Performance Analysis of Flexible A.C. Transmission System Devices for Stability Improvement of Power System

Dissertation submitted to the

National Institute of Technology Rourkela

in partial fulfillment of the requirements

of the degree of

Doctor of Philosophy

in

Electrical Engineering

by

Rajendra Kumar Khadanga

(Roll Number: 512EE1019)

under the supervision of

Prof. Jitendriya Kumar Satapathy

October, 2016

Department of Electrical Engineering

National Institute of Technology Rourkela

Electrical Engineering
National Institute of Technology Rourkela

Dr. Jitendriya Kumar Satapathy, Ph. D. (Bradford)
Professor,
Department of Electrical Engineering,
National Institute of Technology,
Rourkela, India, 769008.
Email: jitendriya@gmail.com

October, 2016

Supervisor's Certificate

This is to certify that the work presented in this dissertation entitled “Performance Analysis of Flexible A.C. Transmission System Devices for Stability Improvement of Power System" by Rajendra Kumar Khadanga, Roll Number: 512EE1019, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Electrical Engineering. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

Place: Rourkela

Date:

Jitendriya Kumar Satapathy

Electrical Engineering
National Institute of Technology Rourkela

October 6, 2016

Certificate of Examination

Roll Number: 512EE1019
Name: Rajendra Ku. Khadanga
Title of Dissertation: Performance Analysis of Flexible A.C. Transmission System Devices for Stability Improvement of Power System

We the below signed, after checking the dissertation mentioned above and the official record book (s) of the student, hereby state our approval of the dissertation submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Electrical Engineering at National Institute of Technology Rourkela. We are satisfied with the volume, quality, correctness, and originality of the work.

Prof. J.K Satapathy
<*Supervisor's Name*>
Principal Supervisor

Prof S. Mohanty
<*Name of Member 1*
Member (DSC)

Prof. P.K. Ray
<*Name of Member 2*>
Member (DSC)

Prof. S. Meher
<*Name of Member 3*>
Member (DSC)

Dr. S.P. Singh
<*Name of Examiner*>
Examiner

Prof. A.K. Panda
<*Name of Chairman*>
Chairman (DSC)

Dedicated

To

My Parents

…Rajendra Kumar Khadanga

Declaration of Originality

I, Rajendra Kumar Khadanga, Roll Number 512EE1019 hereby declare that this dissertation entitled "Performance Analysis of Flexible A.C. Transmission System Devices for Stability Improvement of Power System" represents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

October, 2016

NIT Rourkela *Rajendra Kumar Khadanga*

Acknowledgement

I would like to express my sincere gratitude and appreciation to my supervisor, **Prof. Jitendriya Kumar Satapathy**, Professor and Head, Department of Electrical Engineering, National Institute of Technology, Rourkela, for his criticisms, valuable guidance and constant encouragement throughout the course of this research work and I consider myself extremely lucky to get the opportunity to work under the guidance of such a dynamic personality.

My special thanks are due to **Prof. S. K. Sarangi**, Director, National Institute of Technology, Rourkela for his encouragement, valuable suggestion and providing all the facilities to successfully complete this dissertation work.

I would like to extend special thanks to all the members of my doctoral scrutiny committee – **Prof. Anup Kumar Panda** (Chairman), **Prof. Sukadev Meher**, **Prof. Sanjeeb Mohanty** and **Prof. P.K. Ray,** for their thoughtful advice, inspiration and encouragement throughout the research work. I take this opportunity to thank the other faculty members and the supporting staff members of the Electrical Engineering department for their timely cooperation and support at various phases of my work.

I express my heartfelt thanks to the **International Journal Reviewers** for giving their valuable comments on the published papers in different international journals, which helps to carry the research work in a right direction. I also thank the **International Conference Organizers** for intensely reviewing the published papers

I would like to extend special thanks to my lab members **Mr. P. Sekhar** and **Mr. Amit Kumar** for their valuable suggestions and encouragement. I would also like to extend special thanks to all my elders, friends and well-wishers for their constant help, motivations and encouragement.

I would like to acknowledge Ministry of **Human Resource Development (MHRD)**, Govt. of India for providing financial assistance throughout my research.

And it goes without saying, that I am indebted to my parents **Mr. Simanchala Khadanga**, **Mrs. Jayanti Khadanga**, Brother **Mr. Upendra Bhanja Khadanga** whose patience, support and endurance made completion of my thesis.

Above all, I would like to thank **The Almighty God** for the wisdom and perseverance that he has been bestowed upon me during this research work, and indeed, throughout my life.

October, 2016 *Rajendra Kumar Khadanga*

NIT Rourkela Roll Number: 512EE1019

Abstract

When large power systems are interconnected by relatively weak tie line, low-frequency oscillations are observed. Recent developments in power electronics have led to the development of the Flexible AC Transmission Systems (FACTS) devices in power systems. FACTS devices are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system. To damp electromechanical oscillations in the power system, the supplementary controller can be applied with FACTS devices to increase the system damping. The supplementary controller is called damping controller. The damping controllers are designed to produce an electrical torque in phase with the speed deviation. The objective of this thesis is to develop some novel control techniques for the FACTS based damping controller design to enhance power system stability.

Proper selection of optimization techniques plays an important role in for the stability enhancement of power system. In the present thesis Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Gravitational search algorithm (GSA) along with their hybrid form have been applied and compared for a FACTS based damping controller design. Important conclusions have been drawn on the suitability of optimization technique.

The areas of research achieved in this thesis have been divided into two parts:

The aim of the first part is to develop the linearized model (Philip-Hefron model) of a single machine infinite bus power system installed with FACTS devices, such as Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC).

- Different Damping controller structures have been used and compared to mitigate the system damping by adding a component of additional damping torque proportional to speed change through the excitation system. The various soft-computing techniques have been applied in order to find the controller parameters.

- The recently developed Gravitational Search Algorithm (GSA) based SSSC damping controller, and a new hybrid Genetic Algorithm and Gravitational Search Algorithm (hGA-GSA) based UPFC damping controller seems to the most effective damping controller to mitigate the system oscillation.

The aim of second part is to develop the Simulink based model (to over-come the problem associated with the linearized model) for an SMIB as well as the multi-machine power system.

- Coordinated design of PSS with various FACTS devices based damping controllers are carried out considering appropriate time delays due to sensor time constant and signal transmission delays in the design process. A hybrid Particle Swarm Optimization and Gravitational Search Algorithm (hPSO-GSA) technique is employed to optimally and coordinately tune the PSS and SSSC based controller parameters and has emerged as the most superior method of coordinated controller design considered for both single machine infinite bus power system as well as a multi-machine power system.

- Finally, the damping capabilities of SSSC based damping controllers are thoroughly investigated by considering a new derived modified signal known as Modified Local Input Signal which comprises both the local signal (speed deviation) and remote signal (line active power). Appropriate time delays due to sensor time constant and signal transmission delays are considered in the design process. The hybrid Particle Swarm Optimization and Gravitational Search Algorithm (hPSO-GSA) technique is used to tune the damping controller parameters. It is observed that the new modified local input signal based SSSC controller provides the best system performance compared to other alternatives considered for a single machine infinite bus power system and multi-machine power system.

Keywords*: *Flexible AC Transmission System (FACTS); Static Synchronous Series compensator (SSSC); Unified Power Flow Controller (UPFC); Genetic Algorithm (GA); Particle Swarm Optimization (PSO); Gravitational Search Algorithm (GSA); Hybrid Algorithms.

Contents

List of Figures

List of Tables

Abbreviations

COI	Center of Inertia
CSC	Controllable Series Capacitor
FACTS	Flexible AC Transmission Systems
GA	Genetic Algorithm
GSA	Gravitational Search Algorithm
GTO	Gate Turn Off
HVDC	High Voltage Direct Current
IPFC	Interline Power Flow Controllers
MIMO	Multi-input Multi-output
PID	Proportional Integral and Derivative
PSS	Power System Stabilizer
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
SMIB	Single Machine Infinite Bus
SSR	Sub Synchronous Resonance
SSSC	Static Synchronous Series Compensators
STATCOM	Static Synchronous Compensators
SVC	Static VAR Compensator
TCSC	Thyristor Controlled Series Capacitor
UPFC	Unified Power Flow Controllers
VSC	Voltage Source Converter

List of Notations

C_{dc}	dc link capacitance
E_{fd}	Field voltage of generator
D	Damping constant
H	Inertia constant (M = 2H)
f	Frequency
I_{SH}	Current through shunt converter
K_a	AVR gain
K_A	Excitation system gain
K_S	Gain of SSSC-based controller
K_{dc}	Gain of damping controller
m_B	Modulation index of series converter
m_E	Modulation index of shunt converter
P_e	Electrical power of the generator
P_m	Mechanical power input to the generator
P_L	Tie-line power flow deviations
P_{Li}	Active load at bus 'i'
Q_{Li}	Reactive load at bus 'i'
T_a	Time constant of AVR
T_A	Excitation system time constant
T_{do}	d-axis open circuit time constant of the generator
T''_{do}	Direct axis open circuit time constant of the generator
T_W	Washout time constant
T_{1s}, T_{2s}	Time constants of phase compensator 1
T_{3s}, T_{4s}	Time constants of phase compensator 2
V_b	Infinite bus voltage

V_{dc}	Voltage at dc link
V_i	Voltage magnitude of the i^{th} bus
V_{ref}	Excitation system reference voltage
V_t	Terminal voltage of the generator
W_n	Natural frequency of oscillation (rad/sec)
X_B	Reactance of boosting transformer (BT)
X_{Bv}	Reactance of the transmission line
X_d	Direct axis steady-state synchronous reactance of generator
X'_d	Direct axis transient synchronous reactance of generator
X''_d	Direct axis transient reactance of the generator
X_q	Quadrature axis steady state reactance of the generator
X_E	Reactance of excitation transformer (ET)
X_e	Equivalent reactance of the system
X_{SH}, X_{SR}	Reactance of shunt and series transformer
X_q	Quadrature axis steady-state synchronous reactance of generator
X_{li}	Reactance of transmission line
X_{tE}	Reactance of transformer
X_{ti}	Reactance of the step-up transformer
δ_B	Phase angle of series converter voltage
δ_E	Phase angle of shunt converter voltage
Δ	Incremental operator
ΔU	Output of the damping controller
$\Delta\omega$	Speed deviation of the synchronous generator
V_q	Voltage injected by SSSC
V_{qref}	Steady state injected voltage reference
ω_I	Inter-area mode of oscillations
ω_L	Local mode of oscillations

Chapter 1

Introduction and Literature survey

1.1 Introduction

Recent advances in power electronics have led to the development of the Flexible AC Transmission Systems (FACTS) devices to be effectively used in power systems to enhance the performance. The Flexible AC Transmission Systems (FACTS) is a new technology that acts as a promising tool for power system application during the last decade. Modern utilities are beginning to install FACTS devices in their transmission networks to increase the transmission capacities and enhance controllability. In view of their advantages, there is a growing interest in the use of FACTS devices in the operation and control of power systems. There are two main aspects that should be considered while using FACTS controllers: The first aspect is the flexible power system operation according to the power flow control capability of FACTS controllers. The other aspect is the improvement of stability of power systems. This thesis reports the development of novel control techniques for Flexible AC Transmission System (FACTS) devices for the purpose of power system stability improvement.

The most promising tools for the power engineer is "Evolutionary Techniques" which utilizes the analogies of nature and social systems. In the research community, these techniques are very popular and can be used as a research tool or design tool or a problem solver because they can optimize or solve the complex multi-modal non-differentiable objective functions. These algorithms are Genetic algorithm, Differential evolution (DE), Particle swarm optimization (PSO), Bacteria foraging optimization, Multi-objective evolutionary algorithm, hybrid algorithms, etc. In the present thesis, an attempt has been made to explore the application of these modern heuristic optimization techniques to improve the stability of a power system installed with FACTS controllers.

This chapter is organized as follows: section 1.2 presents an overview of the power system stability, section 1.3 discusses the concept and application of FACTS devices to power system and section 1.4 explains the theoretical background of various soft computing techniques or algorithms. Section 1.5 deals with the literature survey on the power system stability issues and its enhancement methods. The dissertation objectives are explained in Section 1.6. Finally, dissertation outline is presented in section 1.7.

1.2 An Overview of Power System Stability

Power system stability has been recognized as an important problem for secure system operation since the 1920s. Many major blackouts caused by power system instability have illustrated the importance of this phenomenon. Historically, transient instability has been the dominant stability problem on most systems and has been the focus of much of the industry's attention concerning system stability. As power systems have evolved through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions, different forms of system instability have emerged. For example, voltage stability, frequency stability and interred oscillations have become greater concerns than in the past. This has created a need to review the definition and classification of power system stability. A clear understanding of different types of instability and how they are interrelated is essential for the satisfactory design and operation of power systems. As well, consistent use of terminology is required for developing system design and operating criteria, standard analytical tools, and study procedures.

According to the IEEE standards, power system stability is defined as: "Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact". A typical modern power system is a high-order multivariable process whose dynamic response is influenced by a wide array of devices with different characteristics and response rates. Stability is a condition of equilibrium between opposing forces. Depending on the network topology, system operating condition and the form of disturbance, different sets of opposing forces may experience sustained imbalance leading to different forms of instability. In this section, a systematic basis for classification of power system stability is provided.

The classification of power system stability proposed here is based on the following considerations [1]:

- The physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed.
- The size of the disturbance considered which influences the method of calculation and prediction of stability.
- The devices process, and the time span that must be taken into consideration in order to assess stability.

Fig. (1.1) gives the overall picture of the power system stability problem, identifying its categories and subcategories. The following are descriptions of the corresponding forms of stability phenomena.

- Rotor angle stability – ability of the system to maintain synchronism.
- Voltage stability – ability of the system to maintain steady acceptable voltage.
- Frequency stability – ability of the system to maintain frequency within an acceptable variation range.

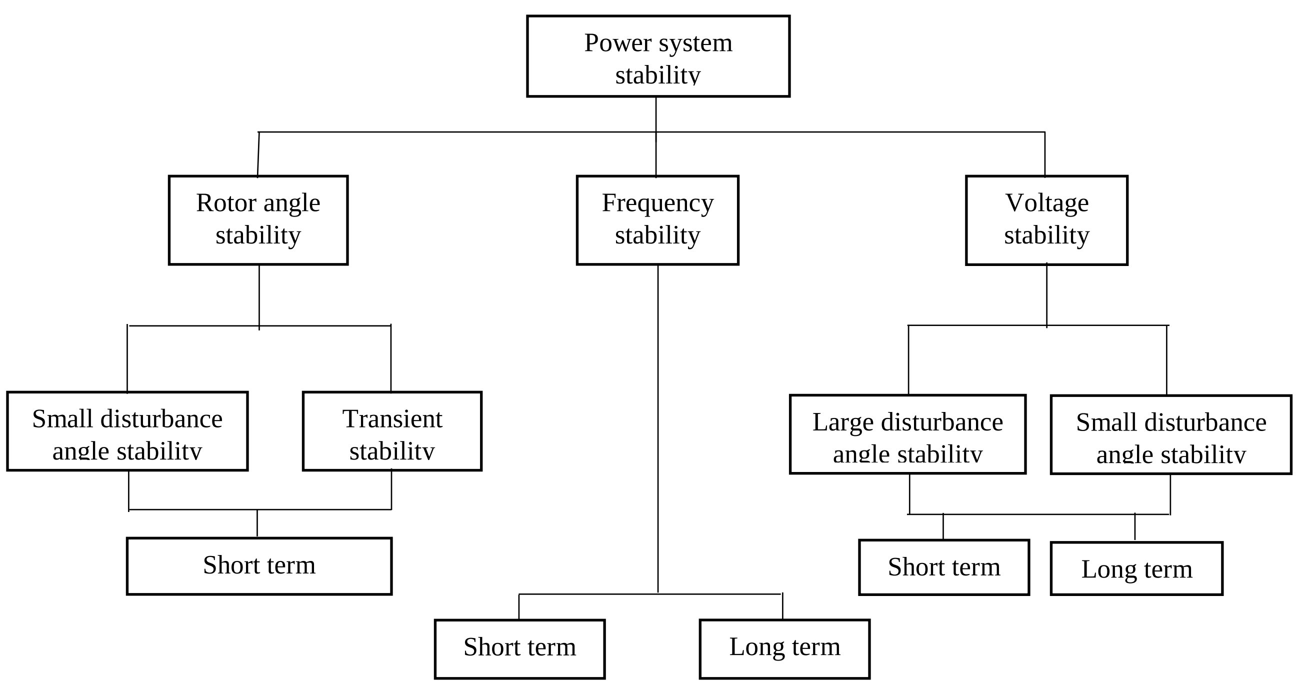


Figure 1.1: Classification of power system stability

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. The instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators. The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor angles change. Under steady-state conditions, there is an equilibrium between the input mechanical torque and the output electromagnetic torque of each generator, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation.

The power-angle relationship is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer such that the angular separation is increased further. Instability results if the system cannot absorb the kinetic energy corresponding to these rotor speed differences. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques. Loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, with synchronism maintained within each group after separating from each other.

Commonly the rotor angle stability is characterized in terms of two subcategories:

- Small-disturbance rotor angle stability (Small-signal stability)
- Large-disturbance rotor angle stability (Transient stability)

Small-disturbance rotor angle stability is usually associated with insufficient damping and is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis. Small disturbance rotor angle stability problems often affect local areas but can affect a wide network area too resulting in local plant mode oscillations and inter-area oscillations respectively.

Large-disturbance rotor angle stability or transient stability, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Instability is usually in the form of a periodic angular separation due to insufficient synchronizing torque, manifesting as first swing instability. However, in large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be a result of the superposition of a slow inter-area swing mode and a local plant swing mode causing a large excursion of rotor angle beyond the first swing. It could also be a result of nonlinear effects affecting a single mode causing instability beyond the first swing. The time frame of interest in transient stability studies is usually 3 to 5 seconds following the disturbance. It may extend to 10–20 seconds for very large systems with dominant inter-area swings.

Recently, with the deregulation of the electricity market, power systems are expected to perform functions well beyond its original design capacity with new loading and power flow conditions. The increase in utilization of existing power systems may get the system operating closer to stability boundaries making it subject to the risk of collapse of power systems. Also, new generators are equipped with modern exciters that have a high gain and a fast response to enhance transient stability. However, these fast response exciters, if used without controllers, can lead to oscillatory instability. This problem is further complicated particularly in areas where there is a large amount of generation with limited transmission capacity available for transmitting the power.

A power system stabilizer (PSS) is universally adopted to damp out these system oscillations. However in some situation the use of PSS is insufficient to provide the adequate damping which leads to a search for other alternatives. In fact, such a situation occurs during a change in the loading condition of the transmission line. Thus, alternative measures can be applied in addition with the PSS to form a coordinate structure to improve system performance. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the stability of a power system [2].

1.3 Application of FACTS Devices to Power System

With the development in the modern power system, it becomes very important to control the power flow along the transmission corridor. Very long high power transmission lines have high series reactance and shunt capacitance. It becomes more difficult to control voltage, power and stability by conventional means. The desire is to find a solution to these problems and limitation led to focus technological developments under FACT (Flexible AC transmission) system. The FACTS technology is not a high power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more interrelated system parameters mentioned above. A well-chosen FACTS controller can overcome the specific limitations of a designated transmission line or corridor. Because all FACTS controllers represent applications of the same basic technology, their production can eventually take advantage of technologies of scale. Just as the transistor is the basic element for a whole variety of microelectronic chips and circuits, the thyristor or high power transistor is the basic element for a variety of high power electronic controllers.

Use of Flexible AC Transmission systems controllers in a power system has the following benefits [2].

- Control the power flow in a transmission line
- Increase the load capability of lines
- Limits the short circuit currents and overloads, prevents blackouts, damp power system oscillations, mitigate subsynchronous resonance, and alleviate voltage instability.
- Reduce reactive power flow.
- Prevents loop power flow.
- Decrease overall generation reserve requirement of interconnected areas.
- Improve HVDC converter terminal performance.
- Wind power generation system.

1.3.1 Classification of FACTS

In general FACTS controllers can be divided into four categories:

- Shunt Controllers
- Series Controllers
- Combined Series-Series Controllers
- Combined Series-Shunt Controllers

1.3.1.1 Shunt Controllers

A shunt controller may be of variable impedance, variable source or a combination of these. In principle all the shunt controllers inject current into the system at the point of connection. The variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Example of Shunt Controller

1. Static Synchronous Compensator (STATCOM)
2. Static Var Compensator (SVC)

1.3.1.2 Series Controllers

All the series controllers inject voltage in series with the line .This controller could be of variable impedance, such as capacitor, reactor etc or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies to serve the desired need. The variable impedance multiplied by the current flow through it represents an injected series voltage in line. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power.

Examples of Series Controller:

1. Static Synchronous Series Compensator (SSSC)
2. Thyristor Controlled Series Capacitor (TCSC)

1.3.1.3 Combined Series-Series Controllers

This could be a combination of series controllers which are controlled in a separate manner in a multiline transmission system. Further, it can be act as a unified controller in which series controllers provide independent series reactive compensation for transmission line and also transfer real power among lines via the power link. The real power transfer capability of the unified series-series controller referred to as interline power flow controller, makes it possible to balance both real and reactive power flow in the line and thereby maximize the utilization of the transmission system.

Example of Combine Series-Series Controllers

1. Interline power flow controller (IPFC).
2. Thyristor-Controlled Voltage Limiter(TCVL)
3. Thyristor-Controlled Voltage Regulator(TCVR)

1.3.1.4 Combined Series-Shunt Controllers

This could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner or a unified power flow controller with series and shunt elements. In principle combined series-shunt controllers injects current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. However when the shunt and series controllers are unified there can be real power exchange between the series and shunt controllers via the power link. Examples of combined series shunt controllers:

1. Thyristor Controlled Phase Shifting Transformer (TCPST)
2. Unified Power Flow Controller (UPFC)

The development of FACTS controllers has followed two distinctly different technical approaches, both resulting in a comprehensive group of controllers able to address targeted transmission problems. The first group employs reactive impedances with thyristor switches as controlled elements; the second group uses self-commutated static converters as controlled voltage sources. The first approach has resulted in the Static Var Compensator (SVC), Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Thyristor Controlled Braking Resistor (TCBR), Thyristor Controlled Series Compensator (TCSC) etc. The second group comprises of Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC) and Interline Power Flow controller (IPFC).

Thyristor based approach, owing to their circuit structure and power semiconductors, offers easier accommodation of necessary protection features required to handle severe fault conditions. Converter based approach provides vastly superior functional characteristic, better performance and greater application flexibility. The main thrust of the research work presented in this thesis is on improving power system stability using FACTS controllers. A brief description highlighting the salient features and characteristics of some of these controllers are presented here which are used for our future studies. **One important conclusion can be drawn from the literature study that, to control current/power flow and damp power system oscillations, a series controller for a given MVA size is several times more powerful than the shunt controller.**

1.3.2 Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator (SSSC) is a modern power quality FACTS device that employs a voltage source converter connected in series to a transmission line through a transformer. The SSSC operates like a controllable series capacitor and series inductor. The primary difference is that it's injected voltage is not related to the line intensity and can be managed independently. This feature allows the SSSC to work satisfactorily with high loads as well as with lower loads [12, 23].

The Static Synchronous Series Compensator has three basic components:

- Voltage Source Converter (VSC) – main component
- Transformer – couples the SSSC to the transmission line
- Energy Source – provides voltage across the DC capacitor and compensate for device loses

Static synchronous series compensator works like the STATCOM, except that it is serially connected instead of shunt [12]. It is able to transfer both active and reactive power to the system, permitting it to compensate for the resistive and reactive voltage drops – maintaining high effective X/R that is independent of the degree of series compensation. However, this is costly as a relatively large energy source is required. On the other hand, if control is limited to reactive compensation then a smaller supply should be enough. Subsequently, the serially injected voltage can advance or delay the line current, meaning, the SSSC can be uniformly controlled.

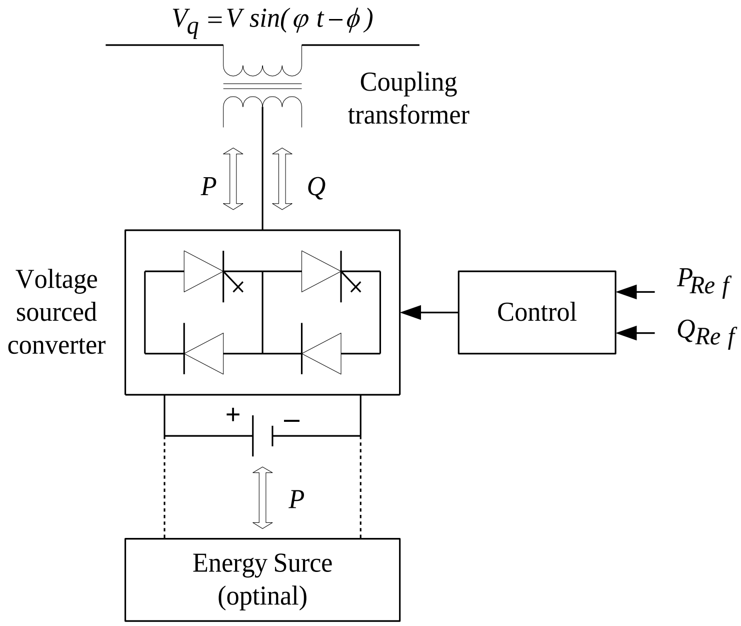


Figure 1.2: Functional block diagram of SSSC

The SSSC, when operated with the proper energy supply, can inject a voltage component, which is of the same magnitude but opposite in phase angle with the voltage developed across the line. As a result, the effect of the voltage drop on power transmission is offset. In addition, the static synchronous series compensator provides fast control and is inherently neutral to sub-synchronous resonance. A Static Synchronous Series Compensator (SSSC) is a solid state voltage sourced based series compensator, originally proposed by Gyugyi in 1989. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The virtual reactance inserted by the injected voltage source influences electric power flow in the transmission lines independent of the magnitude of the line current. The functional block diagram model of the SSSC is shown in Fig. (1.2). References Q_{Ref} and P_{Ref} define the magnitude and phase angle of the injected voltage necessary to exchange the desired reactive and active power between the solid state voltage sourced converter and the AC system. If the device is operated strictly for reactive power exchange, P_{Ref} is set to zero and the external energy source is not required.

The principle of operation of SSSC is shown in Fig. (1.3) for a two-machine system. Figs. (1.4 (a-b)) show the phasor diagrams of SSSC operating in inductive and capacitive modes respectively. It is clear from Fig. (1.4 (a)) that, for the case of SSSC operating in capacitive mode, the injected voltage increases the magnitude of the voltage across the inductance, i.e. the line, and therefore also increases the magnitude of the current I resulting in an increase in the power flow. This corresponds to the effect of a series capacitor compensated transmission line. However, with the voltage source it is possible to maintain a constant compensating voltage in the presence of variable line current because the voltage can be controlled independently of the current, and the voltage source can also decrease the voltage across the line inductance having the same effect as if the reactive line impedance was increased as shown in Fig. (1.4 (b)).

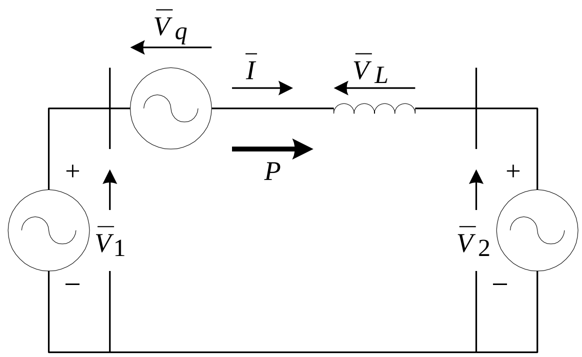
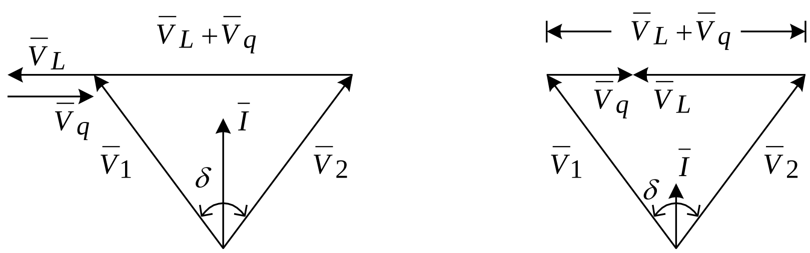


Figure 1.3: Single line diagram of a two-machine system with SSSC



(a) SSSC operating in capacitive mode (b) SSSC operating in inductive mode

Figure 1.4: Phasor diagrams representing compensation modes of SSSC operation

1.3.3 Unified Power Flow Controller (UPFC)

Unified power flow controller (UPFC) is one of the FACTS devices, which can control power system parameters such as terminal voltage, line impedance and phase angle. Therefore, it can be used not only for power flow control but also for power system stabilizing control. Unified power flow controller (UPFC) is a combination of static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle or alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation [3].

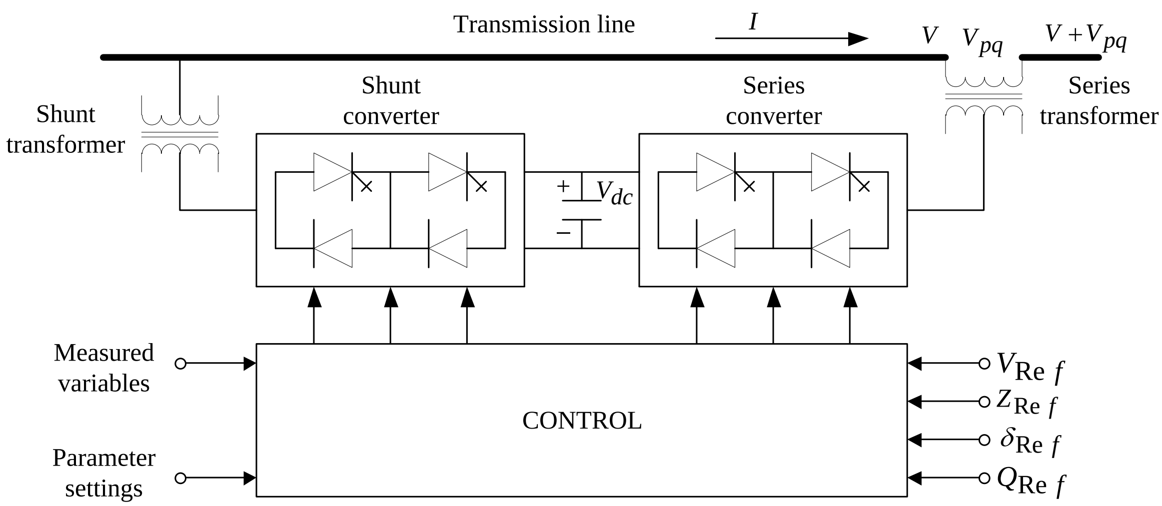


Figure 1.5: Functional block diagram model of UPFC connected to a transmission line

The UPFC consists of two voltage source converters; series and shunt converter, which are connected to each other with a common dc link. Series converter or Static Synchronous Series Compensator (SSSC) is used to add controlled voltage magnitude and phase angle in series with the line, while shunt converter or Static Synchronous Compensator (STATCOM) is used to provide reactive power to the ac system, besides that, it will provide the dc power required for both inverter. Each of the branches consists of a transformer and power electronic converter. These two voltage source converters shared a common dc capacitor [6]. The energy storing capacity of this dc capacitor is generally small. Therefore, the active power drawn by the shunt converter should be equal to the active power generated by the series converter. The reactive power in the shunt or series converter can be chosen independently, giving greater flexibility to the power flow control. The coupling transformer is used to connect the device to the system. Fig. (1.5) shows the schematic diagram of the three phase UPFC connected to the transmission line. Control of power flow is achieved by adding the series voltage, V_S with a certain amplitude. This will give a new line voltage V_2 with different magnitude and phase shift.

1.4 Application of Soft-Computing Techniques

In conventional mathematical optimization techniques, problem formulation must satisfy mathematical restrictions with advanced computer algorithm requirement, and may suffer from numerical problems. Further, in a complex system consisting of a number of controllers, the optimization of several controller parameters using the conventional optimization is a very complicated process and sometimes gets stuck at local minima resulting in sub-optimal controller parameters. In recent years, one of the most promising research fields has been “Heuristics from Nature”, an area utilizing analogies with nature or social systems. Application of these heuristic optimization methods a) may find a global optimum, b) can produce a number of alternative solutions, c) no mathematical restrictions on the problem formulation, d) relatively easy to implement and e) numerically robust. Several modern heuristic tools have evolved in the last two decades that facilitates solving optimization problems that were previously difficult or impossible to solve. These tools include Evolutionary Computation, Simulated Annealing [64, 83], Tabu Search, Genetic Algorithm [12, 66], Particle Swarm Optimization [10, 77], Gravitational Search Algorithm [17, 22] etc. Among these heuristic techniques, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Gravitational search Algorithm (GSA) and hybrid optimization techniques appeared as promising algorithms for handling the optimization problems. These techniques are finding popularity within the research community as design tools and problem solvers because of their versatility and ability to optimize in complex multimodal search spaces applied to non-differentiable cost functions. A brief description highlighting the salient features and characteristics of some of the conventional algorithms is presented here which are used for our future studies.

1.4.1 Genetic Algorithm (GA)

The GA is basically a search algorithm in which the laws of genetics and the law of natural selection are applied. For the solution of any optimization problem (using GA), an initial population is evaluated which comprises a group of chromosomes. Initially, a random population is generated, then from this population fitness value of each chromosome is calculated. This can be found out by calculating the objective function by the process of encoding. Then a set of chromosomes termed as parents are evaluated which are known as offspring generation, which are generated from the initial population. The current population is replaced by their updated offspring that can be obtained by considering some replacement strategy. Fig. (1.6) shows the flow chart for the Genetic algorithm [12].

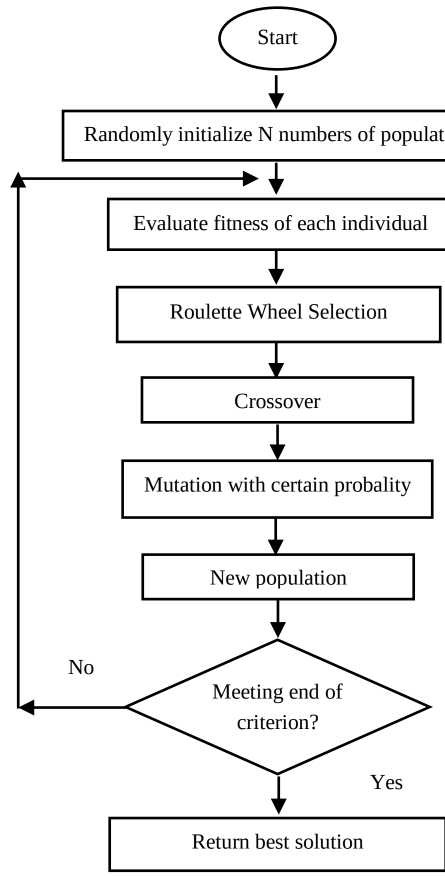


Figure 1.6: Flow chart for Genetic Algorithm

The genetic algorithm begins with a set of solutions (represented by chromosomes) called the population. Solutions from one population are taken and used to form a new population. This is motivated by the possibility that the new population will be better than the old one. Solutions are selected according to their fitness to form new solutions (offspring); more suitable they are, more chances they have to reproduce. This is repeated until some condition (e.g. number of populations or improvement of the best solution) is satisfied.

The basic steps for the algorithms can be stated as [66]:

- Step-1: Generate random population of n chromosomes (i.e. suitable solutions for the problem).
- Step-2: Evaluate the fitness f(x) of each chromosome x in the population.

- Step-3: Create a new population by repeating following steps until the new population is complete.
  - Select two parent chromosomes from a population according to their fitness (better the fitness, bigger the chance to be selected)
  - With a crossover probability, cross over the parents to form new offspring (children). If no crossover was performed, the offspring is the exact copy of parents.
  - With a mutation probability, mutate new offspring at each locus (position in the chromosome).
  - Place new offspring in the new population.
- Step-4: Use newly generated population for a further run of the algorithm.
- Step-5: If the end condition is satisfied, stop, and return the best solution in the current population.
- Step-6: [Loop] Go to step 2

The genetic algorithm's performance is largely influenced by two operators called crossover and mutation. These two operators are the most important parts of GA.

1.4.2 Particle Swarm Optimization (PSO)

The PSO method is a member of the wide category of swarm intelligence methods for solving the optimization problems. It is a population-based search algorithm where each individual is referred to as particle and represents a candidate solution. For solving an optimization problem, the PSO method is generally used. In this algorithm, each individual can be represented by a particle which represent a candidate solution [10]. In PSO each particle moves with a velocity and this velocity is modified in accordance with the own velocity and the velocity of other particles. Here “pbest” is the position corresponds to the best fitness and “gbest” is the best in the population out of all particle.

The PSO search procedure is summarized as [77]:

- Initially, there is the difference in the initial positions of pbest and gbest. And gradually the closeness between the particles increases and they reaches to a global optimum using the different direction of “pbest” and “gbest”.
- This modification of particle position is a continuous one. Using a technique known as grids of XY position and velocity, the positions are verified.

- Again the new and modified velocity an individual particle can be changed by the current velocity and-and the new position can be calculated as a distance from "pbest" to "gbest".

The above procedure can be summarized by the following equations [23]:

$$v_{j,g}^{(t+1)} = w * v_{j,g}^{(t)} + c_1 * r_1(\ ) * (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 * r_2(\ ) * (gbest_g - x_{j,g}^{(t)}) \quad (1.1)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad (1.2)$$

Where j = 1, 2. . . . . .n and g = 1, 2, ... m

n = *a* number of particles in the swarm

n = Total amount of particle in a particular Swarm.

m = Total amount of components in a particular particle.

t = Iterations/generations number

$v_{g,j}^{(t)}$ =Represents "g" th velocity component of particle "j" at "t" th iteration.

$v_g^{min} \le v_{j,g}^{(t)} \le v_g^{max}$

w = A factor represents inertia of weight.

c_1, c_2= Factors which represents to cognitive and social acceleration.

r_1, r_2= Represents a number which are uniformly distributed with a random initialization in the range (0, 1).

$x_{j,g}^{(t)}$ = Represents "g" th component of particle j at "t" th iteration.

$pbest_j$ = "pbest" of particle j.

$gbest_g$ = "gbest" of the group.

The j-th particle in the swarm is represented by a g-dimensional vector $x_j = (x_{j1}, x_{j2}, \ldots\ldots, x_{jg})$ and its rate of position change (velocity) is denoted by another g-dimensional vector $v_j = (v_{j1}, v_{j2}, \ldots\ldots, v_{jg})$. The best previous position of the j-th particle is represented as $pbest_j$ = (pbestj, 1, pbestj, 2… pbestj, g). The index of best particle among all of the particles in the group is represented by the $gbest_g$. In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters 'c_1' & 'c_2' determine the relative pull of 'pbest' and 'gbest' and the parameters 'r_1' & 'r_2' help in stochastically varying these pulls. In the above equations, superscripts denote the iteration number. The computational flow chart of PSO algorithm is shown in Fig. (1.7).

The particle swarm optimization algorithm can be summarized as following steps:

- Step-1: Initialize particles in the search space at random.
- Step-2: Assign random initial velocities for each particle.
- Step-3: Evaluate the fitness of each particle according to a user-defined objective function.
- Step-4: Calculate the new velocities for each particle.
- Step-5: Move the particles.
- Step-6: Repeat steps 3 to 5 until a predefined stopping criterion is satisfied.

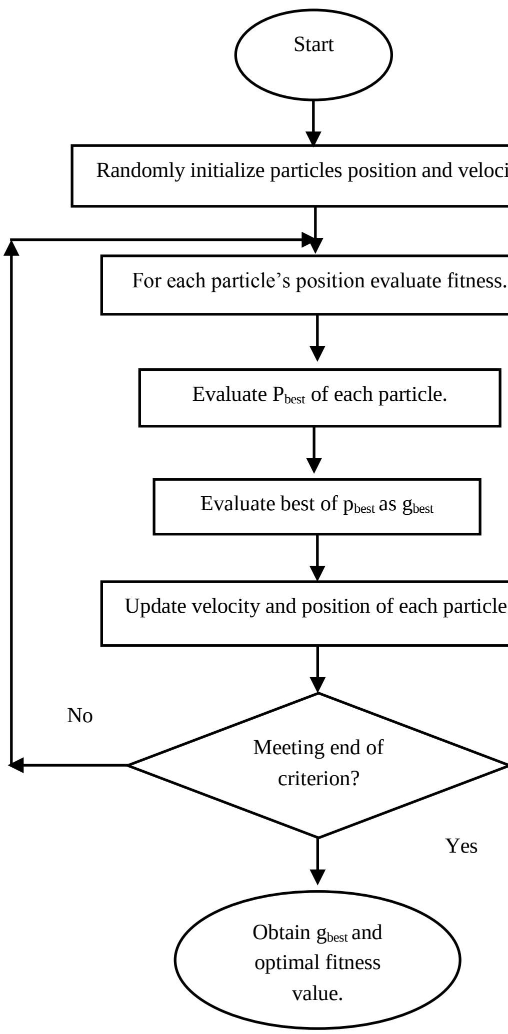


Figure 1.7: Flowchart of Particle Swarm Optimization algorithm

1.5 Review of Literature

Over the last two decades, a large number of research papers have appeared in the area of Flexible AC Transmission Systems (FACTS) controllers. Various control strategies and optimization techniques have found their applications in this area and also various degrees of system modeling have been attempted. The amount of literature in the subject area of FACTS is so vast that, a modest attempt has been made in this section to discuss the most significant works in the area.

The literature review is organized as follows:

- Small-signal modeling (Philips-Heffron) modeling of an SMIB power system installed with FACTS devices.
- Simulink based modeling of the SMIB Power system as well as the multi-machine power system installed with SSSC.
- Coordination Control design of PSS and FACTS based controller
- Application of modern heuristic optimization techniques for the FACTS based controller design to improve the power system stability.

In 1997, H.F. Wang [3] presented, probably for the first time "A Unified linear Model for the Analysis of general FACTS Devices in Damping Power System Oscillations" for a single-machine infinite bus power systems which will enhance the power system stability. This paper presents a unified model known as Philips-Heffron model for the stability studies. Again in the year 2000, H.F. Wang [6] presented "A Unified linear Model for the Analysis of Unified Power flow controller FACTS Devices in Damping Power System Oscillations" for an SMIB power system. In 2003 N. Tambey [8] presented a paper which shows the modified version of the linearized model which is used currently for the power system stability problem. This paper also shows the concept of the damping controller in a prescribed power system to reduce the system damping after being influenced by a disturbance. From the refs. [13, 14, 15] it can be concluded that for the stability analysis of power system the linearize Philip-Heffron model is used and proposes the application of various heuristics algorithm for the evaluation of the damping controller parameters.

