MULTIMACHINE POWER SYSTEM STABILIZER FOR A LOCAL INDUSTRIAL PLANT: MODELING AND OPTIMIZATION

BY

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DEDICATION

For my family,

Who supported me on each step of the way.

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In the Name of Allah, the Beneficent, the Merciful

All gratitude, glory and praise be to Allah Al Qadeer who said in the Holy Qura'n "*And say, my Lord increase me in knowledge*.'' (Taha, 20:114) and peace and blessings of Allah be upon his last prophet Mohammed.

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NOMENCLATURE

Abbreviation

(PSS)	Power System Stabilizer
(AVR)	Automatic Voltage Regulator (AVR)
(CPSS)	Conventional Lead-Lag
(TGR)	Transient Gain Reduction
(SISO)	Single Input-Single Output
(VSC)	Variable-Structure Control
(ANN)	Artificial Neural Networks
(FLS)	Fuzzy-Logic Systems
(EA)	Evolutionary Algorithm
(PSO)	Particle Swarm Optimization
(LTC)	Load tap changer
(FACTS)	Flexible AC Transmission System
(GA)	Genetic Algorithm
(DE)	Differential Evolution
(OEL)	Over Excitation Limiters

(PF)	Participation Factor
(EM)	Electromechanical Mode

Symbols

δ	machines angle
ω	machines speed
Ks	synchronizing torque coefficient.
Kd	damping torque coefficient
ΔTe	electrical torque
ΔP_E	electrical power change
D	damping coefficient
$E_q^{'}$	Voltage proportional to field flux state variable
X_d	d-axis synchronous reactance
X_d'	d-axis transient reactance
X_q	q-axis synchronous reactance
X_q'	q-axis transient reactance
T_E	field circuit time constant
K_F	stabilizer gain

K_A	amplifier gain
T_F	stabilizer time constant
T'_{do}	d-axis open circuit transient time constant
T''_{do}	d-axis open circuit sub transient time constant
Eq', Efd	Generator internal and field voltages
$Vref$	Reference voltage
$EXC(S)$	excitation of the system.
M, H	Machine inertia coefficient and inertia constant
id, iq	d- and q-axis armature current
λ	eigenvalues
ζ	Damping ratio
vd, vq	d- and q-axis terminal voltage
vb	Infinite bus voltage

THESIS ABSTRACT

Name: Yousef Omair Al-Rasheedi
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In this thesis, one of the local industrial plants in Saudi Arabia has been studied. The plant's electric system was modeled and its stability was investigated. Then, a lead/lag PSS was design & tuned using the Differential Evolution Algorithm (DE). The proposed PSS was tested under different operating conditions. Also, in this thesis, the effect of the PSS on the local industrial plant's stability during islanding case was investigated. The results show that the designed DE algorithm achieved the optimum PSS parameters and the proposed approach success in enhancing the local industrial plant's power system stability.

Moreover, the proposed PSS enhanced the local industrial plant's stability during and after the islanding condition.

Keywords: Power system stabilizer, differential evolution, multimachine, local plant stability.

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خلاصة الرسالة

الإسم : يوسف عمير الرشيدي
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في هذه الأطروحة واحدة من المنشآت الصناعية المحلية في المملكة العربية السعودية قد درست. حيث ان نماذج النظام الكهربائي للمصنع قد وضعت ،بالاضافة الى دراسة استقرار النظام، وايضا الى تصميم و ضبط موازن لشبكه الطاقة الكهربائية باستخدام خوارزمية التطور التفاضلية. بالإضافة إلى ذلك، هذا الموازن المقترح قد اختبر تحت ظروف التشغيل المختلفة . أيضا ، في هذه الأطروحة نحن بصدد بحث تأثير الموازن المقترح على استقرار المنشاه الصناعية المحلية خلال حالة الانفصال عن الشبكة. نتائج الاختبارات اثبتت ان خوارزمية التطور التفاضلية المصممه توصلت الى افضل قيم لموازن الشبكه والى نجاح الاسلوب المتبع بتحسين استقرار النظام بشكل عام.

بالاضافه الى ذلك، هذا الموازن المقترح حسن من استقرار نظام المنشأه المحليه اثناء الانفصال عن الشبكه.

الكلمات الرئيسية : موازن نظام الطاقة ، خوارزمية التطور التفاضلية ، المحركات المتعدده، استقرار المصانع الحليه.

درجة الماجستير في العلوم
جامعة الملك فهد للبترول و المعادن
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CHAPTER 1

INTRODUCTION

1.1 Overview

Electric power generators are complex machines with highly non-linear dynamics. Their stability depends on the loading, the system condition and the available system's controllers. To understand this perfectly, let us define the power system stability; which is “property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance” [1]. Based on this definition, two categories of stability are derived: small-signal and transient stability. Small-signal stability is the ability of a system to return to a normal operating state following a small disturbance. Investigations involving this stability concept usually include the analysis of the linearized state space equations that define the power system dynamics. While the transient stability is the ability of the system to return to a normal operating state following a severe disturbance, such as a single or multi-phase short-circuit or even disturbances following a large generator lose. Under these conditions, the linearized power system model does not usually apply and the nonlinear equations must be used directly for the analysis. [1]

Low frequency oscillation is a common problem in large power systems. These frequency oscillations vary from 0.1 to 3 HZ and they are due to disturbances such as changes in loading conditions which could result in fluctuations in the mechanical power. These fluctuations could affect the generation of electric power in some areas or cause the system's generators to lose synchronism.

To come up with a solution for such oscillations, Power System Stabilizer (PSS) was introduced. PSS is an approach that improves the damping of the generator’s electromechanical oscillations (frequency oscillation) by introducing a supplementary signal to the generator exciter. Stabilizers have been employed on large generators for several decades, permitting utilities and plants to improve stability constrained operating limits. Conventional PSS based on simple design principles such as eigenvalue assignment techniques have been widely used in power systems [1]. Such PSS ensure optimal performance only at their nominal operating point and does not guarantee good performance over the entire operating range of the power system [1]. Not only that, a bad tuned PSS could lead to a negative damping which will end up creating instability issues. To guarantee a solid performance, conventional PSSs usually are tuned by one of the optimization techniques that will be discussed in this thesis.

1.2 Motivation

When utilities suffer from the mentioned low frequency oscillations, there will be disturbances in their system that could trip some of the synchronous machines. This is even worse for industrial plants since it could lead to blackout that will cost the plant its reliability. This might result in reducing the industrial plant local power generation to increase the stability of that system and retain the plant’s reliability.

In this thesis, one of the local industrial plants in Saudi Arabia will be considered. This local industrial plant electrical system experienced several stability limits. These limits arise when the plant experience load rejection caused by losing the link between the generation plant and the utilities. This load rejection causes over frequency which is directly proportional to the amount of power transmitted through the point of common coupling. This over frequency raises the generators speed and sometimes caused them to be tripped by protection system.

To survive during this load rejection, one needs to think of a damping mechanism to hold this relatively large frequency fluctuation until the correction action is done by the turbine controller. To do so, the electrical system need to be modeled, the plant’s stability needs to be checked and then a practical solution needs to be found. According to the power system stability definition and as the over frequency that causes this instability is between 1-3 HZ which is caused by losing the link with the utility; we can treat this phenomenon as a small signal stability problem and treat the utilities as a big load or a big generator.

With this assumption we can model the system, study it, and evaluate different solutions. The evaluation will be based on several operation conditions cases; one of them is the islanding condition. This simulates exactly the load rejection issue. What this study is after is to see how PSS can contribute to stability enhancement of this plant.

1.3 Research Goals

In this thesis, the electrical system stability for one of the local industrial plants will be studied. A lead/lag PSS will be design and then the proposed PSS system will be tuned using DE. The main goals of this thesis are:

1. Study the power system of a local industrial plant at Saudi Arabia.
2. Collect the relevant data.
3. Model the local industrial plant system.
4. Identify the stability issues with the subject local industrial plant.
5. Evaluate the existing system stability.

6. Propose and design a lead lag power system stabilizer.
7. Design an optimization program for the power system stabilizer parameters using DE.
8. Test the Optimizer on a standard system.
9. Test the Optimizer on the modeled system for the local industrial plant.
10. Test the system on different operations conditions, different disturbances, loading conditions and system configurations.
11. Evaluate the PSS performance during the islanding case.

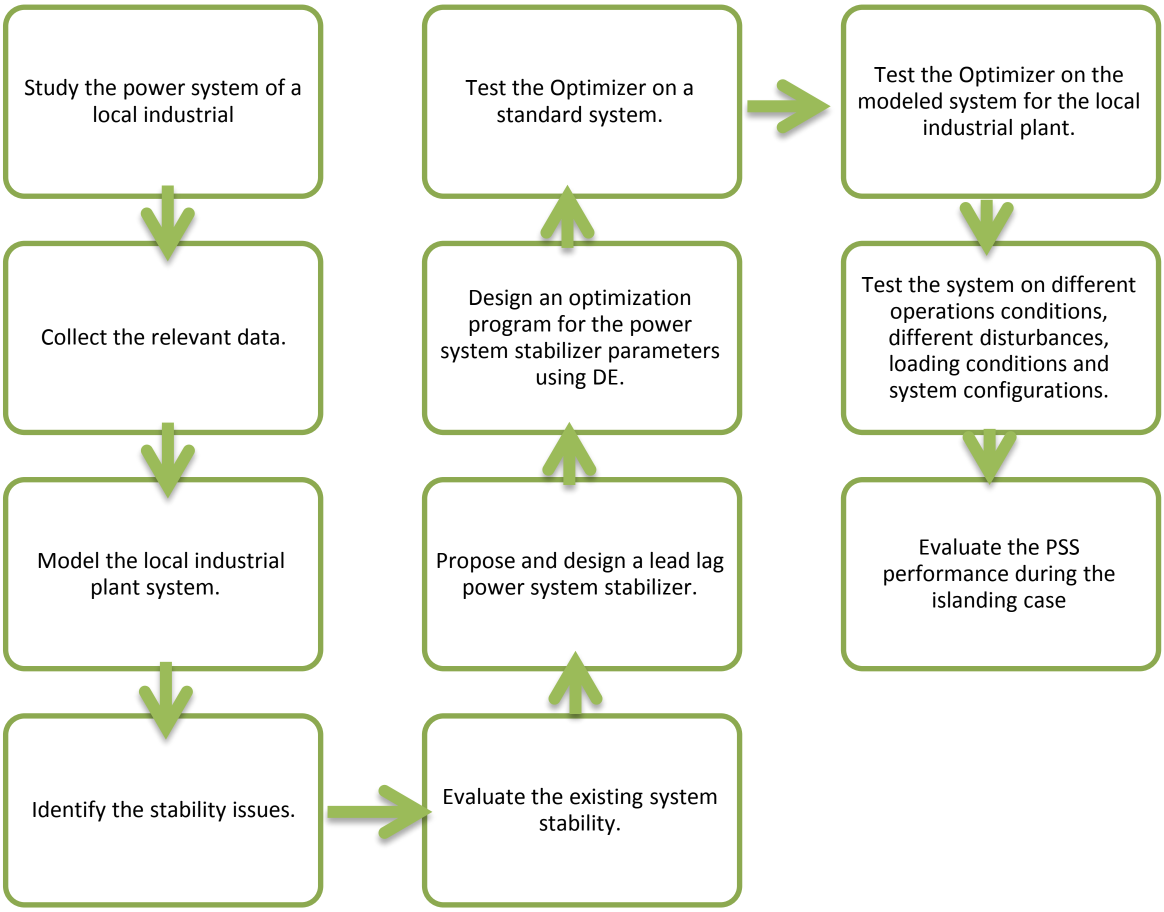

Figure 1.1: Flowchart that summarize the thesis goals.

1.4 Contribution

In this thesis, a local industrial plant in Saudi Arabia will be studied. Where the plant's electric system will be modeled, its stability condition will be investigated and then a PSS system that will improve the stability of the plant will be designed. Also, the designed PSS parameters will be tuned using one of the Evolutionary Algorithm methods. A complete Matlab code have been developed to check the system stability, place PSS on each generator, tune the PSS parameters and run a non-liner simulator to check the system behavior.

Four real scenarios have been developed to fully represent the local industrial plant. Among them, one of the cases reflects the plant condition during islanding. This is to check the PSS contribution to the plant's stability during the islanding case.

1.5 Thesis Organization

This thesis is prepared as follows:

In Chapter 1, a general overview about the power system has been introduced. Also, the motivation, thesis objectives and our contribution have been discussed.

Chapter 2 focuses on the literature review of similar work. A general overview about the power system stability also has been introduced.

Chapter 3 concentrates on the system modeling, where the following models have been considered:

- Synchronous machine model
- Exciter model
- SMIB system model
- Linearized model
- Power system stabilizer model

In Chapter 4, the eigenvalue analysis along with the research proposed approach have been presented. Also this chapter introduces the Differential Evolution optimization approach, where the DE structure processes and optimization steps have been discusses.

Chapter 5 provides an overview about the local industrial plant system.

Chapter 6&7 contain the simulation and results of the IEEE standard systems and the real industrial plant system.

Conclusions and future work are discussed in chapter 8.

CHAPTER 2

POWER SYSTEM STABILITY OVERVIEW

2.1 Literature Review:

2.1.1 Power System Stabilizer:

Conventional PSSs are usually tuned around the nominal operating point. Hence, the offered damping is applicable only around those operating points. However, as known the power systems are highly nonlinear and the machine parameters are changing with loading and time. Add to that, the power system dynamics also vary at different points [2]. Therefore, to achieve the required damping at all points of operations, many approaches based on modern control theory have been utilized to design different power system stabilizer structures [3,4]. These approaches include optimal control, adaptive control, variable structure control and intelligent control [5,6].

These different approaches purpose is to obtain such a PSS that can provide an optimal performance that can be suitable for a wide range of operational conditions. However, according to DeMello and Concordia [7], "a universally applicable stabilizing function is not feasible". Even with this conclusion, still a sort of control and optimization ways have been introduced in this area along with various degrees of system modeling.

Whereas it is difficult to discus in details the historical development of the power system stabilizer and its applications, we will try to run through the most significant works in this area as follows. Heffron and Phillips [8] investigated the relation between the modern voltage regulators and the under-excited operation of large turbine generators. They utilized the small perturbation model for first time on a machine-infinite bus system. Their analysis revealed that the steady state stability limit for turbine generators operated in an under-excited region will be greatly increased by using modern continuously acting regulators.

DeMello and Concordia [7] studied the single machine infinite bus through external reactance. Their assessment investigated the effects of thyristor type excitation systems and the descried stabilizing requirements for such systems. These requirements included many parameters at both the voltage regulator as well as the PSS.

In [9] Larsen and Swann demonstrated application of PSS utilizing speed, frequency or power as an input signals. They also presented guidelines for tuning PSS which enables the user to reach the required dynamic performance. Moreover, they discussed the need for torsional filters in the PSS.

Kundur in [10] described in details the PSS system design at Ontario Hydro generating unit. He evaluated two alternate excitation models, one with Transient Gain Reduction (TGR) and the other without. It was proven that both schemes proved satisfactory performance if the PSS parameters are selected appropriately.

In [11] the application of state feedback optimal PSS was presented by Yu and Siggers.

Moussa and Y.N. Yu in [12] explored the eigenvalue shifting technique to find performance index. This technique focus in shifting of the dominant eigenvalue to the left of the V-plane, it was also applied to a multimachine system. Although this technique found to be a very powerful control theory, it failed to appeal to utilities. This is because the method found to be difficult and costly.

Despite the numerous approaches of modern control techniques with different structures, power system utilities still prefer the conventional lead – lag PSS. The conventional PSS has a simple structure and is considered to be reliable for actual power system applications [13, 14].

2.1.2 PSS Tuning Approaches:

A lot of efforts were reported on multimachine systems coordination and PSS tuning. DeMello in [15] utilized an eigenvalue/eigenvector analysis to locate the most effective generator to be equipped with PSS in a multimachine system that was subject to dynamic instability and poor damping of many inter-area modes of oscillations.

Fleming in [16] presented a sequential eigenvalue algorithm for picking the parameters of the PSS in a multi-machine power system. In sequential tuning the PSS values are calculated using repeated applications of single input-single output (SISO) analysis. This approach allows for the selection of parameters of PSS such that a specified enhancement in the damping ratio of any poorly damped eigenvalue mode can be realized. In this method, utilizing the modal analysis, the PSS stabilizers are applied sequentially at different location.

Nevertheless, it should be noted that, to some extent, in this method the sequential addition of stabilizers interrupts the previously placed eigenvalues.

Abdulla in [17] also proposed a method for the selection of the most active machines for PSS stabilization. He recommended the addition of a damping term to every machine's equation of motion one at a time. Worth mentioning that the sequential tuning methods, discussed previously in [15-17], are computationally simple related to the simultaneous tuning methods. But they suffer from eigenvalue drift within the sequence. However, this eigenvalue drift does not arise at simultaneous tuning method. Although they deliver true optimal solution, these methods are computationally costly.

In [18], Doi and Abe explored the coordinated design and tuning of PSS in multi-machine system via combining linear programming and the eigenvalue sensitivity analysis. The stabilizer parameters are set by minimizing a performance index that is the sum of each PSS gain. This scheme is simultaneously able to choose the generators where the stabilizer can be effectively introduced and to create the adequate transfer function of the stabilizer for these machines.

Elangovan and Lim in [19] & [20] presented a way for designing decentralized PSS controllers in a multimachine system by complex frequency domain method. By this method, the PSS parameters can be obtained so that almost all the system's mechanical mode eigenvalues could be placed at the required locations in the V-plane. The problem of this assignment is; the needed number of iteration of the equivalent characteristic equations.

In [21], the same authors evaluated the efficient pole assignment method for computing the characteristic equations to enhance considerably the calculation speed over the method outlined in [18].

All exposed works above, were developed long time ago. Other control strategies based on Variable-Structure Control (VSC), self-tuning control, Artificial Neural Networks (ANN), Fuzzy-Logic Systems (FLS), and Evolutionary Algorithm , have been explores in the recent works targeting the development of robust PSS systems.

Ghosh in [22] examined the advantages and disadvantages of : minimum variance, pole assigned, linear quadratic and pole shifting adaptive controllers for power systems in detail. The author offered a comparison of a system dynamic performance for three alternate PSS, adaptive pole-shifting, adaptive linear quadratic and a conventional PSS. The studies concluded that the adaptive pole shifting PSS provides the best performance.

Cheng in [23] proposed an adaptive PSS control technique based on self-searching pole-shifting control theory. This adaptive PSS approach found to be effective in damping the system oscillations whether it has small or large perturbations.

Cheng in [24] further presented a dual rate adaptive stabilizer based on self-searching pole-shifting algorithm to damp multimode oscillations. In that paper the system parameters are updated every 80 msecond whereas the control signal is updated every 20 msecond.

Lim and Hiyama [25-27]&[28-29] proposed methods to design a self tuning PSS based on minimization of quadratic performance index. They investigated these methods' effectiveness under either excitation or governor control for different disturbances and at a wide range of operating conditions. In order to solve the problem related to the system parameters variation an alternative method, to the self-tuning PSS, has been explored at several literatures. That is, the Variable Structure PSS (VS-PSS). The VS-PSS considered to be less-sensitive to the system parameter variations and can be easily recognized using micro-computers.

Chan and Hsu [30] presented an optimal VS-PSS for a SMIB system as well as for a multimachine system. By minimizing the quadratic performance index, the switching hyper-plane is obtained. Hence, the presented VS-PSS is considered to be optimal in the sliding mode operation, note that the hyper-plane depends on the weighing matrices that is associated with the performance index.

Kothari in [31] proposed the design of a VS-PSS with required eigenvalues in the sliding-mode, showing that the switching hyper-plane is obtained using the pole placement method. The same author has further extended the mentioned method in [31] to apply a radial pole shifting way to design VS-PSS in the discrete mode. [32]

Fuzzy logic theory is another method to tune PSS. It was reported by Hsu and Cheng in [33].The presented stabilizer utilized a decentralized feedback control that only required local measurements at each generator.

A systematic approach for designing a fuzzy logic control was presented in [34], by Hoang and Tomsovic. The proposed controller parameters can be either calculated offline or online in response to any system changes. This design approach proves that this controller is insensitive to a specific dynamics of the system.

A third PSS tuning method is based on artificial neural network (ANN) method which is based on parallel processing concept. This method has a great ability in analyzing complicated nonlinear mappings and provides fast processing facility for complicated nonlinear problems. Zhang in [35] proposed a PSS design approach which employs the multilayer perceptron method.

A new approach for real time tuning of CPSS with a radial basis function network was presented in [36] by Segal. This is accomplished by using an orthogonal least squares algorithm.

Another successful and powerful tool for PSS tuning is the Evolutionary Algorithm (EA) technique. EAs are population relevant optimizer motivated by the evolution mechanism and by the natural selection. They are useful in locating the global maximum or minimum rather than local ones. They are proven to be robust, simple, and efficient algorithms that can be utilized to solve any type of problems regardless of the function type, like nonlinearity, discontinuity or even the complex. In the last few years, a lot of researches conducted in the EA and they resulted in many optimization methods based on EA concept. This includes Genetic Algorithms, Deferential Evolution… etc.

Genetic Algorithm (GA) is one of the famous EA. M.A. Abido and Abdul-Maged in [37-39] investigated the effect of tuning PSS using classical GA and compared the results with those of CPSS over a wide range of parameters. GA-PSS demonstrated to be more robust over the CPSS.

J. Lu in [40] applied a selection of fuzzy rules used from the operating point settings, to tune the stabilizer parameters online . The membership functions of the fuzzy parameter tuner were optimized using a genetic algorithm (GA).

K.A. Folly presented in [41] a simplified version of GA called Population Based Incremental Learning (PBIL) to design a PSS for multi-machine power system. The control problem was converted into an optimization problem solved with PBIL. The resulting controllers ensured robust stability and good performance for both the nominal and off-nominal operating conditions. Differential Evolution (DE) is another EA method that will be discussed in the next section.

2.2.3 Differential Evolutionary Algorithm:

DE is a stochastic optimization method similar to the GA approach. DE is constructed from differential mutation, search mechanism, and applies selection technique to reach the intended solution in its search space [42, 43, 44]. DE utilizes a one to one survivor selection approach; this method is based on comparing every trial vector to its equivalent target vector. This method ensures that both vectors, the best ones, at each index are kept. Although DE considered to be a very powerful optimization approach, yet it is well known that its implementation is very simple. As DE's performance found to be outstanding, many comparisons with other optimization algorithms took-place, by researchers, to benchmark its performance in several applications. Researchers found DE to have an outstanding efficiency, simplicity and robustness when it was compared to other optimization methods [43].

M.A. Abido in [45] utilized the DE technique to search for the optimal settings of PSS parameters. He utilized an eigenvalue-based objective function that will enhance the system damping to overcome the electromechanical modes. After investigating the proposed DE based PSS

(DE-PSS) under different disturbances, and loading conditions, the eigenvalue analysis and the nonlinear simulation results show the robustness and the effectiveness of the DE-PSSs in damping the modes of oscillations.

Lin and Chung presented, in [46], a new coordinated stabilizer design approach based on non-linear time domain simulation to improve the stabilizer performance and to undertake the drawback of CPSS.

Selvabala and Devaraj in [47] proposed an optimal tuning of the PSS parameters in the synchronous-machines. They formulated the optimal controller parameters challenge as an optimization problem where the DE algorithm was applied to overcome this optimization problem. The proposed DE method resulted in good damping characteristics and had stable convergence characteristics.

In [48] Storn and Price presented another approach that can do minimization of continuous space nonlinear and non-differentiable functions. It was demonstrated that this new method converges faster with more certainty than both the Annealed Nelder Mead approach as well as, the Adaptive Simulated Annealing that have a reputation to be very powerful. This new approach is robust, easy to use, and excellent for parallel computation and only requires few control variables.

Worth mentioning that other PSS design methods are available such as Simulated Annealing (SA) [49] and Particle Swarm Optimization (PSO) [50], which have been applied successfully for long time, but they will not be discussed in this thesis.

2.2 Stability Overview

2.2.1 Definition and Classification

Although the entire subject of power system stability could be fully described by only one comprehensive set of dynamic equations, much respected understanding has been recognized by classification of certain basic phenomena into forms. This will allow for definite simplifying assumptions. Hence, it is not required to utilize the detailed model generally for any stability study. Note that one can reduce the detailed model and simplify it through understanding the stability nature with same expected level of accuracy. [7]

Therefore, it is important to understand the power system classifications to allow for model reduction. In the next paragraphs we will explore the power system stability theories, and its classifications. In fact, stability and of course the related analysis methodologies can be categorized as follow:

- The disturbance size, which is the most appropriate method for classifying the stability.
- The physical nature of the observed instability.

According to the mentioned categorization guide, stability can be classified based on the disturbance size as follow:

Transient Stability; as the name implies, it is associated with the ability of a power system to survive large power disturbances. Angle excursions could be huge which will cause instability due to the nonlinear relationship between the power and the angle. Stability is affected by both; the operating state, and the severity of the disturbance.

Oscillatory Stability; or dynamic stability is linked to the linearized small signal properties of the power system that can be analyzed by the characteristic equation's roots; which can describe the overall system including controls. Instability is typically characterized by un-damped oscillations and therefore its condition cannot be discovered by a simple assessment of a parameter such as; the synchronizing power coefficient which is usually true for steady state stability. Similar to the case of steady state stability; dynamic stability does not heavily depend on the disturbance, rather by the state of the system. [1]

Steady State Stability; that is the stability under very small disturbances; since the form of instability in this group is not restricted to aperiodic drift in angle but, usually involves un-damped oscillations in the angle that cannot be treated analytically. The term dynamic stability, oscillatory stability, was introduced to represent this type of condition. We classified the power system based on the size of the disturbance. Let us explore the stability classification from the physical nature of the resulting instability, which is as follow.

- Voltage stability
- Frequency stability

- Rotor angle stability

2.2.2 Frequency and Angel Stability:

Frequency stability reflects the capability of the power system to maintain a stable frequency after a power system disturbance resulting in an imbalance between the load and local generation. It is restricted by the power system capability to restore the disturbed equilibrium between the connected load and the power system generation. Instability typically occurs in the form of unceasing frequency fluctuation which eventually will trip some generating units, and/or loads. Severe power system disturbance usually cause a large frequency excursions, power flows and voltage variation. Hence, it involves in conventional transient stability studies. These control systems may be very slow; as the example of boiler dynamics; or such as the volts/Hertz protection system that is triggered for extreme system conditions to trip generators. In the large interconnected power systems (utilities) this situation is commonly seen following of systems' islanding. Stability concern in this case is whether each part of the system will reach a new state of operating equilibrium or not. This will be determined by the system frequency not by the individual machine speed. Usually, frequency stability caused by insufficient generation reserve or control and protection coordination issues.

During frequency excursions, there are two kind of control and protection systems. One will act within fraction of a second and another one will act in minutes. For example, load shedding and AVR will act very fast and on the other hand the boiler action will take minutes.

Therefore, frequency stability could be a short term or a long term phenomenon. For example, an island with shortage in power and insufficient load shedding protection system considered to be a short term frequency instability as this will cause frequency deteriorations causing a blackout within a few seconds. Instead, frequency instability can be as a result of either boiler protection or steam turbine controls, which is a longer term phenomena; several minutes.

Rotor angle stability on the other hand, related to the power system synchronous machines and their ability to maintain synchronism after a disturbance. Rotor angle stability is always dependent on the equilibrium between the machine electrical torque and mechanical torque during normal operation and/or after any disturbance. That is; maintaining a constant relationship between the stator and rotor magnetic fields and the rotor speed. Any disturbance could cause acceleration or a deceleration of the machine's rotor or even a loss of synchronism with the rest of the system. Hence, the machine is disengaged from the system.

Rotor angle stability is classified as follow:

- Small signal stability
- Large signal stability

The transient stability will not be covered in this thesis. In small signal stability the disturbances in consideration are small enough, which allow for the linearization of the system for the eigenvalue analysis purpose. Small signal instability can be of two forms:

- Increase in the rotor angle. This is due to inadequate synchronizing torque.

- Rotor oscillations. This is due to the inadequate damping torque.

A disturbance in a power system will affect the machines angle ($\Delta\delta$) and speed ($\Delta\omega$) values relatively. Hence, this will cause a change in electrical torque (ΔTe) that is defined by the below equation:

$$\Delta Te = Ks\ \Delta\delta + Kd\ \Delta\omega\ , \qquad (2.1)$$

Ks $\Delta\delta$: is the synchronizing torque component; Ks, the synchronizing torque coefficient.

Kd $\Delta\omega$, damping torque component; Kd, the damping torque coefficient

Both components of the ΔTe are important for the power system stability. Inadequate synchronizing torque (Ks $\Delta\delta$) will cause a drift in rotor angle and inadequate damping torque (Kd $\Delta\omega$) will cause oscillations. Those instabilities are more related to the AVR availability and action.

The machine swing equation can be demonstrated by the block diagram in Figure (2.1). The electrical power change (ΔP_E) comprises of the following two components;

- The speed.
- The angle.

The damping coefficient D and the synchronizing coefficient T

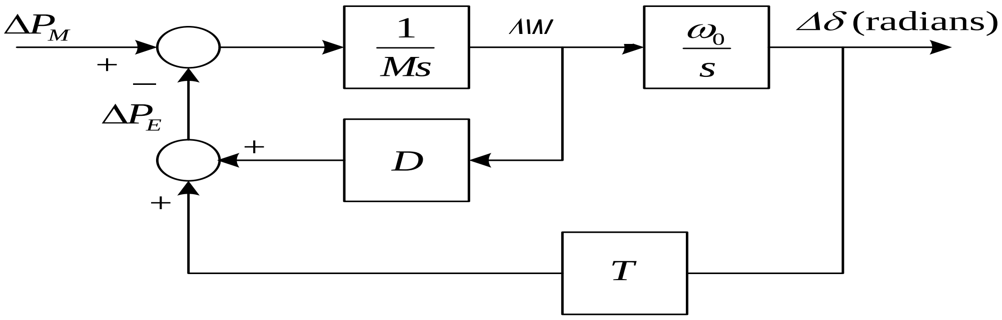

Figure 2.1: Small Perturbation Block Diagram

The stability of that system can be examined using the ordinary algebra to obtain the characteristic equation's roots from the block diagram

$$s = -\frac{D}{2M} \pm \sqrt{\left(\frac{D}{2M}\right)^2 - \frac{\omega_0 .T}{M}} \tag{2.2}$$

The system is considered to be stable; if the characteristic equation roots have no positive real parts. This can be extended to the multimachine example on a power system network, as shown in Figure 2.2.

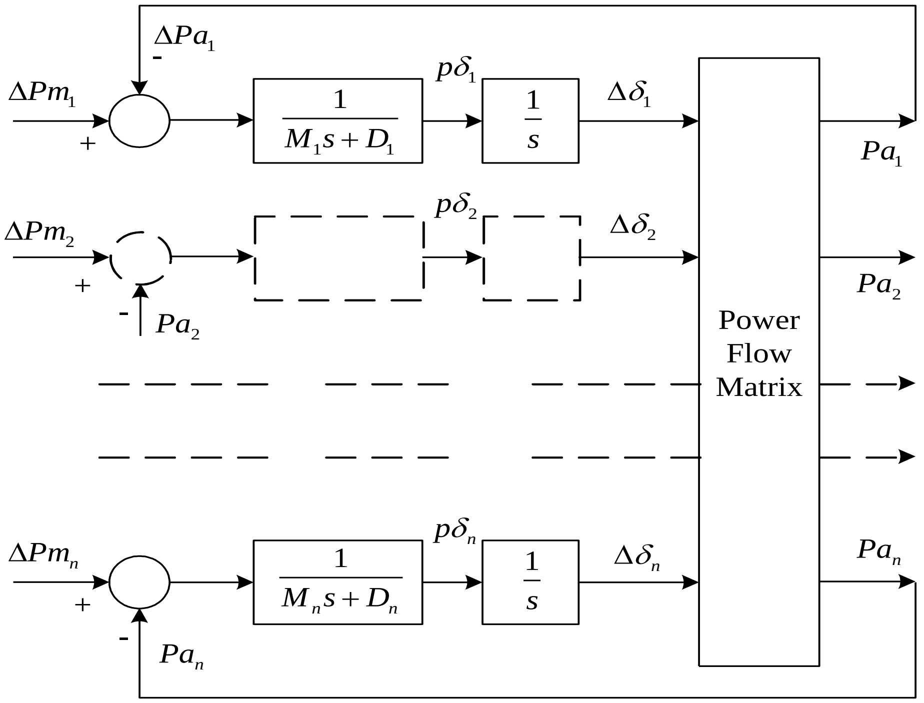

Figure 2.2: Small Perturbation Diagram of Multi Machine System

Note that, the stability of the system and the related modes of oscillation can also be determined from characteristic equation.

For larger perturbations, the linearized model is no longer valid. That is, the relationship between the angle and the electrical power must be expressed as nonlinear power angle equations.

CHAPTER 3

POWER SYSTEM MODELING

3.1 Generator Controls

Modern power system heavily counts on control systems to operate securely. This consists, and not limited, of the speed governing and automatic voltage regulation systems at almost all power plants. Governor's role is to adjust the fuel to the turbine which is driving an electric generator that will keep the rotor speed constant. AVR systems role is to adjust the field current excitation in an electric generator, which will keep the terminal voltage constant. These control systems will manly act on dynamical changes in the system, this include dynamics such as load, which will minimize the voltage and frequency variations.

Thus, their operation is crucial to ensure a quality power is delivered to the system. Although the mentioned controller plays a major role in the network reliability, they have some draw back. AVRs for example are known to reduce damping of oscillations in the machines, due to their high gain negative feedback. Hence, they affect the generator stability. Therefore, in order to the maintain stability, those oscillations must decline. One way is to do it through a power system stabilizer.

The complete excitation control system with the PSS is designed to perform the following functions:

a) Maximize the damping of all electro-mechanical modes of oscillations without affecting the stability of other modes.

b) Improve the system transient stability.

c) Not poorly affect the system performance through major system upsets that cause large frequency excursions.

d) Minimize the impact of excitation system error due to component failures.

3.2 Multi-machine System Representation

In order to perform the dynamic analysis to the electric system of concern and in order to check the system's response to severe disturbances; the system components need to be modeled first. This is to get the state space representation of the system. The state space representation will give great information about the system at any instant of time. To achieve that, the power system is represented by a set of first order nonlinear ordinary differential equations. They can describe the behavior of the dynamic system at any instant.

There are various mathematically models that can be used to build up the electric system model. In this thesis we are not intended to discuss them. Therefore, we will use the single machine infinite bus representation, figure (3.1), with fast decay model for the synchronous machine and the IEEE-type1 exciter. Then, we will linearize the set of equations around the operating point as we are looking for small signal analysis.

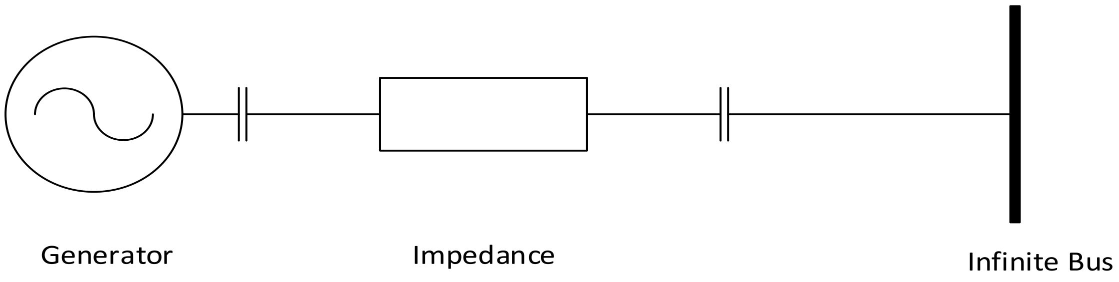

Figure 3.1: Single machine infinite bus system

3.2.1 Synchronous Machine Modeling.

The fast decay model for the synchronous machine is shown below, where we neglect the effect of the fast dynamics of the stator and network transients as well as the fast damper dynamics.

The swing equation can be written as:

$$\dot{\delta}_i = \omega_0 \omega_i \tag{3.1}$$

$$\dot{\omega}_i = (T_{m_i} - E'_{q_i} I_{q_i} - (x_{q_i} - x'_{d_i}) I_{d_i} I_{q_i}) / M_i \tag{3.2}$$

The internal voltage equation given by:

$$\dot{E}'_{q_i} = (-E'_{q_i} - (x_{q_i} - x'_{d_i}) I_{d_i} + E_{fd_i}) / T'_{d0_i} \tag{3.3}$$

Where.

δ ; Angle state variable

ω ; Angular velocity state variable

$E_q^{'}$; Voltage proportional to field flux state variable

X_d : d-axis synchronous reactance

X_d' : d-axis transient reactance

X_q :q-axis synchronous reactance

X_q' :q-axis transient reactance

Stator algebraic equation is given by:

$$\text{Vi}\sin(\delta i-\theta i)-R_{si}I_{di}+X_{qi}^{'}I_{qi}=0 \qquad (3.4)$$

$$E_{qi}^{'}\text{-}\ \text{Vi}\cos(\delta i-\theta i)-R_{si}I_{qi}+X_{di}^{'}I_{di}=0 \qquad (3.5)$$

Network equations:

$$I_{di}V_i \sin(\delta i - \theta i) + I_{qi}V_i \cos(\delta i - \theta i) + P_{Li}(V_i) - \sum_{k=1}^{n} V_iV_kY_{ik}\cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{3.6}$$

$$I_{di}V_i \cos(\delta i - \theta i) + I_{qi}V_i \sin(\delta i - \theta i) + Q_{Li}(V_i) - \sum_{k=1}^{n} V_iV_kY_{ik}\sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{3.7}$$

For i=1,2,3…m

$$P_{Li}(V_i) - \sum_{k=1}^{n} V_iV_kY_{ik}\cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{3.8}$$

$$Q_{Li}(V_i) - \sum_{k=1}^{n} V_iV_kY_{ik}\sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{3.9}$$

For i=m+1….n

3.2.2 Exciter Models

The excitation system was modeled and it found to be close to the IEEE Type-1 exciter model. The exciter block diagram is as shown in Figure (3.2). The block diagram equations are given below. This model contains the exciter dynamic circuit and the voltage regulator dynamic circuit.

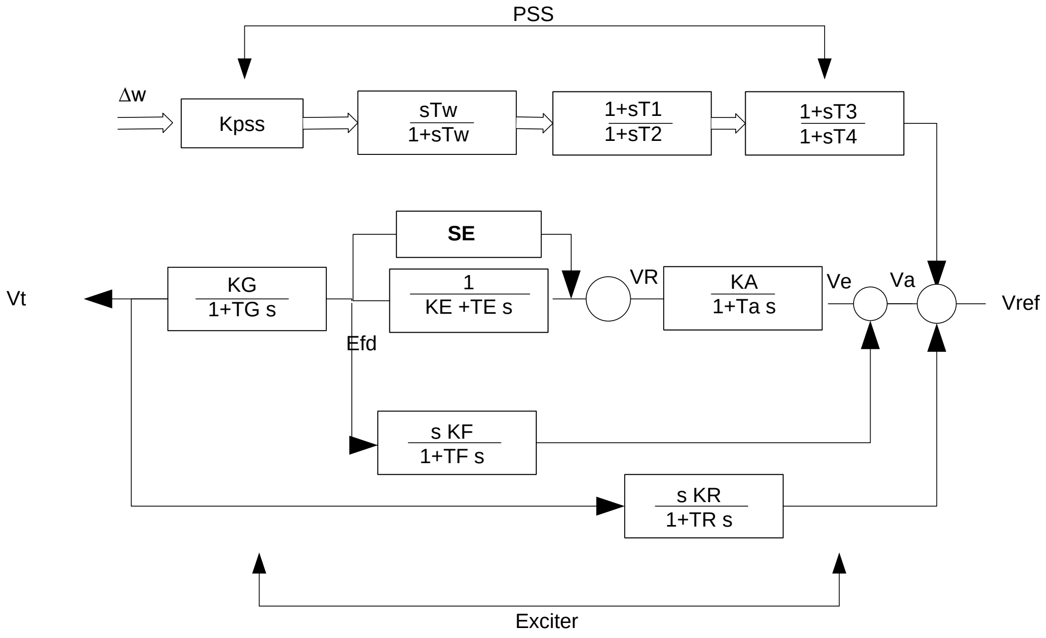

Figure 3.2: Block diagram of the IEEET1 dynamic model

Differential equitation:

$$\dot{E}_{fdi} = -(K_{Ei} + S_{Ei}(E_{fdi}))E_{fid} + (V_{Ri})/T_{Ei} \qquad (3.10)$$

$$\dot{R}_{fi} = -R_{fi}/T_{Fi} + (K_{Fi}/T_{Fi}^{\ 2})E_{fdi} \qquad (3.11)$$

$$\dot{V}_{Ri} = -V_{iR} + \frac{K_{Ai}}{T_{Ai}}(R_{fi} - (K_{Fi}/T_{Fi})E_{fdi} - (V_{refi} - V_{Ti}) \qquad (3.12)$$

Where,

T_E : field circuit time constant

K_F :stabilizer gain

K_A :amplifier gain

T_F :stabilizer time constant

T'_{do} :d-axis open circuit transient time constant

T''_{do} :d-axis open circuit sub transient time constant

3.2.3 Linearized Model:

Now we need to merge the synchronous generator differential equation with the exciter differential equations. Then, as those equations are describing the steady state operation of a synchronous generator connected to an infinite bus through an external reactance; we have to linearize them about any particular operating point as follows:

$$\Delta\dot{\delta}_i = \omega_{i0}\Delta\omega_i \tag{3.13}$$

$$\Delta\dot{w}_i = (\Delta T_{mi} - E'_{qi0}\Delta I_{qi} + X'_{di}I_{di0}\Delta I_{qi} + X'_{di}I_{qi0}\Delta I_{di} - I_{di0}\Delta E'_{qi}$$

$$-\dot{E}'_{di0}\Delta I_{di} - I_{di0}\Delta E'_{di} - X'_{qi}I_{di0}\Delta I_{qi} + X'_{qi}I_{qi0}\Delta I_{di} - D'_i Iw_i)/M_i \tag{3.14}$$

$$\Delta \dot{E}'_{qi} = (-\Delta E'_{qi} - (x_{qi} - x'_{di})\Delta I_{di} + \Delta E_{fdi}) / T'_{d0i} \tag{3.15}$$

$$\Delta \dot{E}_{fdi} = -(K_{Ei} + S_{Ei}(\Delta E_{fdi}))\Delta E_{fid} + (\Delta V_{Ri}) / T_{Ei} \tag{3.16}$$

$$\Delta \dot{R}_{fi} = -\Delta R_{fi} / T_{Fi} + (K_{Fi} / T_{Fi}{}^{2})\Delta E_{fdi} \tag{3.17}$$

$$\Delta \dot{V}_{Ri} = -\Delta V_{iR} + \frac{K_{Ai}}{T_{Ai}}(\Delta R_{fi} - (K_{Fi} / T_{Fi})\Delta E_{fdi} - (\Delta V_{refi} - \Delta V_{Ti}) \tag{3.18}$$

The K-constants can be defined as following:

K$_1$=

$$-(1/\Delta)[(x'_d - x_q)i_{q0}V_\infty\{(x_q - x_e)\sin\delta_0 - R_e\cos\delta_0\} + [V_\infty\{(x'_d - x_q)i_{d0} - E'_{q0}\}\cos\delta_0 + R_e\sin\delta_0\}] \tag{3.20}$$

K$_2$ = $(1/\Delta)[i_{q0}\Delta - i_{q0}(x'_d - x_q)(x_q + x_e) - R_e(x'_d - x_q)i_{d0} + R_e E'_{q0}]$ (3.21)

1/K$_3$ = $1 + \dfrac{(x_d - x'_d)(x_q - x_e)}{\Delta}$ (3.22)

K$_4$ = $(1/\Delta)V_\infty(x_d - x'_d)[(x_q - x_e)\sin\delta_0 - R_e\cos\delta_0]$ (3.23)

K$_5$= $\begin{array}{l}(1/\Delta)\{(V_{d0}/V_t)x_q[R_eV_\infty\sin\delta_0 + V_\infty\cos\delta_0(x'_d - x_e)] + (V_{q0}/V_t)\ldots \\ [x'_d(R_eV_\infty\cos\delta_0 - V_\infty\sin\delta_0(x_q + x_e)\}\end{array}$ (3.24)

$$K_6 = (1/\Delta)\{(V_{d0}/V_t)x_q R_e - (V_{q0}/V_t)[x_d'(x_q + x_e) + (V_{q0}/V_t)\} \qquad (3.25)$$

The state space representation of the system including excitation system and AVR is given by:

$$X^{\cdot} = \begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{W} \\ \Delta\dot{E}q' \\ \Delta\dot{V}T \\ \Delta\dot{R}f \\ \Delta\dot{V}R \\ \Delta\dot{E}fd \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -(K/M_i) & -(D_i/M_i) & -(K2/M_i) & 0 & 0 & 0 & 0 \\ -(K4/T_{doi'}) & 0 & -(K3/T_{doi'}) & 0 & 0 & 0 & 1/T_{doi'} \\ 0 & 0 & 0 & (1/T_R) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (-1/T_F) & 0 & -(K_F/T_F^2) \\ 0 & 0 & 0 & (-K_A/T_A) & (K_A/T_A) & (-1/T_A) & -(K_A K_F/T_A T_F) \\ 0 & 0 & 0 & 0 & 0 & 1/T_E & (-(S_E + K_E)/TE) \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta W \\ \Delta Eq' \\ \Delta VT \\ \Delta Rf \\ \Delta VR \\ \Delta Efd \end{bmatrix}$$

3.3 Power System Stabilizer

3.3.1 Power System Stabilizer Theoretical Background

Power system stabilizer acts as an add-on device to the Automatic Voltage Regulator (AVR) or the Generator Governor. The PSS usually uses shaft speed, active power output or even the bus frequency as an input. The basic function of the PSS is to apply a signal to the excitation system, creating electrical torques to the rotor, in phase with speed variation, which damps out the oscillations. This is a supplementary control which is a useful tool during line outage if large power is transmitting on the line. However, as a drawback power system instabilities can arise in certain condition due to negative damping effects of the PSS on the rotor [1]. That is, because PSSs are tuned around a steady-state operating point. Their damping effect is only applicable for small excursions around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field. Extensive researches have been conducted in PSS fields like PSS input signals, PSS optimum locations, and PSS tuning techniques.

The most common PSS types are the conventional lead-lag (CPSS). A CPSS block diagram is shown in Figure (3.3). As shown, the PSS output signal is a voltage signal and added as an input signal to the AVR/exciter.

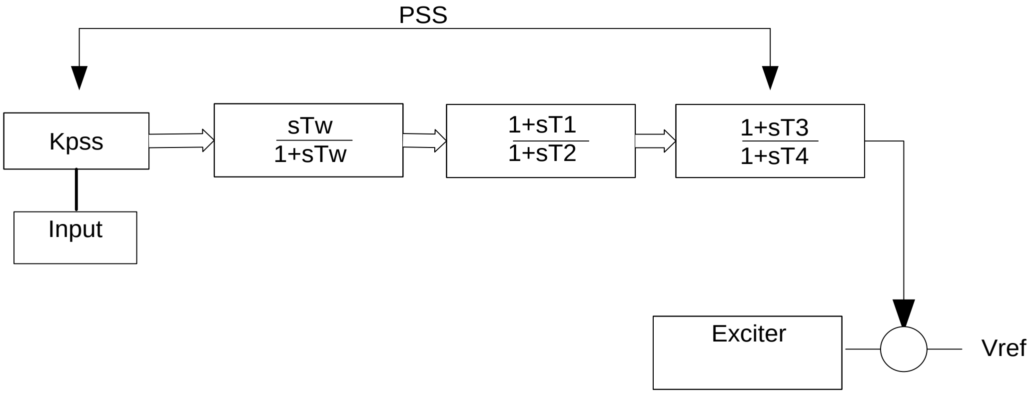

Figure 3.3: PSS structure.

