stability analyses, the objective is maintaining a constant speed of the rotor machines.

The traditional control techniques employ power system stabilizers PSS on the generator excitation systems. PSSs are effective for damping local modes. In large inter-area power systems, PSSs may not provide enough damping voltage for the inter-area modes. As a result, more efficient substitutes are needed in place of PSSs. Nonlinear controllers have been successfully applied on the excitation systems of power systems to maintain stability under different operating conditions as these controllers are capable of operating over a wide variation range of operating points [4].

1.2 Problem Statement

Since power systems are highly nonlinear systems, they alter their configurations and parameters through time. In a practical operating environment, the linearized controller design model of the power system cannot guarantee its performance.

Moreover, the exact parameter measurement of the power system is quite hard because these parameters vary during the course of practical operations. For example, power system loads change continually during the operation, which then affect the generator input mechanical power [5].

Fuzzy Logic control is one of the most suitable approaches for nonlinear, ill-defined and time varying systems where it has demonstrated many advantages such as robustness, a short computational time and the ability to handle uncertainties in the system model. The performance of the Fuzzy logic-based PSS depends on the operating conditions of the system. Therefore, to make it adaptable and to get a better response, the parameters of the Fuzzy Logic PSS should be tuned to adapt to the changes in the power system operating conditions [6].

The task of optimizing fuzzy logic power system stabilizer parameters is very challenging and time consuming because there is no systematic procedure, it has to be done either iteratively or by trial and error.

1.3 Objectives

The objectives of this work are as follows:

- Design a Fuzzy Logic based Power System Stabilizer (FLPSS) to maintain the stability of multi-machine power systems when they are subjected to a severe disturbance.
- Optimize the controller parameters in order to get better performance.
- Simulate the proposed controller and validate its performance by comparing it with a Conventional Power System Stabilizer (CPSS).

1.4 Thesis Outlines

This work is divided into five parts as follows:

- **Chapter 1** introduced the problem of transient stability as a major issue in the control of multi-machine power systems. Additionally, the problem formulation, basic objectives of the study and thesis outlines are briefly discussed.
- **Chapter 2** proposed the related work that has been done in the literature to address this problem.
- **Chapter 3** represented the methodology of this thesis by designing a mathematical model of the multimachine power system and describing the fuzzy logic PSS controller with the artificial bee colony as an optimization technique.
- **Chapter 4** is an application of the proposed controller on SMIB and MMPS power systems with various levels of disturbance to investigate its performance.
- **Chapter 5** Finally the work is concluded, and the results are summarized.

CHAPTER 2

LITERATURE REVIEW

There are several methods of control proposed in the literature to maintain the transient stability of multi machine power systems, which are affected by the large oscillations caused by large power networks. These techniques vary from conventional control ([7], [8]), to intelligent fuzzy control techniques [9], in addition these techniques include optimal control ([10], [11]) and adaptive control ([12], [13]).

Excitation systems equipped with power system stabilizers on synchronous machines are used to provide more damping to the rotor shafts. In 1960s, the first conventional PSS was suggested and designed by using classical control theory.

In 1969, DeMello and Concordia made a significant improvement in PSSs to make them efficient for controlling multi-machine power systems (MMPS) and single-machine infinite bus power systems (SMIB) [14].

The effects of PSSs on local and inter-area modes in multi-machine power systems were simulated by Klein et al. ([15], [16]). they concluded that the location of PSSs in the system network is a major factor in the design of PSSs controllers to achieve better results. Nowadays, many types of PSSs are used by utilities such as proportional-integral derivative power system stabilizers (PID-PSS), and proportional-integral power system stabilizers (PI-PSS). the most frequently used one is the conventional lead-lag power system stabilizer (CPSS) [17].

PSSs are designed by linearizing the system model around a specific operating point, and they are effective in damping local area oscillations. However, they are not suitable in damping inter-area oscillations. In [18], the performance of a simultaneous controller of a PSS and a Thyristor Controlled Series Capacitor (TCSC) improves the transient stability of SMIB with a three-phase fault compared to the performance of only CPSS.

The design of optimal parameters for damping controllers is a very challenging optimization problem when improving the transient stability of power systems. Hence, this area has been studied extensively to achieve the local and global optimum solutions using different optimization methods. Tuning the PSS parameters allows it to work sufficiently in a wide range of operating conditions. Many optimization techniques have been designed in the literature for this purpose, such as genetic algorithm, particle swarm optimization, simulated annealing and others [19] [20] [21] [22] [23] [24] [25]. However, due to power system’s nonlinear nature and the parameter variations with the operating conditions, its performance may be degraded.

Advanced techniques have been proposed to improve the performance of PSSs. These techniques include robust, adaptive, optimal and artificial optimization techniques [26].

Power electronic devices are used for damping system oscillations and improving the dynamic stability performance of the power systems. The Flexible AC Transmission Systems (FACTS) devices such as the Thyristor Controlled Series Capacitor TCSC and the Static VAR Compensator (SVC) are a common example of these devices. In [27], a PSS and SVC-based controller are thoroughly discussed when applied individually and in a coordinated manner. the coordinated design showed real potential for enhancing the stability of power systems. In [28], the authors developed a simultaneous coordinated design of a PSS and a TCSC stabilizer using Particle Swarm Optimization algorithm (PSO) in MMPS. This coordinated design performe very well when handling the power system inter-area oscillations.

Feedback linearization controllers were used to control the power systems, but these controllers demand exact measurements of the system parameters to give superior performance, which is a challenging task as some of the power system parameters change gradually with time and cannot be measured precisely. For example, it is hard to detect the damping coefficient parameter while the generator transient reactance is slowly varying over time. This issue means that the feedback linearization controllers lack the required robustness for damping the oscillation of power systems.

Nonlinear controllers are widely used to overcome this problem as they have the ability to operate over a wide operating region and provide enough damping to maintain the dynamic stability of multi-machine power systems [29]. The most interesting thing is that these nonlinear controllers include the critical parameters of the power system and can achieve them adaptively. A fuzzy logic-based power system stabilizer doesn’t require the mathematical model of the plant and it can be designed efficiently to handle the problem of the parameter sensitivity of feedback linearization controllers where these sensitive parameters are considered as unknown and can only be estimated dynamically by the fuzzy controller [30].

Various power system stabilizers can be obtained based on fuzzy logic control. The first method is the Fuzzy-P controller which is a technique used for fuzzy logic control in a closed loop control. The inputs to the controller are derived from the process of making measurements and the output of the fuzzy logic system is used to control the process. This process is considered as a pure fuzzy logic system that indicated by the term Fuzzy-P controller. The second method uses the PID-fuzzy controllers which are categorized into two main types. The first type is the fuzzy logic controller, which is realized as a set of heuristic control rules, while the second type is referred to as a PD or PI-fuzzy controller, which is comprised of a conventional “PID controller” in conjunction with a set of fuzzy reasoning mechanisms and fuzzy rules to tune the (PID) gains online. Fuzzy logic control application to power systems is effective as this technique is suitable for non-linear system control [31]. If the fuzzy rules are designed to be more robust, fuzzy controllers can enhance the disturbance response by reducing the degree of undershoot / overshoot present in the controlling variable. There are major issues in designing a fuzzy logic based PSS such as the selection of membership function, number of linguistic variables, rule bases and scaling factors ([32], [33]).

Fuzzy logic control is a rule base control system which doesn’t depend on the mathematical model of the plant. Hence, the selection of an optimal set of rules for the fuzzy controller is the most crucial step in designing a successful fuzzy controller. Numerous optimization techniques are used to generate fuzzy rules automatically, such as the Genetic Algorithm in [34], the ABC in [35] and others [36] [37]. The motivation of using these automated techniques is to reduce the effort involved in designing fuzzy controllers and handling the parametric uncertainties of the power systems. Also, this technique will make fuzzy controllers more robust and flexible under different power system operating conditions.

Fuzzy system input-output variables need to be normalized before they are injected into the fuzzy controller. Selecting the optimal values for these normalization factors (Scaling Factors) plays a basic role in improving the performance of fuzzy controllers and must be carefully considered. The Cuckoo Search algorithm is used for this purpose in [38]. The Bat algorithm is used in [39] and it showed superior performance compared to the Particle Swarm Optimization (PSO) in [22] and the Harmony Search Algorithm (HSA) in [40].

The Artificial Bee Colony algorithm (ABC) technique has gained much attention and has been used for solving many complex optimization problems since its invention in 2005 by Karaboga [41]. It simulates the foraging behavior of honey bee swarms. The effectiveness and superiority of the ABC algorithm compared to other well-known algorithms such as Genetic Algorithm (GA) and PSO were shown in [42].

The ABC algorithm has a simple structure, ease of implementation and only one control parameter called a limit (L), in addition to the common control parameters of any population-based optimization algorithm which are the population size and the maximum number of iterations.

In this work, the input-output variables of the FLPSS are considered as the generator speed deviation and power acceleration for the inputs and the stabilized voltage for the output, then the input-output scaling factors are optimized using the ABC algorithm. The proposed controller is designed with a nonlinear model of a two-area four-machine 11-bus multi-machine power system.

CHAPTER 3

METHODOLOGY

The main purpose of this thesis is to investigate the performance of an Artificial Bee Colony (ABC) optimization algorithm for tuning the input-output scaling factors of a Fuzzy-Logic PSS (FLPSS) in order to enhance the transient stability of the power systems. Therefore, the modelling of the power system equipment, such as a synchronous machine, an excitation system and a PSS is essential. Also, the Fuzzy Logic controller should be designed in connection with the ABC algorithm and the objective function should be defined for the tuning process.

3.1 Test Power System

The power system consists of several synchronous generators and other equipment connected to each other by electrical transmission lines. Each generator is equipped with an excitation system. The dynamic model of the power system is essential for designing the excitation controller.

3.1.1 Power System Dynamic Model

The power system of an N order, is a highly nonlinear system and it can be represented by the following differential equations based on the symbol representation of the power system dynamic model as in Table 3.1.

Table 3.1: Symbols Representation of the Power System Dynamic Model

Term	Indication
δ	rotor angle (radians).
ω	rotor speed (radians/sec).
ω_0	reference speed (radians/sec).
I_d & I_q	stator currents in the d-q axis.
P_m	input mechanical power (p.u.).
P_e & Q_e	active and the reactive electrical powers.
E_q	internal voltage in the quadrature axis
H	moment of inertia (sec.).
D	damping coefficient (p.u.).
x_d & x'_d	synchronous reactance and transient reactance in the direct axis (p.u.).
T'_{do}	field winding time constant (sec.).
G_{ij} & B_{ij}	transfer conductance and transfer susceptance of the admittance matrix Y_{ij} between buses i and j (p.u.).
E_{fd}	excitation voltage (p.u.).

$$\dot{\delta_\imath} = \omega_i - \omega_0 \tag{3.1}$$

$$\dot{\omega_\imath} = \frac{\omega_0}{2H}\left[P_{mi} - \frac{D_i}{\omega_0}[\omega_i - \omega_0] - P_i\right] \tag{3.2}$$

$$\dot{E'_{q\imath}} = \frac{1}{T'_{doi}}[E_{fdi} - E_{qi}] \tag{3.3}$$

Equations (3.1) and (3.2) represent the mechanical dynamics while equation (3.3) represents the electrical dynamics.

Here the internal voltage (E_{qi}) in the quadrature axis can be represented as:

$$E_{qi} = E'_{qi} + (x_d - x'_d)I_{di} \tag{3.4}$$

the active and reactive electrical powers are as follows:

$$P_{ei} = I_{qi}E'_{qi} \tag{3.5}$$

$$Q_{ei} = I_{di}E'_{qi} \tag{3.6}$$

and the stator currents (I_{di} , I_{qi}) in the d-q axis are:

$$I_{di} = -E'_{qi}G_{ii} - \sum_{j=1}^{N} E'_{qj}B_{ij} \cos \delta_{ij} \tag{3.7}$$

$$I_{qi} = E'_{qi}G_{ii} - \sum_{j=1}^{N} E'_{qj}B_{ij} \sin \delta_{ij} \tag{3.8}$$

Now the terminal voltage on the side of each generator can be represented as:

$$V_{ti} = \sqrt{\left(E'_{qi} - x'_{di}I_{di}\right)^2 - \left(x'_{di}I_{qi}\right)^2} \tag{3.9}$$

By substituting the electrical equations into the main model, the final dynamical model of the power system can be written as:

$$\dot{\delta_i} = \Delta\omega_i \tag{3.10}$$

$$\dot{\omega}_i = \frac{\omega_0}{2H}\left[P_{mi} - I_{qi}E'_{qi}\right] - \frac{D_i}{2H}\Delta\omega_i \tag{3.11}$$

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}E_{fdi} - \frac{1}{T'_{doi}}E'_{qi} + (x_d - x'_d)I_{di} \tag{3.12}$$

These three differential equations can represent the dynamics of a power system with one machine, and there will be 3N differential equations for representing N-machines power system, where N is the number of machines in the power system.

3.1.2 Single Machine Infinite Bus Power System (SMIB)

A single Machine Infinite Bus (SMIB) power system is very useful in studying the transient stability phenomenon of power systems and for testing alternative control techniques. It is simple to study and it shows the exact behavior of (MMPS).

The SMIB power system consists of a synchronous machine connected to an infinite bus through a weak transmission line. Figure 3.1 depicts the particular SMIB power system used in this study. Its parameters and more information can be found in [17].

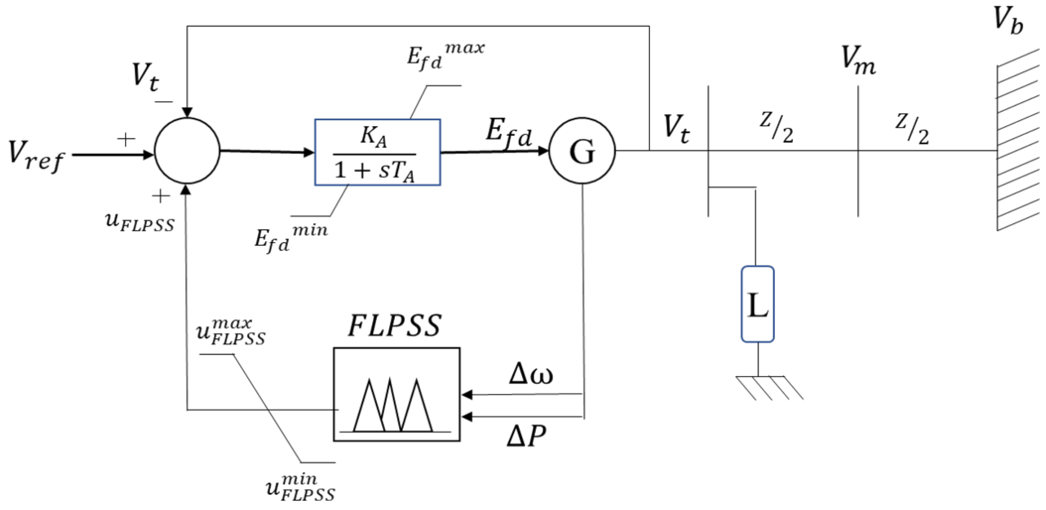


Figure 3.1: Single-Machine Infinite Bus Test Power System

The generator is equipped with an additional excitation system which contains a FLPSS that induces an electric torque to the Automatic Voltage Regulator (AVR) to generate an additional damping voltage signal compensating for the opposite damping of the disturbed system due to the parameters changing or due to the fault disturbances.

3.1.3 Multi-Machine Power System (MMPS)

Figure 3.2 shows the MMPS power system considered in this study. It contains two separated areas with two sets of generators represented by the same dynamic model and generates 900MVA with a 20KV rating. The two areas are identical and connected by two weak tie lines. Area 1 transfers 413MW of active power to Area 2. At about 700MW of generator loads, 967MW Area 1 loads and 1767MW Area 2 loads are considered. More information about this power system, such as line data, bus data, machines parameters and dynamic characteristics can be found in [1].