In 2007, S. Panda [26], presented a paper "MATLAB/SIMULINK based model of single-machine infinite bus with TCSC for stability studies and tuning employing GA" which indicate the problem associated with the linearized model and extension of the linearized model to Simulink based model. This paper also indicates the concept of the damping controller to the power system and application of soft computing techniques to tune the parameters of the damping controller. The SSSC has been applied to different power system studies to improve the system performance [35]. There has been some work done to utilize the characteristics of the SSSC to enhance power system stability [37]. Wang [39] investigated the damping control function of an SSSC installed in power systems. The linearized model of the SSSC integrated into power systems was established and methods to design the SSSC damping controller were proposed.

Artificial Intelligence (AI) techniques which provide a global optimum or nearly so, such as Artificial Neural Network (ANN) [69], Fuzzy Logic (FL) [9], Genetic Algorithm (GA) [15,16], Particle Swarm Optimization (PSO) [10, 16], Differential Evolution (DE) [31, 32], Gravitational Search Algorithm (GSA) [17, 19], Bacteria Foraging Optimization Algorithm (BFOA) [43,53] have emerged in recent years in power systems as a complement tool to mathematical approaches. ES is a knowledge-based or rule-based system, which uses the knowledge and interface procedure to solve problems that are difficult enough to require human expertise for their solution and has been applied in various areas of power systems. Fuzzy logic uses human experiences and preferences via membership functions and fuzzy rules and so the system can be made understandable to a non-expert operator [9]. GA, PSO and GSA optimization techniques are promising algorithms for handling the optimization problems and are finding popularity within the research community as design tools and problem solvers because of their versatility and ability to optimize in complex multimodal search spaces applied to non-differentiable cost functions.

Mahran *et al.* [12] presented a coordinated PSS and SVC controller for a synchronous generator. However, the proposed approach uses recursive least squares identification which reduces its effectiveness for on-line applications. Various approaches for the coordinated design of PSS and SVC are also presented in [43]. In other work, Wang and Swift [56] presented a phase compensation based approach to the coordinated setting of TCSC-based stabilizer and PSS. The results were promising and encourage further research in this direction. However, all controllers were assumed proportional and no efforts have been done towards the controller design. Ramirez *et al*. [29] presented a technique to design and coordinate PSSs and STATCOM-based stabilizers to enhance the system stability and avoid the adverse interaction among stabilizers. S. Panda at al. [45] presents an approach for the coordinated structure of PSS and SSSC for the improvement of the power system stability.

1.6 Motivation

From the literature survey, for the small signal study generally, the FACT based linear Philips-Heffron (Linear) model is used. It has been found that until now, limited research work has been attempted in the area of power system stability problems employing modern heuristic optimization techniques especially Genetic Algorithm (GA), Particle Swarm optimization (PSO), Gravitational Search Algorithm (GSA) and the hybrid soft computing techniques. Since the approaches such as GA, PSO and GSA optimization techniques basically aimed at finding a solution to a given objective function however as they employ different strategies and computational effort, it is appropriate to compare their performances. Hence, GA, PSO and GSA optimization techniques and its hybrid form have been applied for designing a FACTS based controller. The design objective is to enhance the power system stability.

A Single-Machine Infinite-Bus (SMIB) power system equipped with SSSC controller is used to model the system in these studies. The design problem is formulated as an optimization problem and modern heuristic optimization techniques are employed to search for optimal controller parameters. The performance of optimization techniques in terms of computational efforts is compared on a power system subjected to different disturbances. Further, the performance of the hybrid heuristic algorithm techniques based on UPFC controller are analyzed and compared under various loading conditions and disturbances. The linear simulation results are used to show the effectiveness of modern heuristic the techniques in designing an FACTS-based controller. A comparison is made between the SSSC and UPFC FACTS devices and concluded that the SSSC provides better results in terms of various system parameters and cost, hence is used further.

Now as the linear model uses various assumption, some important parameters have been omitted and according the Simulink (non-linear) based model is used. Power System Stabilizers (PSS) are now routinely used in the industry to damp out oscillations. The problem of FACTS controller parameter tuning in the presence of PSS is a complex exercise as uncoordinated local control of FACTS controller and PSS may cause destabilizing interactions. To improve overall system performance, PSSs and FACTS power oscillation damping controller should operate in a coordinated manner. In view of the above, to avoid such adverse interactions, PSS and FACTS-based controllers are simultaneously designed. The proposed controllers are tested on a weakly connected power system. Nonlinear simulation results are analyzed to show the effectiveness of the coordinated design approach over individual design. The effectiveness of the developed model with the proposed controllers are tested under various large disturbance (3-phase fault, line outage) and small disturbance (increase/decrease in mechanical power input and reference voltage settings) as well as under different operating conditions. Further, the approach is extended to a multi-machine power system installed with FACTS and PSSs, where the location of the FACTS controller has so chosen that it improves the transient stability of the system for the most severe situation where the critical fault clearing time is minimum.

Finally, proper selection of controller structure and input signals for FACTS based controller design problem has not been reported in the literature. So the proper selection of control inputs are proposed. A new modified signal has been proposed and compared with the existing signals and found to be the best signal for the controller.

The main objectives of the proposed research work are:

- Development of linearized Philips-Heffron model for an SMIB power system installed with an SSSC and UPFC FACT devices.
- Application and comparison of modern heuristic optimization techniques, namely GA, PSO, GSA optimization techniques for the FACT based damping controller design to improve the system stability.
- Development of the modern heuristic hybrid algorithms for the above FACTS based SMIB power system design.
- Development of MATLAB/SIMULINK models for the SMIB power systems with SSSC and extending into the multi-machine power system.
- Coordinated design of Power System Stabilizer (PSS) and SSSC based damping controller by considering the system time delays to improve the system stability. Application of modern heuristics algorithm as well as the hybrid optimization technique to tune the coordinated controller parameters in both single machine and multi-machine power system.
- Selection and Comparison of the proper input signal and different methodologies for a SSSC-based damping controller for stability improvement.

1.7 Dissertation Outline

This thesis has been organized into six chapters.

Chapter 1: In this chapter introduces a topic of a brief introduction to power system stability problems. A short overview of FACTS controllers used in the present dissertation has been briefed upon. The literature survey of modeling and control of various FACTS controllers, the role of FACTS controllers in distribution systems and application of intelligent techniques is presented. The modern heuristic optimization techniques such as PSO, DE and GSA optimization are briefly described. The author's contribution towards this research work is briefly discussed.

Chapter 2: This chapter presents the linearized Philips-Heffron model of a single-machine infinite bus power system with an SSSC. A systematic procedure for designing the SSSC based damping controller employing a modern heuristic optimization technique known as Gravitational Search Algorithm (GSA) is presented. The damping controller parameters are tuned and tested using some conventional algorithms. The performance of the optimization techniques has been compared in terms of computational efforts. The objective function namely Integral of Time Multiplied Absolute value of error (ITAE) is considered and the performance of the proposed controllers are compared under various operating conditions and disturbances to show the effectiveness of the proposed approach.

Chapter 3: Application of a new hybrid Genetic Algorithm – Gravitational Search Algorithm (hGA-GSA) to the power system problem have been investigated in this chapter. The concept of the hybrid GA-GSA algorithm has been proposed and tested with the UPFC based linearized models. Power system stability improvement by employing UPFC based damping controllers is thoroughly investigated in this chapter. The damping controller parameters are tuned and tested using the hybrid algorithms. The performances of the proposed controllers with the hybrid algorithm are evaluated under different disturbances for both single-machine infinite bus power system and multi-machine power system. Linear simulation results are presented under various disturbances to show the effectiveness and robustness of the proposed approach.

Chapter 4: This chapter deals with the development of nonlinear Simulink model of an SMIB as well as a multi- machine (3 machine-9 bus) power system with an SSSC. The Hybrid algorithms i.e. hybrid particle swarm optimization and gravitational search algorithm (hPSO-GSA) is proposed to coordinately design of power system stabilizer and static synchronous series compensator (SSSC)-based controller. Time delays owing to sensor and signal transmission delays are included in the design. The coordinated design problem is formulated as an optimization problem and is employed to search for the optimal controller parameters. The performance of hPSO-GSA has been compared with the recent hybrid hBFOA-PSO algorithm and the conventional PSO and GSA. The performance of the proposed controllers is evaluated for both single-machine infinite bus power system and multi-machine power system. Results are presented over a wide range of loading conditions and system configurations to show the effectiveness and robustness of the proposed coordinated design approach.

Chapter 5: This chapter deals with the analysis of the various input signals to the SSSC based damping controller to test the system stability. Both local signal and remote signals with associated time delays are considered as an input signal of Power system stabilizer for analysis purposes. A new modified signal has been derived, tested and compared with both local and remote signal. The design problem of the proposed controller is formulated as an optimization problem, and the hPSO-GSA algorithm is employed to search for the system stability by tuning the optimal controller parameters. The performances of the proposed controllers are evaluated under different disturbances for both SMIB and multi-machine (4machine-9bus) power system. The proposed algorithm is presented and compared with a recent hybrid algorithm known as an hBFOA-MOL algorithm (For a similar problem). Nonlinear simulation results are presented to show the effectiveness and robustness of the proposed control schemes over a wide range of loading conditions and disturbances.

Chapter 6: This chapter gives the overall conclusions and findings of the research work. It presents suggestions for future developments in this direction.

Chapter 2

Development of Linearized Philips–Heffron Model for a Single-Machine Infinite-Bus Power System Installed With SSSC

2.1 Introduction

Main causes of the power systems to be operated near their stability limits are due to the fact that power systems are today much more loaded than before. This is because power demand grows rapidly and expansion in transmission and generation is restricted with the limited availability of resources and the strict environmental constraints. In few occasions interconnection between remotely located power systems gives rise to low-frequency oscillations in the range of 0.2-3.0 Hz. These low-frequency oscillations are also observed when large power systems are interconnected by relatively weak tie lines. If the system is not well damped, these oscillations may keep increasing in magnitude until loss of synchronism results. The installation of Power System Stabilizer (PSS) is both economical and effective; in order to damp these power system oscillations and increase system stability [12, 63, 84].

During the last decade, continuous and fast improvement in power electronics technology has made Flexible AC Transmission Systems (FACTS) a promising concept for power system applications [71]. With the application of FACTS technology, power flow along transmission lines can be controlled more flexibly. Due to the fact that extremely fast control action is associated with FACTS-device operations, they have been the most suited candidates to find the right place in enhancing the power system damping [72]. Two distinct categories exists for the realization of power electronics-based FACTS controllers: while the first type employs conventional Thyristor-switched capacitors, Thyristor controlled reactors and quadrature tap-changing transformers, the second classification refers to gate turn-off (GTO) thyristor-switched converters as voltage source converters (VSCs) [73]. The earlier configuration has resulted in the Static VAR Compensator (SVC), the Thyristor- Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS). The subsequent evolution in FACTS devices brought new architectures namely Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), and the Unified Power Flow Controllers. (UPFC), and the Interline Power Flow Controller (IPFC) etc. These two groups of FACTS controllers have distinctly different operating and performance characteristics [2]. Traditionally, for the small signal stability studies of a power system, the linear model of Phillips-Heffron has been used for years, providing reliable results [4-6]. Although it is a linear model, it is quite accurate for studying low-frequency oscillations and stability of power systems. A conventional lead-lag controller structure is preferred by the power system utilities. The Static Synchronous Series Compensator (SSSC) is regarded as one of the most versatile devices in the FACTS family. The main function of SSSC is to control of the power flow in the transmission line, improve the transient stability, alleviate system oscillation and offer voltage support [2].

Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power. Subsequently, with the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the lines and improving stability. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The ability of SSSC to operate in capacitive, as well as inductive mode, makes it very effective in controlling the power flow the system. Apart from the stable operation of the system with bi-directional power flows, the SSSC has an excellent response time and the transition from positive to negative power flow through zero voltage injection is perfectly smooth and continuous [12]. The tuning of SSSC based damping controller parameter is a very complex exercise. The conventional techniques reported in the literature are time-consuming. These techniques are iterative and require heavy computational burden and slow convergence [16]. In recent years, one of the most promising research fields has been “Evolutionary Techniques”. This is an area utilizing analogies with nature or social systems [67]. Various techniques have been derived and successfully applied to the power system problems. These techniques involve Genetic Algorithm [15], Particle Swarm Optimization [75, 76], Bacteria foraging optimization [52, 53] etc.

Recently, Gravitational Search Algorithm (GSA) appeared as a promising technique for handling the optimization problems [17]. GSA has been popular in academia and the industry. The advantages of this method are mainly because of its ease of implementation, intuitiveness, and the ability to effectively solve highly nonlinear optimization problems that are typical of complex engineering systems. In the literature, it is reported that GSA is more efficient in terms of CPU time and offers higher precision with more consistent results [21]. In view of the above, this paper proposes to use GSA optimization technique for designing a controller to achieve superior damping so far as the system oscillation is concerned. For the proposed controller design, a time-domain based approach is employed taking into account the integral of time multiplied by speed deviation error. The optimal SSSC controller parameters are obtained using GSA. Simulation results are presented and compared with a conventional tuning technique (phase compensation technique) to show the effectiveness and robustness of the proposed approach.

The main objectives of the research work presented in this chapter are as follows:

1. To develop a linearized Philips-Heffron model for a single machine infinite bus (SMIB) installed with a Static Synchronous Series compensator (SSSC).
2. To investigate the effect of different types of the damping controller for the power system study.
3. To present a systematic procedure for designing an SSSC-based damping controller using the Gravitational Search Algorithm (GSA).
4. To study the dynamic performance of computational intelligence technique based optimized SSSC controller and conventionally tuned SSSC based controller when subjected to different disturbances and parameter variations
5. To compare the performance of the proposed SSSC based controller design with the modern heuristic-based optimization technique and a conventional tuning technique.
6. To compare the performance of the proposed lead-lag based SSSC controller with the other conventional methods like PI and PID.

2.2 System Under Study

For the proposed study a single machine infinite bus (SMIB) power system installed with Static Synchronous Series Compensator (SSSC) is investigated, as shown in Fig. (2.1). From the proposed figure, it can be seen that, the SSSC consists of a boosting transformer with a leakage reactance X_{SCT}, a three-phase voltage source converter (VSC), and a DC capacitor (C_{DC}). From the figure it can be seen that 'm' and 'Ψ' are two input control signals to the SSSC. Signal m is the amplitude modulation ratio of the pulse width modulation (PWM) based VSC. Again, the signal 'ψ' is the phase of the injected voltage and is kept in quadrature with the line current (inverter losses are ignored). Therefore, the level of compensation of the SSSC can be controlled dynamically by changing the magnitude of the injected voltage. Hence, if the SSSC is equipped with a damping controller, it can improve the power system dynamic stability [33].

2.2.1 Modeling of Single Machine Infinite-Bus (SMIB) Power System with SSSC

A nonlinear dynamic model of the system is derived neglecting:-

- The resistances of all the components of the system (i.e. transmission lines, generator, transformer and series converter transformer).
- The transients related with the transmission lines, fixed series capacitor, synchronous generator stator, and transformers.

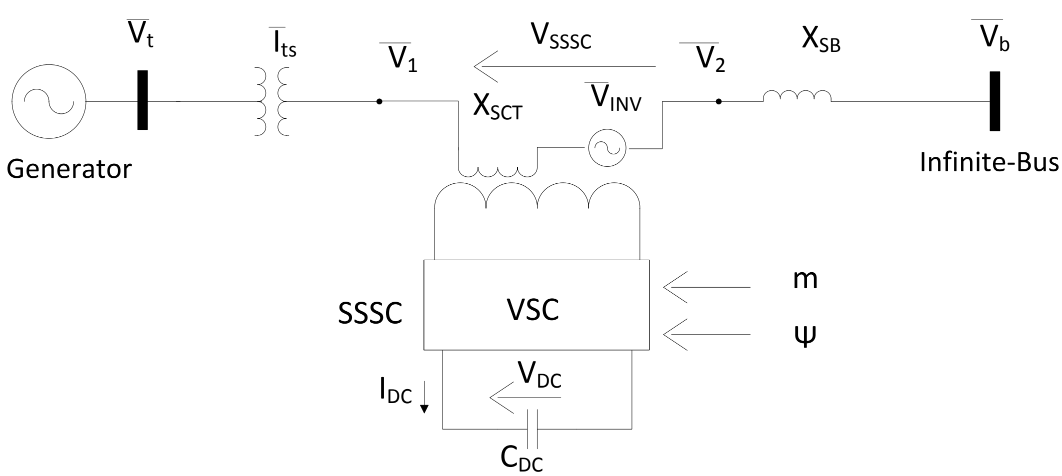


Figure 2.1: Single machine infinite bus power system with SSSC

2.2.1.1 The Non-Linear Equations

The nonlinear dynamic model of the system with SSSC is described below [26]:

$$\dot{\omega} = \frac{P_m - P_e - D\Delta\omega}{M} \tag{2.1}$$

$$\dot{\delta} = \omega_0 (\omega - 1) \tag{2.2}$$

$$\dot{E}_q' = \frac{1}{T_{do}'}\left[-E_q + E_{fd}\right] \tag{2.3}$$

$$\dot{E}_{fd} = \frac{-E_{fd} + K_A (V_{ref} - V_t + V_s)}{T_A} \tag{2.4}$$

$$\dot{V}_{dc} = \frac{m}{C_{dc}}\left(I_{t2d} Cos\psi + I_{t2q} Sin\psi\right) \tag{2.5}$$

Where,

$$P_e = V_{td} I_{td} + V_{tq} I_{tq}$$

$$E_q = E_q' + \left(X_d - X_d'\right) I_{td}$$

$$V_t = V_{td} + jV_{tq}$$

$$V_{td} = X_q I_{tq}$$

$$V_{tq} = E_q' - X_d' I_{td}$$

$$I_{td} = I_{tld} + I_{t2d}$$

$$I_{tq} = I_{tlq} + I_{t2q}$$

$$I_{tld} = \frac{(X_{BV} - X_{CF})}{X_{ds}} E_q' - \frac{(X_{BV} - X_{CF})}{X_{ds}} V_b Cos\delta + \frac{(X_d' + X_{tE})}{X_{ds}} mV_{dc} Cos\psi$$

$$I_{tlq} = \frac{(X_{BV} - X_{CF})}{X_{qs}} V_b Sin\delta - \frac{(X_q + X_{tE})}{X_{qs}} mV_{dc} Sin\psi$$

$$I_{t2d} = \frac{X_{T1}}{X_{ds}} E_q' - \frac{X_{T1}}{X_{ds}} V_b Cos\delta - \frac{X_1}{X_{ds}} mV_{dc} Cos\psi$$

$$I_{t2q} = \frac{X_{T1}}{X_{qs}} V_b \text{Sin}\delta + \frac{X_3}{X_{qs}} V_{dc} \text{Sin}\psi$$

$$X_1 = X_d^{'} + X_{tE} + X_T$$

$$X_2 = X_d^{'} + X_{tE} + X_{BV} - X_{CF}$$

$$X_3 = X_q + X_{tE} + X_T$$

$$X_4 = X_q + X_{tE} + X_{BV} - X_{CF}$$

$$X_{ds} = X_1 X_2 - (X_{tE} + X_d^{'})^2$$

$$X_{qs} = X_3 X_4 - (X_q + X_{tE}^{'})^2$$

V_s= The stabilizing signal from PSS.

2.2.1.2 The Linearized Equations

In the design of electromechanical mode damping stabilizer, a linearized incremental model around an operating point is usually employed. The FACTS based Phillips-Heffron model of the power system is obtained by linearizing the non-linear equations around an operating condition of the power system. The expressions in the linearized form are as follows [34]:

$$\Delta \dot{\omega} = \frac{\left(\Delta P_m - \Delta P_e - D\Delta\omega\right)}{M} \tag{2.6}$$

$$\Delta \dot{\delta} = \omega_0 \Delta\omega \tag{2.7}$$

$$\Delta \dot{E}_q = \frac{\left(-\Delta E_q + \Delta E_{fd}\right)}{T_{do}^{'}} \tag{2.8}$$

$$\Delta \dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A \left(\Delta V_{ref} - \Delta V_t + V_s\right)}{T_A} \tag{2.9}$$

$$\begin{aligned} \Delta \dot{V}_{dc} = {} & K_7 \Delta\delta + K_8 \Delta E_q^{'} + K_9 \Delta V_{dc} + K_{cm} \Delta m_E \\ & + K_{c\delta m} \Delta\psi + K_{cb} \Delta m_B \Delta\psi \end{aligned} \tag{2.10}$$

Where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pm}\Delta m + K_{p\delta m}\Delta\psi$$
$$+ K_{pb}\Delta m_B + K_{pd}\Delta V_{dc}$$

$$\Delta E_q = K_3\Delta E'_q + K_4\Delta\delta + K_{qm}\Delta m + K_{q\delta m}\Delta\psi$$
$$+ K_{qd}\Delta V_{dc}$$

$$\Delta Vt = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta m + K_{v\delta e}\Delta\delta_E$$
$$+ K_{vdm}\Delta\psi + K_{vd}\Delta V_{dc}$$

The Kpu, Kqu, Kvu and Kcu are row vectors defined as:

$$K_{pu} = \left[K_{pm}\ K_{p\delta m}\right]$$

$$K_{qu} = \left[K_{qm}\ K_{q\delta m}\right]$$

$$K_{vu} = \left[K_{vm}\ K_{v\delta m}\right]$$

$$K_{cu} = \left[K_{cm}\ K_{c\delta m}\right]$$

The vector u is defined as:

$$u = \left[\Delta m \quad \Delta\psi\right]^T$$

Δm =Deviation in modulation index of the series converter. The magnitude of the series injection voltage can be modulated, by modulating m.

$\Delta\Psi$ = deviation in the phase angle of series injected voltage.

The voltage on the dc link can be regulated, by modulating ψ

ΔP_m = Deviation in mechanical power input to the generator.

2.2.1.3 Modified Heffron-Phillips Small Perturbation Transfer Function Model of a SMIB Power System Including SSSC

For computing K-constants of the modified Phillips-Heffron model some initial components are needed and these constants are computed at the nominal operating condition. These components are listed below [26]:

The K - constants of the model are:-

K_1 = 0.8160	K_2 = 0.9645	K_3 = 1.7592
K_4 = 0.5998	K_5 = - 0.0998	K_6 = 0.6069
K_7 = 0.0074	K_8 = 0.0179	K_9 = 0.00017

K_{pm}=0.9042	$K_{p\delta m}$=-0.059	K_{qm}=0.4574
$K_{q\delta m}$=0.075	K_{vm}=-0.0172	$K_{v\delta m}$=-0.0463
K_{cm}=0.0026	$K_{c\delta m}$=-0.0173	K_{pd}=0.0604
K_{qd}=0.0306	K_{vd}=-0.0012.	

The constants of the model are functions of the system parameters and operating condition. By using the linearized equations (2.6)-(2.10), the modified Phillips-Heffron model of the single machine infinite bus (SMIB) power system with SSSC is obtained. The corresponding block diagram model is shown in Fig. (2.2).

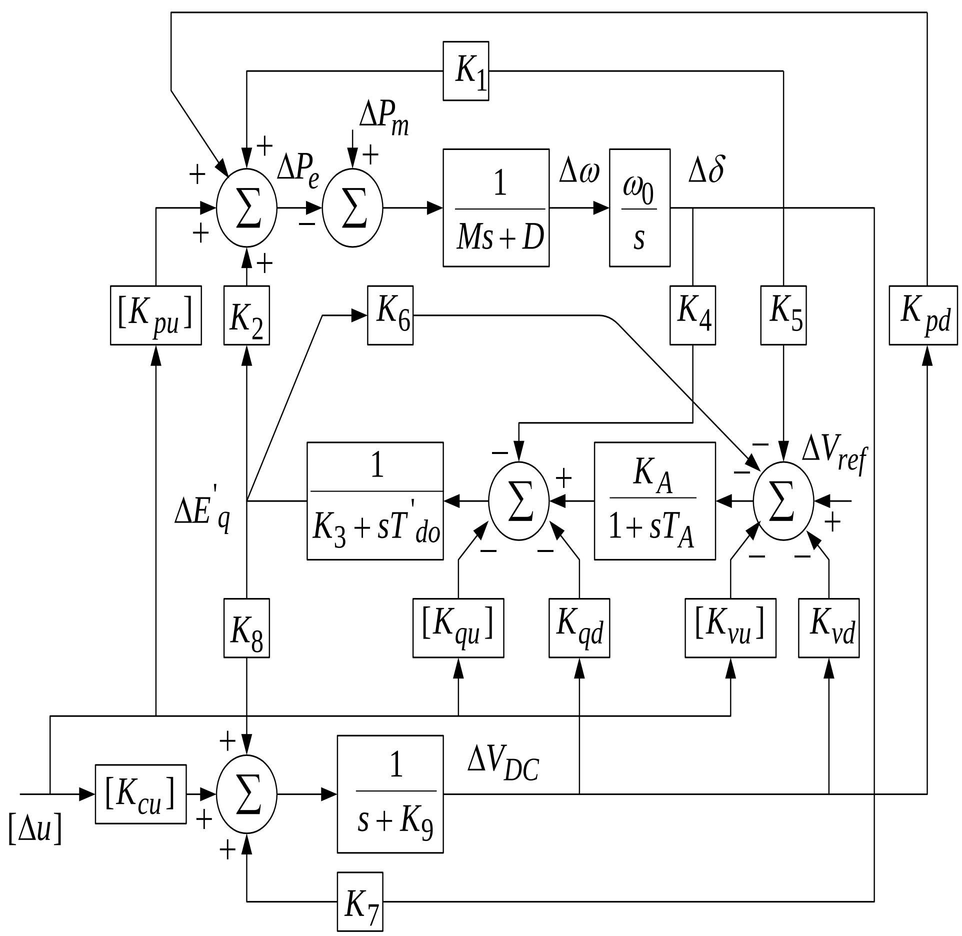


Figure 2.2: Modified Heffron-Phillips model of SMIB system with SSSC

2.3 The Proposed Approach

2.3.1 Concept of Damping Controller

The low-frequency oscillations can be damped with the help of damping controllers. The function of the damping controller is to introduce a component of additional damping torque proportional to speed change through the excitation system. In this study, a comparison is made on the performance of PI, PID and Lead-Lag based damping controller. Various types of damping controllers are available for the power system studies. Some of the structures are discussed below.

2.3.1.1 PID Based Damping Controller

The structure of PID-PSS is as shown in Fig. (2.3). The input to the PID-PSS controller is a change in rotor speed (Δω) of the machine on which it is installed. K_P, K_I and K_D are the Proportional, Integral and derivative supplementary stabilizing signals. V_s is generated with the help of PID-PSS installed in the feedback loop is as shown in Fig. (2.3). The generator terminal voltage is represented by V_t.

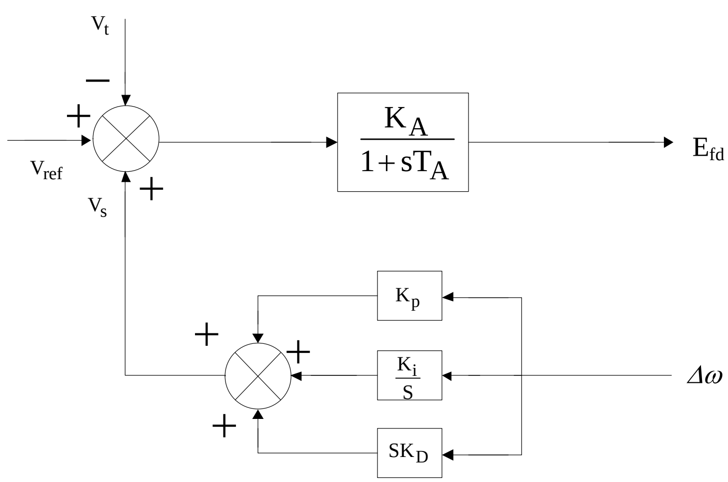


Figure 2.3: Structure of PID damping controller

2.3.1.2 Lead-Lag Based Damping Controller

The lead–lag structure is considered in this study as SSSC-based supplementary damping controller and is shown in Fig. (2.4). The structure mainly consists of three blocks. They are gain block, a signal washout block and two-stage phase compensation block. The function of the phase compensation block is to provide the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block mainly works as a high-pass filter which allows signals associated with oscillations in the input signal to pass unchanged. Any steady state changes in input would modify the output without this block. The speed deviation $\Delta\omega$ is the input signal of the proposed SSSC-based controller and the output is the change in control vector Δu [16].

From the viewpoint of the washout function, in lead-lag structure, the value of washout time constant is not critical for the controllers and may be in the range 1 to 20 seconds. In the present study, K_{WT} washout time constant is considered to be 10 seconds. The controller gain K_T; and the time constants T_1, T_2 are to be determined. The optimized value for the controller using the phase compensation technique is given below.

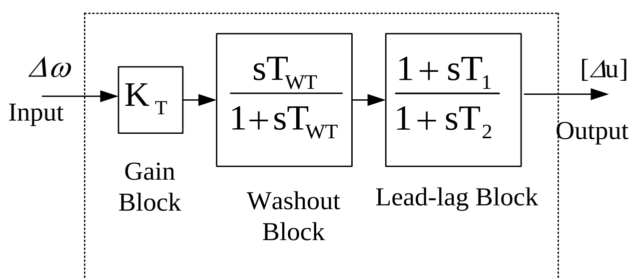


Figure 2.4: Structure of lead- lag damping controller

2.3.2 Objective Function

The main aim of any optimization technique is basically minimization or maximization an objective function or fitness function satisfying the constraints of either state or control variable or both depending upon the requirement. In the present study, objective function J is an integral time absolute error for the speed deviation. This may be expressed as [34]:

$$J = \int_0^{t_1} t\,|e(t)|\,dt \qquad (2.11)$$

Where, ‘e’ is the error signal ($\Delta\omega$) and t_1 is the time range of simulation.

For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots. The problem constraints are the SSSC controller's parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J (2.12)

Subject to

$$K_S^{min} \le K_S \le K_S^{max}$$

$$T_{1S}^{min} \le T_{1S} \le T_{1S}^{max}$$

$$T_{2S}^{min} \le T_{2S} \le T_{2S}^{max}$$

K_i^{min} is the lower bound of the gain for the Damping controllers.
K_i^{max} is the upper bounds of the gain for the Damping controller.
T_j^{min} is the lower bound of the time constants for the Damping controller.
T_j^{max} is the upper bounds of the time constants for the Damping controller.

2.4 Application and Comparison of Tuning Methods

2.4.1 Application of Phase Compensation Technique (PCT)

For computing the parameters of the damping controllers using phase compensation technique, the detailed step-by-step procedure is given below [26]:

- From the mechanical loop, computation of the natural frequency of oscillation ω_n is calculated.

$$\omega_n = \frac{\sqrt{K_1\omega_0}}{M} \tag{2.13}$$

- Computation of $\angle$GEPA (Phase lag between Δ u and ΔPe) at s = jω_n. Let it be γ.

- Design of phase lead/lag compensator G_c:

  For the degree of phase compensation the phase lead/lag compensator, G_c is designed. For 100% phase compensation,

$$\angle Gc(j\omega_n) + \angle GEPA(j\omega_n) = 0 \tag{2.14}$$

  Assuming one lead-lag network, $T_1 = \alpha T_2$, the transfer function of the phase compensator becomes,

$$Gc(s) = \frac{1+s\alpha T_1}{1+sT_2} \tag{2.15}$$

- Since the phase angle compensated by the lead-lag network is equal to γ, the parameters α and T_2 are computed as,

$$\alpha = \frac{1+\sin\psi}{1-\sin\psi} \tag{2.16}$$

$$T_2 = \frac{1}{\omega_n\sqrt{\alpha}} \tag{2.17}$$

- Computation of optimum gain K_{dc}.

  The required gain setting K_{dc} for the desired value of damping ratio $\zeta = 0.5$, is obtained as,

$$K_{dc} = \frac{2\xi\omega_n M}{|G_c(s)|\,|GEPA(S)|} \tag{2.18}$$

  Where $G_c(s)$ and $GEPA(S)$ are evaluated at $s = j\omega_n$

By using the above technique, the SSSC based single stage controller parameters are found to be

K_P = 54.08, T_1=0.1631, T_2=0.1594.

2.4.2 Application of Genetic Algorithm

The Genetic algorithm is a search algorithm in which the laws of genetics and the laws of natural selection are applied. For the solution of any optimization problem, an initial population is evaluated which comprises a group of chromosomes [13]. Initially, a random population is generated, then from this population, fitness value of each chromosome is calculated. This can be found out by calculating the objective function using the process of encoding. Then a set of chromosomes termed as parents are evaluated known as offspring generation, from the initial population [14]. The current population is replaced by their updated offspring by considering some replacement strategy [15]. The detailed of the GA algorithm is given in Chapter-1. The best SSSC based controller parameters among the 20 runs of GA is shown in Table 2.2.

2.4.3 Application of Particle Swarm Optimization

In the mid of 1990s, the PSO technique was invented while attempting to simulate the choreographed motion of swarms of birds as part of a socio-cognitive study investigating the notion of collective intelligence in biological populations [10]. PSO is inspired by the ability of flocks of birds, and avoid predators by implementing an information sharing approach. For solving an optimization problem, the PSO method is generally used. In this algorithm, each individual can be represented by a particle which represent a candidate solution [11]. In PSO each particle moves with a velocity and this velocity is modified in accordance with the own velocity and the velocity of other particles. Here pbest is the position corresponds to the best fitness and gbest is the best in the population out of all particle. The detailed of the PSO algorithm is given in Chapter-1. The optimized parameters for the SSSC based controller among the 20 runs using the PSO algorithm is shown in Table 2.2.

2.4.4 Application of Gravitational Search algorithm

Gravitational Search Algorithm (GSA) is one of the newest heuristic algorithms that have been inspired by the Newtonian laws of gravity and motion [17]. In GSA agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the force of gravity and this force causes a global movement of all objects towards the objects with a heavier mass. Hence, masses co-operate using a direct form of communication through gravitational force. The heavy masses which correspond to good solution-move more slowly than lighter ones, this guarantees the exploitation step of the algorithm. In GSA, each mass (agent) has four specifications: position, inertial mass, active gravitational mass and passive gravitational mass. The position of the mass corresponds to a solution of the problem and it's gravitational and inertia masses are determined using a fitness function. In other words, each mass presents a solution and the algorithm is navigated by properly adjusting the gravitational and inertia masses. After the time elapses, it is expected that masses be attracted by the heavier mass. This mass will present an optimum solution in the search space.

The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. More precisely, masses obey the following laws [22].

Law of Gravity

Each particle attracts every other particle and the gravitational force between the two particles is directly proportional to the distance between them R In fact here R is used instead of R^2 because according to the result obtained from the experiment, R provides much better solution than R^2 in all the observations.

Law of Motion

The current velocity of any mass is equal the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the force acted on the system divided by the mass of inertia.

For a system with *N*-agent (masses), the *i-th* position of an agent X_i is defined by:

$$X_i = (x_i^1,........,x_i^d,........x_i^N) \quad \text{For } i = 1,2,\ldots.N \tag{2.19}$$

Where

x_i^d Presents the position of "i" th agent in the "d" *th* dimension.

At a specific time 't', the force acting on mass 'i ' from mass 'j' is defined as following:

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t) * M_{aj}(t)}{R_{ij}(t) + \in}(x_j^d(t) - x_i^d(t)) \tag{2.20}$$

Where M_{aj} is the active gravitational mass related to agent 'j', M_{pi} is the passive gravitational mass related to agent 'i', $G(t)$ is the gravitational constant at time 't', $\in$ is small constant, $R_{ij}(t)$ is the Euclidian distance between two agents 'i' and 'j' given by:- $R_{ij}(t) = \left\|X_i(t), X_j(t)\right\|_2$

To give a stochastic characteristic to GSA algorithm, it is assumed that the total force that acts on agent '*i*' in a dimension 'd' be a randomly weight sum of 'd' th components of the forces exerted from other agents as:

$$F_i^d(t) = \sum_{j=1, j=i}^{N} \text{rand}_j F_{ij}^d(t) \tag{2.21}$$

Where rand_j is a random number in the interval [0, 1]

Hence, by the law of motion, the acceleration of the agent 'i' at the time 't' and in the direction "d" th, $a_i^d(t)$ is given as follows:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii}(t)} \tag{2.22}$$

Where $M_{ii}(t)$ is the inertia mass of 'i' th agent.

Furthermore, the next velocity of an agent is considered as a fraction of its current velocity added to its acceleration.

Therefore, its position and velocity could be calculated as follows:

$$v_i^d(t+1) = rand_i * v_i^d(t) + a_i^d(t) \quad (2.23)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (2.24)$$

Where $rand_i$ is a uniform random variable in the interval [0, 1] which is used to give a randomized characteristic to the search.

The gravitational constant 'G' is initialized at the beginning and will be reduced with time to control the search accuracy. In other word G is a function of the initial value (G_0) and time 't' expressed as:

$$G(t) = G(G_0, t) \quad (2.25)$$

Gravitational and inertia masses are simply calculated by the fitness evaluation. A heavier mass means a more efficient agent. This means that better agents have higher attraction and walk more slowly. Assuming the equality of the gravitational and inertia mass, the values of mass are calculated using the map of fitness. The gravitational and inertial masses are updated by the following equations:

$$M_{ai} = M_{pi} = M_{ii} = M_i, \; i = 1,2, .. N. \quad (2.26)$$

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (2.27)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \quad (2.28)$$

Where $fit_i(t)$ represents the fitness value of the agent 'i' at time 't' and best(t), worst(t) are defined as follows (for a minimization problem)

$$best(t) = \min_{j \in (1....N)} fit_j(t) \quad (2.29)$$

$$worst(t) = \max_{j \in (1.....N)} fit_j(t) \quad (2.30)$$

One way to perform a good compromise between exploration and exploitation is to reduce the number of agents with the lapse of Eq. (2.21). Hence, it is proposed to use only a set of agents with bigger mass for applying their force to the other. In order to avoid trapping in a local optimum, the algorithm must use the exploration at the beginning. By lapse of iterations, exploration must fade out and exploitation must fade in. To improve the performance of GSA by controlling exploration and exploitation only the 'kbest' agents will attract the others. 'kbest' is a function of time, with the initial value K_0 at the beginning and decreasing with time. In such a way, at the beginning, all agents apply the force, and as time passes, 'kbest' is decreased linearly and at the end there will be just one agent applying force to the others.

Therefore, Eq. (1.5) could be modified as:

$$F_i^d(t) = \sum_{j \in kbest,\, j \neq i} rand_j F_{ij}^d(t) \qquad (2.31)$$

Where 'kbest' is the set of first 'k' agents with the best fitness value and biggest mass. The computational flow chart of GSA algorithm is shown in Fig. (2.5).

The different steps of the GSA are the followings [23]:

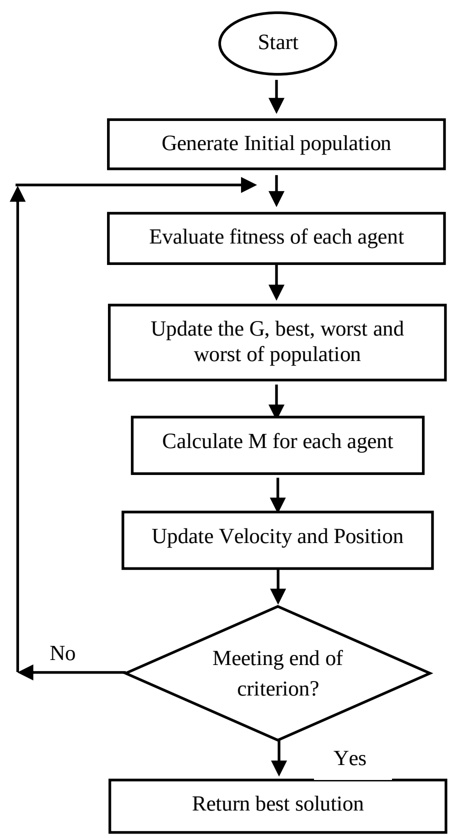


Figure 2.5: Flow chart of proposed Gravitational Search Algorithm

- Step-1: Initialize particles in the search space at random.
- Step-2: Search space identification.
- Step-3: Randomized initialization.
- Step-4: Fitness evaluation of agents.
- Step-5: Update G(t), best(t), worst(t) and $M_i(t)$ for i = 1,2,. . .,N.
- Step-6: Calculation of the total force in different directions.
- Step-7: Calculation of acceleration and velocity.
- Step-8: Updating agent's position.
- Step-9: Repeat steps 3 to 8 until the stop criteria is reached.
- Step-10: End.

The objective function is formulated from time domain simulation of power system model. Using each set of controllers' parameters the fitness value is determined and the time domain simulation is performed. By considering a 10% step increase in mechanical power input (P_m) at t=1s, the objective function is evaluated by simulating the system dynamic model. The objective function J attains a finite value since the deviation in rotor speed is regulated to zero. The best parameters of SSSC based controller from among the 20 runs of GSA is shown in Table 2.2. Another important factor that affects the optimal solution more or less is the range for unknowns. For the very first execution of the program, a wider solution space can be given and after getting the solution, one can shorten the solution space nearer to the values obtained in the previous iteration. The parameters employed for each algorithm (GA, PSO and GSA) is summarized in Table 2.1.

Table 2.1: Optimal parameter settings for GA, PSO, and GSA

GA Parameters	PSO Parameters	GSA Parameters
Maximum generation =200 Population size n_p =30 Pc = Crossover rate = 0.7 Pm = Mutation rate = 0.5	Maximum generation = 200 Swarm size = 30 Cognitive constant $c_1 = 2$ Social constant c_2 = 2 Maximum inertia weight (w_{max}) = 0.9 Minimum inertia weight (w_{min}) = 0.2	Maximum generation = 200 Number of agent N = 30 G_0 = 100 ά = 20 R_{norm} = 2 G_0 and α are the initial gravitational constants

Table 2.2: Best parameters for SSSC controller found in 20 runs of GA, PSO and GSA

Techniques/ Parameters	SSSC-based controller parameters			Minimum Fitness Values
	K_S	**T_{1s}**	**T_{2s}**	
GA	64.4543	0.1673	0.1996	$5.316*10^4$
PSO	62.9969	0.4039	0.3652	$5.236*10^4$
GSA	68.6674	0.2980	0.2658	$5.028*10^4$

The optimization process is repeated 20 times for GA, PSO and GSA. The best (Minimum) among the final fitness values and the related optimized controller parameters are shown in Table 2.2. It is clear from the summary of the results shown in Table 2.2 that, the performance of GSA is better as compared to the GA and PSO based damping controller in terms of its fitness values.