PSS designers use various input signals such as speed deviation, electrical power, and rotor frequency as shown below:

- Speed Input: shaft speed can be utilized as an input to the PSS, however it must compensate for the lags at the transfer function. This is to produce a torque component in phase with the speed variations to increase the damping of the oscillations in the rotor.

- Power Input: power acceleration can be used as an input signal to the power system stabilizer; this has received a great attention due to the low level torsional interaction. The effects of the mechanical power variations can be minimized by using a heavily filtered speed signal.
- Frequency Input: the frequency signal is more sensitive to the rotor variation in comparison to the speed as an input.

Since the drive of a Power System Stabilizer is to introduce a damping torque element, the speed deviation represents an excellent signal to be used as input for the PSS. Practically, both the exciter and the generator exhibit frequency dependent gain and phase characteristics GEP(S). Therefore, the PSS transfer function shall have an appropriate phase lead circuits which can compensate for the phase lag between the electrical torque and the exciter input.

3.3.2 Conventional Lead-Lag PSS Components

Referring to the structure shown in Figure (3.3), this supplementary controller contains a washout block; used to reduce the over-response of damping during severe events. Phase lead blocks circuits which are used to compensate for the lag between the PSS output and the control action. The number of lead-lag blocks needed depends on the particular system and the tuning of the PSS. There is also the PSS gain that is an important factor as the damping provided by the PSS increases in proportion to an increase in the gain up to a certain critical gain value, after which the damping begins to decrease. Accordingly all of the variables of the PSS must be determined for each type of generator separately because of the dependence on the machine parameters. Note that also, the power system dynamics influence the PSS values. Finally, to overcome the limitations on this CPSS; modern control systems can use lead-lag based PSS tuned using modern control theory to have optimum performance at almost all the operating conditions.

3.3.3 Conventional Power System Stabilizer Design

In figure (3.4) the composite transfer-function for GEP(S) can be written as follows [6]:

$$GEP(S) = \frac{K_2 K_3 EXC(s)}{(1 + ST_{d0} K_3) + K_3 K_6 EXC(s)} \tag{3.26}$$

Where, EXC(S) is the excitation of the system.

GEP(S), is the transfer function block between the electric torque and the reference voltage input.

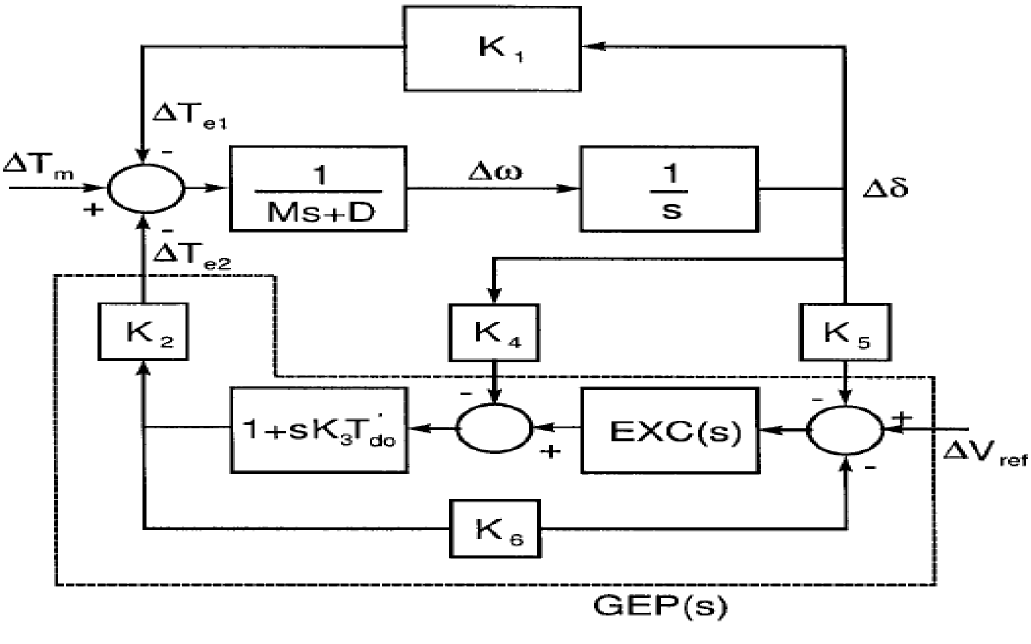

Figure 3.4: Heffron-Philips block diagram of single machine infinite bus system

To provide a pure damping throughout the frequency range G(s), the transfer function of the controller, should be a pure lead function. That is

G(s)= K_{pss} $(1+ST_{d0}K_3)+K_3K_6EXC(s)$, which is physically not realistic. Therefore, a phase lag has to be also available and tunable. That's why it called lead/lag PSS to provide enough phase lead for the expected range of frequencies.

The transfer function of the lead-lag PSS on the I^{th} machine is shown in equation (3.27) and the corresponding block diagram is shown in figure(3.5).

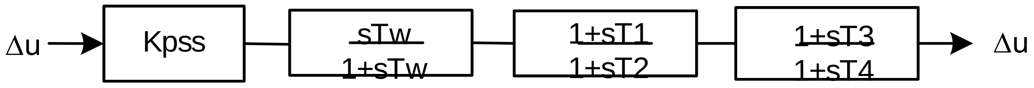

Figure 3.5: lead lag PSS

$$\mathrm{GPSS}(s) = \frac{\mathrm{KpssTw}(1+s\mathrm{T1})(1+s\mathrm{T3})}{(1+s\mathrm{Tw})(1+s\mathrm{T2})(1+s\mathrm{T4})} \tag{3.27}$$

The time constants should be set to provide the required damping over the intended frequency range. Hence, they need to compensate for the phase lag introduced by the generator, exciter and the network as mentioned earlier.

A typical technique for phase lag compensation is explained in (71) where the author suggested having the phase compensation for the net phase lag to be as follow:

- Between 0 to 45° from 0.3 to 1 HZ
- Less than 90° up to 3 HZ

Table 3.1: Typical values of the gain and time constants:

Constant	Minimum	Maximum
K_{pss}	0.1	100
T_1	0.2	1.5
T_2	0.02	0.15
T_3	0.2	1.5
T_4	0.02	0.15
Tw	5	10

Now, how to select the appropriate time constants? Several approaches have been developed to select the PSS parameters.

We will utilize the following procedure (71):

Step1:

In this step we need to find the natural frequency (un-damped) in rad/sec of the torque-angle loop of the Phillips-Heffron model which will be as follow:

$$\frac{2H}{W_s}s^2 + K_1 = 0, \quad S_{1,2} = \pm jW_n \tag{3.28}$$

$$W_n = \sqrt{K_1 W_s / 2H} \tag{3.29}$$

Step 2:

Find the phase lag of GEP(s) at $S = jW_n$ (3.30)

Step 3:

Adjust the phase lead of G(s) such that:

$$\angle G(s)\big|s = jw_n + \angle GEP(s)\big|s = jw_n = 0 \tag{3.32}$$

Step 4:

Find the K_{pss}, this can be done by either using the root locus method or by finding the damping ration due to the PSS alone.

For the latter method, find the loop characteristic equation which as follow:

$$\frac{2H}{W_s}s^2 + Ds + K_1 = 0, \quad S_{1,2} = \pm jW_n \tag{3.32}$$

The damping ration is $\xi = \frac{1}{2} D / \sqrt{MK_1}, \quad M = 2H / W_s$ (3.33)

$$S_{1,2} = -\frac{D/M \pm \sqrt{(D/M)^2 - \frac{4K_1}{M}}}{2} \tag{3.34}$$

Note that $W_n = \sqrt{K_1 / M}$

Hence, $\xi^2 W^2{}_n = (D/2M)^2$ (3.35)

The damping coefficient can be found as:

$$D_{PSS} = K_{PSS} \left| GEP(s) \right| s = jw_n \ \left\| G(s) \right| s = jw_n \ \right| \tag{3.36}$$

Therefore the characteristic equation becomes:

$$s^2 + \frac{Dpss}{M} s + \frac{K_1}{M} = 0 \tag{3.37}$$

Finally, $D_{PSS} = 2\xi W_n M = K_{PSS} \left| GEP(s) \right| s = jw_n \ \left\| G(s) \right| s = jw_n \ \right|$ (3.38)

Thus we can find K_{PSS} as W_n and ξ are known.

Step 5:

Design the Tw constant. It should be set with a high value to overcome the steady state error.

CHAPTER 4

PROPOSED APPROACH AND WORK METHODOLOGY

4.1 Eigenvalues Analysis

In order to investigate a power system dynamic behavior, first the ODE model has to be derived, like what we have derived in the former chapters. Hence, a complete set of tools based on eigen-analysis can be applied to this power system, which is the modal analysis. This analysis identifies oscillating modes of the system.

The stability of the subject power system can be evaluated and analyzed when the state space system for that power system is written in the linearized form. First of all, the eigenvalues need to be calculated for the A-matrix, note that they are the nontrivial solutions of the following equation:

$$A\Phi = \lambda\Phi \tag{4.1}$$

Note: Φ is an nx1 vector. If look for λ solution then the last equation become,

$$\det\left(\mathbf{A} - \lambda\mathbf{I}\right) = 0 \tag{4.2}$$

The n solutions of this equation are the eigenvalues (λ_i) of the nxn A-matrix. These eigenvalues could be of any form like real or complex, and they could be also of the form of s±jw. If A-matrix is real, then the complex eigen-values always found to occur in conjugate pairs. The operating point (δo, ωo) stability can be analyzed via studying the eigen-values. The power system is stable if all of its eigenvalues are on the left hand side of the complex plane. Otherwise, it is not stable. If the real part of any one of the eigenvalues appears on or to the right side of this axis; then the system is not stable. If the real part of the eigenvalue is negative, the mode should decays over time. The magnitude is associated with the time of decay; that is the larger the magnitude; the faster the decay. If the real part of the eigenvalue is positive; the mode is periodically instable. Oppositely, the complex conjugate pair eigenvalues related to an oscillatory mode.

Eigen-values associated with; poorly damped or an unstable oscillatory mode are also named dominant modes. This is since their influence dominates the time response of that power system.

The oscillatory frequency and the related damping factor can also be determined from the eigen-values analysis. The oscillatory frequency in Hertz is given by

$$f = \frac{W}{2\Pi} \tag{4.3}$$

and the damping ratio is given by

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + W^2}} \tag{4.4}$$

The right eigenvector Φi associated with any eigenvalue λi, is an n-column vector which satisfies

$$A\Phi_{\mathrm{i}} = \lambda_i \Phi_{\mathrm{i}} \tag{4.5}$$

It is also called the right eigenvector of A-matrix associated with the eigenvalue λi. similarly; Ψi is an n-row vector that is called the left eigenvector which satisfies

$$A\psi_i = \lambda_i \psi_i \tag{4.6}$$

The eigenvectors can be normalized so that

$$\Phi_{\mathrm{i}} \psi_i = 1 \tag{4.7}$$

The modal matrices of the A-matrix can be developed as follow:

$$\Phi = [\Phi_1 \quad \Phi_2 \quad .... \quad \Phi_n] \tag{4.8}$$

$$\psi = [\psi_1 \quad \psi_2 \quad .... \quad \psi_n]^T \tag{4.9}$$

When the modal matrices are constructed and the oscillatory modes are identified the analysis can be done to find the specific rotor/angle modes. These modes contribute heavily to the low frequency oscillations. The rotor/angle modes can be identified by examining the right and left eigenvectors in along with the participation factors.

4.2 PSS Tuning, Differential Evolution (DE) Optimization

4.2.1 Differential Evolutionary Algorithm

In this thesis the DE method is proposed to be used to tune the PSS parameters T1-T4 and Kpss. DE is a parallel direct search method that uses a population of points to search for a global minimum of a function over wide search space [51]. DE like any EA uses famous operators; crossover, mutation and selection. However, DE search methods differ from other optimization methods in some aspects. The main difference is that, other methods rely on the crossover to escape from local optima and search in different zones of the search space. Whereas, DE relies on the mutation parameters as a search mechanism and selection operation to direct the search toward the prospective regions in the search space [59-70].

4.2.2 Differential Evolution Cycle

DE process starts by choosing initial random points (search space) and then produces new points, which are mutations of the existing points.

The mutations or perturbation is accomplished by adding a scaled variance between two vectors randomly selected to a third vector. The offspring (trial) vector is generated by crossing over the resultant mutation vector with the corresponding parent vectors [16], [50], [51]. Finally, the offspring vector along with its parent vector is evaluated and selected based on their fitness value, where the vector with the higher fitness value lasts and enters the next generation. This process is repeated for each vector, in the search space, to form the new generation. The search process ends when; either the true optimum converges or when the maximum iteration number is reached [16]. DE cycle is shown in figure (4.1).

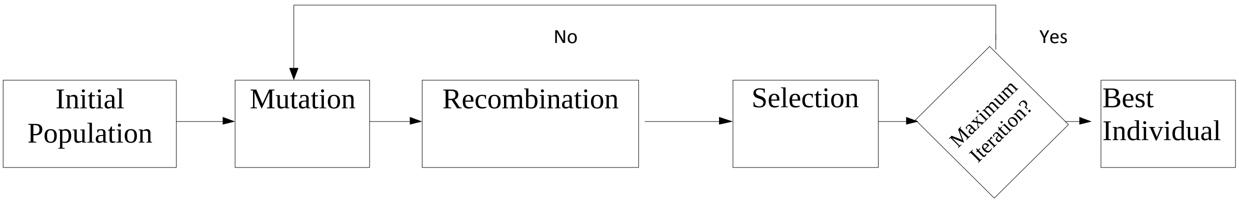

Figure 4.1: Differential Evolution cycles

Further explanation is in the following sections.

Population Structure:

The population (P_x) is consists of candidates of solutions ($X_{i,g}$) , each candidate consists of D number of optimized parameters, as shown in (4.10). [16].

$$P_{x,g} = X_{i}, g, \quad i = 0,1,..., \quad N_{i} - 1, \quad g = 0,1,... g_{\max}$$
$$X_{i}, g = x_{j}, i, g, \; j = 0,1,..., D - 1 \qquad (4.10)$$

Initialization

The optimization process in DE is begin by creating an initial population (Po) of Np vectors $X_{i,g}$ that is encoded with D parameters $x_{j,i,D}$. All the parameters in the vector are initialized using the specified lower and upper bound, as in equation (4.11) .Then, after initialization the population is mutated.

$$x_{j}^{L} \leq x_{j}, i, g \leq x_{j}^{U} \qquad (4.11)$$

Mutation:

Mutation is the process of forming mutant vectors, which are constructed from sampling four new random vectors via manipulating vectors in the present population using simple mathematics operations [51].

Recombination or Crossover:

In DE crossover is the process of recombining the mutant vector with its target vector, which result in creating a trial vector. As defined, there will be a mutant vector corresponding to each vector in the current population. Hence, by applying equation (4.12), a D-dimensional trial vector $U_{ig} = [u_{1,i,g}, u_{2,i,g}, ..., u_{D,i,g}]$, is obtained.

$$U_{j,i,g} = v_{j,i,g} - if rand_j - 0,1 \leq CR - j = j_{rand}, - j = 1,2,..., D$$

$$otherwise \quad U_{j,i,g} = x_{j,i,g} \qquad (4.12)$$

Selection

In this step DE process choose individuals that will be transferred to the next generation. The selection is applied when either choosing the vectors to recombine or when choosing survivors. Conventionally, Genetic Algorithm utilized parent selection via the fitness values, where individuals that have the highest fitness value are selected for the recombination process. This selection could trap the search to converge to a local optimum. DE employs a one to one survivor choice to overcome this problem. This selection method entails the comparing of each “trial vector” to its corresponding “target vector”. This process assures that the very best solution is kept at all the time. The selection is done based on (4.13).

$$X_{i,g+1} = U_{i,g} \quad if \quad f(U_{i,g}) \le f(X_{i,g})$$
$$otherwise \quad X_{i,g+1} = x_{i,g} \tag{4.13}$$

Termination

DE optimization process can be terminated using several ways. Following are some ways:

- Objective function met.
- Maximum generation met.

4.2.3 The PSS Objective Function:

The objective function is formulated to increase the damping factor or the damping ratio of the electromechanical mode eigenvalues. Therefore, the system response to disturbances will be improved. The function can be defined as:

J = min{ζi }; Where ζ i is the damping ratio of the electromechanical mode eigenvalue.

It is clear that the objective function will identify the minimum value of the damping ratio among electromechanical modes of all loading conditions considered in the design process. Hence, it is aimed to Maximize J in order to increase the damping ratios of electromechanical modes. This will reduce the system response overshoots and enhance the system damping characteristics.

4.2.4 Tuning Process

The tuning process of the PSS involves a number of steps to find the optimal parameters. After intense performance checks on each individual, the best performing one is selected as the optimal set of PSS parameters. In this study the MATLAB program is used to model the power system, design PSS, and tune the PSS parameter and simulating the system.

The tuning process of the PSS involves a number of steps, given below, to find the optimal parameters.

Step 1:

Set the minimum and maximum boundaries of the PSS parameters.

Step 2:

Calculate the system’s operating conditions.

Step 3:

Generate an initial population.

Step 4:

Run the system load flow to check if the system converges. If the system did not coverage, then change the operating condition.

Step 5:

Form the state space matrices and get the eigenvalues vector.

Step 6:

Identify the eigenvalues associated with the electromechanical modes, using the participation factor.

Step 7:

Evaluate the optimization problem objective function J.

Step 8:

Check for positive eigenvalues which are on the right hand side of the s-plane.

Step 9:

Check the damping of the system.

Step 10:

Check the electromechanical eigenvalue frequency.

Step 11:

Repeat step 4 to step 10, until maximum generation is reached.

After repeating Step 1 – Step 11 many time on each individual. The best answer is selected as the optimization solution. The above process is summarized in flow chart of figure (4.2) .

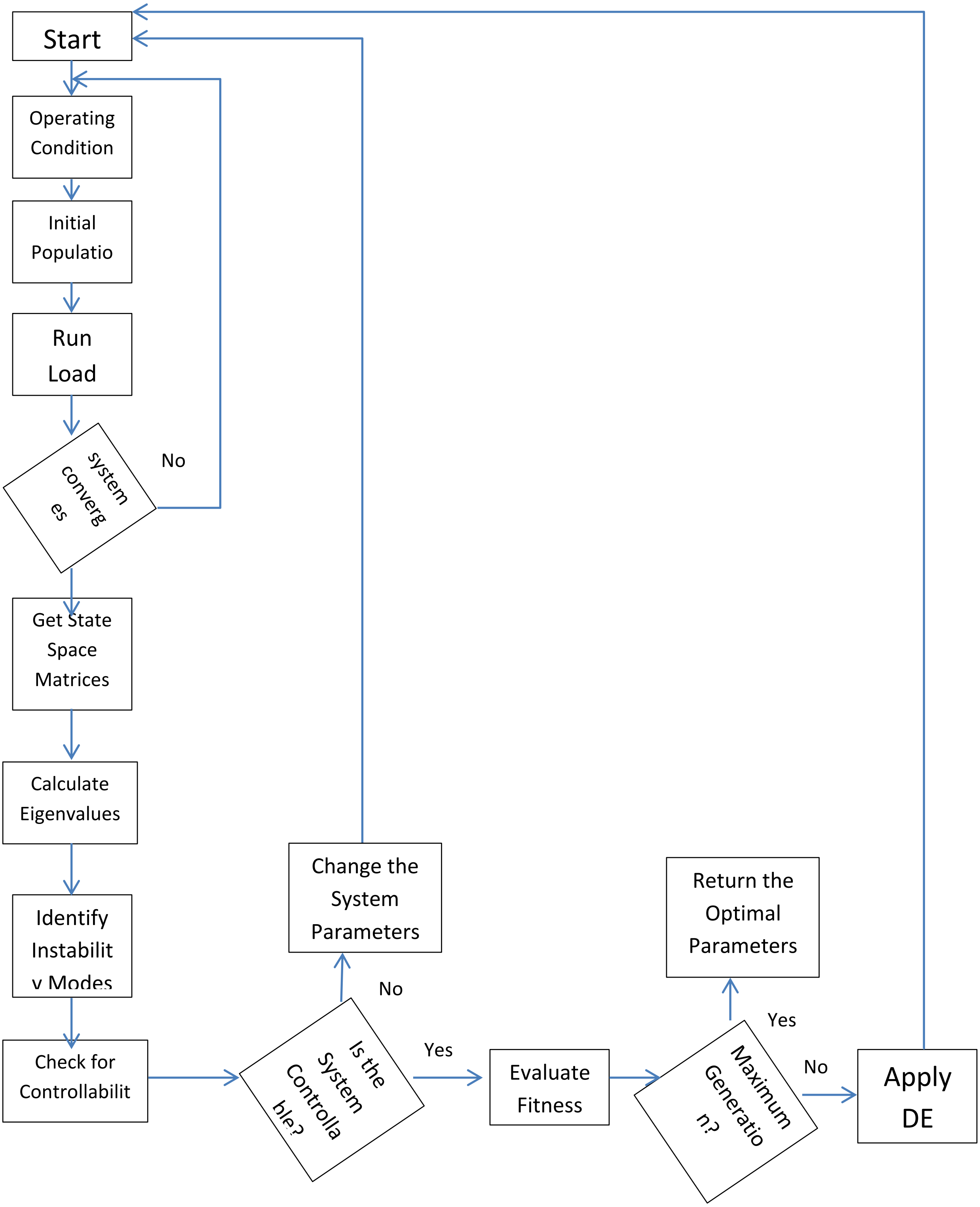

Figure 4.2: DE process summarized flow chart.

CHAPTER 5

THE LOCAL INDUSTRIAL POWER SYSTEM

The goal of this thesis is to analyze the stability of a real industrial plant at different loading. Also, it is intended to design and apply an optimized power system stabilizer to the local industrial plant to investigate the effect of the PSS on its power system stability during interruption. Moreover, in order to validate the PSS optimization package that has been delivered as part of this thesis; we applied the optimization package on standard IEEE power systems. It is therefore appropriate to introduce some information about the electric of the system local industrial plant in order to serve as a background to this thesis.

5.1 Capacity and Generation

According to the local plant Distributed Control System at the real industrial plant and according to the system operators in the plant; the installed capacity of the power system in the year 2013 was 125 MW. The installed capacity constitutes roughly 74% Cogen power, and 16% Steam power. Four cases have been defined in this thesis to represent the real scenarios of loading.

5.2 Network

The transmission system in the real plant is mainly operated at voltages 69 kV. The distribution system mainly operated at 13.8KV as shown in the below figure (5.1).

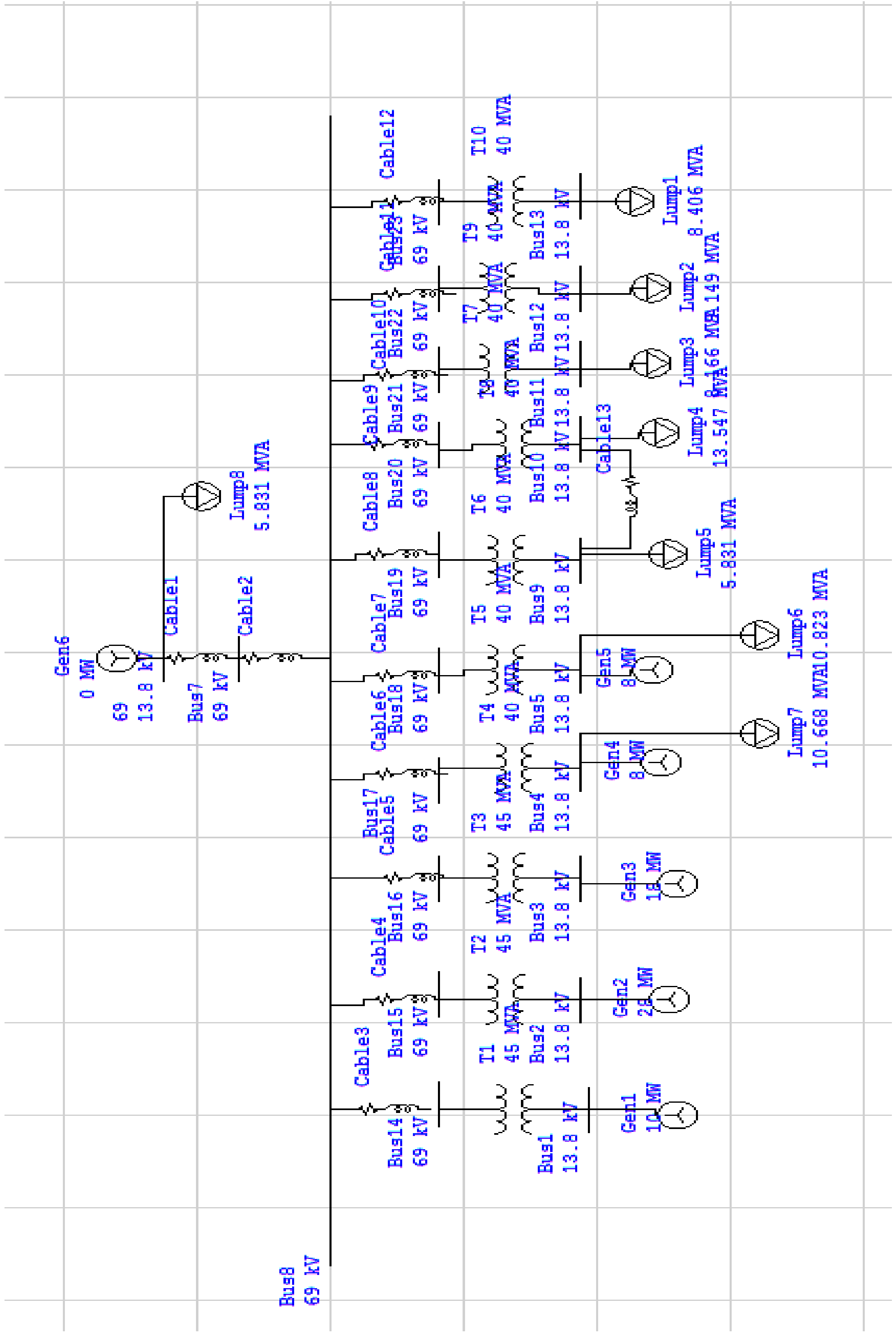

Figure 5.1: Study System.

5.3 Load

The main consumer is the industrial plant, consisting mostly of induction motors, heaters, lighting and etc... It is worth mentioning that this plant also power up a small residential camp.

5.4 Data Collection

This local plant system consists of five generators and several buses as demonstrated in figure (5.1) and the system data is given in Appendix D.

CHAPTER 6

IEEE STANDARD SYSTEMS SIMULATION RESULTS AND DISCUSSIONS

As our system is a real industrial system that was modeled and will be examined and enhanced as part of this work, we need to have a way of evaluating the modeling and the optimization process. This will be achieved by modeling and applying the PSS optimizer on a standard system to see the effect of the optimization process. Therefore, the IEEE standard systems will be used to validate the new optimizer. To achieve that, the system will be exposed to a fault at one of the buses and the power, power angular, and the angular speed deviation will be all measured before, during and after the fault. All the software work in the thesis was done with the aid of Matlab software.

6.1 IEEE 4 Machines System Analysis

Stabilizer Design

By applying the linearized power system model in chapter 3, adding the Power System Stabilizer and finally applying the DE optimization to search for optimal settings of the applied stabilizers. We found the final optimized parameters for the added power system stabilizers, which are given in Table 6.1.

Table 6.1: Optimal parameter settings

Parameter	Generator #1	Generator #2	Generator #3	Generator #3
Tw	5	5	5	5
K1	88.0129	9.4474	23.2604	2.9869
T1	0.3408	0.6512	0.2118	0.9981
T2	0.0576	0.0595	0.0580	0.0935
T3	0.0179	0.7819	0.5075	0.8696
T4	0.0661	0.0942	0.0743	0.0511

We now will apply the proposed PSSs on the nominal case.

Nominal Case:

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for nominal loading condition is given in Table 6.2 and 6.3. The bolded rows of table 6.2 represent the electromechanical (EM) mode eigenvalue and its damping ratio. Three EM shown in the system without PSS, two of these modes are classified to be local modes as they are within frequency range of 0.7-3 Hz. The remaining one is an inter area mode as its frequency is 0.57 Hz. They are with low damping factor of (8%). It is clear that after applying the proposed stabilizers the system stability greatly improved. This is because table 6.11 shows no EM modes.

Table6.2: Eigenvalues without PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-0.4996 + 6.8527i	**1.0906**	**0.0727**
-0.4646 + 6.9346i	**1.1037**	**0.0668**
-0.0017 + 3.5840i	**0.5704**	**0.0005**

Table 6.3: Eigenvalues with PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-1.5955 + 8.2963i	*1.3204*	*0.1889*
-1.5329 + 7.3257i	*1.1659*	*0.2048*
-0.8949 + 4.0734i	*0.6483*	*0.2146*

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to a 3-phase fault between bus 8&9. The fault last for 0.05 seconds. The system response shown as follow:

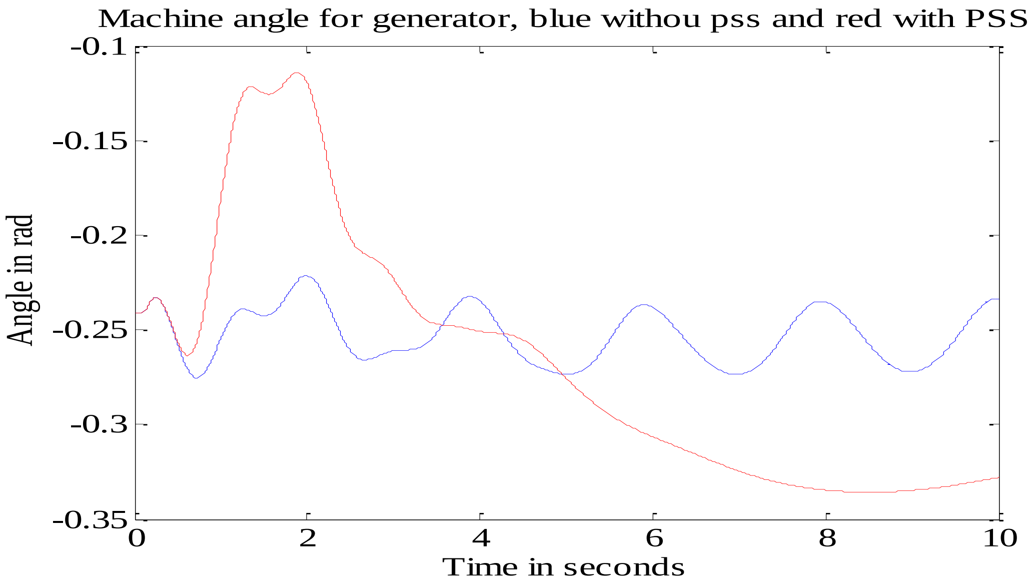

Figure 6.1: Generator 2 angle; blue line without PSS, Red line with PSS

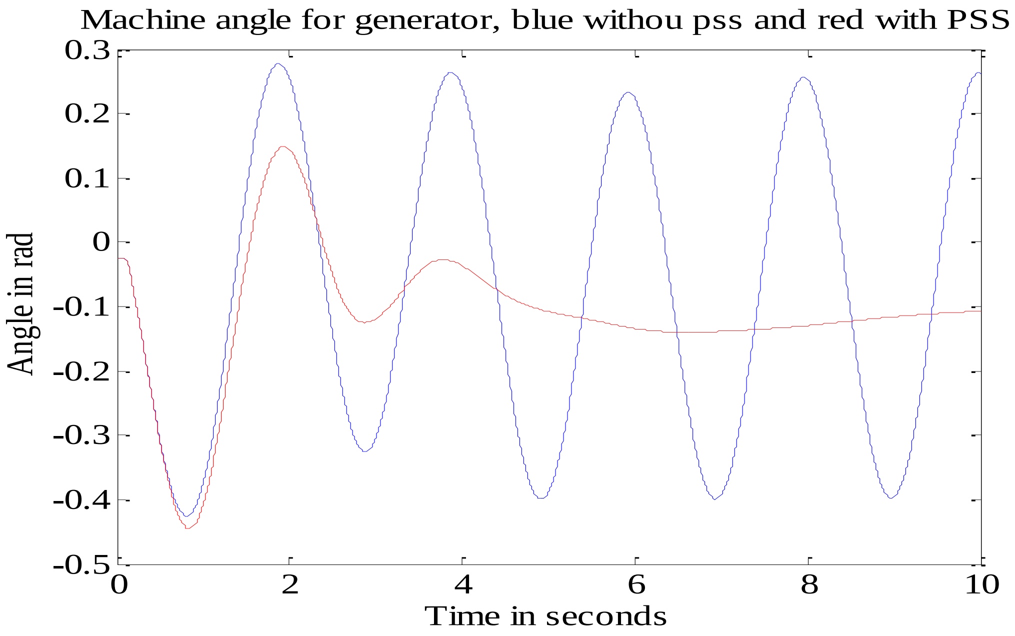

Figure 6.2: Generator 3 angle; blue line without PSS, Red line with PSS

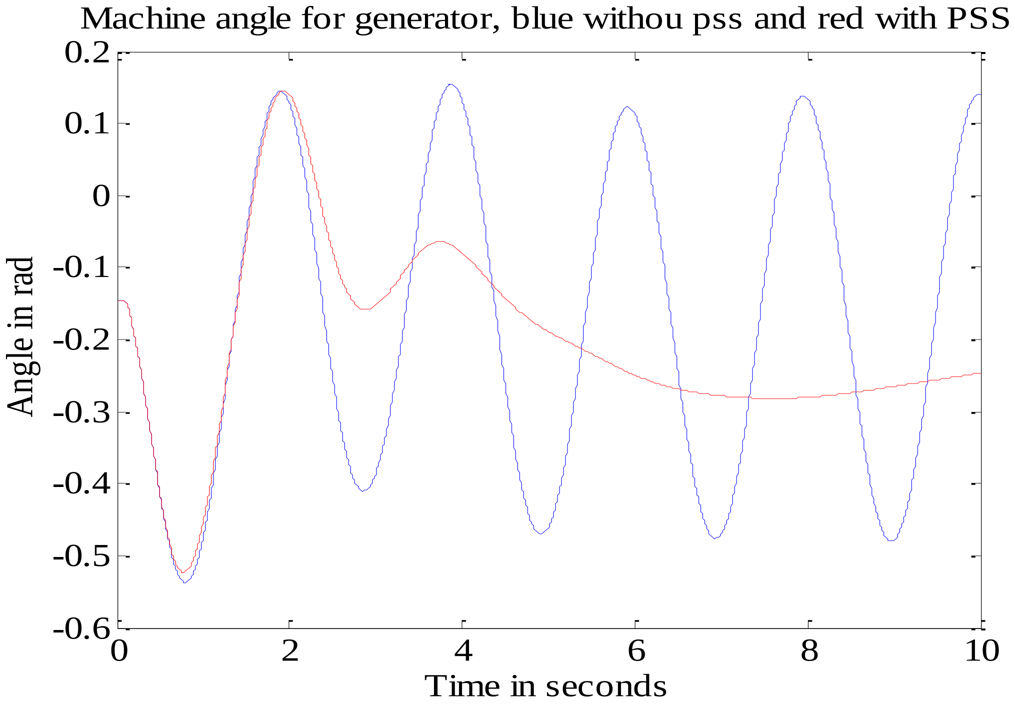

Figure 6.3: Generator 4 angle; blue line without PSS, Red line with PSS

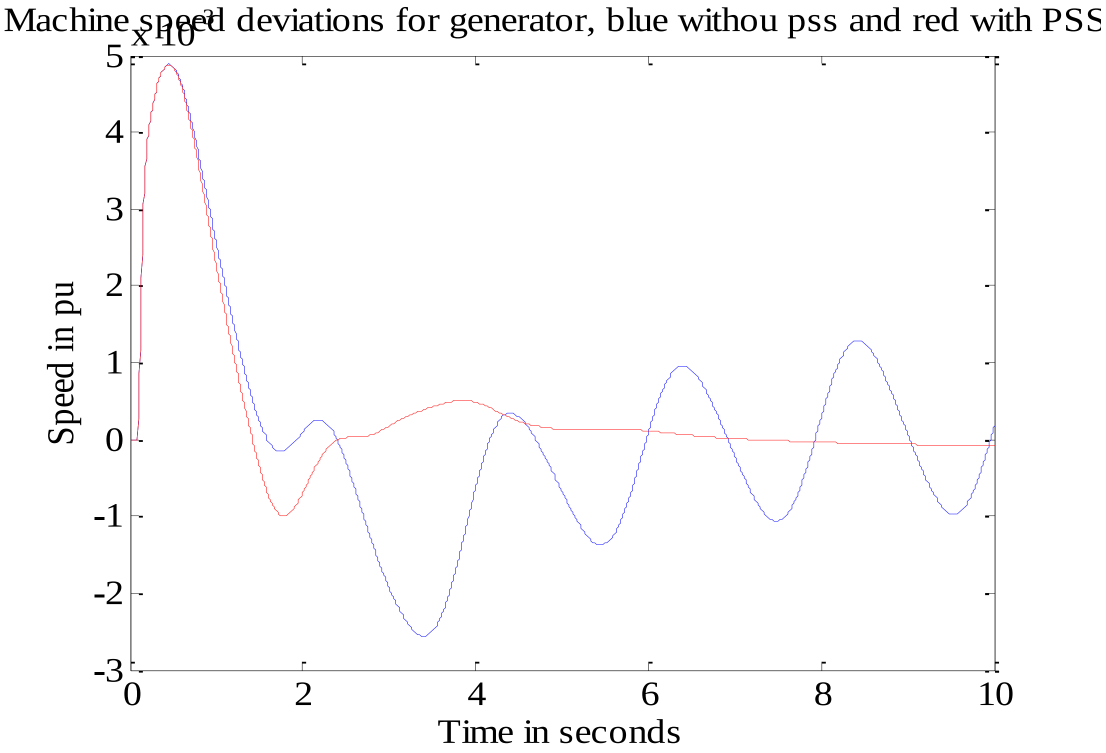

Figure 6.4: Generator 1 speed deviation; blue line without PSS, Red line with PSS

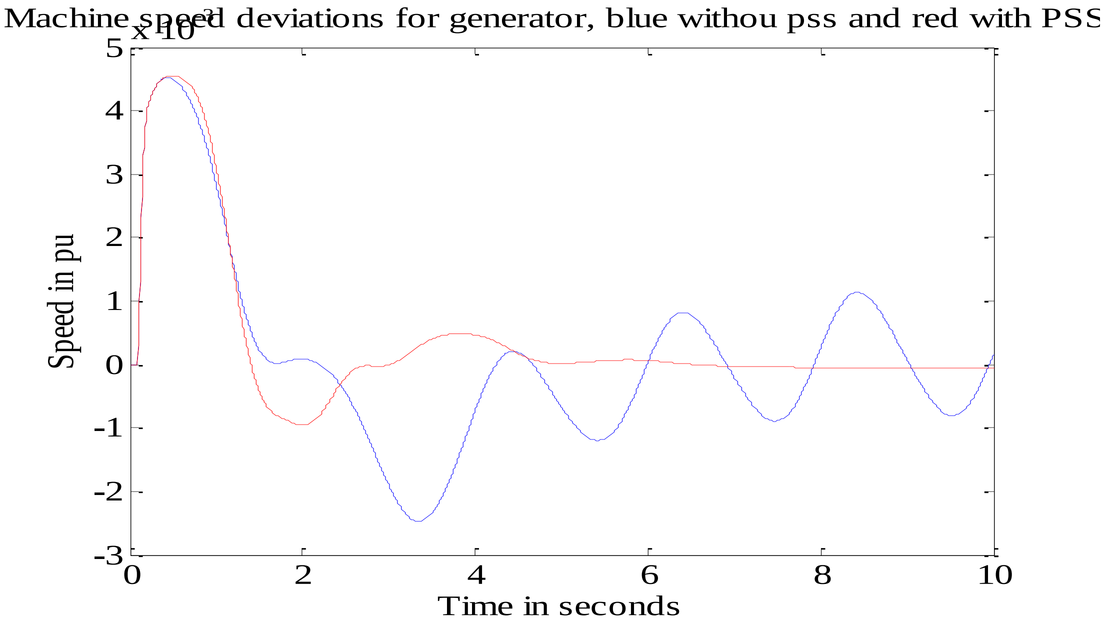

Figure 6.5: Generator 2 speed deviation; blue line without PSS, Red line with PSS

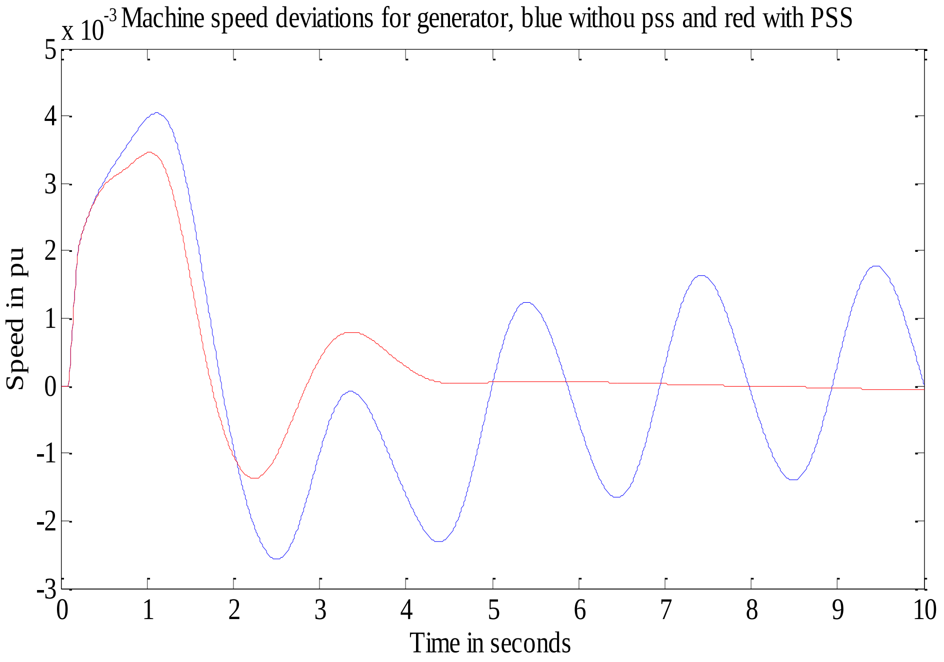

Figure 6.6: Generator 3 speed deviation; blue line without PSS, Red line with PSS

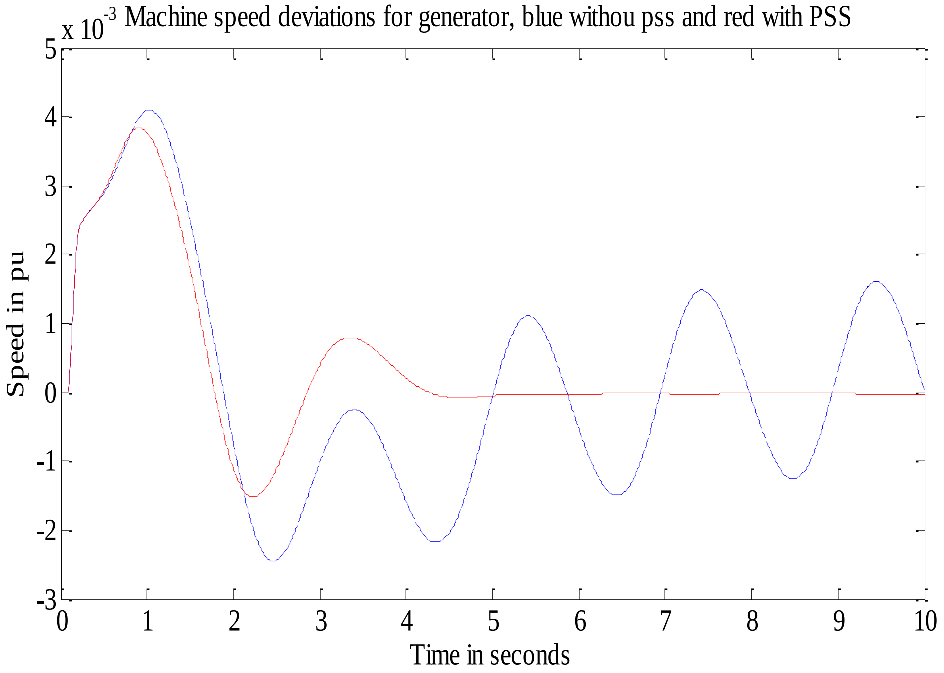

Figure 6.7: Generator 4 speed deviation; blue line without PSS, Red line with PSS

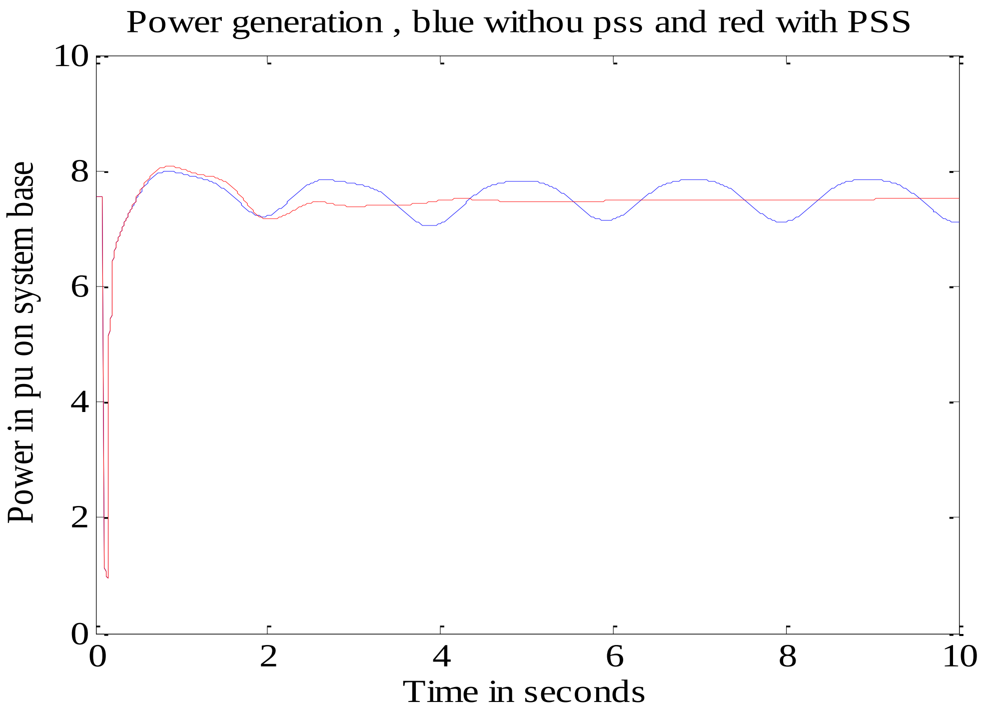

Figure 6.8: Generator 1 Power; blue line without PSS, Red line with PSS without PSS .