Each generator is equipped with an excitation system. The generator’s excitation system contains PSS that induces an electric torque in phase with the rotor’s speed deviation, the PSS feeds a supplementary stabilizing signal to the Automatic Voltage Regulator (AVR) to produce an additional damping voltage compensating for the negative damping of the disturbed system due to the parameters changing or due to fault disturbances.

The CPSS can use various inputs, such as the speed deviation of the generator shaft, the change in electrical power or accelerating power, or even the terminal bus frequency. In this thesis speed deviation ($\Delta\omega$) is used as an input to the CPSS and the output of any CPSS is a voltage signal and it is present only when the rotor is oscillating or there is oscillation in the system.

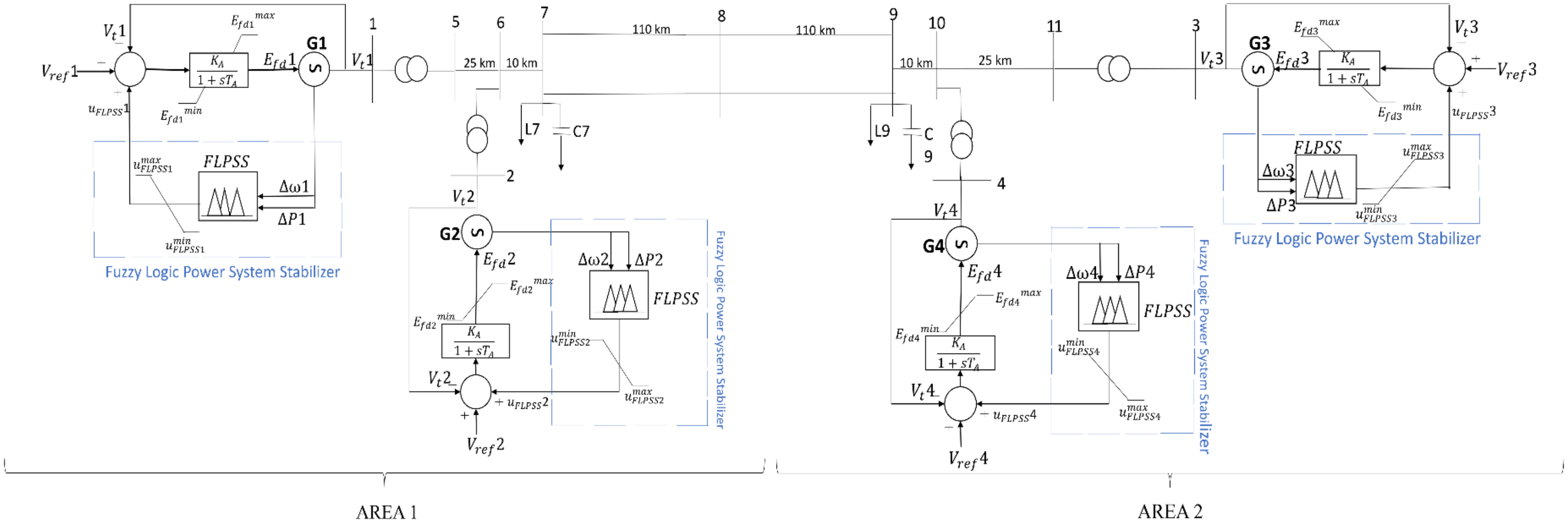


Figure 3.2: Test Multi-Machine Power System

Figure 3.3 shows the structure of the CPSS. It comprises of a PSS gain block (K_{pss}) to provide the desired positive damping, a washout or filter block with time constant (T_w) to reject low frequencies (0.8-2.0Hz), two lead-lag phase compensators with time constants T_1, T_2, T_3, T_4 to provide the appropriate phase lead characteristic to compensate for the phase lag between the exciter input and the generator electrical torque, and finally the voltage limiter which satisfies the control constraints and avoids over-excitation [42]. The parameters used in this paper are K_{pss}=20, T_w=10s, T_1=0.05s, T_2=0.02s, T_3=3s, T_4=5.4s, and $-0.15 \leq V_{pss} \geq 0.15$ [1]. The transfer function of the Conventional PSS (CPSS) is given by:

$$V_{pss}(s) = K_{pss} \frac{sT_w}{1 + sT_w} \frac{1 + sT_1}{1 + sT_2} \frac{1 + sT_3}{1 + sT_4} * \Delta\omega \qquad (3.13)$$

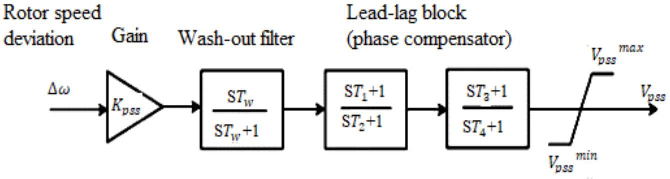


Figure 3.3: Conventional Power System Stabilizer Structure

3.2 Fuzzy Logic based Power System Stabilizer

PSSs parameters are obtained by linearizing the system model around a specified operating point but, in practical nonlinear systems, this may degrade the controller performance as the system parameters changing gradually [39], so linear control theory is a limitation in the design and analysis process. On the other hand, fuzzy control theory is a rule-based control theory where human knowledge is approached by means of linguistic fuzzy rules in the form of if-then statements as shown in Figure 3.4. In such a changing nonlinear environment, fuzzy logic control provides more efficient stabilizing signals to the excitation system than CPSS.

The Fuzzy Logic controller doesn’t rely on a mathematical model of the system under study, although, detailed knowledge about the input processing and how to achieve the output should be clear [32]. Fuzzy logic control performs the control action in three main steps: fuzzification, Fuzzy Inference Rules and finally defuzzification.

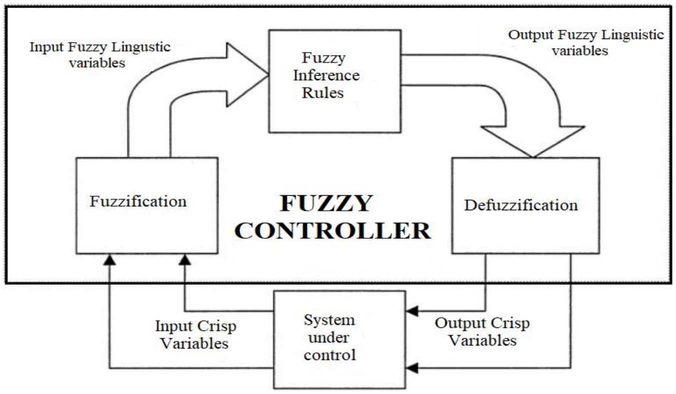


Figure 3.4: Fuzzy Control Concept

3.2.1 Fuzzification

The fuzzification step comprises two steps:

1. Measure and scale the input variables (speed, power acceleration).
2. Transform the measured crisp values to their corresponding linguistic variables based on an appropriate membership function. Consequently, the membership functions are defined for each system variable to transform it into a fuzzy domain.

The system input variables selected for the proposed controller are the generator speed deviation, the active power deviation, and the system output variable which is the supplementary voltage signal that is required to stabilize the generator excitation system.

Each system variable (input or output) is assigned a set of seven linguistic values, which is a common way of making rules for power engineering problems, ranging from Negative Big (NB) to Positive Big (PB). A set of membership functions is defined for seven linguistic variables Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB), as shown in Figure 3.5.

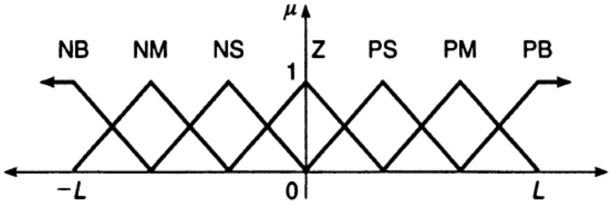


Figure 3.5: Triangular Membership Function

There are many shapes for the Membership functions. The most common are: the triangular membership function, the trapezoidal membership function, and the bell membership function. The triangular membership function shown in Figure 3.5 is used for the proposed controller.

Practically, membership functions are normalized in the interval $[-L, L]$, which is symmetrical around zero. Thus, the fuzzy variables are expressed in terms of the controller parameters. These parameters can be defined as:

$$K_i = \frac{2L}{X_{range_i}} \tag{3.14}$$

Where X_{range_i} defines the control variable X_i full range that is:

$$X_{range_i} = X_{max_i} - X_{min_i} \tag{3.15}$$

And X_{max_i}, X_{min_i}. are the maximum value and the minimum value of the control variable

X_i. The input and output gains K_i, are referred to as the FLC parameters. Previous information of the controlled system is needed for better selection of these parameters.

3.2.2 Fuzzy Inference Rules

Mapping the input fuzzy values (speed and power deviation) to the output fuzzy values (voltage signal) is performed using a rule base. These rules are designed using the concept that: if the output is moving far away from a set point a large control signal is needed to push it towards this set point, and if it moves very near to the set point a small or zero control signal is needed to stabilize it around the set point.

Consider the two input fuzzy variables selected for the proposed controller, the rotor speed deviation ($\Delta\omega$), the active power deviation (Δp), the output fuzzy variable, and the control signal (Δu), each quantized to seven fuzzy sets. This leads to a 7 x 7 fuzzy rule matrix, as shown in Table 3.2 every entity in the matrix represents a rule, for example,

If $\Delta\omega$ is NB and Δp is NM, then Δu is NB.

The information required to generate the fuzzy rules can be derived from an off-line simulation, a design engineer, or an expert operator. Some of the information can be based on understanding the behavior of the dynamic system being controlled [43].

3.2.3 Defuzzification

The fuzzy values representing the controller output in the linguistic domain must be transformed back again into the actual output signal or the stabilizing voltage signal, as in this case.

Table 3.2: Fuzzy Rules of the Proposed Fuzzy Logic PSS

$\Delta\omega$ Δp	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

There are some methods for finding the output based on the membership function, such as the maximum product and the minimum maximum method. The output is obtained based on the membership function by applying a special rule. In the proposed fuzzy controller, the minimum maximum method is used and then the output membership function is calculated for each rule.

The defuzzification process is needed to transform the fuzzy values back into real numerical values where the excitation system uses nonfuzzy signals. In the proposed fuzzy controller, the centroid defuzzification method is used.

3.3 Artificial Bee Colony Optimization Algorithm

The Artificial Bee Colony Optimization Algorithm was discovered by Karaboga in (2005) [41]. It is a swarm-based search algorithm that is inspired by the intelligent foraging behavior of a honey bee swarm process. It attempts to balance local and global optimal solutions within a short computational time. Hence, ABC is a strong optimization technique and efficient in handling large and complex stability problems, such as the stability of power systems that have complicated and changing structures.

Moreover, the ABC algorithm has many advantages, such as flexible structure, short computational time, robust, easy implementation and tuning; all of which make it suitable for practical complex power systems.

There are three essential components of forage selection:

1. Food Sources: they are a probable solution for the optimized problem. Food source quality value depends on many factors, such as its richness of energy, its proximity to the nest and the ease of extracting its energy.
2. Employed bees: they are associated with a specified food source which they are currently exploiting. They share the information about this source with onlooker bees with a certain probability, which includes the profitability of the source and its direction and distance from the nest.
3. Unemployed bees: they are waiting for the information from the employed bees. There are two types of unemployed bees: scouts, searching for new food sources surrounding the nest, and onlookers, waiting in the nest to make a source choice based on the information shared by the employed bees.

The ABC flowchart and detailed steps are as described below:

3.3.1 Initial Population

Initially, ABC algorithm generates SN number of randomly D-dimensional vectors, where SN denotes food sources number. If we consider the ith food source in the population as $X_i = (x_{i,1}, x_{i,2}, \dots, x_{i,n})$. Therefore, initial food sources are generated as:

$$x_{i,j} = x_j{}^{min} + rand(0,1)\left(x_j{}^{max} - x_j{}^{min}\right) \qquad (3.16)$$

$$i = 1,2,3, \dots, n \qquad j = 1,2,3, \dots, D$$

Where D is the optimization parameters number. $x_j{}^{min}$ and $x_j{}^{max}$ are the lower and upper bounds for the j, respectively. After initializing the population, it is subjected to iterative search processes of the employed bees, the onlooker bees and the scout bees as follows:

3.3.2 Employed Bee Phase

Each employed bee X_i generates a new candidate solution V_i about its current position. The position of the new solution is defined as:

$$v_{i,j} = x_{i,j} + \emptyset_{i,j}\left(x_{i,j} - x_{k,j}\right) \qquad (3.17)$$

where $k = 1,2,3, \dots, SN$ and $j = 1,2,3, \dots, D$ are random indexes, k must be different from i. $\emptyset_{i,j}$ is a random number in the period [−1, 1].

If a parameter value produced by Equation (3.17) exceeds its limits, the parameter will be fixed on its limit value. Then, a fitness value is calculated for the candidate solution V_i. If the fitness value of V_i is equal or greater than the fitness value of X_i, X_i will be replaced by the new candidate solution (V_i), otherwise X_i is retained.

3.3.3 Onlooker Bee Probability

When the employed bees finished the search process; every onlooker bee chooses a food source based on a food source probability calculated by the following equation:

$$P_i = \frac{fitness_i}{\sum_{n=1}^{SN} fitness_i} \tag{3.18}$$

The bigger the fitness of that food source, the bigger the chance it will be chosen by the onlooker bees.

3.3.4 Unemployed Bee Phase

After the selection of the food source X_i, onlooker bee produces a modification on X_i using Equation (3.17). If the quality of the modified food source is equal or better than the quality of the old one, X_i will be replaced by the modified food source.

If a food source X_i cannot be improved further over a predetermined number of generations called limit L, the food source is replaced by a new food source discovered by the scout bee. The scout bee generates a new food source by the following equation:

$$x_{i,j} = {x_j}^{max} + rand(0,1)\left({x_j}^{max} - {x_j}^{min}\right) \tag{3.19}$$

3.4 Objective Function

In the proposed work, the ABC optimization algorithm is used to determine the optimum value of the scaling factors of the proposed Fuzzy Logic PSS controller. The input-output variables of the FLPSS are: speed deviation ($\Delta\omega$), power acceleration (Δp) for the inputs and change in the correction voltage (Δu) as output with the associated scaling factors as $K_{\omega i}$, K_{pi} and K_{ui}, respectively. The integral of the squared error (ISE) of the generator speed deviation is formulated as an objective function to optimize the fuzzy Logic scaling factors.