2.5 Simulation Results and Discussion

Here, the proposed Gravitational Search Algorithm (GSA) is compared with the conventional phase compensation techniques (PCT). By employing GSA, the optimization of the proposed SSSC-based supplementary damping controller parameters is carried out by minimizing the fitness given in Eq. (2.11). MATLAB/SIMULINK environment is used for the system under study and GSA program has been written in .mfile. For objective function calculation, a disturbance is considered and the developed model is simulated in a separate program (by another .m file using initial population/controller parameters). From the SIMULINK model, the objective function value is evaluated and is moved to the workspace. This is continued or repeated for each individual in the population.

2.5.1 Change in Mechanical Power Input (P_m)

To assess the effectiveness and robustness of the proposed damping controllers various disturbances and parameter variations are considered. At the first instance, a 10% increase in mechanical power input is considered for the objective function calculation. For simulation result point of view, the performance of the proposed controllers is compared with a conventional design technique [26] which is known as the phase compensation technique. The legend 'WC' represents the response without a controller and the response with conventional phase compensation technique is shown with legend 'PCT'. The legend 'GSA' represents the response with proposed Gravitational Search Algorithm (GSA) shown in solid lines. The responses of the system in terms of speed deviation (Δω), power angle deviation (Δδ) and electrical power deviation (ΔP_e) are shown in Figs. (2.6)- (2.8).

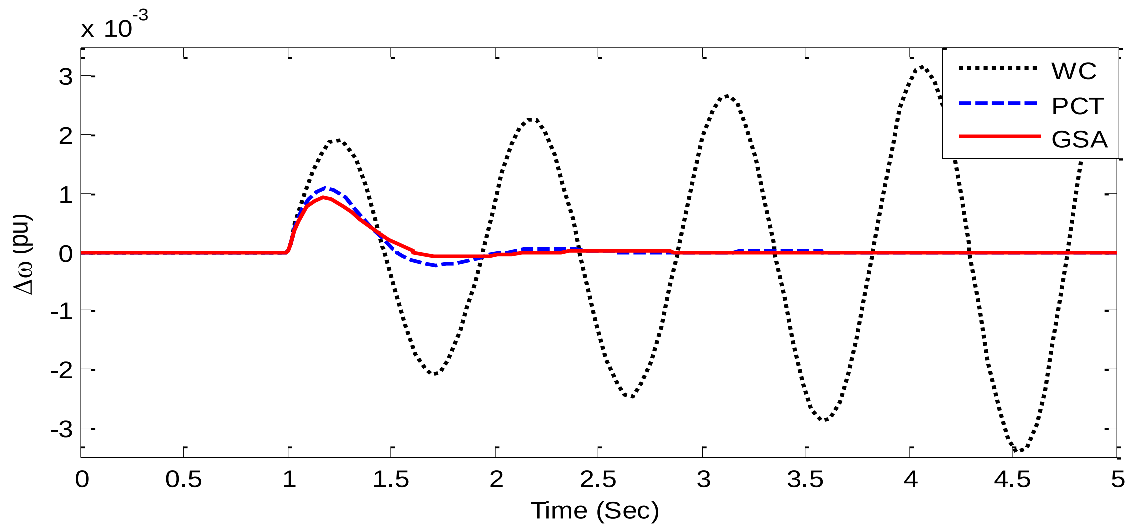


Figure 2.6: Speed deviation response for a 10% step increase in P_m

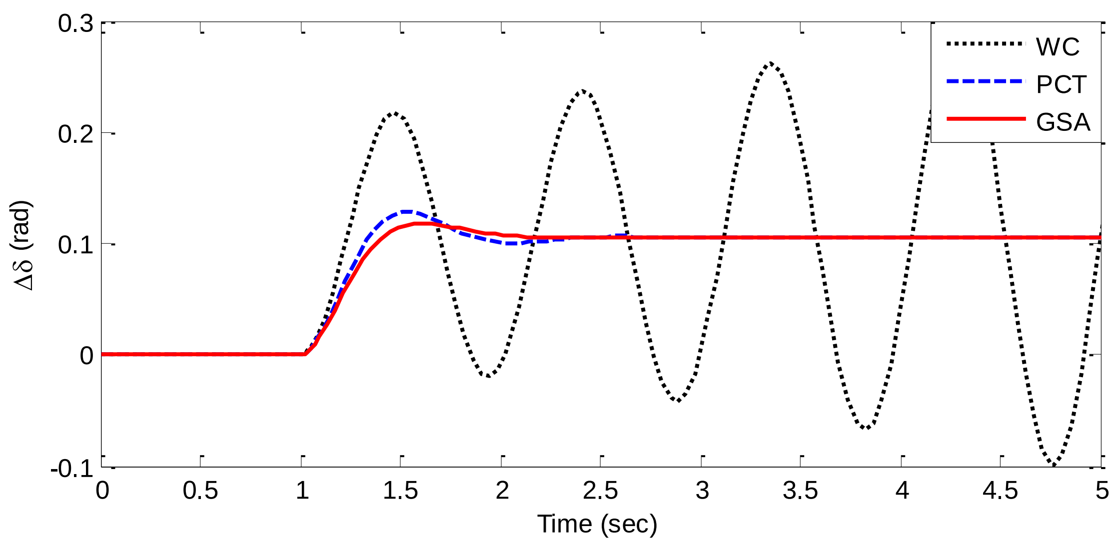


Figure 2.7: Power angle deviation response for a 10% step increase in P_m

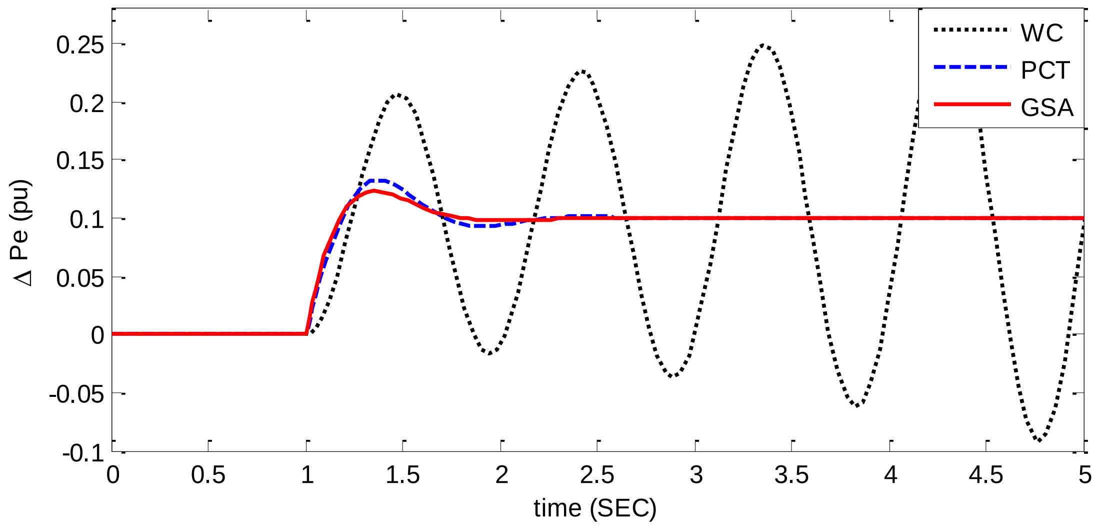


Figure 2.8: Electrical power deviation response for a 10% step increase in P_m

It can be observed from the responses that, without control the system is unstable and both PCT and GSA tuned SSSC based controller maintains stability. However, compared to PCT tuned SSSC based controller the responses with GSA optimized SSSC based controller are much faster, with less overshoot and settling time.

2.5.2 Change in Reference Voltage Input (V_{Ref})

Further to validate, the effectiveness of the proposed controller is also tested by considering a disturbance in reference voltage setting.

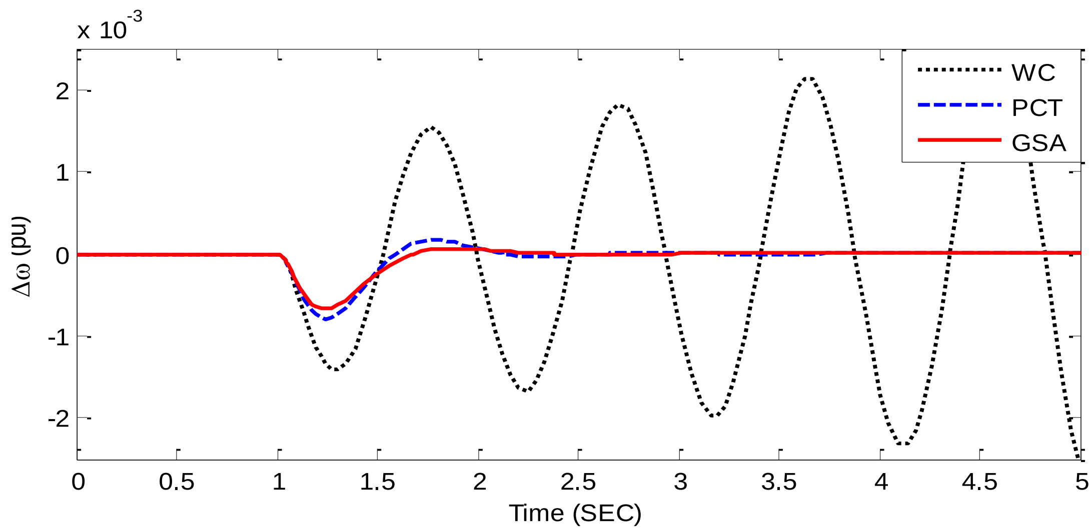


Figure 2.9: Speed deviation response for a 5% step increase in V_{ref}

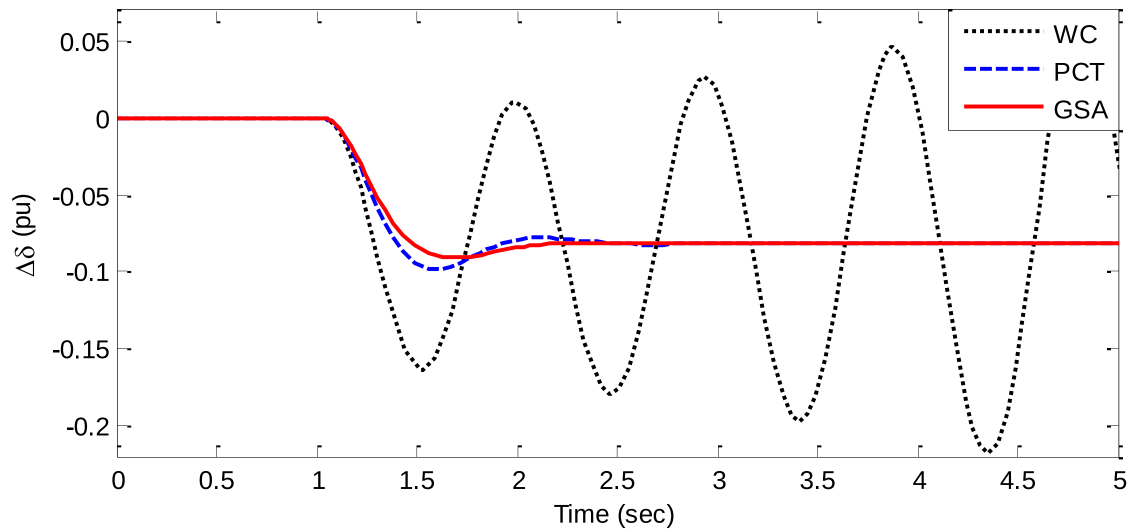


Figure 2.10: Power angle deviation response for a 5% step increase in V_{ref}

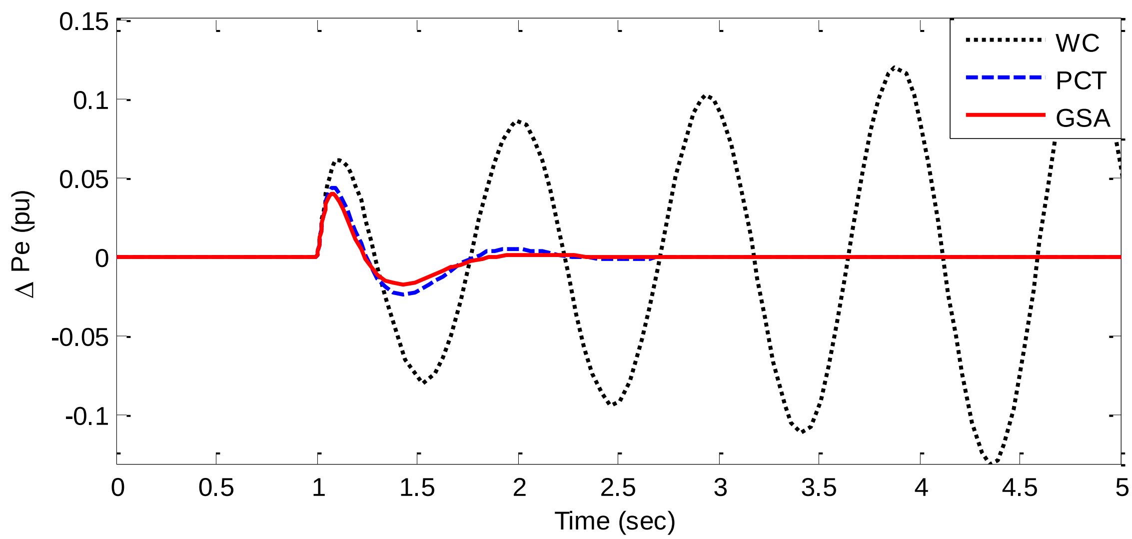


Figure 2.11: Electrical power deviation response for a 5% step increase in V_{ref}

The reference voltage (V_{ref}) is increased by a step of 5% at t =1 s. The system responses for the above condition for all the three cases are shown in Figs. (2.9) - (2.11). It can be clearly concluded that the proposed GSA optimized SSSC based controller has a faster response with less overshoot compared to that of PCT.

2.5.3 Change in Loading Condition

2.5.3.1 Change in Machine Inertia Constant

In the design of damping controllers for any power system, it is extremely important to investigate the effect of variation of system parameters on the dynamic performance of the system. In order to examine the robustness of the damping controllers to variation in system parameters, a 25% decrease in machine inertia constant is considered.

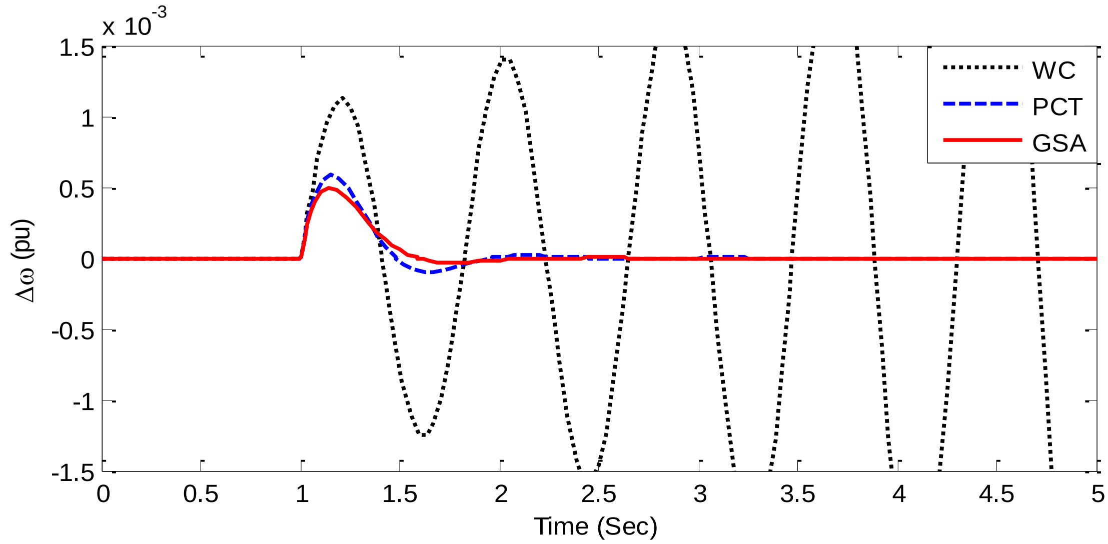


Figure 2.12: Speed deviation response for the change in machine inertia constant

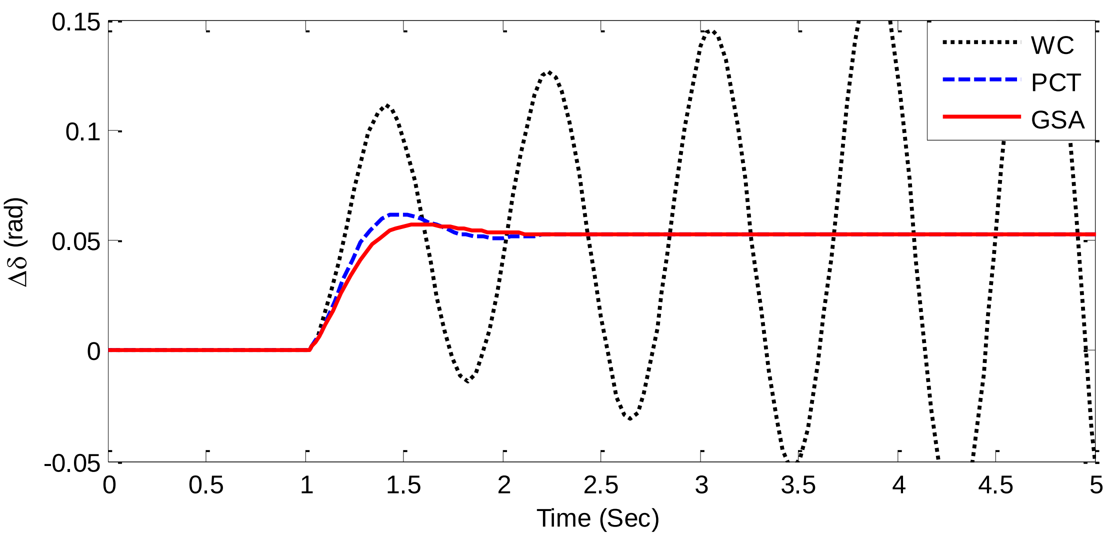


Figure 2.13: Power angle deviation response for the change in machine inertia constant

The system response with the above parameter variations for a 25% decrease in machine inertia constant are shown in Figs. (2.12) - (2.13). It can be seen that GSA optimized SSSC controller has good damping characteristics to low frequency oscillations and stabilize the system much faster.

2.5.3.2 Change in Open Circuit Direct Axis Transient Time Constant

To test the robustness of the proposed controller, a 30% decrease of open circuit direct axis transient time constant is considered.

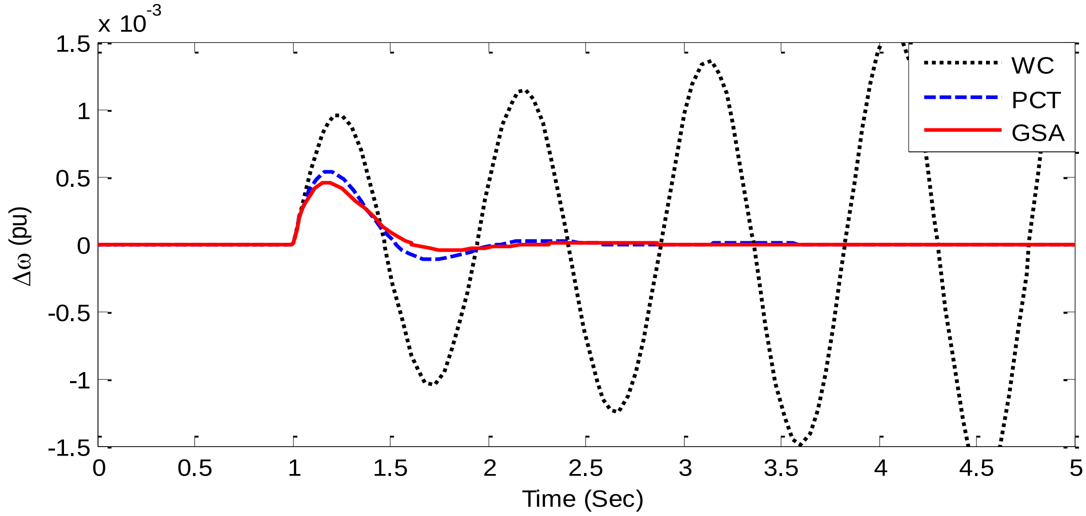


Figure 2.14: Speed deviation response for a change in open circuit time constant

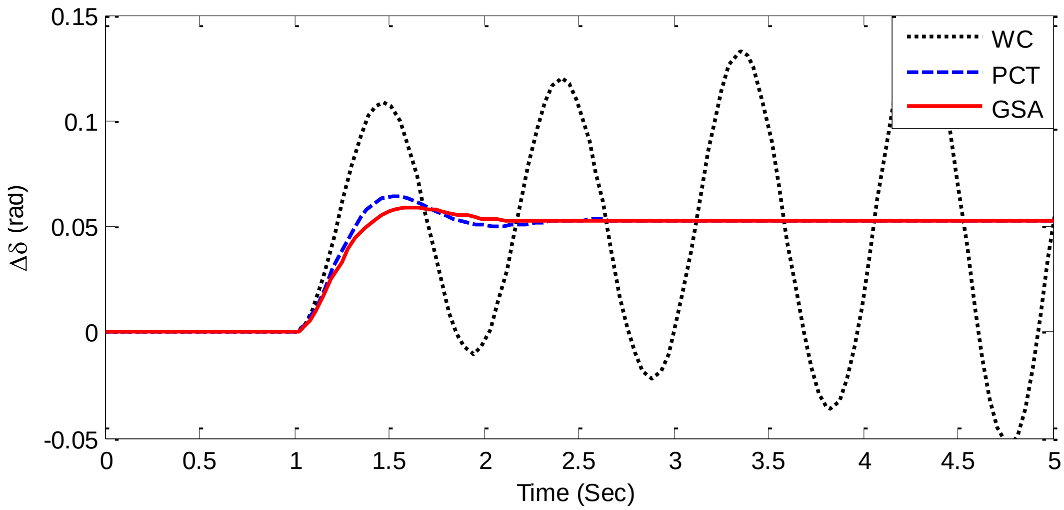


Figure 2.15: Power angle deviation response for a change in open circuit time constant

In order to prove the efficiency of the proposed methods a 30%decrese in direct axis transient axis transient time constant is considered. The system responses for the above condition are shown in Figs. (2.14) – (2.15). It is clear from the above figures that the proposed SSSC-based damping controller yields better stability operating condition.

2.5.4 Comparison of Different Algorithms

2.5.4.1 Change in Mechanical Power Input (P_m)

In order to prove the superiority of the proposed GSA algorithm, it is compared with the conventional techniques like GA and PSO. At the first instance, the mechanical power input to the system is increased by 10%. The system response are shown in Figs. (2.16) – (2.17). From the response curves, it can be concluded as the GSA based SSSC damping controller yields better performance as compared to GA and PSO based damping controller. For the simulation point of view, the legend GA represents the response of the system with the GA and the legends PSO and GSA represent the response with particle swarm and gravitational search algorithm respectively.

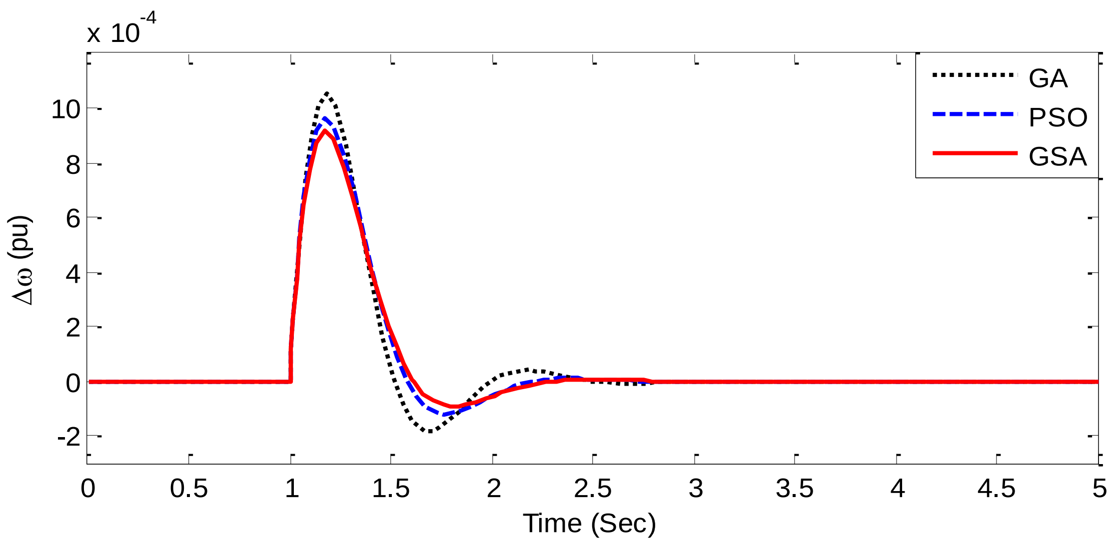


Figure 2.16: Speed deviation response for a 10% step increase in P_m comparing different algorithms

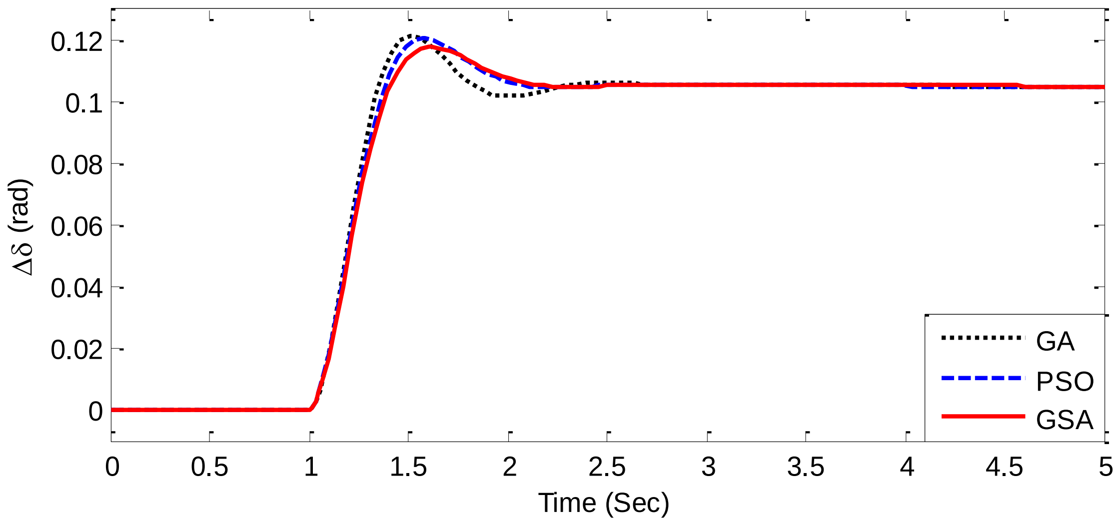


Figure 2.17: Power angle deviation response for a 10% step increase in P_m comparing different algorithms

2.5.4.2 Change in Reference Voltage (V_{Ref})

At the next instance, the electrical power input to the system (V_{Ref}) is increased by 5%. The system response is shown in Figs. (2.18) – (2.19). It can be observed as, the damping of the system is highly reduced and the system reaches to the stable point very quickly for the GSA based SSSC damping controller as compared to GA and PSO based damping controller.

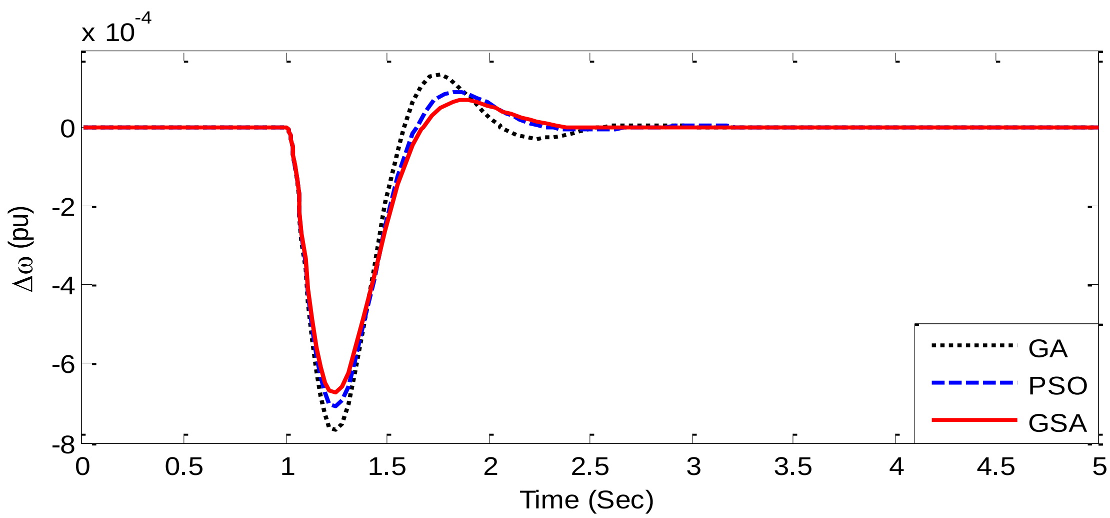


Figure 2.18: Speed deviation response for a 5% step increase in V_{ref} comparing different algorithms

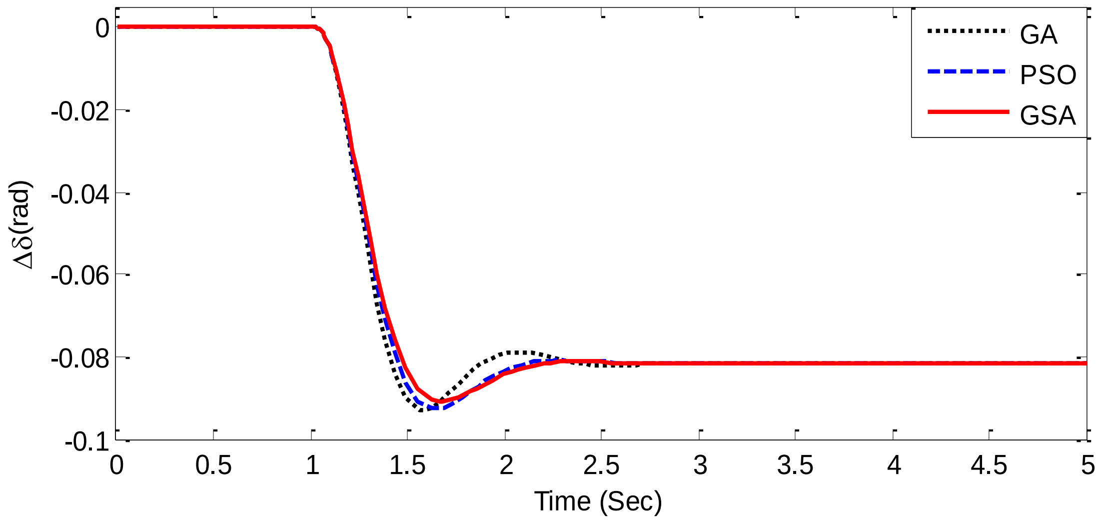


Figure 2.19: Power angle deviation for a 5% step increase in V_{ref} comparing different algorithms

2.5.5 Comparison of different Objective Function

To study the effect of objective function on the performance of the SSSC based damping controllers, other objective functions are considered. The objective functions are given by:

Integral Absolute Error (IAE) $IAE = \int_0^{t_{sim}} |e(t)|\, dt$ (2.32)

The Integral of Time Multiply Squared Error (ITSE) $ITSE = \int_0^{t_{sim}} t\, e^2(t)\, dt$ (2.33)

Integral of Time Multiplied Absolute value of Error (ITAE) $ITAE = \int_0^{t_{sim}} t\, |e(t)|\, dt$ (2.34)

As minimum objective function value is obtained with GSA, it is employed to optimize the SSSC based controller with different objective functions. The same procedure is followed as explained earlier to optimize the controller parameters. The optimized parameters are given in Table 2.3.

Table 2.3: Optimized lead-lag controller parameters for IAE, ITSE and ITAE

PARAMETERS	SSSC-based controller parameters			
	Gain	Time Constant		Fitness Values
	K_S	T_{1s}	T_{2s}	
IAE	81.4051	0.5978	0.7182	$6.0210*10^4$
ITSE	71.8861	0.5151	0.6149	$6.6826*10^4$
ITAE	68.6674	0.2980	0.2658	$5.0285*10^4$

2.5.5.1 Change in Mechanical Power Input (P_m)

In order to verify the effectiveness of the proposed SSSC based damping controller using the different types of objective functions, various simulation studies are carried out. The responses with SSSC controller using IAE and ITSE are shown with a dotted line and dashed line (with legends IAE and ITSE) respectively. The response of the system with ITAE is shown in solid line (with legend ITAE). The same disturbance (i.e. Pm is increased by 10%) is considered first. It is clear from the Figs. (2.20) – (2.21) that, when ITAE is used as an objective function, better system performance is observed.

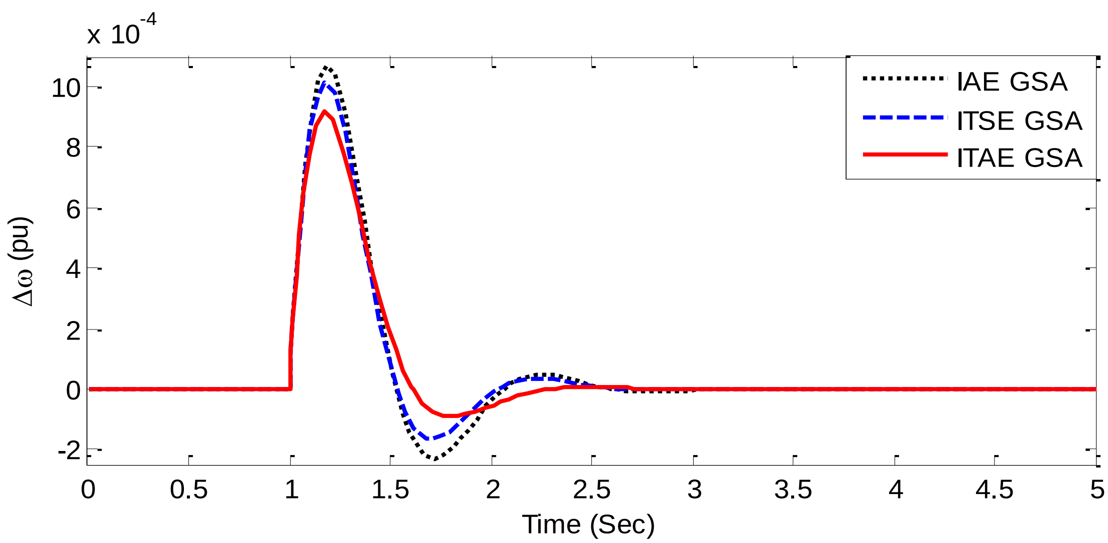


Figure 2.20: Speed deviation response for a 10% step increase in Pm comparing different objective functions

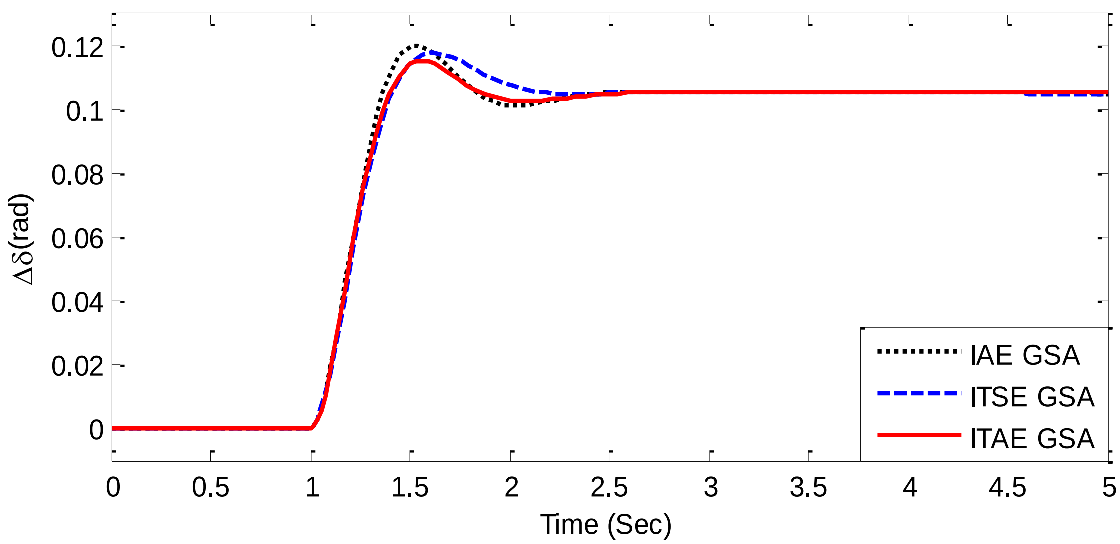


Figure 2.21: Power angle deviation response for a 10% step increase in Pm comparing different objective functions

ITAE based SSSC controller provides good damping characteristics to low frequency oscillations by stabilizing the system much faster. The first swing in the power angle is also slightly reduced when ITAE is used as an objective function instead of IAE and ITSE.

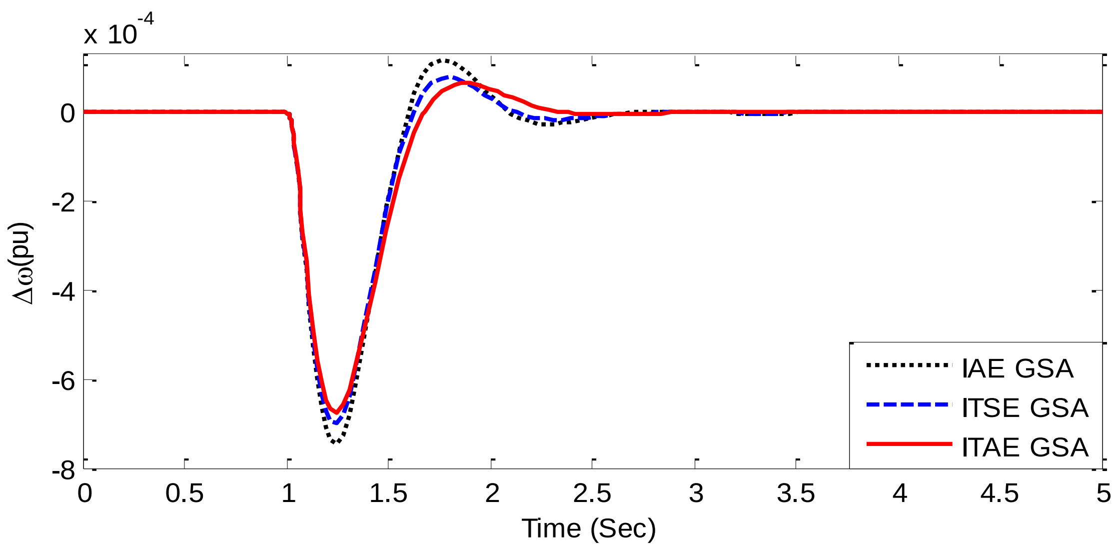


Figure 2.22: Speed deviation response for a 5% step increase in V_{ref} comparing different objective functions

2.5.5.2 Change in Reference Voltage (V_{Ref})

The effectiveness of selecting objective functions on system performance is also tested by applying a different disturbance. The reference voltage (V_{Ref}) is increased by a step of 5% at t =1 s. Figs. (2.22) – (2.23) show the responses of speed deviation, power angle for the above contingency. It can be observed from these results that, when ISE is used as objective function oscillations remain for a longer time. Improved damping characteristic with lower settling time is observed when ITAE is used as an objective function.

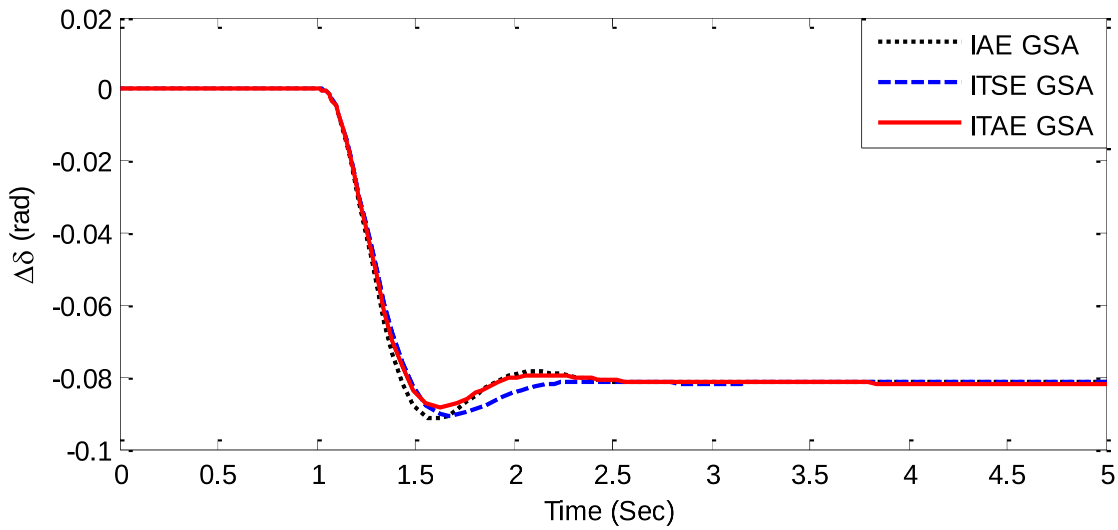


Figure 2.23: Power angle deviation response for a 5% step increase in V_{ref} comparing different objective functions

2.5.6 Effect of Different Damping Controller Structures

2.5.6.1 Change in Mechanical Power Input (P_m)

Finally in order to show the superiority of the proposed GSA based lead-lag damping controller structure, it is tested and compared with some conventional structures like PI and PID. The mechanical power input (P_m) is increased by a step of 10% at t =1 s. Figs. (2.24) – (2.25) show the responses of speed deviation and electrical power deviation for the above situation. To represent the simulation results, the GSA based PI and PID damping controller response are shown with the legend 'GSA PI' and 'GSA PID' respectively. The proposed lead-lag based damping controller structure is shown with the legend 'GSA LEAD-LAG'. A conclusion can be drawn from the simulation response curves that, the lead-lag based SSSC damping controller yields better performance as compared to the other damping controller structures.