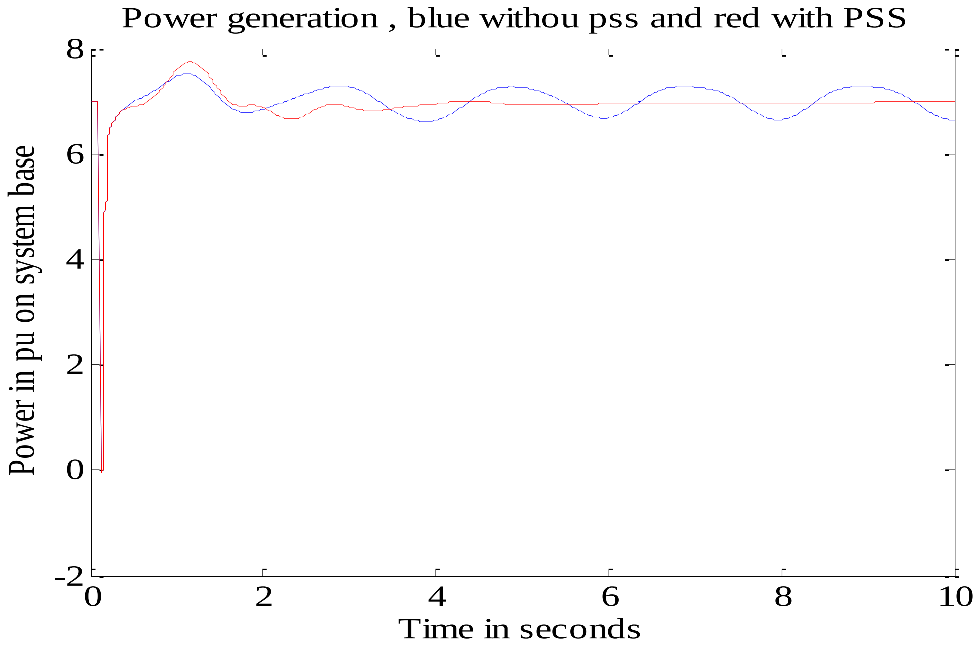

Figure 6.9: Generator 2 Power; blue line without PSS, Red line with PSS without PSS .

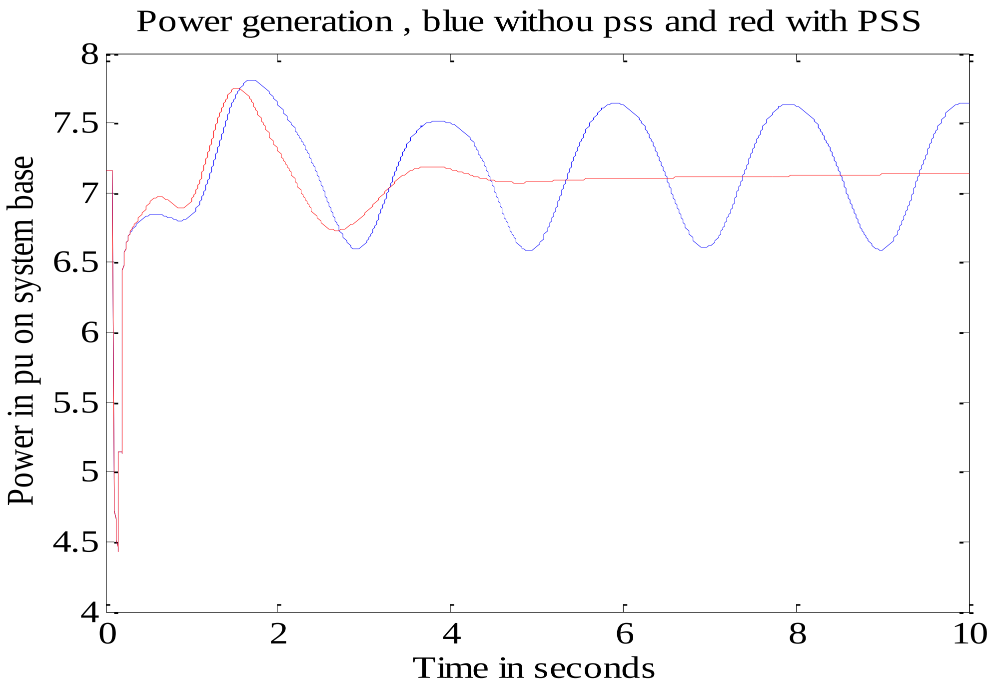

Figure 6.10: Generator 3 Power; blue line without PSS, Red line with PSS without PSS .

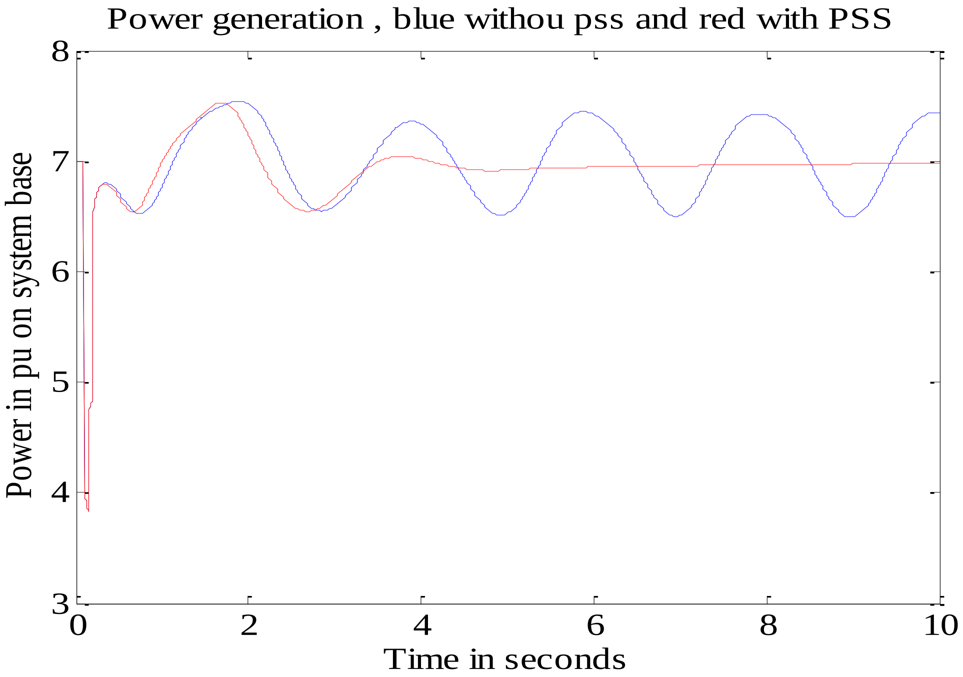

Figure 6.11: Generator 4 Power; blue line without PSS, Red line with PSS without PSS .

In this case although the system was stable without the proposed PSS, however the PSS addition improved the system stability extremely.

6.2 IEEE 16 Machines System Analysis

Stabilizer Design

By applying the linearized power system model in chapter 3, adding the Power System Stabilizer and finally applying the DE optimization to search for optimal settings of the applied stabilizers. We found the final optimized parameters for the added power system stabilizers applied to the system shown in Appendix A, which are given in Table 6.4.

Table 6.4: Optimal parameter settings

Parameter	Generator #1	Generator #2	Generator #3	Generator #4
Tw	10	10	10	10
K1	99.7690	10.8209	67.5492	55.2548
T1	0.2579	0.0624	0.1692	0.0686
T2	0.0916	0.0958	0.0972	0.0961
T3	0.1717	0.4691	0.1305	0.1312
T4	0.0546	0.0699	0.0532	0.0501
Parameter	Generator #5	Generator #6	Generator #7	Generator #8
Tw	10	10	10	10
K1	18.1306	47.0879	0.6979	0.4145
T1	0.0999	0.3786	0.1633	0.0813
T2	0.0849	0.0501	0.0539	0.0886
T3	0.1938	0.0247	0.9749	0.8927
T4	0.0670	0.0789	0.0781	0.0671

Parameter	Generator #9	Generator #10	Generator #11	Generator #12
Tw	10	10	10	10
K1	21.7844	27.1616	2.8275	16.9885
T1	0.9473	0.0639	0.3921	0.0826
T2	0.0844	0.0678	0.0504	0.0848
T3	0.2162	0.9645	0.1119	0.1474
T4	0.0995	0.0502	0.0877	0.0999
Parameter	Generator #13	Generator #14	Generator #15	Generator #16
Tw	5	5	5	5
K1	33.2312	26.4268	37.5857	26.4818
T1	0.0736	0.2684	0.2423	0.3572
T2	0.0500	0.0889	0.0900	0.0846
T3	0.1625	0.1826	0.0894	0.0648
T4	0.0579	0.0806	0.0920	0.0501

We now will apply the proposed PSSs on the nominal case.

Nominal Case:

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for nominal loading condition is given in Table 6.5 and 6.6. The bolded rows of table 6.5 represent the electromechanical (EM) mode eigenvalue and its damping ratio. The system found to be unstable as there are many eigenvalues with positive real part. That is there are many eigenvalues in the right side of the s-plane. Moreover, there are many EM shown in the system without PSS, they are classified to be local and inter area modes

.They are with low damping factor of (less than1%). It is clear that after applying the proposed stabilizers the system stability greatly improved and the system become stable. This is because table 6.6 shows no EM modes.

Table 6.5: Eigenvalues without PSS

Eigenvalues	Frequency (HZ)	Damping Ratio
0.3008 +11.6845i	**1.8596**	**-0.0257**
-2.1289 +12.1147i	1.9281	0.1731
-0.5061 + 9.6274i	**1.5323**	**0.0525**
-0.6291 + 9.3425i	**1.4869**	**0.0672**
-0.8703 + 8.7224i	**1.3882**	**0.0993**
-0.0336 + 8.2057i	**1.3060**	**0.0041**
0.0004 + 8.0629i	**1.2832**	**-0.0000**
0.4160 + 6.7896i	**1.0806**	**-0.0612**
0.0580 + 6.9360i	**1.1039**	**-0.0084**
-0.0091 + 7.3577i	**1.1710**	**0.0012**
-0.4714 + 7.4313i	**1.1827**	**0.0633**
0.0669 + 4.5079i	**0.7175**	**-0.0148**
-0.4288 + 4.9864i	**0.7936**	**0.0857**
-0.2604 + 3.3163i	**0.5278**	**0.0783**
-0.1548 + 2.8426i	**0.4524**	**0.0544**
-0.2348 + 0.8617i	0.1371	0.2628

Table 6.6: Eigenvalues with PSS

Eigenvalues	Frequency (HZ)	Damping Ratio
-3.3034 +17.5099i	2.7868	0.1854
-1.0515 + 8.9574i	1.4256	0.1166
-1.0617 + 8.1780i	1.3016	0.1287
-0.2436 + 2.2862i	0.3639	0.1060

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to a 3-phase fault between bus 1&2. The fault last for 0.05 seconds. The system response shown as follow:

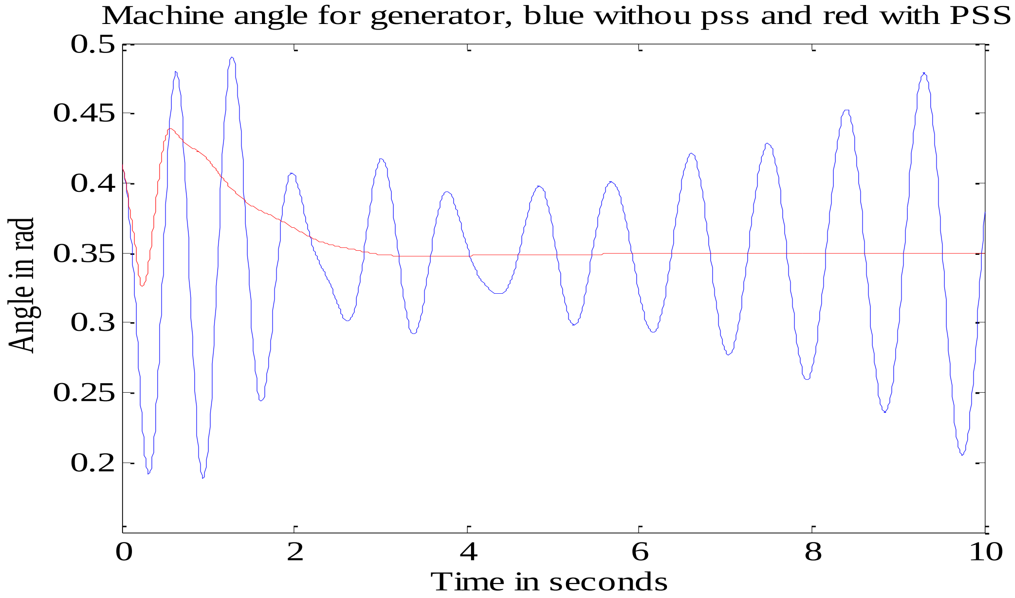

Figure 6.12: Generator 2 angle; blue line without PSS, Red line with PSS

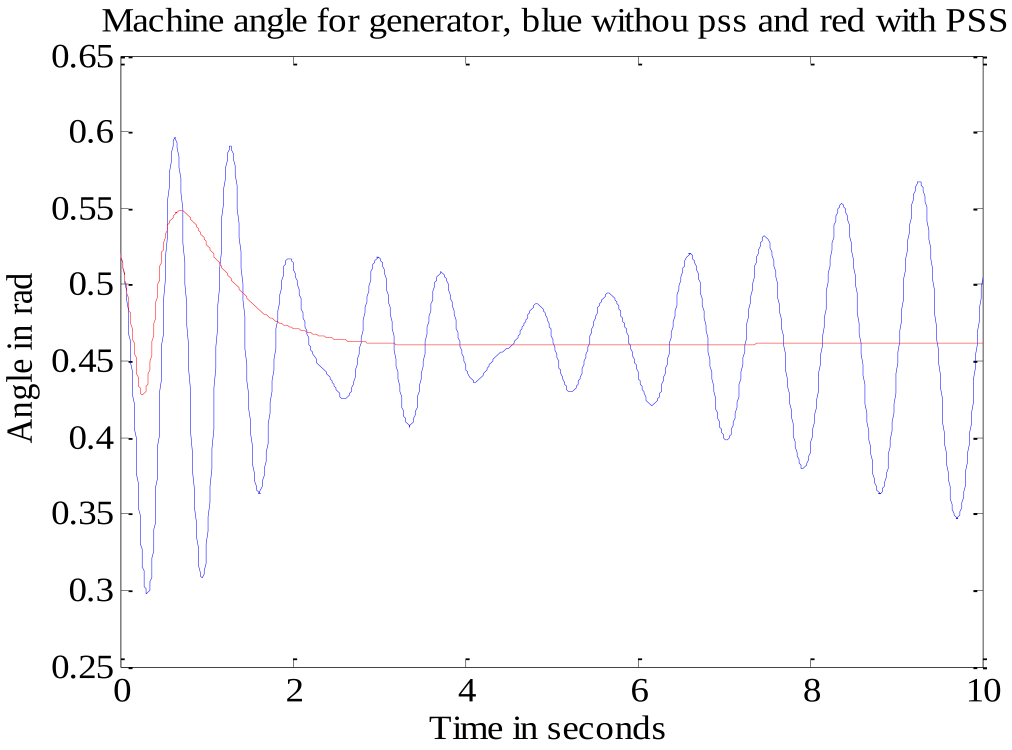

Figure 6.13: Generator 3 angle; blue line without PSS, Red line with PSS

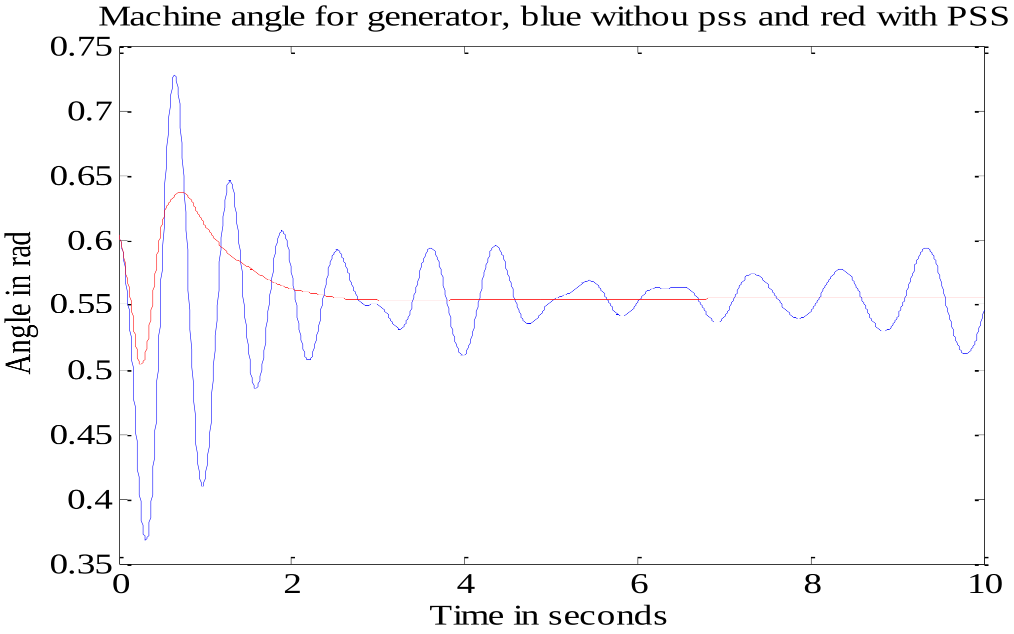

Figure 6.14: Generator 4 angle; blue line without PSS, Red line with PSS

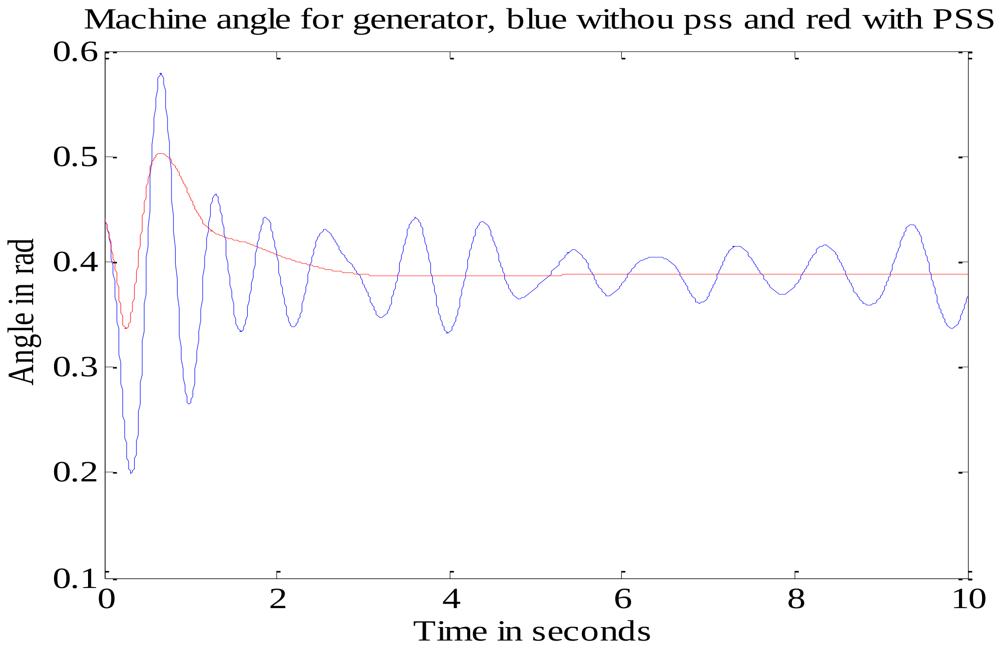

Figure 6.15: Generator 5 angle; blue line without PSS, Red line with PSS

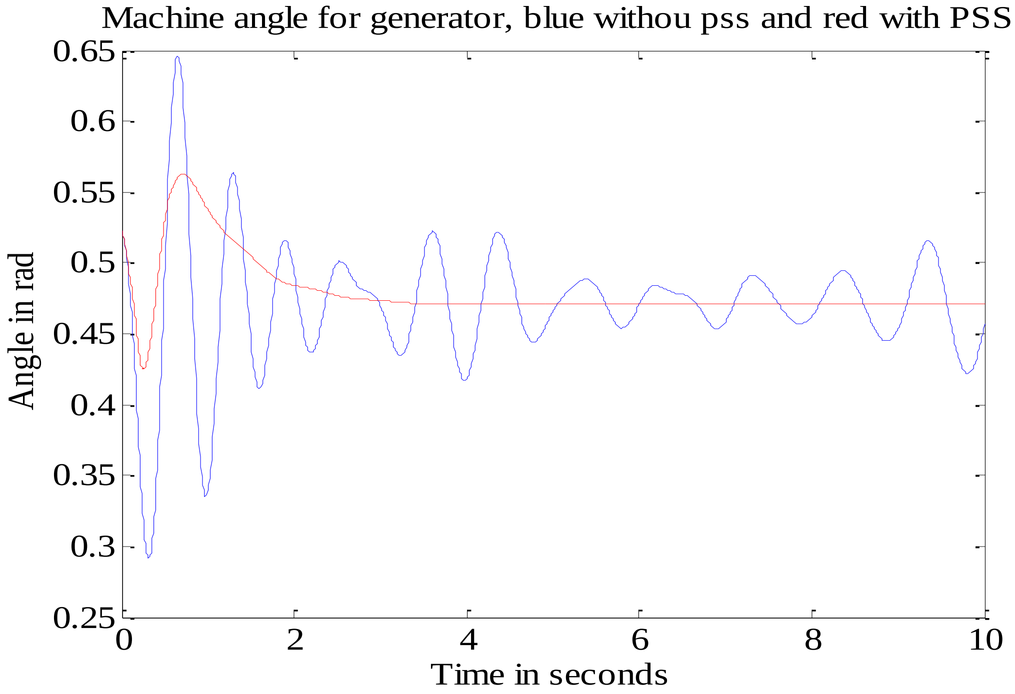

Figure 6.16: Generator 6 angle; blue line without PSS, Red line with PSS

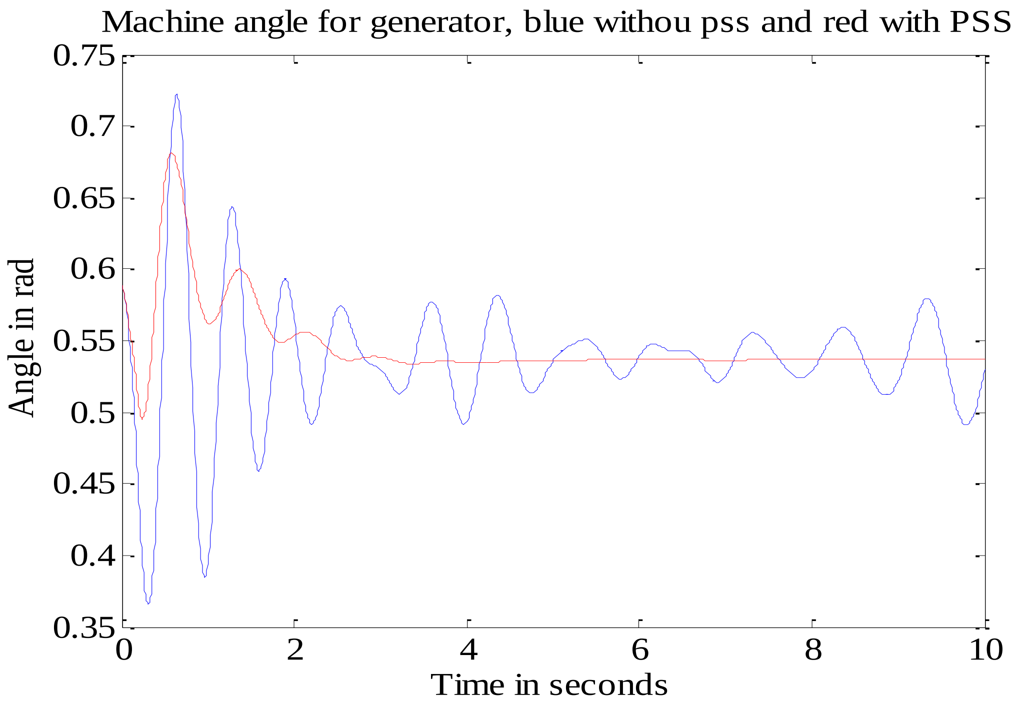

Figure 6.17: Generator 7 angle; blue line without PSS, Red line with PSS

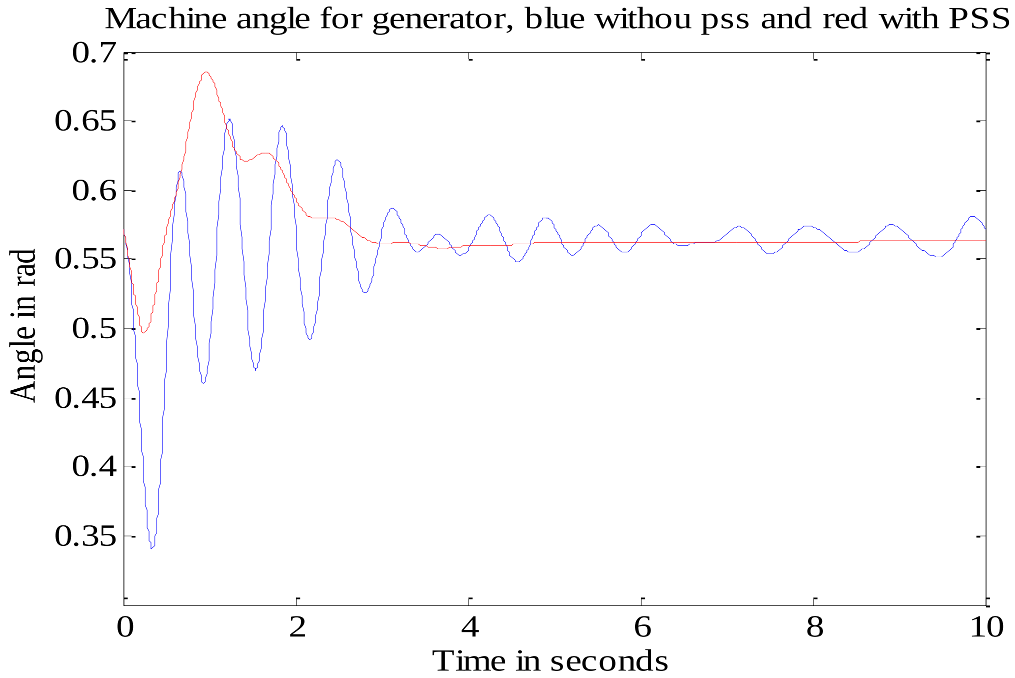

Figure 6.18: Generator 8 angle; blue line without PSS, Red line with PSS

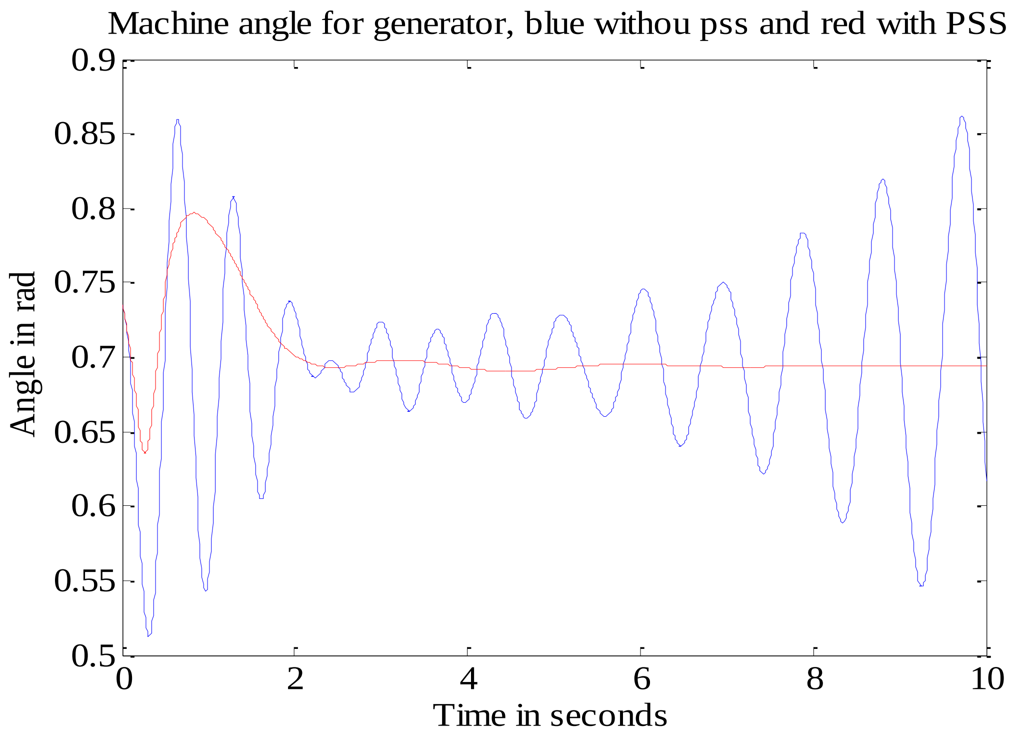

Figure 6.19: Generator 9 angle; blue line without PSS, Red line with PSS

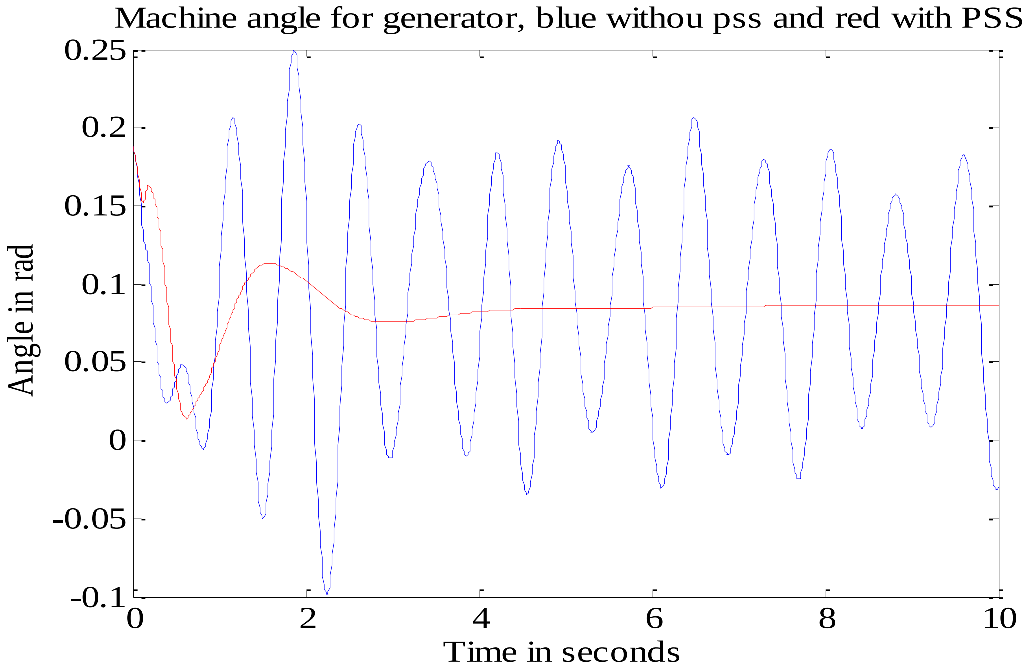

Figure 6.20: Generator 10 angle; blue line without PSS, Red line with PSS

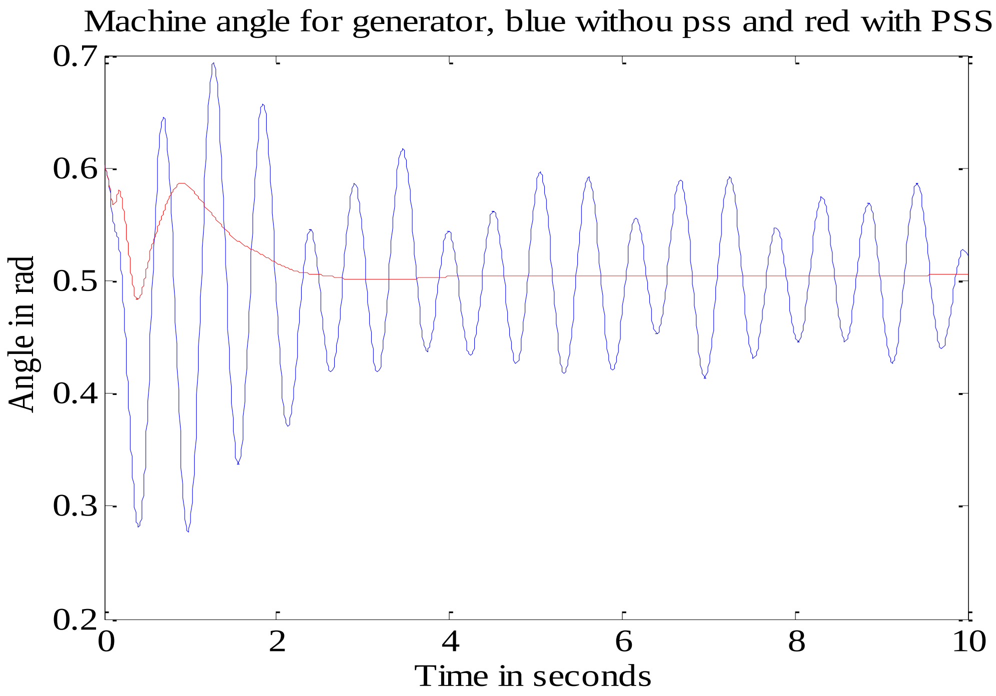

Figure 6.21: Generator 11 angle; blue line without PSS, Red line with PSS

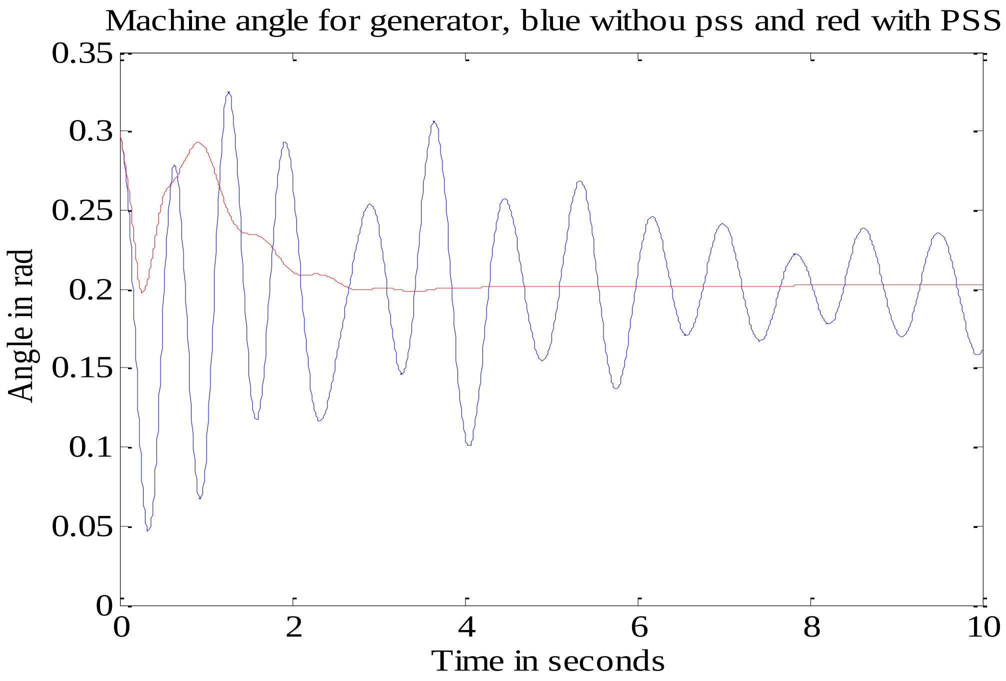

Figure 6.22: Generator 12 angle; blue line without PSS, Red line with PSS

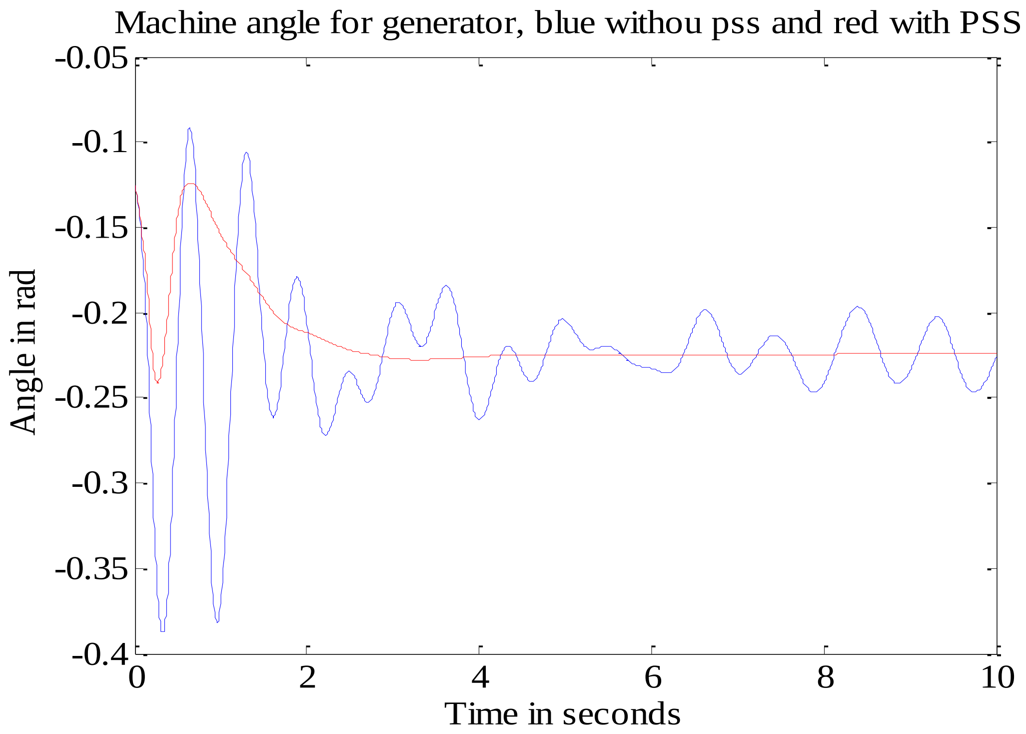

Figure 6.23: Generator 13 angle; blue line without PSS, Red line with PSS

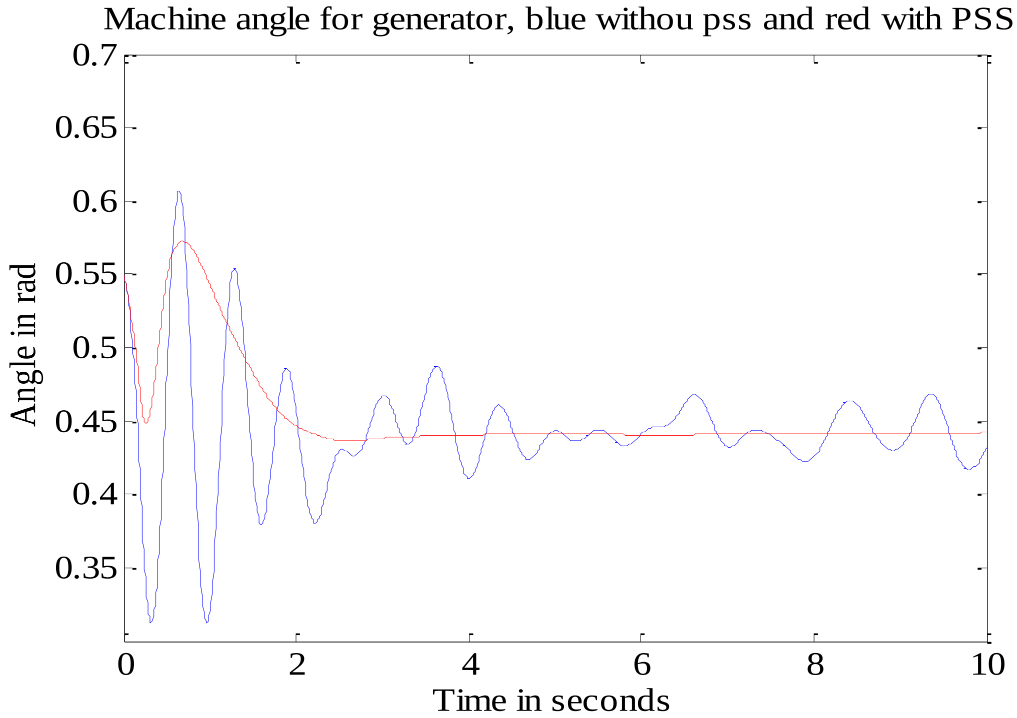

Figure 6.24: Generator 14 angle; blue line without PSS, Red line with PSS

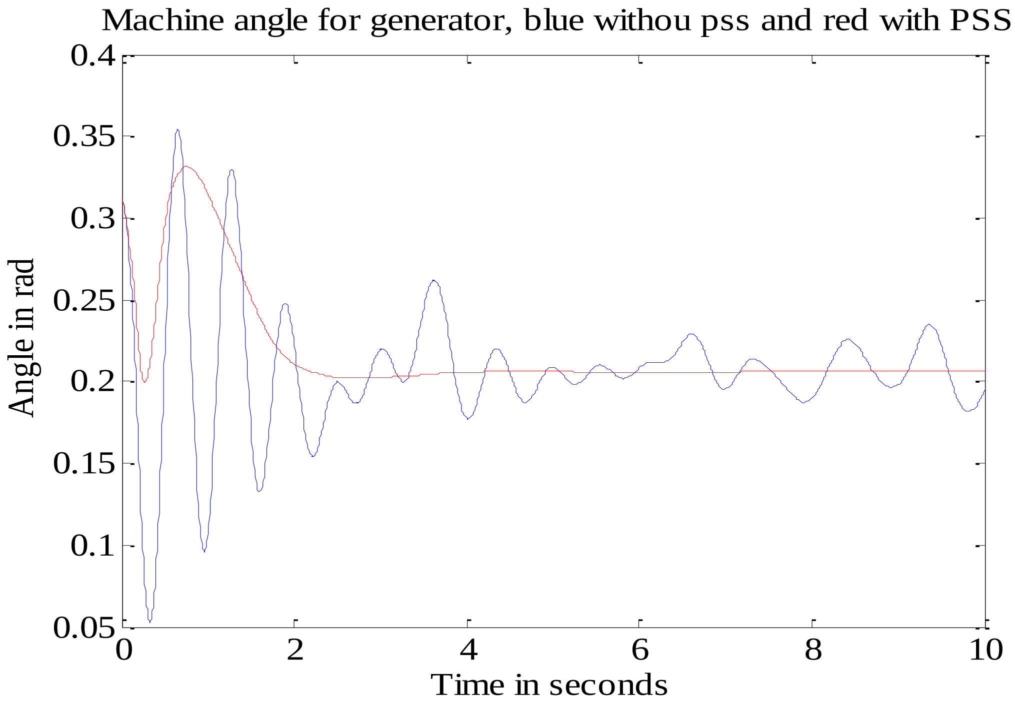

Figure 6.25: Generator 15 angle; blue line without PSS, Red line with PSS

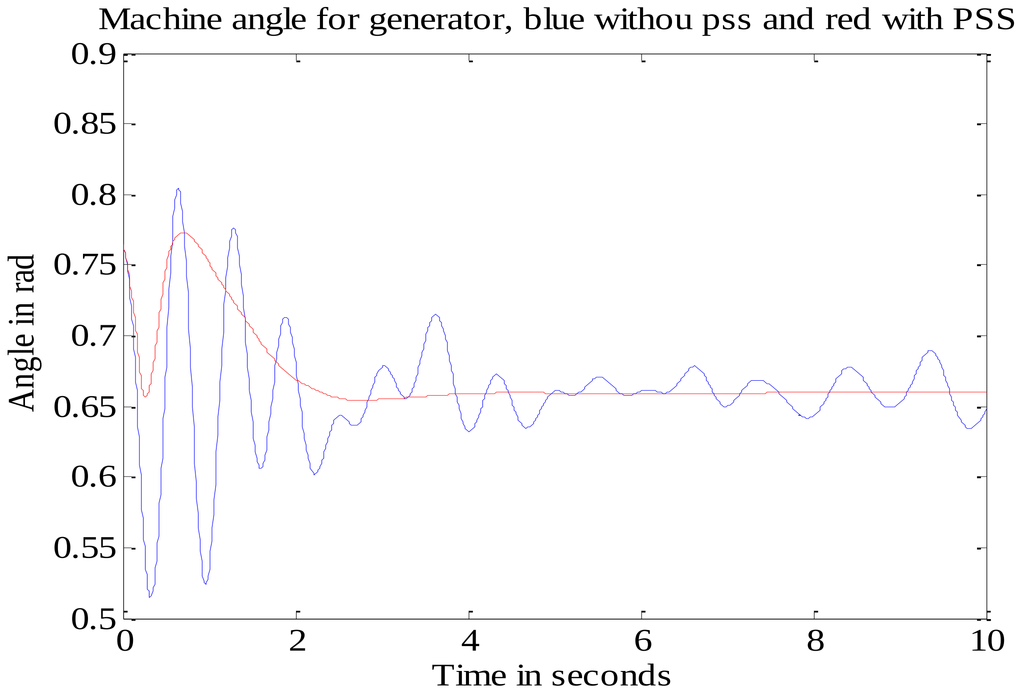

Figure 6.26: Generator 16 angle; blue line without PSS, Red line with PSS

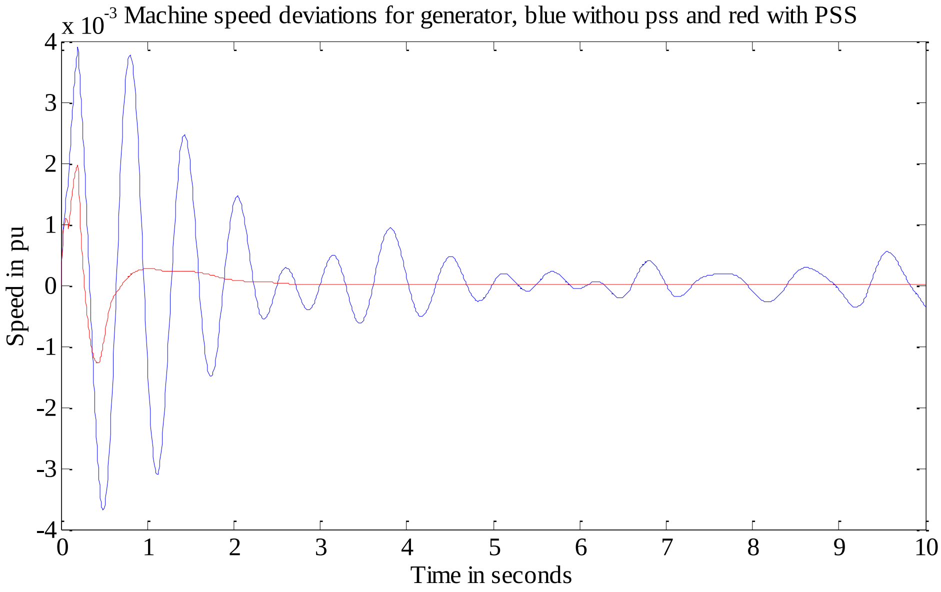

Figure 6.27: Generator 1 speed deviation; blue line without PSS, Red line with PSS