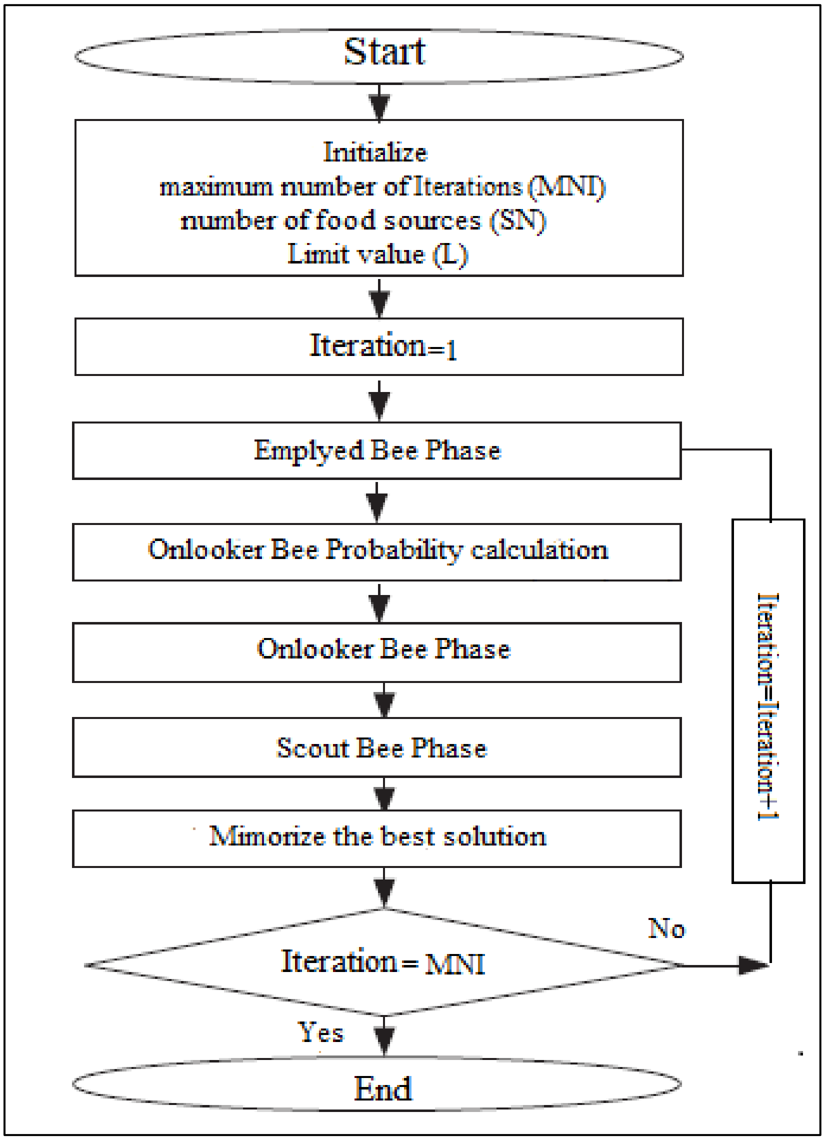


Figure 3.6: ABC Algorithm Flowchart

The ISE based cost function for the test power system is represented by:

$$J = \sum_{i=1}^{4} \int_{0}^{T_{sim}} (\Delta\omega_i(t))^2 \, . dt \tag{3.20}$$

And the parameters are subjected to these constraints:

$$\left.\begin{array}{c} {K_{\omega i}}^{min} \leq K_{\omega i} \leq {K_{\omega i}}^{max} \\ {K_{pi}}^{min} \leq K_{pi} \leq {K_{pi}}^{max} \\ {K_{ui}}^{min} \leq K_{ui} \leq {K_{ui}}^{max} \end{array}\right\} \tag{3.21}$$

Where i is the i_{th} generator and T_{sim} is the simulation time.

The scheme of the scaling factors of the FLPSS is shown in Figure 3.7 where the ABC algorithm is used to minimize the speed deviation to obtain the optimal set of input-output fuzzy logic scaling factors.

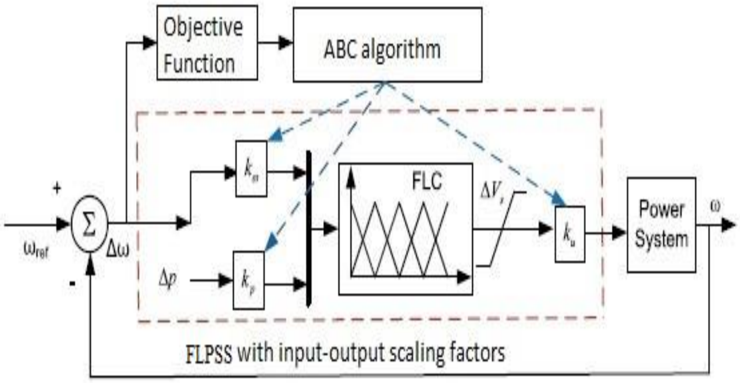


Figure 3.7: FLPSS Input-Output Scaling Factors Tuning Scheme using ABC Algorithm

CHAPTER 4

SIMULATION RESULTS and DISCUSSION

When dealing with the transient stability of power systems, the damping of power system oscillations is a very important factor, particularly when a disturbance occurs in the system. This work deals with the damping of oscillations in an SMIB power system and an MMPS system by using the proposed fuzzy logic PSS optimized by an ABC algorithm. Additional new support for PSS, even during severe disturbances, is also provided by the proposed fuzzy logic controller. ABC is also added to tune the scaling factors of the proposed FLPSS controller which will further enhance the damping of the oscillations.

In this work, the considered power systems have been modeled in a MATLAB SIMULINK environment and then a fuzzy logic controller has been designed as the power System stabilizer. Damping the transients of the synchronous generator is the aim of designing the fuzzy logic controller where the input power of the generator has been changed suddenly. The proposed ABC-FLPSS performance is also examined using simulation studies and the results validate the efficiency of the proposed controller.

4.1 Single-Machine Infinite Bus (SMIB) Power System

The performance of the proposed ABC-FLPSS controller is analyzed on an SMIB test power system using the MATLAB Simulink program. The test power system is equipped with an FLPSS along with an ABC optimization algorithm, as designed in the methodology. The tuning scheme is shown in Figure 3.9. The initializing parameters of the

ABC algorithm are selected based on a trial-and-error method. After several attempts, the initial parameters were found to be: the population size (number of food sources) and the number of employed bees is equal to 5, which is also equal to the number of onlooker bees, and the maximum number of iteration is found to be 20 iterations which terminates the optimization search process. The convergence of the ABC optimization algorithm in terms of objective function with the number of iterations is shown in Figure 4.1. In addition, the optimal set of input-output scaling factors using the ABC algorithm are listed in Table 4.1.

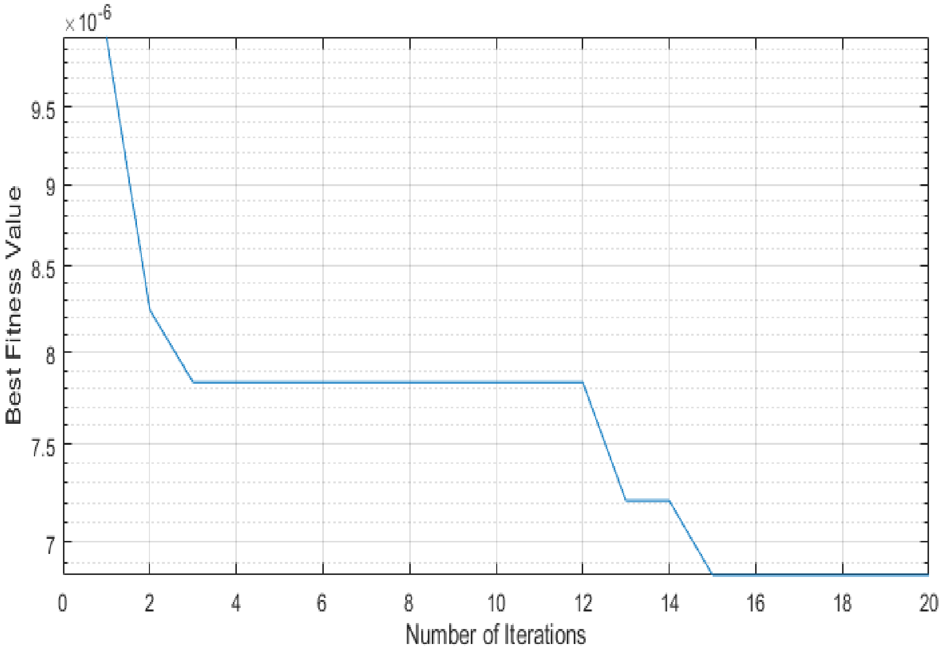


Figure 4.1: Objective Function Convergence of ABC Optimization Algorithm in SMIB

Table 4.1: Optimal Set of Input-Output FLPSS Scaling Factors using ABC Algorithm for SMIB Test Power System

Parameter	*Optimal Value*
K_ω	*2.2582*
K_p	*1.4528*
K_u	*2.0921*

The simulation is done under various levels of disturbances imposed on the system including:

- Changing the generator voltage reference (V_{ref}) for 12 cycles (0.2s).
- Single-phase fault on the transmission line.
- Three-phase fault on the transmission line.

4.1.1. Changing the Generator Voltage Reference

In this scenario, a small disturbance is considered in order to better understand of the behavior of the system with the proposed stabilizer. The system is simulated in the steady state operation for 1s, at T_{sim}=1s, 15% step increase of the generator voltage reference is imposed on the system for 12 cycles (0.2s). It is clear from the system responses that the system kept oscillating during the fault condition, and it stabilized during the post-fault condition. The proposed ABC-FLPSS design exhibited a superior damping for the system oscillations compared to the CPSS and the FLPSS without optimization in terms of a fast settling time with less overshoot, as shown in the following figures.

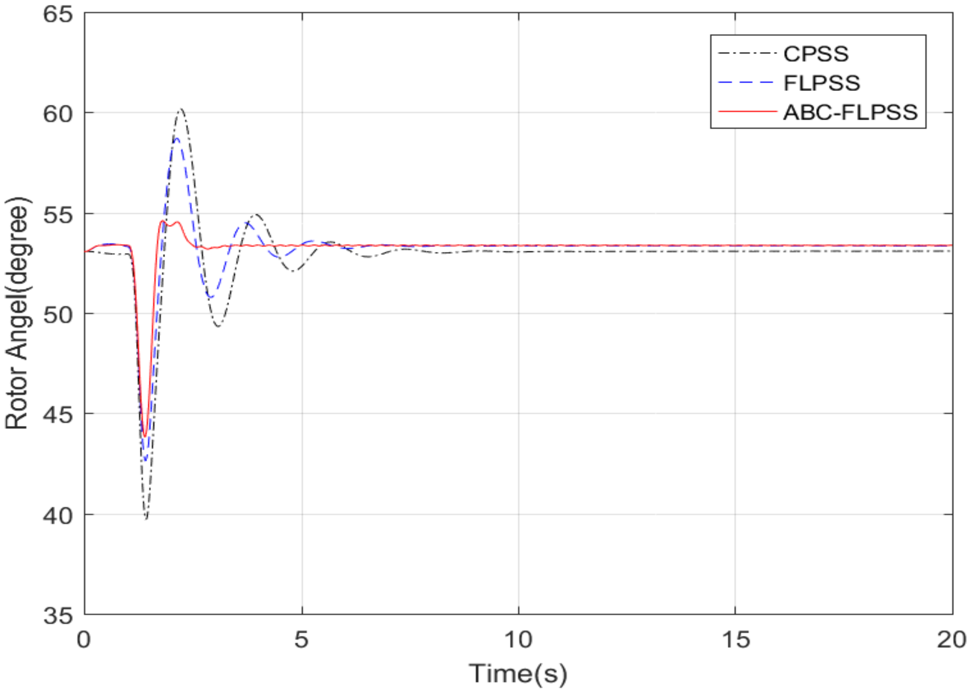


Figure 4.2: Rotor Angle Response with 15% Step Increase of V_{ref} in SMIB

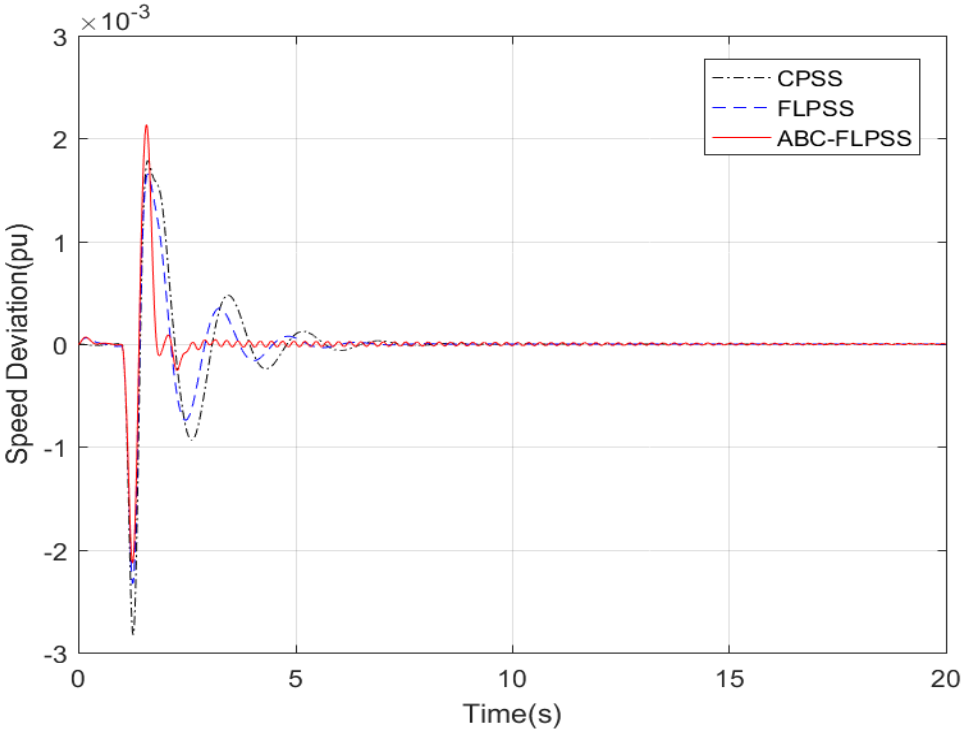


Figure 4.3: Rotor Speed Response with 15% Step Increase of V_{ref} in SMIB

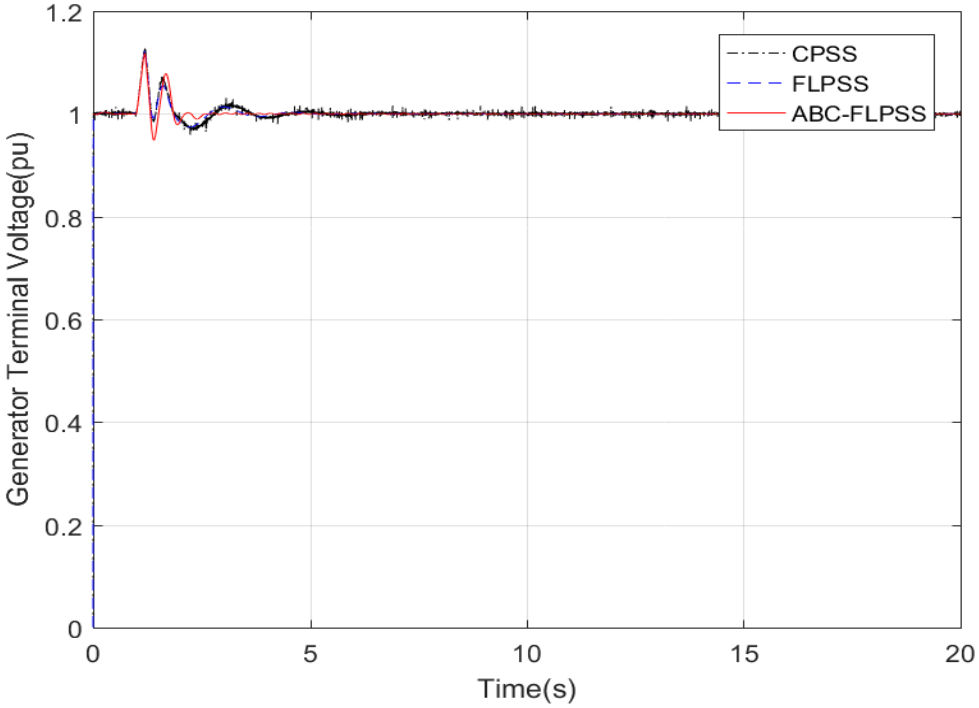


Figure 4.4: Terminal Voltage Response with 15% Step Increase of V_{ref} in SMIB

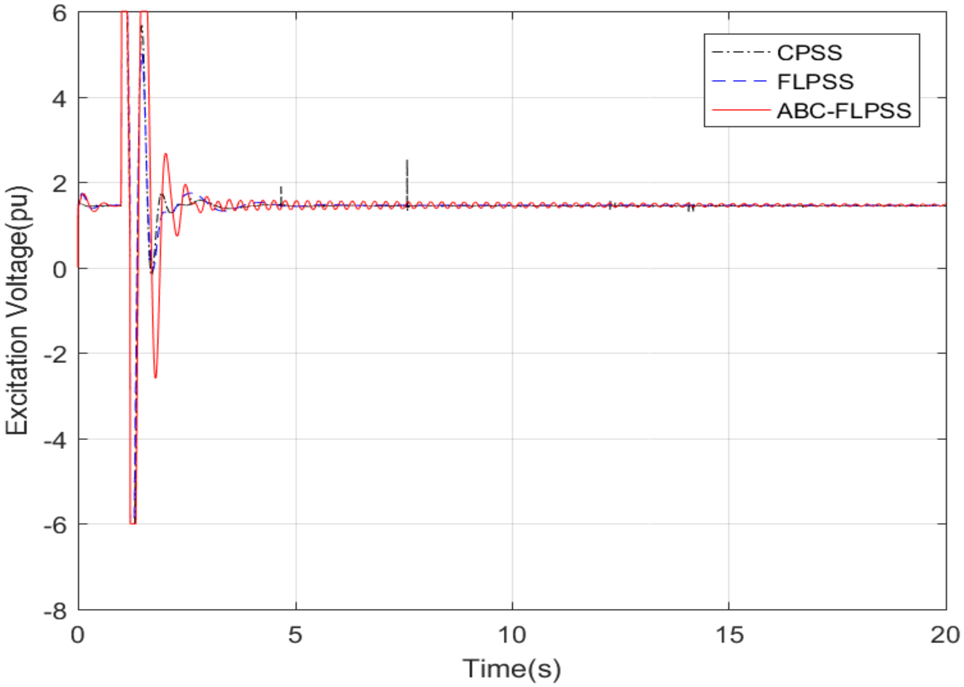


Figure 4.5: Control Effort with 15% Step Increase of V_{ref} in SMIB

4.1.2. Single-phase Fault on the Transmission Line

A single-phase fault is applied to the system by connecting phase (A) to ground for 12 cycles (0.2s) at T_{sim}=1s. Figure 4.6 shows the rotor angle response. This signal is a good indication of system stability. If it goes above 90° for too long a time, the system will lose its synchronism and become unstable. The same response was exhibited for the rotor speed as in Figure 4.7. In all system responses, the proposed ABC-FLPSS outperforms the other controllers and provides faster damping for the system oscillations.