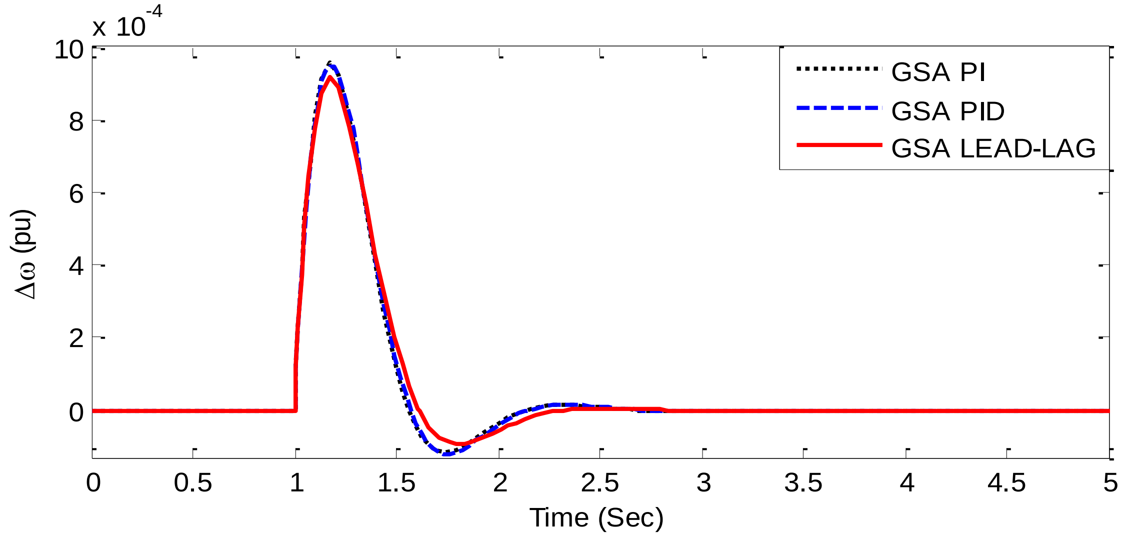


Figure 2.24: Speed deviation response for a 10% step increase in P_m comparing different damping controller structure

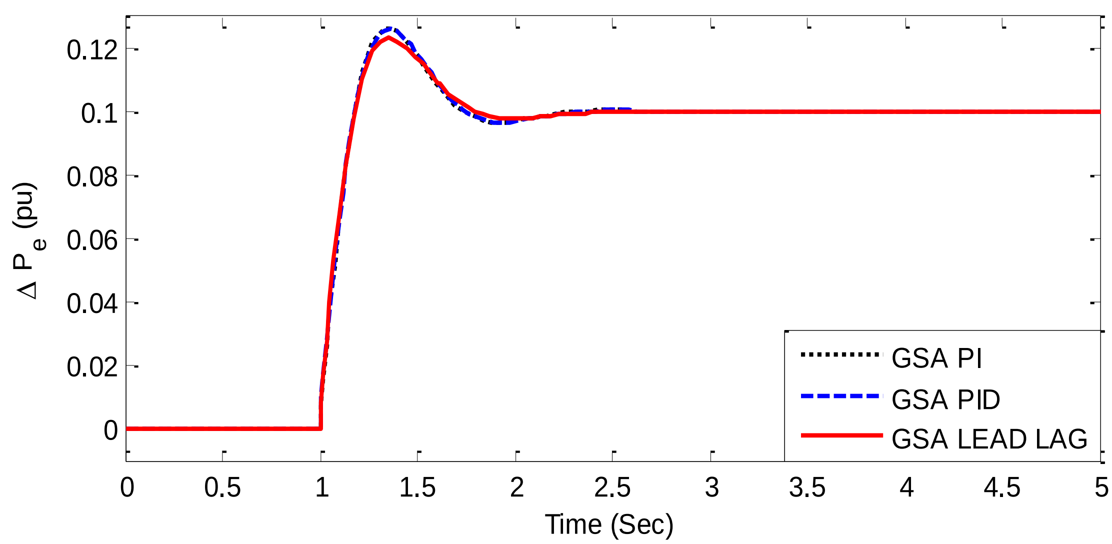


Figure 2.25: Power angle deviation response for a 10% step increase in P_m comparing different damping controller structure

2.5.6.2 Change in Reference Voltage (V_{Ref})

The next disturbance considered is, the change (increase) in the reference voltage (V_{ref}) by 5%. The system responses in terms of speed deviation and electrical power deviation are shown in Fig. (2.26) and (2.27). The conclusion can be made from the response curves that, the GSA based lead-lag damping controller is superior to the PI and PID based damping controller structures.

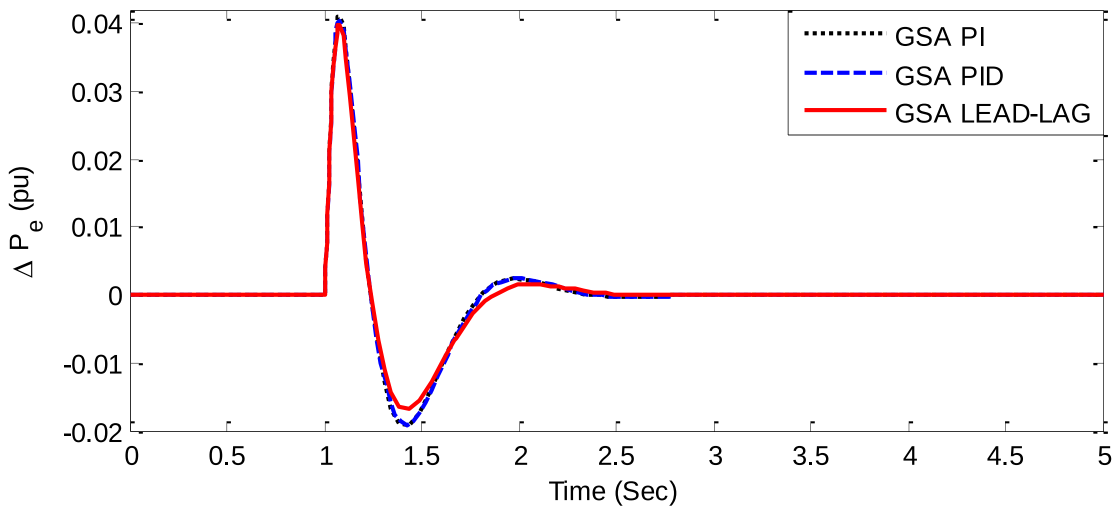


Figure 2.26: Speed deviation response for a 5% step increase in V_{ref} comparing different damping controller structures

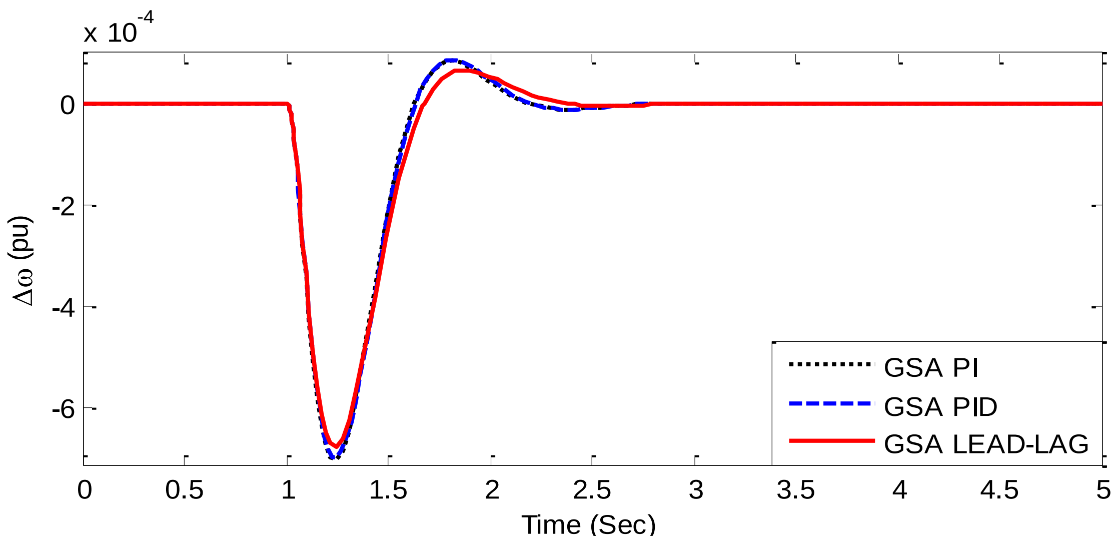


Figure 2.27: Power angle deviation response for a 5% step increase in V_{ref} comparing different damping controller structures

2.6 Chapter Summary

The significant contributions of the research work presented in this chapter are:

1. Modeling of SMIB system installed with SSSC for the power system stability studies has been provided.
2. A systematic approach for designing an SSSC-based controller employing modern gravitational search algorithm (GSA) has been presented.
3. The performance of GSA with another conventional algorithm has been investigated. It is observed that, in terms of computational effort, the GSA approach is faster as compared to other algorithms.
4. The effect of different objective functions namely Integral square error (ISE), Integral of Time Multiply Squared Error (ITSE) and Integral of Time Multiplied Absolute value of error (ITAE) on the performance of the controllers are compared.
5. The performance of GSA based lead-lag damping controller is compared with other damping controller structure like PI and PID.
6. From the above comparative study about the SSSC based controller design, it can be concluded that lead-lag based SSSC controller with the controller parameters optimized using Integral of Time multiplied Absolute value of the Error (ITAE) as objective function provides much better system response compared to all other alternatives under various disturbances over wide ranges of loading conditions.

2.7 Chapter:-2 to Chapter:-3

2.7.1 Application of Advanced FACTS Devices like UPFC for Power System Studies

To test the stability of a given power system other improved FACTS devices can be tested. A Unified Power Flow Controller (or UPFC) is an important part of the FACTS family which can provide fast-acting reactive power compensation on high-voltage electricity transmission networks. It uses a pair of three-phase controllable bridges to produce current that is injected into a transmission line using a series transformer. The controller can control active and reactive power flows in a transmission line. The UPFC uses solid state devices, which provide functional flexibility, generally not attainable by conventional thyristor controlled systems. The UPFC is a combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link. The main advantage of the UPFC is that it can smoothly control both the active and reactive power flows in the transmission line. If there are any disturbances or faults on the source side, the UPFC will not work. The UPFC operates only under balanced sine wave source. The controllable parameters of the UPFC are reactance in the line, phase angle and voltage. The UPFC concept was developed in 1995 by L. Gyugyi of Westinghouse. The UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system.

2.7.2 Application of Advanced Hybrid Soft-Computing Techniques for the FACT Based Damping Controller Design

For several problems, a simple Evolutionary algorithm might be good enough to find the desired solution. As reported in the literature, there are several types of problems where a direct evolutionary algorithm could fail to obtain a convenient (optimal) solution. This clearly paves the way to the need for hybridization of evolutionary algorithms with other optimization algorithms, machine learning techniques, heuristics etc. Some of the possible reasons for hybridization are as follows:-

- To improve the performance of the evolutionary algorithm (example: speed of convergence).
- To improve the quality of the solutions obtained by the evolutionary algorithm.
- To incorporate the evolutionary algorithm as part of a larger system.

The integration of different learning and adaptation techniques, to overcome individual limitations and achieve synergetic effects through hybridization or fusion of these techniques, has in recent years contributed to a large number of new hybrid evolutionary systems. Most of these approaches, however, follow an ad hoc design methodology, further justified by success in certain application domains. Due to the lack of a common framework, it remains often difficult to compare the various hybrid systems conceptually and evaluate their performance comparatively. There are several ways to hybridize a conventional evolutionary algorithm for solving optimization problems.

Chapter 3

Application of Hybrid Genetic Algorithm & Gravitational Search Algorithm for UPFC Based Damping Controller Design

3.1 Introduction

The Flexible AC Transmission Systems (FACTS) is a new technology that acts as a promising tool for power system application during the last decade. A critical and versatile member of the FACTS family is the Unified power flow controller (UPFC) which typically comprises of voltage source converter (VSC). The basic advantage of UPFC is that it can control all the parameters of the system like line impedance, voltage, and the phase angle thus justifies the name as "unified". The key function of this device is to control the transmission line power as well as to improve the transient stability of the system. The UPFC can offer voltage support and alleviate the system oscillation of the power system while it is subjected to changes in ambient conditions [1, 80].

In the power system stability studies, preference is always given to lead-lag controllers. The online tuning of the parameters of these controllers is always a challenge to the power engineers and development of suitable soft-computing techniques for tuning of this controller for better stability have been reported [2, 81]. Over the years, in order to carry out the power system study (small signal stability study) the linear Phillips-Heffron model has been used [3] that can be utilized for analyzing the low-frequency oscillation of the power system [4-6].

In this study, a UPFC based lead-lag damping controller is used for the stability analysis of power system. Tuning of the damping controller of the UPFC is an uphill task as the structure is highly complex [7, 8, and 72]. The literature study shows that the conventional techniques are very time-consuming, convergence rate is slow, being iterative, requires substantial computational burden [9-11].

Genetic Algorithm (GA) is the most widely used method of finding a damping control parameters [12, 64]. This algorithm is commonly used for function approximation and pattern classifications [13]. GA algorithm is likely to reach local minima especially in the case that the error surface has multiple minima, thus, it is a suitable choice for the parameter estimation [14-15]. Although, Genetic Algorithm is an option for finding the optimum parameters but due to its exploration and exploitation properties, it suffers from the mutation problem leading to premature convergences and needs more time to converge to an optimum solution comparing to the other algorithms like particle swarm optimization [16].

Further, another algorithm known as Gravitational Search Algorithm (GSA) has been reported. The said algorithm utilizes the concept of the law of gravity, the mass interactions [17]. GSA is a simple concept, and this can be easily implemented and is also computationally efficient. The GSA method is quite well-known and provides better performance while solving the nonlinear functions [18]. Some modification has been done to GSA algorithm like adaptive GSA [19], opposition based GSA [20] in order to improve its efficiency. Although GSA provides some adequate result for optimizing a problem, it suffers from certain drawbacks like trapping in local optima [21]. To overcome this, hybridization of GSA with other algorithms are presented. The different hybrid algorithms are fuzzy-GSA [22], hPSO-GSA [23], etc

In this work, a new hybrid approach by combining GA and GSA algorithm (GSA) is developed to form a new hybrid algorithm known as Hybrid Genetic Algorithm-Gravitational Search Algorithm (hGA-GSA), which can be used to find the optimum damping controller parameters [24]. This hybrid concept is based on the fact that, GA is used to search the global value at the initial stage and after that GSA is applied for the local search [25]. Simulation results show that the approach of genetics in hGA-GSA increases its convergence efficiency and thus prevents being trapped into the local optima. Moreover, it shows good convergence characteristics near minimum points and is good at finding the global minimum point. It can be concluded that by adopting this hybrid algorithm the probability of trapping in local optimum can be reduced to a great extent. Further the results show that the hybrid algorithm is superior compared to the conventional GA, GSA algorithms. In view of the above advantages, hGA-GSA algorithm is used in the proposed work in order to find an optimal tuned damping controller parameters.

The main objectives of the research work presented in this chapter are as follows:

1. To develop a linearized Philips- Heffron model for a single machine infinite bus (SMIB) installed with a Unified Power Flow Controller (UPFC).
2. Development of Hybrid Genetic Algorithm and Gravitational Search Algorithm (hGA-GSA)
3. To present a systematic procedure for designing a UPFC-based damping controller using the hybrid Genetic Algorithm-Gravitational Search Algorithm (hGA-GSA).
4. Verification of the proposed hybrid GA-GSA algorithm using some standard benchmark functions.
5. To compare the performance of the proposed UPFC based controller design with the modern heuristic-based optimization technique and a conventional tuning technique.
6. To study the dynamic performance of computational intelligence technique based optimized SSSC controller and conventionally tuned SSSC controller subjected to different disturbances and parameter variations.

3.2 System Investigated

Fig. 3.1 shows a typical power system that consists of a single machine connected to an infinite bus (SMIB) and is installed with a UPFC. The line is considered to be two parallel paths with a UPFC which can control the system power (both real and reactive). The IEEE-STIA configuration has been considered here. The UPFC is composed of two voltage source converters out of which, one is series connected and the other is shunt connected. Through a DC Capacitor, these two VSCs are connected back-to-back. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance and angle or alternatively, the real and reactive power flow in the line. Further, the pulse width modulation (PWM) scheme based UPFC is considered in this proposed study [4, 5].

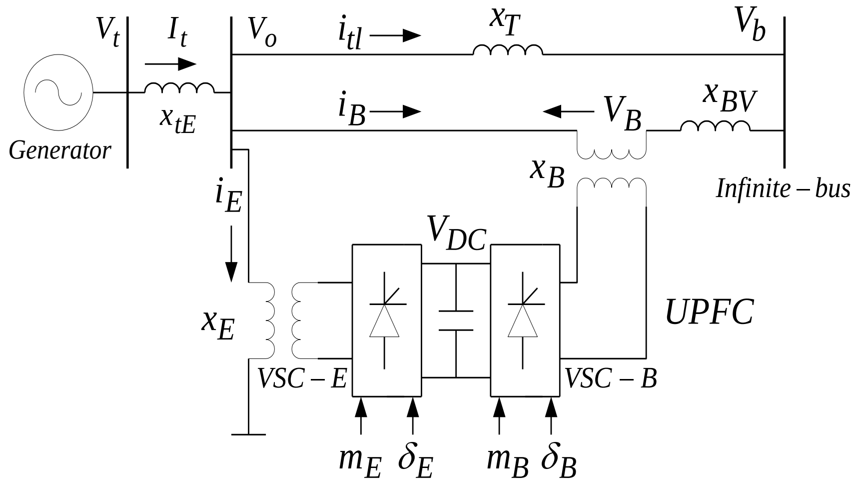


Figure 3.1: Single machine infinite bus power system with UPFC

3.2.1 Single Machine Connected to an Infinite Bus-Bar Installed with UPFC

3.2.1.1 The Non-Linear Equations

In order to obtain the non-linear equations, the resistances associate with the above power system are neglected i.e. transmission lines, generator, transformer and series converter transformer. The system differential equation in the nonlinear form for the above system can be expressed as [6]:

The nonlinear dynamic model of the system with UPFC is described below:

$$\dot{\delta} = \omega_0(\omega - 1) \tag{3.1}$$

$$\dot{\omega} = \frac{P_m - P_e - D\Delta\omega}{M} \tag{3.2}$$

$$\dot{E}_q^{'} = \frac{1}{T_{do}^{'}}\left[-E_q + E_{fd}\right] \tag{3.3}$$

$$\dot{E}_{fd} = \frac{K_A}{1 + sT_A}\left[V_{ref} - V_t\right] \tag{3.4}$$

$$V_{dc} = \frac{3m_E}{4C_{dc}}\left(I_{Ed}Sin\delta_E + I_{Eq}Cos\delta_E\right) + \frac{3m_B}{4C_{dc}}\left(I_{Bd}Sin\delta_B + I_{Bq}Cos\delta_B\right) \quad (3.5)$$

Where,

$$P_e = V_{td}I_{td} + V_{tq}I_{tq}$$

$$E_q = E_q' + \left(X_d - X_d'\right)I_{td}$$

$$V_t = V_{td} + jV_{tq},\ V_t = X_q I_{tq}$$

$$V_{tq} = E_q' - X_d' I_{td},\ I_{td} = I_{tld} + I_{Ed} + I_{Bd}$$

$$I_{tld} = \frac{X_E}{X_T}I_{Ed} + \frac{1}{X_T}\frac{m_E V_{dc}}{2}Cos\delta_E - \frac{1}{X_T}V_b Cos\delta$$

$$I_{tlq} = \frac{X_E}{X_T}I_{Eq} - \frac{1}{X_T}\frac{m_E V_{dc}}{2}Sin\delta_E + \frac{1}{X_T}V_b Sin\delta$$

$$I_{Ed} = \frac{\left(X_{dT} + X_{BB}X_{b3}\right)}{X_{dE}}V_b Cos\delta - \frac{\left(X_{dT} + X_{BB}X_{b2}\right)}{X_{dE}}\frac{m_E V_{dc}}{2}Cos\delta_E + \frac{X_{BB}}{X_{dE}}E_q' - \frac{X_{dT}}{X_{dE}}\frac{m_B V_{dc}}{2}Cos\delta_B$$

$$I_{Bd} = \frac{1}{X_{dE}}\left(X_E E_q' + \left(X_{b1} - X_E X_{b2}\right)\right) \frac{m_E V_{dc}}{2}Cos\delta_E + \frac{\left(X_{b3}X_E - X_{b1}\right)}{X_{qE}}V_b Cos\delta + X_{b1}\frac{m_B V_{dc}}{2}Cos\delta_B$$

$$I_{Bq} = \frac{1}{X_{qE}} \begin{pmatrix} \left(X_{a1} - X_E X_{a2}\right) \frac{m_E V_{dc}}{2} Sin\delta_E \\ + \frac{\left(X_{a3} X_E - X_{a1}\right)}{X_{qE}} V_b Sin\delta \\ + X_{a1} \frac{m_B V_{dc}}{2} Sin\delta_B \end{pmatrix}$$

The variables of the above equations can be formulated as:-

$$X_{qT} = X_q + X_{tE}$$

$$X_{ds} = X_{tE} + X_d' + X_E$$

$$X_{qs} = X_q + X_{tE} + X_E$$

$$X_{a1} = \frac{\left(X_{qs} X_T + X_{qT} X_E\right)}{X_T}$$

$$X_{a2} = 1 + \frac{X_{qT}}{X_T}$$

$$X_{a3} = -\frac{X_{qT}}{X_T}$$

$$X_{b1} = \frac{\left(X_{ds} X_T + X_{dT} X_E\right)}{X_T}$$

$$X_{b2} = 1 + \frac{X_{dT}}{X_T}$$

$$X_{b3} = \frac{X_{dT}}{X_T}$$

The power balance equation of the real power between the two converters which are series and shunt connected can be expressed as:

$$R_e\left(\overline{V}_B \overline{I}_B^* + \overline{V}_E \overline{I}_E^*\right) = 0 \qquad (3.6)$$

3.2.1.2 The Linear Equations

Usually, a linearized incremental model is taken into consideration around an operating point to design the electromechanical mode of the damping controller. The nonlinear system equations can be linearized around an operating point. These can be expressed as [7]:

$$\Delta\dot{\delta} = \omega_0 \Delta\omega \tag{3.7}$$

$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \tag{3.8}$$

$$\Delta \dot{E}' = \frac{(-\Delta E_q + \Delta E_{fd})}{T_{do}'} \tag{3.9}$$

$$\Delta \dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A (\Delta V_{ref} - \Delta V_t)}{T_A} \tag{3.10}$$

$$\begin{aligned}\Delta \dot{V}_{dc} &= K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta V_{dc} K_{ce}\Delta m_E \\ &+ K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B\end{aligned} \tag{3.11}$$

Where,

$$\begin{aligned}\Delta P_e &= K_1\Delta\delta + K_2\Delta E_q' + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E \\ &+ K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B + K_{pd}\Delta V_{dc}\end{aligned}$$

$$\begin{aligned}\Delta E_q &= K_4\Delta\delta + K_3\Delta E_q' + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E \\ &+ K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B + K_{qd}\Delta V_{dc}\end{aligned}$$

$$\begin{aligned}\Delta V_t &= K_5\Delta\delta + K_6\Delta E_q' + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E \\ &+ K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B + K_{vd}\Delta V_{dc}\end{aligned}$$

3.2.1.3 Modified Heffron-Phillips Small Perturbation Transfer Function Model of the SMIB Power System Including UPFC

Fig. (3.2) shows the small perturbation transfer function block diagram of a single machine infinite bus (SMIB) system including UPFC relating the pertinent variables of electric torque, speed, angle, terminal voltage, field voltage, flux linkages, UPFC control parameters, and dc link voltage. This model has been obtained, by using the linearized Eqs. (3.7) - (3.11) and by modifying the basic Heffron- Phillips model including UPFC. This linear model has been developed by linearizing the nonlinear differential equations around a nominal operating point. The twenty-eight constants of the model depend on the system parameters and the operating condition is listed below. In Fig. (3.2), [Δu] represents a column vector and [K_{pu}], [K_{qu}], [K_{vu}] and [K_{cu}] represents a row vectors. These vectors are defined as below:-

$[\Delta u] = [\Delta m_E \ \Delta\delta_E \ \Delta m_B \ \Delta\delta_B]^T$

$[K_{pu}] = [K_{pu} \ K_{p\delta e} \ K_{pb} \ K_{p\delta b}]$

$[K_{vu}] = [K_{ve} \ K_{v\delta e} \ K_{vb} \ K_{v\delta b}]$

$[K_{qu}] = [K_{qe} \ K_{q\delta e} \ K_{qb} \ K_{q\delta b}]$

$[K_{cu}] = [K_{ce} \ K_{c\delta e} \ K_{cb} \ K_{c\delta b}]$

The significant parameters of UPFC, which can control the system performance are:-

m_B:- Series inverter's modulating index. The magnitude of the series injected voltage can be controlled by controlling the m_B, thus, system reactive power is controlled. δ_B:- Phase angle of the series inverter. The real power exchange is controlled by controlling δ_B. m_E:- modulating index of shunt inverter. By controlling m_E, the voltage at a bus where UPFC is installed is controlled through reactive power compensation. δ_E: - Phase angle of the shunt inverter. This regulates the dc link dc voltage.

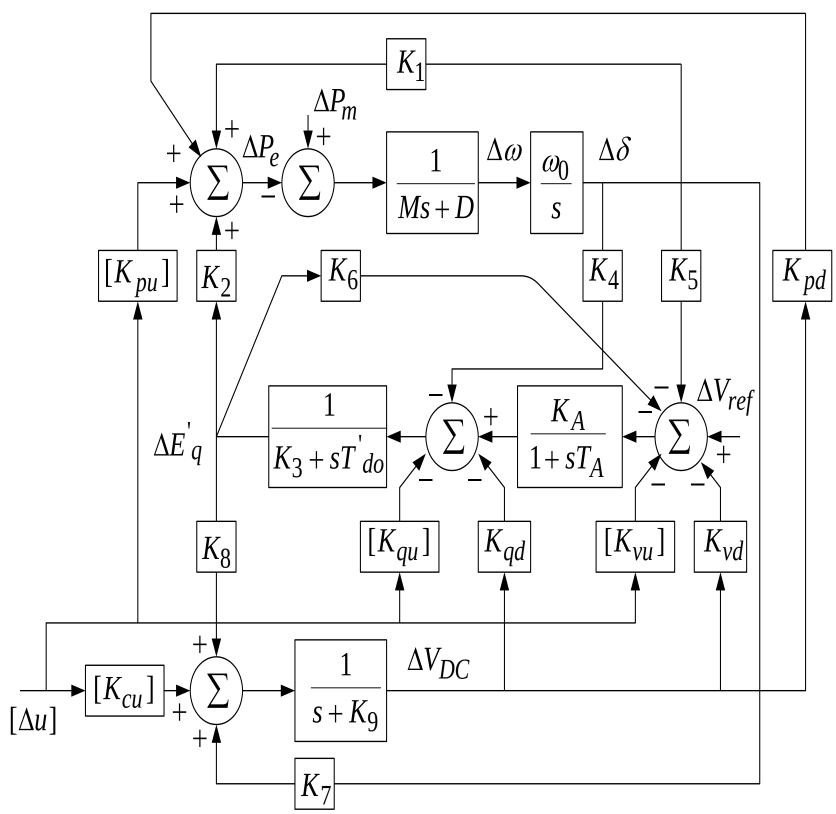


Figure 3.2: Modified Heffron-Phillips model of the SMIB system with UPFC

3.2.1.4 Computation of Constants of the Model

For computing K-constants, some initial components are needed and these constants are computed at the nominal operating condition. These components are listed below [8]:

$\delta_o = 47.1304°$	$i_{qo} = 0.6665$ pu
$e_{do} = 0.3999$ pu	$E_{bqo} = 0.6801$ pu
$e_{qo} = 0.9166$ pu	$i_{do} = 0.4729$ pu
$Q = 0.1670$ pu	$E_{bdo} = 0.7331$ pu

The K - constants of the model are:-

$K_1 = 0.3561$	$K_2 = 0.4567$	$K_3 = 1.6250$
$K_4 = 0.09164$	$K_5 = -0.0027$	$K_6 = 0.0834$
$K_7 = 0.1371$	$K_8 = 0.0226$	$K_9 = -0.0007$
$K_{pb} = 0.6667$	$K_{qb} = 0.6118$	$K_{vb} = -0.1097$
$K_{p\delta b} = 0.0924$	$K_{q\delta b} = -0.0050$	$K_{v\delta b} = 0.0061$
$K_{c\delta b} = -0.041$	$K_{cb} = 0.1763$	$K_{pd} = 0.0323$
$K_{qd} = 0.0524$	$K_{vd} = -0.0107$	$K_{pe} = 1.4821$
$K_{qe} = 2.4918$	$K_{ce} = 0.0018$	$K_{ve} = -0.5125$
$K_{p\delta e} = 1.9315$	$K_{q\delta e} = -0.0404$	$K_{v\delta e} = 0.1128$
$K_{c\delta e} = 0.4987$		

3.3 The Proposed Approach

3.3.1 Structure of the Proposed Damping Controller

Fig. (3.3) shows the structure of a lead–lag controller that mainly used to reduce the system damping which is considered for the analysis of the proposed study. The structure mainly consists of three blocks [14]. First is the gain block, which provides the appropriate gain for the controller. Next is the phase compensation block**.** This block is used to compensate the phase lag between the input and output signal of the controller thus helps to provide the required phase-lead. Last one is the signal washout block which is a high-pass filter. This section allows the signals to pass unchanged which are associated with the input oscillations signal.

The change in speed deviation [Δω] input to the controller and the change in control vector [Δu] is considered as the output of the proposed controller [18]. The time constant of the washout function is taken within 1 to 20 seconds range in lead-lag structure and this constant is not critical for the controllers. In the proposed study, T_{WT} is considered to be 10 seconds which represents the washout time constant. By using the evolutionary algorithms, three parameters, gain (K_T), the time constants T_1 and T_2, of the controller, is calculated. The algorithm considered here are Genetic algorithm, Gravitational search algorithm and the proposed hybrid GA-GSA algorithm.

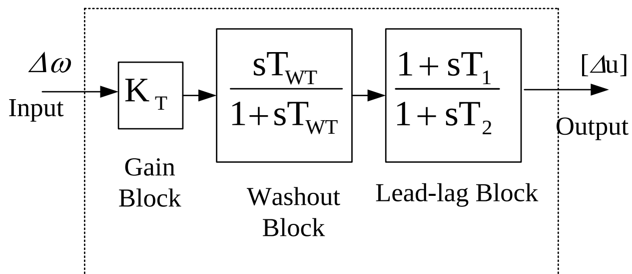


Figure 3.3: Structure of lead-lag based damping controller

3.3.2 Objective Function

The system oscillation can be seen through the speed deviation of the rotor, the power angle deviation or tie-line power. To minimize any one of the above deviation is the main focus of the proposed work. It has been reported that from the viewpoint of power system stability improvement speed deviation signal is a better choice than other signals for a FACTS based damping controller. In view of the above 'J' is taken as the objective function which is an integral time absolute error of the speed deviation (Δω). This is considered to be the objective function for the above study. This 'J' may be stated as [23]:

$$J = \int_{0}^{t_{sim}} t|e(t)|dt \qquad (3.12)$$

Where, 'e' represents an error signal of the speed deviation (Δω), t_{sim} represents simulation range of time.

For a stipulated period, the time domain simulation of the above power system is worked out and then the objective function is calculated. The prescribed range of the gain and the time constants for the damping controller is bounded. Thus, the following optimization problem is formulated from the above design approach.

Minimize J (3.13)

Subject to

$$K_i^{min} \le K_i \le K_i^{max}$$
$$T_{1i}^{min} \le T_{1i} \le T_{1i}^{max}$$
$$T_{2i}^{min} \le T_{21i} \le T_{2i}^{max} \quad (3.14)$$

Where K_i^{min} is the lower bound, K_i^{max} is the upper bounds of the gains, T_{ji}^{min} is the lower bound, T_{ji}^{max} is the upper bounds for the time constants damping controller. Using the above said three algorithms namely GA, GSA and proposed hybrid GA-GSA, the above parameters of the controller are obtained [11].

3.4 Application of Proposed Hybrid GA-GSA Algorithms

3.4.1 Genetic Algorithm (GA)

The GA is a search algorithm in which the laws of genetics and the law of natural selection are applied. For the solution of any optimization problem, using GA, an initial population is chosen which comprises a group of chromosomes [12]. Initially, a random population is generated then from this population fitness value of each chromosome is calculated. This can be found out by calculating the objective function by the process of encoding. Then a set of chromosomes termed as parents are evaluated which are known as offspring generation, generated from the initial population. Now the current population is replaced by their updated offspring which can be obtained by considering some replacement strategy [13].

3.4.2 Gravitational Search Algorithm (GSA)

For finding an optimal solution, gravitational search algorithm (GSA) is an alternative approach. This algorithm is compared with the previous algorithm and seems to be a promising method and gives a better performance that can be viewed from the various simulated results. The algorithm is mainly based on the Newtonian law, which states, "There is a force of attraction force between each particle of the world. The force of attraction can be calculated by directly multiplying the masses and by dividing the product to their square of the distance between the particles". 'R' is used in place of 'R^{2}' because simulation results prove that 'R' is giving much better result as compared to 'R^{2}' [17].

3.4.3 Proposed Hybrid Genetic Algorithm Gravitational Search Algorithm (hGA-GSA)

In this work a new algorithm is developed by hybridization of Genetic Algorithm (GA) and Gravitational Search Algorithm (GSA) [24]. This algorithm is termed as an hGA-GSA algorithm, mainly used to calculate the parameters of a damping controller. The advantage of combining this two algorithm is that the proposed method made use of the genetic algorithm for arranging features as populations of chromosomes whose fitness is evaluated by means of gravitational force presented in GSA to get the most coherent combination of features [25]. Fig. (3.4) shows the flow chart for the proposed hybrid GA-GSA algorithm.

The steps for combining standard GA with GSA algorithm which forms the basic hGA-GSA algorithm are stated as follows.

- Step-1: Randomly initialize the parent chromosomes a wider search space.
- Step-2: Initiate the iteration count while maximum count is pre-decided.
- Step-3: Evaluate the fitness of each chromosome and assign rank based on their fitness values. GA is used first for global search and then GSA is for local search.
- Step-4: The particles are taken as parent chromosome, from which off-springs are generated by applying simulated binary crossover and polynomial mutation [x, y].
- Step-5: Generate new chromosome matrix by combining parent chromosome matrix with the off-spring matrix.
- Step-5: K% of chromosomes is selected according to their fitness values where K is surviving pool depends on crossover probability. Transfer (1-K) % of chromosomes for GSA operation.
- Step-6: Update position and velocity as per the GSA procedure.
- Step-7: Generate new population by combining (1 - K) % of the population from GSA algorithm and K% of chromosome from GA.
- Step-8: This process is repeated until the maximum iteration is achieved.

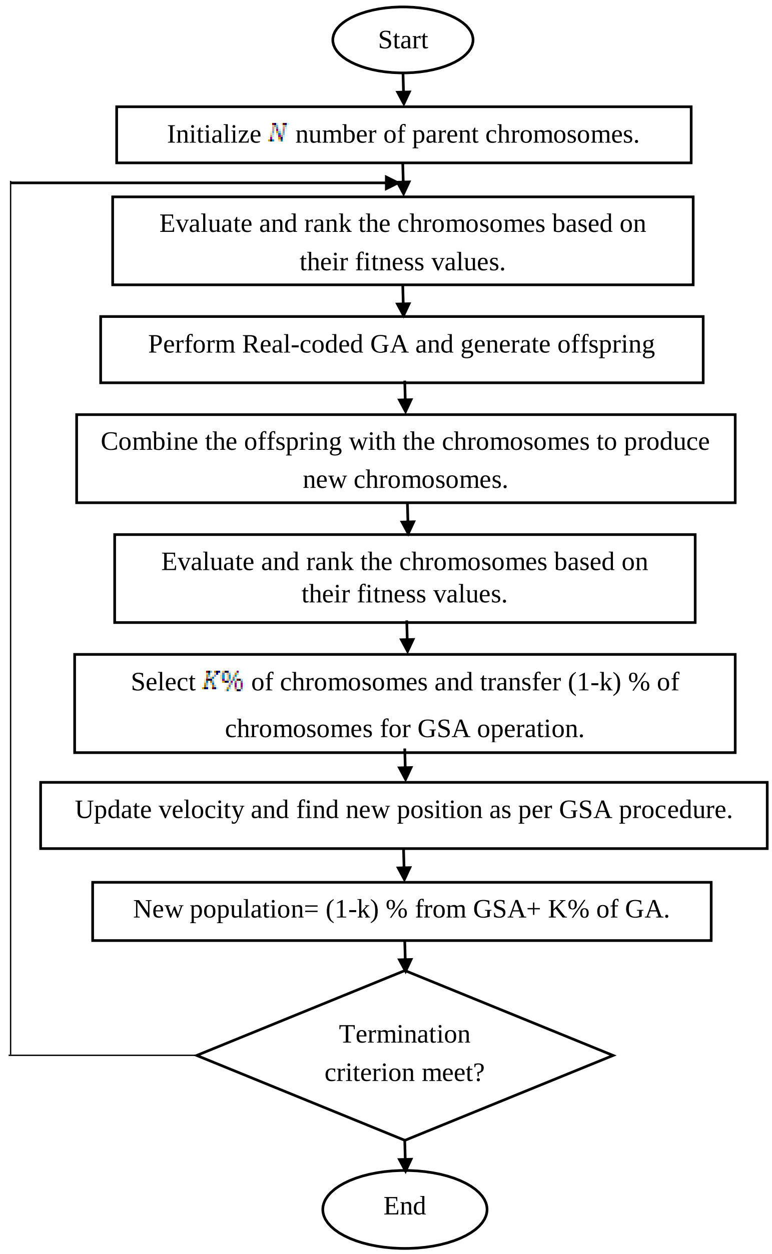


Figure 3.4: Flow chart for the proposed Hybrid GA-GSA Algorithm

3.5 Simulation Results and Discussion

For determining the parameters of the damping controller, Eq. (3.12) is considered by minimizing its fitness value. The fitness value is determined in the MATLAB/SIMULINK environment by considering each parameter and simultaneously the time domain simulations are carried out by considering GA, GSA and hGA-GSA.

Table 3.1: Optimized Controller Parameters Using hGA-GSA

Damp. Controller	Min	Max	Avg.	Avg. Time (Sec)	K_T, T_1, T_2
m_B - based	17.1941*10^{-4}	17.67452*10^{-4}	17.3946*10^{-4}	1134.92332	67.1237,0.6718, 0.9939
δ_B - based	19.1444*10^{-4}	19.74307*10^{-4}	19.5567*10^{-4}	1153.08784	499.2499,0.2664, 0.4351
m_E - based	17.1211*10^{-4}	17.4193*10^{-4}	17.2981*10^{-4}	1056.14754	41.4650,0.5313, 0.9929
δ_E - based	17.6719*10^{-4}	17.8795*10^{-4}	17.376*10-4	930.43913	34.0769, 0.4922, 0.9910

Table 3.2: Optimized Controller Parameters Using GSA

Damp. Controller	Min	Max	Avg.	Avg. Time (Sec)	K_T,T_1, T_2
m_B - based	18.6167*10^{-4}	19.3146*10^{-4}	18.9984*10^{-4}	391.09330	66.7929,0.3638, 0.9583
δ_B - based	26.3213*10^{-4}	26.9923*10^{-4}	26.8822*10^{-4}	333.61399	312.1209,0.2587, 0.3500
m_E - based	17.9167*10^{-4}	18.6527*10^{-4}	17.9764*10^{-4}	418.31601	22.2328, 0.3178, 0.1694
δ_E - based	18.2754*10^{-4}	18.8260*10^{-4}	18.6973*10^{-4}	490.84072	14.8356, 0.8352 0.9776

Table 3.3: Optimized Controller Parameters Using GA

Damp. Controller	Min	Max	Avg.	Avg. Time (Sec)	K_T,T_1, T_2
m_B - based	19.1526*10^{-4}	20.9317*10^{-4}	19.9875*10^{-4}	560.66480	20.0152,0.0103, 0.0123
δ_B - based	27.5766*10^{-4}	27.9854*10^{-4}	27.8498*10^{-4}	551.84729	199.9908,0.00999, 0.00999
m_E - based	19.4644*10^{-4}	19.9654*10^{-4}	19.8763*10^{-4}	690.31601	13.6834,0.1645, 0.1645
δ_E - based	19.9569*10^{-4}	20.2549*10^{-4}	20.3459*10^{-4}	570.540525	39.8651,0.1207, 0.9830

Table 3.4: Standard bench functions and their minimization results over 30 independent runs with T_{max}=2000 by applying GA, GSA, and hGA-GSA algorithms

Functions Name	Test Functions	Dim.	Range	Algorithms	Best	Worst	Mean
Schwefel	$F_1(x)=\sum_{i=1}^{n}\lvert x_i\rvert+\prod_{i=1}^{n}\lvert x_i\rvert$	30	$[-10,10]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	$3.065*10^{-9}$ $3.795*10^{-8}$ 102.8622	$3.814*10^{-9}$ $4.435*10^{-8}$ 131.0020	$3.575*10^{-9}$ $3.985*10^{-8}$ 119.6575
Sphere	$F_2(x)=\sum_{i=1}^{n}x_i^2$	30	$[-100,100]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	$1.134*10^{3}$ $2.040*10^{3}$ $2.500*10^{3}$	$5.092*10^{3}$ $6.536*10^{3}$ $7.718*10^{3}$	$3.0685*10^{3}$ $4.1967*10^{3}$ $4.9969*10^{3}$
Schwefel	$F_3(x)=\max\{\lvert x_i\rvert, 1\le i\le n\}$	30	$[-100,100]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	$1.275*10^{-14}$ $1.361*10^{-13}$ 5.0013	$4.084*10^{-14}$ $6.302*10^{-13}$ 12.3145	$3.985*10^{-14}$ $4.689*10^{-13}$ 9.6454
Step	$F_4(x)=\sum_{i=1}^{n}([x_i+0.5])^2$	30	$[-100,100]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	$1.874*10^{-27}$ $6.405*10^{-24}$ 9.8885	$2.330*10^{-28}$ $4.505*10^{-25}$ 26.3481	$9.764*10^{-27}$ $2.964*10^{-25}$ 11-9775
Ackly	$F_5=-20\exp\left(-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n}x_i^2}\right)-\exp\left(\frac{1}{n}\sum_{i=1}^{n}\cos 2\pi x_i\right)+20+e$	30	$[-32, 32]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	1.6844 1.3459 2.6701	1.6844 1.9844 8.1364	1.6844 1.6746 6.0023
Noisy quadric	$F_6=\sum_{i=1}^{n}ix_i^4+\text{random}(0,1)$	30	$[-1.28,1.28]^n$	1. hGA-GSA 2. Std.-GSA 3. Std.-GA	$8.672*10^{-6}$ $1.853*10^{-4}$ $2.570*10^{5}$	$7.099*10^{-5}$ $9.637*10^{-4}$ $6.901*10^{5}$	$2.064*10^{-6}$ $7.975*10^{-4}$ $4.436*10^{5}$

An Intel (R) Core (TM) 2 Duo 2.93 GHz, 2 G.B RAM computer, with the MATLAB environment is used for the simulation study. Table 3.1, Table 3.2 and Table 3.3 represent the optimized fitness values obtained based on 30 independent runs for hGA-GSA, GSA and GA respectively. The proposed lead-lag structure is compared using three algorithms namely hGA-GSA, GSA and GA. The legend 'WC' represents the response of the system without any controller**.** The legend 'GA' with a dotted line shows the system response with the application of Genetic Algorithm. The legend 'GSA' with a dashed line represents the system response with the Gravitational Search Algorithm. And finally, the legend 'hGA-GSA' with a solid line represents the response system considering the proposed algorithm.