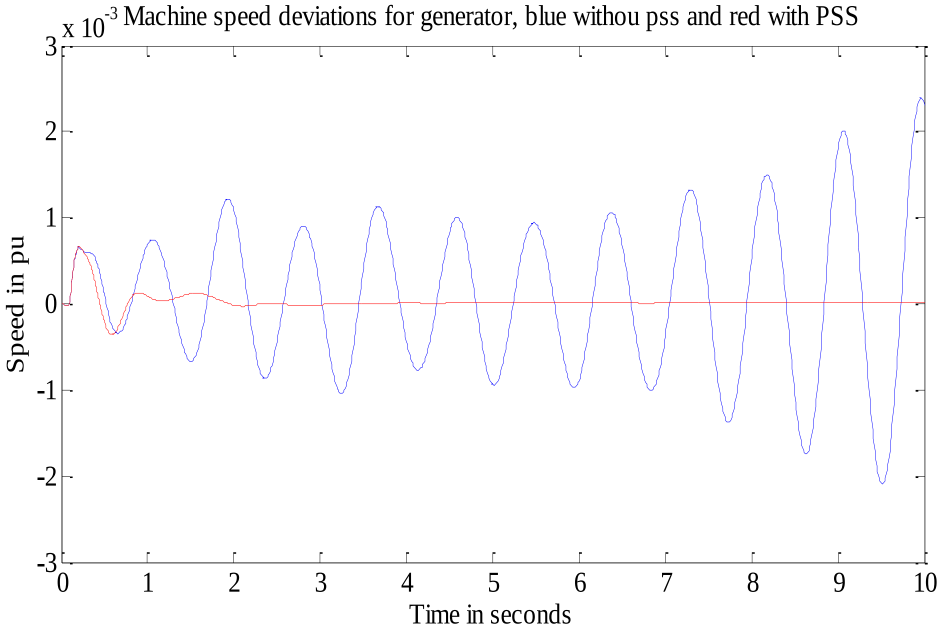

Figure 6.28: Generator 2 speed deviation; blue line without PSS, Red line with PSS

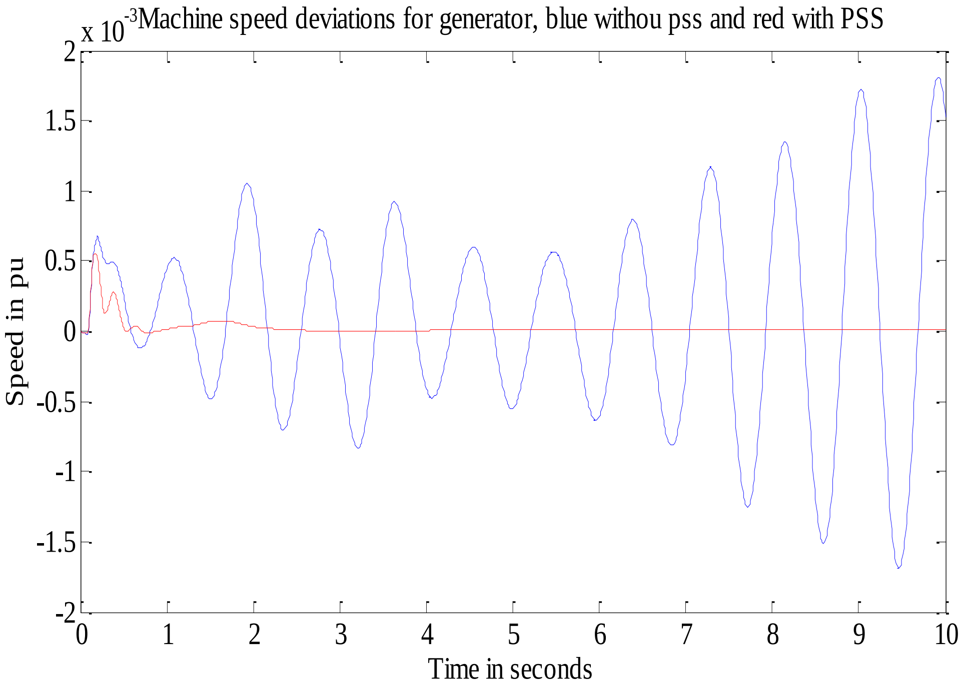

Figure 6.29: Generator 3 speed deviation; blue line without PSS, Red line with PSS

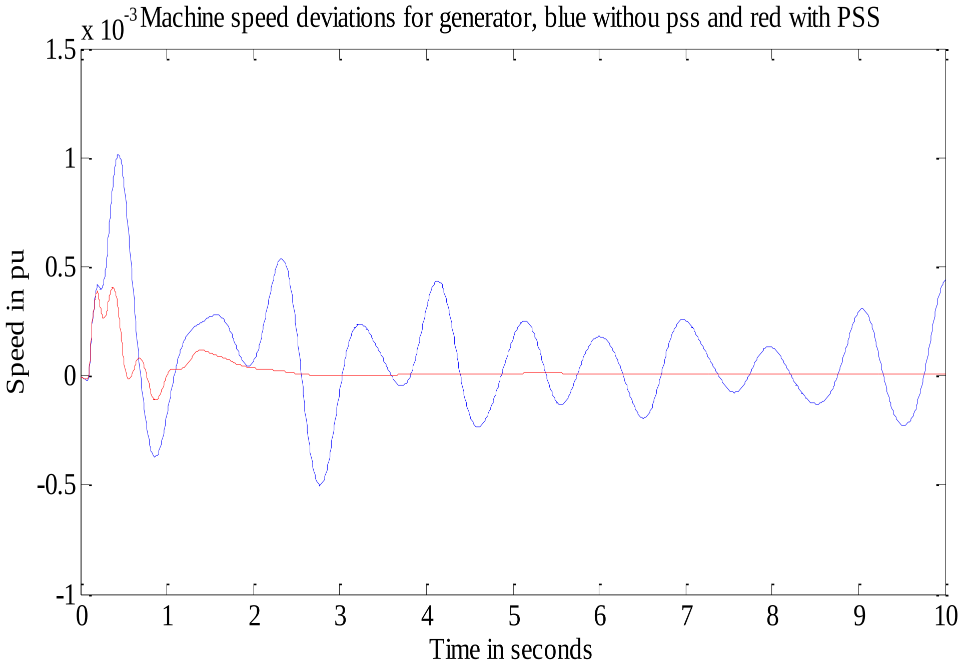

Figure 6.30: Generator 4 speed deviation; blue line without PSS, Red line with PSS

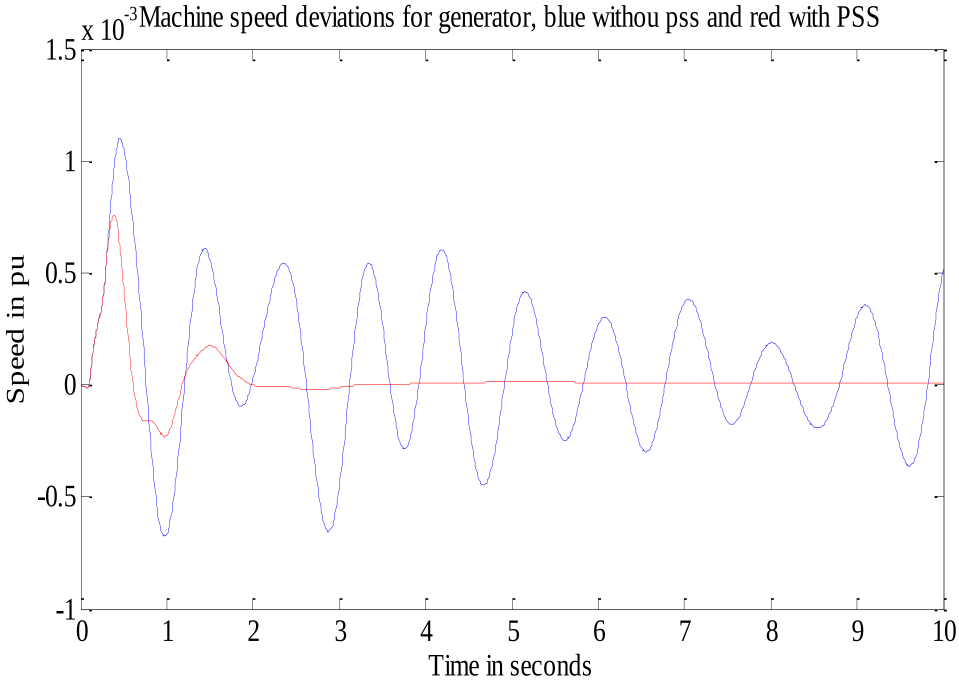

Figure 6.31: Generator 5 speed deviation; blue line without PSS, Red line with PSS

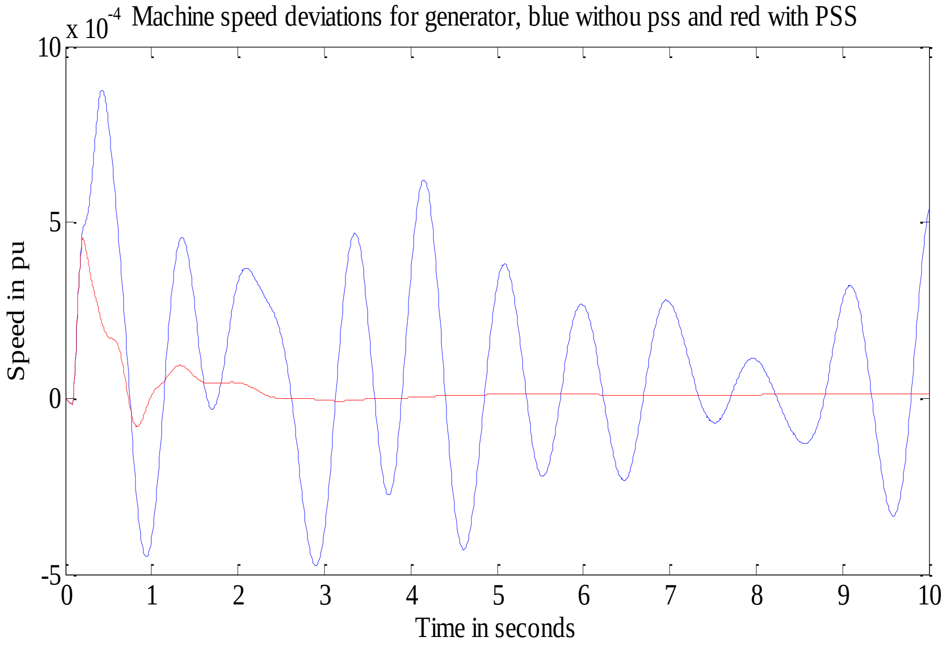

Figure 6.32: Generator 6 speed deviation; blue line without PSS, Red line with PSS

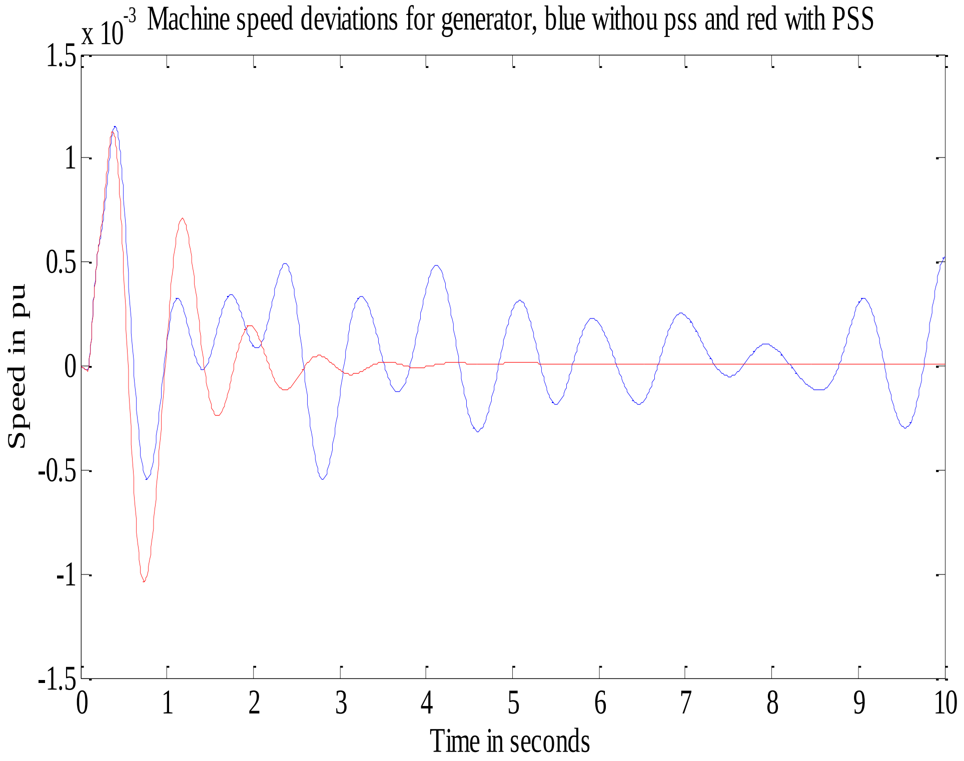

Figure 6.33: Generator 7 speed deviation; blue line without PSS, Red line with PSS

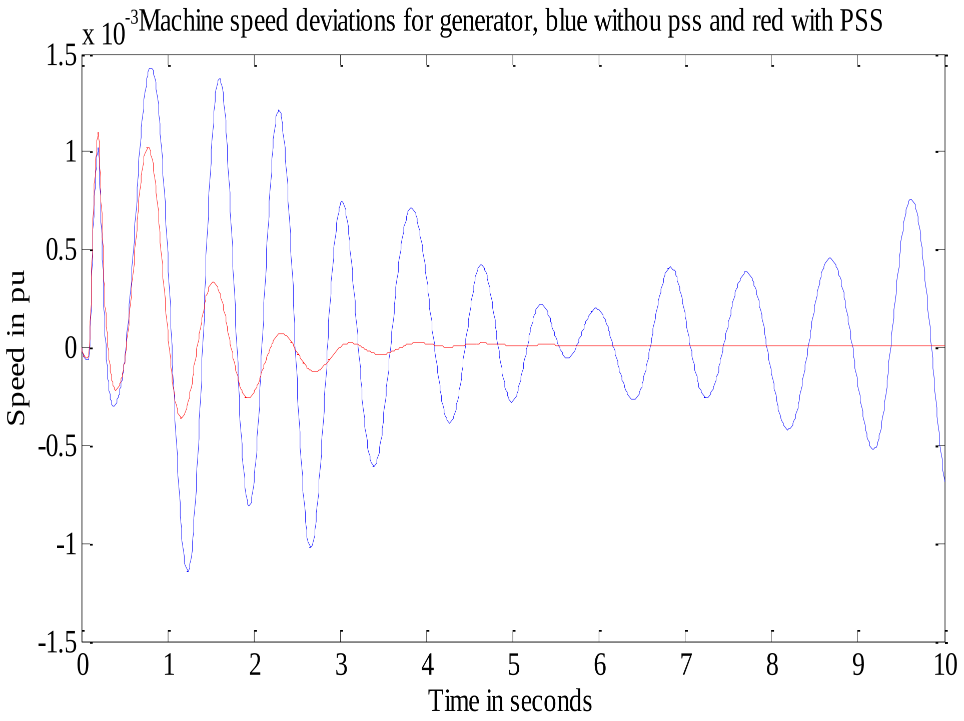

Figure 6.34: Generator 8 speed deviation; blue line without PSS, Red line with PSS

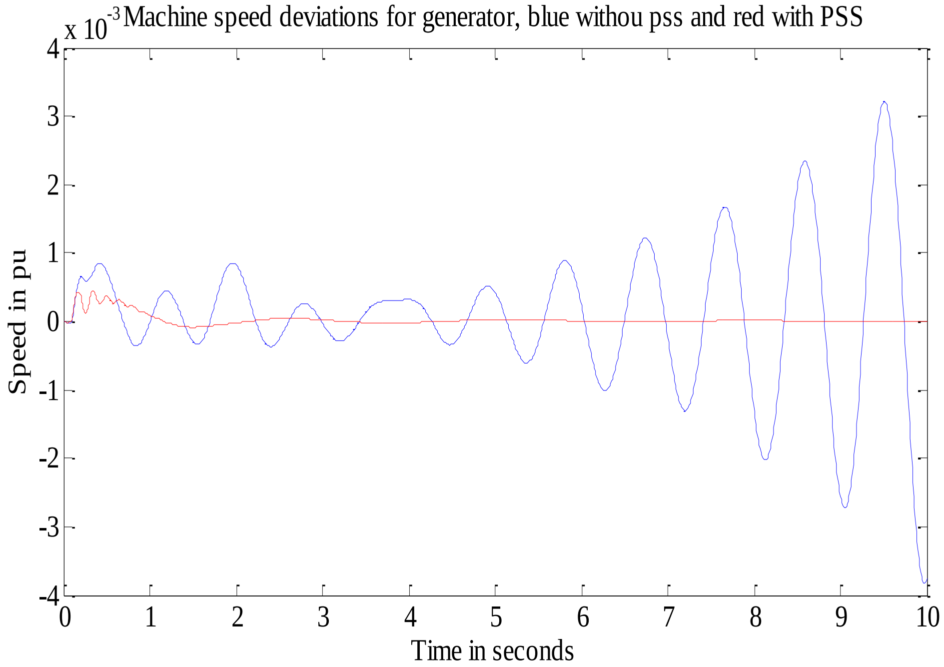

Figure 6.35: Generator 9 speed deviation; blue line without PSS, Red line with PSS

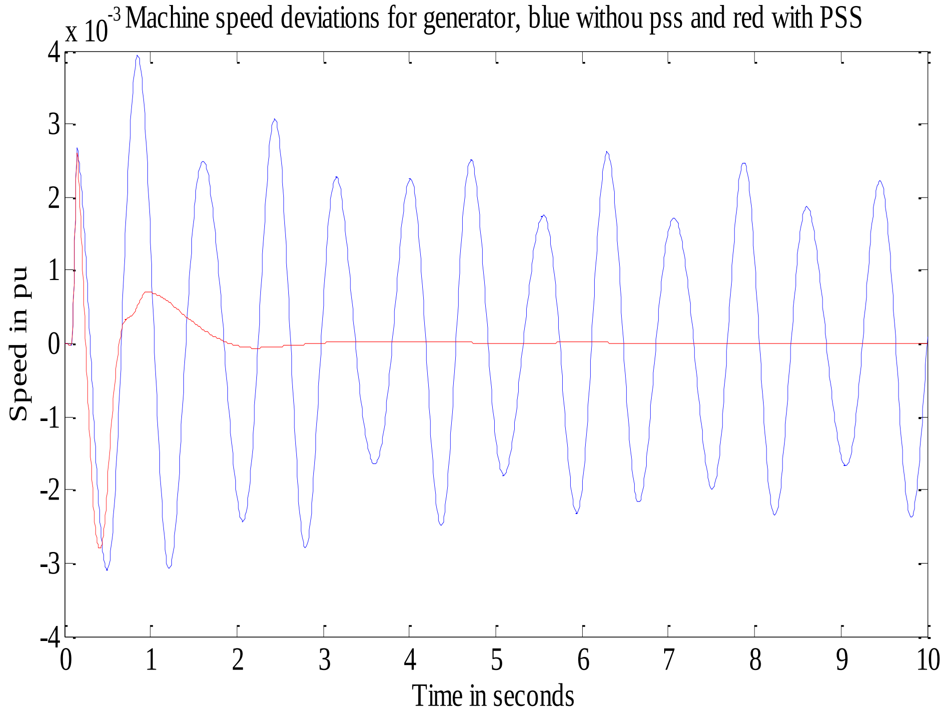

Figure 6.36: Generator 10 speed deviation; blue line without PSS, Red line with PSS

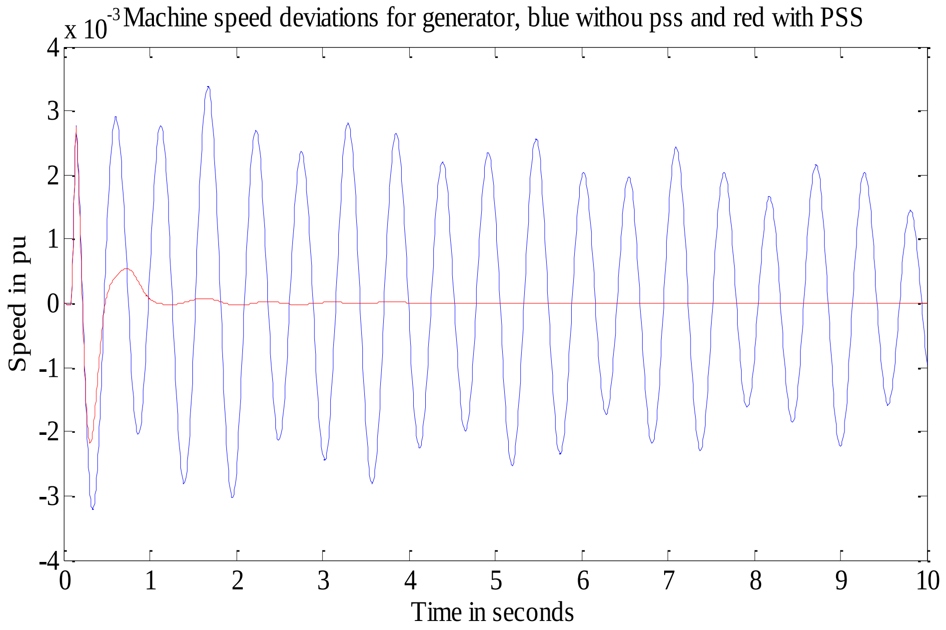

Figure 6.37: Generator 11 speed deviation; blue line without PSS, Red line with PSS

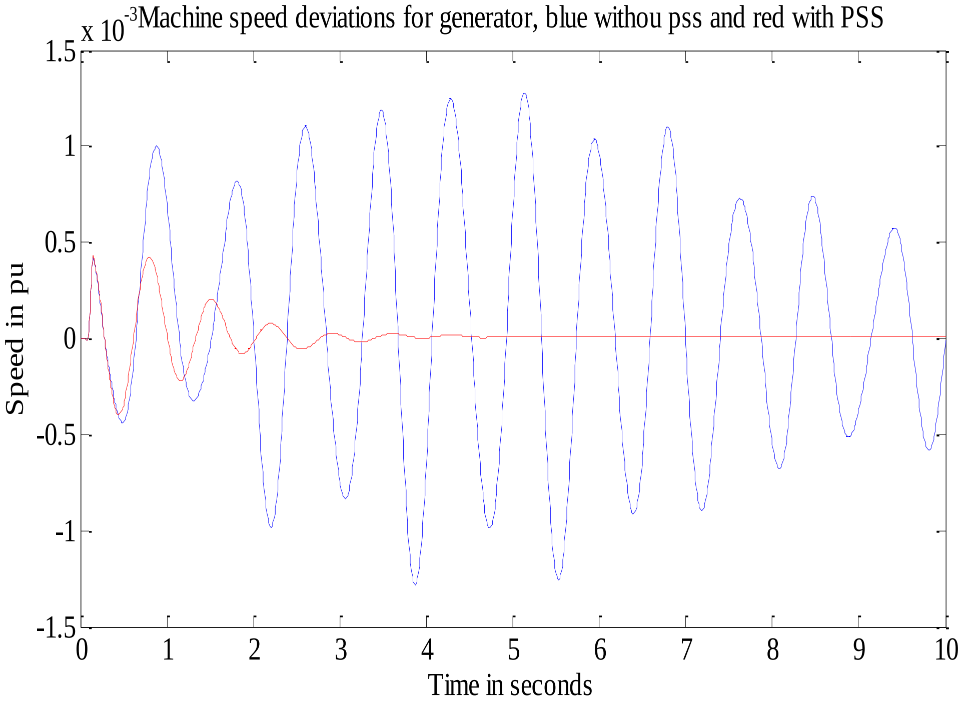

Figure 6.38: Generator 12 speed deviation; blue line without PSS, Red line with PSS

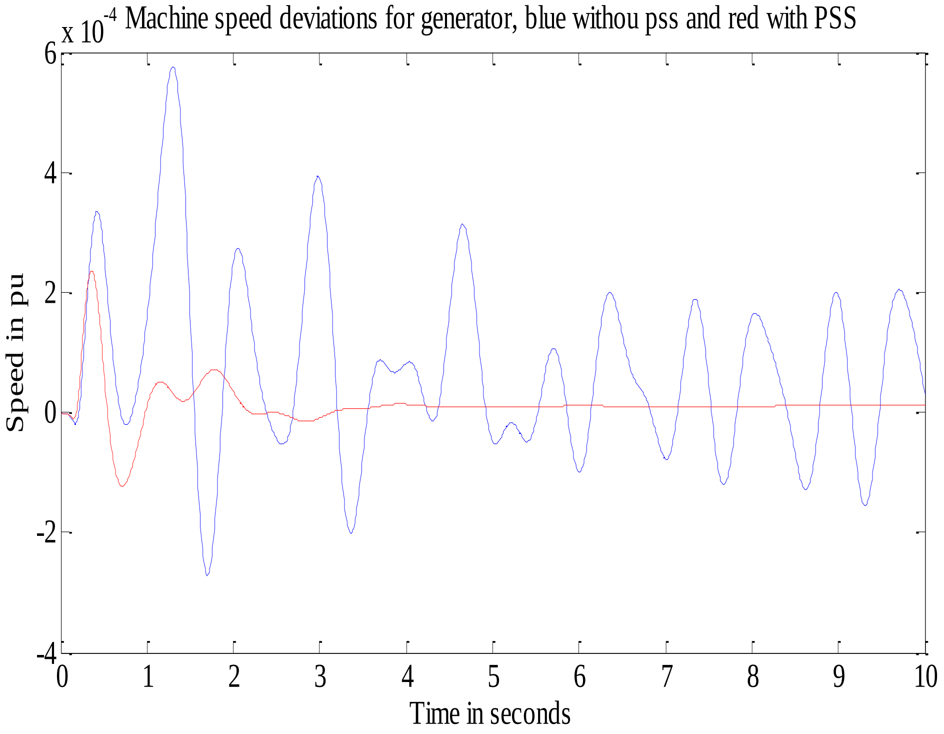

Figure 6.39: Generator 13 speed deviation; blue line without PSS, Red line with PSS

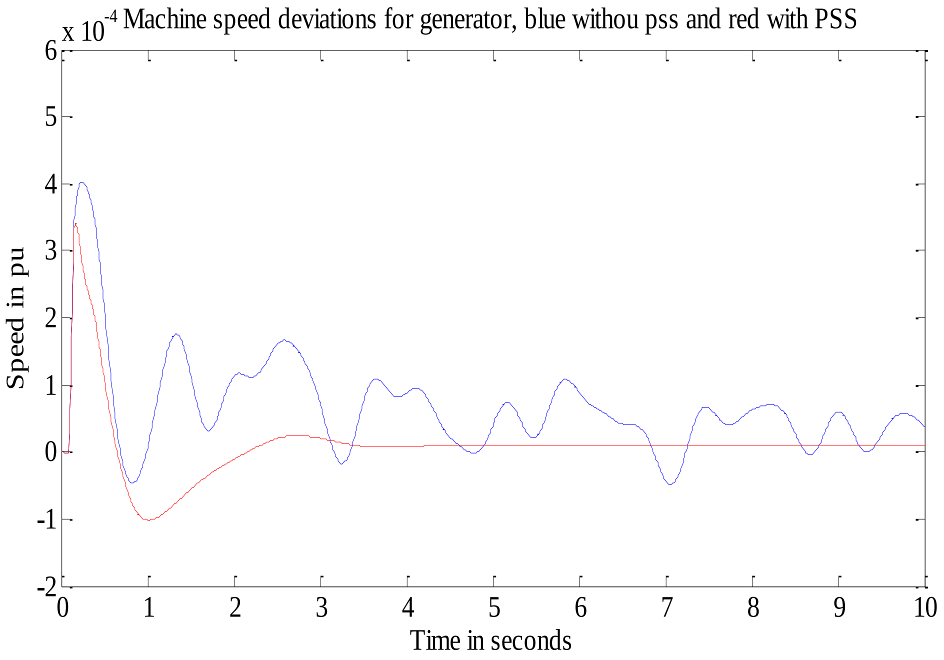

Figure 6.40: Generator 14 speed deviation; blue line without PSS, Red line with PSS

Figure 6.41: Generator 15 speed deviation; blue line without PSS, Red line with PSS

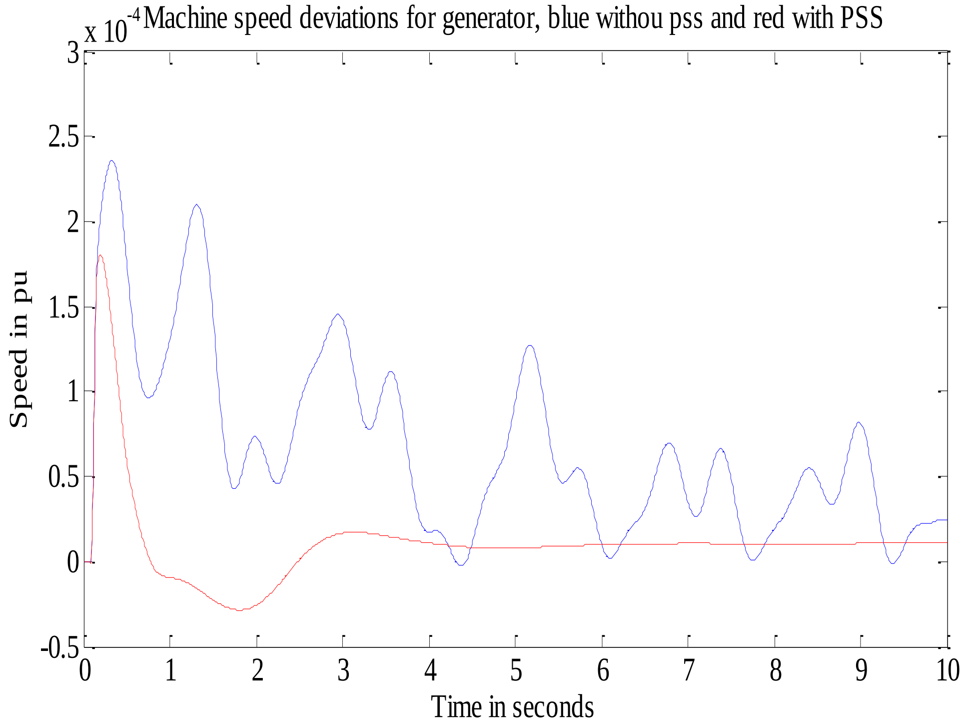

Figure 6.42: Generator 16 speed deviation; blue line without PSS, Red line with PSS