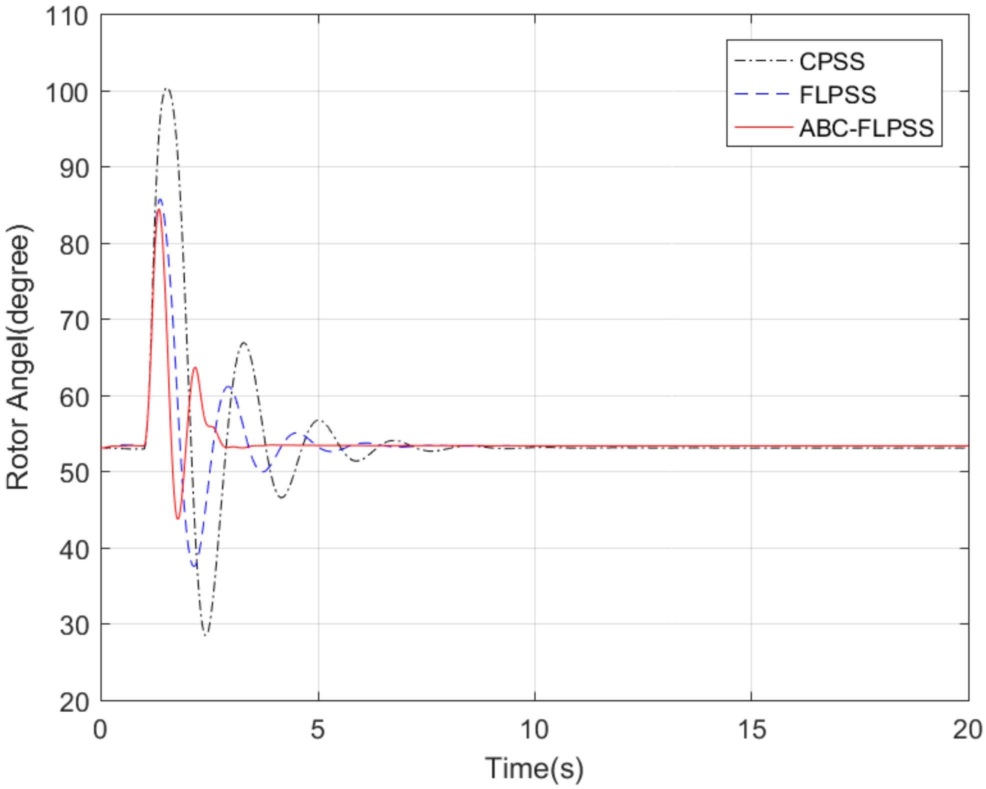


Figure 4.6: Rotor Angle Response with Single-Phase Fault on the Transmission Line in SMIB

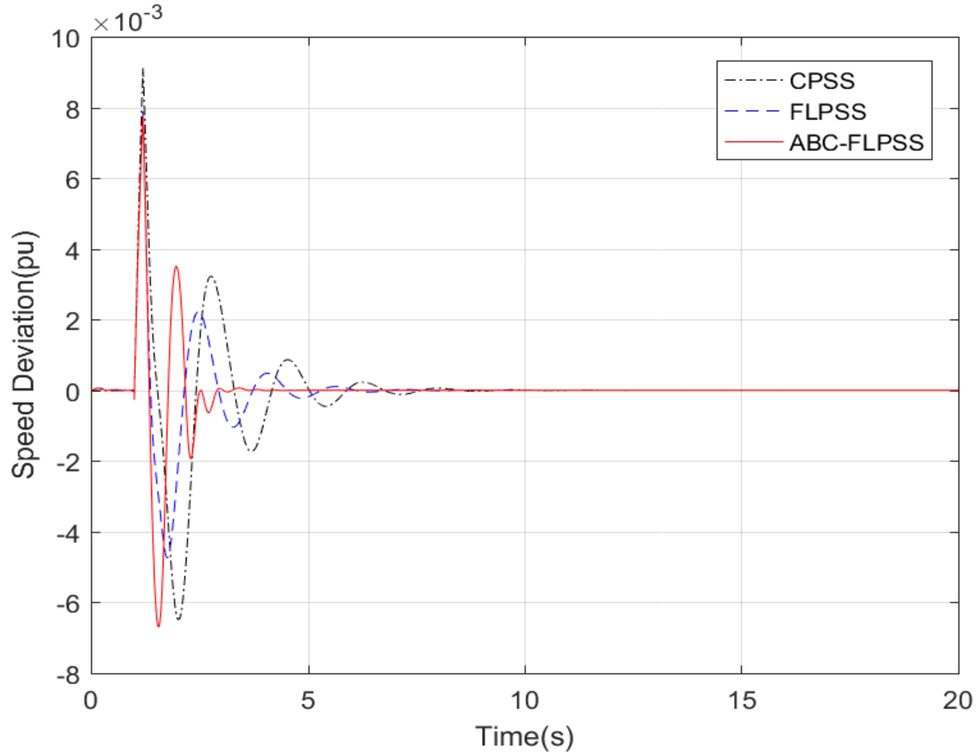


Figure 4.7: Rotor Speed Response with Single-Phase Fault on the Transmission Line in SMIB

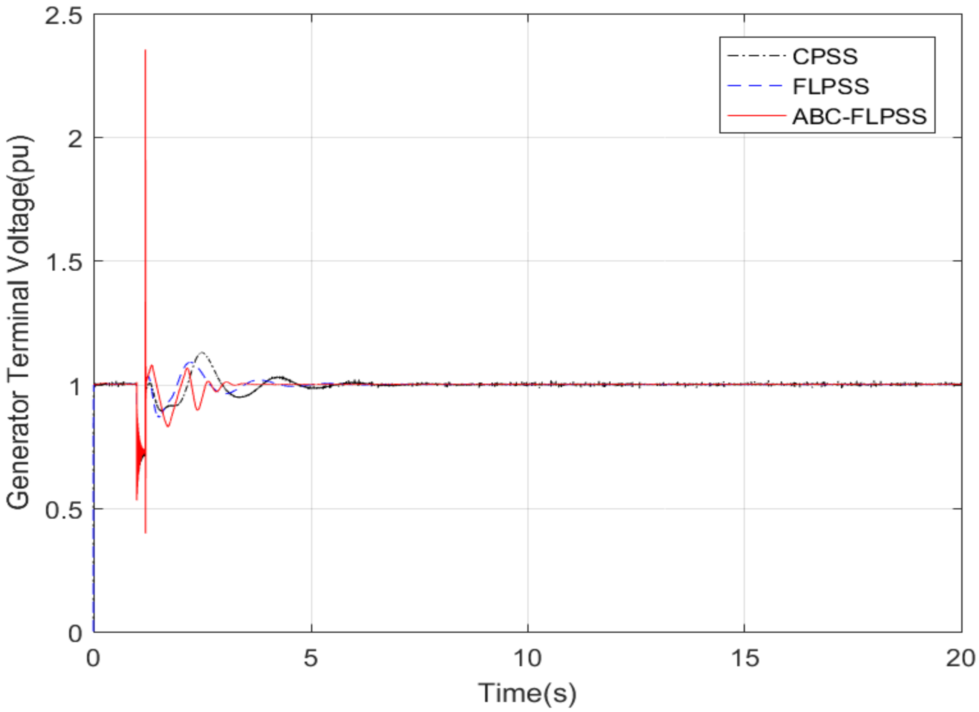


Figure 4.8: Terminal Voltage Response with Single-Phase fault on the Transmission Line in SMIB

4.1.3. Three-Phase Fault on the Transmission Line

A three-phase to ground fault is applied on the transmission line to observe the impact of the proposed ABC-FLPSS controller design for maintaining the system stability during a severe contingency. By looking at the rotor angle signal, if the fault is continuous for 6 cycles (0.1s), the system with CPSS quickly fall out of synchronism at ($T_{sim} = 2.140s$) and with the FLPSS at ($T_{sim} = 2.384s$), while it maintains the synchronism with the proposed ABC-FLPSS, as shown in Figure 4.9.

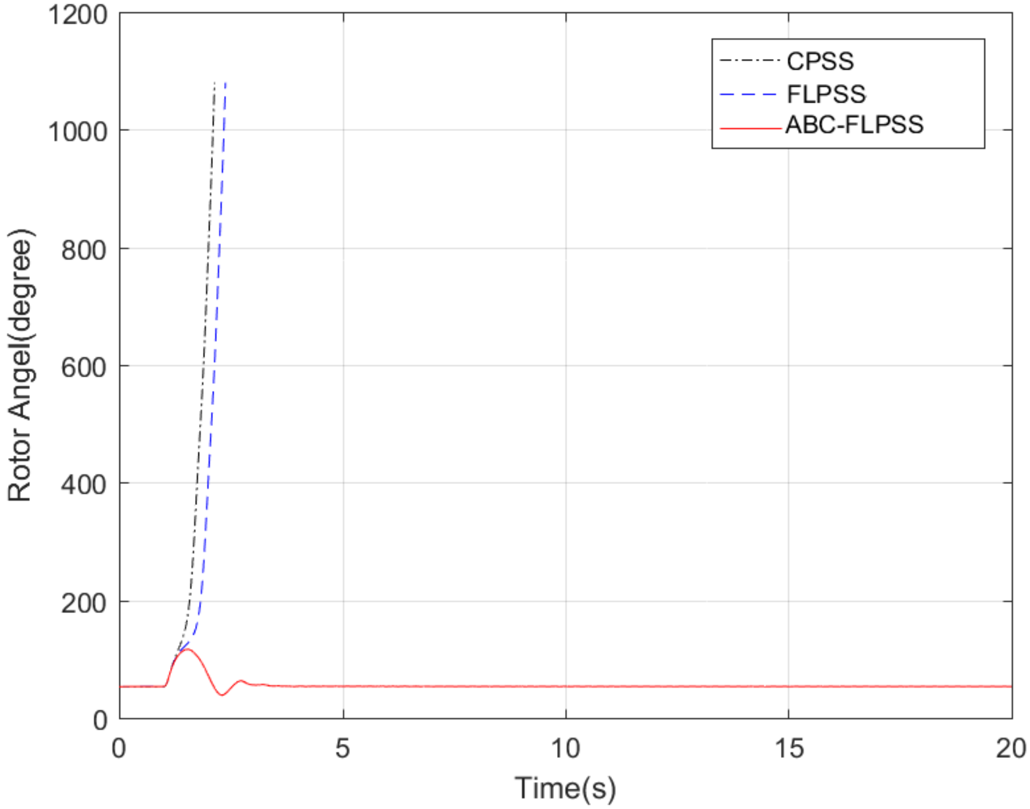


Figure 4.9: Rotor Angle Response with Three-Phase Fault on the Transmission Line in SMIB for (0.1s)

System responses with a three-phase fault on the transmission line are shown in the following Figures. By following a trial and error procedure, it was found that the fault critical clearing time for the system with CPSS is ($T_{sim} = 0.085s$) and with FLPSS is ($T_{sim} = 0.097s$), while it is ($T_{sim} = 0.100s$) with the proposed ABC-FLPSS. It is clearly shown that with the proposed ABC-FLPSS, the convergence is much faster than with CPSS and FLPSS which indicates that the proposed controller improves power oscillation damping and the transient stability of the system.