3.5.1 Model Verification

The proposed hGA-GSA algorithm is tested on some standard benchmark functions in order to validate its effectiveness. The primary purpose of this optimization algorithm is to evaluate the performance characteristics of the test functions. Table-3.4 represents the minimization of these functions. It has been observed that the proposed algorithm has much better performance compared to GSA or GA. For this study, population size is fixed to (N=30). Dimensions of all the algorithm are set to 30 and the maximum number of iteration is (T_{max}) is taken as 2000 to minimize the functions as shown in Table 3.4. In order to archive a fair comparison, the number of function evaluation for all the algorithm is kept same. The simulation of the algorithm is carried out for 30 times and the corresponding results were recorded. Table 3.4 summarizes the statistical analysis of the recorded results. The worst, best and mean fitness, from the recorded values achieved, were calculated, tabulated and compared.

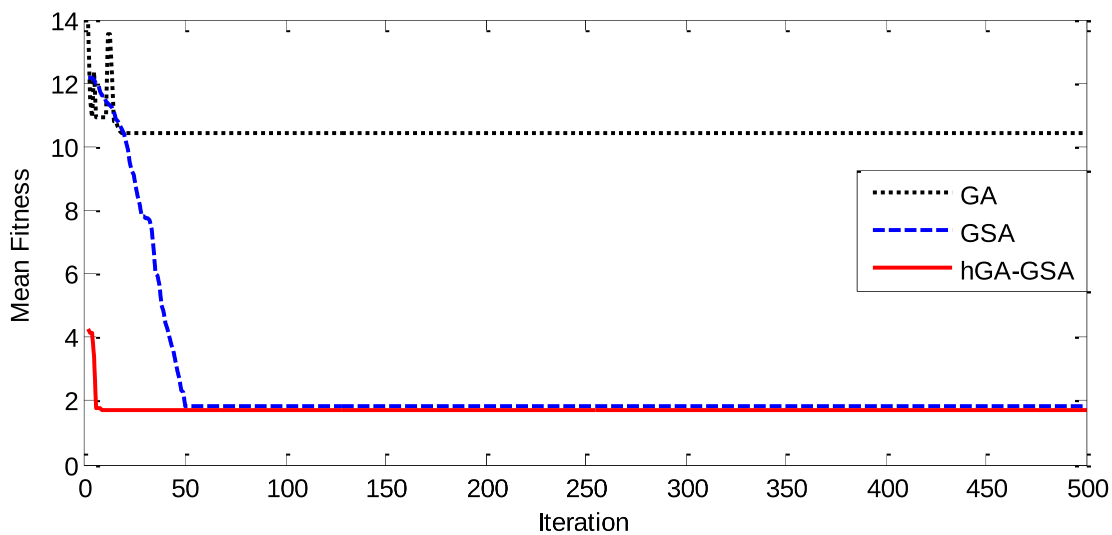


Figure 3.5: Performance comparison of hGA-GSA, GSA and GA for minimization with n=30

Now if the mean value is less for an algorithm as compared to others then, the algorithm is said to be consistent. From Table 3.4, it is concluded that for the proposed hGA-GSA algorithm the mean fitness is low as compared to the other two algorithms GSA and GA. Hence, it is expected that the hGA-GSA approach shall provide a better solution compared to the other algorithms as far as the UPFC power flow controller is concerned. Fig. (3.5) indicates the convergence characteristic for all the algorithms on a Sphere standard benchmark function. Here the representative variations of the mean best fitness in the form of logarithm values over the number of iterations are depicted. Further, it can be seen from the Fig. (3.5) that the performance of the proposed hybrid GA-GSA algorithm is much superior to the standard version of the GA and GSA algorithms and the number of iteration required for the proposed hGA-GSA is less.

3.5.2 Comparison of Computational Time

Further a comparison is made with reference to computational time requirement. In all the three algorithms the generation number is varied while the population size of 100 is fixed. In any optimization algorithm, the range of any unknown constraints is of significant importance. Hence, in the present work, a wider range is selected for the first case and then after successive iteration the range is gradually shortened to compare it with previous runs. The variation of computational time with respect to the generation is shown in Fig. (3.6). It can be concluded from the figure that the time of computation for the proposed hGA-GSA is higher compared to the other two techniques because of the higher mathematical burden.

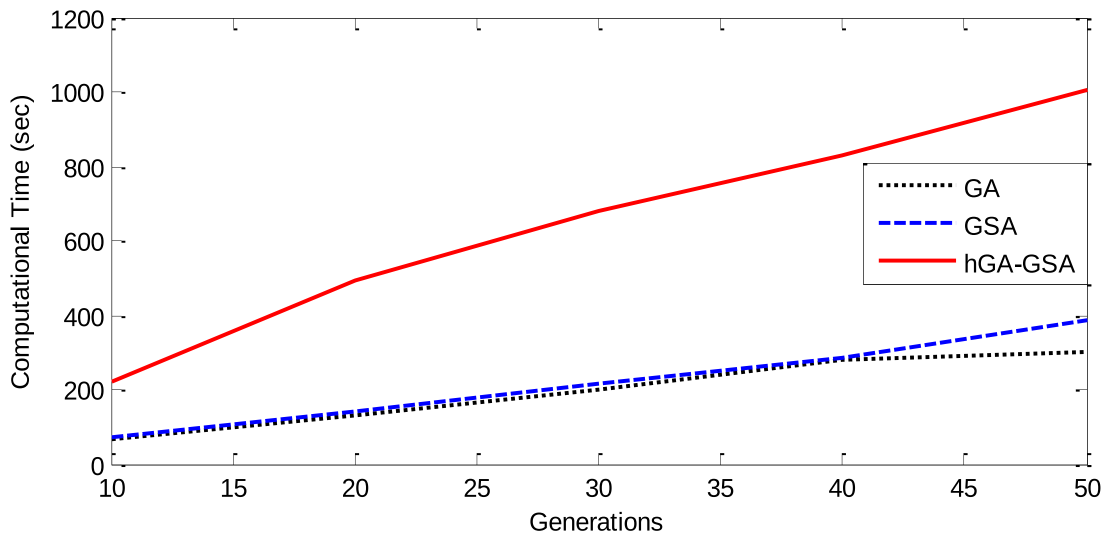


Figure 3.6: Computational time vs. Generation variation for hGA-GSA, GSA and GA

Further, from the Fig. (3.6) it can be observed that for all optimization techniques i.e. hGA-GSA, GSA, GA, the time of computation increases linearly with the increase in a number of generation. But for the case of hGA-GSA, as the number of generation increases there is a more rapid increase in computational time as it employs both the techniques and while GSA has the disadvantages of quickly getting into the local optimum, GA is popular for its exploration and exploitation properties. However while computation time is sacrificed for the hybrid GA-GSA algorithm, the much better optimum condition is achieved.

3.5.3 Eigen Value Analysis

The system eigenvalues with UPFC (i.e. m_B, m_E, δ_E and δ_B based controllers) for all the three algorithms (hGA-GSA, GSA and GA) are given in Table 3.5. In this table, the first row shows the Eigenvalues without a controller. For comparison point of view, the system's Eigenvalues are calculated with the damping controller using different algorithms**.** It can be concluded from Table 3.5, that the above system is said to be unstable because of the negative damping. The system reaches the stable point as the Eigenvalues of the system shifts in the s-plane. Again it can be seen that the parameters of the system with hGA-GSA shifts to a significant value to the left half of the s-plane. Therefore, hGA-SA based UPFC provides must better stability compared to the GA and GSA based UPFC.

Table 3.5: System Eigenvalues with and without controller

Without control	With GA lead-lag	With GSA lead-lag	With hGA-GSA lead-lag
-98.3125	-97.0874	-97.1993	-97.0320
-0.0270	-7.2736	-7.7056	-5.5683
-2.0356	-7.5108	-2.2314	-1.7560
0.0268 + 4.1010i	-1.6883	-0.6216	-0.6891
0.0268 - 4.1010i	-0.0270	-0.1088	-0.1085
-97.0874	-0.1022	-0.0269	-0.0269
0	0	0	0

3.5.4 m_B- Based UPFC Damping Controller

The performance of m_B based UPFC controllers is analyzed while the system is subjected to a disturbance. The disturbance is attributed as 10% increase in mechanical power input

(Pm) at t=1sec. Fig. (3.7) and (3.8) show the system speed deviation and electrical power angle deviation. It can further be concluded from the figure that, with hGA-GSA the system becomes more stable. Simultaneously system oscillations are also damped out efficiently. It is clearly evident from Figs. (3.7) and (3.8) that the system performance improves significantly with the proposed hGA-GSA optimization technique compared to the other two techniques known as GA and GSA.

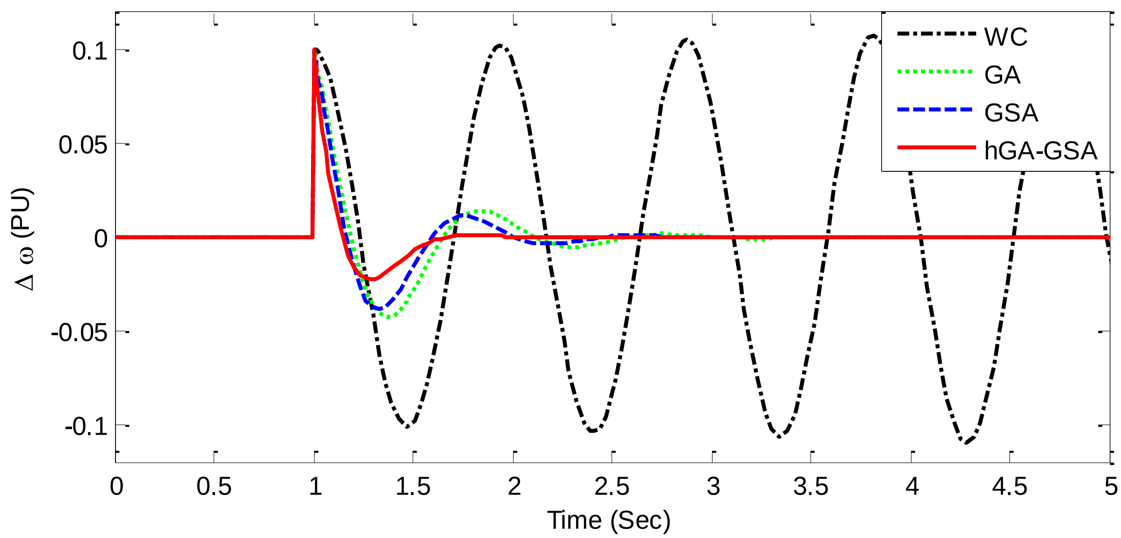


Figure 3.7: Change in Speed deviation with m_B-based UPFC damping controller

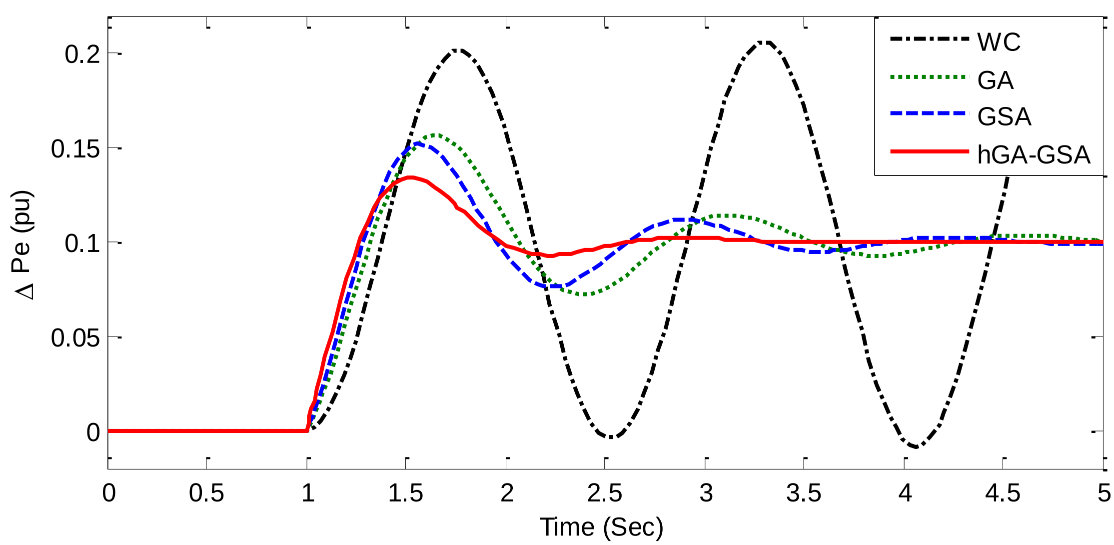


Figure 3.8: Electrical Power deviation curve with m_B -based UPFC damping controller

3.5.5 δ_B- Based UPFC Damping Controller

To assess the system performance**,** the same disturbance is considered (mechanical power input increase to a step of 10%) and the δ_B - based UPFC damping controller is taken into consideration. For the said disturbance, Figs. (3.9) and (3.10) clearly show that the system shows much better results with the proposed hGA-GSA as compared to the other two techniques.

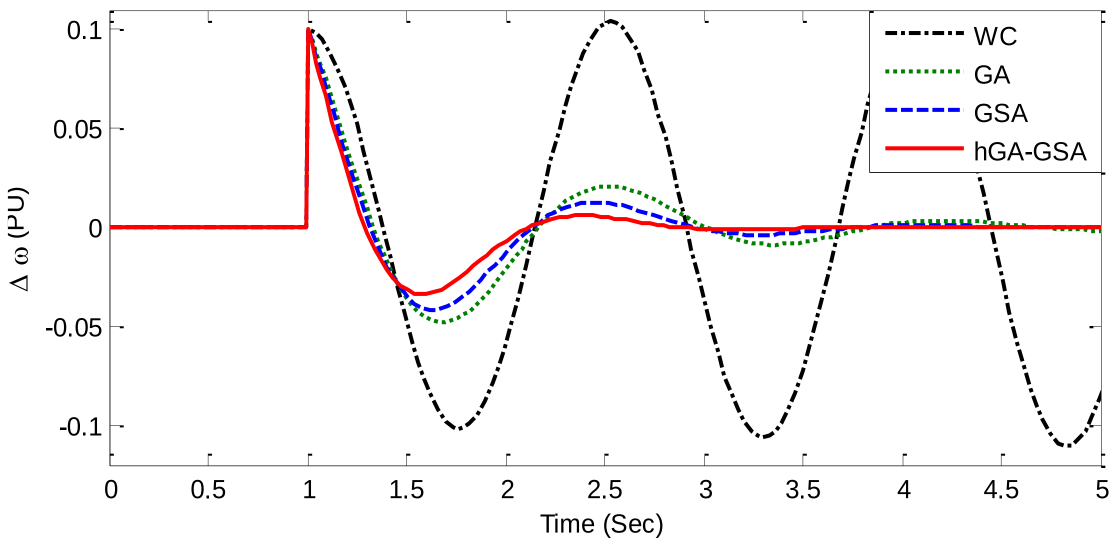


Figure 3.9: Change in Speed deviation with δ_B-based UPFC damping controller

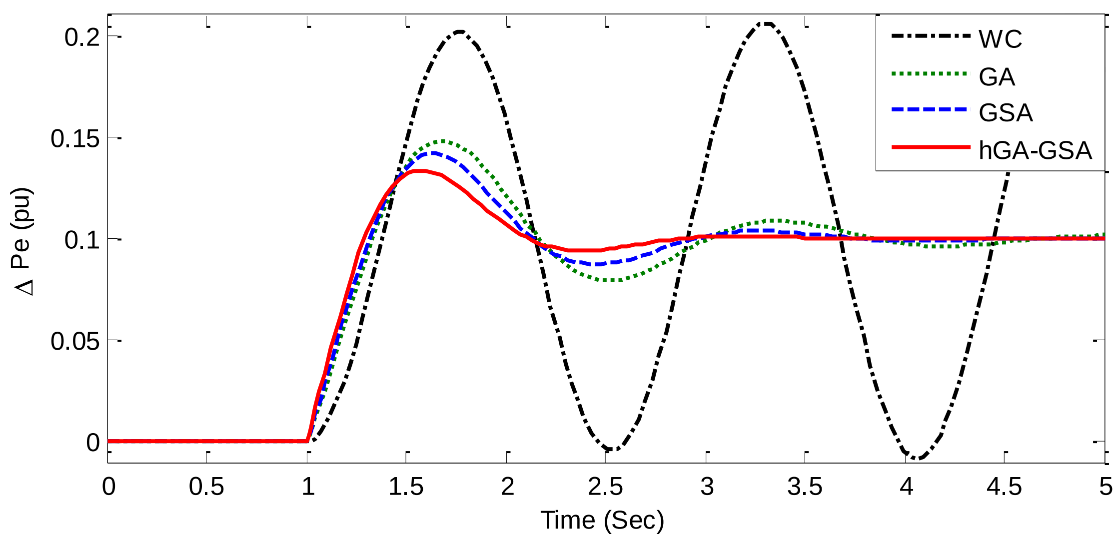


Figure 3.10: Electrical Power deviation curve with δ_B-based UPFC damping controller

3.5.6 m_E - Based UPFC Damping Controller

Again the same disturbance is considered (mechanical power input increase to a step of 10%) for m_E - based UPFC**.** Figs. (3.11) and (3.12) represent the responses of the system. It is seen from these two figures that the system incorporating the proposed hGA-GSA technique yields much better results as compared to the other two techniques.

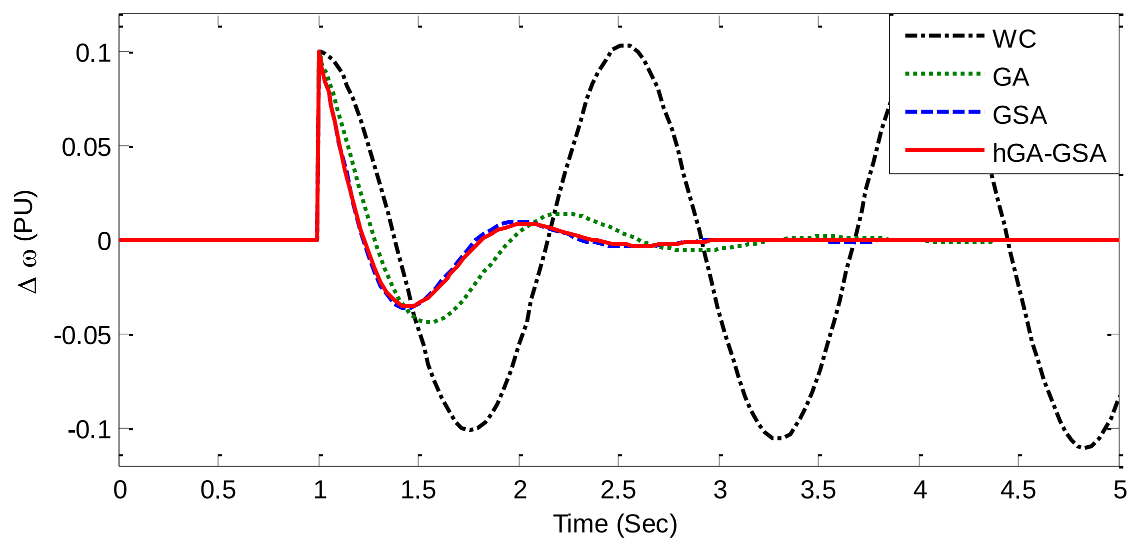


Figure 3.11: Change in speed deviation curve with m_E -based UPFC damping controller

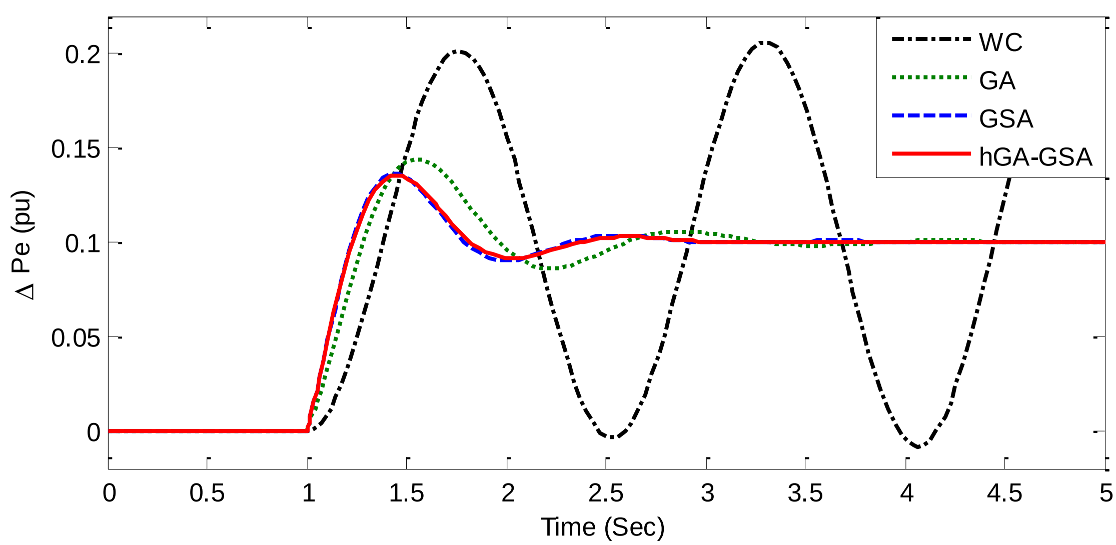


Figure 3.12: Electrical power deviation curve with m_E -based UPFC damping controller

3.5.7 δ_E - Based UPFC Damping Controller

In order to analyze the δ_E - based UPFC controller the same contingency i.e. the mechanical power input P_m is increased by 10% is considered and from the Figs. (3.13) and (3.14) it is concluded that the system provides much better results with hGA-GSA approach compared to GSA and GA tuned UPFC damping controller.

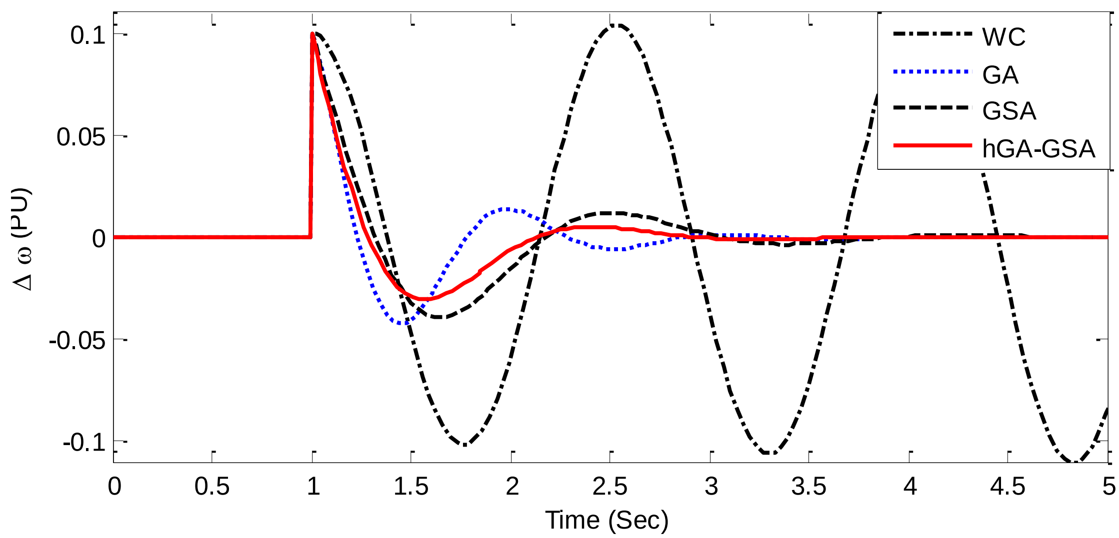


Figure 3.13: Change in Speed deviation with δ_E -based UPFC damping controller

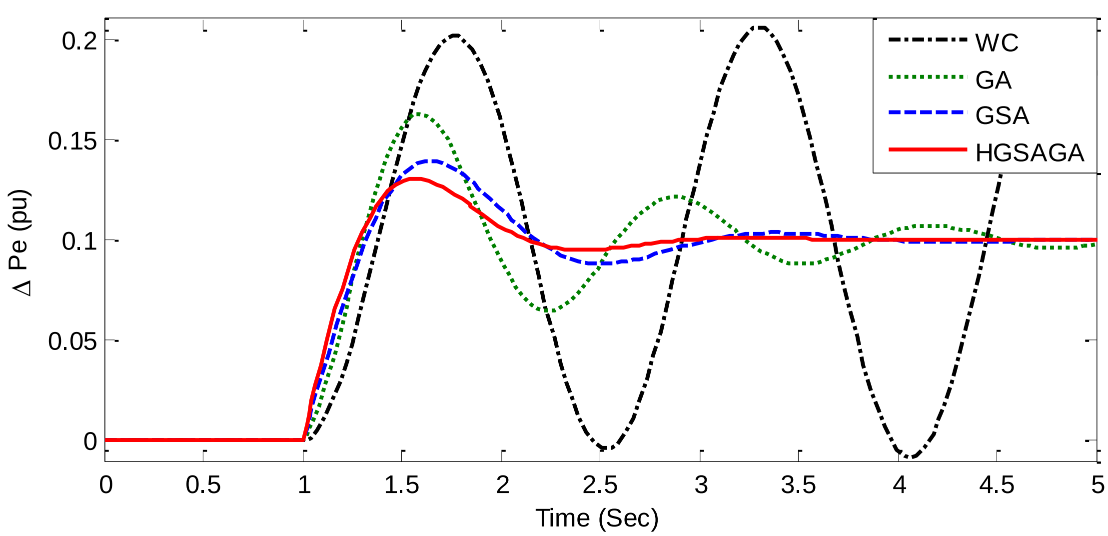


Figure 3.14: Electrical power deviation curve with δ_E -based UPFC damping controller

3.5.8 Comparison of all UPFC-Based Damping Controllers

For a complete validation, another disturbance is taken into account. In this disturbance, the reference voltage (V_{Ref}) has been increased by 10% (step change) at t =1 s. Figs. (3.15) – (3.17) represents the system responses for a change in V_{ref}.

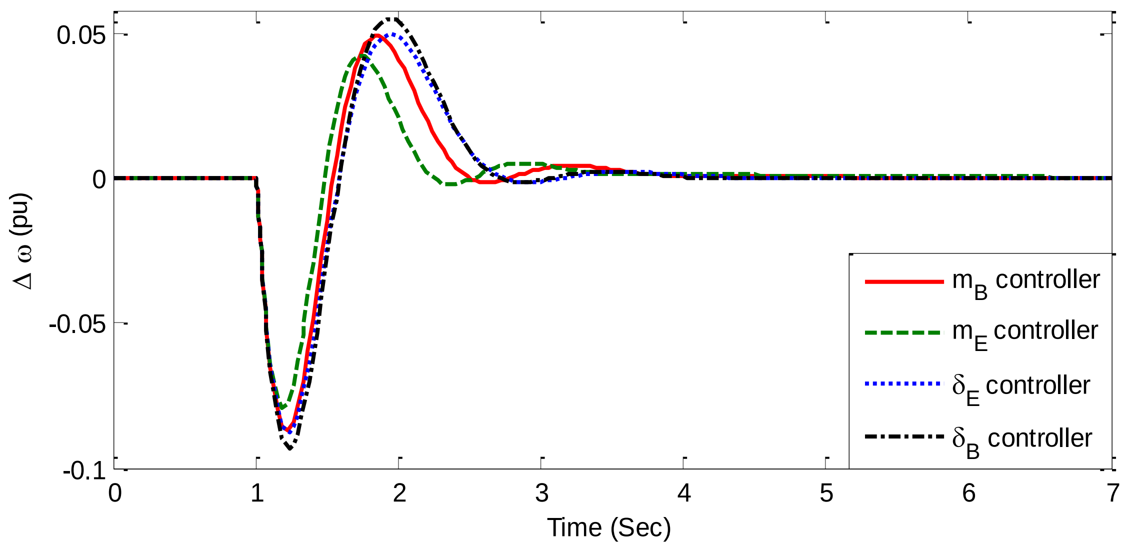


Figure 3.15: Speed deviation response with all UPFC based damping controllers for a change in V_{ref} using hGA-GSA algorithm

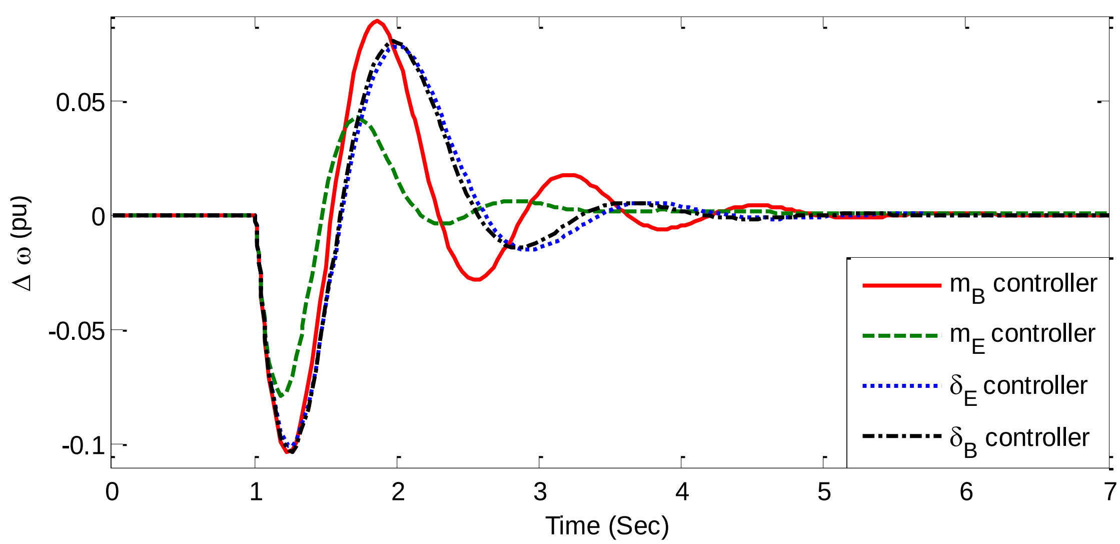


Figure 3.16: Speed deviation response with all UPFC based damping controllers for a change in V_{ref} using GSA algorithm

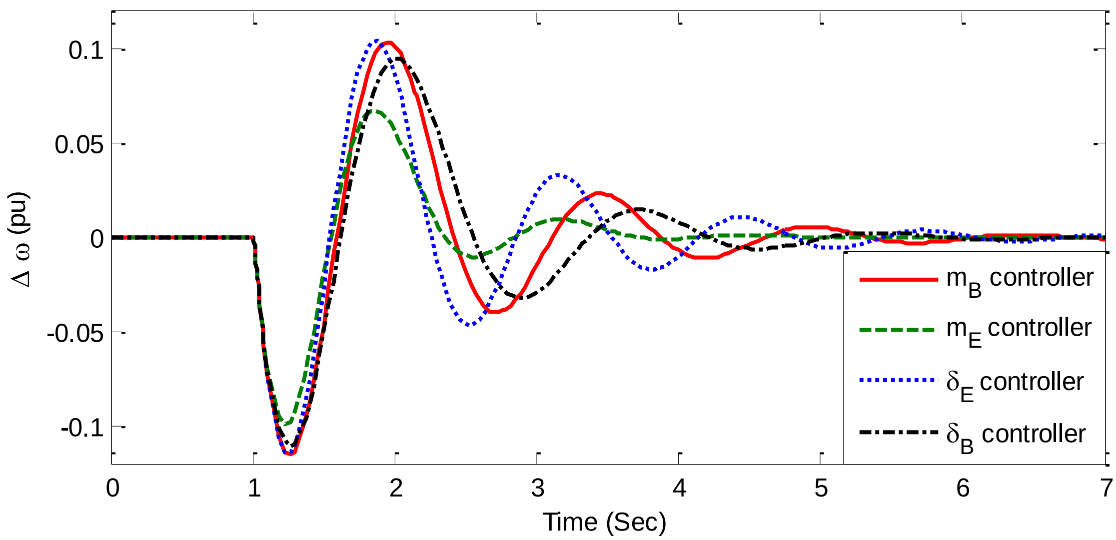


Figure 3.17: Speed deviation response with all UPFC based damping controllers for a change in V_{ref} using GA algorithm

From the figures again it can be concluded that satisfactory results for all the four controllers are obtained. From the Fig. (3.15) - (3.17) it clearly observed that the system yields less time to regain the original state with the proposed hGA-GSA algorithm compared to conventional GA and GSA optimization technique while a variation in the reference voltage (V_{Ref}) is considered.

3.6 Chapter Summary

The significant contributions of the research work presented in this chapter are:

1. Modeling of SMIB system installed with UPFC for the power system stability studies has been provided.
2. A systematic approach for designing a UPFC-based controller employing a new hybrid Genetic Algorithm - Gravitational Search Algorithm (hGA-GSA) has been presented.
3. The proposed hybrid GA-GSA algorithm is verified by using some standard benchmark functions.
4. It is seen from the simulation and the comparison of results that, GSA based algorithm provides a faster solution in terms of computational time for obtaining the optimum values. In this case, the time of computation increases almost linearly with

the generation number whereas in the case of hGA-GSA the time of computation exponentially increases with the generation number and in the case of hGA-GSA the system responses are much faster.

5. Studies show that the proposed hybrid algorithm based controllers are robust and perform satisfactorily under various disturbances over wide ranges of loading conditions.

3.7 Chapter:- 3 to Chapter:- 4

3.7.1 Problem Associated with the Linearized Model

The linearized models are the popular tools amongst power engineers for studying the dynamic behavior of synchronous generators, with a view to design control equipment. However, the model only takes into account the generator main field winding and hence these models may not always yield a realistic dynamic assessment of the SMIB power system with FACTS because the generator damping winding in q-axis is not accounted for. Further, linear models cannot properly capture complex dynamics of the system, especially during major disturbances. This poses difficulties for designing the FACTS controllers, because controllers designed to provide desired performance at small signal conditions do not guarantee acceptable performance in the event of major disturbances [26].

Chapter 4

Hybrid Particle Swarm Optimization and Gravitational Search Algorithm for the Coordinated Design of PSS and SSSC Based Damping Controller

4.1 Introduction

The major problem associated with an interconnected power system is the low-frequency oscillation when weak line is connected. If the damping of the system is not adequate, then these oscillations will lead to system separation. In industries to damp out these oscillations, generally, Power system stabilizers (PSS) are used [1]. However, the application of PSS is insufficient in some cases in order to provide sufficient damping when the loading on a long transmission line increases. For this purpose, other alternatives which may be effective are used in addition to the PSS.

Application of FACTS controllers have been the obvious choice for the power system engineers to address such issues. The main objective of the FACTS controller is to control the system parameter at a very fast rate, which can improve the system stability [2, 85]. The SSSC is considered to be a member of the FACTS family. The SSSC has a unique capability that it can change reactance from capacitive to inductive [35]. An auxiliary stabilizing signal is used here which can improve the system stability in a significant manner. This auxiliary signal is basically used in the control function of the SSSC [36]. The application of SSSC to improve stability and to damp out the system oscillation is discussed in [37-40].

Generally, a FACTS device is installed far away from the generator. On the other hand, PSS is installed near to the generator. Thus, a transmission delay is observed due to various signal transmission and sensors used in the powers system [44]. These delays should be included when designing a FACT/PSS based damping controller design. However in the above literature study, these time delays have not been considered. Also, the literature includes various algorithms such as residue method, linear matrix inequality technique, eigenvalue-distance minimization approach, and multiple model adaptive control approach, for the coordinated controller's damping enhancement. The key issue which need to be discussed in the coordinated design technique is to verify the robustness of the design approach. Very efficient and effective techniques are highly beneficial in order to design the robust controller which can change according to the system configurations.

''Heuristics from Nature'' is the most promising field in recent years which is basically an area which utilizes the analogies of nature or some social systems [46]. In the research community, these techniques are very popular and can be used as a research tool or design tool or a problem solver because they can optimize or solve the complex multi-modal non-differentiable objective functions [69]. In order to design a FACT based damping controller some new approaches or algorithms based on artificial intelligence have been proposed. These algorithms are genetic algorithm [13, 47, 64], differential evolution (DE) [32], particle swarm optimization (PSO) [48, 49, 79], modified particle swarm optimization [50, 51], bacteria foraging optimization [52, 53], multi-objective evolutionary algorithm [36, 54, 65] etc.

Recently Gravitational search algorithm (GSA) have been developed which utilizes the law of gravity and the concept of mass interaction [17]. In this approach, a random number of solution is taken as an initial population for the algorithm. Then in order to achieve the optimum solution, the generation number is varied/updated [33]. The various advantages of GSA algorithm are, ease of implementation, very simple concept and it is computationally very efficient [55]. Also, GSA provides better performance in solving a highly nonlinear function. Some modification has been done to GSA algorithm like adaptive GSA [32], opposition based GSA [48] in order to improve its efficiency. Although GSA provides some adequate result for optimizing a problem but is often problematic. This causes a large timing in the implementation of the algorithm and thus trapped in local optima [21]. In order to avoid the disadvantages of the particular algorithm, hybridization of GSA with another algorithm is implemented. The different hybrid algorithm is fuzzy-GSA [22, 56, 57], hGSA-GA [24].

In this chapter, the particle swarming principle is used with the GSA framework and the newly developed algorithm is termed as hybrid PSO-GSA (hPSO-GSA) algorithm. The hPSO-GSA is basically two concepts combined into one. The first concept is PSO's ability of social thinking ("gbest") and the second concept is GSA's local search capability [58, 59]. Simulation results show that the approach of swarming in hPSO-GSA increases its convergence efficiency and thus prevents being trapped into the local optima [60].

Further a comprehensive assessment of the effects of PSS and SSSC-based damping controller when applied coordinately has been carried out. The design problem of the proposed controllers to improve power system stability is transformed into an optimization problem. The hPSO-GSA based optimal tuning algorithm is used to optimally and simultaneously tune the parameters of the PSS and SSSC-based damping controller. The proposed hybrid based controller design approach has been applied and evaluated for both single-machine infinite bus and a multi-machine power system. The simulation results show that this hybrid algorithm is superior compared to the conventional GSA, PSO algorithm. Further, from the simulation result, it can be concluded that the proposed hybrid algorithm provides a better performance compared to the hBFOA-PSO algorithm for a similar problem. In view of the above advantages, hPSO-GSA algorithm is used in the proposed work in order to find an optimal and coordinated tuned damping controller.

The main objectives of the research work presented in this chapter are as follows:

1. To develop the Simulink based model for the SMIB and multi-machine power system installed with a Static synchronous series compensator (SSSC).
2. To test the effectiveness of the hybrid PSO-GSA algorithm for the coordinated design of PSS and SSSC based controllers.
3. To investigate the effect of potential time delays on the performance of various FACTS based controller
4. To compare the performance of proposed hPSO-GSA algorithm with the existing hBFOA-PSO and the conventional PSO and GSA algorithms.

5. To plot, compare and analyze the system response profiles of the system under study subjected to various disturbances and compare the simulation results with already existing modern heuristic optimization techniques for the same system under study.
6. To extend the study to a multi-machine power system.

4.2 The System Under Study

4.2.1 The Power System Modelling Installed with SSSC

At the first instant in order to verify the performance of the operation, an SMIB power system is taken into consideration. Fig. (4.1) shows the said structure of power system which is composed of a synchronous generator, an infinite bus, and an SSSC.

4.2.1.1 Modelling of Generator

In this analysis, all the dynamics associated with the stator, field and damper windings have been considered. The two axis reference frames (two-axis d–q frame) is used to express the quantity associated with the stator and the rotor.