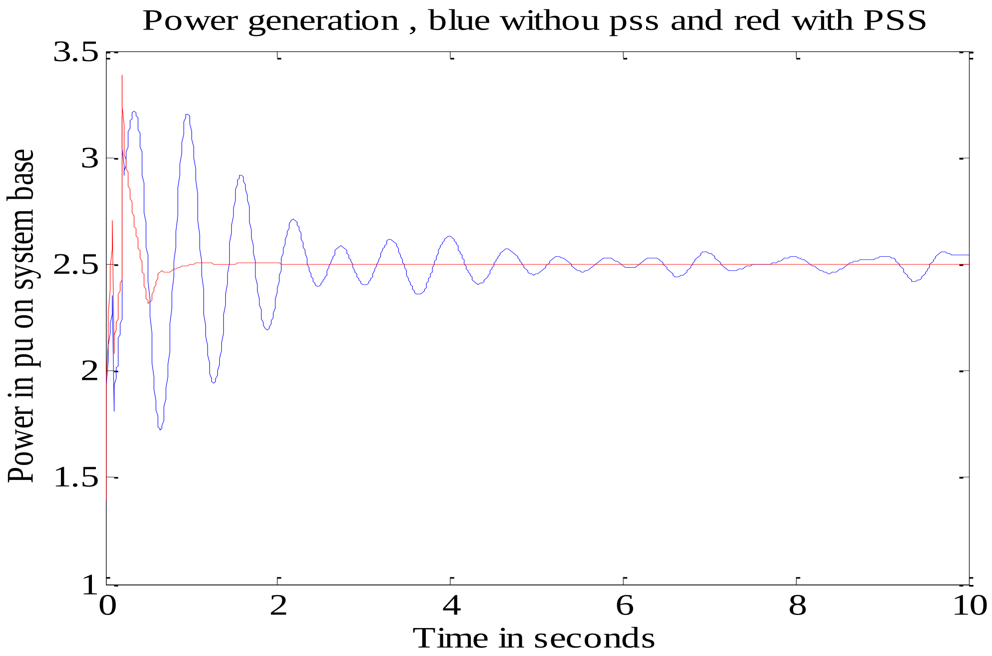

Figure 6.43: Generator 1 Power; blue line without PSS, Red line with PSS

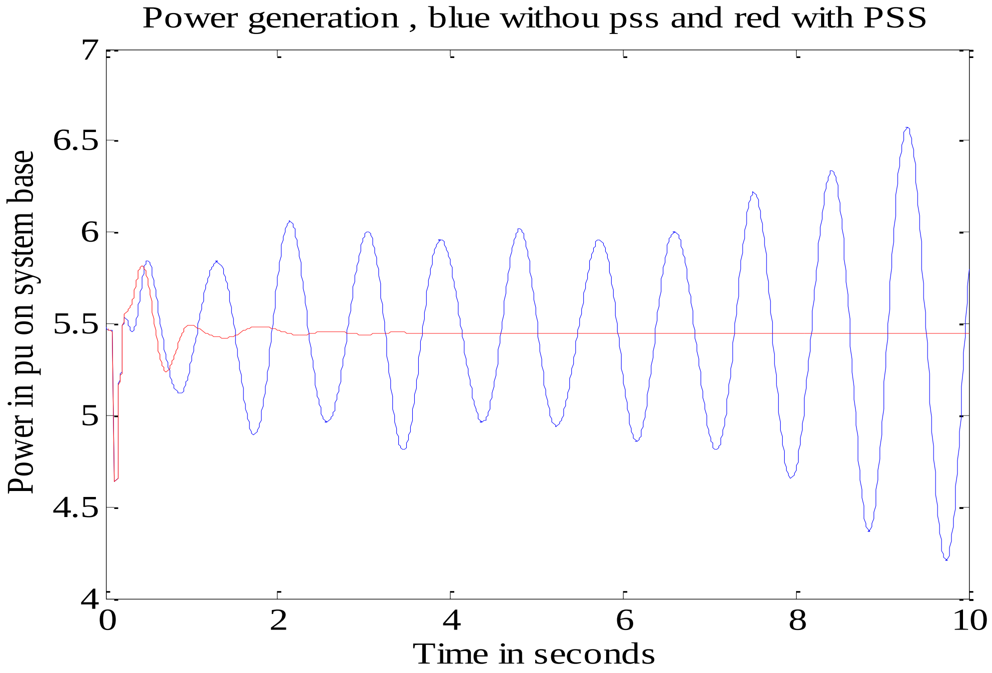

Figure 6.44: Generator 2 Power; blue line without PSS, Red line with PSS

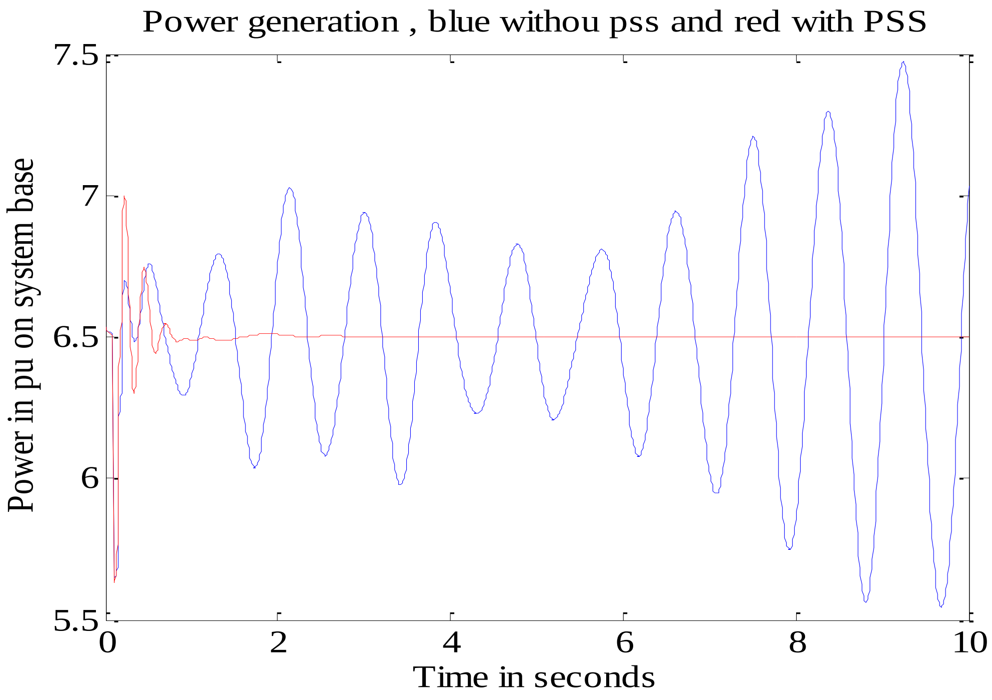

Figure 6.45: Generator 3 Power; blue line without PSS, Red line with PSS

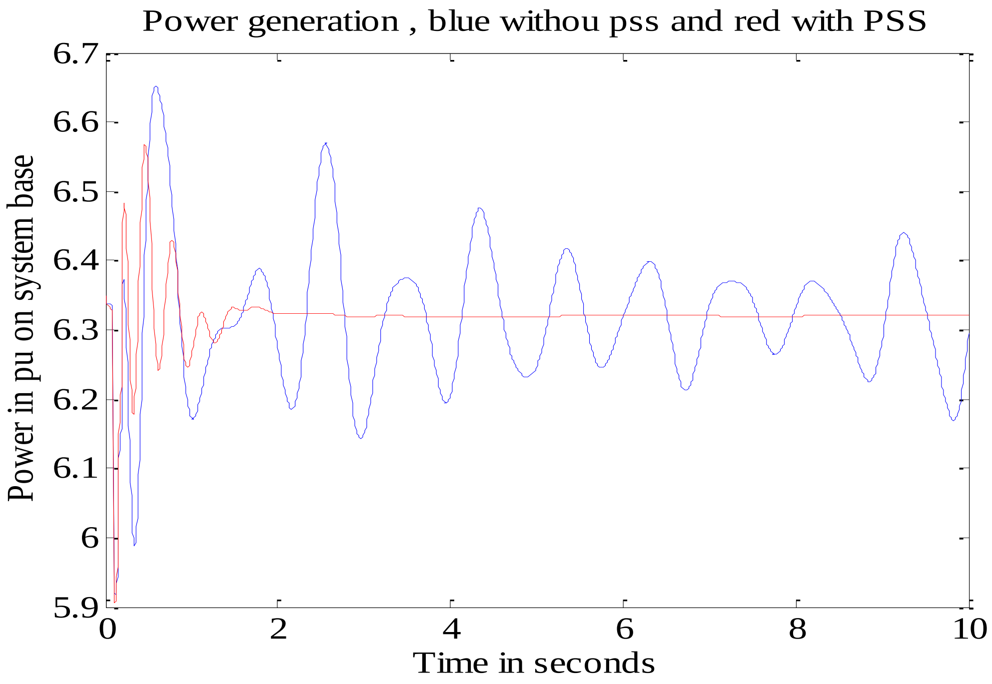

Figure 6.46: Generator 4 Power; blue line without PSS, Red line with PSS

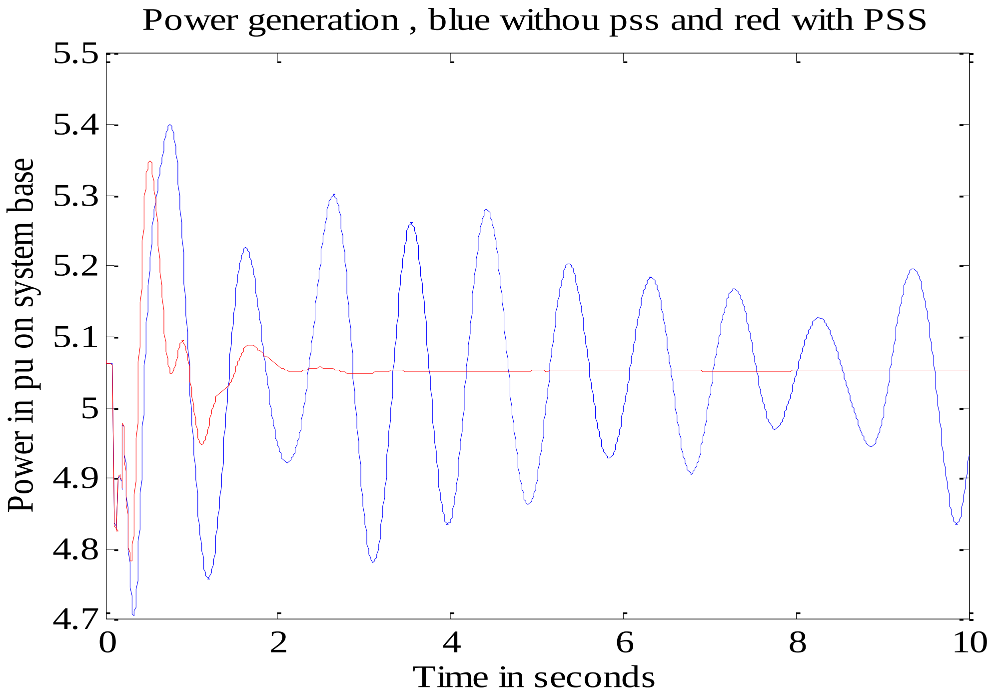

Figure 6.47: Generator 5 Power; blue line without PSS, Red line with PSS

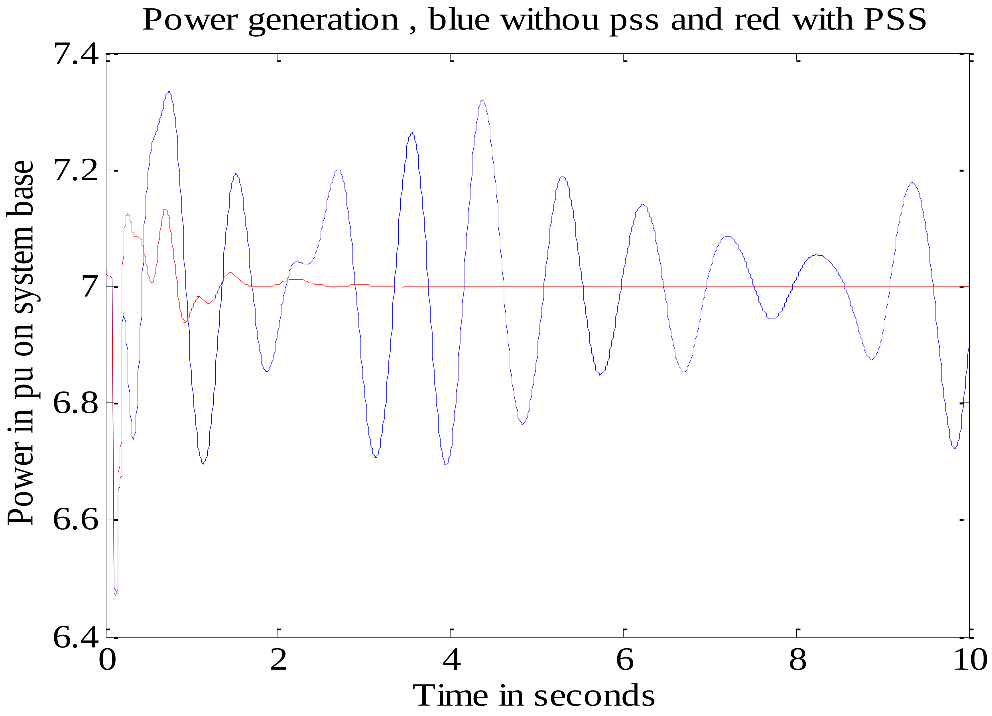

Figure 6.48: Generator 6 Power; blue line without PSS, Red line with PSS

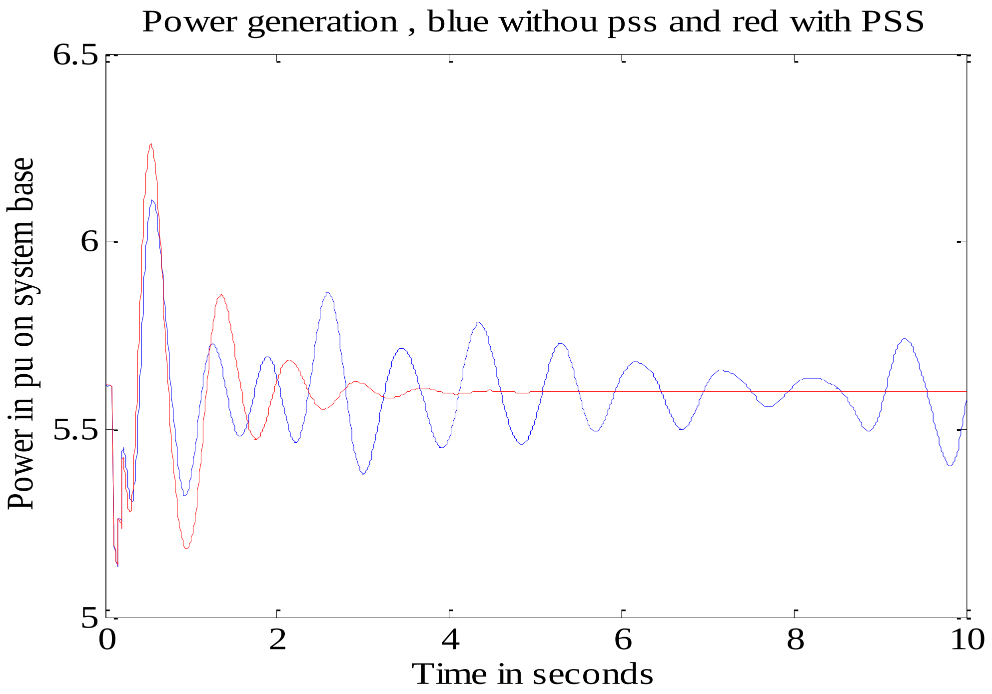

Figure 6.49: Generator 7 Power; blue line without PSS, Red line with PSS

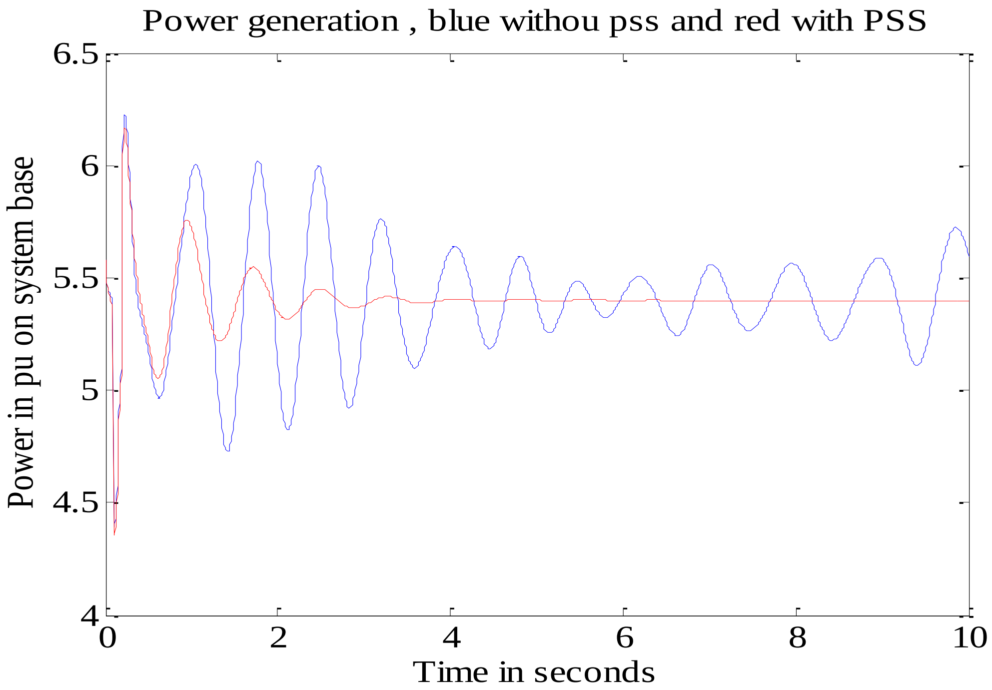

Figure 6.50: Generator 8 Power; blue line without PSS, Red line with PSS

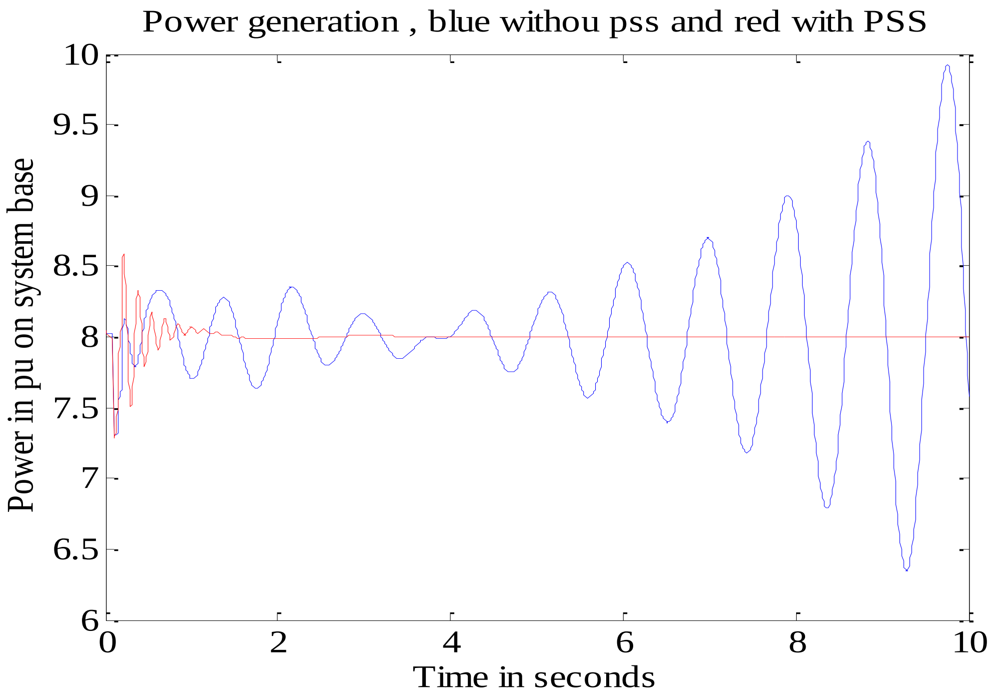

Figure 6.51: Generator 9 Power; blue line without PSS, Red line with PSS

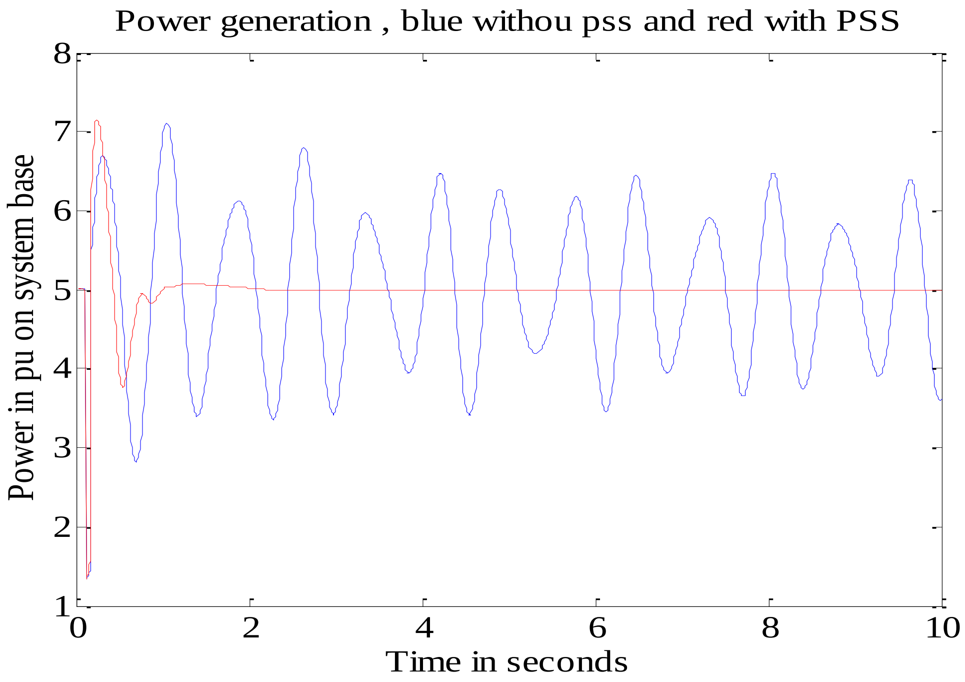

Figure 6.52: Generator 10 Power; blue line without PSS, Red line with PSS

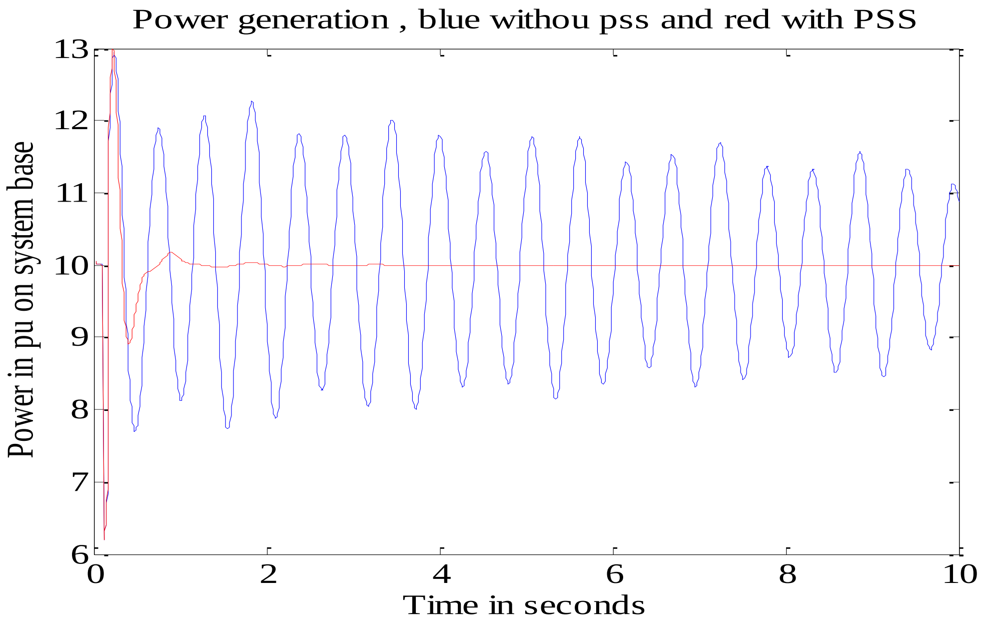

Figure 6.53: Generator 11 Power; blue line without PSS, Red line with PSS

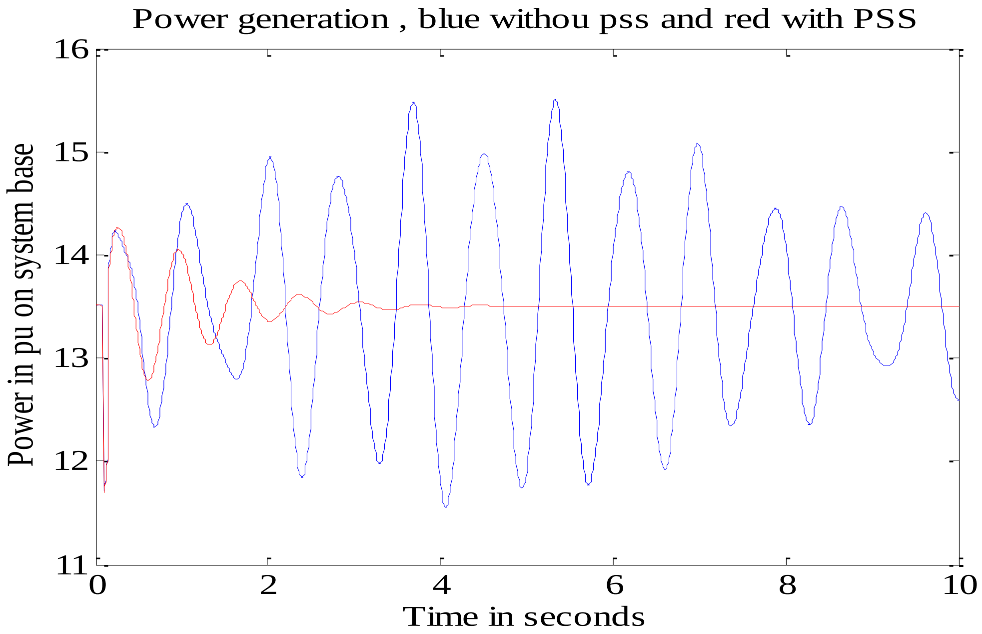

Figure 6.54: Generator 12 Power; blue line without PSS, Red line with PSS

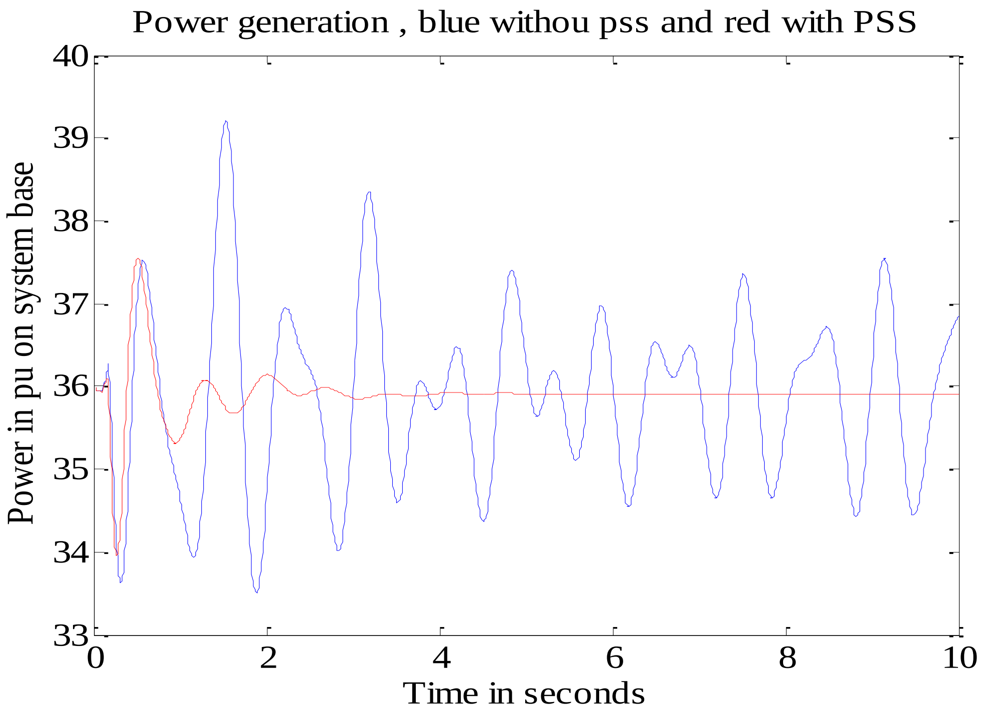

Figure 6.55: Generator 13 Power; blue line without PSS, Red line with PSS

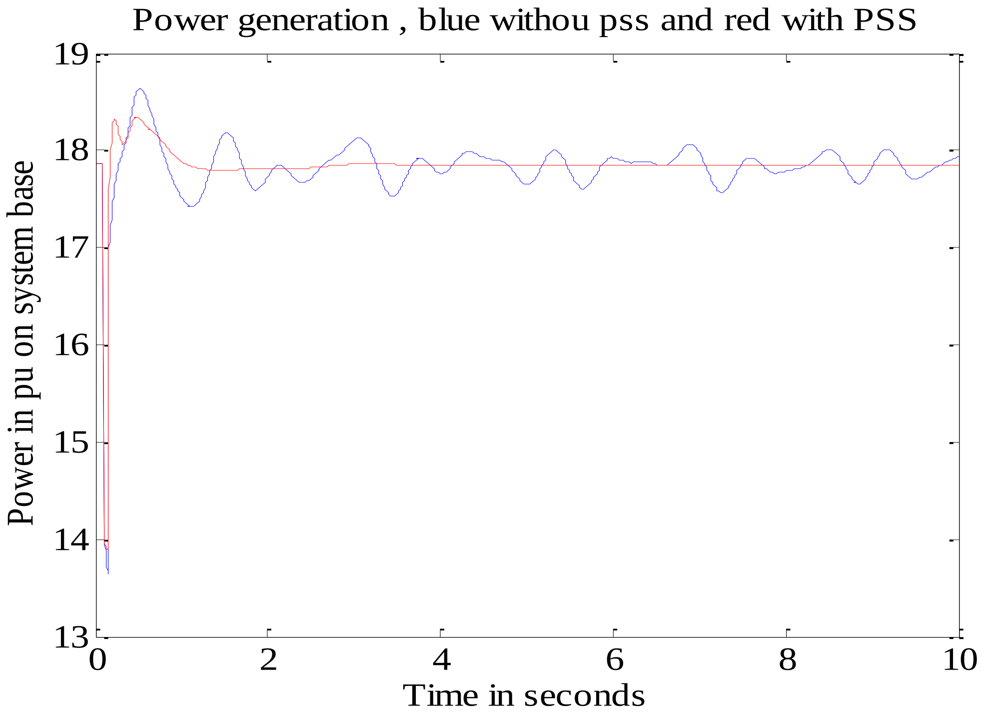

Figure 6.56: Generator 14 Power; blue line without PSS, Red line with PSS

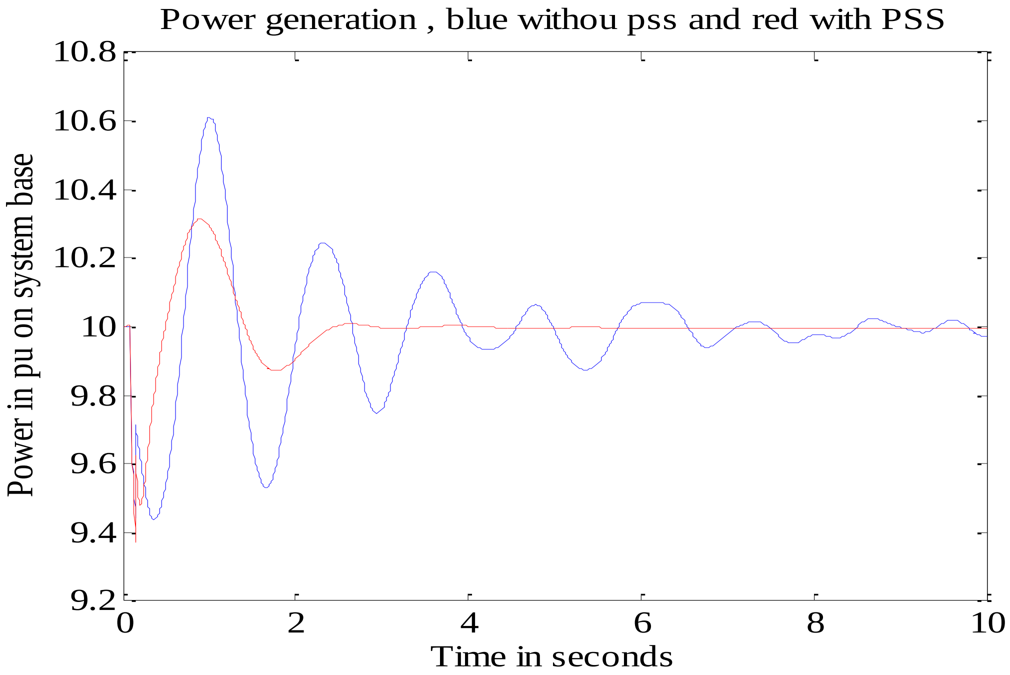

Figure 6.57: Generator 15 Power; blue line without PSS, Red line with PSS

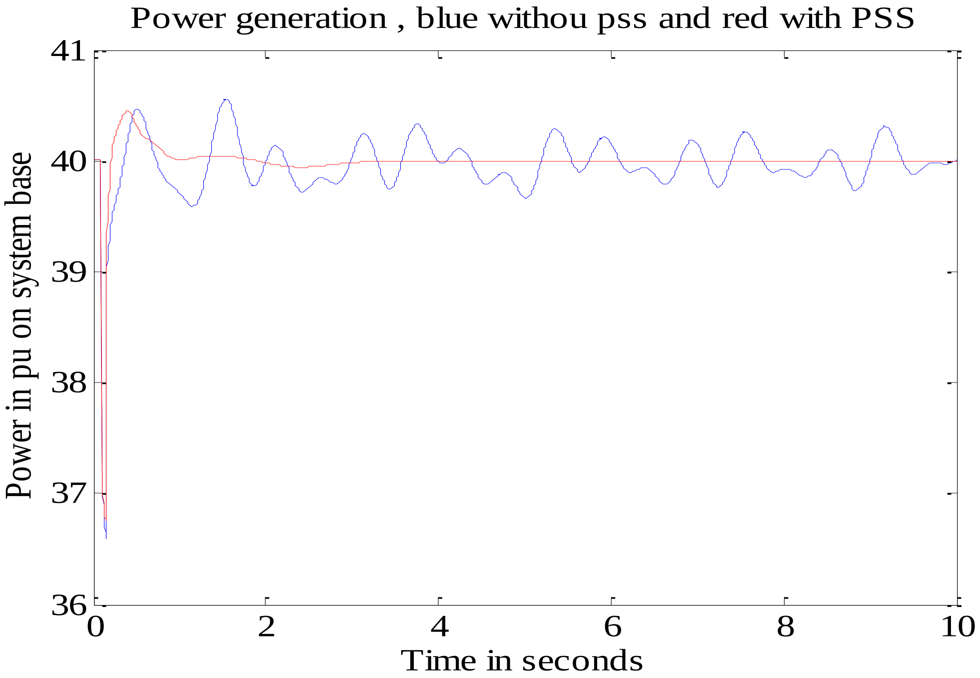

Figure 6.58: Generator 16 Power; blue line without PSS, Red line with PSS

In this case the system found to be not stable without the proposed PSS. It was proven that the of PSS addition improved the system stability and make the system very stable.

CHAPTER 7

REAL INDUSTRIAL PLANT SIMULATION RESULTS AND DISCUSSIONS

Stabilizer Design

By applying the linearized power system model in chapter 3, adding the Power System Stabilizer and finally applying the DE optimization to search for optimal settings of the applied stabilizers. We found the final optimized parameters for the added power system stabilizers, which are given in Table 7.1.

Table 7.1: Optimal parameter settings

Parameter	Generator #1	Generator #2	Generator #3	Generator #4	Generator #5
Tw	5	5	5	5	5
K1	99.5303	4.7548	4.2076	40.5961	21.1061
T1	0.3998	0.9225	0.9579	0.0868	0.9061
T2	0.0501	0.0849	0.0553	0.0697	0.0619
T3	0.1997	0.7725	0.6947	0.7230	0.9556
T4	0.0504	0.0806	0.0523	0.0993	0.0507

We now can apply the proposed PSSs on the following cases:

7.1 Case 0 (Base Case, plant load with 14 Mw export)

7.2 Case 1 (heavy load, plant load with 45 Mw export)

7.3 Case 2 (Plant load, import from utilities 14 Mw)

7.4 Case 3 (Islanding Case, plant load with 45 Mw)

7.1 Case 0 (Base Case, plant load with 14 MW export)

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for nominal loading condition and 14 Mw export to the utilities is given in Table 7.2 and 7.3 In this case there is one EM shown in the system. Although the system is stable, it is clear that after applying the proposed stabilizers the system stability is slightly improved. This is because table 7.3 shows more damping ratio for each mode and EM mode.

Table 7.2: Eigenvalues without PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-2.3676 +15.7171i	2.5015	0.1490
-2.5147 +16.2226i	2.5819	0.1532
-0.9380 + 8.8436i	1.4075	0.1055
-0.9244 + 8.3043i	1.3217	0.1106
-0.4792 + 7.9228i	**1.2609**	**0.0604**

Table 7.3: Eigenvalues with PSS

Eigenvalues	Frequency (HZ)	Damping Ratio
-2.6832 +16.7153i	2.6603	0.1585
-1.4011 + 8.5967i	1.3682	0.1609
-1.2428 + 8.2664i	1.3156	0.1487
-1.0151 + 7.8943i	1.2564	0.1275

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to a 3-phase fault between bus 9&10. The fault last for 0.05 seconds. The system response shown as follow:

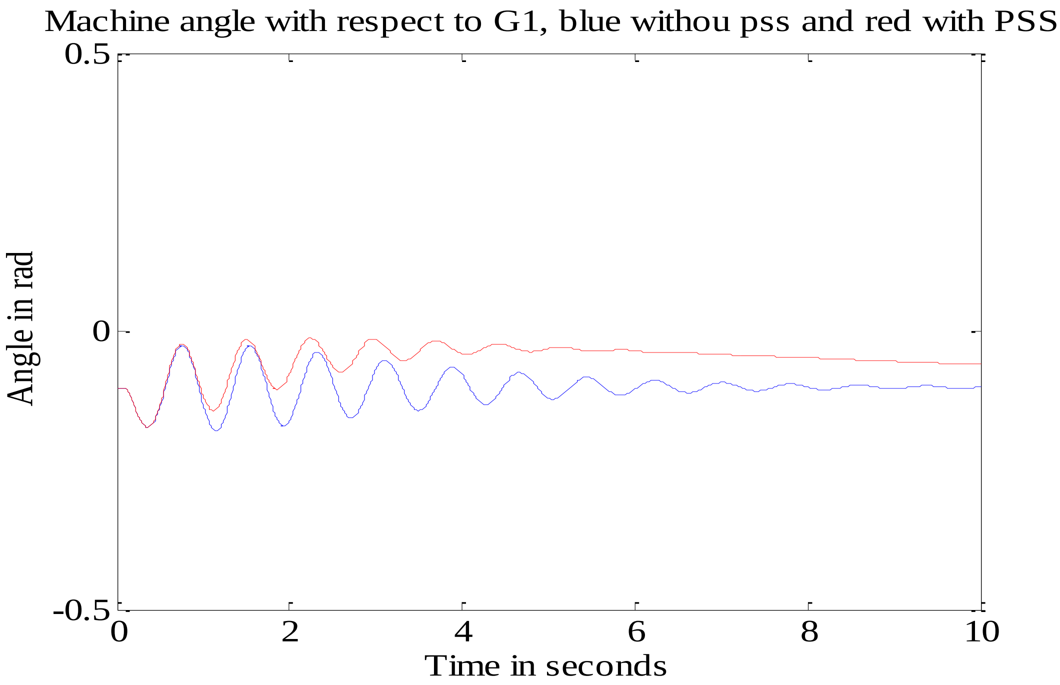

Figure 7.1: Generator 2 angle; blue line without PSS, Red line with PSS

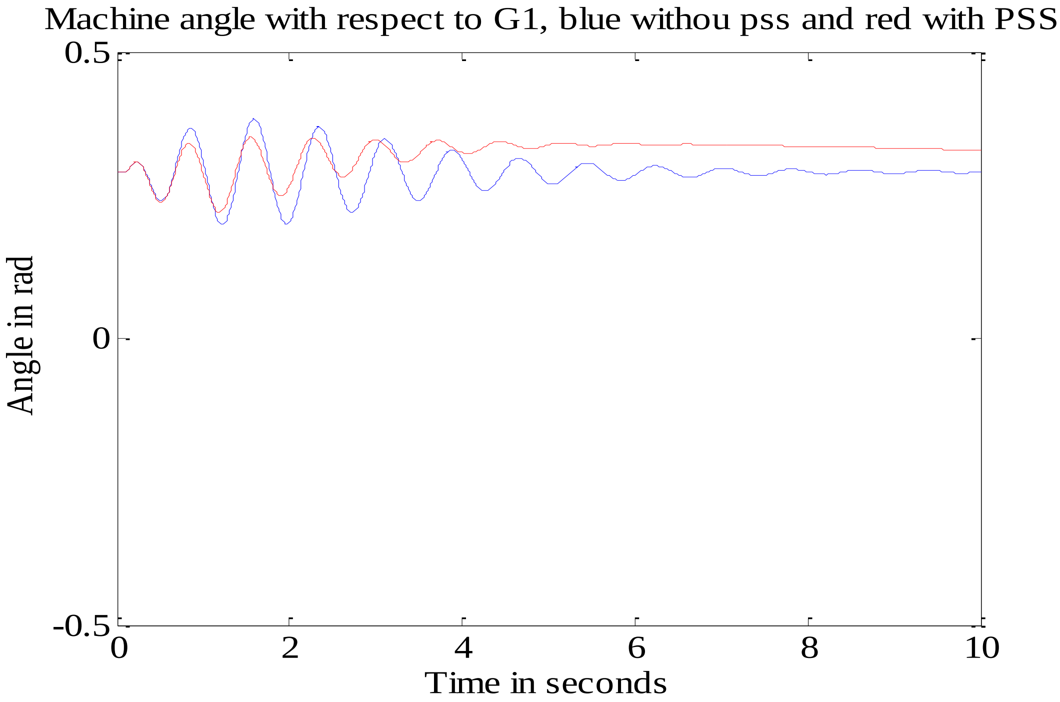

Figure 7.2: Generator 3 angle; blue line without PSS, Red line with PSS

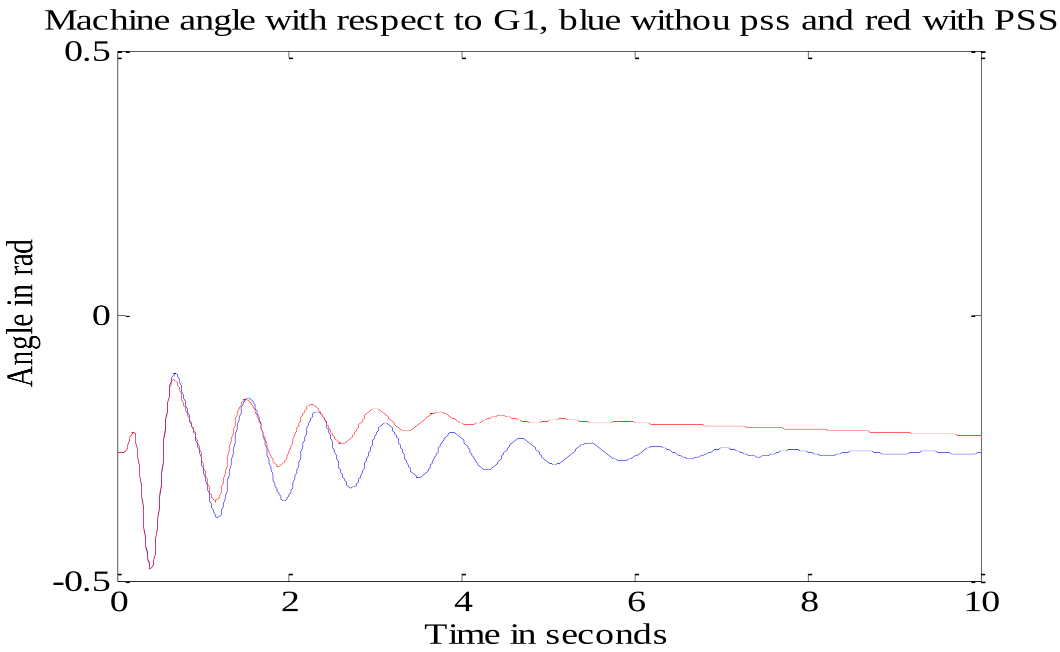

Figure 7.3: Generator 4 angle; blue line without PSS, Red line with PSS

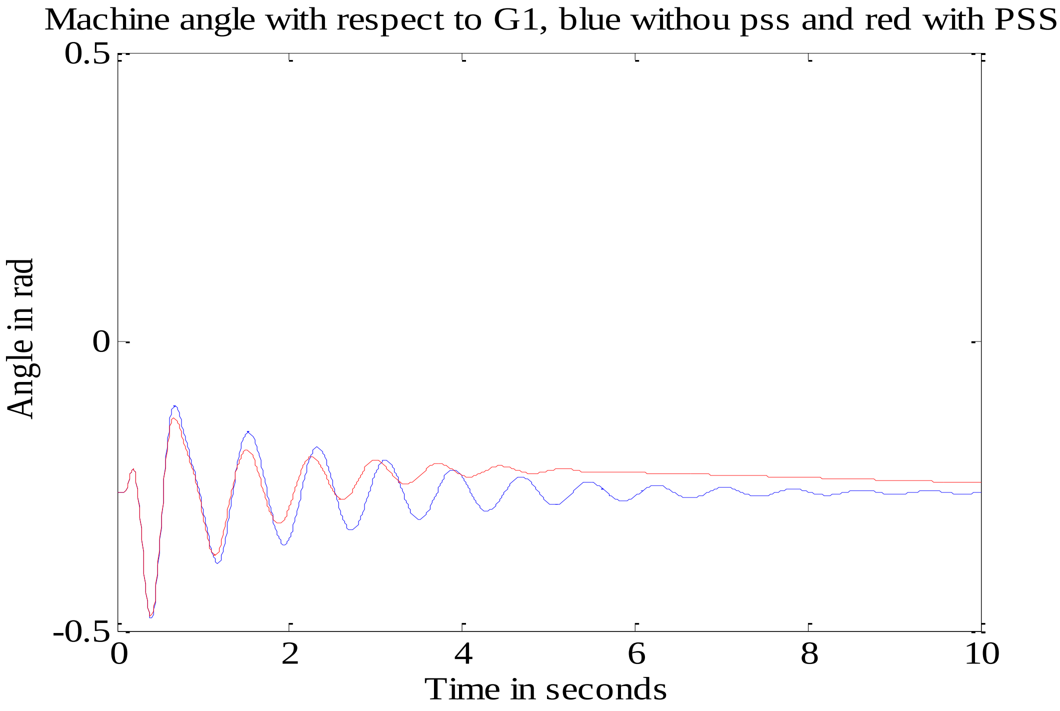

Figure 7.4: Generator 5 angle; blue line without PSS, Red line with PSS

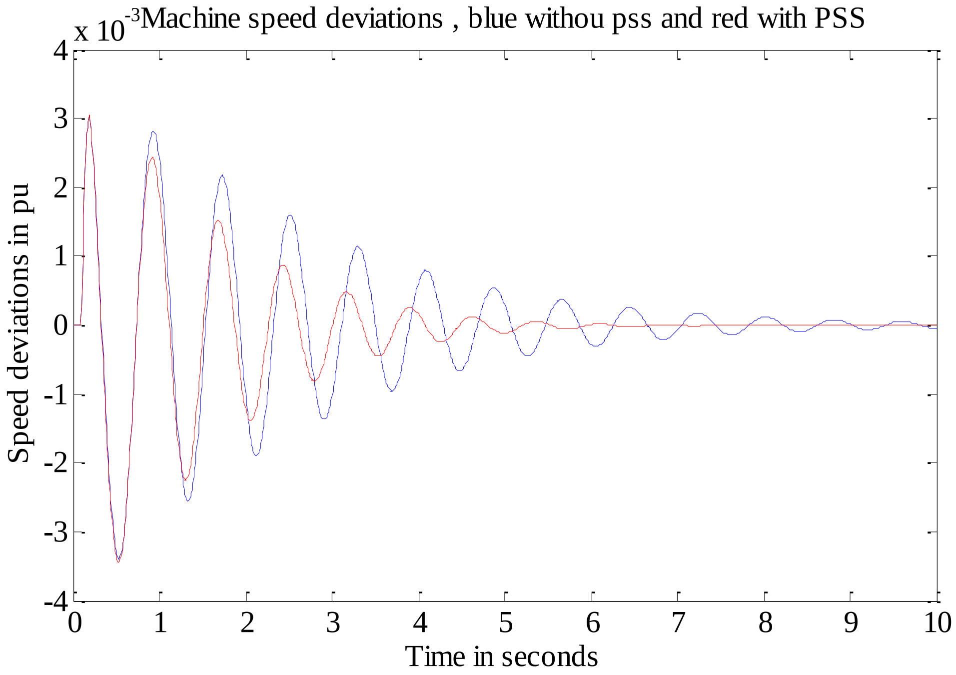

Figure 7.5: Generator 1 speed deviation; blue line without PSS, Red line with PSS

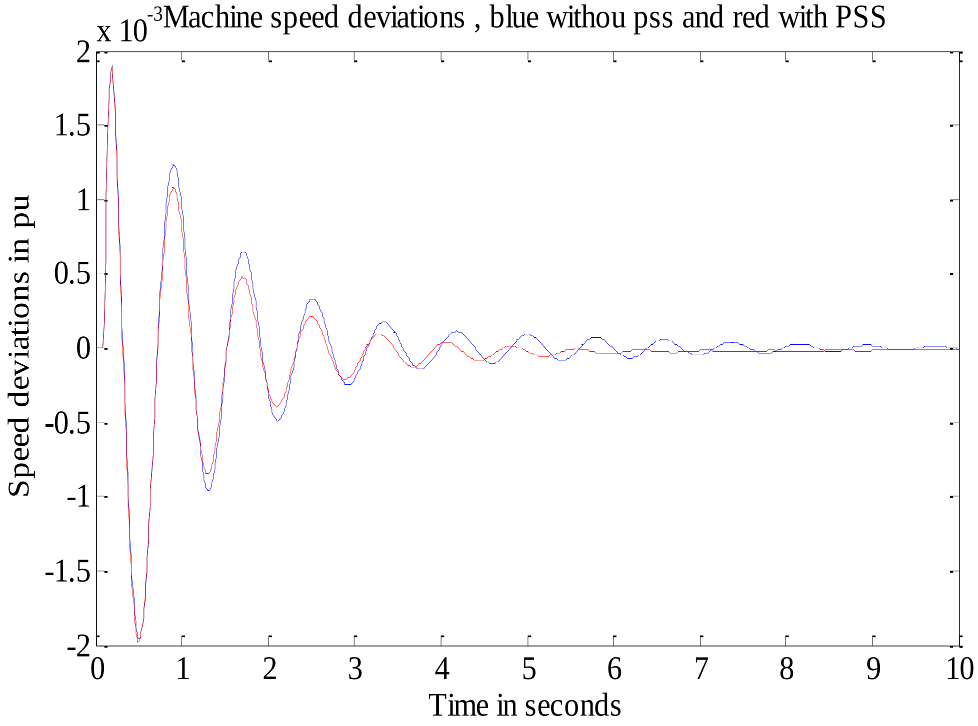

Figure 7.6: Generator 2 speed deviation; blue line without PSS, Red line with PSS

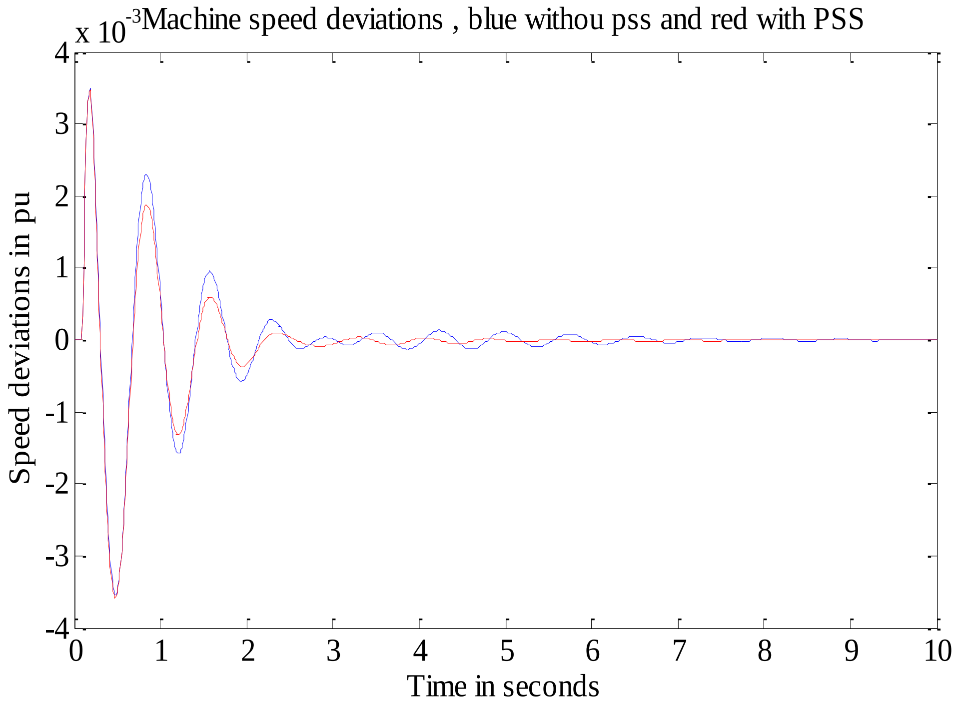

Figure 7.7: Generator 3 speed deviation; blue line without PSS, Red line with PSS

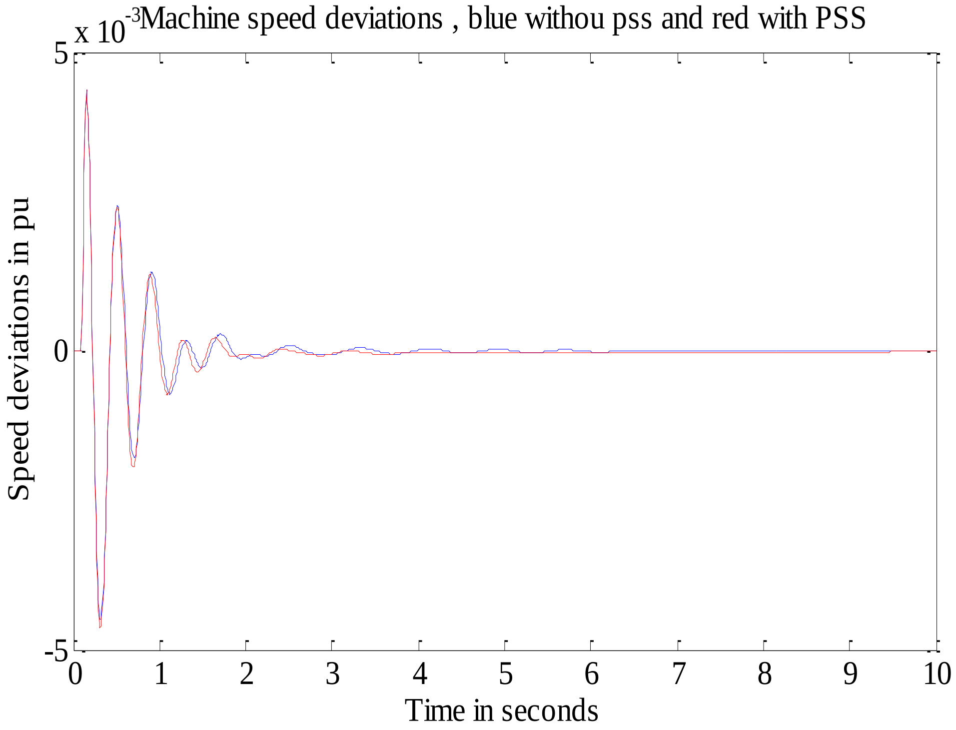

Figure 7.8: Generator 4 speed deviation; blue line without PSS, Red line with PSS

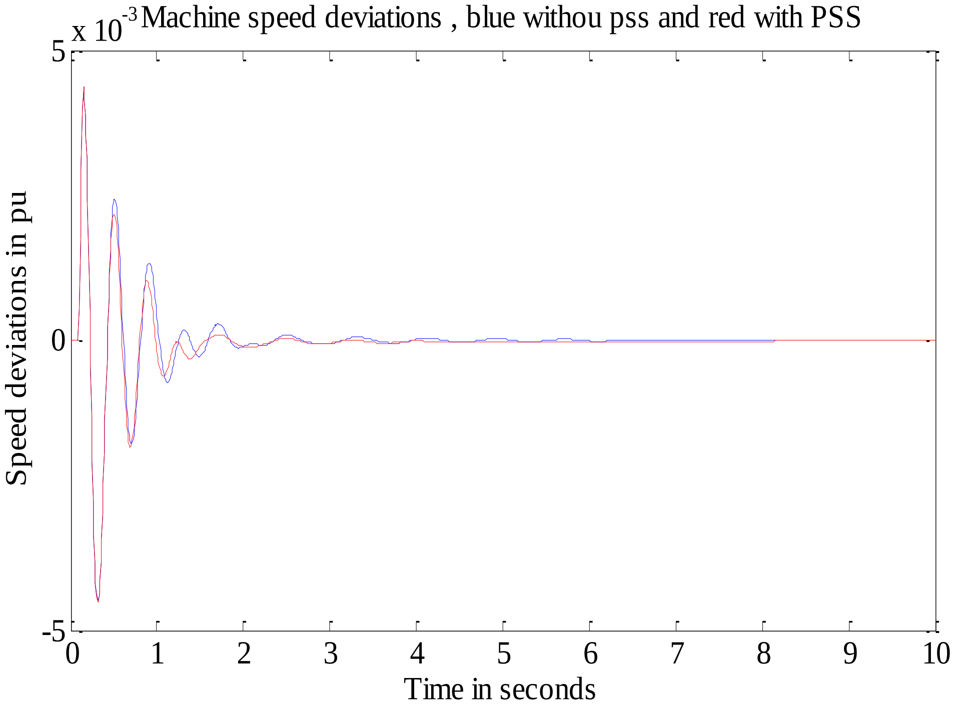

Figure 7.9: Generator 5 speed deviation; blue line without PSS, Red line with PSS

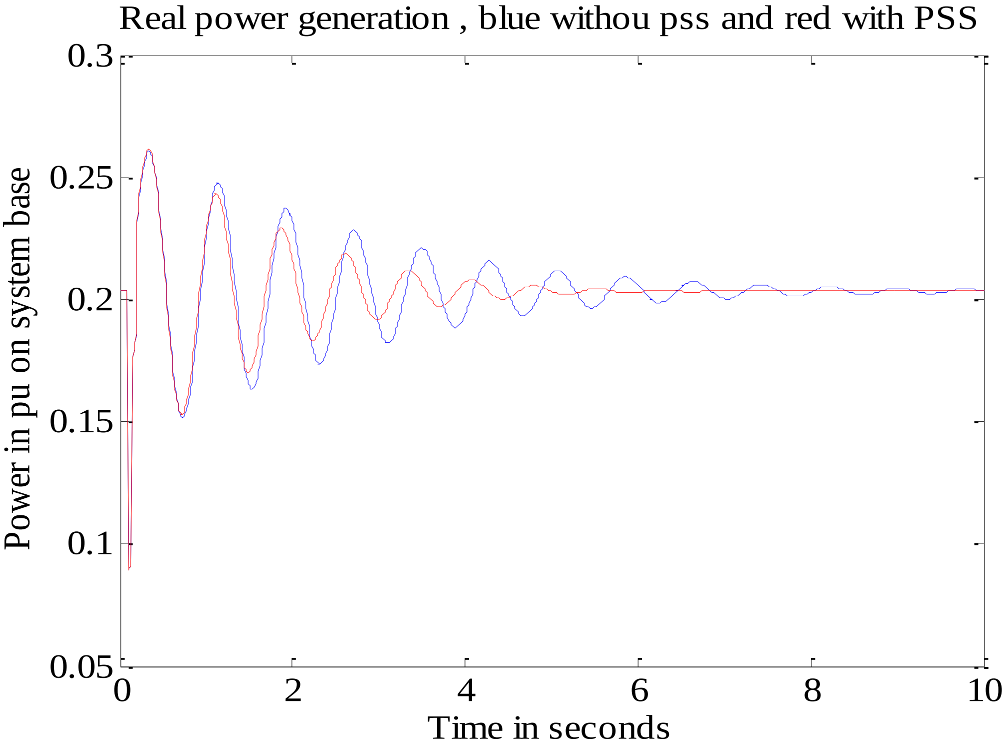

Figure 7.10: Generator 1 Power; blue line without PSS, Red line with PSS *without PSS* .

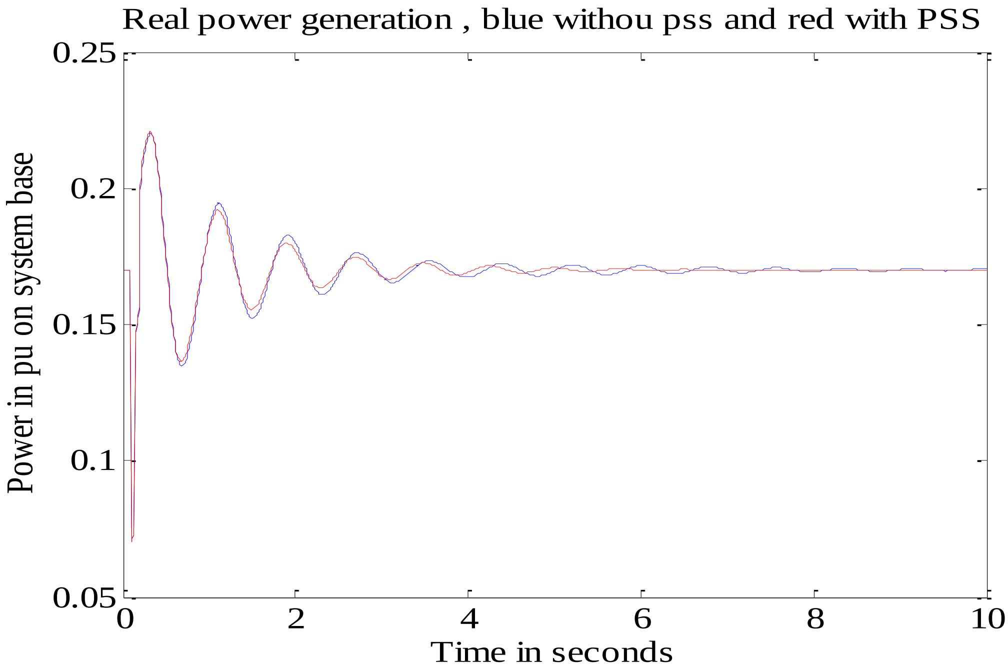

Figure 7.11: Generator 2 Power; blue line without PSS, Red line with PSS without PSS .