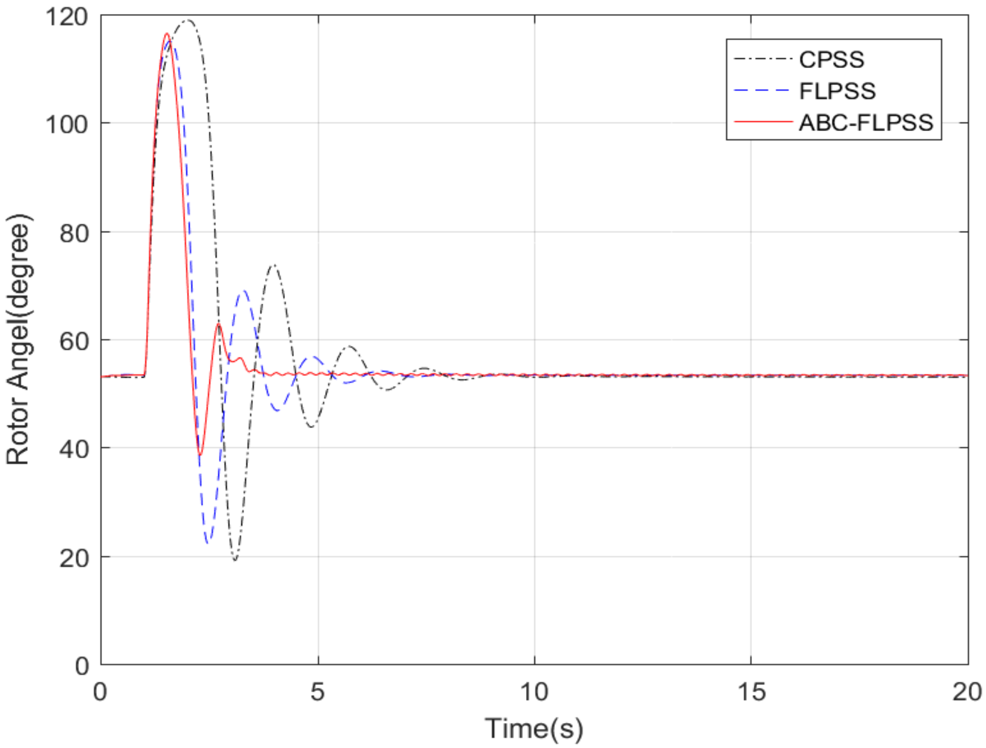


Figure 4.10: Rotor Angle Response with Three-Phase Fault on the Transmission Line in SMIB

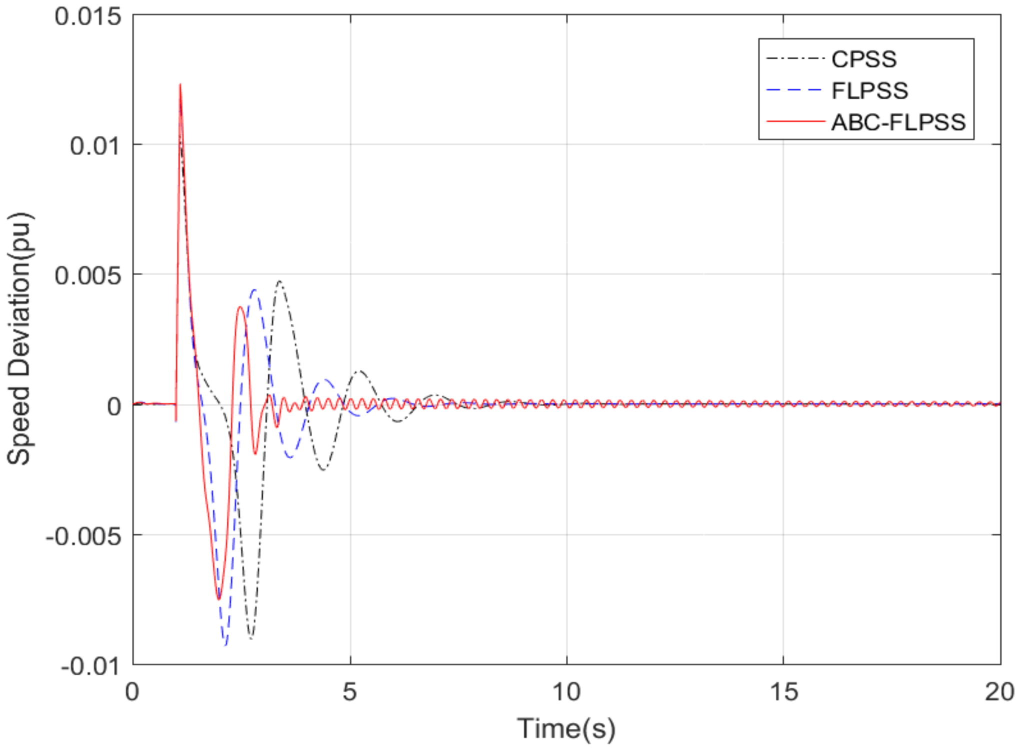


Figure 4.11: Rotor Speed Response with Three-Phase Fault on the Transmission Line in SMIB

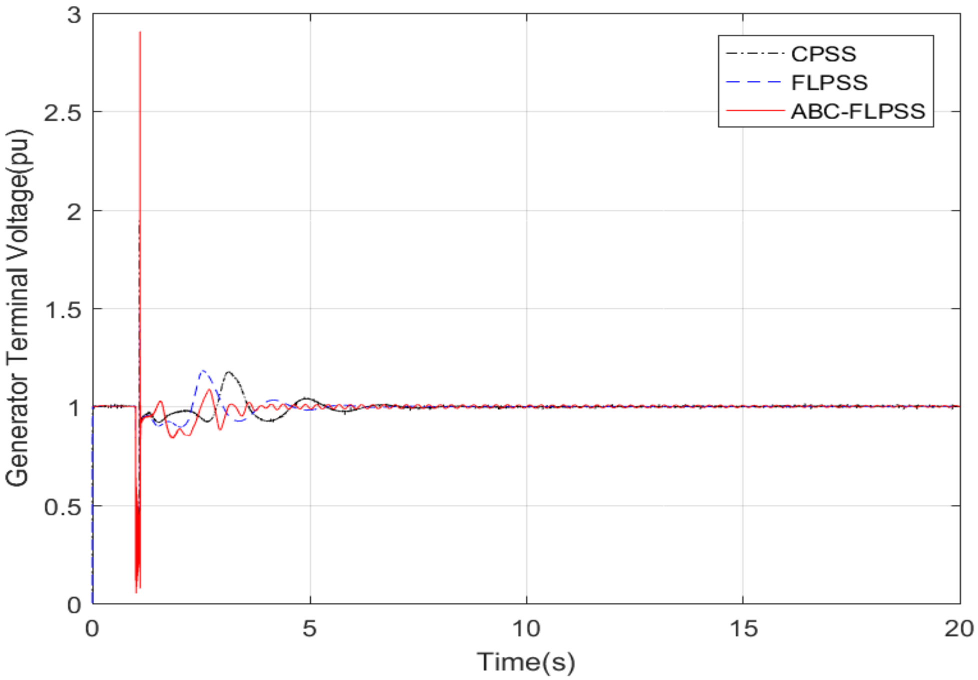


Figure 4.12: Terminal Voltage Response with Three-Phase Fault on the Transmission Line in SMIB

4.2 Multi-Machine Power System (MMPS) Power System

The performance of the proposed controller is analysed on a test power system with a 2-arae 4-machine 11-bus multi-machine power system to test its effectiveness. The system is consisting of two separated areas connected by two weak tie-lines, each area has two synchronous machines with considering generator two as a reference for the system as it is connected to an infinite bus. Despite its small size, this system mimics the behaviour of typical power systems in practical operation as shown in Figure 3.3. Parameters and more information about the test system can be found in [1].

The test power system is equipped with FLPSS along with input-output scaling factors optimized by the ABC algorithm as designed in the methodology, the tuning scheme is shown in Figure 3.9. The initializing parameters for the ABC algorithm are selected based on a trial-and-error method. After several attempts, the initial parameters were found to be: the population size (number of food sources) and the number of employed bees is equal to 5 which is also equal to the number of onlooker bees, and the maximum number of iteration is found to be 50 iterations which terminates the optimization search process. The parameter bounds for all input-output FLPSS scaling factors are considered the same as $1 \leq K_{\omega i}\,,\; K_{pi}\,, K_{ui} \geq 3$. The convergence of the ABC optimization algorithm in terms of objective function with the number of iterations is shown in Figure 4.13. In addition, the optimal set of input-output scaling factors using the ABC algorithm are listed in Table 4.2.

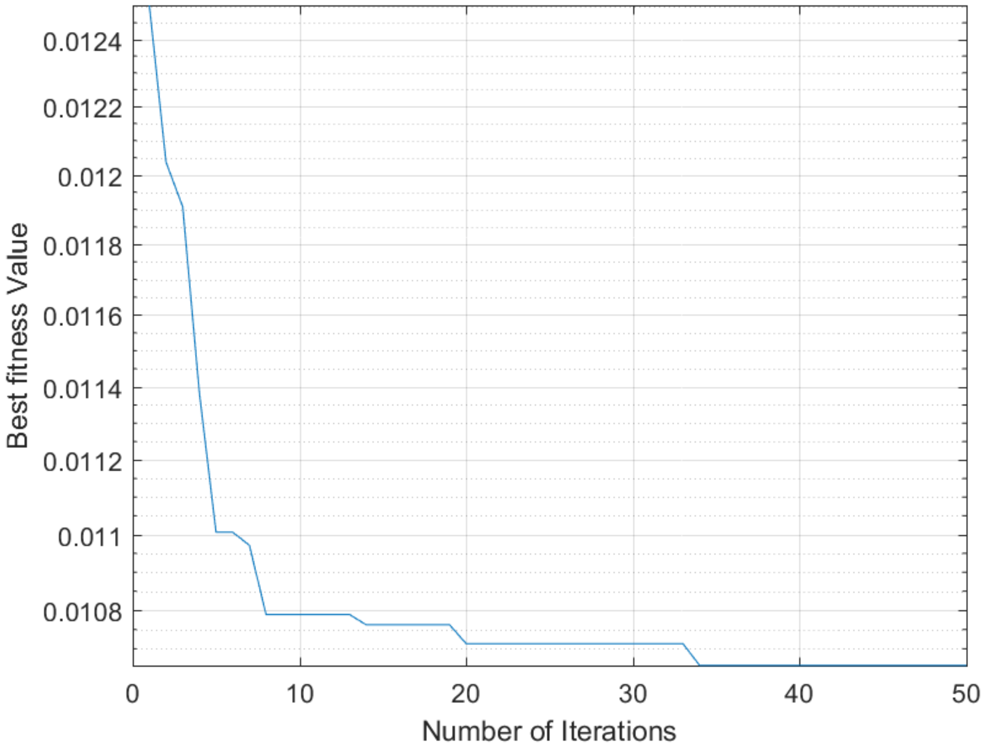


Figure 4.13: Objective Function Convergence of ABC Optimization Algorithm in MMPS

Table 4.2: Optimal Set of Input-Output FLPSS Scaling Factors using ABC Algorithm for MMPS Test Power System

Generator / Parameter	G1	G2	G3	G4
$K_{\omega i}$	1	1.0170	1.0495	2.4589
K_{pi}	1.6657	1.3569	3	1.3075
K_{ui}	1.1488	1.0150	1.7374	1.4932

The simulation is done under various disturbance imposed on the system including:

- Changing the voltage reference of generator 1 (G1)
- Three-phase fault at the terminal of generator one

- Three-phase fault at the middle of line1 between bus-7 and bus-8
- Changing the input mechanical power of generator three
- Removing one of the two parallel lines connected the two areas

In all the above scenarios, the system is simulated from (0-1s) in the steady state operation, then the disturbance is imposed to the system at t=1s for (0.2s). a comparison between the proposed controller and a conventional power system stabilizer as proposed in [1] has been done.

4.2.1. Changing the Voltage Reference of Generator 1

In this scenario, a small disturbance is considered to better understand the behaviour of the system with the compared power system stabilizers. Where a step of 5% is applied to the voltage reference of generator 1 for 12 cycles (0.2 s). It is clear from the following Figures that the system is stabilized during the post-fault condition, and it keeps oscillating during the fault condition, while it maintains the stability with the use of power system stabilizers and the ABC-FLPSS controller has a small superiority over the CPSS and the fixed parameters FLPSS controllers.

The speed deviation and rotor angle responses of G1 and G3 are shown in Figures (4.15, 4.16), respectively. It is clearly shown that with ABC-FLPSS the convergence of the dynamical responses is much faster than with the CPSS and the fixed parameter FLPSS in terms of settling time and overshot.

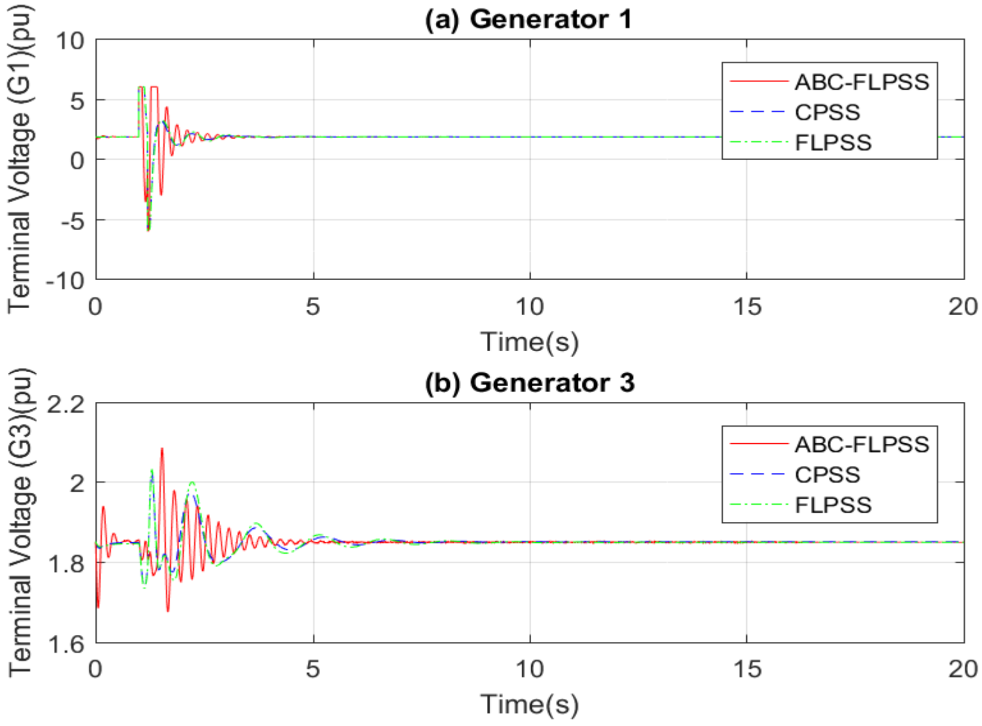


Figure 4.14: Terminal Voltage of G1 with a 5% Increase of Voltage Reference of G1