The system equation of the above power system is given by [45]:

$$V_d = R_s i_d + \frac{d}{dt}\phi_q - \omega_R \phi_q \quad (4.1)$$

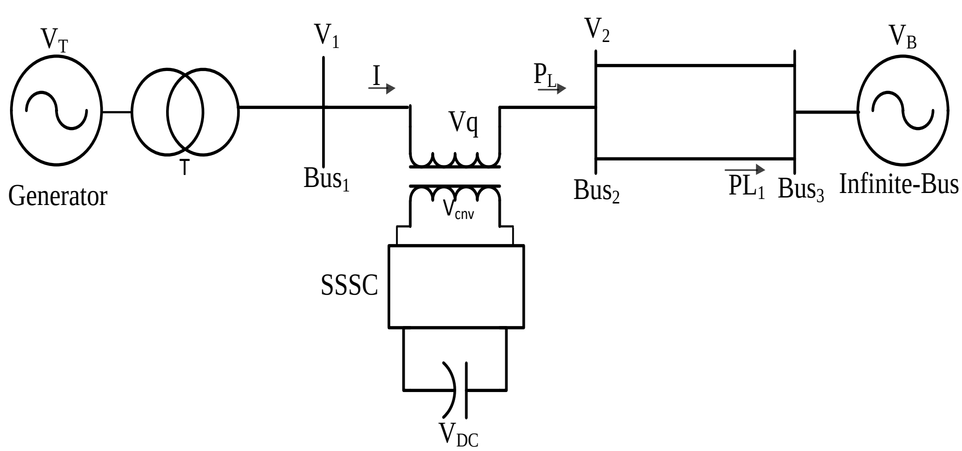


Figure 4.1: Single machine infinite bus power system with SSSC

$$V_q = R_s i_q + \frac{d}{dt}\phi_q + \omega_R \phi_d \tag{4.2}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\phi'_{fd} \tag{4.3}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\phi'_{kd} \tag{4.4}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\phi'_{kq1} \tag{4.5}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\phi'_{kq2} \tag{4.6}$$

Where:

$\phi_d = L_d i_d + L_{md}\left(i_{fd} + i_{kd}\right),\ \phi_q = L_q i_q + L_{mq} + i'_{kq}$,

$\phi'_{fd} = L'_{fd} i'_{fd} + L_{md}\left(i_d + i'_{kd}\right),\ \phi'_{kd} = L'_{kd} i'_{kd} + L_{md}\left(i_d + i'_{fd}\right)$,

$\phi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \phi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$

The different subscripts of the above equation are:

d represents d-axis and q represents q-axis quantities;

R represents rotor and S represents stator quantities;

f represents field and k represents damper winding;

l represents leakage and m magnetizing inductance.

Now the mechanical equations of the above system are given by

$$\frac{d}{dt}\omega_r = \frac{1}{J}\left(P_e - F\omega_r - P_m\right) \tag{4.7}$$

$$\frac{d}{dt}\theta = \omega_r \tag{4.8}$$

Where ω_r represents the rotor angular velocity and θ represents the angular position, P_e is the electrical power and P_m represents the mechanical power, J is the inertia of rotor and F is the friction of rotor.

4.2.1.2 Modelling of Transmission line

The role of the transmission line is to deliver power the produced in generating stations to loads. The transmission network is made up by the interconnection of a number of transmission lines which can be as long as several hundreds of kilometers. The most detailed mathematical description of a line is in the form of the partial differential equation, which takes propagation wave phenomena into account since power system stability usually involves slow oscillations and study time intervals of several seconds; this level of detail is often unnecessary. In commonly used models all transients associated with transmission lines are neglected and the network is assumed constantly in steady-state.

The Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron's traveling wave method used by the Electromagnetic Transient Program (EMTP). In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance $z_c = \sqrt{L/C}$ and the phase velocity $\gamma = 1/\sqrt{LC}$. Where L and C represents inductance and capacitance of transmission line per unit lengths. The model uses the fact that the quantity e+ Z i (where e is line voltage and i is line current) entering one end of the line must arrive unchanged at the other end after a transport delay. The system is modelled by lumping R/4 at both ends of the line and R/2 in the middle and using the current injection method of Sim-Power-Systems software.

4.2.1.3 Modelling of Excitation System

As the name suggests, the excitation system is basically responsible for the supply of the field current fed into the field winding. The excitation system must be able to automatically adjust and maintain the terminal voltage of the generator within its limitations. Within the overall excitation system, there are effectively 5 different subsystems. They are the following:-

1. Exciter
2. Regulator (AVR)
3. Terminal Voltage transducer and load compensator
4. Power System Stabilizer
5. Limiter and protective circuits.

Each of the subsystems has its function to perform and basic description is given below.
Exciter: This is an amplifier that provides the power to the field winding.

Regulator (AVR): Regulates the exciter in order to maintain a constant terminal voltage as well as to enhance transient stability by processing the input control signals and giving appropriate responses at the output.

Terminal Voltage transducer and load compensator: Transform the terminal voltage into d.c quantity and compares it with the desired reference voltage. Load compensation is also provided if the voltage to be maintained is not at the generator terminals.

Power System Stabilizer (PSS): Provides additional damping for system oscillations through an additional input into the regulator. The use of PSS is optional.

Limiters and protective circuits: Includes a wide range of devices offering protection from over-excitation, under excitation to volts-per-hertz protection in order to safeguard the synchronous machine. Also, the protection circuits such as the over and under exciter limiters are not utilized for short-term stability analysis such as transient and small-signal analysis. Hence, such circuits are usually not modeled in these studies. Therefore, modeling of such circuits will not be included in this report.

4.2.1.4 Modelling of SSSC

An SSSC is a solid-state voltage sourced converter (VSC), which generates a controllable AC voltage, and connected in series to power transmission lines in a power system. SSSC provides the virtual compensation of transmission line impedance by injecting the controllable voltage (V_q) in series with the transmission line. Vq is in quadrature with the line current and emulates an inductive or a capacitive reactance so as to influence the power flow in the transmission lines. The virtual reactance inserted by Vq influences electric power flow in the transmission lines independent of the magnitude of the line current [35]. The variation of V_q is performed by means of a VSC connected on the secondary side of a coupling transformer. The compensation level can be controlled dynamically by changing the magnitude and polarity of V_q and the device can be operated both in capacitive and inductive mode [45]. The VSC uses forced commutated power electronic devices to produce an AC voltage from a DC voltage source. A capacitor connected on the DC side of the VSC acts as a DC voltage source. To keep the capacitor charged and to provide transformer and VSC losses, a small active power is drawn from the line. VSC using IGBT-based PWM inverters is used in the present study.

4.3 The Proposed Approach

4.3.1 Structure of the PSS and SSSC- Based Damping Controller

Fig. (4.2) shows a damping controller structure which is basically used to control the voltage injected (V_q) by the SSSC. The change in speed deviation ($\Delta\omega$) is considered to be the input of the controllers and Vq is considered to be the output of the controller. The damping structure considered here consists of three blocks [18], namely gain block with gain K_s, signal washout block and two-stage phase compensation block as shown in Fig. (4.2). The signal washout block will serve as a high-pass filter and the appropriate phase-lead characteristics will be provided by the phase compensation block, with time constants T_{1S}, T_{2S}, T_{3S} and T_{4S}.

The structure of Power system stabilizer (PSS) is shown in Fig. (4.3). the output of the PSS (V_s) will be added to V_{ref} where V_{ref} is the excitation system reference voltage.

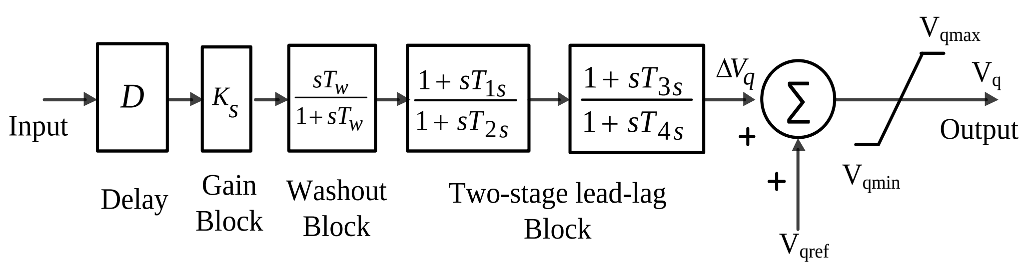


Figure 4.2: Structure of SSSC based damping Controller

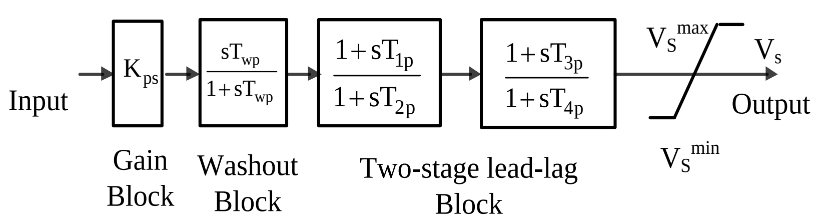


Figure 4.3: Structure of power system stabilizer

4.3.2 Concept of Time Delays in Power System

As far as the optical fiber communication is concerned, there is continues phasor measurement by the wide-area measurement system and this phasor measurement can be delivered to the control centers in real time. Thus, there is a chance of using remote signals in order to design the efficient control schemes. The biggest problem associated with these type of signal is the delay involved in the channel of the transmission line. Generally, a dedicated communication channel provides not more than 50 ms delay in any condition during transmission [44]. This time delay can cause the significance degradation in the performance of a particular transmission line. Therefore, these delays should be taken care of during the controller design. For PSS a time constant delay of 15 ms is considered and that for the damping controller 50ms is chosen with a 15 ms sensor delay [45, 86].

4.3.3 Optimization Problem

In the proposed work, $T_w=T_{wp}=10$ is taken which is generally pre-specified. In the steady state condition, ΔV_q seems to be zero and therefore, V_{qref} is constant, and during the dynamic condition, in order to damp out system oscillation, the injected voltage V_q is varied by applying some algorithm. In our study V_{qref} is assumed to be constant as the power flow loop during steady state operation is very slow. Thus, the effective value of V_q in dynamic condition is formulated as,

$$V_q = V_{qref} + \Delta V_q \quad (4.9)$$

The oscillation of a system can be seen through the speed deviation of the rotor, the power angle deviation or tie-line power. Minimization of any one of the above deviation can be viewed as research objectives. For the SMIB system an integral time absolute error (J) of the speed deviations ($\Delta\omega$) is considered to be the objective function and for the multi-machine, the same error of the speed signals of the local ($\Delta\omega_L$) and inter-area modes ($\Delta\omega_1$) of oscillations are considered. The above explanation can be summarized as:

Single machine infinite bus power system [21]:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| .t.dt \quad (4.10)$$

Multi-machine power system:

$$J = \int_{t=0}^{t=t_{sim}} \left(\sum |\Delta\omega_L| + \sum |\Delta\omega_1| \right).t.dt \qquad (4.11)$$

Where

t_{sim} = simulation time range.

For a stipulated period of time, the time domain simulation of the above power system is worked out and from the simulation, the objective function is evaluated. The prescribed range of the PSS and damping controller are limited in a boundary. Thus, the following optimization problem is formulated from the above design approach.

Minimize J (4.12)

Subject to

$$K_i^{min} \le K_i \le K_i^{max}$$
$$T_{1i}^{min} \le T_{1i} \le T_{1i}^{max}$$
$$T_{2i}^{min} \le T_{21i} \le T_{2i}^{max}$$
$$T_{3i}^{min} \le T_{3i} \le T_{3i}^{max}$$
$$T_{4i}^{min} \le T_{4i} \le T_{4i}^{max} \qquad (4.13)$$

Where

K_i^{min} is the lower bound of the gain

K_i^{max} is the upper bounds of the gain for the controllers (PSS and Damping Controller).

T_j^{min} is the lower bound of the time constants

T_J^{max} is the upper bounds of the time constants for the controllers (PSS and Damping Controller).

Again the SMIB system is composed of a PSS and a damping controller. Therefore, the two gains and eight number of constant parameters needs to be optimized. Again in the case of a multi-machine power system, parameter needs to be optimized are damping controller gain and multiple PSSs which is equal to the number of generators and the corresponding time constants.

4.4 Hybrid Particle Swarm Optimization & Gravitational Search Algorithm (hPSO-GSA)

4.4.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is one of the very popular method. In this algorithm, each individual can be represented by a particle which represents a candidate solution [48]. In PSO each particle moves with a velocity and this velocity is modified in accordance with the own velocity which of other particles. Here "pbest" is the position corresponds to the best fitness and "gbest" is the best in the population out of all particles.

4.4.2 Gravitational Search Algorithm (GSA)

ravitational Search Algorithm (GSA) is one of the newest heuristic algorithms. This algorithm is inspired by the Newtonian laws of gravity and motion. In GSA each agents are considered as objects and the performance is measured by their masses. By the force of gravity, all these objects attract each other and the force of gravity causes a global movement of all objects towards the objects with a heavier mass. Hence by using gravitational force all the masses co-operate using a direct form of communication. The heavy masses move more slowly than lighter ones, which correspond to good solution this guarantees the exploitation step of the algorithm [33].

4.4.3 Hybrid Particle Swarm Optimization and Gravitational Search Algorithm (hPSO-GSA)

The hybrid PSO and GSA algorithm use the concept of PSO and GSA algorithm, thus holds the advantages of both the algorithms. This technique deals with the ability of social thinking of PSO and local search ability of GSA algorithm [58].

The combination of this two algorithm can be summarized as follows:

$$V_i\left(t+1\right)=w*V_i\left(t\right)+c_i^{'}*rand*ac_i\left(t\right)+c_2^{'}*rand*\left(g_{best}-X_i\left(t\right)\right) \tag{4.14}$$

Where V_i (t) represents 'i' agent velocity at 't' iteration, w is a weighting function, 'c_j' is a weighting factor, ac_i (t) is the acceleration of agent 'i' at iteration 't', rand is a random number between 0 and 1, 'gbest' is the best solution so far.

To update the positions of each individual particles, the following expression can be used:

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (4.15)$$

In the first step of hPSO-GSA, there is a random initialization of all agents and this agent is treated to be a candidate solution [59]. Once the initialization is completed, the calculation of different forces and constants among the agents is carried out. The different constants which need to calculate are gravitational constant, gravitational force, resultant forces etc. Then each particle's accelerations is computed using the GSA algorithm. The best solution so far achieved should be updated in each iteration. Finally, the velocity and the position of all the agents can be found out using the Eqs. (4.14) and (4.15). The updating process will stop after the criteria for the velocities and position satisfy the end criterion. Fig. (4.4) shows the flow chart for the proposed hPSO-GSA algorithm.

In order to improve the efficiency of the hPSO-GSA algorithm, some strategy has to be carried out. For the updating process, the fitness is taken into account. The agents which are near to the good solution attract the other agents and hence the search space is explored. The agents move very slowly when they try to reach a good solution. The 'gbest' is mainly responsible for exploiting the global best. The "gbest" is a memory which is used to save the best solutions so that it can be accessible at any moment of time. A balance can be obtained by adjusting the 'c_1' and 'c_2' between the global search and the local search ability.

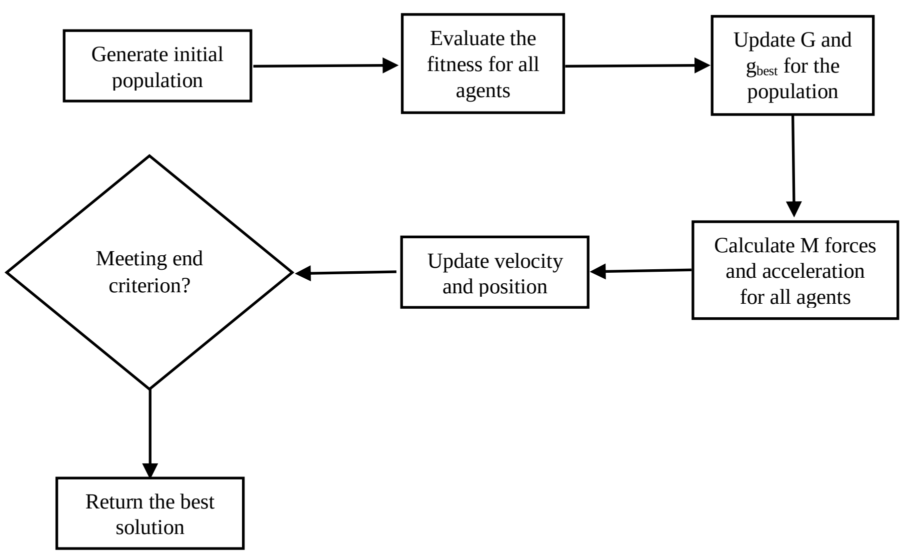


Figure 4.4: Flow chart for the proposed Hybrid PSO-GSA Algorithm

In order to find the optimal values of the parameters for the controllers under some constraints, the hybrid particle swarm optimization algorithm and gravitational search algorithm (hPSO-GSA) can be described as follows:

- Step 1: The input data including the hPSO–GSA parameters are defined and then randomly initialized the position of each particle $X_i = \{x_{i1}, x_{i2} \ldots\ldots\ldots\ldots\ldots\ldots.. x_{im}\}$ under the above constraints (Eq. 4.13). Here, "m" is the dimension of each particle.
- Step 2: Evaluate the fitness function of each particle "$F_i(t)$" at t iteration.
- Step 3: Calculate the g_{best} using PSO, inertial mass by using the gravitational search algorithm.
- Step 4: Evaluate the gravitational force and acceleration as per gravitational search algorithm.
- Step 5: Update the velocity and position of each particle as per Eq. (4.14) and Eq. (4.15) respectively.
- Step 6: At each iteration the position of the particle should be maintained within the prescribed range.
- Step 7: Increase the iteration counter.
- Step 8: Repeat step 2 to step 6 until the termination condition is satisfied.

Therefore, the control parameters for the above system are generated randomly and these values lie within some prescribed ranges, which can be updated successfully by using an hPSO-GSA algorithm to minimize the objective function (J).

4.5 Result and Discussion

To design and simulate the PSS and damping controller, the Sim-Power Systems (SPS) toolbox has been used [60]. In order to design the Simulink model of any power system, SPS is generally used which is basically an MATLAB-based platform. A block called 'Powergui' of SPS provides a graphical user interface (GUI) tool which can analyze the developed models. The purpose of this block is, to carry out the load flow analysis of the system and to initialize the parameters of the machine in the steady state.

4.5.1 Single Machine Infinite Bus Power System

The developed MATLAB/SIMULINK SMIB power system model with SSSC is (shown in Fig. (4.1)) is shown in Fig. (4.5). The said power system is composed of a generating unit which is connected to a transmission line. This transmission line is basically a double-circuit parallel line. A 3-phase step-up transformer and an SSSC is connected in between the generator unit and transmission line. The ratings of all the components are given in Appendix 1. The Sim-Power Systems (SPS) of the MATLAB/SIMULINK environment is used in order to develop the said power system example. Considering a disturbance the above developed model is simulated and simultaneously the objective function calculation is carried out. For finding the parameters of the controller, Eq. (4.10) is considered by minimizing its fitness value. For fitness calculation, the Simulation study is carried out on an Intel (R) Core (TM), 2 G.B RAM computer, with the MATLAB environment by considering the above algorithms. In order to solve Eq. (4.10), the hPSO-GSA algorithm is used.

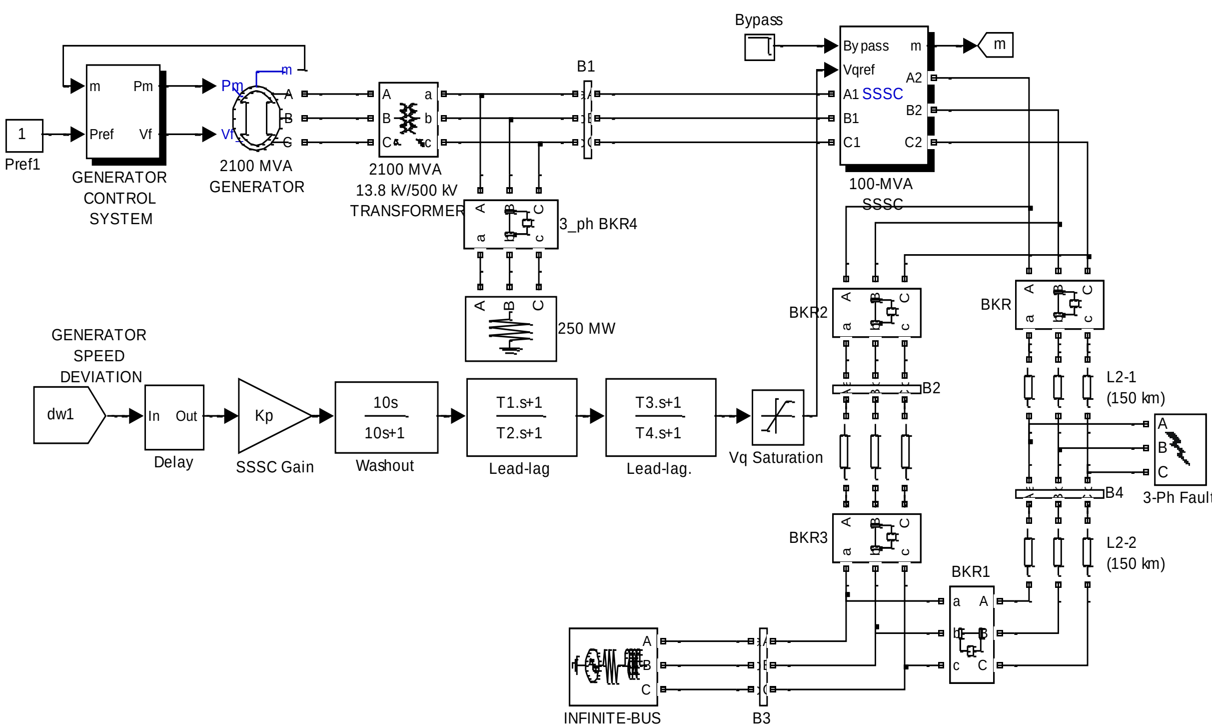


Figure 4.5: MATLAB/SIMULINK model of SMIB power system with SSSC

Table 4.1: Optimized Controller Parameters Using hPSO-GSA

	K_T	T_1,T_2	T_3,T_4	Min	Max	Avg.
Damping Controller	67.871	0.4232,0.146	0.296,0.349	$1.275*10^{-4}$	$1.881*10^{-4}$	$1.564*10^{-4}$
Power System Stabilizer	4.0771	0.496,0.109	0.101,0.740			

Table 4.2: Optimized Controller Parameters Using GSA

	K_T	T_1,T_2	T_3,T_4	Min	Max	Avg.
Damping Controller	55.772	0.798,0.503	0.984,0.566	$1.529*10^{-4}$	$1.981*10^{-4}$	$1.726*10^{-4}$
Power System Stabilizer	11.904	0.907,0.998	0.862,0.678			

Table 4.3: Optimized Controller Parameters Using PSO

	K_T	T_1,T_2	T_3,T_4	Min	Max	Avg.
Damping Controller	53.052	0.741,0.424	0.556,0.657	$1.745*10^{-4}$	$1.956*10^{-4}$	$1.812*10^{-4}$
Power System Stabilizer	12.655	0.637,0.245	0.956,0.574			

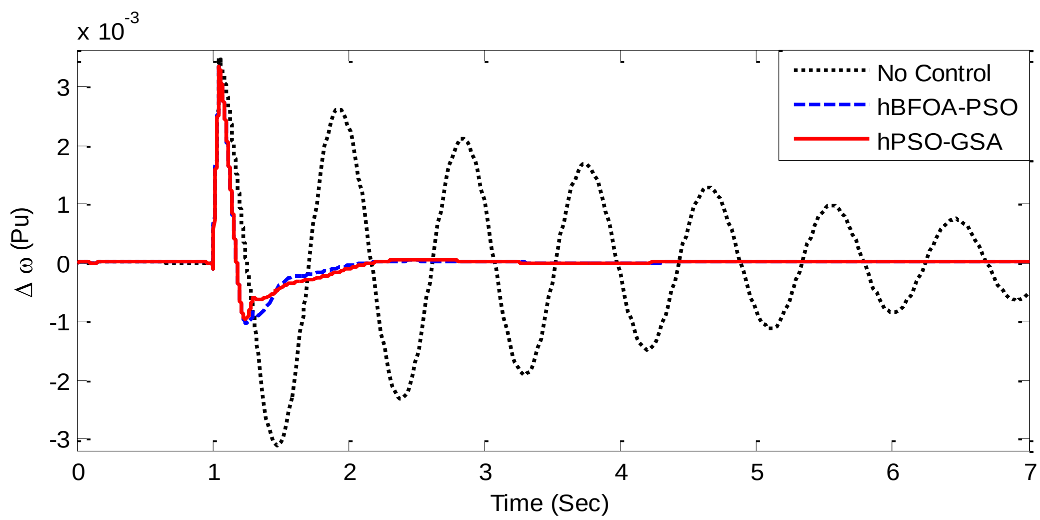
For the application of PSO, GSA and hPSO-GSA the following settings have been used. In case of PSO: swarm size=30, c_1=2, c_2=2, w is decreased linearly from 0.9 to 0.2, maximum iteration=50, and stopping criteria=maximum iteration. For GSA and hPSO-GSA c_1'=0.5, c_2'=1.5, population size=30, max. iteration=50, G_0=1, α=20,and when the iteration reaches the maximum count, the simulation stops [62].

Tables (4.1- 4.3) represent the best-optimized value using hPSO-GSA, GSA and PSO. The abbreviation K_T, T_1-T_4, Min, Max and Avg. used in the tables are the gain, time constants of the controller, minimum fitness, maximum fitness, and an average fitness of the system respectively. From the tables, it can be concluded that statistically the hPSO-GSA provides a better result in terms of objective function and optimized parameter values. Further, it can be concluded that, by adopting this hybrid algorithm the probability of being trapped in local optimum can be reduced to a great extent. This new algorithm is good at finding the global minimum. Moreover, it shows good convergence speed near minimum since it utilizes the social concept of the best individual at each generation. From Table 4.1, it can be inferred that the hPSO-GSA algorithm compared to PSO and GSA algorithm provides the minimum fitness and hence justifies the application of the hPSO-GSA algorithm. For one particular system disturbance, the above controller is designed at a nominal operating condition.

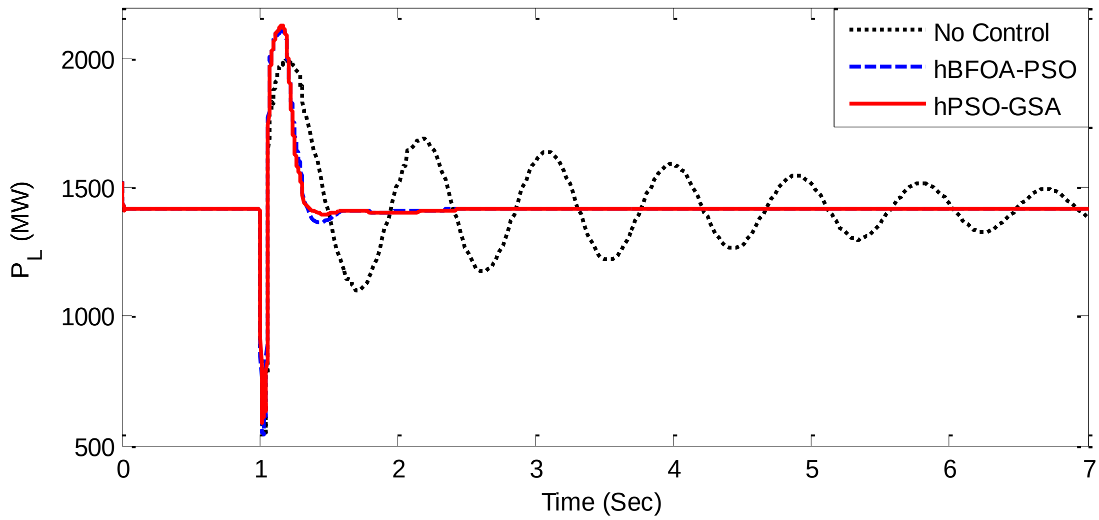
Some different loading conditions are taken into account for the study and the simulation is carried out by considering some fault clearing sequences. The hybrid PSO-GSA algorithm is compared with the conventional GSA and PSO algorithm by considering the system disturbance. The results obtained from the simulation have been shown as, the dotted line with legend 'No Control' representing the response of the system without any controller and the legend 'hPSO-GSA' with a solid line represents the system response for the above coordinated design. For the sake of comparison, the response of the system is compared with a recent hybrid BFOA-PSO algorithm which is shown with a caption 'hBFOA-PSO' [45].

4.5.1.1 3-Phase Self-Clearing Fault Created with Nominal Loading

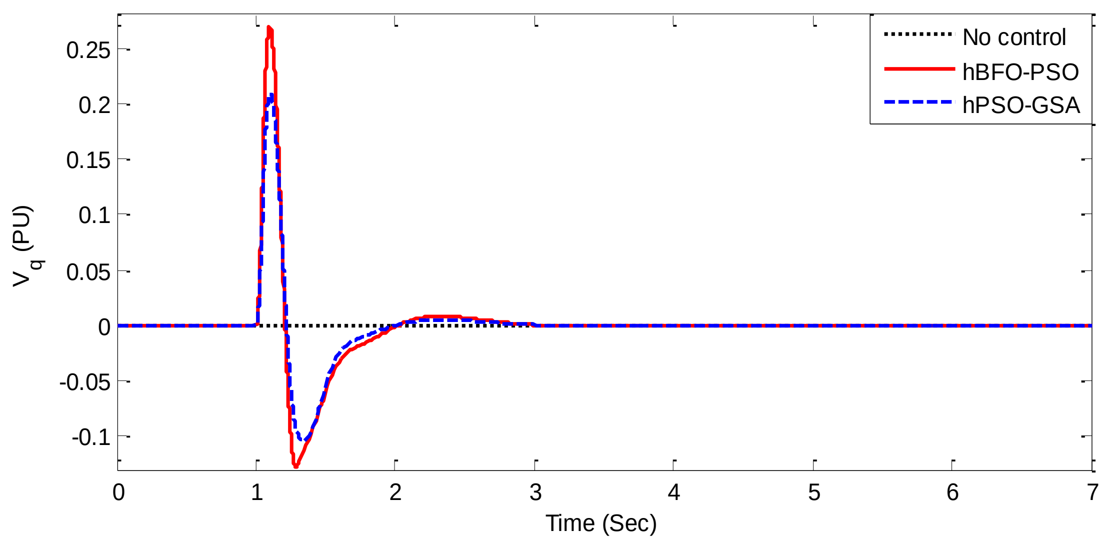
At nominal loading i.e. P_e=0.8 pu and δ_0=48.4^0, the behavior of the controller is tested by considering a severe disturbance. At t=1 sec a 3 cycle 3 phase fault applied in the line connecting bus-2 and bus-3 and after the fault is cleared the system is restored. The various system responses like speed deviation Δω in pu, tie-line power PL in MW, SSSC injected voltage Vq is shown in Figs. 4.6 (a-c). From the responses, it can be concluded that the system goes to an oscillatory stage without any controller under this disturbance.



(a)



(b)



(c)

Figure 4.6: System response for the nominal loading case (a) Speed deviation, (b) tie-line power (c) SSSC injected voltage

Further, from Figs. 4.6 (b-c), it can be seen that the above said controller delivers a better performance as far as the real power flow and the injected voltage to the system is concerned, as compared to the hBFOA-PSO algorithm as in [15], which validates and opens up new avenues for the application of a hPSO-GSA algorithm for further study.

Fig. (4.7) shows the system variation with time delays. A wide range of delay is taken into consideration. It can be concluded that the response slightly deteriorates when there is an increase in transport delays in the presence of the proposed controller but the system responses improves if there is a decrees in the delay.

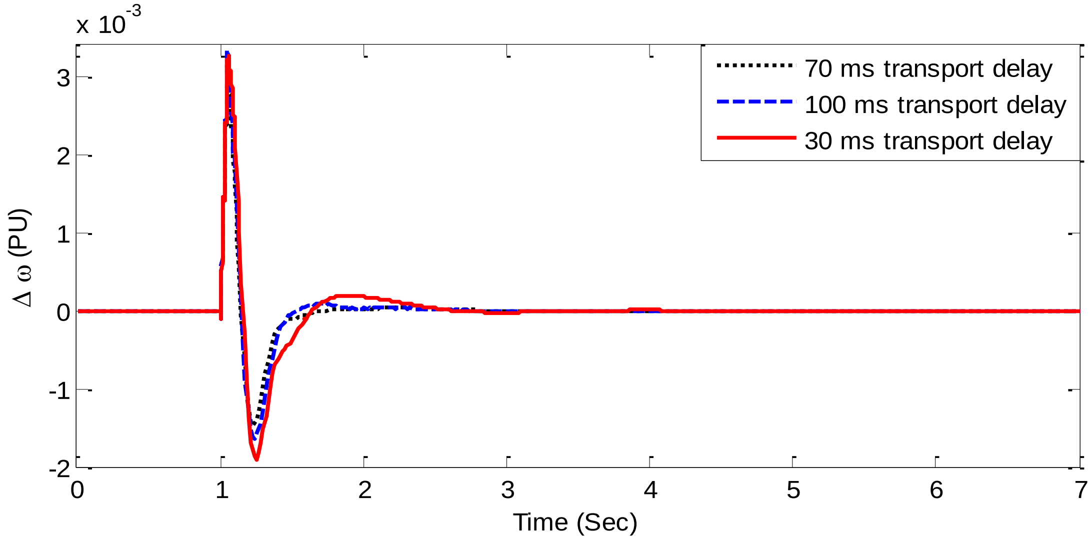


Figure 4.7: Speed deviation response of the system with a variation of signal transmission delays.

4.5.1.2 3-Phase Fault Cleared by Line Tripping with Light Loading

For the next instance, the loading condition is changed from nominal to light loading i.e. P_e=0.5 pu and δ_0=29.47^0 and a 3-cycle, the 3-phase fault is considered near to bus-3.

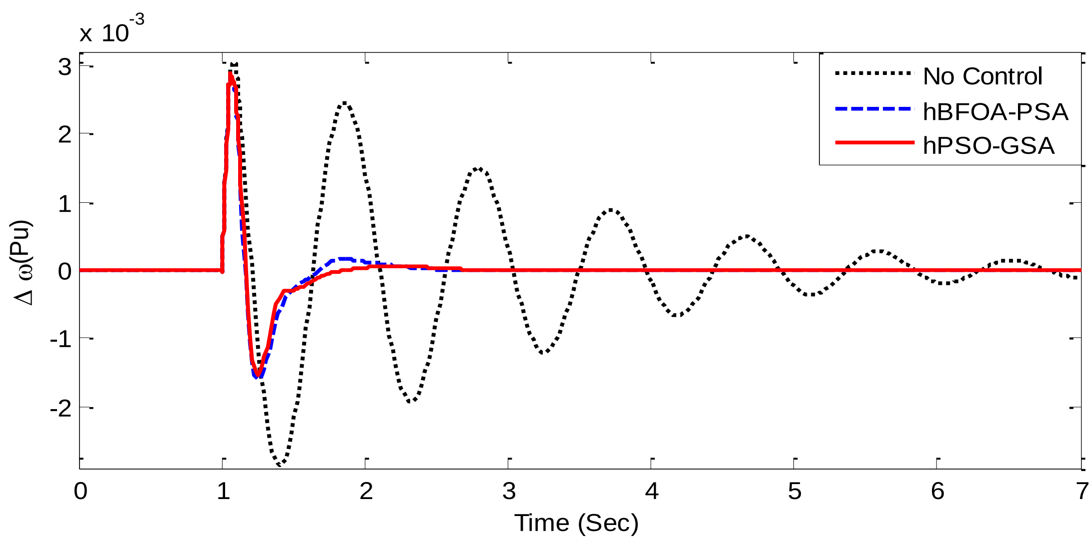


Figure 4.8: Speed deviation response for a 3 phase fault with light loading condition

The faulty line is opened and after 3-cycles, the fault is cleared. Fig. (4.8) shows the system response under this contingency. The response curve clearly shows that the proposed controller is very effective for the change in the operating system and the new fault location. Fig. (4.8) clearly demonstrates that the controller applying hPSO-GSA algorithm provides the better result as compared to the published hBFOA-PSO algorithm.

4.5.1.3 Small Disturbance Applied at Heavy Loading Condition

Now finally, at heavy loading condition i.e. P_e=1.0 pu and δ_0=60.73^0 the performance of the controller is evaluated. In this condition, the load at bus-1 is disconnected at t=1sec for a period of 100 msec. To validate the robustness of the proposed algorithm, it is compared with the existing algorithms like particle swarm optimization (shown with the legend 'PSO') and gravitational search algorithm (shown with the legend 'GSA'). Fig. (4.9) shows the system speed deviation response under such condition. From this figure, it is observed that the proposed controller is very much effective for the new operating condition and the change in the power system configuration. Further, the hPSO-GSA based controller provides more stable performances compared to other controllers.

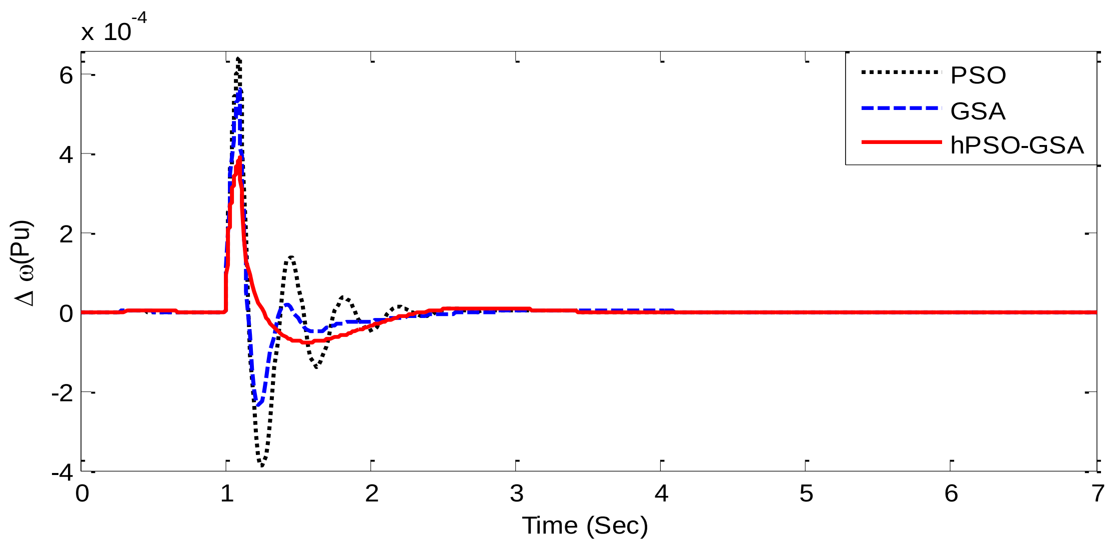


Figure 4.9: Speed deviation response for a small disturbance with heavy loading condition

4.5.2 Extension to three-machine six-bus power system

Fig. (4.10) shows the extension of the above coordinated single machine infinite bus approach to a two are multi-machine power system. This power system is similar to the power system as in Refs. [4, 6, and 15]. This system mainly consists of three no. of generators. These three generators are arranged in such a manner that two subsections are created. These two sections are connected to each other through a tie-line. When any disturbance occurs, there will be a swinging of the two systems, which causes an instability. At the mid-point of the tie-line an SSSC is installed which can improve the system stability and each of the generators are connected to PSS. Appendix 2 shows all the data related to the above system.

As explained for an SMIB system earlier, the same approach is continued in order to optimize the coordinated PSS and damping controller for the multi-machine case. The speed deviations of generators G_1 and G_3 is considered as the input to the PSS as well as to the damping controller. The MATLAB/SIMULINK based multi-machine power system modeling is shown in Fig. (4.11). Different optimized values obtained the damping controller and PSS, by applying the hPSO-GSA algorithm are shown in the table (4.4).