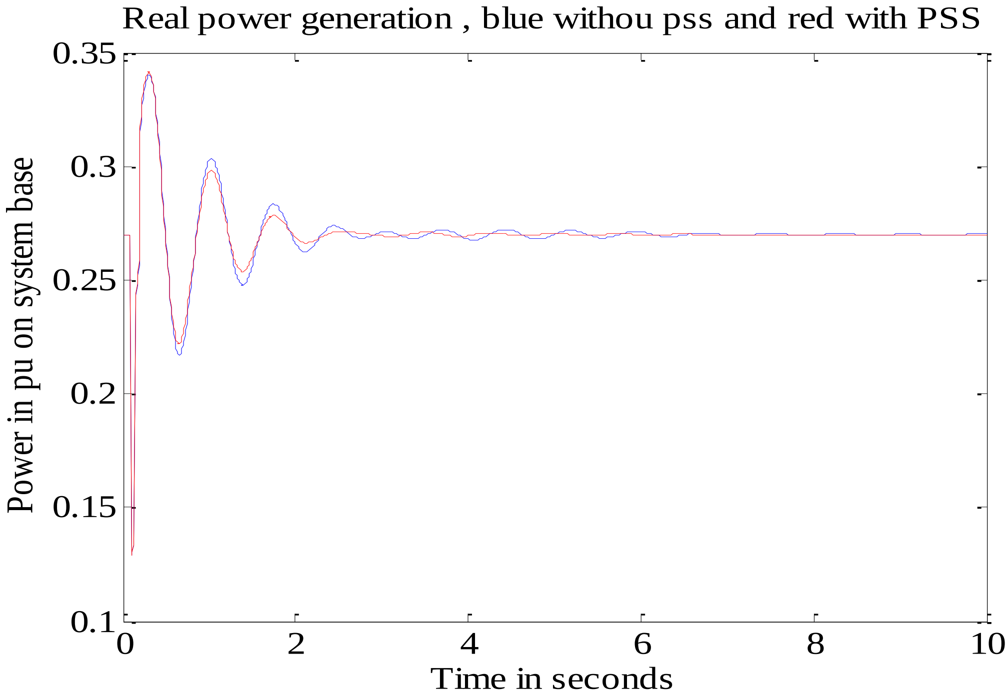

Figure 7.12: Generator 3 Power; blue line without PSS, Red line with PSS without PSS .

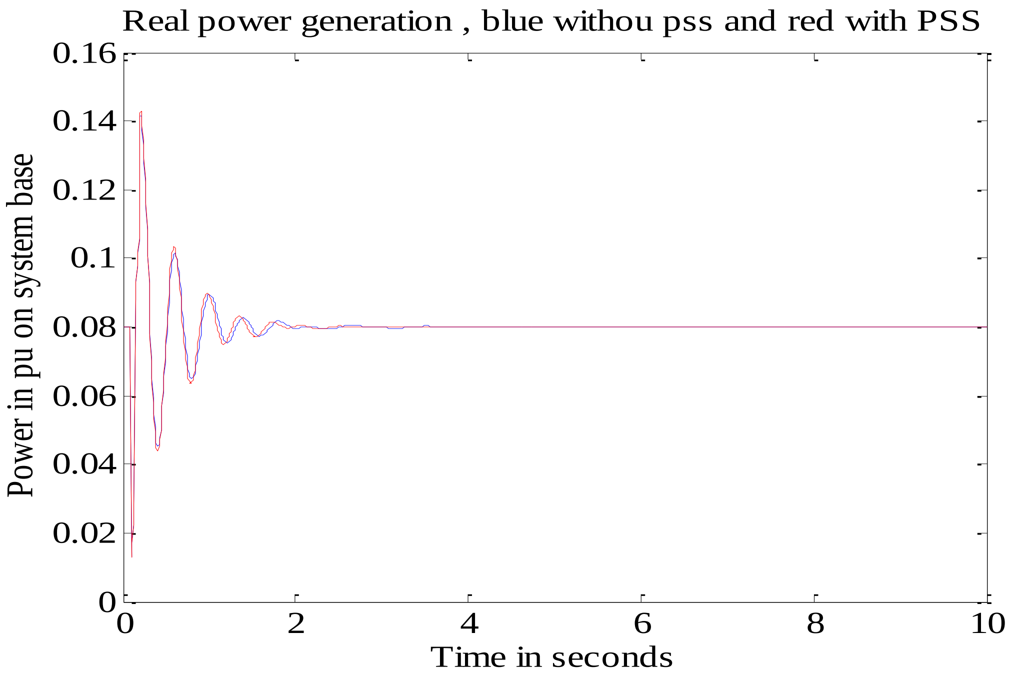

Figure 7.13: Generator 4 Power; blue line without PSS, Red line with PSS without PSS .

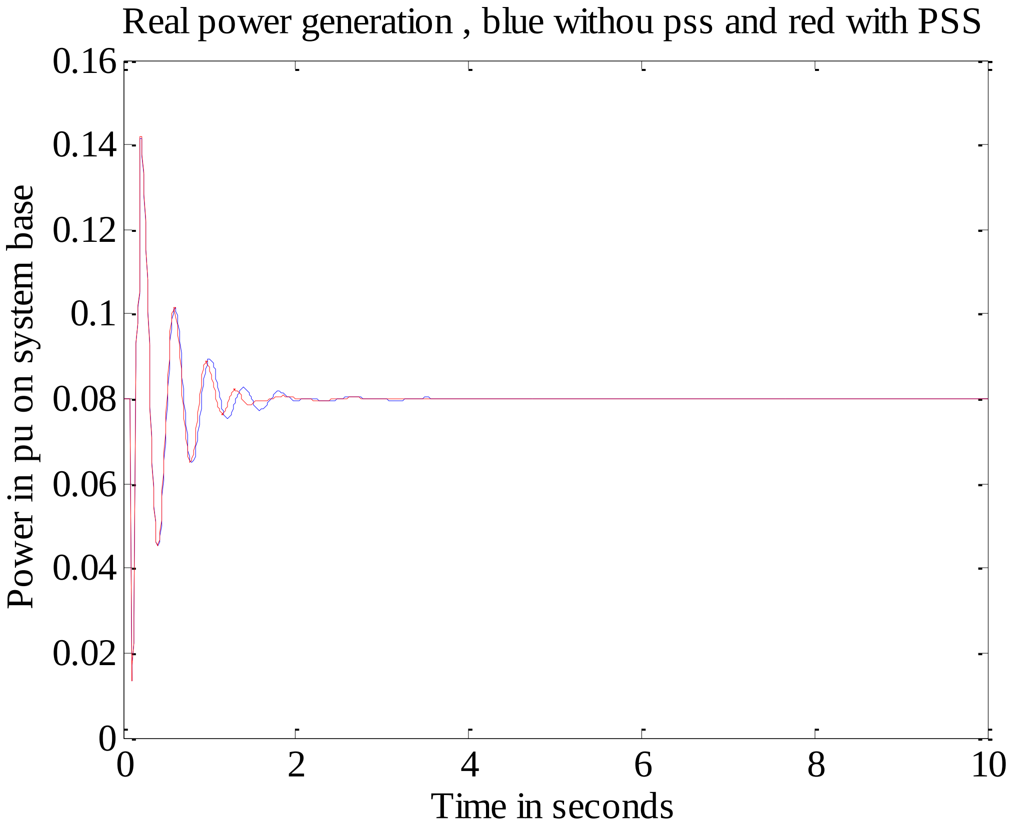

Figure 7.14: Generator 5 Power; blue line without PSS, Red line with PSS *without PSS* .

In this case although the system is very stable without the proposed PSS, the PSS addition improved the system stability during the fault.

7.2. Case 1 (heavy load, plant load with 45 MW export)

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for heavy loading condition is given in Table 7.4 and 7.5. In this case there is one EM shown in the system. Although the system is stable, it is clear that after applying the proposed stabilizers the system stability slightly improved. This is because table 7.5 shows more damping factors for each mode.

Table 7.4: Eigenvalues without PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
$-1.6504 + 12.5992i$	2.0052	0.1299
$-1.3355 + 11.6762i$	1.8583	0.1136
$\boldsymbol{-0.5316 + 9.9177i}$	**1.5784**	**0.0535**
$-0.3057 + 0.4078i$	0.0649	0.5997

Table 7.5: Eigenvalues with PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-2.5983 +12.8561i	2.0461	0.1981
-2.3284 +11.4543i	1.8230	0.1992
-1.7496 + 9.9146i	1.5780	0.1738
-0.3016 + 0.4111i	0.0654	0.5915

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to a 3-phase fault between bus 9&10. The fault last for 0.05 seconds. The system response shown as follow:

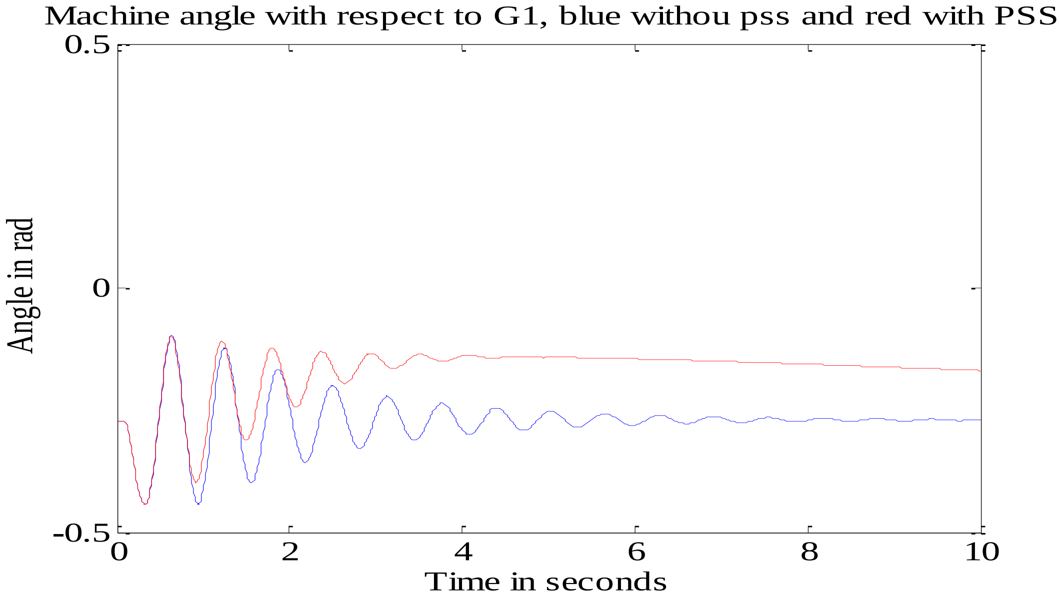

Figure 7.15: Generator 2 angle; blue line without PSS, Red line with PSS

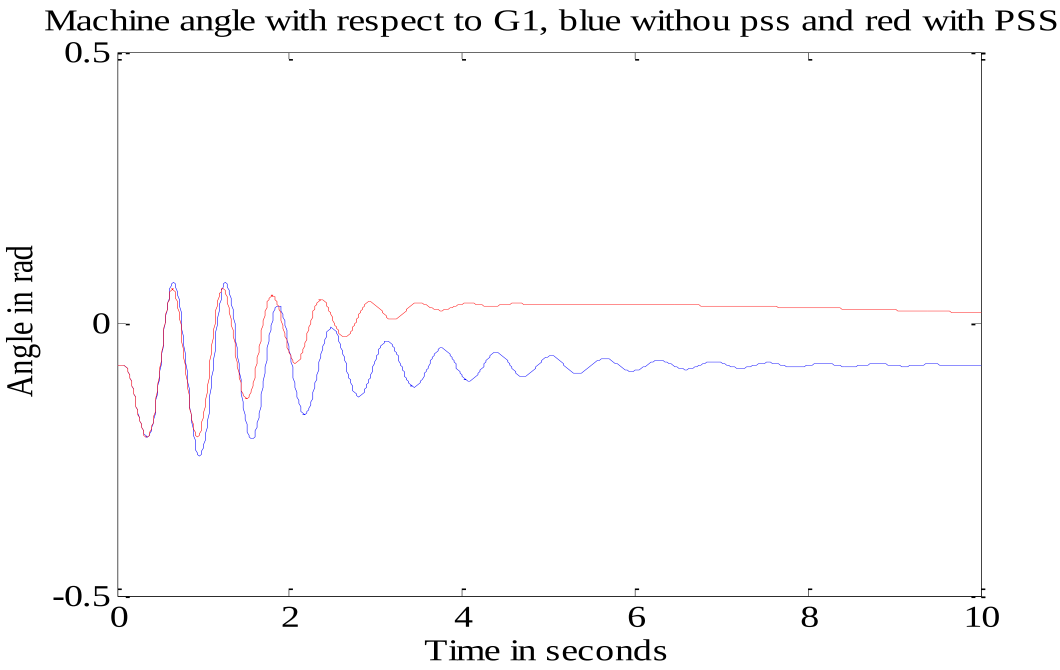

Figure 7.16: Generator 3 angle; blue line without PSS, Red line with PSS

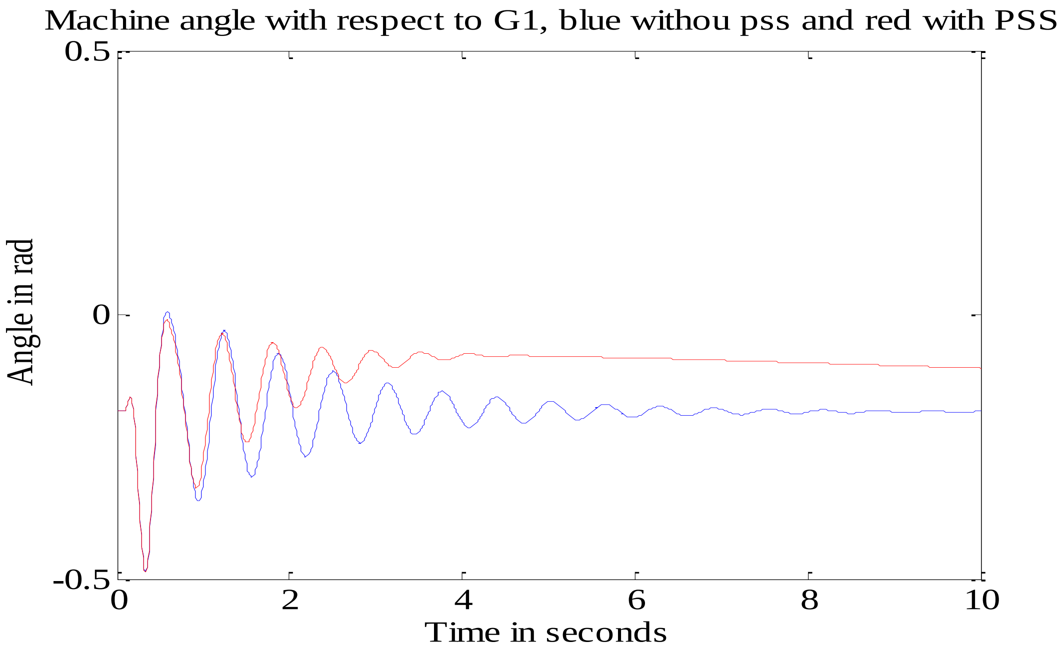

Figure 7.17: Generator 4 angle; blue line without PSS, Red line with PSS

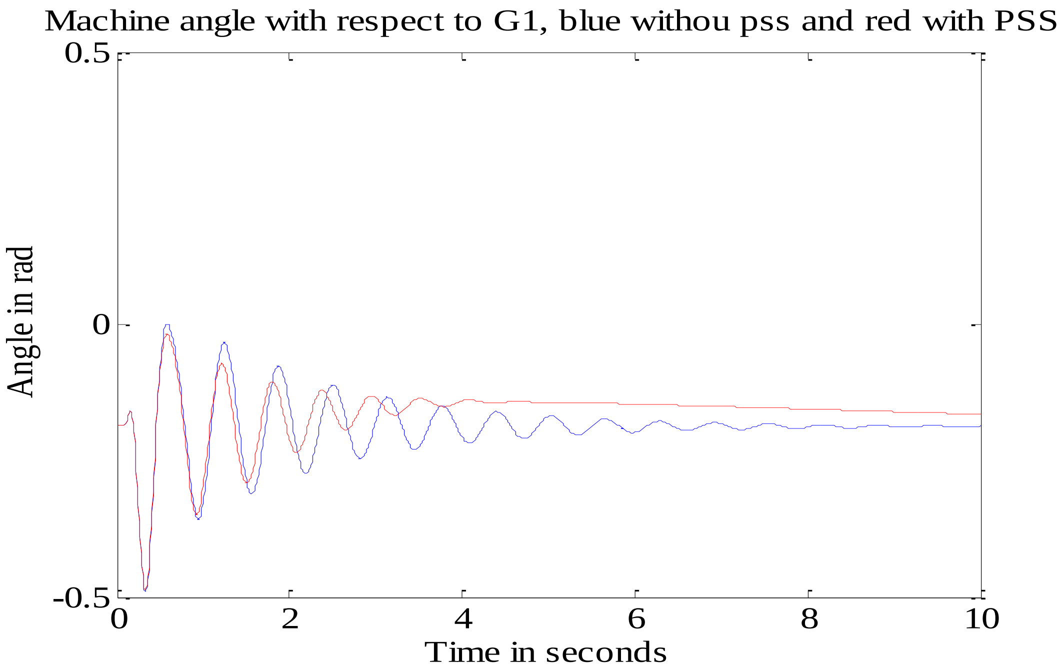

Figure 7.18: Generator 5 angle; blue line without PSS, Red line with PSS

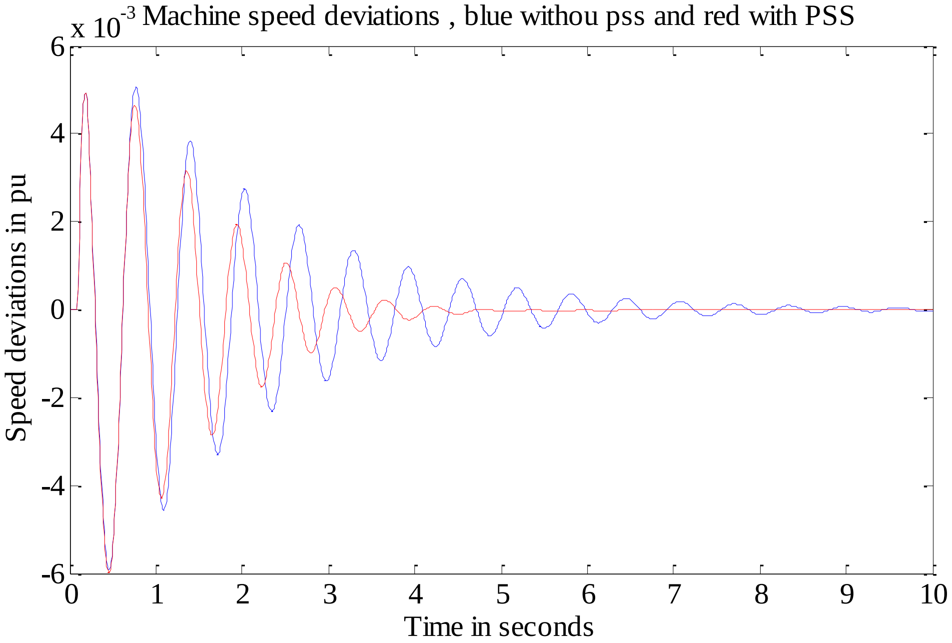

Figure 7.19: Generator 1 speed deviation; blue line without PSS, Red line with PSS

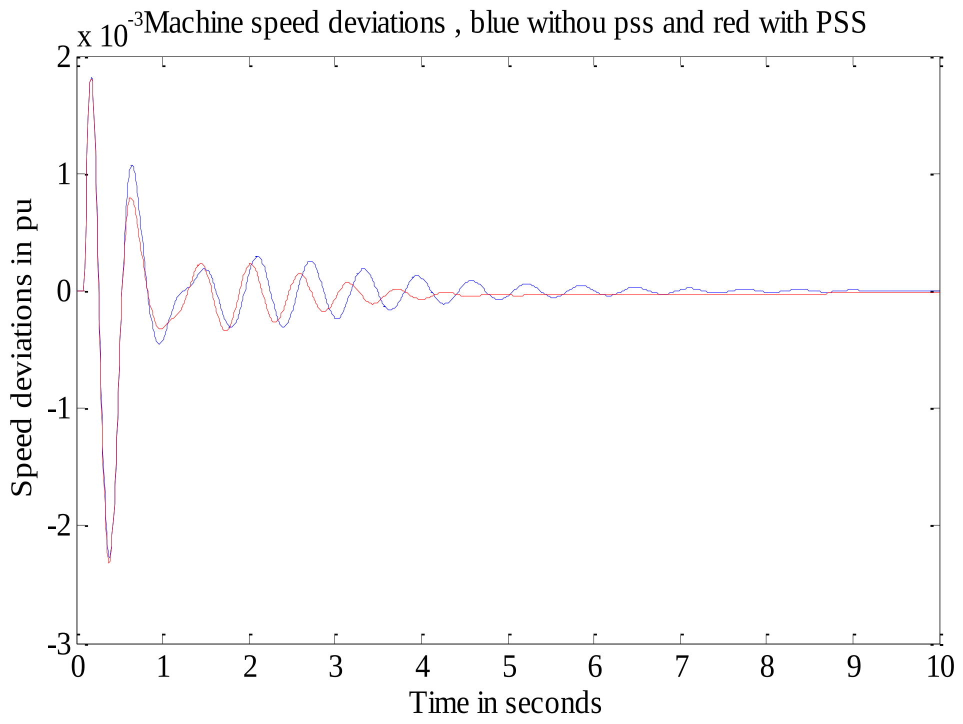

Figure 7.20: Generator 2 speed deviation; blue line without PSS, Red line with PSS

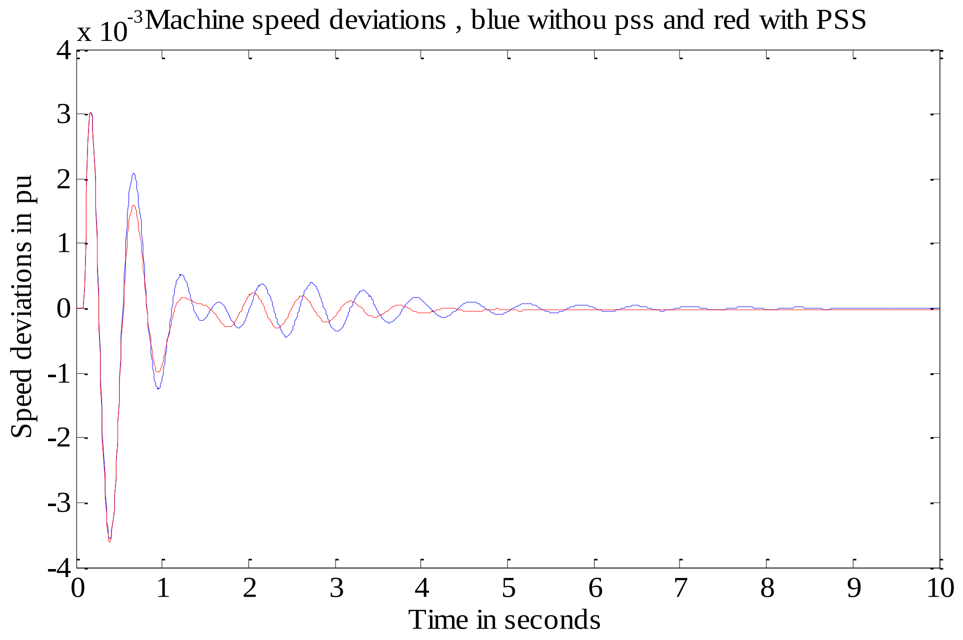

Figure 7.21: Generator 3 speed deviation; blue line without PSS, Red line with PSS

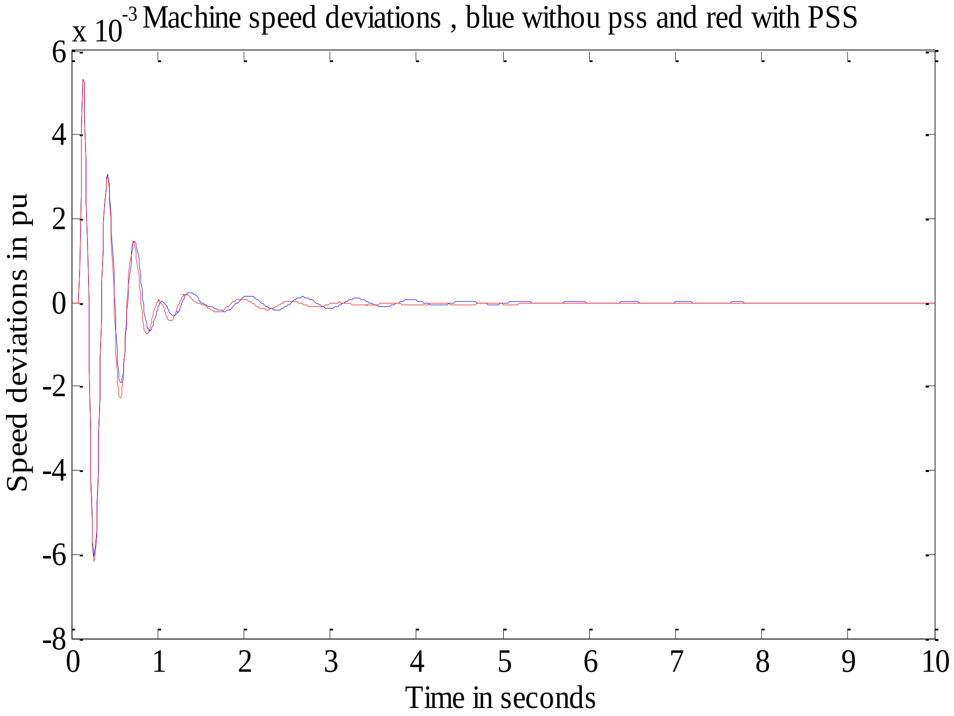

Figure 7.22: Generator 4 speed deviation; blue line without PSS, Red line with PSS

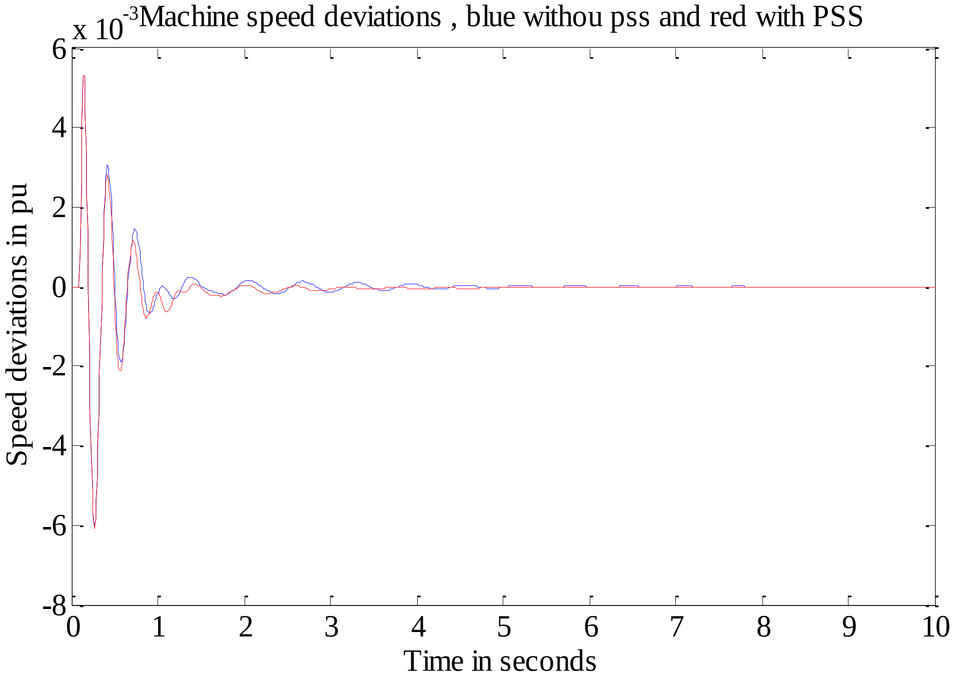

Figure 7.23: Generator 5 speed deviation; blue line without PSS, Red line with PSS

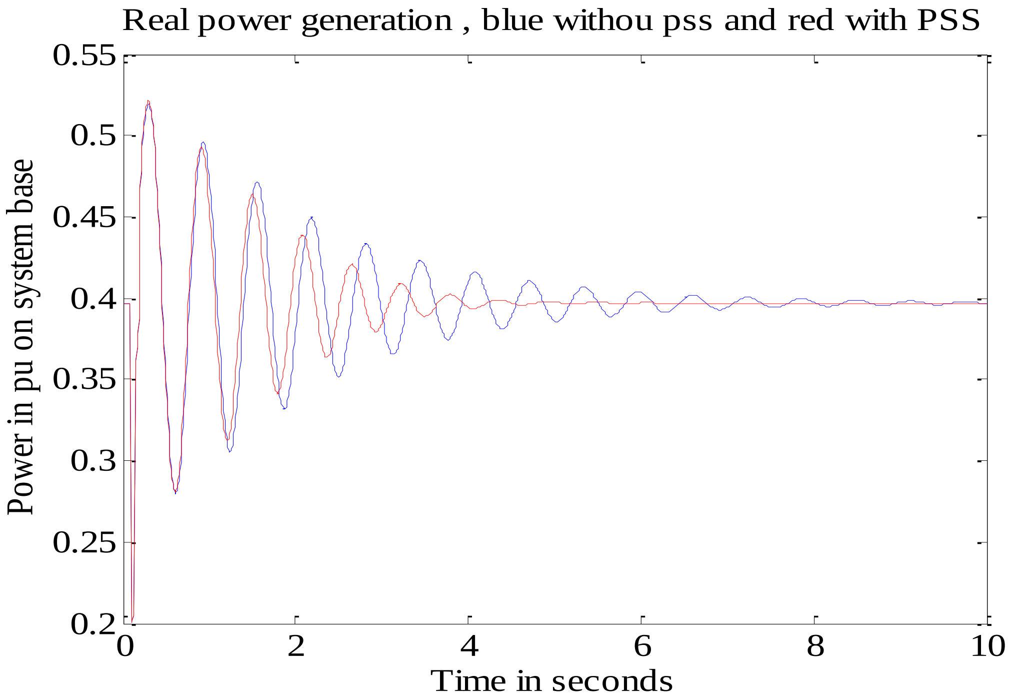

Figure 7.24: Generator 1 Power; blue line without PSS, Red line with PSS *without PSS .*

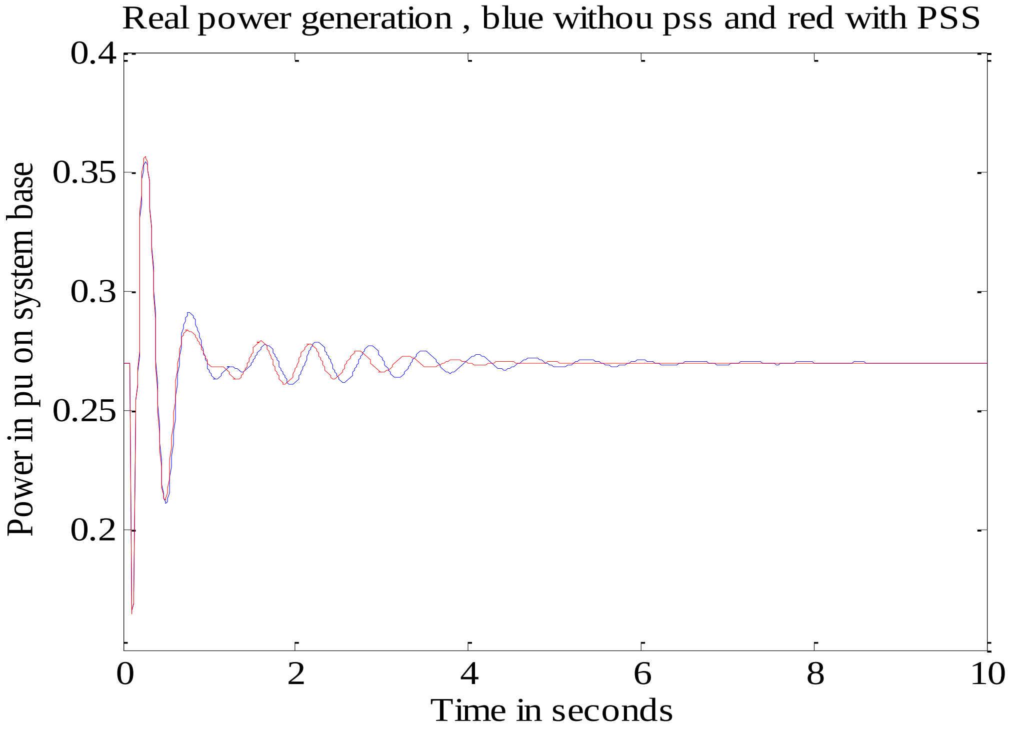

Figure 7.25: Generator 2 Power; blue line without PSS, Red line with PSS without PSS .

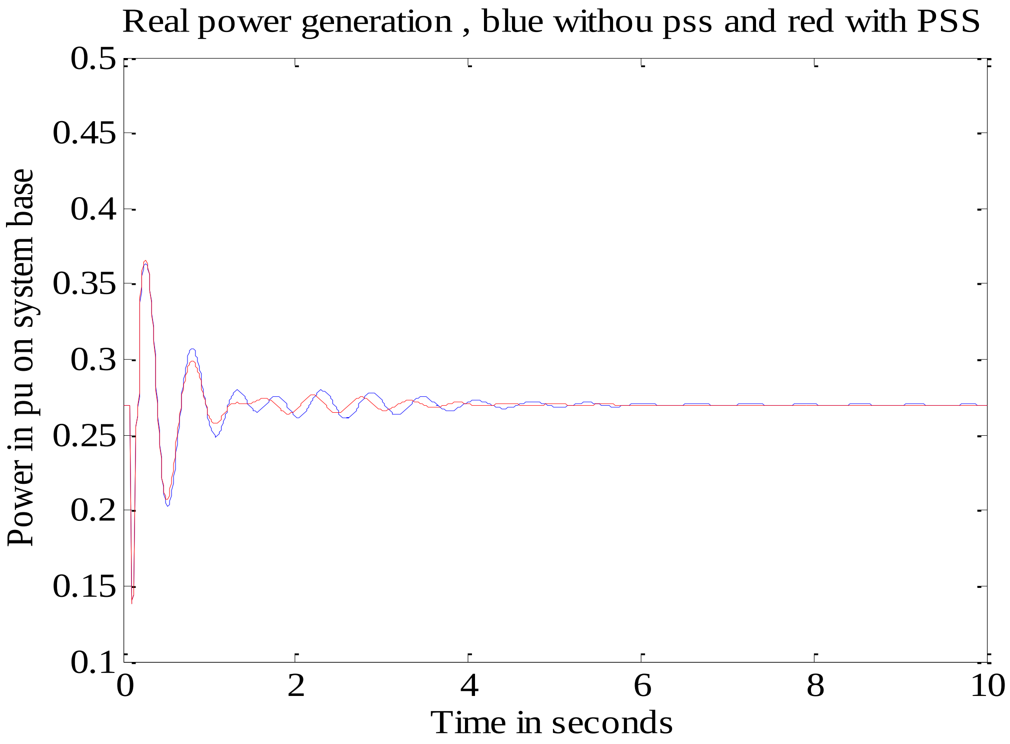

Figure 7.26: Generator 3 Power; blue line without PSS, Red line with PSS *without PSS* .

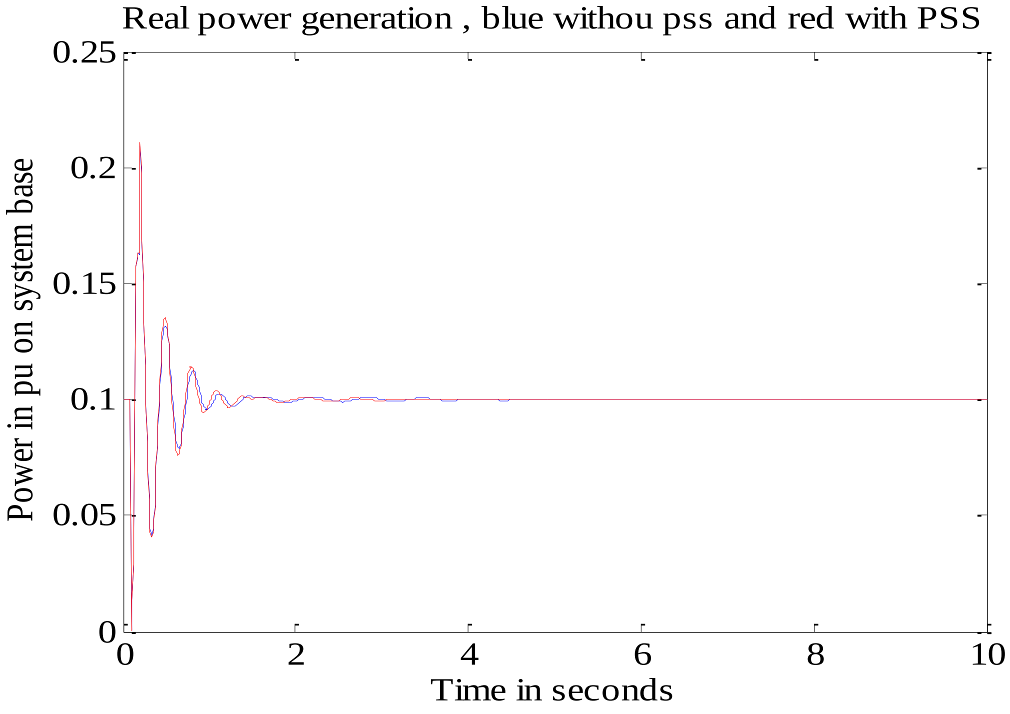

Figure 7.27: Generator 4 Power; blue line without PSS, Red line with PSS *without PSS* .

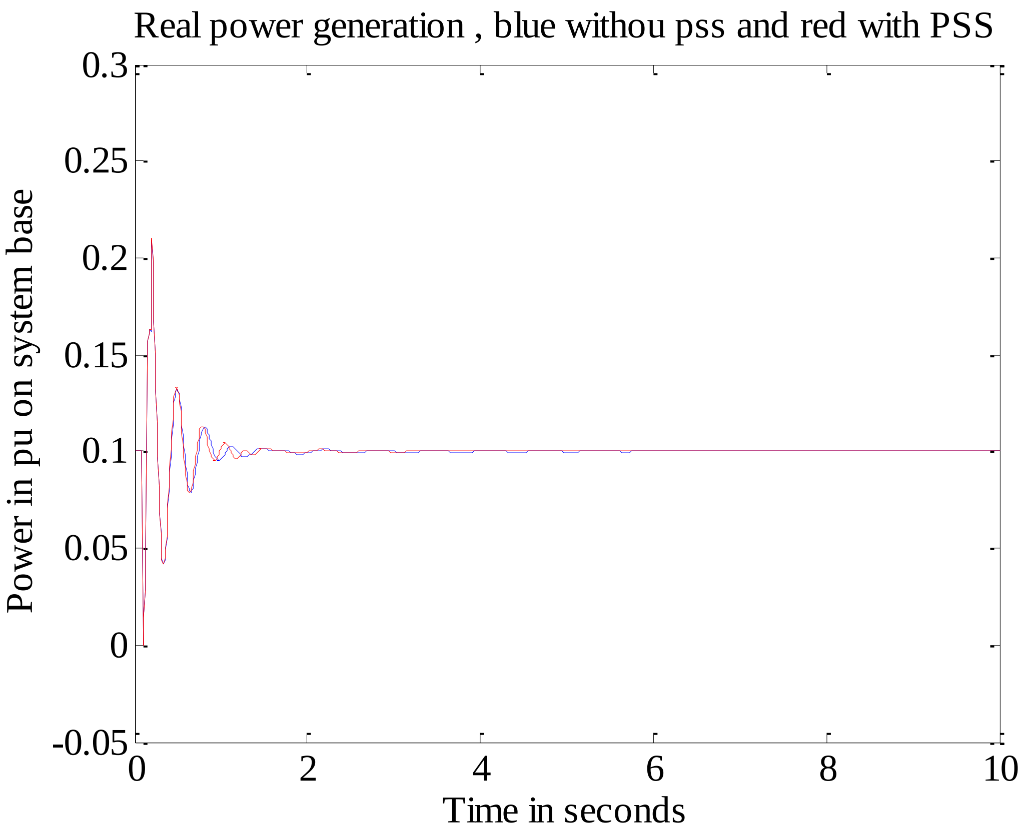

Figure 7.28: Generator 5 Power; blue line without PSS, Red line with PSS without PSS .

In this case although the system is very stable without the proposed PSS, the PSS addition improved the system stability during the fault.

7.3. Case 2 (Plant load, import from utilities 14 MW)

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for nominal loading condition is given in Table 7.6 and 7.7. In this case there is one EM shown in the system. Although the system is stable, it is clear that after applying the proposed stabilizers the system stability slightly improved. This is because table 7.7 shows more damping factors for each mode.