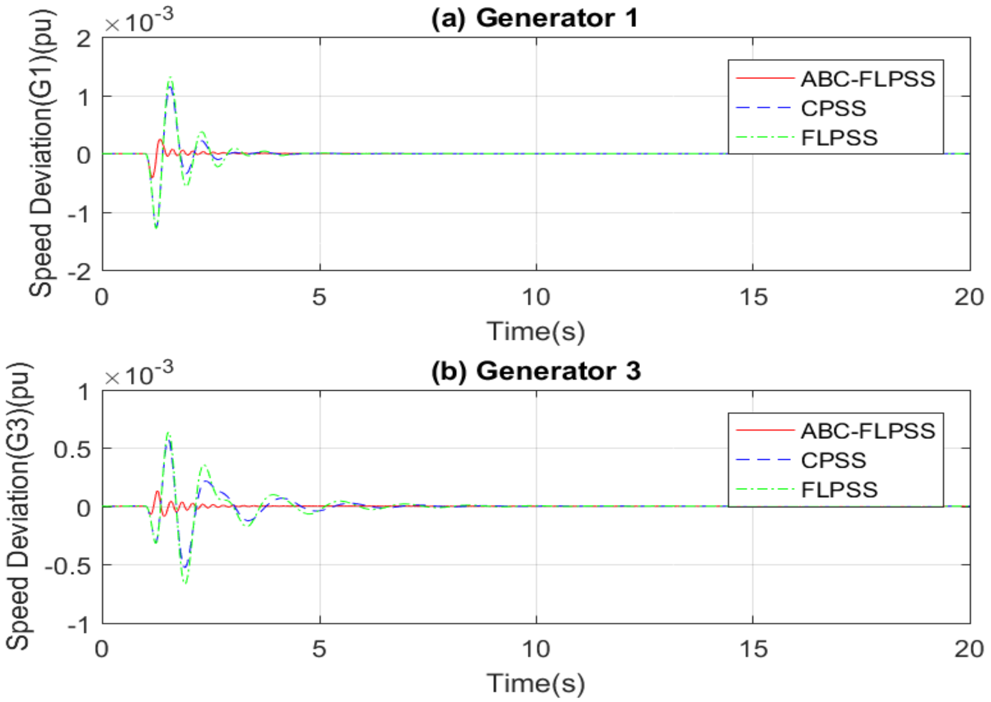


Figure 4.15: Speed Deviation of G1 with a 5% Increase of Voltage Reference of G1

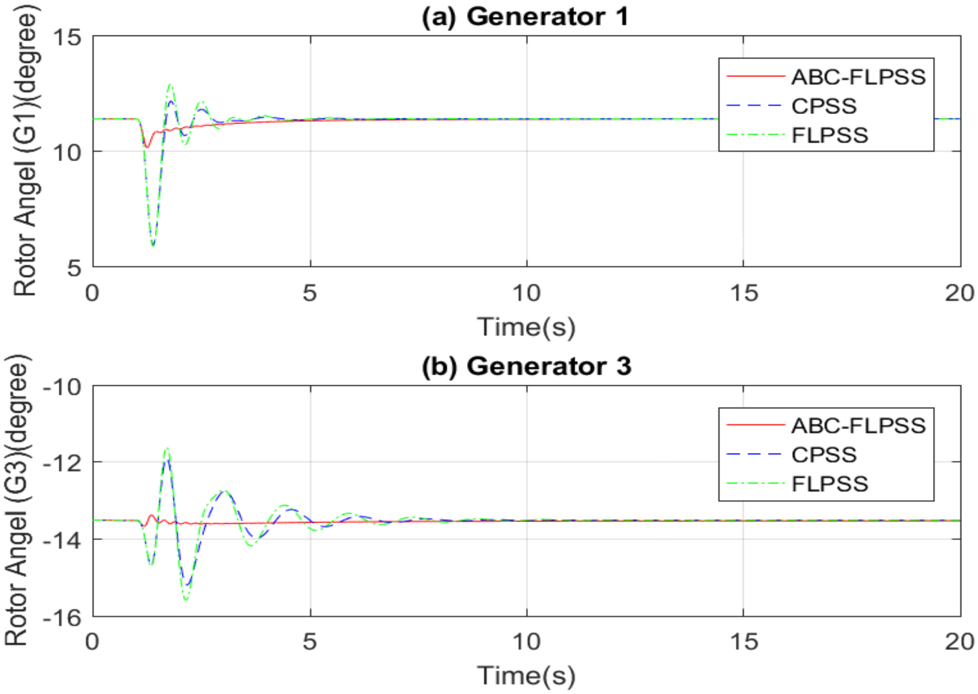


Figure 4.16: Rotor Angle of G1 with a 5% Increase of Voltage Reference of G1

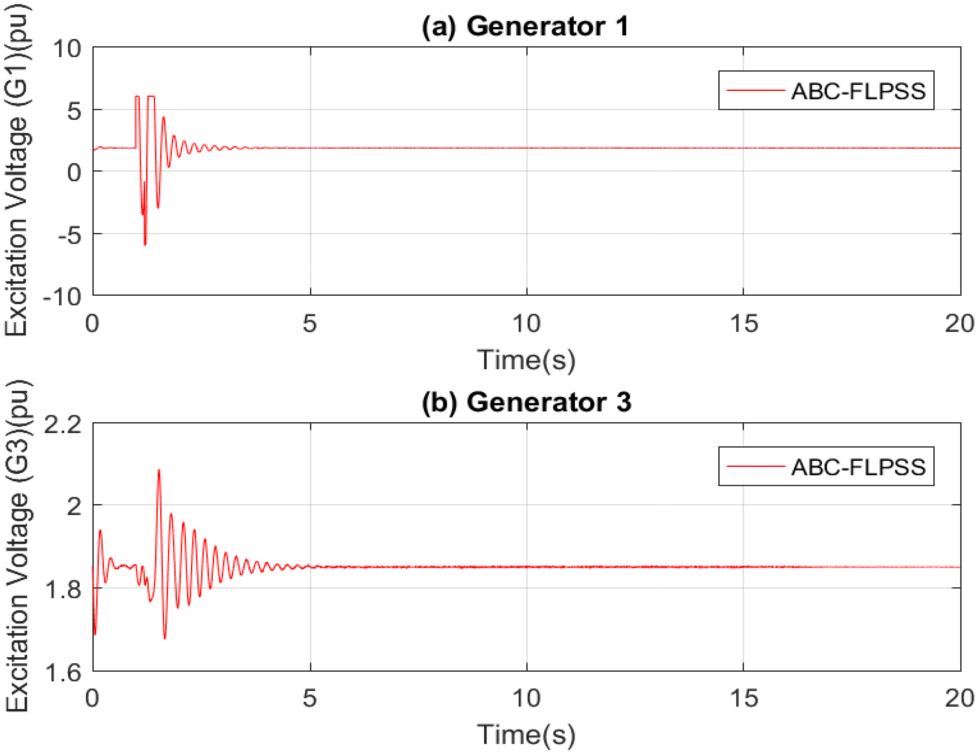


Figure 4.17: Control Inputs with a 5% Increase of Voltage Reference of G1

4.2.2. Three-phase Fault at the Terminal of Generator 1

This scenario considered the most critical situation, where a three-phase fault is applied at the terminal of generator 1 for 12 cycles. During the fault condition, the terminal voltage of generator 1 goes to zero and settles down to the pre-fault condition after the fault is removed by adding a supplementary voltage signal from the PSSs as in Figure 4.18. Also, the terminal voltage of generator 3 is disturbed and stabilized at the pre-fault condition.

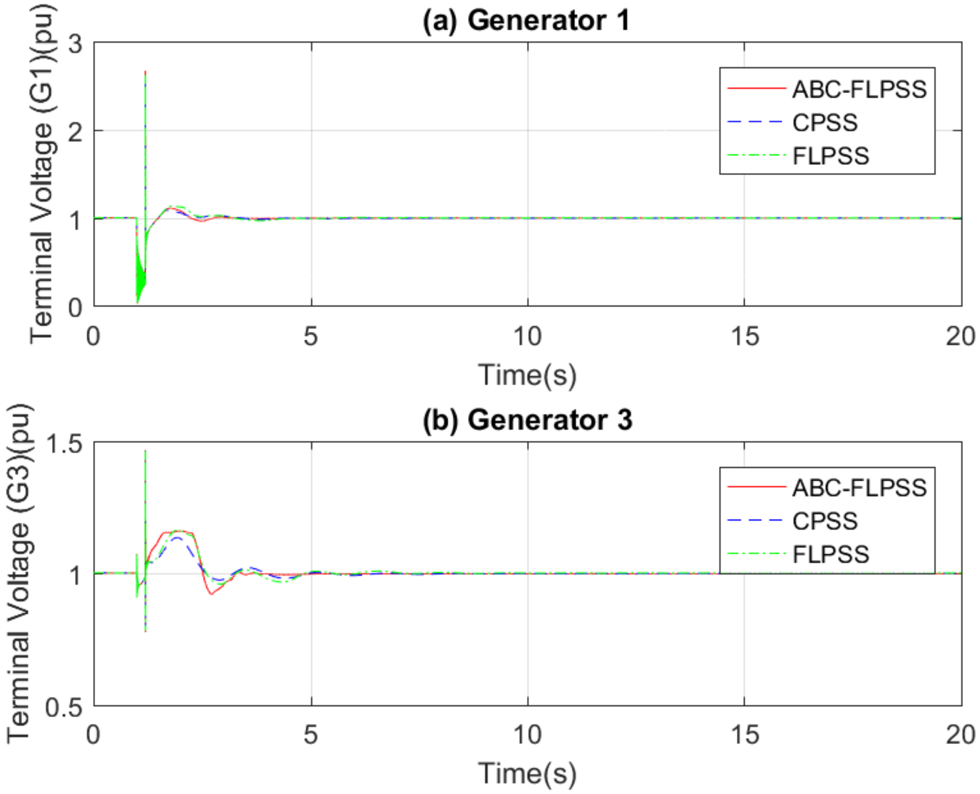


Figure 4.18: Terminal Voltages with Three-Phase Fault at the Terminal of Generator 1

The corresponding speed deviation response and rotor angle response of G1 and G3 are shown in Figure 4.19 and Figure 4.20. From Figure 4.19, obviously all controllers achieve zero speed deviation during the post-fault condition. However, during-fault condition the proposed ABC-FLPSS has a better response than the other controllers which indicates the superiority of the proposed ABC-FLPSS. This superiority can also be seen from the rotor angle responses of G1 and G3 as shown in Figure 4.20.

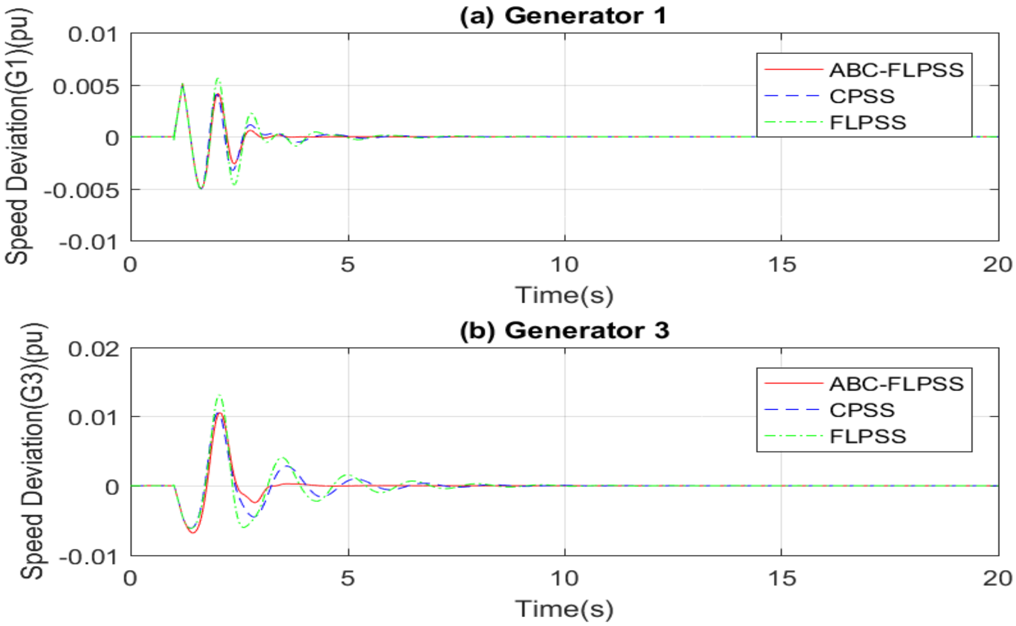


Figure 4.19: Speed Deviations with Three-Phase Fault at the Terminal of Generator 1.

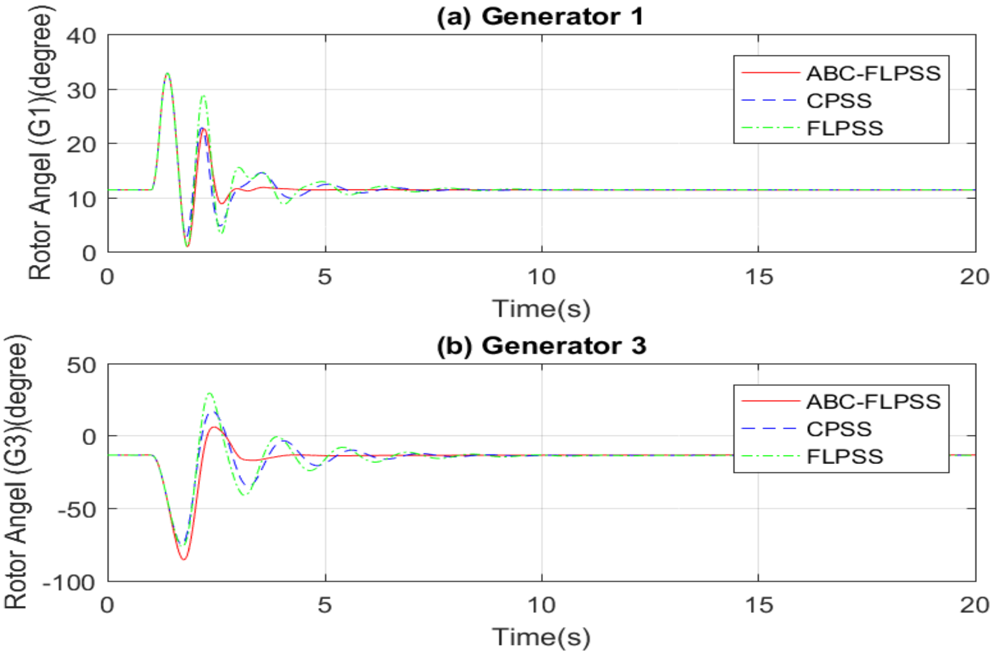


Figure 4.20: Rotor Angles with Three-Phase Fault at the Terminal of Generator 1

It is clear from the above Figures that the performance of the proposed controller is much better than the other controllers, especially, in damping the inter-area oscillation between generator 2 in the first area and generator 3 in the second area.

The control efforts (excitation voltages) EFD1 and EFD3 are shown in Figure 4.21. The ABC-FLPSS controller applied large control efforts in order to bring the system to equilibrium as quickly as possible. It is seen that all the inputs are stayed within the constraints $(-6 \leq EFD \leq 6)$ as stated in [1].

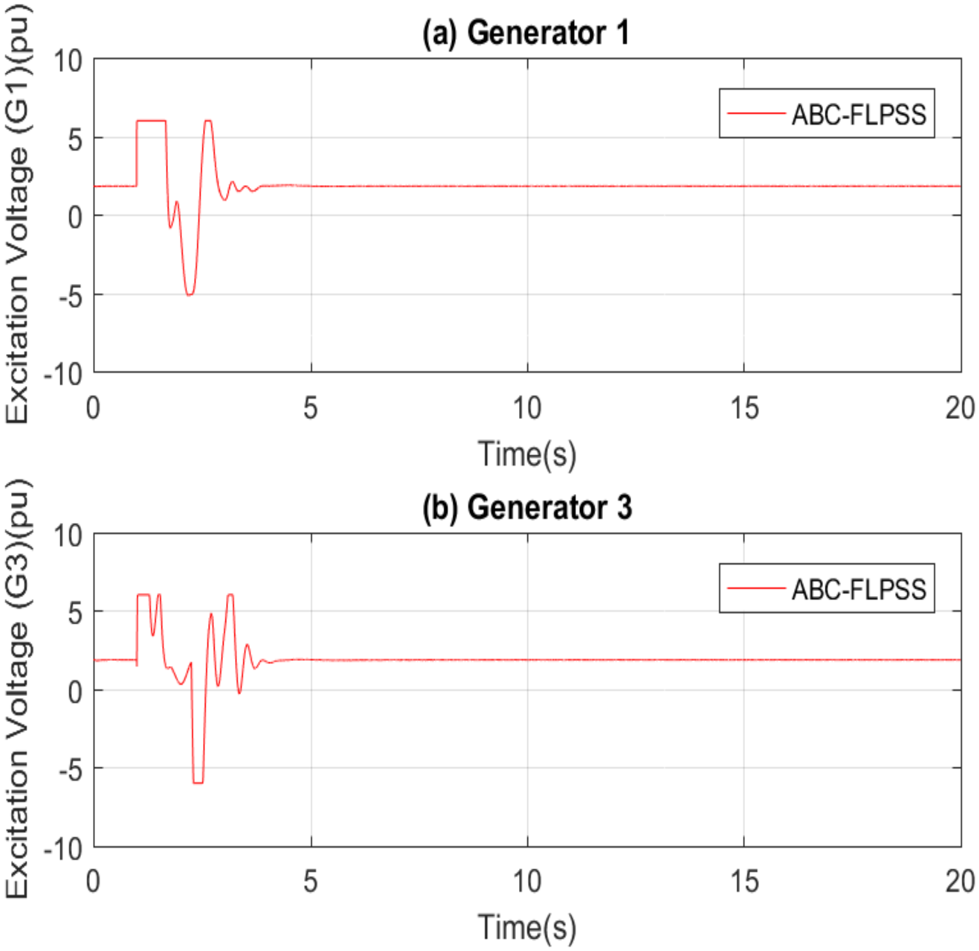


Figure 4.21: Control Inputs with Three-Phase Fault at the Terminal of Generator 1

4.2.3. Three Phase Fault at the Middle of Transmission Line 1

In this scenario, a three-phase to ground fault is applied on the middle of transmission line1 between bus 7 and bus 8, as this is one of the key transmission lines to transfer power from area 1 to area 2. Figure 4.22 shows the terminal voltage responses of G1 and G3 with the CPSS, the FLPSS and the proposed ABC-FLPSS, where the proposed ABC-FLPSS settles down to its pre-fault condition earlier than the other controllers.