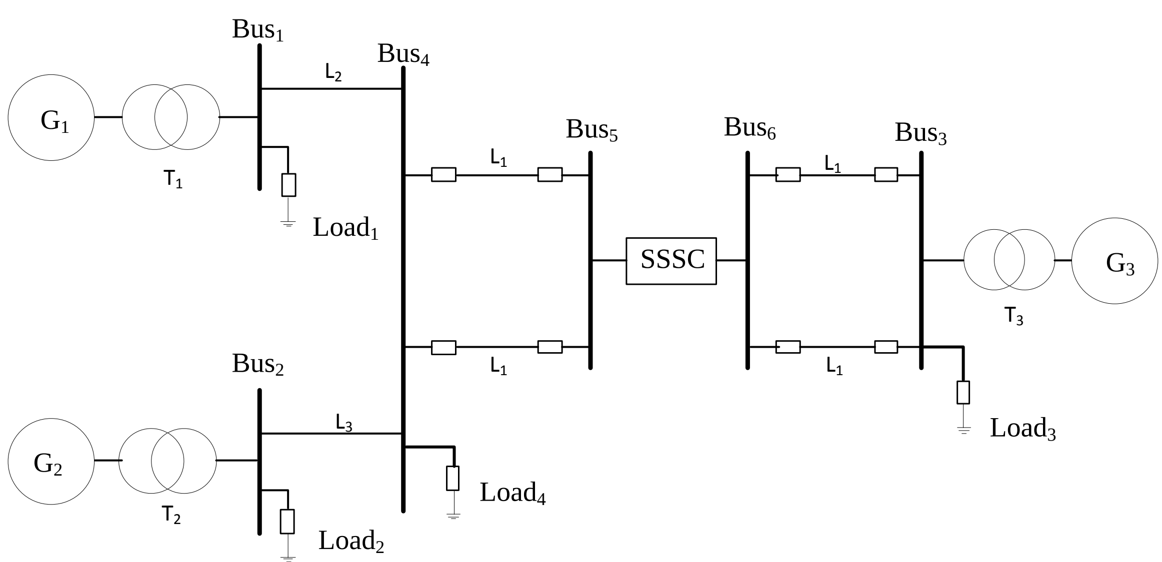


Figure 4.10: An example of a three (3) machine six (6) bus power system

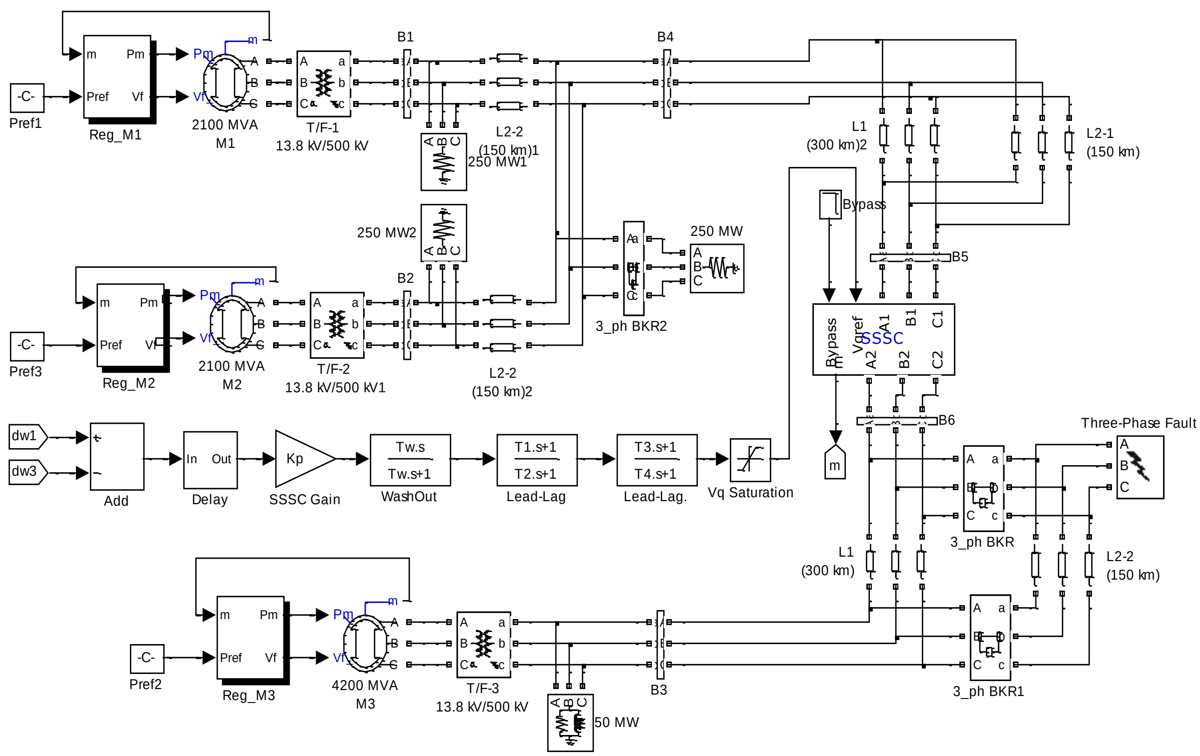


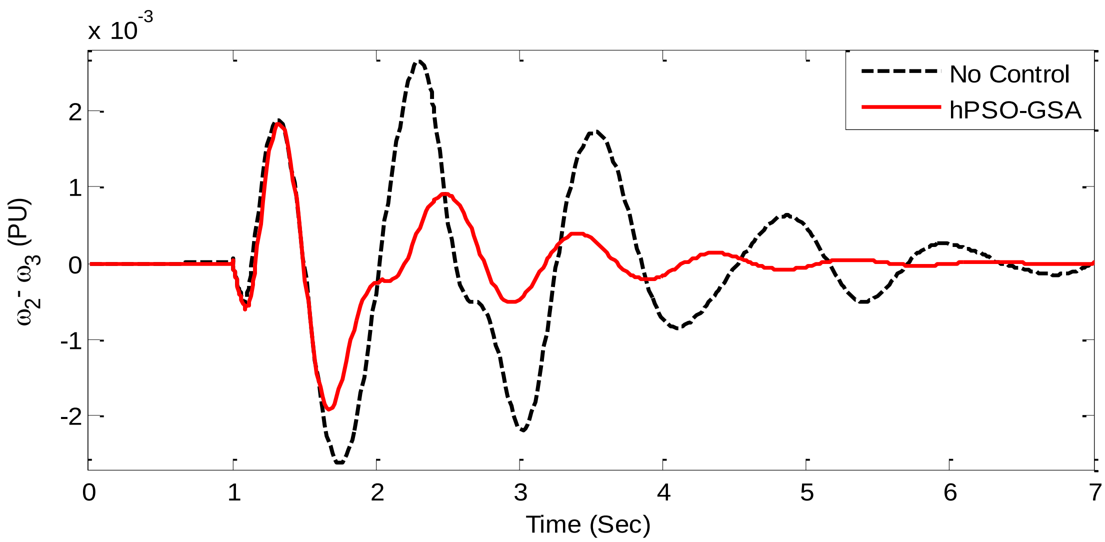
Figure 4.11: Developed multi-machine MATLAB/SIMULINK Model power system with SSSC

Table 4.4: Optimized Controller Parameters for the multi-machine power system using hPSO-GSA

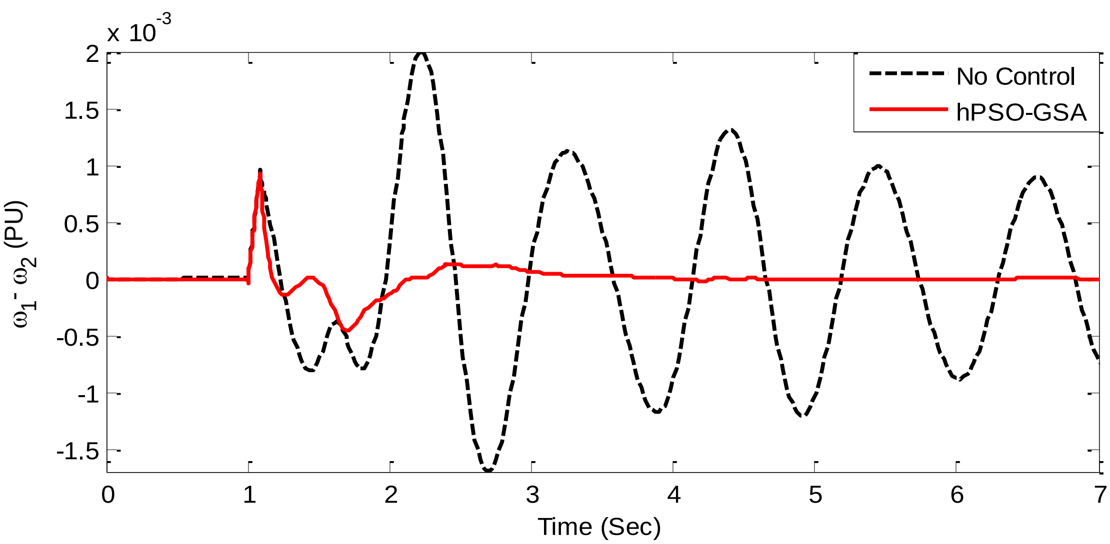
	K_T	T_1,T_2	T_3,T_4	Min	Max	Avg.
Damping Controller	101.0779	0.0744,0.1120	0.7999,0.4878	$10.1535*10^{-2}$	$24.1508*10^{-2}$	$18.4645*10^{-2}$
Power System Stabilizer-1	8.1304	0.2972, 0.110	0.7196,0.1130			
Power System Stabilizer-2	4.0127	0.7439,0.4546	0.3608,0.7990			
Power System Stabilizer-3	5.1381	0.1123,0.1112	0.8839,0.1905			

4.5.2.1 3-Phase Fault Disturbance

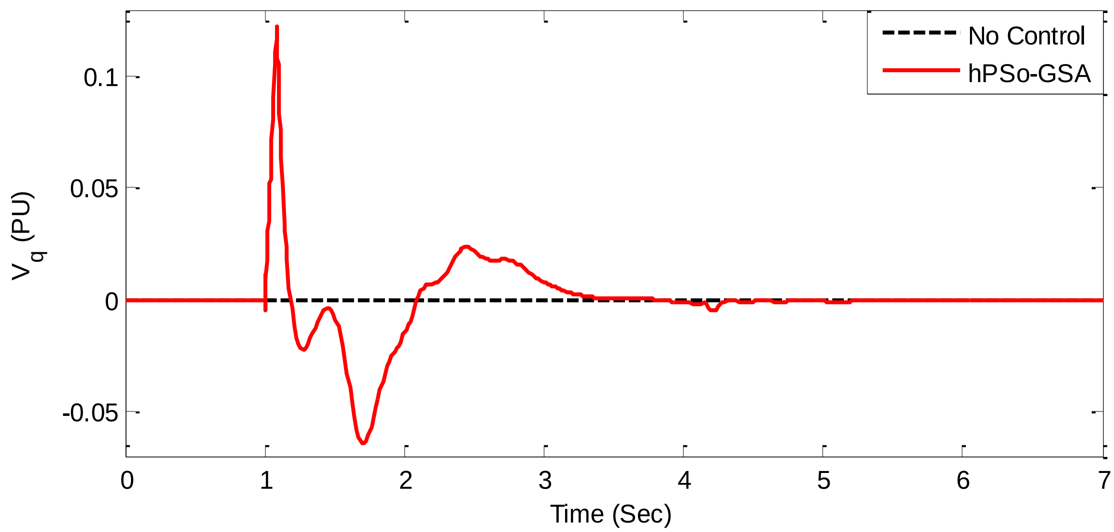
In this case at t = 1 sec, in between bus 1 and bus 6 a 3-cycle, 3-phase self-clearing fault is applied near bus 6. After the fault is cleared the previous original section is restored. Figs. (4.12 (a–c)) represent the system responses with this type of disturbance. These figures clearly demonstrate that both the responses are oscillatory in nature if the controllers are not present in the system. The system response without any controller is represented in a dotted line with legend 'No Control' and in order to represent the proposed hPSO-GSA optimized PSS and damping controller a solid line with legend 'hPSO-GSA' is given. By modifying the stabilizing signals and injected voltage of PSS and SSSC simultaneously, the response of the power system is significantly improved.



(a)



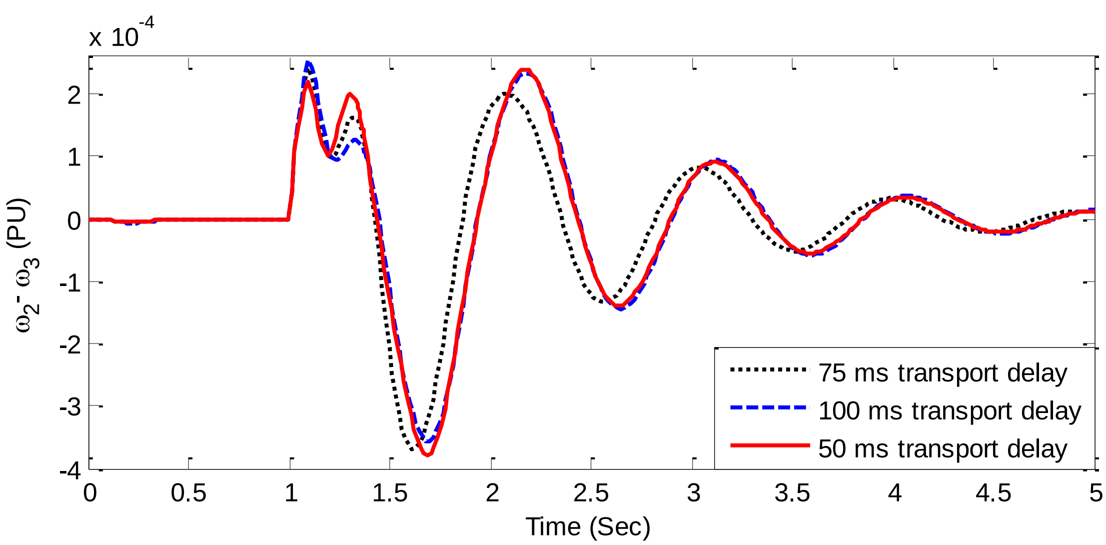
(b)



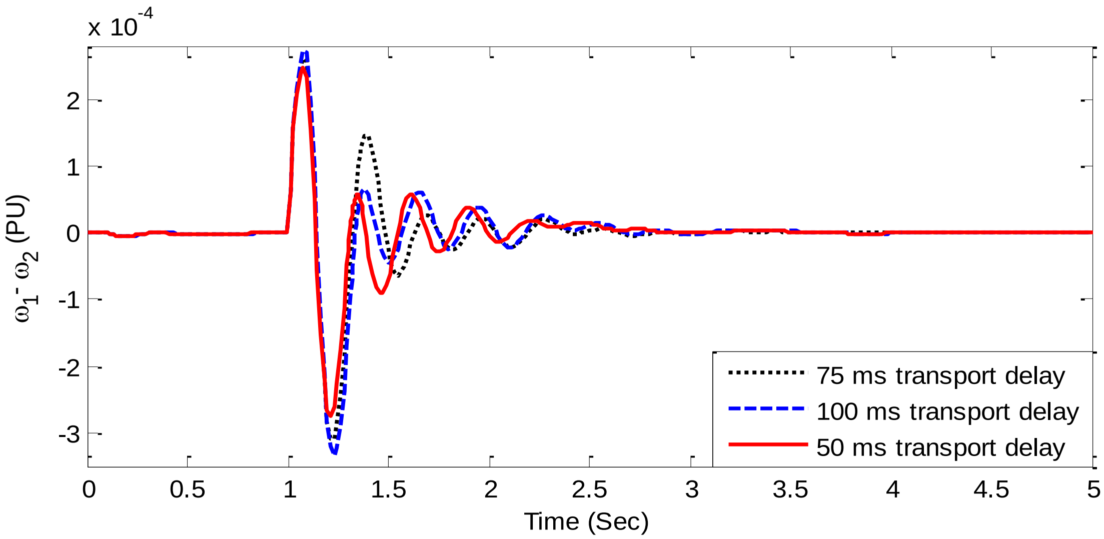
(c)

Figure 4.12: Response of the system variation (a) Inter-area mode of oscillations, (b) local mode of oscillations and (c) SSSC injected voltage, response with a 3-phase fault disturbance

Again using signal time delays the effectiveness of the Coordinated PSS is verified for the above disturbance. A wide range of time delay is taken into consideration as in the previous case. Figs. (4.13 (a-b)) show the responses of the system and it can be concluded that the effect is almost negligible with the variation of the time delays.



(a)

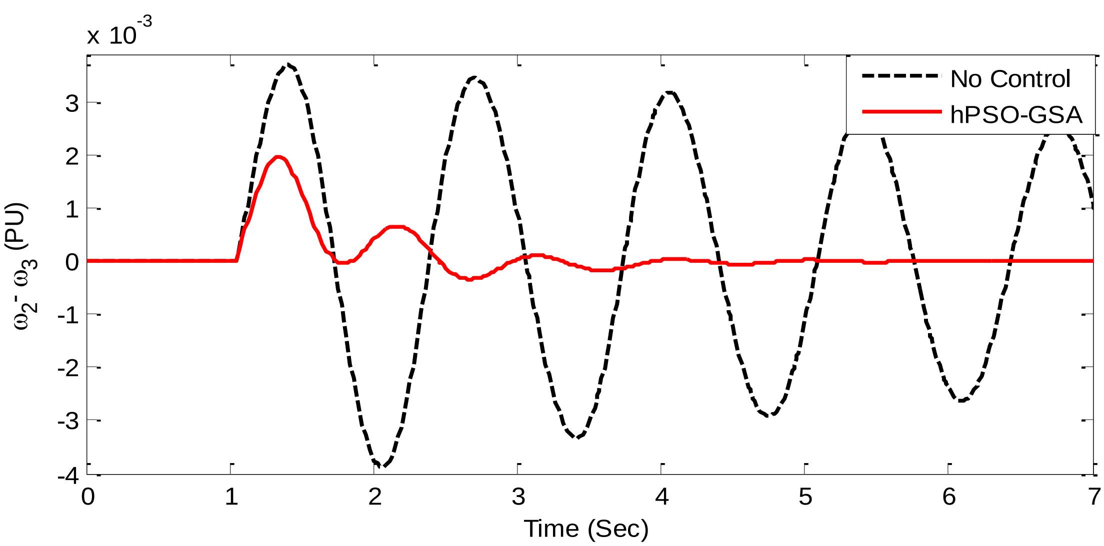


(b)

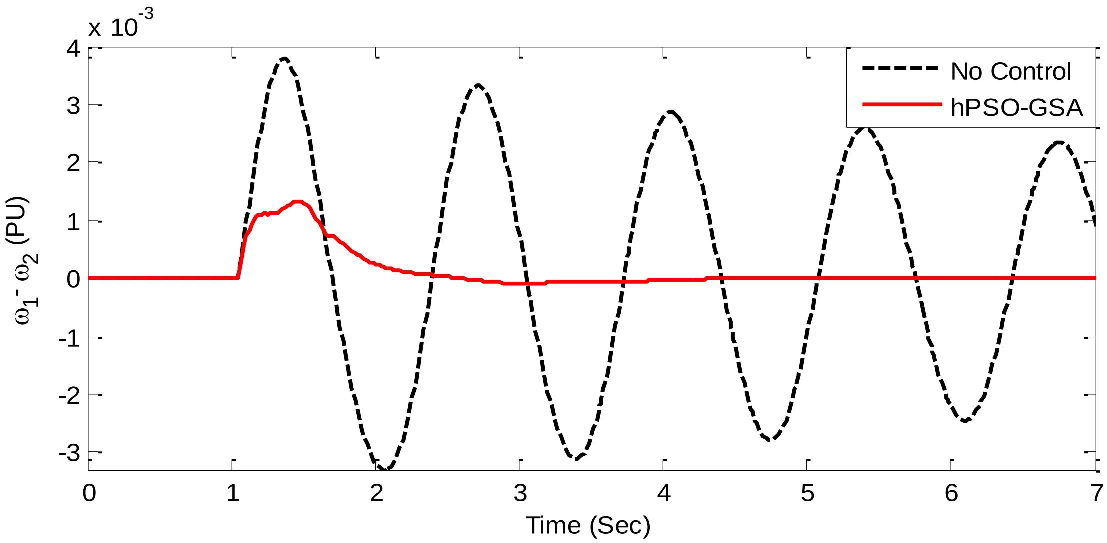
Figure 4.13: Response of the system variation (a) Inter-area mode of oscillations and (b) local mode of oscillations with signal transmission delays

4.5.2.2 Line Outage Disturbance

The 2nd disturbance considered is that, at t=1 sec. between bus 1 and bus 6 one of the parallel transmission line is tripped off. After the operation of the line reclosure, the previous system is restored in almost 3-cycles. The response of the above system is shown in Figs. (4.14 (a-b)).



(a)

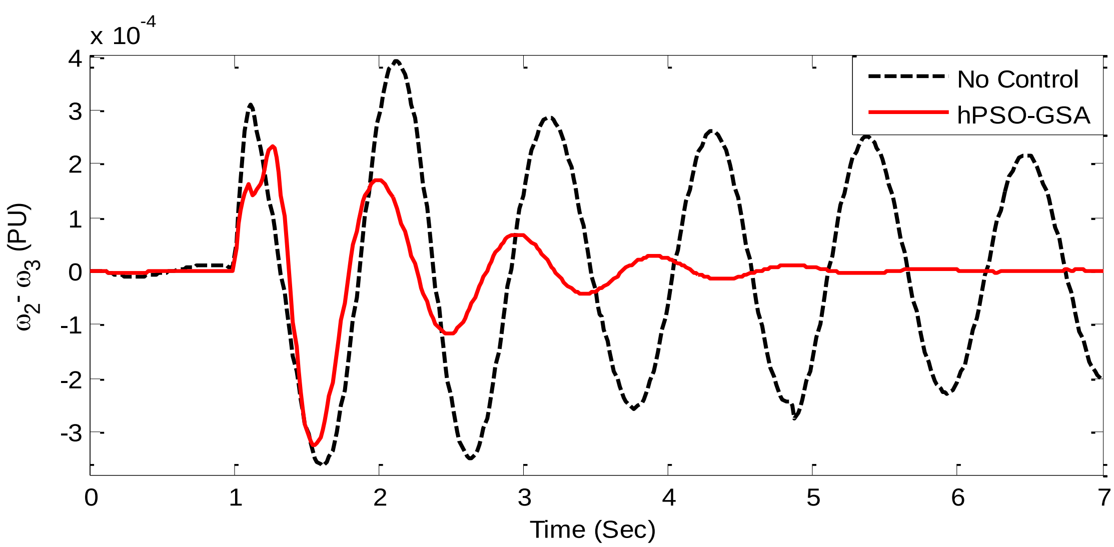


(b)

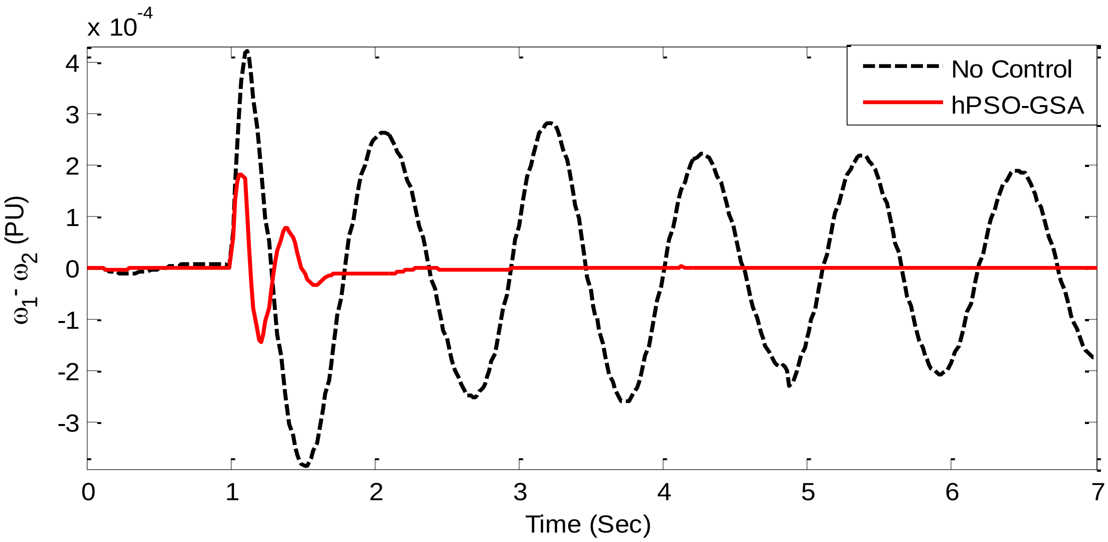
Figure 4.14: Response of the system variation (a) Inter-area mode of oscillations and (b) local mode of oscillations response for a line outage disturbance

4.5.2.3 Small Disturbance

The last disturbance considered for the above power system is that at t=1 sec, the load at bus 4 is taken out for a period of 100ms. This disturbance can be treated as a small disturbance. The responses are shown in Figs. (4.15 (a- b)). From the figures, it can be concluded that the proposed controller provides efficient and robust damping under small and all other disturbances.



(a)



(b)

Figure 4.15: Response of the system variation (a) Inter-area mode of oscillations and (b) local mode of oscillations response with a small disturbance

4.6 Chapter Summary

The significant contributions of the research work presented in this chapter are:

1. Modelling of SMIB as well as the multi-machine power system installed with SSSC for the power system stability studies has been provided.
2. An investigation is carried out for the stability improvement of the coordinate (PSS and damping controller) controller design power system.
3. The hybrid particle swarm optimization-gravitational search algorithm (hPSO-GSA) is employed for the SSSC-based coordinated controller design.
4. To prove the effectiveness of the coordinated structure, different results and simulation figures are demonstrated for various disturbances.
5. The superiority of the proposed hPSO-GSA algorithm has been demonstrated by comparing the results with hybrid BFOA-PSO and the conventional PSO and GSA algorithms
6. Finally, the extension of the above design approach to the multi-machine power system is carried out. Simulation results conclude that the above proposed control mechanism is very much adaptive for the application to the power system.

4.7 Chapter:- 4 to Chapter:- 5

4.7.1 Verification of Different Types of Input Signal to the FACT Based Damping Controller.

In the design of a robust damping controller, selection of the appropriate input signal is a major issue. Input signal must give correct control actions when a disturbance occurs in the power system. Both local and remote signals can be used as a control. Most of the available literature on damping controller design are based on either local signal or remote signal. It has been reported in the literature that from power system stability improvement point of view remote signal is a better choice than the local signal. Local control signals, although easy to get, may not contain the desired oscillation modes. So, compared to wide-area signals, they are not as highly controllable and observable. But, to avoid additional costs associated with communication and to improve reliability, input signal should preferably be locally measurable. Therefore, a new modified local input signal is used to calculate an equivalent remote speed deviation and the modified signal is used as the input signal to the SSSC-based controller.

Chapter 5

Application and Comparison of Different Input Signal for the SSSC Based Damping Controller

5.1 Introduction

Low-frequency oscillation seems to be a major problem associated with an interconnected power system having by a weak tie-line. If the damping of the system is not adequate, then it leads to system separation. In fact, such a situation occurs during a change in the loading condition of the transmission line [80]. Recently Flexible A.C. transmission system (FACTS) based controller is used in the power system to enhance the system stability [70]. The SSSC is a primary member of the FACTS family which is used to improve the system damping. The key feature of the SSSC is that it can modulate its reactance such that the effective value can span from capacitive to inductive [35]. In order to improve the system stability, an auxiliary stabilizing signal is used in the control function of SSSC [37]. The application of the SSSC to improve the system stability has been reported [39].

In the power system utilities, preference is always given to the conventional lead-lag controller because it is used to mitigate the system oscillation. These controllers are the obvious choice as, the online tuning of its parameters can be done with much ease [38, 21].

The parameter tuning of a FACTS based controller is a tedious process. In the literature some of the conventional techniques have been reported pertaining to the design problem. These are gradient search procedure and mathematical programming for function optimization, the eigenvalue value analysis and also some of the modern control theory. The problem associated with the techniques are time-consuming as they are iterative, and the convergence rate to a steady state is very slow. And moreover these are very much susceptible to be trapped into local minima; thus, the solution is not optimal [74].

In the recent years, a new tool has been developed which seems to be the most promising field known as ‘‘Heuristics from Nature". This mainly utilizes the different analogies of nature and some social system [46]. These techniques seem to be very popular in the research community as these can be used as a design tool or research tool or a problem solver because these techniques successfully optimize or solve various complex multi-modal non-differential objective functions. Some of the new algorithms based on the artificial intelligence have been developed are genetic algorithm [47], differential evolution [32], particle swarm optimization [48, 49], modified version of particle swarm optimization [77, 78], bacteria foraging optimization [52], multi-objective evolutionary algorithm [54, 66, 68] etc.

Recently a new and promising algorithm has been developed known as gravitational search algorithm (GSA) which utilizes the concept of the law of gravity and the mass interaction principle [17]. GSA algorithm is better in terms of, easy to implement, uses a simple concept, and it is very efficient as far as computational work is concerned [33]. To improve the performance of the GSA algorithm, many modified versions have been developed such as adaptive GSA [19], opposition based GSA [20] etc. Although the GSA algorithm gives a better performance for solving a nonlinear function, it has its limitations. This algorithm involves in considerable computational time and has a tendency to be trapped into local optima [18]. It is expected that the disadvantages associated with the GSA can be alleviated by hybridizing it with other algorithms.

Here the particle swarming principle has been used with the framework of GSA and thus forms an algorithm, known as hybrid PSO-GSA (hPSO-GSA) algorithm [58, 59]. Two basic concepts have been used to develop the hybrid algorithm. First is the ability of social thinking (“gbest”) of PSO and the second is the ability of local search of GSA [23]. Simulation results show that the approach of swarming in hPSO-GSA increases its convergence efficiency and thus prevents being trapped into the local optima. It is further observed that the proposed hybrid algorithm is superior compared to the other conventional algorithms. To test the efficacy of the hPSO-GSA algorithm, it is compared with a hybrid BFAO-MOL algorithm [81] and found to be superior for various operating conditions. Thus, the hPSO-GSA algorithm has been used to tune the parameters of the lead-lag damping controller.

One of the important aspects while designing a robust damping controller is the appropriate selection of the input signal. During any abnormal condition of the system, the input signal should provide a correct control. For any disturbance, both local and remote signal can be used in the closed loop a control. Literature study shows that, while designing a damping control structure either local or remote signal can be used as a control mechanism and it has been found out that for the stability point of view generally the remote signal provides better performance than the local signal [44]. Although the local signal is easy to get, it is not an appropriate signal as it may not contain the desired mode of oscillation. Thus, these signals are not highly controllable and observable as compared to the wide-area signals.

In this proposed work, a new modified local input signal is used which calculates the equivalent speed deviation and thus considered as the input signal for the damping controller. The design problem of the SSSC based controller is formulated into an optimization problem and the hPSO-GSA algorithm is used to tune the parameters of the SSSC based damping controller. In this work a single machine infinite bus (SMIB) and a two-area power system with SSSC based damping controller is analyzed under different disturbances. The dynamics associated with the power system have been considered and simulation results are presented and compared with both local and remote signals. Some general conclusion is drawn from the results, which proves the effectiveness of the hybrid algorithm.

The main objectives of the research work presented in this chapter are as follows:

1. To develop the simulink based model for the SMIB and multi-machine power system installed with a Static synchronous series compensator (SSSC).
2. To investigate the effect of a new modified new controller input signals known as modified local input signal on the performance of various FACTS based controller.
3. To compare the performance of the proposed modified signal with local as well as the remote signal as a controller input.
4. To design the FACTS based controller in a multi-machine power system.

5.2 The Proposed Approach

5.2.1 Structure of SSSC-Based Damping Controller

A structure of a lead-lag damping controller is shown in Fig. (5.1). The primary objective is to control the injected voltage (V_q) of the SSSC. The change in speed deviation ($\Delta\omega$) is taken as the input to the controller and simultaneously, the injected voltage (V_q) is taken as the output of the controller. This structure consists of three blocks as the gain block (K_s), signal washout block and two-stage phase compensation block [21]. The function of the washout block is that it will act as a high-pass filter and the phase compensation block provides an appropriate phase-lead characteristic. Here T_{1S}, T_{2S}, T_{3S} and T_{4S} represent the different time constants of the phase compensation block.

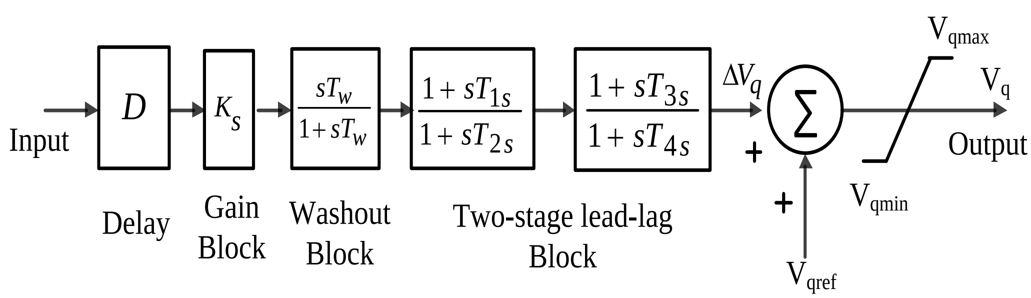


Figure 5.1: Structure of SSSC based damping Controller

5.2.2 Selection of Input Signal

As discussed previously, selection of an input signal is the fundamental criterion while designing a robust damping controller. There should be a correct control action given by an input signal during an abnormal condition of the power system. For providing a control input, both local and remote signal can be used [23]. The additional costs associated with the signal communication can be avoided which can improve the system reliability, by measuring the input signals locally. Although the local signals are easy to get, but fail to represent the required oscillation modes. Thus, these signals are not controllable and observable as compared to wide area (remote signals) signals. A delay is always associated with the different channel of the transmission line with these signal. Various reports communicated have proved that a dedicated communication channel provides a 50 ms delay during transmission [44].

For any power system the line active power and the generator speed are related by the equation:

$$\dot{\omega} = \left[P_m - P_e - D(\omega - 1) \right] / M \tag{5.1}$$

where, P_m and P_e represent the input and output powers of the generator; M and D represent the inertia constant and damping coefficient; and ω is the rotor speed.

Therefore, the speed of the rotor can be expressed as:

$$\Delta\omega = \int \left(\left[\Delta P - D(\omega - 1) \right] / M \right) \tag{5.2}$$

Fig. (5.2) represents the block diagram representation of Eq. (2).

In the present work, three different input signals are taken into account for the detailed analysis. These are:

- Remote signal which is the generator speed deviation,
- Local signal which is the line active power flow of the nearest bus,
- The proposed modified local signal which is the line active power in a modified version to get the equivalent speed deviation represented by Eq. (2).

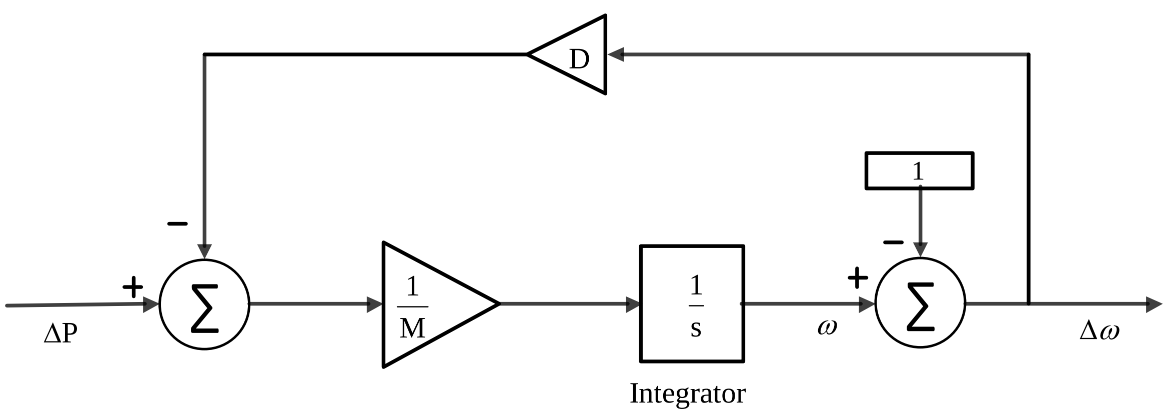


Figure 5.2: Block diagram representation for input signal

5.2.3 Problem Formulation

The washout block time constants are pre-specified in this study and is taken as T_w=T_{wp}=10. The ΔV_q in steady state condition is always approached to zero and thus V_{qref} appears to be constant. During dynamic condition, the injected voltage V_q is varied so as to damp out the system oscillation. In the proposed study, the V_{qref} is considered as a constant quantity. Therefore, the value of the V_q can be formulated as:

$$V_q = V_{qref} + \Delta V_q \tag{5.3}$$

It is obvious that an SSSC-based damping controller is generally used to reduce the system oscillation resulting out of a large disturbance to improve the stability. These oscillations can be seen in terms of the speed deviation, power angle deviation, and tie-line power. To minimize any one or all can be considered and accordingly the objective function can be formulated according to the said SMIB power system an integral time absolute error of the speed deviation is taken as the objective function and for the multi-machine case an integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations are considered as the objective functions. The stated objective functions are:

For a single-machine infinite bus power system [23]:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| .t.dt \tag{5.4}$$

For a Multi-machine power system:

$$J = \int_{t=0}^{t=t_{sim}} \left(\sum|\Delta\omega_L| + \sum|\Delta\omega_1|\right).t.dt \tag{5.5}$$

where t_{sim} = simulation time range.

The simulation is carried out for a given stipulated time as given below so as to formulate the design problem as:

$$\text{Minimize } J \tag{5.6}$$

Subject to $K_i^{min} \le K_i \le K_i^{max}$

$T_{1i}^{min} \le T_{1i} \le T_{1i}^{max}$

$$T_{2i}^{min} \le T_{21i} \le T_{2i}^{max}$$
$$T_{3i}^{min} \le T_{3i} \le T_{3i}^{max}$$
$$T_{4i}^{min} \le T_{4i} \le T_{4i}^{max} \quad (5.7)$$

Where K_i^{min} and K_i^{max} stands for the lower and upper bounds of the gain for the damping controllers. T_i^{min} and T_i^{max} represent for the lower and upper bounds of the time constants for the damping controllers.

5.3 Application of Proposed Hybrid Particle Swarm Optimization & Gravitational Search Algorithm

5.3.1 Particle Swarm Optimization (PSO)

The PSO method is a member of wide category of Swarm Intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution [48]. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers.

5.3.2 Gravitational Search Algorithm (GSA)

Gravitational search algorithm (GSA) is an alternative approach which is used to find the optimal solution of a controller. This algorithm seems to an adequate method that can give a better performance compared to other developed methods as reported in the reference [17]. The basic concept behind this algorithm is the Newtonian law of motion which states, "There is a force of attraction between each particle of the world. The force of attraction can be calculated by directly multiplying the masses and by dividing the product of the square of distance [R^2] between the particles" [19]. Instead of R^2, only R is considered because simulation results prove that R yields a better result in place of R^2.

5.3.3 Hybrid Particle Swarm Optimization and Gravitational Search (hPSO-GSA) Algorithm

In this work, a hybrid algorithm is developed by combining the Particle Swarm Optimization (PSO) and Gravitational Search Algorithm (GSA) termed as a hPSO-GSA algorithm for calculating the parameters of the damping controller. The advantages of the proposed method are that it uses the ability of social thinking of PSO and the local search ability of GSA algorithm [21].

The procedure for the hPSO-GSA algorithm can be summarized as [23]:

- Step 1: All the initial data and the parameters of the hPSO-GSA algorithm is chosen. Then the position of each particle is randomly initialized as $X_i = \{x_{i1}, x_{i2}, \ldots\ldots\ldots\ldots\ldots\ldots. x_{im}\}$. Where m represents the dimension of each particle.
- Step 2: The fitness function of each particle $F_i(t)$ is evaluated for the t'th iteration.
- Step 3: Calculate the g_{best} using PSO, inertial mass by using the gravitational search algorithm
- Step 4: Evaluate the gravitational force and acceleration as per gravitational search algorithm.
- Step 5: Update the velocity and position of each particle as per the hPSO-GSA algorithm.
- Step 6: The position of each particle is moved within a prescribed range and the range is maintained for each iteration.
- Step 7: Iteration counter is increased.
- Step 8: Step 2 to step 6 is continued till the termination condition is satisfied.

Therefore, there is a random generation of the control parameters which moves in a prescribed range and these values can be successfully updated by applying the proposed hybrid PSO-GSA algorithm which can minimize the objective function (J).

5.4 Simulation Result and Discussion

The Sim-Power-System (SPS) tool box is universally adopted in order to design the FACTS based damping controller [61]. This 'SPS' tool box is mainly applicable in MATLAB- based platform that is used to simulate the various Simulink model of the power system. A graphical user interface (GUI) tool of the SPS known as ‘Powergui' is used to analyze the developed models. The basic objective of this block is that, while it can perform the load flow analysis in the steady state it will also initialize the parameters of the machine. In the proposed study, for local signals while a delay of 15ms is considered, for remote signals the delay is chosen to be 50 ms along with a 15 ms delay for the sensor time constant [23].

5.4.1 Single-Machine Infinite Bus Power System with SSSC

In this system, a generator is used which is being connected to a transmission line. A double-circuit transmission line is considered here. An SSSC and a three phase transformer are connected between the generator unit and the transmission line. Appendix 1 shows the ratings of all these components. As discussed earlier, the SPS SIMULINK environment is used in order to design the said power system which is shown in Fig. (5.3) and is developed using ‘SPS’ block set.

In order to calculate the objective function of the above system, some disturbance is considered and the simulation is carried out. To find the parameters of the damping controller the Eq. (5.4) is considered with an objective to minimize its fitness value. An Intel (R) Core (TM) 2 Duo 2.93 GHz, 2 G.B RAM computer, with the MATLAB environment is used for all simulations and fitness calculation.

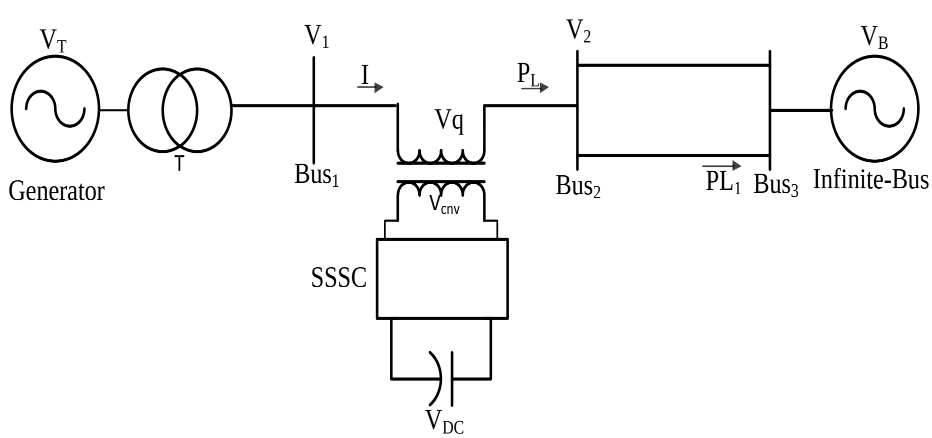


Figure 5.3: Single machine infinite bus power system installed with SSSC

While applying the hPSO-GSA, the following parameters have been used: the population size = 20, maximum iteration = 50, c_1' =0.5, c_2' =1.5, w is a random number which is varied in the range of 0-1. G_0= 1, α = 20. Stopping criteria is selected based on maximum iteration count [23]. Tab. (5.1), represents the optimized controller parameters obtained by applying the hPSO-GSA algorithm, considering both the remote and the proposed modified local signal. In order to test the efficacy of the hybrid algorithm, different loading conditions and operating conditions of the system are considered.

As far as simulation result is concerned, the following cases have been investigated:

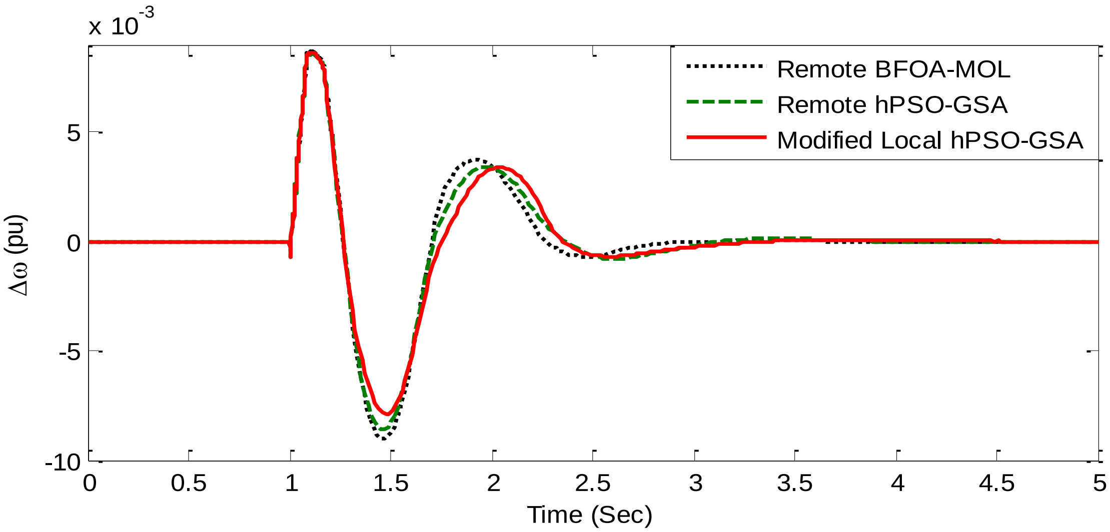
- Case-1: The system response with the remote signal using a hybrid BFOA-MOL algorithm (dotted line) (For a similar problem) [64].
- Case-2: The system response with the remote signal with the hybrid PSO-GSA algorithm (dashed line).
- Case-3: The system response with the proposed modified local input signal using the hybrid PSO-GSA algorithm (solid line).