Table 7.6: Eigenvalues without PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-3.4426 +15.1888i	2.4174	0.2210
-2.6909 +13.7169i	2.1831	0.1925
-0.7041 +11.6739i	**1.8580**	**0.0602**

Table 7.7: Eigenvalues with PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-4.3855 +15.3768i	2.4473	0.2743
-3.4787 +13.7464i	2.1878	0.2453
-2.2538 +11.7343i	1.8676	0.1886

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to a 3-phase fault between bus 9&10. The fault last for 0.05 seconds. The system response shown as follow:

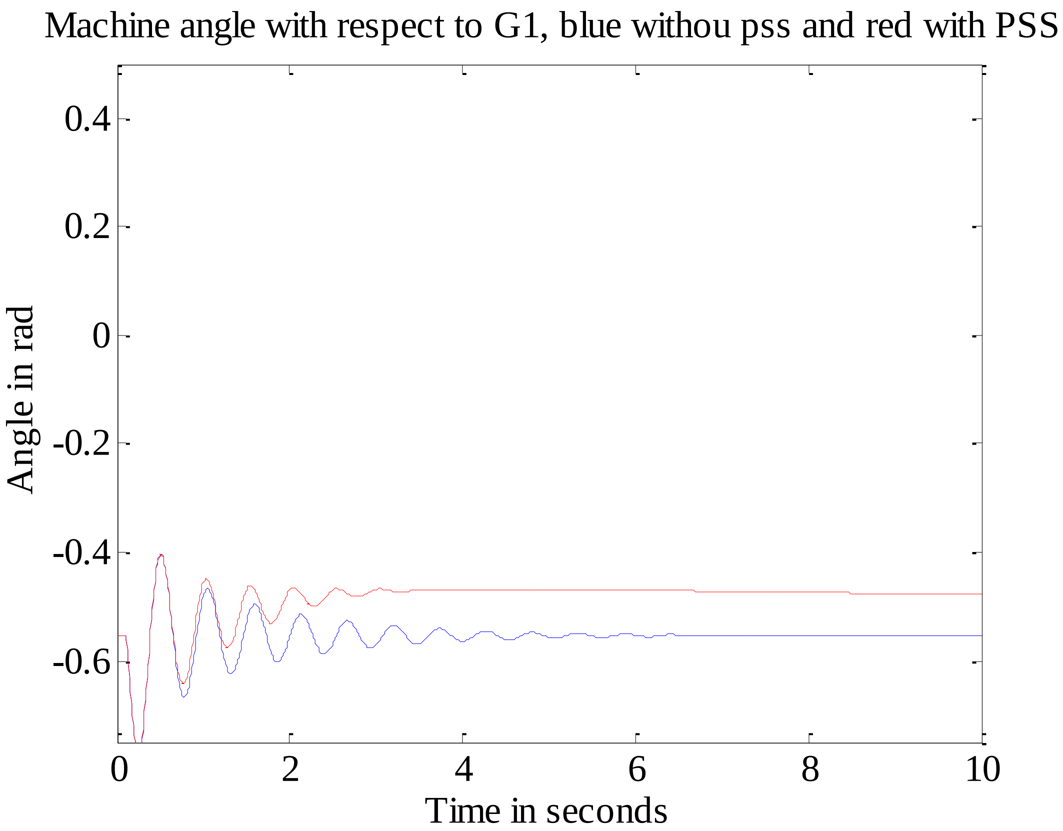

Figure 7.29: Generator 2 angle; blue line without PSS, Red line with PSS

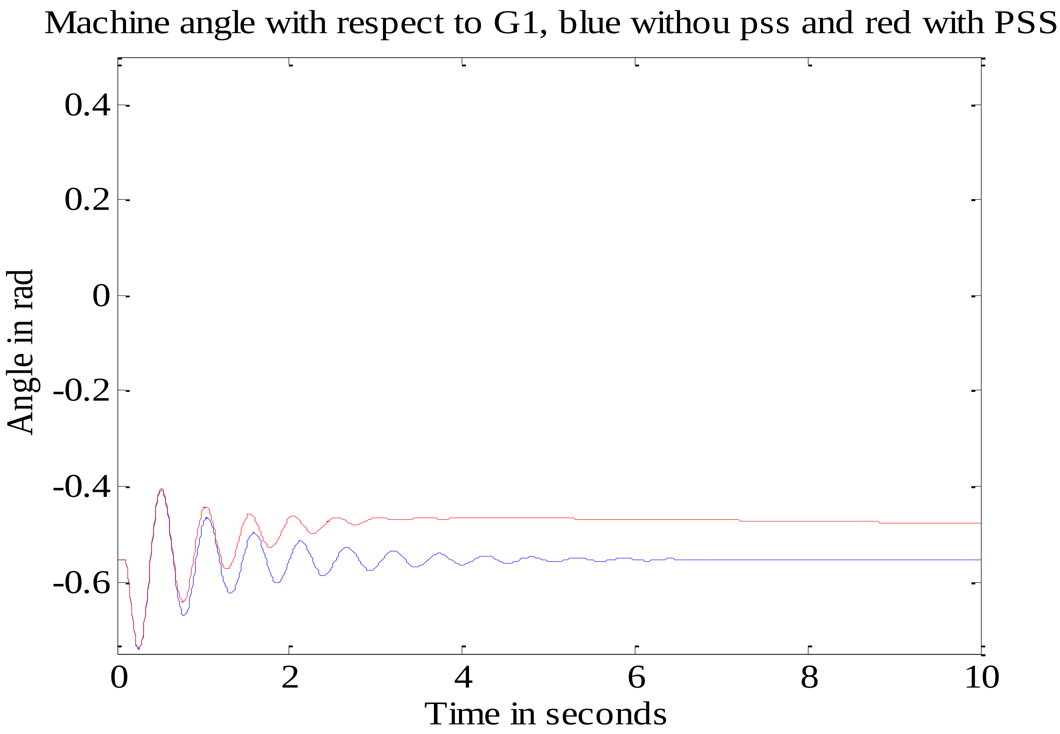

Figure 7.30: Generator 3 angle; blue line without PSS, Red line with PSS

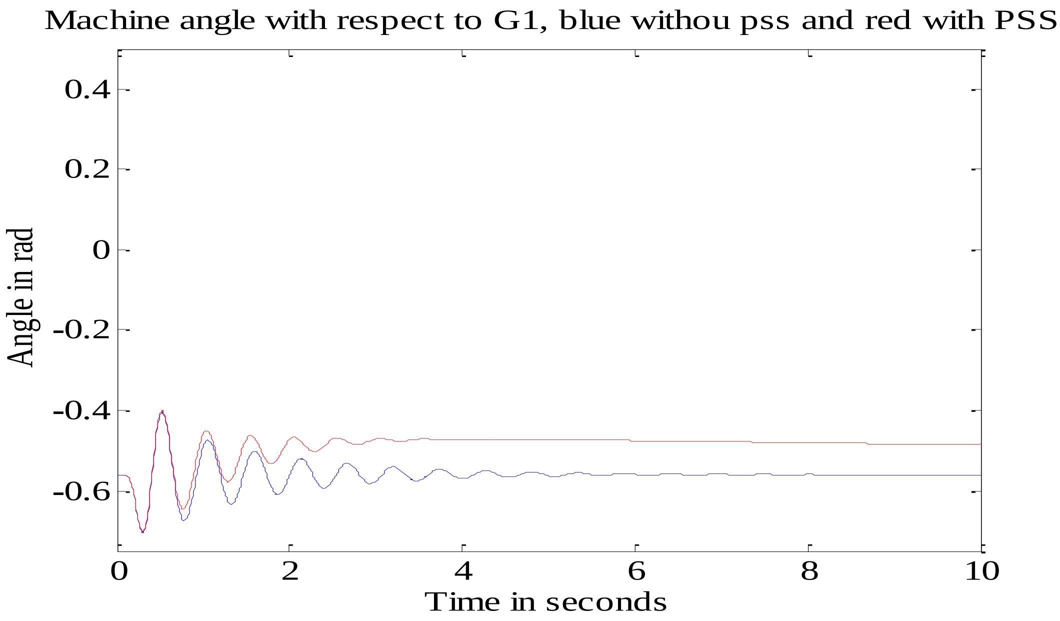

Figure 7.31: Generator 4 angle; blue line without PSS, Red line with PSS

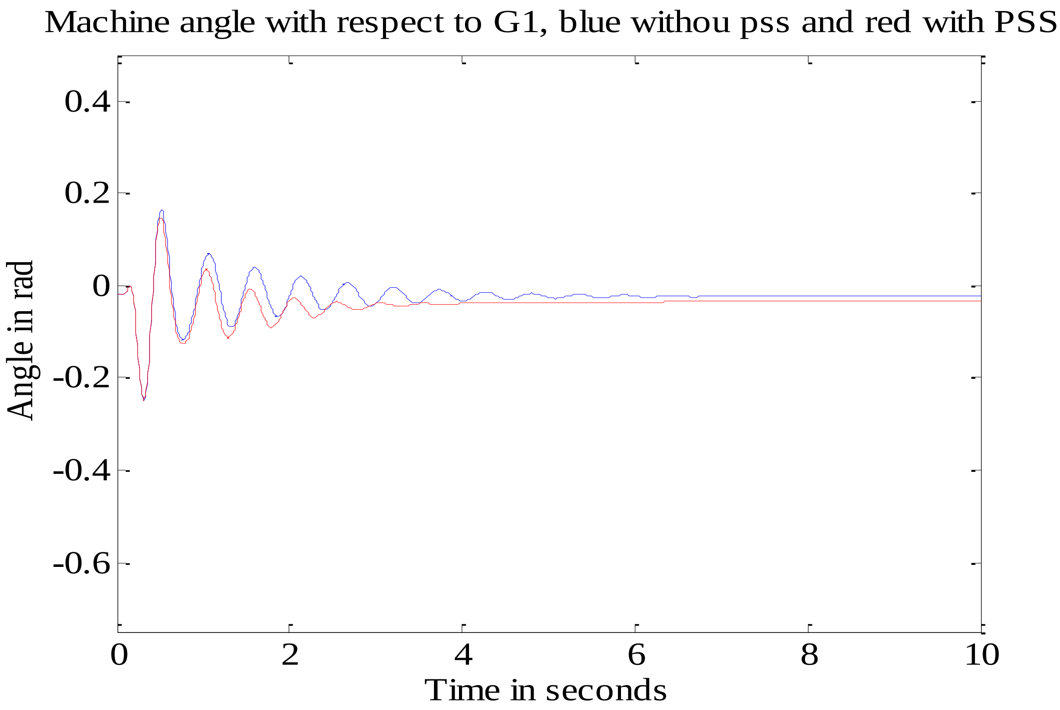

Figure 7.32: Generator 5 angle; blue line without PSS, Red line with PSS

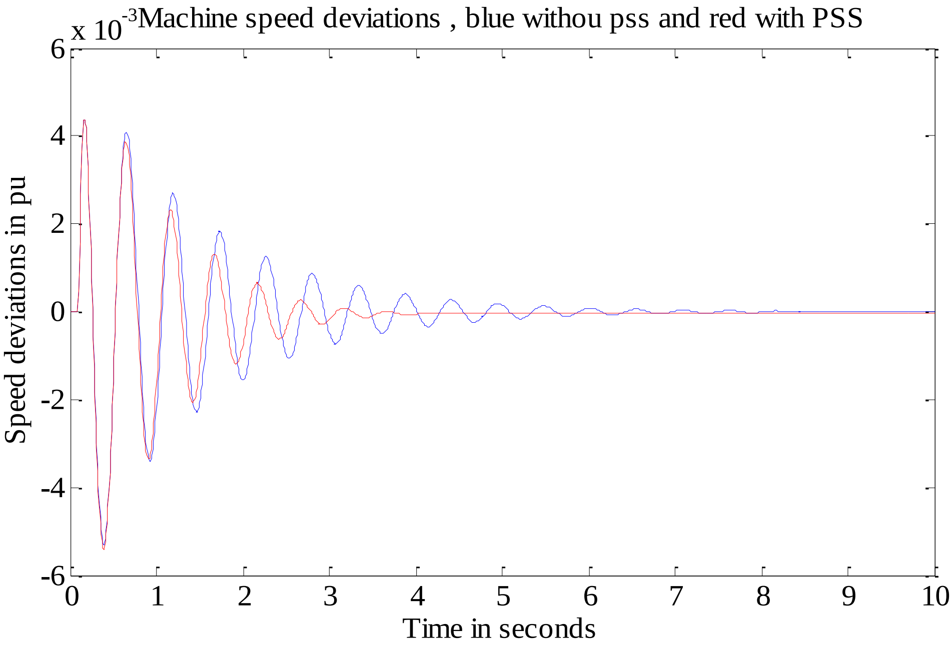

Figure 7.33: Generator 1 speed deviation; blue line without PSS, Red line with PSS

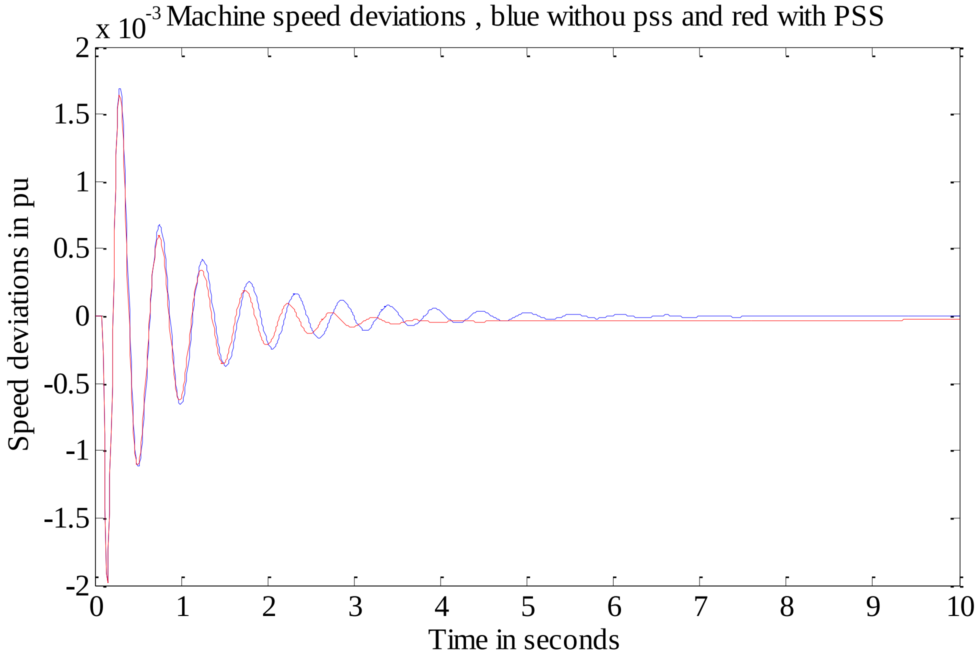

Figure 7.34: Generator 2 speed deviation; blue line without PSS, Red line with PSS

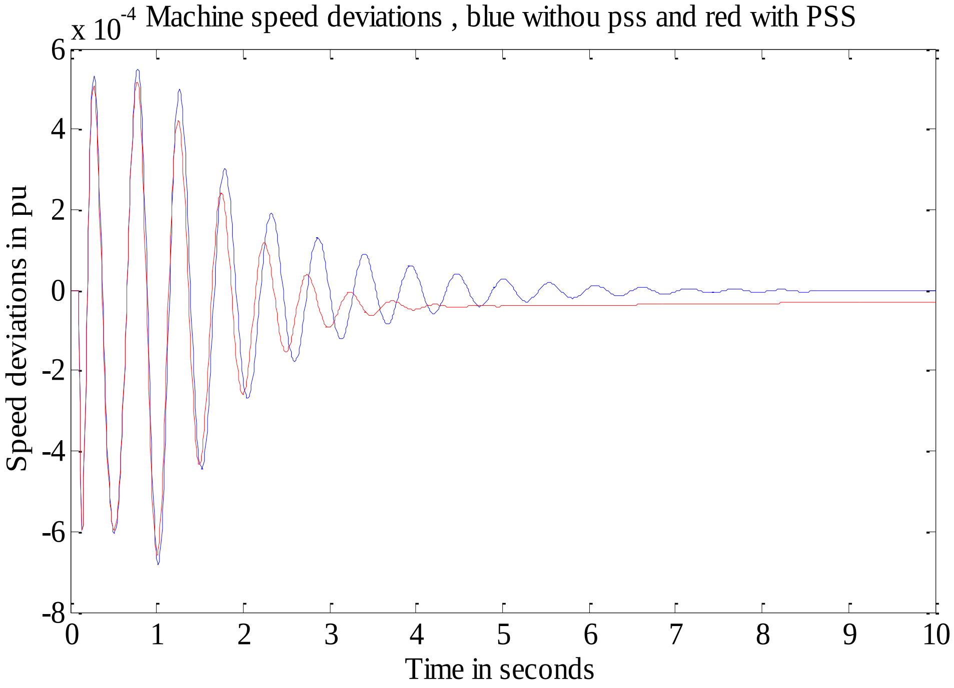

Figure 7.35: Generator 3 speed deviation; blue line without PSS, Red line with PSS

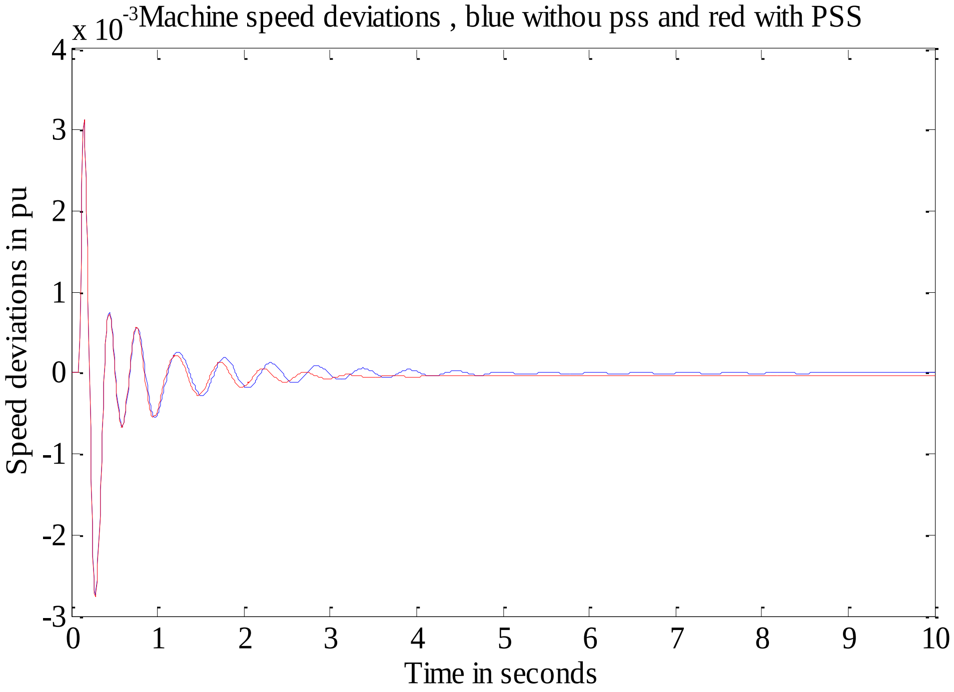

Figure 7.36: Generator 4 speed deviation; blue line without PSS, Red line with PSS

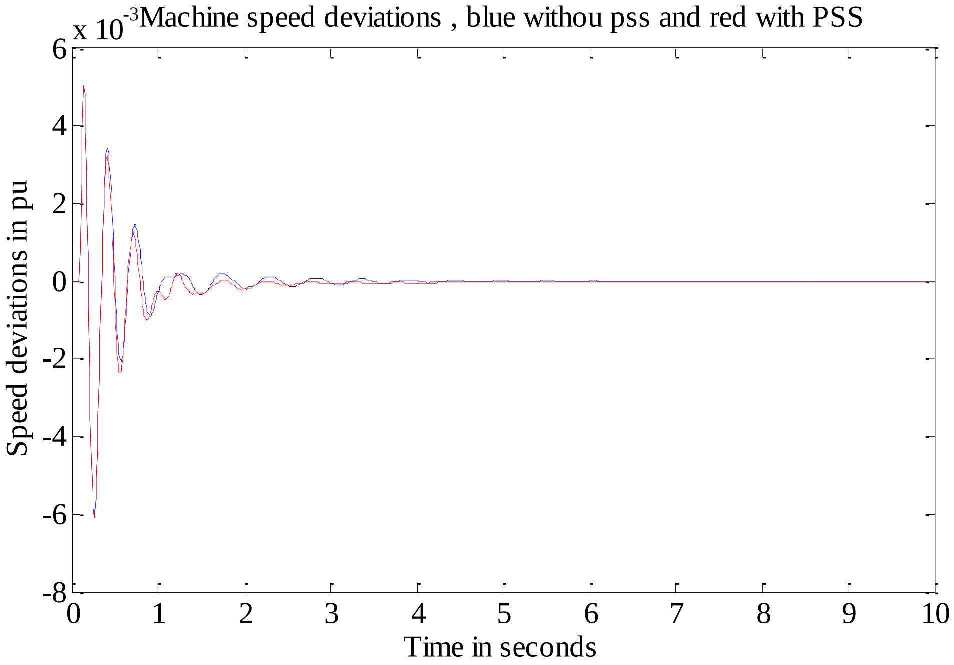

Figure 7.37: Generator 5 speed deviation; blue line without PSS, Red line with PSS

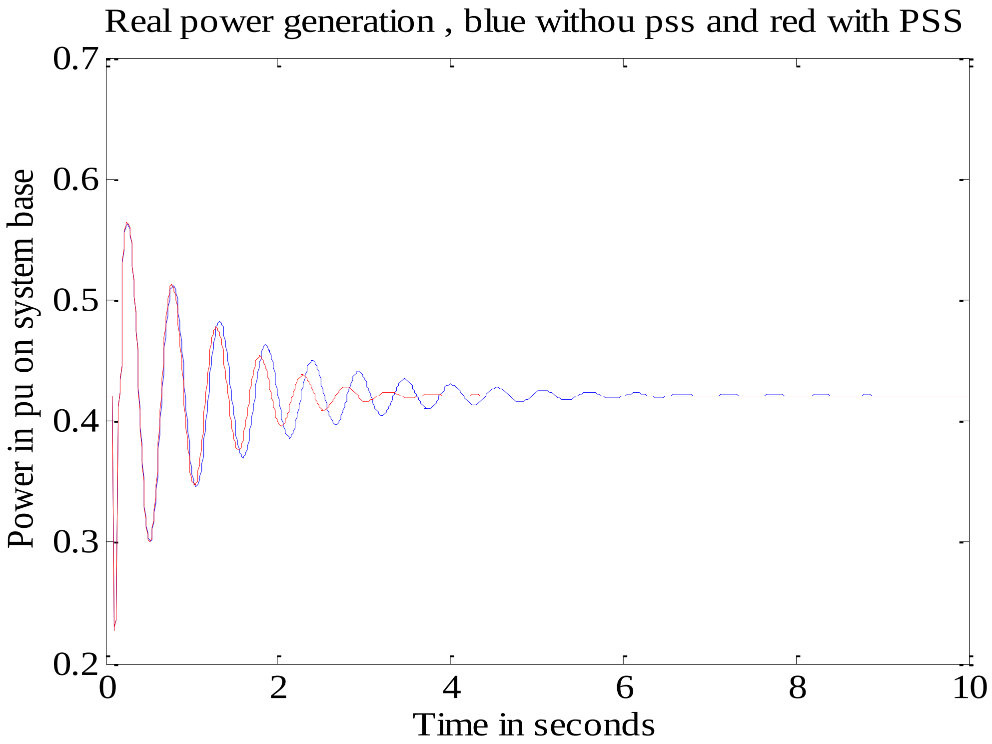

Figure 7.38: Generator 1 Power; blue line without PSS, Red line with PSS *without PSS* .

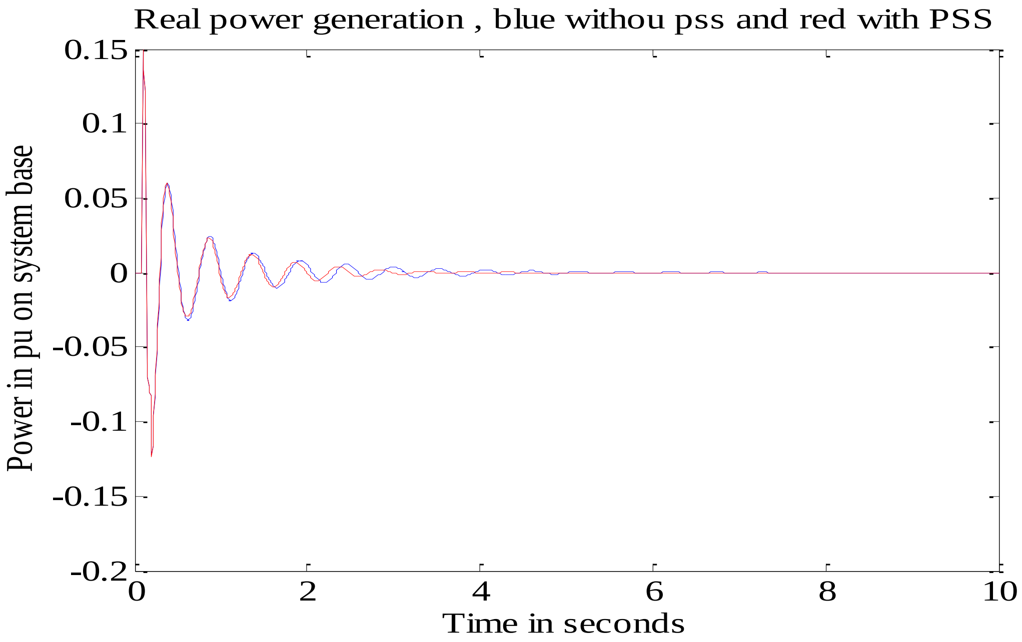

Figure 7.39: Generator 2 Power; blue line without PSS, Red line with PSS without PSS .

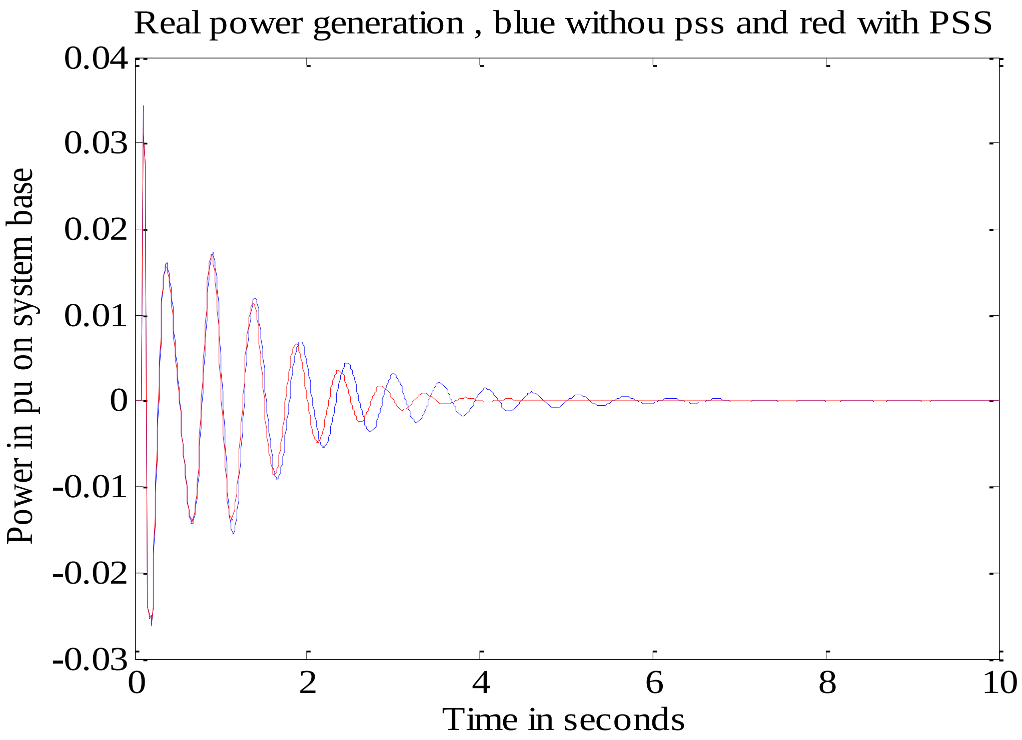

Figure 7.40: Generator 3 Power; blue line without PSS, Red line with PSS without PSS .

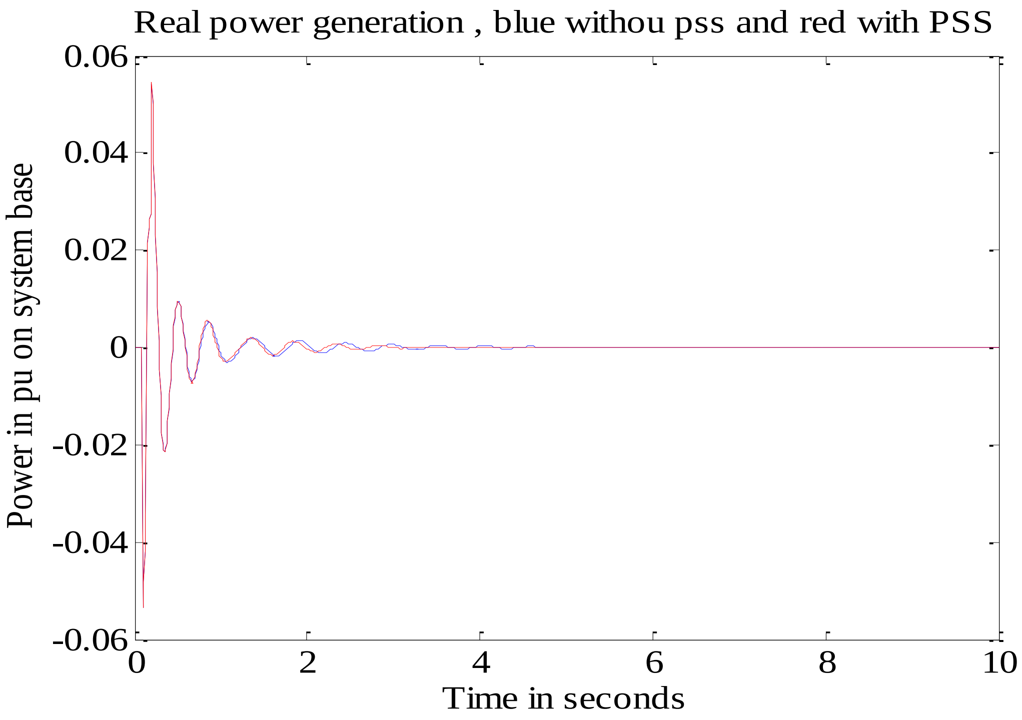

Figure 7.41: Generator 4 Power; blue line without PSS, Red line with PSS *without PSS* .

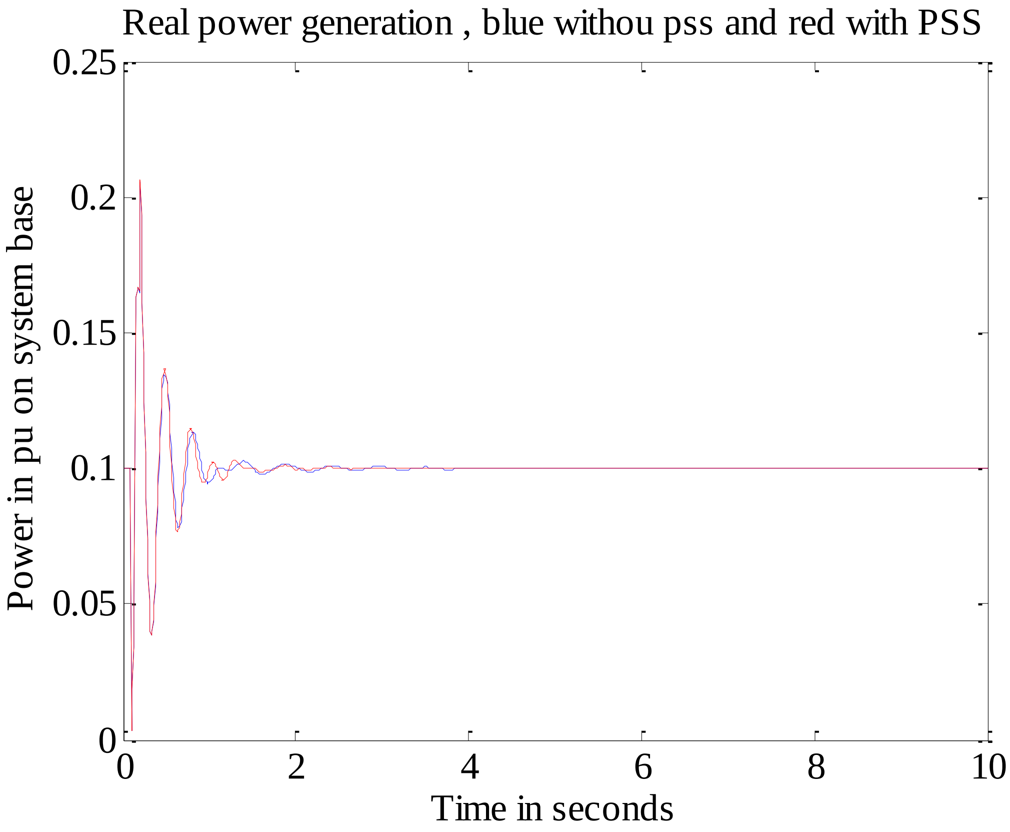

Figure 7.42: Generator 5 Power; blue line without PSS, Red line with PSS without PSS .

In this case although the system is very stable without the proposed PSS, the PSS addition improved the system stability during the fault.

7.4 Case 3 (Islanding Case, plant load with 45 MW)

Eigenvalue Analysis

The system eigenvalues with and without the proposed stabilizers for heavy loading with islanding condition is given in Table 7.8 and 7.9. In this case there is one EM shown in the system. Although the system is stable, it is clear that after applying the proposed stabilizers the system stability greatly improved. This is because table 7.9 shows more damping factors for each mode.

Table 7.8: Eigenvalues without PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-1.6504 +12.5992i	2.0052	0.1299
-1.3355 +11.6762i	1.8583	0.1136
-0.5316 + 9.9177i	**1.5784**	**0.0535**

Table 7.9: Eigenvalues with PSS

Eigenvalues	*Frequency (HZ)*	*Damping Ratio*
-2.5983 +12.8561i	2.0461	0.1981
-2.3284 +11.4543i	1.8230	0.1992
-1.7496 + 9.9146i	1.5780	0.1738

Non-linear time domain simulation

The system was tested with a non-linear simulator code using the matlab. The system was subjected to an islanding condition by opening the line between bus 6&7. The system response shown as follow:

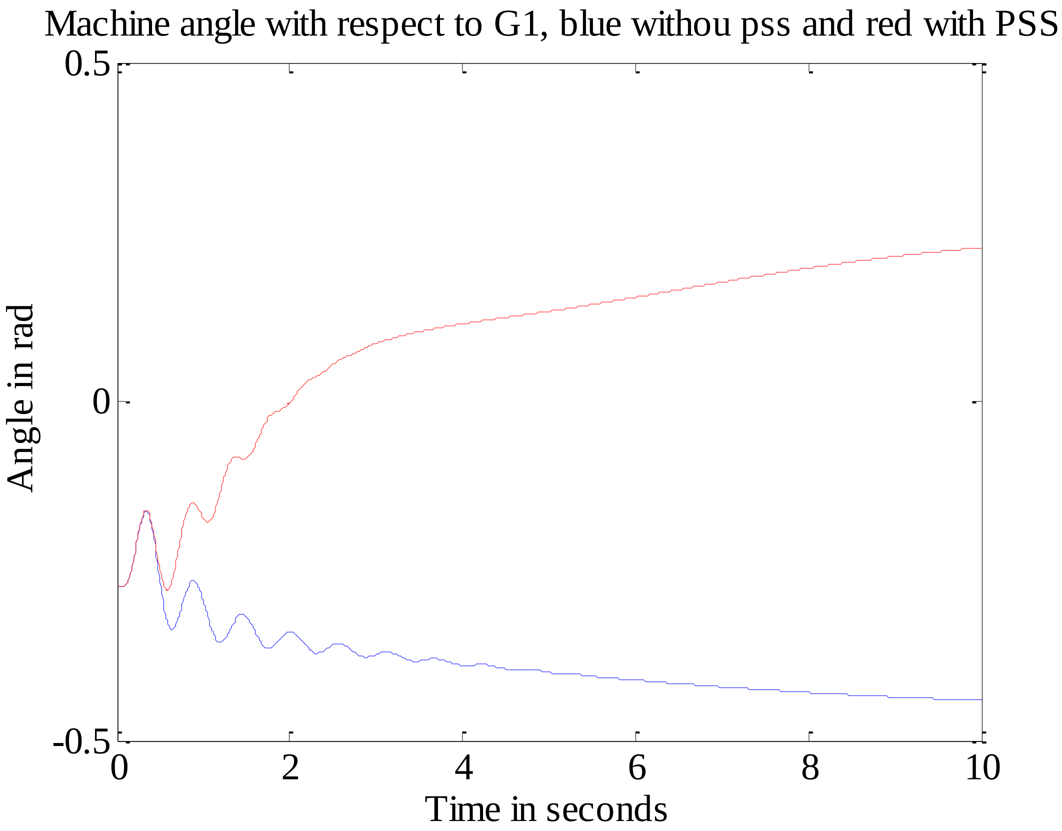

Figure 7.43: Generator 2 angle; blue line without PSS, Red line with PSS

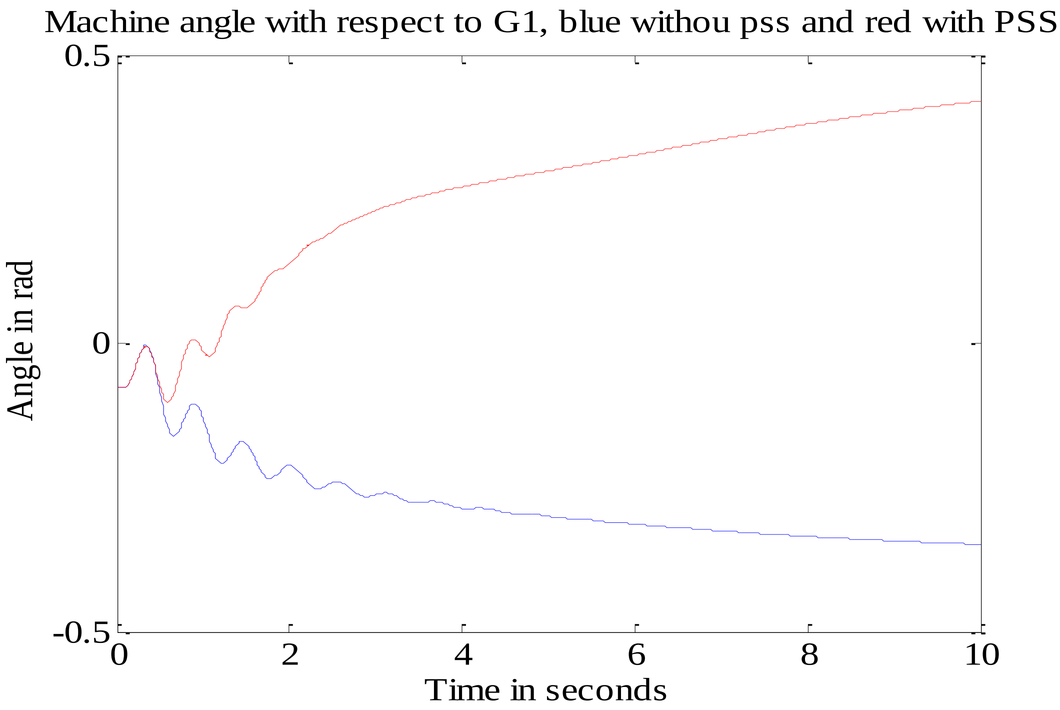

Figure 7.44: Generator 3 angle; blue line without PSS, Red line with PSS

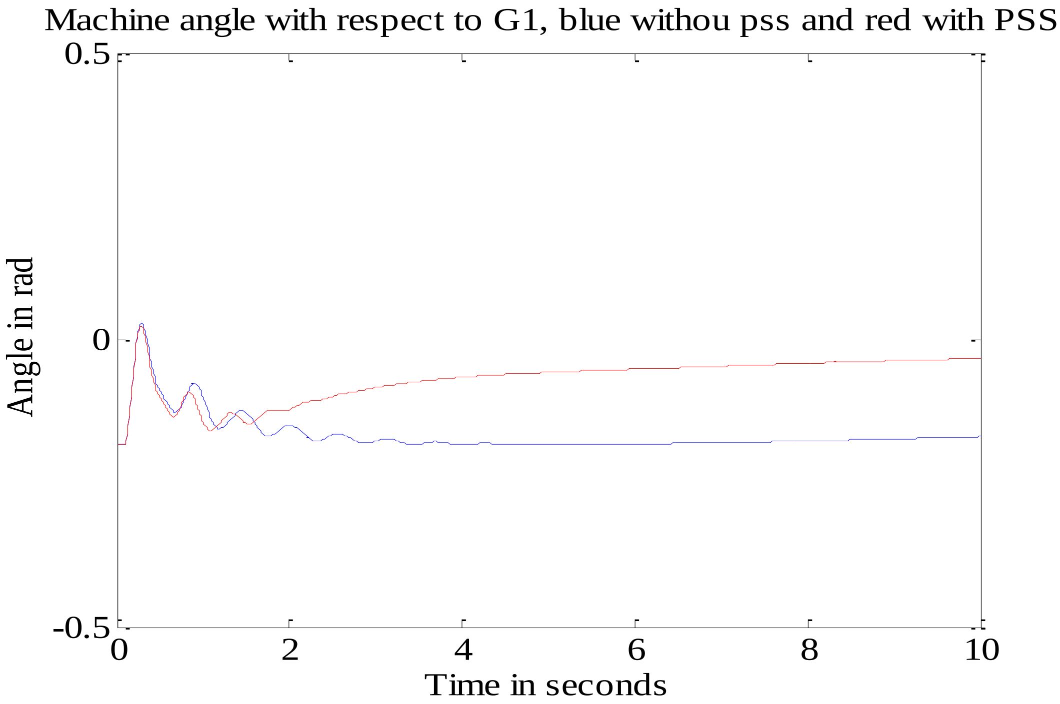

Figure 7.45: Generator 4 angle; blue line without PSS, Red line with PSS

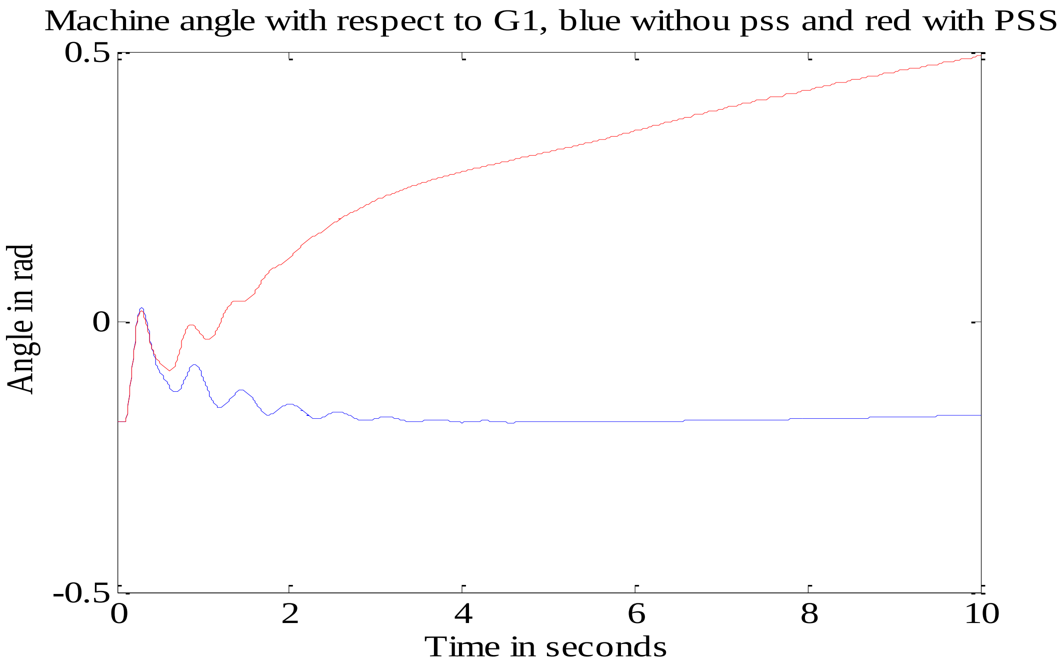

Figure 7.46: Generator 5 angle; blue line without PSS, Red line with PSS

With PSS it is obvious that the power angle of the machines (related to machine #1) increased. This is caused by the PSS action as a result of increasing the excitation to add a breaking torque in phase with the speed deviation. This is governed by the swing equation ($\dot{\delta}_i = \omega_0 \omega_i$), that is the increase in the generator speed will increase the angle too. The speed increased because of the load rejection.

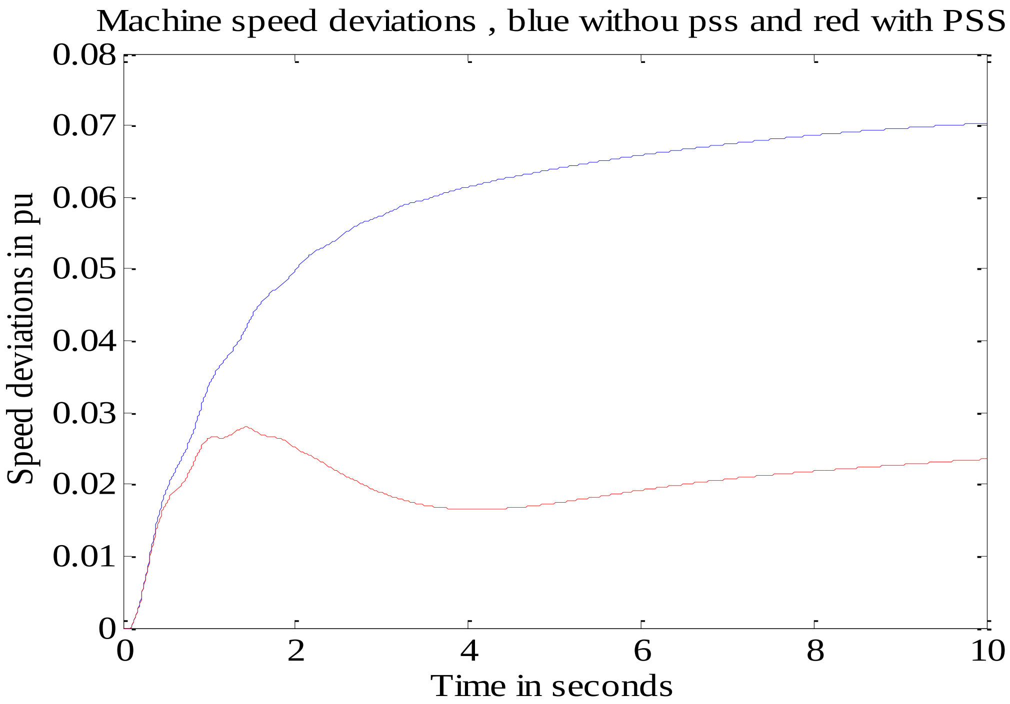

Figure 7.47: Generator 1 speed deviation; blue line without PSS, Red line with PSS

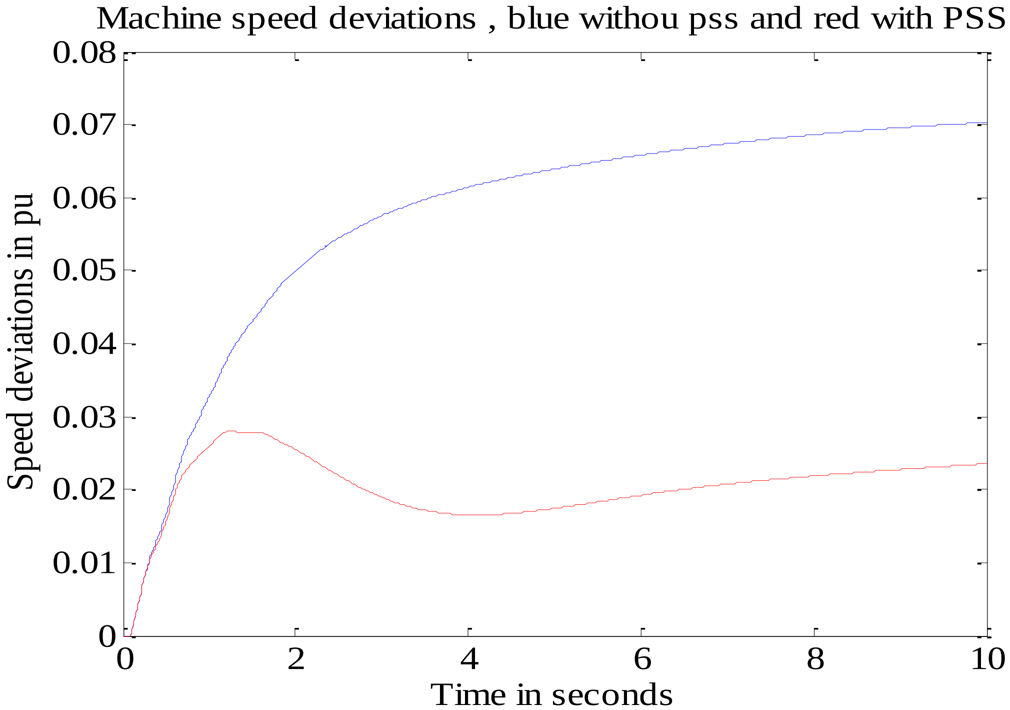

Figure 7.48: Generator 2 speed deviation; blue line without PSS, Red line with PSS

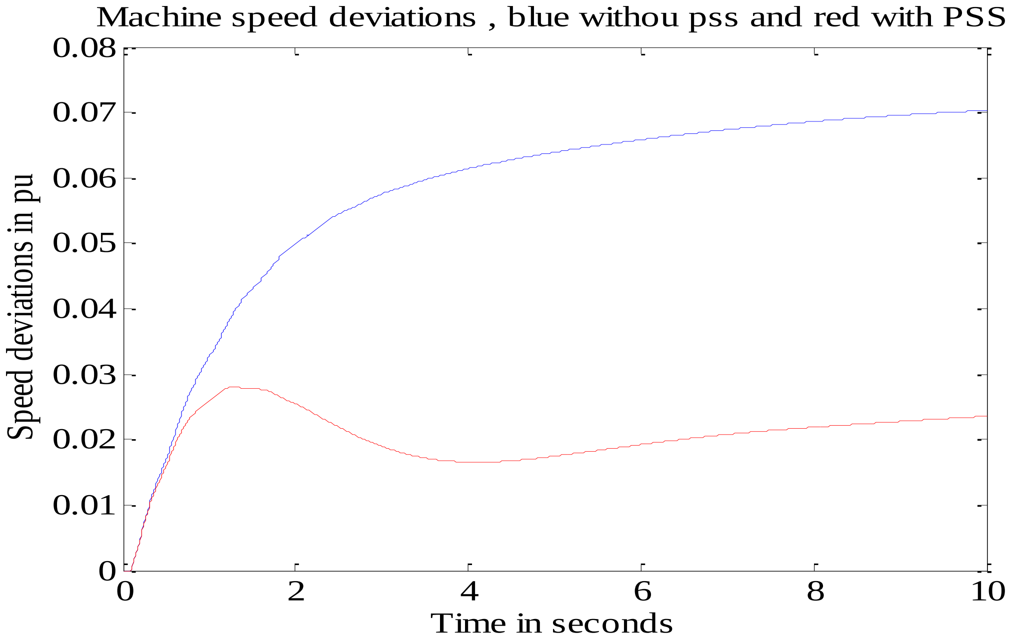

Figure 7.49: Generator 3 speed deviation; blue line without PSS, Red line with PSS

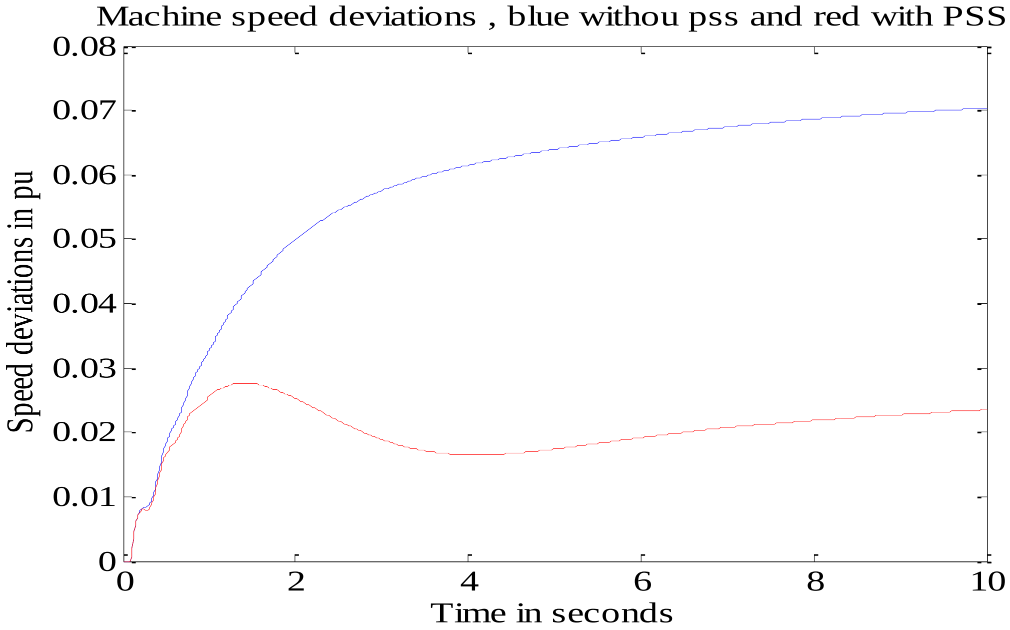

Figure 7.50: Generator 4 speed deviation; blue line without PSS, Red line with PSS

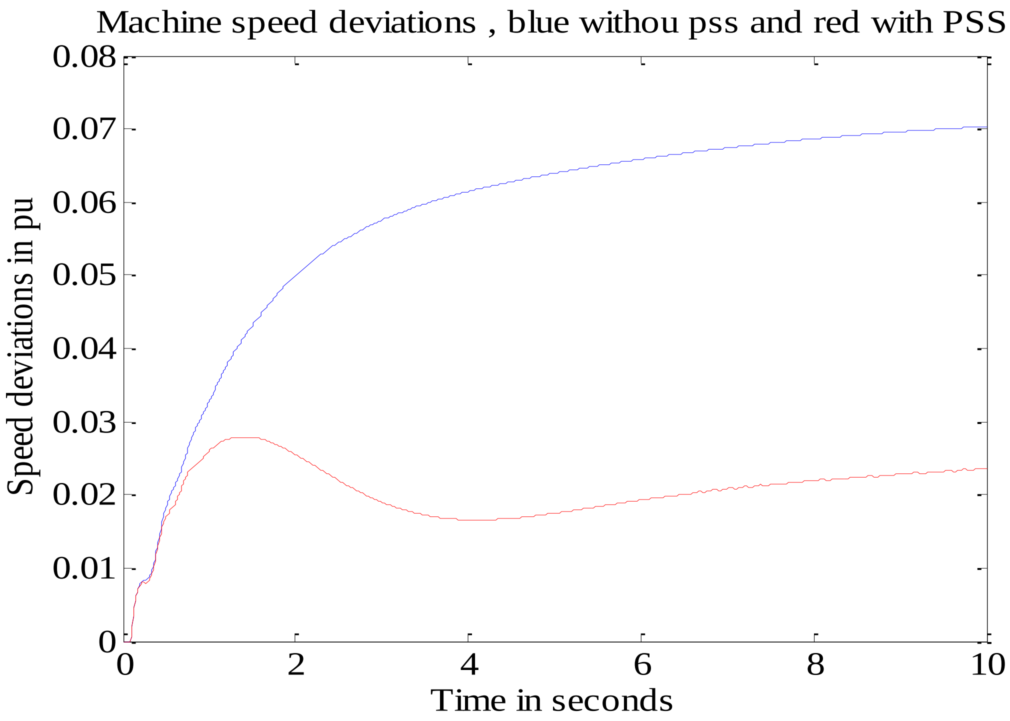

Figure 7.51: Generator 5 speed deviation; blue line without PSS, Red line with PSS

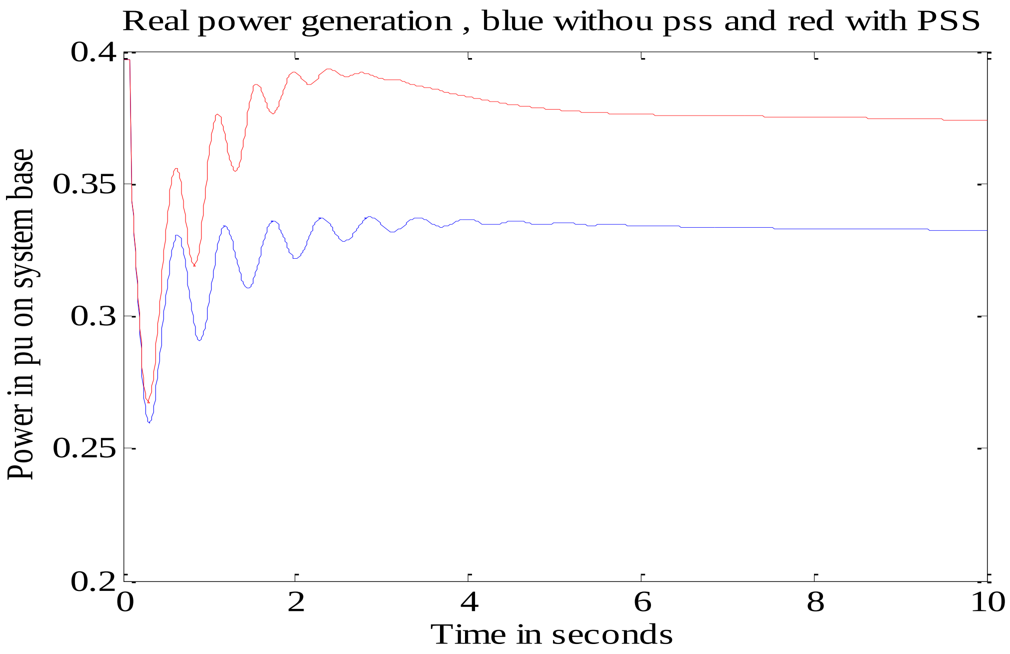

Figure 7.52: Generator 1 Power; blue line without PSS, Red line with PSS *without PSS* .