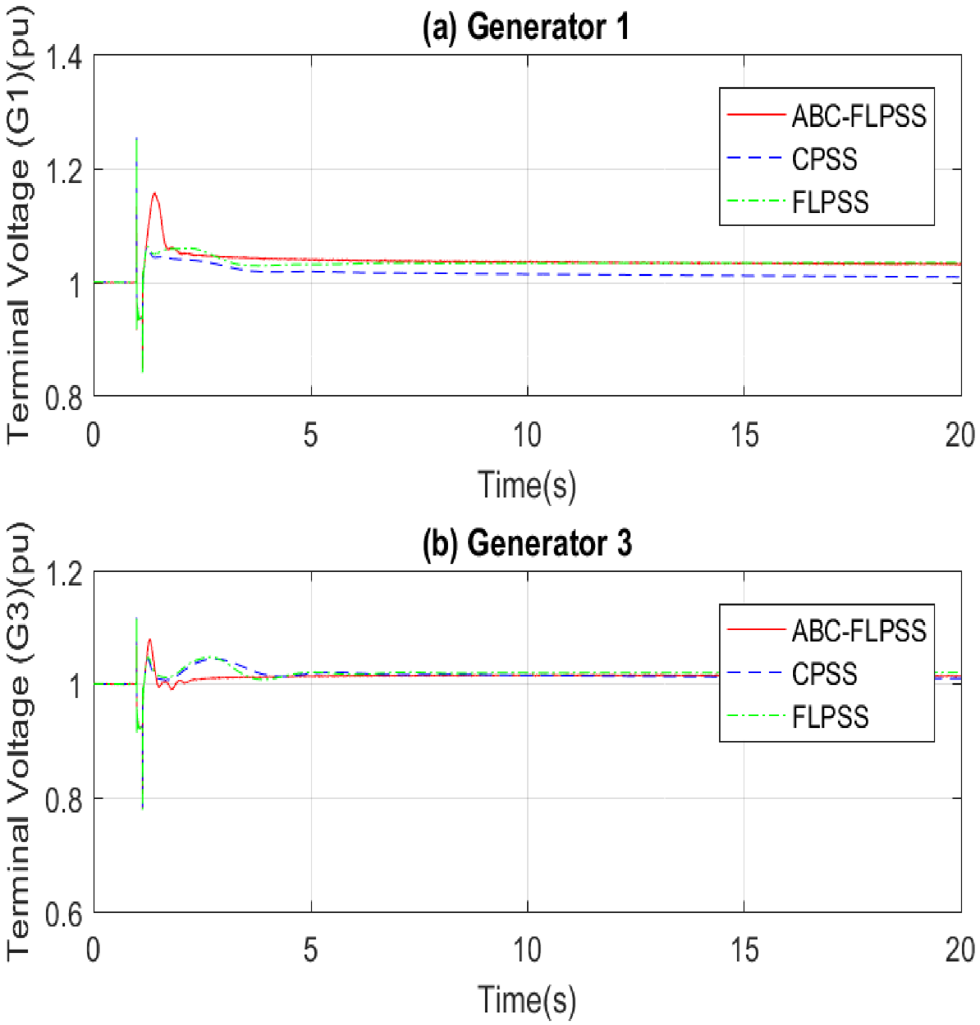


Figure 4.22: Terminal Voltages with Three-Phase Fault at the Middle of Transmission Line 1

The speed deviation and rotor angle responses of G1 and G3 are shown in Figure 4.23 and Figure 4.24, respectively. It is clearly shown that with ABC-FLPSS the convergence is much faster than with CPSS and FLPSS.

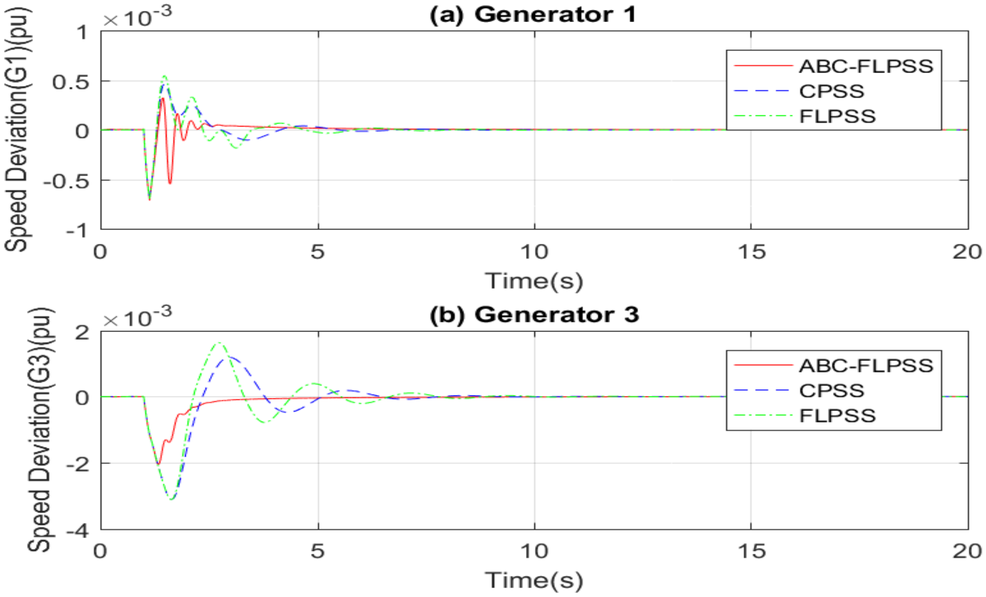


Figure 4.23: Speed Deviations with Three-Phase Fault at the Middle of Transmission Line 1

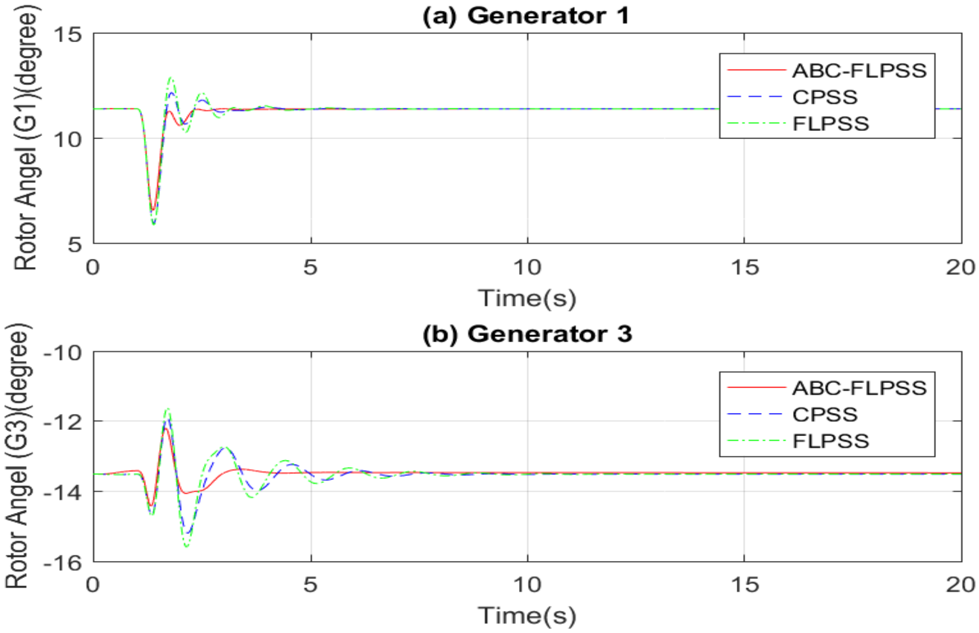


Figure 4.24: Rotor Angles with Three-Phase Fault at the Middle of Transmission Line 1

Also, the control signal is within the limits:

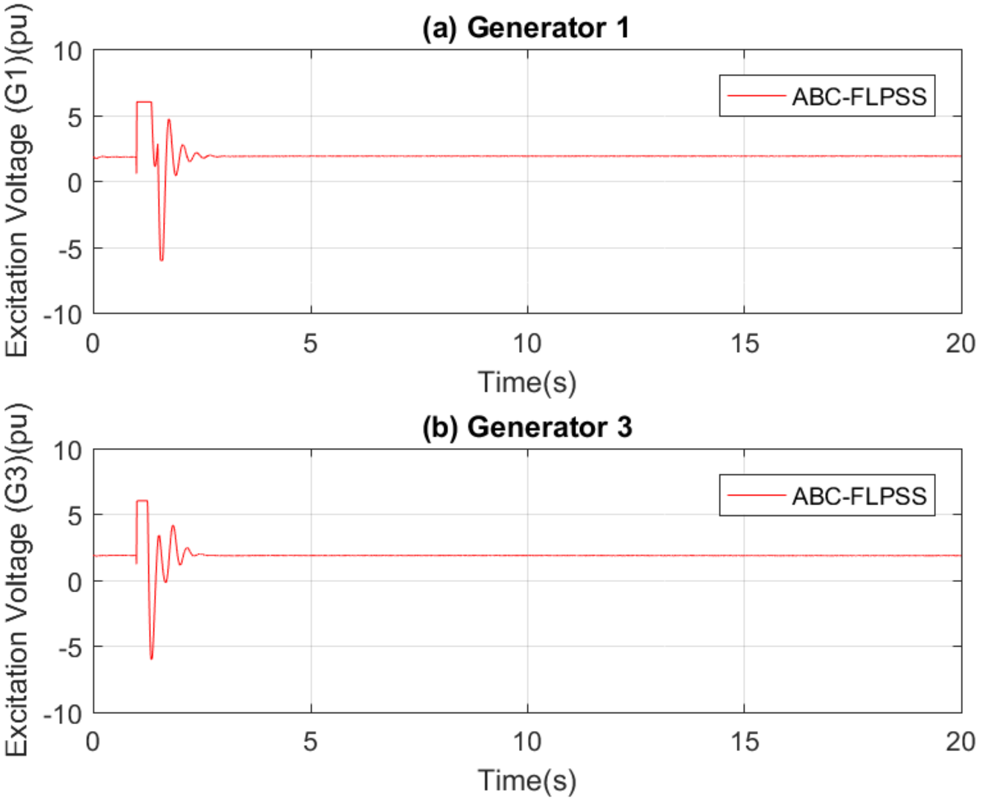


Figure 4.25: Control Inputs with Three-Phase Fault at the Middle of Transmission Line1

4.2.4. Changing the Input Mechanical Power of Generator 3

In this scenario, the disturbance is imposed on the test power system by changing the input mechanical power of G3 at T_{sim}=1s from 0.8 pu to 0.9 pu for a period of 10s and it returns back to its nominal value at T_{sim}=11s. This scenario simulates the changes in the electrical loads of the power system under practical operation which affects the output electrical power and consequently the input mechanical power of the synchronous generators.

Changing the nominal parameters of the power system will shift the power system to operate on another operating point as will be seen in the system mechanical responses. From Figure 4.26 of the terminal voltages of G1 and G3, the system is shifted to a new equilibrium point when the input mechanical power is changed and the proposed ABC-FLPSS behaves much better in damping the system oscillations than the other controllers. The response of the CPSS is very bad and this is expected, because CPSS is designed based on linearizing the system around a specific equilibrium point and it will not behave correctly when this equilibrium point is changed.

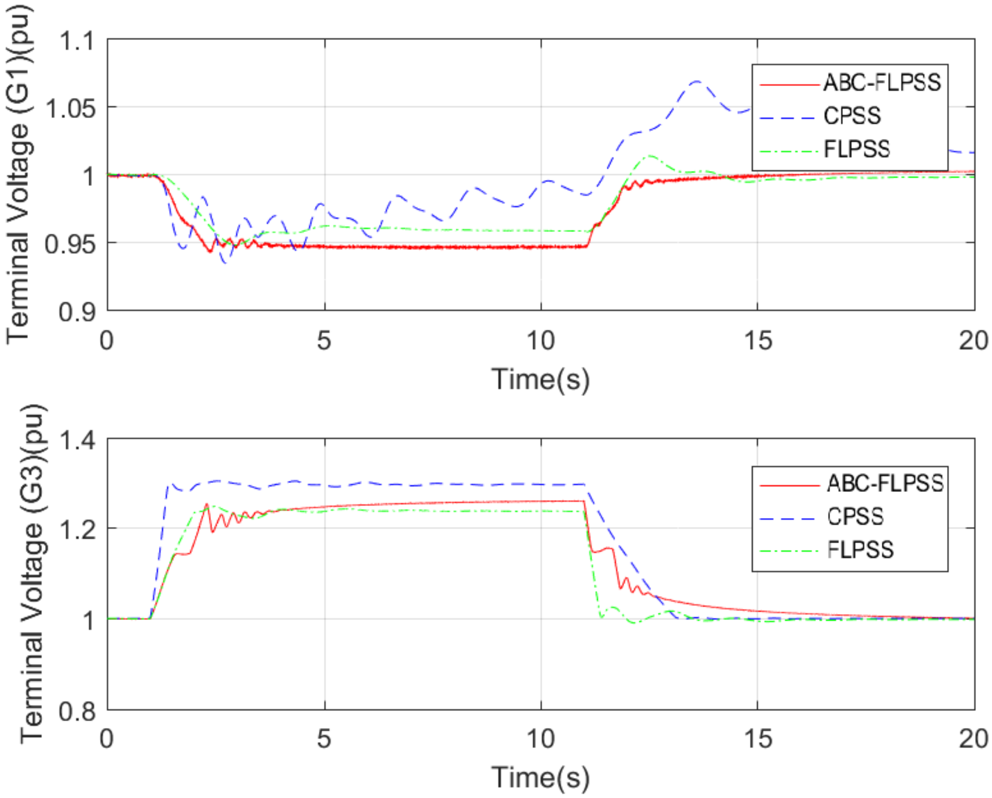


Figure 4.26: Terminal Voltages with Changing the Input Mechanical Power of G3

The rotor speed deviations of G1 and G3 are shown in Figure 4.27. Under this scenario, the convergence speed with ABC-PSS is not comparable with CPSS. Also, the rotor angle response demonstrates superior behavior and the rotor angle of G3 is settled to a new equilibrium point faster than with the other controllers as in Figure 4.28.

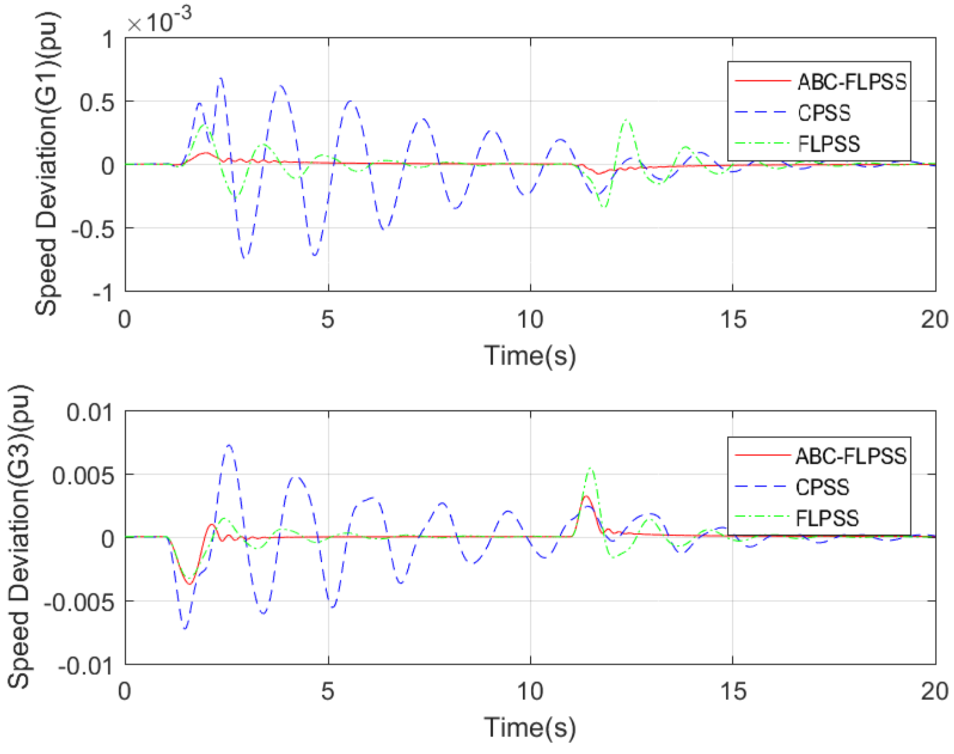


Figure 4.27: Rotor Speed Response with Changing the Input Mechanical Power of G3

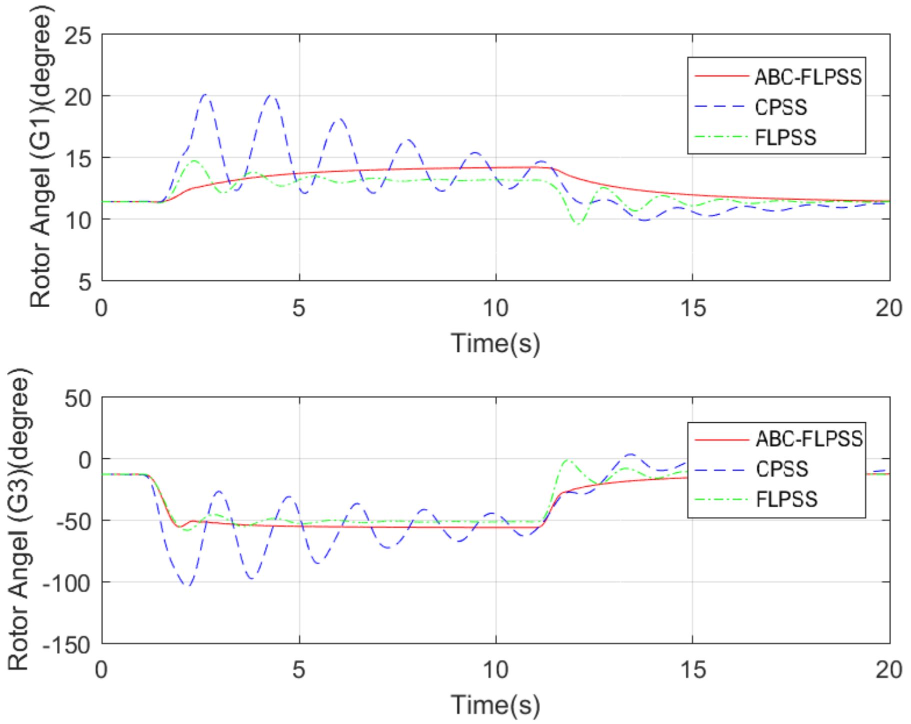


Figure 4.28: Rotor Angle Response with Changing Input Mechanical Power of G3

4.2.5. Removing One of the Two Parallel Transmission Lines

For further evaluation of the proposed ABC-FLPSS controller, the simulation is done under a sever situation by permanently removing Line 1 between bus 7 and bus 8 that connects area 1 with area 2. As shown in the following Figures, the system is shifted to a new operating condition and becomes very stressed. In this situation, after the occurrence of the fault, all the power will flow through transmission line 2 as in Figure 4.29. It clearly shows the effectiveness of the proposed ABC-FLPSS compared to the CPSS in damping inter-area oscillations and improving the transient stability and power transfer limit.

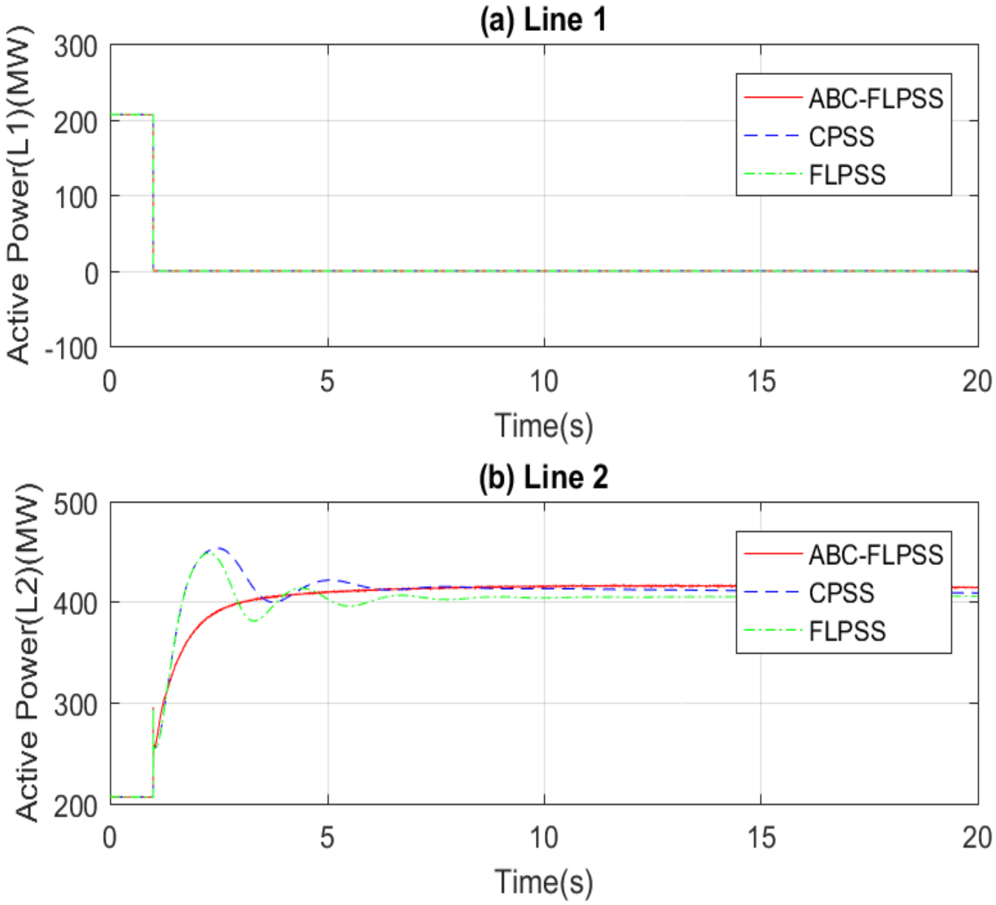


Figure 4.29: Active Power Flow with Removing Line 1 between Bus 7 and Bus 8

The dynamic responses (terminal voltages, speed deviation and rotor angle) of the system settle down to a new equilibrium point with the ABC-FLPSS faster than the other controllers.

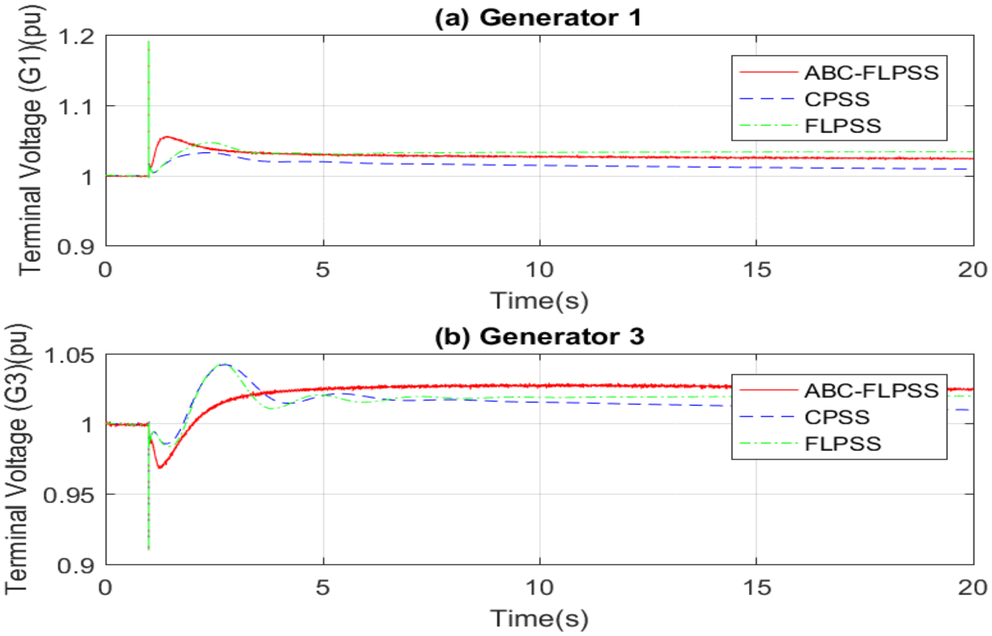


Figure 4.30: Terminal Voltages with Removing Line 1 between Bus 7 and Bus 8

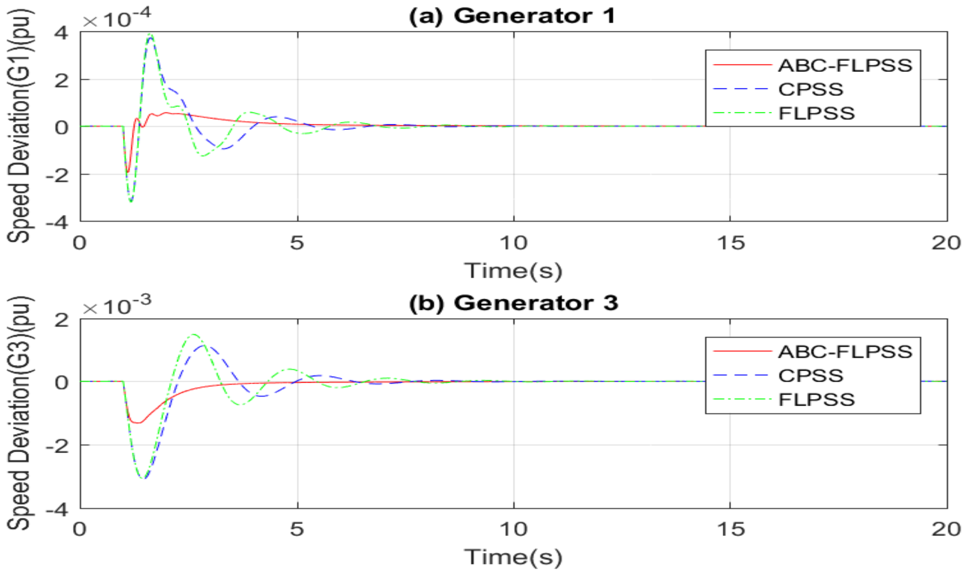
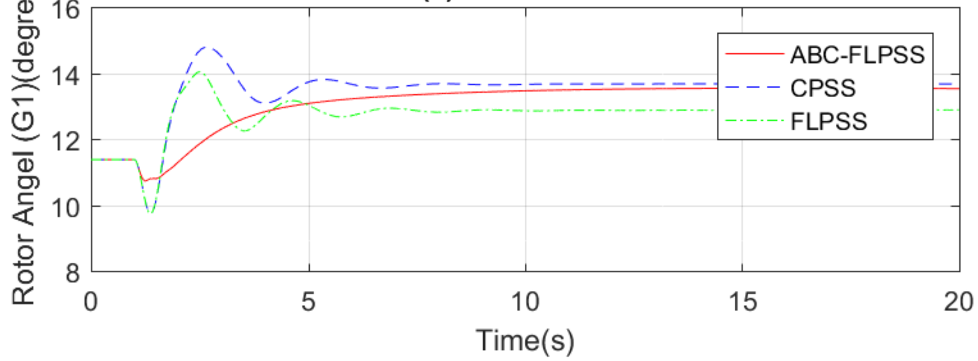


Figure 4.31: Speed Deviations with Removing Line 1 between Bus 7 and Bus 8

(a) Generator 1



(b) Generator 3

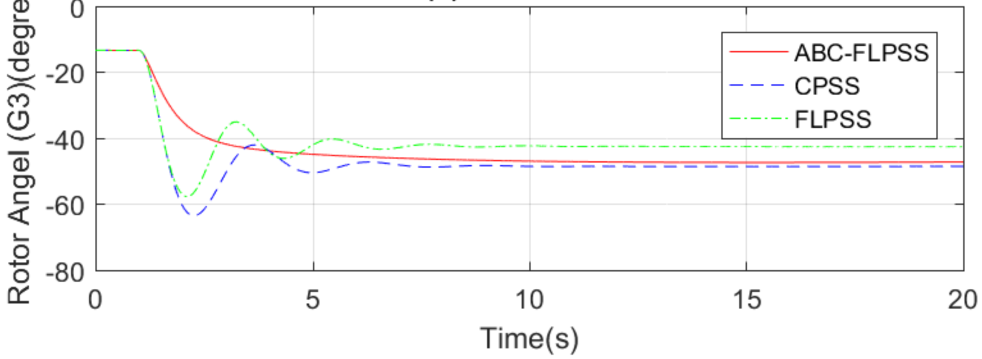


Figure 4.32: Rotor Angles with Removing Line 1 between Bus 7 and Bus 8

CHAPTER 5

CONCLUSION and RECOMENDATION

5.1 CONCLUSION

In conclusion, fuzzy logic controllers are suitable for nonlinear dynamical systems where they can handle the system uncertainties, unlike classical controllers that require exact mathematical modeling and measurements. In this thesis, an Artificial Bee Colony optimization technique is used to optimize the input-output scaling factors of a fuzzy logic PSS to enhance the transient stability of power systems. The proposed controller is compared with a conventional power system stabilizer by studying the nonlinear time-domain simulation of the generator rotor angle and speed. Simulation results showed clearly that the proposed ABC-FLPSS is superior when compared to the CPSS in damping power system oscillation and improving the transient stability and the robustness of multi-machine power systems when they are subjected to external disturbances. The ABC-FLPSS showed superior fast damping performance under both small and large disturbances, even with changes in the system operating conditions. The superior damping performance is clearly demonstrated in the damping of the inter-area oscillation.

5.2 RECOMMENDATION

This work can be further extended in several ways:

1. The proposed ABC optimization algorithm can be used with other objective

functions rather than the ISE such as the Integral of the Absolut value of Error (IAE) and the Integral of the Time weighed Absolut Error (ITAE).

2. The FLPSS can be designed with other inputs and rules, where these rules can be generated automatically using any optimization technique.

3. The input-output fuzzy logic scaling factors can be optimized with different algorithms and compared with the ABC algorithm.

4. The simulation can be done with other scenarios for further investigation of the proposed ABCFLPSS controller such as loss of one generator.

5. The proposed ABCFLPSS can be applied to a larger power system with more machines.

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Vitae

Name: ABDULLAH MOHAMMED SALEM BARAEAN.

Nationality: YEMENI.

Date of Birth: 6/15/1989

Email: sugratt@gmail.com.

Mobile: +966533952438.

Address: Yemen/Hadhramout/AL-Mukalla.

Academic Background:

- M.S in Electrical Engineering, March 2018

  King Fahd University of Petroleum and Minerals

  Dhahran, Saudi Arabia.
- B.S in Electronic and Communication Engineering, April 2013

  Hadhramout University for Science and Technology

  Hadhramout, Republic of Yemen.

Work Experience:

- Electrical Engineer trainee at Arab Iron & Steel Corporation (AISCO)

  April 2014-august 2014

  Aden, Yemen.

- PLC Trainee at ARABIAN YEMEN CEMENT COMPANY

  July 2013-july 2013

  Hadhramout, Yemen.

Publications:

- Abdullah M. Baraean and Hussain N. Al-Duwaish, "Coordinated Design of a Fuzzy Logic Power System Stabilizer and an SVC-based Stabilizer for Single-Machine Infinite-Bus Power System" *in the 5th International Conference on Control, Decision and Information Technologies,* April, 2018, Thessaloniki, Greece (Accepted).
- Abdullah M. Baraean and Hussain N. Al-Duwaish, " Optimal Design of a Fuzzy Logic Power System Stabilizer based on an Artificial Bee Colony Algorithm for Multimachine Power Systems" , (in progress)