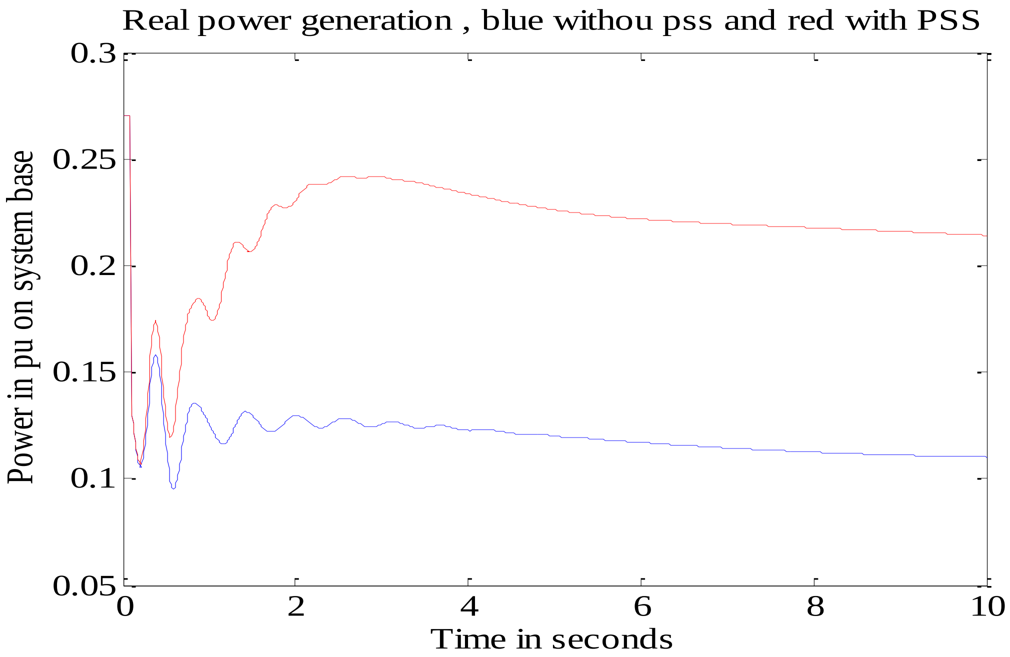

Figure 7.53: Generator 2 Power; blue line without PSS, Red line with PSS *without PSS* .

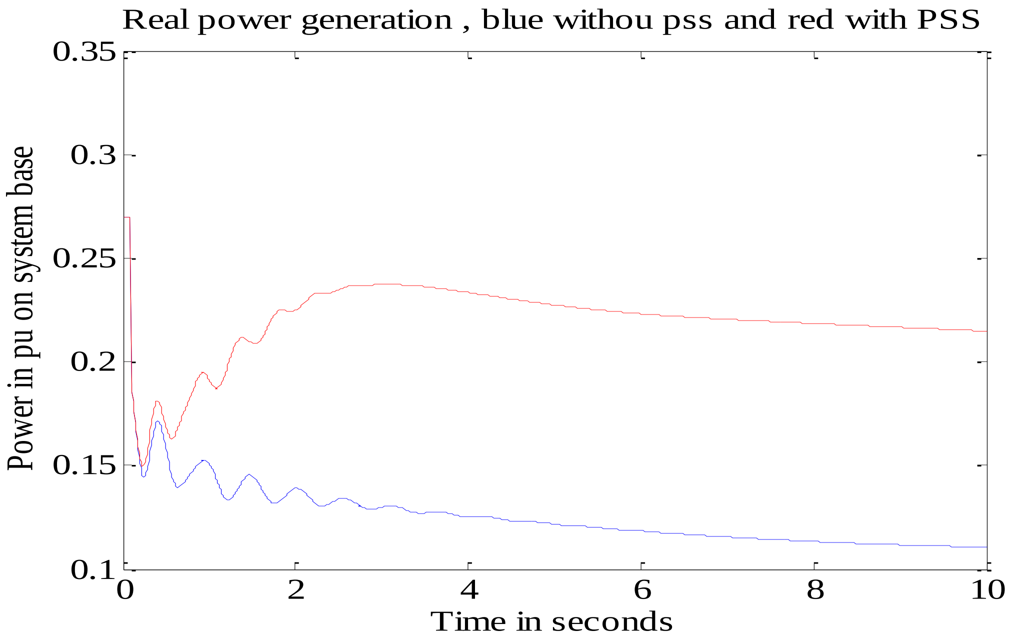

Figure 7.54: Generator 3 Power; blue line without PSS, Red line with PSS without PSS .

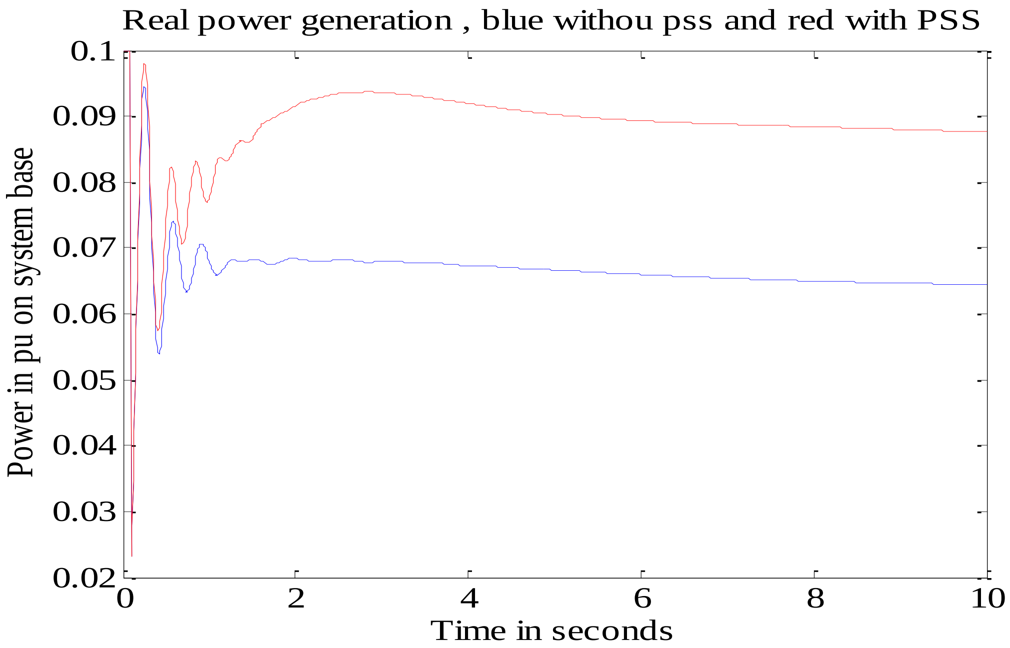

Figure 7.55: Generator 4 Power; blue line without PSS, Red line with PSS without PSS .

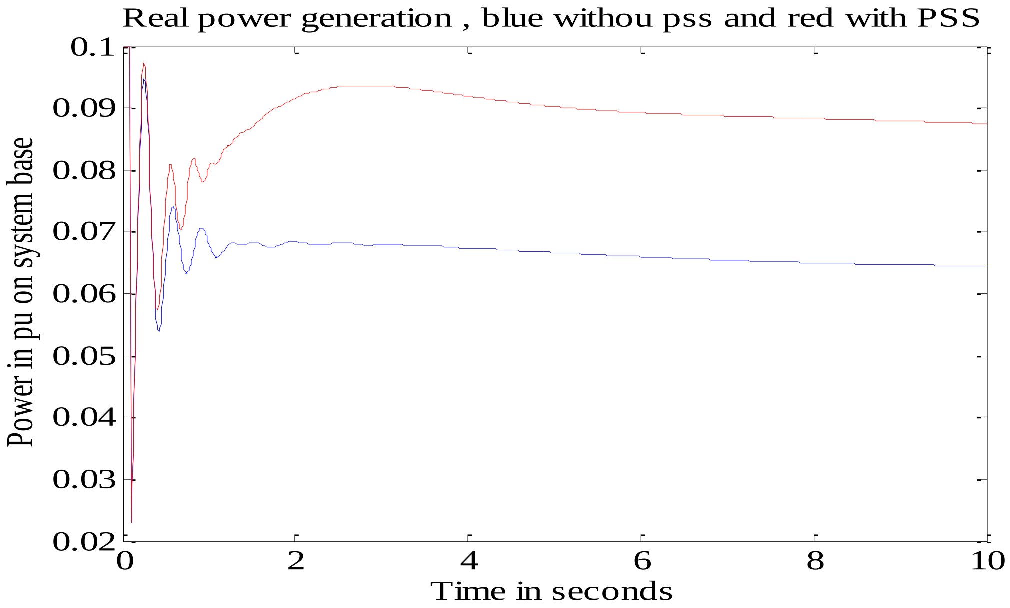

Figure 7.56: Generator 5 Power; blue line without PSS, Red line with PSS without PSS .

The red curves in the above figures reflect the generated power by each machine with PSS. It is very obvious that the electric breaking power increased after the islanding to apply forces on the generator shaft to counter act the speed deviations.

In this case the local industrial plant's system found to be not stable and the load rejection after the islanding will cause the generators frequency to reach the protection set point only after 3 seconds. This will lead to collapse the entire system. The addition of PSS at each generator will help in holding the generators frequency for 35 seconds before the activation of the protection system. This will allow the governor and other slow control system to reduce the mechanical power to or to trip one of the generators regain the system's stability.

CHAPTER 8

CONCLUSION AND FUTURE WORK

8.1 Conclusion

The main objective of this work is to model, study and enhance the stability of one of the local industrial plants at Saudi Arabia. This is to check if the plant has any stability issue that needs to be resolved to enhance the overall stability. Therefore, the local plant's electrical system has been modeled, studied and then a lead/lag PSS was proposed to enhance the stability. After that the PSS parameters were tuned to have optimized parameters for the PSS that are valid for all the possible operational scenarios. Differential evolution algorithm was used to acquire the best values for the PSS parameters. The DE algorithm optimally tuned the PSS parameters within the specified constrained. The tuned PSS successfully shows its capability of enhancing the tested system's stability over a wide-ranging of operating conditions.

A Matlab package was developed as part of this work and it was applied on three standard IEEE systems to verify its accuracy. The developed package improved dramatically the stability in all the test systems and even more in the 16-machines test system it shifted the system from being unstable to be a stable system with highlight damped EM modes. Moreover, we investigated the effectiveness of the proposed power system stabilizer in limiting the frequency change during the load rejection, which is usually happen during islanding .The nonlinear simulation showed promising results where the speed deviation was improved after adding the proposed PSS. Also, the simulation showed that without PSS the machines will be subject to a frequency change of +2.5 HZ where the protection system will isolate the generator. The protection relay will trip the machine once the frequency reaches 62.5

HZ. Therefore, we conclude that the proposed PSS can improve the subject plant even during islanding case.

Finally, the local plant’s electric system is found to be stable as long as it is connected to the utilities. However, if the plant is islanded while it is exporting 45 MW or more, the electric system is no longer stable and the frequency will reach a non-acceptable value. Addition of a PSS system is proven to solve this problem, which will limit the frequency escalation to an acceptable value. Therefore, the main objective of this thesis was met and the proposed approach enhanced the local plant stability in all cases.

8.2 Future Work:

Although it has been shown that Power System Stabilizer tuned by DE can improve the stability of the subject industrial plant during all operations cases, it is recommended to extend the research to cover the following:

- Utilize different approach to tune the proposed PSS, this may include utilizing Particle Swarm Optimization Algorithm (PSO) or Genetic Algorithm (GA).

- Compare the results obtained from using GA or PSO with the DE.
- Utilize the Real time dynamic simulator

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APPENDIX

A. IEEE Four Machine test system data [85]

```
% bus data format
% bus:
% col1 number
% col2 voltage magnitude(pu)
% col3 voltage angle(degree)
% col4 p_gen(pu)
% col5 q_gen(pu),
% col6 p_load(pu)
% col7 q_load(pu)
% col8 G shunt(pu)
% col9 B shunt(pu)
% col10 bus_type
%       bus_type - 1, swing bus
%               - 2, generator bus (PV bus)
%               - 3, load bus (PQ bus)
% col11 q_gen_max(pu)
% col12 q_gen_min(pu)
% col13 v_rated (kV)
% col14 v_max  pu
% col15 v_min  pu

bus = [...
   1 1.03     18.5   7.00   1.61  0.00  0.00  0.00  0.00 1  5.0  -2.0  22.0   1.1  .9;
   2 1.01     8.80   7.00   1.76  0.00  0.00  0.00  0.00 2  5.0  -2.0   22.0   1.1  .9;
   3 0.9781  -6.1    0.00   0.00  0.00  0.00  0.00  1.50 3  0.0   0.0   500.0  1.5  .5;
   4 0.95    -10     0.00   0.00  14.00 1.00  0.00  0.00 3  0.0   0.0   115.0  1.05 .95;
  10 1.0103    12.1  0.00   0.00  0.00  0.00  0.00  0.00 3  0.0   0.0   230.0  1.5  .5;
  11 1.03    -6.8    7.16   1.49  0.00  0.00  0.00  0.00 2  5.0  -2.0   22.0   1.1  .9;
  12 1.01    -16.9   7.00   1.39  0.00  0.00  0.00  0.00 2  5.0  -2.0   22.0   1.1  .9;
  13 0.9899  -31.8   0.00   0.00  0.00  0.00  0.00  4.10 3  0.0   0.0   500.0  1.5  .5;
  14 0.95    -38     0.00   0.00  14.00 1.00  0.00  0.00 3  0.0   0.0   115.0  1.05 .95;
  20 0.9876   2.1    0.00   0.00  0.00  0.00  0.00  0.00 3  0.0   0.0   230.0  1.5  .5;
 101 1.05    -19.3   0.00   1.00  0.00  0.00  0.00  2.00 2  2.0   0.0   500.0  1.5  .5;
 110 1.0125  -13.4   0.00   0.00  0.00  0.00  0.00  0.00 3  0.0   0.0   230.0  1.5  .5;
 120 0.9938  -23.6   0.00   0.00  0.00  0.00  0.00  0.00 3  0.0   0.0   230.0  1.5  .5 ];
```

```
% line data format
% line: from bus, to bus, resistance(pu), reactance(pu),
%      line charging(pu), tap ratio, tap phase, tapmax, tapmin, tapsize

line = [...
1   10  0.0     0.0167   0.00    1.0  0. 0.  0.  0.;
2   20  0.0     0.0167   0.00    1.0  0. 0.  0.  0.;
3    4  0.0     0.005     0.00   1.0  0. 1.2 0.8 0.05;
3   20  0.001   0.0100   0.0175  1.0  0. 0.  0.  0.;
3   101 0.011   0.110    0.1925  1.0  0. 0.  0.  0.;
3   101 0.011   0.110    0.1925  1.0  0. 0.  0.  0.;
10  20  0.0025  0.025    0.0437  1.0  0. 0.  0.  0.;
11  110 0.0     0.0167   0.0     1.0  0. 0.  0.  0.;
12  120 0.0     0.0167   0.0     1.0  0. 0.  0.  0.;
13   14 0.0     0.005    0.00    1.0  0. 1.2 0.8 0.05;
13  101 0.011   0.11     0.1925  1.0  0. 0.  0.  0.;
13  101 0.011   0.11     0.1925  1.0  0. 0.  0.  0.;
13  120 0.001   0.01     0.0175  1.0  0. 0.  0.  0.;
110 120 0.0025  0.025    0.0437  1.0  0. 0.  0.  0.];


% Machine data format
% Machine data format
%      1. machine number,
%      2. bus number,
%      3. base mva,
%      4. leakage reactance x_l(pu),
%      5. resistance r_a(pu),
%      6. d-axis sychronous reactance x_d(pu),
%      7. d-axis transient reactance x'_d(pu),
%      8. d-axis subtransient reactance x"_d(pu),
%      9. d-axis open-circuit time constant T'_do(sec),
%     10. d-axis open-circuit subtransient time constant
%               T"_do(sec),
%     11. q-axis sychronous reactance x_q(pu),
%     12. q-axis transient reactance x'_q(pu),
%     13. q-axis subtransient reactance x"_q(pu),
%     14. q-axis open-circuit time constant T'_qo(sec),
%     15. q-axis open circuit subtransient time constant
%               T"_qo(sec),
%     16. inertia constant H(sec),
```

```
%      17. damping coefficient d_o(pu),
%      18. dampling coefficient d_1(pu),
%      19. bus number
%
% note: all the following machines use sub-transient model
mac_con = [ ...

1 1 900 0.200  0.00    1.8  0.30  0.25 8.00  0.03...
                      1.7  0.55  0.25 0.4   0.05...
                      6.5  0  0  3  0.0654  0.5743;
2 2 900 0.200  0.00    1.8  0.30  0.25 8.00  0.03...
                      1.7  0.55  0.25 0.4   0.05...
                      6.5  0  0  3  0.0654  0.5743;
3 11 900 0.200  0.00   1.8  0.30  0.25 8.00  0.03...
                      1.7  0.55  0.25 0.4   0.05...
                      6.5  0  0  3  0.0654  0.5743;
4 12 900 0.200  0.00   1.8  0.30  0.25 8.00  0.03...
                      1.7  0.55  0.25 0.4   0.05...
                      6.5  0  0  3  0.0654  0.5743;
              ];

% all dc exciters, no pss
% col1 type
% col2 machine number
% col3 Tr
% col4 Ka
% col5 Ta
% col6 Tb
% col7 Tc
% col8 Vrmax
% col9 Vrmin
% col10 Ke
% col11 Te
% col12 E1
% col13 Se(E1)
% col14 E2
% col15 Se(E2)
% col16 Kf
% col17 Tf
% cols 18 to 20 required for exc_st3 only
exc_con = [...
1 1 0.01 46.0   0.06  0     0    1.0   -0.9...
   0.0  0.46   3.1   0.33  2.3  0.1   0.1   1.0    0    0   0;
```

```
1 2 0.01 46.0   0.06  0     0    1.0   -0.9...
   0.0  0.46   3.1   0.33  2.3  0.1   0.1   1.0    0    0   0;
1 3 0.01 46.0   0.06  0     0    1.0   -0.9...
   0.0  0.46   3.1   0.33  2.3  0.1   0.1   1.0    0    0   0;
1 4 0.01 46.0   0.06  0     0    1.0   -0.9...
   0.0  0.46   3.1   0.33  2.3  0.1   0.1   1.0    0    0   0];


% governor model
% tg_con matrix format
%column        data         unit
%  1    turbine model number (=1)
%  2    machine number
%  3    speed set point   wf        pu
%  4    steady state gain 1/R       pu
%  5    maximum power order  Tmax   pu on generator base
%  6    servo time constant   Ts    sec
%  7    governor time constant  Tc  sec
%  8    transient gain time constant T3 sec
%  9    HP section time constant   T4   sec
% 10    reheater time constant    T5    sec

tg_con = [...
1  1  1  25.0  1.0  0.1  0.5 0.0 1.25 5.0;
1  2  1  25.0  1.0  0.1  0.5 0.0 1.25 5.0;
1  3  1  25.0  1.0  0.1  0.5 0.0 1.25 5.0;
1  4  1  25.0  1.0  0.1  0.5 0.0 1.25 5.0];



%Switching file defines the simulation control
% row 1 col1  simulation start time (s) (cols 2 to 6 zeros)
%       col7  initial time step (s)
% row 2 col1  fault application time (s)
%       col2  bus number at which fault is applied
%       col3  bus number defining far end of faulted line
%       col4  zero sequence impedance in pu on system base
%       col5  negative sequence impedance in pu on system base
%       col6  type of fault  - 0 three phase
%                            - 1 line to ground
%                            - 2 line-to-line to ground
%                            - 3 line-to-line
%                            - 4 loss of line with no fault
```

```
%                       - 5 loss of load at bus
%                       - 6 no fault
%       col7  time step for fault period (s)
% row 3 col1  near end fault clearing time (s) (cols 2 to 6 zeros)
%       col7  time step for second part of fault (s)
% row 4 col1  far end fault clearing time (s) (cols 2 to 6 zeros)
%       col7  time step for fault cleared simulation (s)
% row 5 col1  time to change step length (s)
%       col7  time step (s)
%
%
%
% row n col1 finishing time (s)  (n indicates that intermediate rows may be inserted)

sw_con = [...
0    0    0    0    0    0    0.01;%sets intitial time step
0.1  3  101    0    0    0    0.005; %3-ph fault at bus 3
0.15 0    0    0    0    0    0.005556; %clear fault at bus 3
0.20 0    0    0    0    0    0.005556; %clear remote end
10   0    0    0    0    0    0]; % end simulation
% monitor all line flows
lmon_con = [1:length(line(:,1))]';
```

B. IEEE 16 machines test system data [85]

```
% Bus data format
% bus:
% col1 number
% col2 voltage magnitude(pu)
% col3 voltage angle(degree)
% col4 p_gen(pu)
% col5 q_gen(pu),
% col6 p_load(pu)
% col7 q_load(pu)
% col8 G shunt(pu)
% col9 B shunt(pu)
% col10 bus_type
%       bus_type - 1, swing bus
%                - 2, generator bus (PV bus)
```

```
%             - 3, load bus (PQ bus)
% col11 q_gen_max(pu)
% col12 q_gen_min(pu)


bus = [...
  1 1.00   0.00  0.00  0.00  2.527  1.1856  0.00 0.00  3  0  0;
  2 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  3 1.00   0.00  0.00  0.00  3.22   0.02    0.00 0.00  3  0  0;
  4 1.00   0.00  0.00  0.00  5.00   1.840   0.00 0.00  3  0  0;
  5 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  6 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  7 1.00   0.00  0.00  0.00  2.34   0.84    0.00 0.00  3  0  0;
  8 1.00   0.00  0.00  0.00  5.22   1.77    0.00 0.00  3  0  0;
  9 1.00   0.00  0.00  0.00  1.04   1.25    0.00 0.00  3  0  0;
  10 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  11 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  12 1.00   0.00  0.00  0.00  0.09   0.88    0.00 0.00  3  0  0;
  13 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  14 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  15 1.00   0.00  0.00  0.00  3.200  1.5300  0.00 0.00  3  0  0;
  16 1.00   0.00  0.00  0.00  3.290  0.32    0.00 0.00  3  0  0;
  17 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  18 1.00   0.00  0.00  0.00  1.58   0.30    0.00 0.00  3  0  0;
  19 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  20 1.00   0.00  0.00  0.00  6.800  1.03    0.00 0.00  3  0  0;
  21 1.00   0.00  0.00  0.00  2.740  1.15    0.00 0.00  3  0  0;
  22 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  23 1.00   0.00  0.00  0.00  2.480  0.85    0.00 0.00  3  0  0;
  24 1.00   0.00  0.00  0.00  3.09   -0.92   0.00 0.00  3  0  0;
  25 1.00   0.00  0.00  0.00  2.24   0.47    0.00 0.00  3  0  0;
  26 1.00   0.00  0.00  0.00  1.39   0.17    0.00 0.00  3  0  0;
  27 1.00   0.00  0.00  0.00  2.810  0.76    0.00 0.00  3  0  0;
  28 1.00   0.00  0.00  0.00  2.060  0.28    0.00 0.00  3  0  0;
  29 1.00   0.00  0.00  0.00  2.840  0.27    0.00 0.00  3  0  0;
  30 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  31 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  32 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  33 1.00   0.00  0.00  0.00  1.12   0.00    0.00 0.00  3  0  0;
  34 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  35 1.00   0.00  0.00  0.00  0.00   0.00    0.00 0.00  3  0  0;
  36 1.00   0.00  0.00  0.00  1.02   -0.1946  0.00 0.00  3  0  0;
  37 1.00   0.00  0.00  0.00  60.00  3.00    0.00 0.00  3  0  0;
```

```
  38 1.00    0.00   0.00   0.00   0.00   0.00    0.00 0.00  3  0  0;
  39 1.00    0.00   0.00   0.00   2.67   0.126   0.00 0.00  3  0  0;
  40 1.00    0.00   0.00   0.00   0.6563 0.2353  0.00 0.00  3  0  0;
  41 1.00    0.00   0.00   0.00  10.00   2.50    0.00 0.00  3  0  0;
  42 1.00    0.00   0.00   0.00  11.50   2.50    0.00 0.00  3  0  0;
  43 1.00    0.00   0.00   0.00   0.00   0.00    0.00 0.00  3  0  0;
  44 1.00    0.00   0.00   0.00   2.6755 0.0484  0.00 0.00  3  0  0;
  45 1.00    0.00   0.00   0.00   2.08   0.21    0.00 0.00  3  0  0;
  46 1.00    0.00   0.00   0.00   1.507  0.285   0.00 0.00  3  0  0;
  47 1.00    0.00   0.00   0.00   2.0312 0.3259  0.00 0.00  3  0  0;
  48 1.00    0.00   0.00   0.00   2.4120 0.022   0.00 0.00  3  0  0;
  49 1.00    0.00   0.00   0.00   1.6400 0.29    0.00 0.00  3  0  0;
  50 1.00    0.00   0.00   0.00   1.00  -1.47    0.00 0.00  3  0  0;
  51 1.00    0.00   0.00   0.00   3.37  -1.22    0.00 0.00  3  0  0;
  52 1.00    0.00   0.00   0.00  24.70   1.23    0.00 0.00  3  0  0;
  53 1.045   0.00   2.50   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  54 0.98    0.00   5.45   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  55 0.983   0.00   6.50   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  56 0.997   0.00   6.32   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  57 1.011   0.00   5.052  0.00   0.00   0.00    0.00 0.00  2  999  -999;
  58 1.050   0.00   7.00   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  59 1.063   0.00   5.60   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  60 1.03    0.00   5.40   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  61 1.025   0.00   8.00   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  62 1.010   0.00   5.00   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  63 1.000   0.00  10.000  0.00   0.00   0.00    0.00 0.00  2  999  -999;
  64 1.0156  0.00  13.50   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  65 1.011   0.00  35.91   0.00   0.00   0.00    0.00 0.00  1  0  0;
  66 1.00    0.00  17.85   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  67 1.000   0.00  10.00   0.00   0.00   0.00    0.00 0.00  2  999  -999;
  68 1.000   0.00  40.00   0.00   0.00   0.00    0.00 0.00  2  999  -999];


% Line data format
% line: from bus, to bus, resistance(pu), reactance(pu),
%       line charging(pu), tap ratio, phase shift(deg)

line = [...
  1   2  0.0035  0.0411  0.6987  0     0.;
  1  30  0.0008  0.0074  0.48    0     0.;
  2   3  0.0013  0.0151  0.2572  0     0.;
  2  25  0.007   0.0086  0.146   0     0.;
  2  53  0.      0.0181  0.      1.025  0.;
```

```
3   4  0.0013  0.0213  0.2214  0.    0.;
3  18  0.0011  0.0133  0.2138  0.    0.;
4   5  0.0008  0.0128  0.1342  0.    0.;
4  14  0.0008  0.0129  0.1382  0.    0.;
5   6  0.0002  0.0026  0.0434  0.    0.;
5   8  0.0008  0.0112  0.1476  0.    0.;
6   7  0.0006  0.0092  0.1130  0.    0.;
6  11  0.0007  0.0082  0.1389  0.    0.;
6  54  0.      0.0250  0.      1.07   0.;
7   8  0.0004  0.0046  0.078   0.    0.;
8   9  0.0023  0.0363  0.3804  0.    0.;
9  30  0.0019  0.0183  0.29    0.    0.;
10  11  0.0004  0.0043  0.0729  0.    0.;
10  13  0.0004  0.0043  0.0729  0.    0.;
10  55  0.      0.02    0.      1.07   0.;
12  11  0.0016  0.0435  0.      1.06   0.;
12  13  0.0016  0.0435  0.      1.06   0.;
13  14  0.0009  0.0101  0.1723  0.    0.;
14  15  0.0018  0.0217  0.366   0.    0.;
15  16  0.0009  0.0094  0.171   0.    0.;
16  17  0.0007  0.0089  0.1342  0.    0.;
16  19  0.0016  0.0195  0.3040  0.    0.;
16  21  0.0008  0.0135  0.2548  0.    0.;
16  24  0.0003  0.0059  0.0680  0.    0.;
17  18  0.0007  0.0082  0.1319  0.    0.;
17  27  0.0013  0.0173  0.3216  0.    0.;
19  20  0.0007  0.0138  0.      1.06   0.;
19  56  0.0007  0.0142  0.      1.07   0.;
20  57  0.0009  0.0180  0.      1.009  0.;
21  22  0.0008  0.0140  0.2565  0.    0.;
22  23  0.0006  0.0096  0.1846  0.    0.;
22  58  0.      0.0143  0.      1.025  0.;
23  24  0.0022  0.0350  0.3610  0.    0.;
23  59  0.0005  0.0272  0.      0.    0.;
25  26  0.0032  0.0323  0.5310  0.    0.;
25  60  0.0006  0.0232  0.      1.025  0.;
26  27  0.0014  0.0147  0.2396  0.    0.;
26  28  0.0043  0.0474  0.7802  0.    0.;
26  29  0.0057  0.0625  1.0290  0.    0.;
28  29  0.0014  0.0151  0.2490  0.    0.;
29  61  0.0008  0.0156  0.      1.025  0.;
9  30  0.0019  0.0183  0.29    0.    0.;
9  36  0.0022  0.0196  0.34    0.    0.;
```

```
  9  36  0.0022  0.0196  0.34    0.     0.;
  36  37  0.0005  0.0045  0.32    0.     0.;
  34  36  0.0033  0.0111  1.45    0.     0.;
  35  34  0.0001  0.0074  0.      0.946  0.;
  33  34  0.0011  0.0157  0.202   0.     0.;
  32  33  0.0008  0.0099  0.168   0.     0.;
  30  31  0.0013  0.0187  0.333   0.     0.;
  30  32  0.0024  0.0288  0.488   0.     0.;
  1  31  0.0016  0.0163  0.25    0.     0.;
  31  38  0.0011  0.0147  0.247   0.     0.;
  33  38  0.0036  0.0444  0.693   0.     0.;
  38  46  0.0022  0.0284  0.43    0.     0.;
  46  49  0.0018  0.0274  0.27    0.     0.;
  1  47  0.0013  0.0188  1.31    0.     0.;
  47  48  0.0025  0.0268  0.40    0.     0.;
  47  48  0.0025  0.0268  0.40    0.     0.;
  48  40  0.0020  0.022   1.28    0.     0.;
  35  45  0.0007  0.0175  1.39    0.     0.;
  37  43  0.0005  0.0276  0.      0.     0.;
  43  44  0.0001  0.0011  0.      0.     0.;
  44  45  0.0025  0.073   0.      0.     0.;
  39  44  0.      0.0411  0.      0.     0.;
  39  45  0.      0.0839  0.      0.     0.;
  45  51  0.0004  0.0105  0.72    0.     0.;
  50  52  0.0012  0.0288  2.06    0.     0.;
  50  51  0.0009  0.0221  1.62    0.     0.;
  49  52  0.0076  0.1141  1.16    0.     0.;
  52  42  0.0040  0.0600  2.25    0.     0.;
  42  41  0.0040  0.0600  2.25    0.     0.;
  41  40  0.0060  0.0840  3.15    0.     0.;
  31  62  0.      0.026   0.      1.04   0.;
  32  63  0.      0.013   0.      1.04   0.;
  36  64  0.      0.0075  0.      1.04   0.;
  37  65  0.      0.0033  0.      1.04   0.;
  41  66  0.      0.0015  0.      1.     0.;
  42  67  0.      0.0015  0.      1.     0.;
  52  68  0.      0.0030  0.      1.     0.;
  1  27  0.032   0.32    0.41    1.     0.];


% Machine data format
%       1. machine number,
```

```
%       2. bus number,
%       3. base mva,
%       4. leakage reactance x_l(pu),
%       5. resistance r_a(pu),
%       6. d-axis sychronous reactance x_d(pu),
%       7. d-axis transient reactance x'_d(pu),
%       8. d-axis subtransient reactance x"_d(pu),
%       9. d-axis open-circuit time constant T'_do(sec),
%      10. d-axis open-circuit subtransient time constant
%              T"_do(sec),
%      11. q-axis sychronous reactance x_q(pu),
%      12. q-axis transient reactance x'_q(pu),
%      13. q-axis subtransient reactance x"_q(pu),
%      14. q-axis open-circuit time constant T'_qo(sec),
%      15. q-axis open circuit subtransient time constant
%              T"_qo(sec),
%      16. inertia constant H(sec),
%      17. damping coefficient d_o(pu),
%      18. dampling coefficient d_1(pu),
%      19. generator type
%             1 - classical
%             2 - salient pole
%             3 - round rotor
%      20. saturation factor S(1.0)
%      21. saturation factor S(1.2)
% note: all the following machines use subtransient reactance model

 mac_con = [...
    1  53    300  0.003     0   0.969   0.248    0.147    12.6    0.045  ...
                           0.600   0.250    0       0.035    0  ...
                           3.4     0       0       3     0.0654  0.5743;% hydro unit
    2  54    800  0.035     0   1.8     0.42529   0.30508   6.56  0.05 ...
                           1.7207  0.3661    0.30508   1.5   0.035  ...
                           4.9494  0       0       3     0.0654  0.5743;
    3  55    800  0.0304  0    1.8    0.38309   0.32465   5.7   0.05 ...
                           1.7098  0.36072   0.32465   1.5   0.035  ...
                           4.9623  0       0       3     0.0654  0.5743;
    4  56    800  0.0295  0    1.8    0.29954   0.24046   5.69  0.05 ...
                           1.7725  0.27481   0.24046   1.5   0.035  ...
                           4.1629  0       0       3     0.0654  0.5743;
    5  57    700   0.027    0   1.8     0.36     0.27273   5.4   0.05 ...
                           1.6909  0.32727   0.27273   0.44  0.035  ...
                           4.7667  0       0       3     0.0654  0.5743;
```

```
  6  58    900  0.0224    0   1.8    0.35433   0.28346   7.3   0.05 ...
                 1.7079  0.3189    0.28346   0.4   0.035  ...
                 4.9107  0       0       3    0.0654  0.5743;
  7  59    800  0.0322    0   1.8    0.29898   0.24407   5.66  0.05 ...
                 1.7817  0.27458   0.24407   1.5   0.035  ...
                 4.3267  0       0       3    0.0654  0.5743;
  8  60    800  0.028    0   1.8    0.35379   0.27931   6.7   0.05 ...
                 1.7379  0.31034   0.27931   0.41  0.035   ...
                 3.915   0       0       3    0.0654  0.5743;
  9   61    1000  0.0298    0   1.8    0.48718   0.38462   4.79  0.05 ...
                 1.7521  0.42735   0.38462   1.96  0.035  ...
                 4.0365  0       0       3    0.0654  0.5743;
 10  62    1200  0.0199    0   1.8    0.48675   0.42604   9.37  0.05 ...
                 1.2249  0.47929   0.42604   1.5   0.035  ...
                 2.9106  0       0       3    0.0654  0.5743;
 11  63    1600  0.0103    0   1.8    0.25312   0.16875   4.1   0.05 ...
                 1.7297  0.21094   0.16875   1.5   0.035  ...
                 2.0053  0       0       3    0.0654  0.5743;
 12  64    1900  0.022    0   1.8    0.55248   0.44554   7.4   0.05 ...
                 1.6931  0.49901   0.44554   1.5    0.035  ...
                 5.1791  0       0       3    0.0654  0.5743;
 13  65   12000  0.003    0   1.8    0.33446   0.24324   5.9   0.05 ...
                 1.7392  0.30405   0.24324   1.5    0.035  ...
                 4.0782  4.0782    0       3    0.0654  0.5743;
 14  66   10000  0.0017    0   1.8    0.285    0.23     4.1    0.05   ...
                 1.73    0.25     0.23      1.5   0.035      ...
                 3       3        0        3    0.0654  0.5743;
 15  67   10000  0.0017    0   1.8    0.285    0.23     4.1    0.05   ...
                 1.73    0.25     0.23      1.5   0.035      ...
                 3       3        0        3    0.0654  0.5743;
 16  68   11000  0.0041    0   1.8    0.35899   0.27809   7.8    0.05 ...
                 1.6888  0.30337   0.27809   1.5    0.035    ...
                 4.45    4.45     0        3     0.0654  0.5743;
];
```

C. Real industrial plant system data

```
% bus: number, voltage(pu), angle(degree), p_gen(pu), q_gen(pu),
%      p_load(pu), q_load(pu),G shunt,B shunt, bus_type
%      bus_type - 1, swing bus
%               - 2, generator bus (PV bus)
%               - 3, load bus (PQ bus)


bus = [...
1    1.05   0   0     0  0.000   0.000 0.00  0.00 1;
2    1.04  0   0.17  0  0.000   0.000 0.00  0.00 2;
3    1.04   0   0.27  0  0.000   0.000 0.00  0.00 2;
4    0.96  0   0.080 0  0.0908  0.056 0.00  0.00 2;
5    0.96  0   0.080 0  0.092   0.057 0.00  0.00 2;
6    0.97   0   0     0  0.14    0.13   0.00  0.00 3;
7    1.0    0   0.000 0  0.050   0.030 0.00  0.00 3;
8    1.01   0   0.000 0  0.000   0.000 0.00  0.00 3;
9    0.99   0   0.000 0  0.058   0.036 0.00  0.00 3;
10   0.98   0   0.000 0  0.115   0.0716 0.00  0.00 3;
11   0.99   0   0.000 0  0.06948 0.0429 0.00  0.00 3;
12   0.99   0   0.000 0  0.0778  0.04815 0.00  0.00 3;
13   0.99   0   0.000 0  0.071   0.045  0.00  0.00 3;
14   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
15   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
16   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
17   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
18   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
19   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
20   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
21   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
22   1.0    0   0.000 0  0.000   0.000  0.00  0.00 3;
23   0.99   0   0.000 0  0.000   0.000  0.00  0.00 3;];



% line data format
% line: from bus, to bus, resistance(pu), reactance(pu),
%      line charging(pu), tap ratio, line charging is dubld.

line = [...
```

```
6   7   0.007000 0.01536 0.000     1.01;
7   8   0.02080  0.04717 0.000     1.0;
8   20  0.0256   0.01    0.000     1.0;
20  10  0.00     0.065   0.000     1.0;
8   21  0.0256   0.01    0.000     1.0;
21  11  0.00     0.065   0.000     1.0;
8   22  0.0256   0.01    0.000     1.0;
22  12  0.00     0.065   0.000     1.0;
8   23  0.3837   0.1517  0.000     1.0;
23  13  0.00     0.065   0.000     1.0;
8   19  0.001417 0.01581 0.000     1.0;
19  9   0.00     0.065   0.000     1.0;
8   18  0.0256   0.1     0.000     1.0;
18  5   0.00     0.72    0.000     1.0;
8   17  0.0256   0.1     0.000     1.0;
17  4   0.00     0.72    0.000     1.0;
8   16  0.1791   0.70    0.00      1.0;
16  3   0.00     0.72    0.000     1.06;
8   15  0.1532   0.606   0.00      1.0;
15  2   0.00     0.72    0.000     1.06;
8   14  0.1532   0.606   0.00      1.0;
14  1   0.0      0.72    0.000     1.061;
9   10  0.001417 0.2581 0.000      1.0;];

% Machine data format
% Machine data format
%       1. machine number,
%       2. bus number,
%       3. base mva,
%       4. leakage reactance x_l(pu),
%       5. resistance r_a(pu),
%       6. d-axis sychronous reactance x_d(pu),
%       7. d-axis transient reactance x'_d(pu),
%       8. d-axis subtransient reactance x"_d(pu),
%       9. d-axis open-circuit time constant T'_do(sec),
%      10. d-axis open-circuit subtransient time constant
%              T"_do(sec),
%      11. q-axis sychronous reactance x_q(pu),
%      12. q-axis transient reactance x'_q(pu),
%      13. q-axis subtransient reactance x"_q(pu),
%      14. q-axis open-circuit time constant T'_qo(sec),
%      15. q-axis open circuit subtransient time constant
%              T"_qo(sec),
```

```
%      16. inertia constant H(sec),
%      17. damping coefficient d_o(pu),
%      18. dampling coefficient d_1(pu),
%      19. bus number
%
% note: all the following machines use sub-transient model

mac_con = [ ...

1 1 45 0.15   0.00    1.46  0.608  0.0  8.96  0.0 0.969 0.608  0.0  0.31  0.0 2.364 2  5  2
0.1269  0.4104;
2 2 45 0.1    0.00    0.8958 0.1198  0.0 6.0    0.0 0.8645  0.2396  0.0 0.535  0.0 3.2   5  0
3 0.1269  0.4104;
3 3 45 0.15   0.00    1.3125  0.2357   0.0 5.89  0.0 1.2578  0.2357   0.0 0.6   0.0 2.3154
5  0  3 0.1269  0.4104;
4 4 10 0.1    0.00    0.8958 0.1198  0.0 6.0    0.0 0.8645  0.2396  0.0 0.535  0.0 3.2   5  0
3 0.1269  0.4104;
5 5 10 0.1    0.00    0.8958 0.1198  0.0 6.0    0.0 0.8645  0.2396  0.0 0.535  0.0 3.2   5  0
3 0.1269  0.4104;
6 6 10000 0.15   0.00    1.3125  0.2357   0.0 5.89  0.0 1.2578  0.2357   0.0 0.6   0.0
2.3154  5  0  3 0.1269  0.4104];


% Exciter data format
% exciter:  1. exciter type - 1 for Simple exciter
%           2. machine number
%           3. input filter time constant T_R
%           4. voltage regulator gain K_A
%           5. voltage regulator time constant T_A
%           6. voltage regulator time constant T_B
%           7. voltage regulator time constant T_C
%           8. maximum voltage regulator output V_Rmax
%           9. minimum voltage regulator output V_Rmin
%          10. maximum internal signal V_Imax
%          11. minimum internal signal V_Imin
%          12. first stage regulator gain K_J
%          13. potential circuit gain coefficient K_p
%          14. potential circuit phase angle theta_p
%          15. current circuit gain coefficient K_I
%          16. potential source reactance X_L
%          17. rectifier loading factor K_C
%          18. maximum field voltage E_fdmax
%          19. inner loop feedback constant K_G
```

```
%          20. maximum inner loop voltage feedback V_Gmax


exc_con = [...
1 1 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;
1 2 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;
1 3 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;
1 4 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;
1 5 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;
1 6 0   200 0.03 0 0 15 -15 1 1.20 0 0 0 0 0.65 1 0 0 0;];
```

Vita

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