Table 5.1: PSO–GSA Optimized SSSC-Based Controller Parameters for SMIB Power System

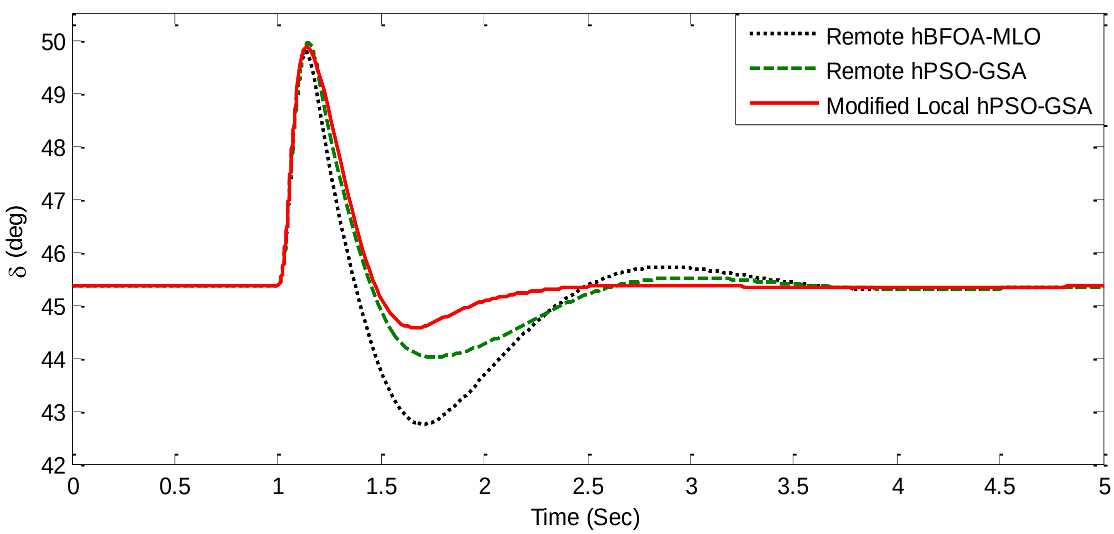
Parameters/Signal	K_S	T_{1S} (s)	T_{2s}(s)	T_{3s} (S)	T_{4s} (S)
Remote signal	29.1335	0.5807	0.1684	0.3624	0.4001
Modified local signal	0.01570	0.4978	0.2758	0.5786	0.8809

5.4.1.1 Nominal Loading (P_e=0.75 pu and δ_0=45.3^0)

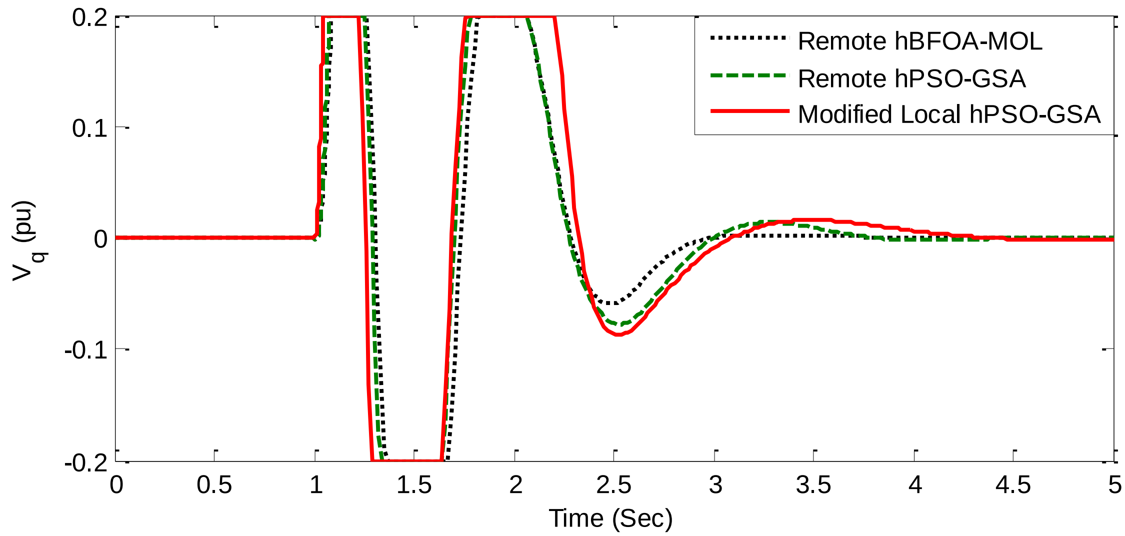
At the first instance, a severe disturbance at the nominal system loading (P_e=0.75 pu and δ_0=45.3^0) is considered. A 3 phase 5 cycle fault is applied at the middle of one transmission line connecting Bus2 and Bus3, at t = 1.0 s. and the original system is restored after the fault is cleared. The fault is cleared by tripping of the faulted line and the faulty line is restored after 5-cycles. The system responses in terms of speed deviation $\Delta\omega$, power angle deviation δ and the SSSC injected voltage V_q are shown in Figs. (5.4 (A-C)). From the response curves, it is concluded that, the hPSO-GSA based remote signal provides a better result as compared to the hBFOA-MOL based remote signal [64]. It is further observed that compared to all other signals, hPSO-GSA based modified local signal suppresses the system oscillation much faster and hence justifying the use of the proposed signal.



(A) Speed Deviation



(B) Power angle

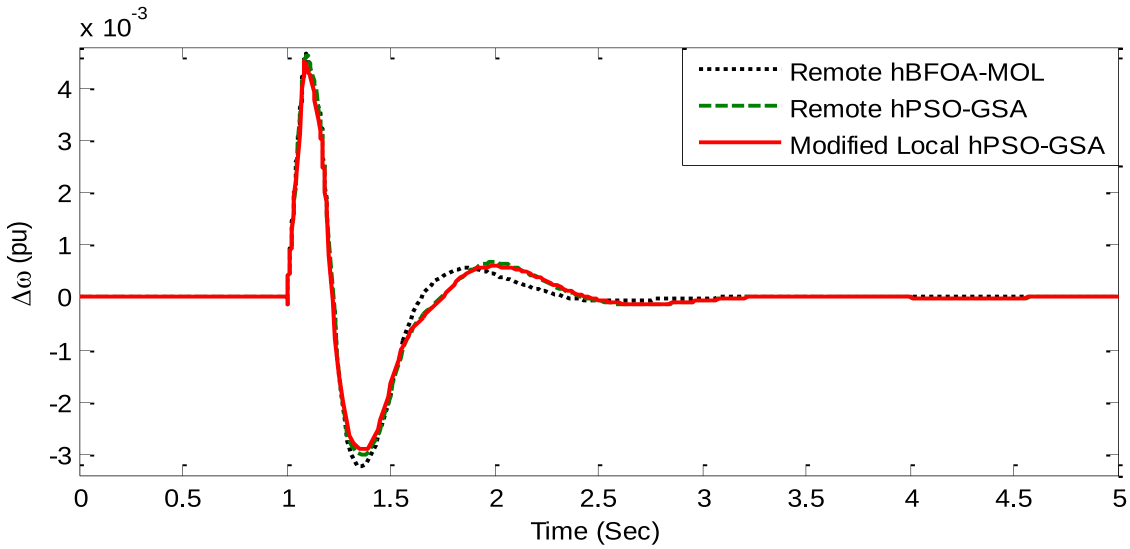


(C) SSSC Injected Voltage

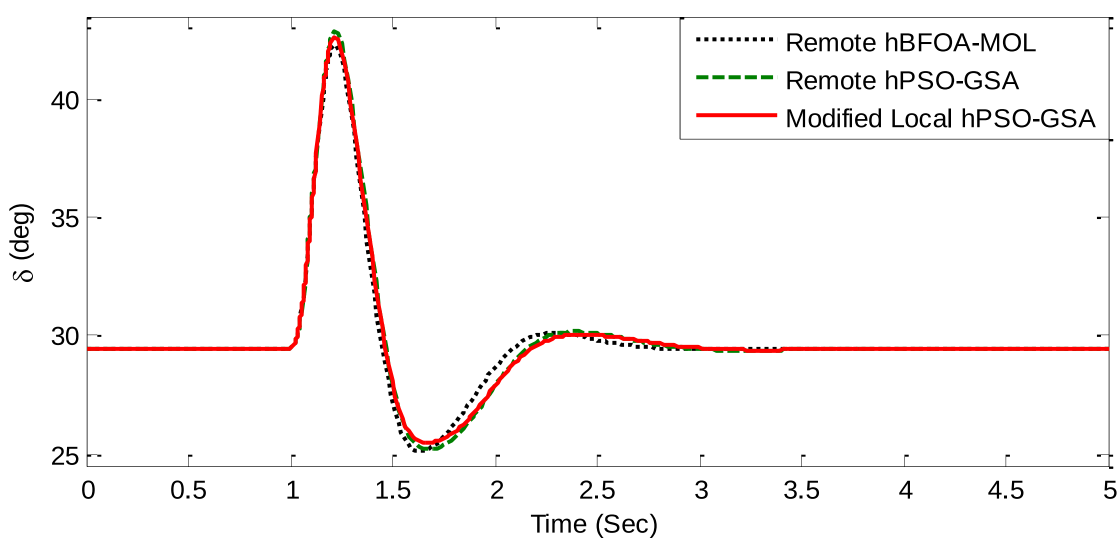
Figure 5.4: System response for a 5cycle 3 phase fault cleared by line tripping with nominal loading condition

5.4.1.2 Light Loading (P_e=0.5 pu and δ_0=29.5^0)

Another example of light loading condition of the system is considered (P_e=0.5 pu and δ_0=29.5^0) with a 3 phase 5 cycle fault applied at the end of one transmission line connecting Bus2 and Bus3, near Bus3 at t = 1.0 s. The fault is cleared after 3 cycles by opening the faulty line. The faulty line is restored after 100ms. Under such circumstances, the system responses are shown in Figs. (5.5 (A-B)). It is observed from the transient response curve that, the hPSO-GSA based remote signal provides a better result when compared to the hBFOA-MOL based remote signal and the proposed hPSO-GSA based modified local input signal is superior to all the input signals.



(A) Speed Deviation

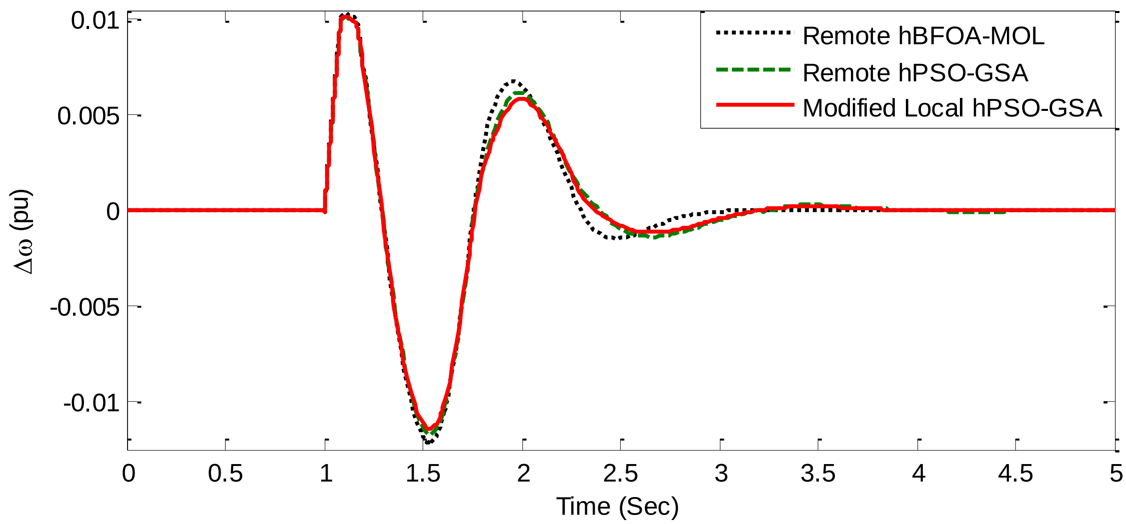


(B) Power Angle

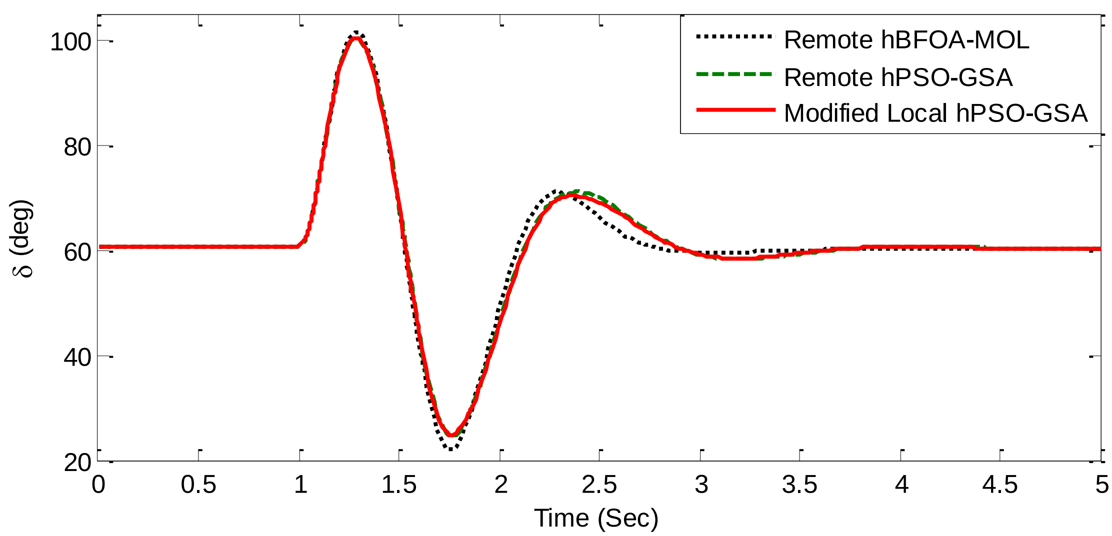
Figure 5.5: System response for a 5cycle 3 phase fault cleared by line tripping with light loading condition

5.4.1.3 Heavy LOADING (P_e=1 pu and δ_0=60.7^0)

Finally, the system is considered with the heavy loading condition (P_e=1.0 pu and δ_0=60.7^0). This is purposefully done to test the robustness of the proposed hybrid algorithm. Here at t=1 sec. a 100 ms self-clearing 3-phase fault is applied near Bus3 and the system responses are shown in Figs. (5.6 (A, B)). The response curves indicate that the system oscillation is significantly reduced at the given operating condition and thus the stability is maintained. The same comparison is made to test the superiority of the hybrid PSO-GSA algorithm. Further, it can be seen that the proposed modified local input signal based SSSC damping controller provides a slightly better transient response compared to all the remote speed deviation signals.



(A) Speed Deviation



(B) Power Angle

Figure 5.6: System response for a 5 cycle 3 phase fault at bus-3 cleared by line tripping with heavy loading condition

5.4.2 Extension to Four-Machine Two Area Power System

The extension of the SMIB power system to a multi-machine system is shown in Fig. (5.7). The system is composed of two sections as discussed in the references [6, 15 and 24]. This system consists of four generators, arranged to form two sections termed as Area-1, Area-2 and connected through a time-line. These two sub-sections seem to be swinging with each other, when the system is subjected to disturbances, causing system instability. An SSSC is connected at the mid-point of the tie-line. This can significantly improve the system stability under any disturbance. All the relevant data related to the above system is presented in Appendix 3.

The same approach is considered to design the multi-machine power system as done for the SMIB case. For choosing the local input signal, the line active power is considered as the input to the damping controller. To compare this signal, a remote signal (speed deviation of generators) is selected as the input to the damping controller which is the speed difference of generators in each area i.e. G_1 and G_4. For wide area signal (speed deviation of generators), a 50 ms time delay is chosen to account for the signal transmission delay [23]. The optimized values of the controller are shown in Table: 5.2.

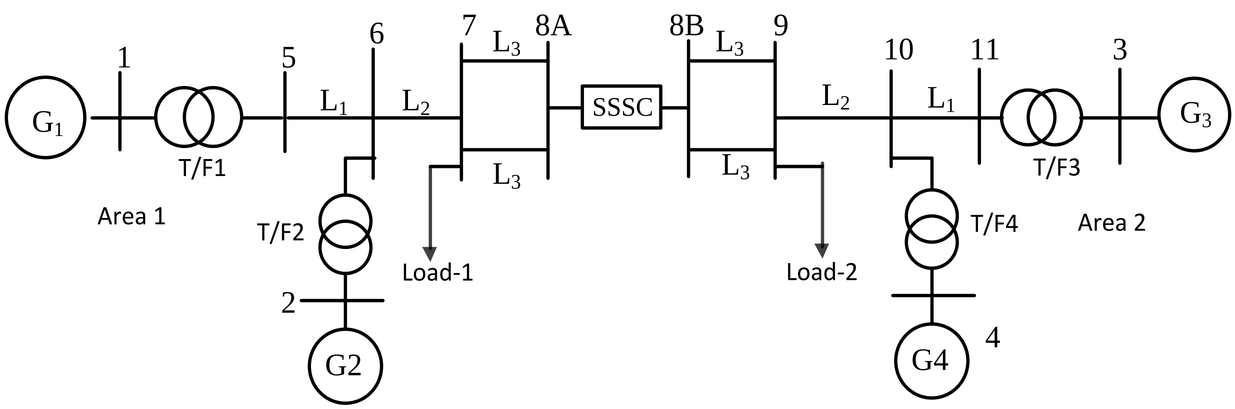


Figure 5.7: Example of a two-area four-machine power system with SSSC

To compare the different input signal, the following cases are considered:

- Case-1: Represents the response of the system with hPSO–GSA optimized SSSC-based damping controller with local line active power input signal (dotted line).
- Case-2: Represents the response with hPSO-GSA optimized SSSC-based damping controller with Remote speed deviation as input signal (dashed lines).

- Case-3: Response with hPSO–GSA optimized SSSC-based damping controller with proposed modified local input signal (Solid lines).

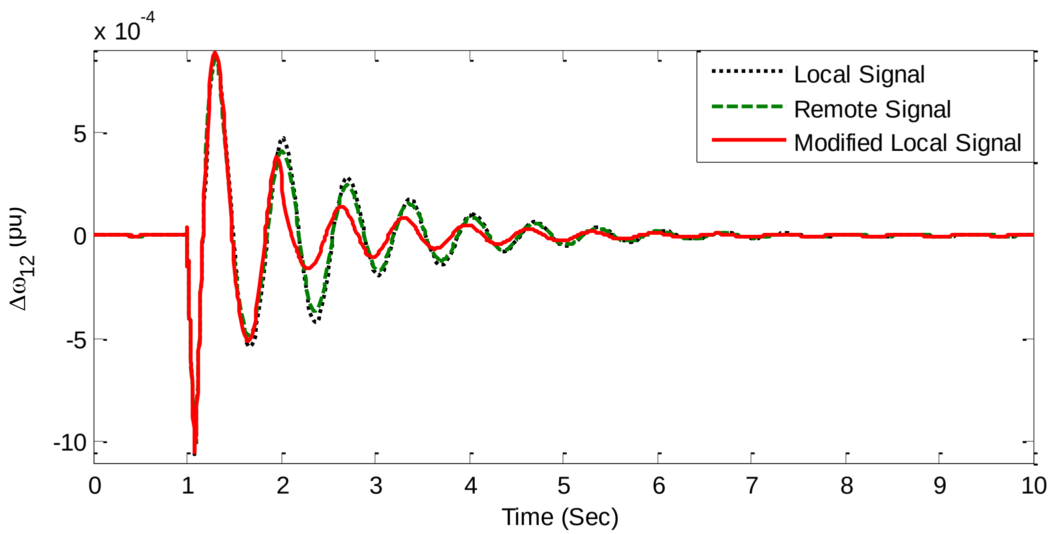
Table 5.2: hPSO–GSA Optimized SSSC-Based Controller Parameters for a Two Area Four Machine Power System

Parameters/Signal	K_S	T_{1S} (s)	T_{2s}(s)	T_{3s} (S)	T_{4s} (S)
Local Signal	0.7851	0.9966	0.9090	0.0009	0.2776
Wide area/ Remote signal	12.9101	0.5763	0.6274	0.0841	0.9998
Modified local signal	0.9577	0.8995	0.6081	0.9998	0.6039

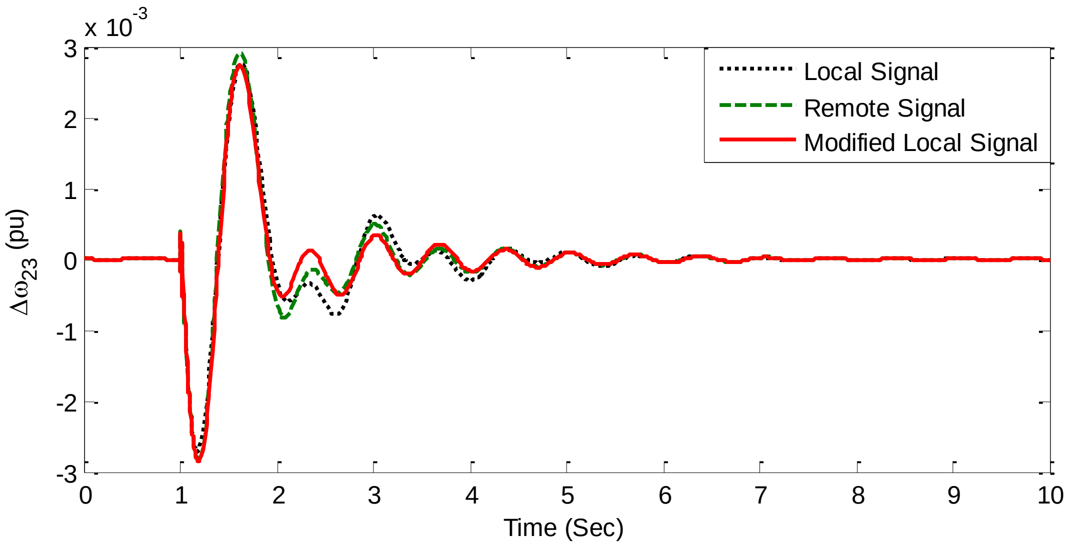
Now to test the robustness of the proposed input signal and the hybrid algorithm, following disturbances are considered:

5.4.2.1 Three Phase Fault Cleared by Line Reclousure

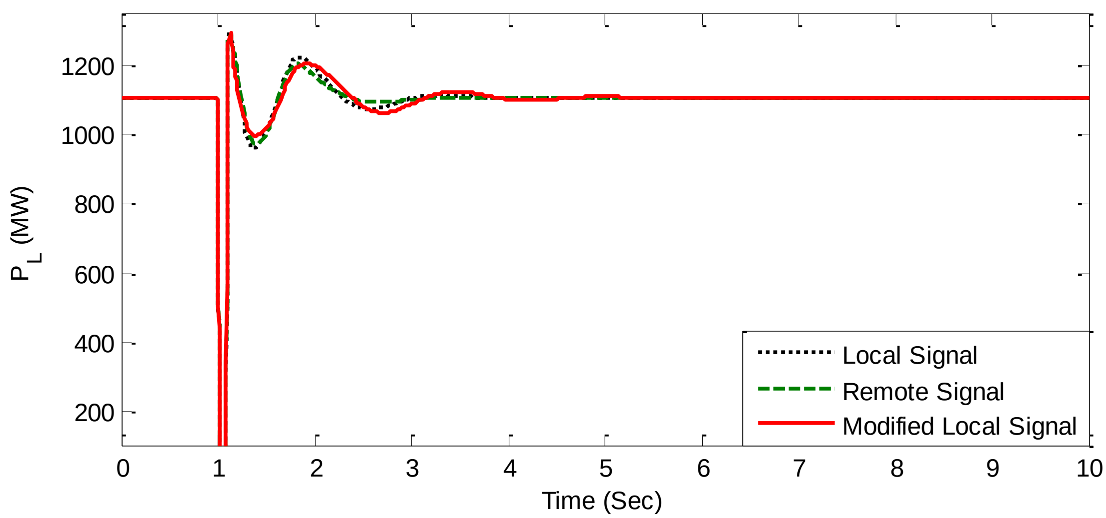
A 100 ms, the 3-phase fault is applied near to bus-9 at t=1 sec. and the original system is restored when the line is reclosed after 100 ms. The system responses for this case are shown in Figs. (5.8 (a-c)).



(a) Local mode of Oscillation



(b) Inter-area Mode of Oscillation



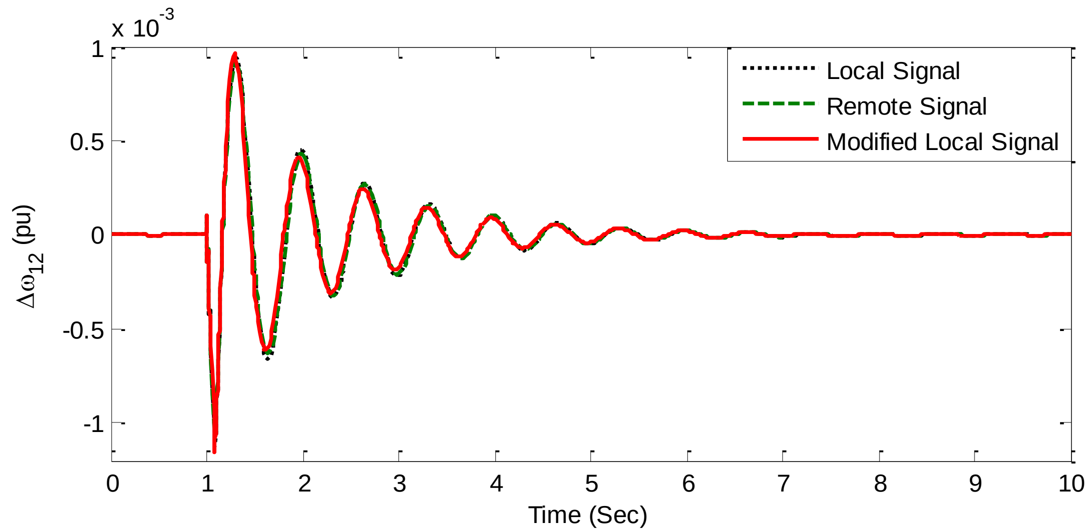
(c) Tie-line active power

Figure 5.8: System response for a 100 ms-3 phase fault near to bus-9 (a) Local mode of Oscillation (b) Inter-area mode of oscillation (c) Tie-line active power

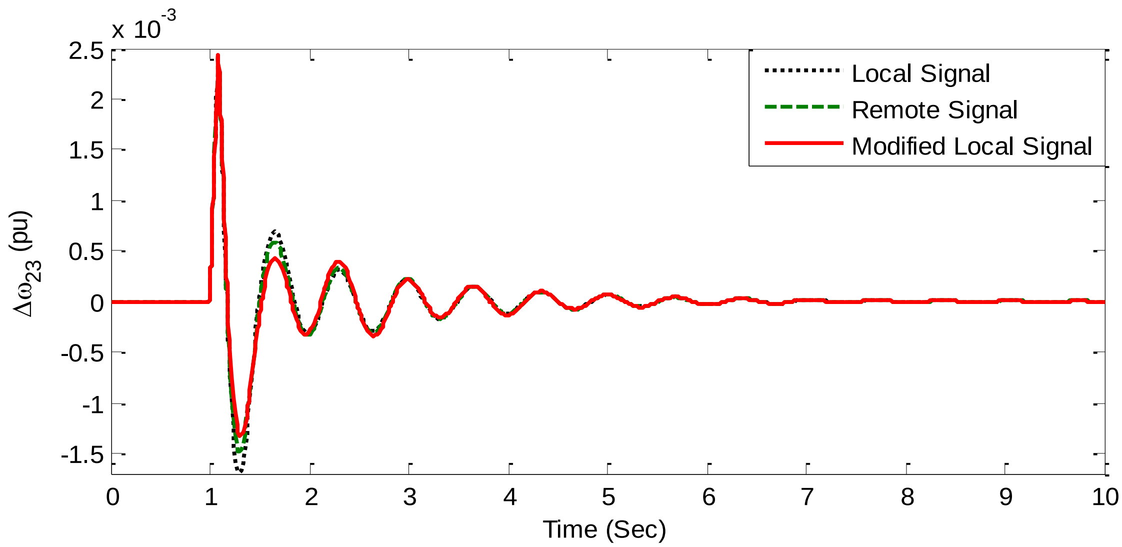
The responses are the inter-area mode of oscillation, local mode of oscillation and the tie line active power flow. These responses clearly indicate that, proposed modified local input signal yields better results as compared to the local and remote signals

5.4.2.2 Three Phase Self-Clearing Fault

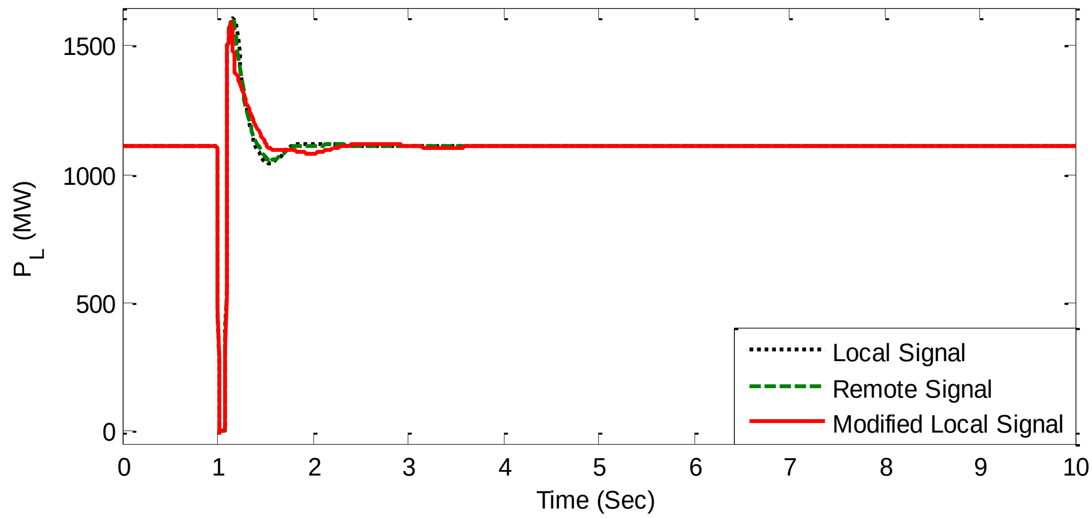
Further, a self-clearing 100 ms 3-phase fault applied near Bus 8A. The system responses for such case are shown in Figs. 5.9 (A-C). An inference can be made from these responses that, the system reaches a stable equilibrium point more quickly with the proposed hPSO-GSA based modified local input signal as compared to the hybrid algorithm based on remote and the local input signals.



(A) Local Area mode of Oscillation



(B) Inter-Area mode of Oscillation



(C) Tie-Line Active Power

Figure 5.9: System response for a 100 ms-3 phase self-clearing fault at bus-8A (a) Local mode of Oscillation (b) Inter-area mode of oscillation (c) Tie-line active power

5.5 Chapter Summary

In the proposed work, an investigation is carried out to improve the system transient stability by considering an SSSC-based damping controller using a modified local signal. The locally measurable line active power is used to derive the modified signal. A time domain simulation is executed in order to minimize an objective function for the controller design. The hybrid PSO-GSA algorithm is used, which can tune the parameters of the FACTS based damping controller. To test the effectiveness of the proposed input signal various simulations are performed by considering different loading conditions. The simulation results clearly prove that the said modified input signal based damping controller provides very efficient damping and yields better result as it adapts itself to generate a suitable variation of the control signals depending on the operating condition and disturbance in the power system. Finally, the extension of SMIB power system to multi-machine is simulated and is tested for the different contingency of the system. From the simulation results, it is shown that the inter-area mode oscillation and local modes of oscillations are effectively damped out by using the proposed hPSO-GSA based SSSC damping controller in a multi-machine power system. Further, it is also concluded that with modified local input signal much better result is obtained compared to the remote and the local signals so far as the damping of the power system is concerned.

Chapter 6

Conclusions and Future Scope

6.1 Conclusions

The work presented in this thesis mainly focuses on the aspects related to Flexible AC Transmission Systems (FACTS) based controller design and assessment of their contribution to system stability improvement ensuring secure and stable operation of the power system. In this context, modern heuristic optimization techniques have been employed to design the FACTS-based controllers. Investigations have been carried out considering Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC).Several modern heuristic optimization techniques have been proposed recently for solving optimization problems that were previously difficult or impossible to solve.

In this thesis GA, PSO and GSA optimization techniques have been applied for designing a modified Philips-Heffron model (Linearized model) installed with an SSSC-based controller. The design objective is to enhance the stability of a Single-Machine Infinite-Bus (SMIB) power system equipped with SSSC controller. The design problem is formulated as an optimization problem and GSA, PSO and GA techniques are employed to search for optimal controller parameters. The performance of above optimization techniques is compared on a weakly connected power system under various loading conditions and disturbances. It is observed that, in terms of computational effort, the GSA approach is faster as compared with PSO and GA. The effect of objective functions namely Integral square error (ISE) and Integral of Time Multiplied Absolute value of Error (ITAE) on the performance of the controllers are compared and it is observed that ITAE is better objective function than ISE for optimization problems concerning SSSC based damping controller design.

The damping capabilities of an SMIB power system installed with Unified Power Flow Controller (UPFC) controllers are also thoroughly investigated. A hybrid Genetic Algorithm and Gravitational Search Algorithm (hGA-GSA) is successfully applied to tune the damping controller. The existence of the proposed Hybrid GA-GSA Algorithm is tested by applying various standard benchmark functions. This hybrid concept is based on the fact that, GA is used to search the global value at the initial stage and after that GSA is applied for the local search. Simulation results and the fitness values of the standard benchmark functions suggest that the proposed hybrid GA-GSA algorithm based UPFC damping controller design is superior as compared to other algorithms.

To avoid the disadvantages associated with the linearized model the Simulink based coordinated design of PSS with various FACTS devices based damping controllers are carried out. The various system time delays owing to signal transmission and various system components is considered in the design. The speed deviation signal $\Delta\omega$ is considered as an input to the PSS and the damping controller. A hybrid particle swarm optimization and gravitational search algorithm (hPSO-GSA) technique is employed to optimally and coordinately tune the PSS and SSSC based controller parameters. The hPSO-GSA algorithm is the combination of two concepts. The first concept is PSO's ability of social thinking ("gbest") and the second concept is GSA's local search capability. The superiority of the proposed hBFOA-PSO has been demonstrated by comparing the results with the hybrid BFOA-PSO, PSO and GA. The designed controllers are found to be robust to fault location and change in operating conditions and generate appropriate stabilizing output control signals to improve stability for an SMIB as well as a multi-machine power system.

Finally, the detailed analysis of various input signal to the SSSC based damping controller is carried out. A new derived signal known as the modified local input signal is compared with both local signal (speed deviation) and remote signal (line active power). Appropriate time delays due to sensor time constant and signal transmission delays are considered in the design process. The performance of the proposed controller is evaluated under different disturbances for both single-machine infinite bus power system and multi-machine power system. For both single-machine infinite bus power system and multi-machine power system, it is noticed that the performance of the modified local input signal is superior as compared to the remote (speed deviation) signal and the local (line active power) signal.

6.2 Future Scope

Research and development are a non-stopping process. For any research work carried out, there is always a possibility of further improvement and lot many avenues are opened for further investigation. The future work that can be carried out in the area of power system stability improvement with FACTS controllers has been identified and listed as given below.

1. The Simulink based power system design can be extended with other generalized FACT devices like TCSC, IPFC and UPFC
2. The system investigated has been limited up to a four-machine power system. It would be desirable to extend the proposed approach for larger and more realistic systems.
3. The above work can be realized by considering the modified local input signal as an input to the damping controller.
4. Different strategies could be tested and implemented in an attempt to achieve a less time-consuming process and gain a better understanding of heuristic optimization techniques applied to various power system phenomena.
5. Finally, real testing of the simulated result for the power system can be realized in an RTDC (Real-time design and simulator) module.

Bibliography

[1] P. Kundur. *Power System Stability and Control*. Mc Graw-Hill Professional Publishing, 1994.

[2] N.G. Hingorani and L. Gyugyi. *Understanding FACTS: concepts and technology of flexible ac transmission systems*, New York: IEEE Press, 2000.

[3] L. Gyugyi. Unified power-flow control concept for flexible AC transmission systems, *IEE proceedings C (generation, transmission and distribution)*, 139(4):323--331, July 1992.

[4] H. F. Wang and F. J. Swift. A unified model for the analysis of FACTS devices in damping power system oscillations. I. Single-machine infinite bus power systems. *IEEE Transactions on Power Delivery*, 12(2):941--946, April 1997.

[5] H. F. Wang and F. J. Swift and M. Li. A unified model for the analysis of FACTS devices in damping power system oscillations. II. Multi-machine power systems. *IEEE Transactions on Power Delivery*, 13(4):1355--1362, October 1998.

[6] H. Wang. A unified model for the analysis of FACTS devices in damping power system oscillations. III. Unified power flow controller. *IEEE Transactions on Power Delivery*, 15(3):978--983, July 2000.

[7] S. A. Taher, R. Hemmati, A. Abdolalipour and S. Akbari. Comparison of different robust control methods in the design of decentralized UPFC controllers. *International Journal of Electrical Power & Energy Systems*, 43(1):173--184, December 2012.

[8] N. Tambey and M. L. Kothari. Damping of Power System Oscillations with Unified Power Flow Controller (UPFC). *IEE Proceedings-Generation, Transmission and Distribution*, 150(2):129--140, March 2003.

[9] S. Mishra, P. K. Dash and G. Panda. TS-fuzzy controller for UPFC in a multi-machine power system. *IEE Proceedings of Generation, Transmission and Distribution*, 147(1):15--22, January 2000.

[10] M. Eslami, H. Shareef, M. R. Taha and M. Khajehzadeh. Adaptive Particle Swarm Optimization for Simultaneous Design of UPFC Damping Controllers. *International Journal of Electrical Power & Energy Systems*, 57(31); 116--128, May 2014.

[11] N. Talebi and A. Akbarzadeh. Damping of Low Frequency Oscillations in power systems with neuro-fuzzy UPFC controller, *10th International Conference on Environment and Electrical Engineering (IEEE-EEEIC),* 1--4, May 2011.

[12] A. R. Mahran, B. W. Hogg, and M. L. El-Sayed, Coordinated Control of Synchronous Generator Excitation and Static VAR Compensator, *IEEE Trans. Energy Conversion, 7(4*): 615--622, December 1992.

[13] W. Chang, Nonlinear system identification and control using a real-coded genetic algorithm, *Applied Mathematical Modelling*, 31(3): 541--550, March 2007.

[14] S. Panda, S. C. Swain, A. K. Baliarsingh and C. Ardil, Optimal Supplementary Damping Controller Design for TCSC Employing RCGA, *International Journal of Computational Intelligence*, 5(1): 36--45, 2009.

[15] L. H Hassan, M. Moghavvemi, H. A. Almurib and O. Steinmayer, Application of genetic algorithm in optimization of unified power flow controller parameters and its location in the power system network, *International Journal of Electrical Power & Energy Systems*, 46, 89--97, March 2013.

[16] S. Panda and N. P. Padhy, Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design, *Applied soft computing*, 8(4):1418--1427, September 2008.

[17] E. Rashedi, H. N. Pour and S. Saryazdi, GSA: a gravitational search algorithm, *Information sciences*, 179(13): 2232--2248, June 2009.

[18] R. K. Khadanga and J. K. Satapathy, Gravitational search algorithm for the static synchronous series compensator based damping controller design, *In Students Technology Symposium (IEEE- TechSym)*, 356--361, February 2014.

[19] A. A Ibrahim, A. Mohamed and H. Shareef, Optimal power quality monitor placement in power systems using an adaptive quantum-inspired binary gravitational search algorithm, *International Journal of Electrical Power & Energy Systems*, 57: 404--413, May 2014.

[20] A. R Bhowmik and A. K. Chakraborty, Solution of optimal power flow using non dominated sorting multi objective opposition based gravitational search algorithm, *International Journal of Electrical Power & Energy Systems,* 64; 1237--1250, January 2015.

[21] R. K. Khadanga and S. Panda. Gravitational search algorithm for Unified Power Flow Controller based damping controller design, *International Conference on Energy, Automation, and Signal (IEEE-ICEAS)*, 1--6, 2011.

[22] R. E. Precup, R. C. David, E. M. Petriu, S. Preitl and A. S. Paul, Gravitational Search Algorithm-Based Tuning of Fuzzy Control Systems with a Reduced Parametric Sensitivity, *Advances in Intelligent and Soft Computing*, 96:141--150, January 2011.

[23] R. K. Khadanga, J. K. Satapathy, Time delay approach for PSS and SSSC based coordinated controller design using hybrid PSO–GSA algorithm, *International Journal of Electrical Power & Energy Systems*, 71:262--273, October 2015.

[24] S. Sheikhpour, M. Sabouri and S. H. Zahiri, A hybrid Gravitational search algorithm-Genetic algorithm for neural network training, *21st Iranian Conference on Electrical Engineering (IEEE ICEE)*, 1--5, 2013.

[25] S. Mirjalili, G.G. Wang and L.D Coelho. Binary optimization using hybrid particle swarm optimization and gravitational search algorithm, *Neural Computing and Applications*, 25(6):1423--1435, November 2014.

[26] S. Panda and N. P. Padhy, MATLAB/SIMULINK based model of single-machine infinite-bus with TCSC for stability studies and tuning employing GA, *International Journal of Computer Science and Engineering*, 1(1): 50--59, March 2007.

[27] K. R. Padiyar and N. Prabhu, Analysis of sub synchronous resonance with three level twelve-pulse VSC based SSSC, *Conference on Convergent Technologies for the Asia-Pacific Region (IEEE TENCON)*, 76--80, October 2003.

[28] S. Panda, Differential evolutionary algorithm for TCSC-based controller design, *Simulation Modelling Practice and Theory*, 17(10): 1618--1634, November 2009.

[29] J. M. Ramirez, R. J. Davalos, and I. Coronado, Use of an Optimal Criterion for Coordinating FACTS-based Stabilizers, *In Generation, Transmission and Distribution IEE*, 149(3): 345--351, May 2002.

[30] K. R. Padiyar and N. Prabhu, Design and performance evaluation of sub synchronous damping controller with STATCOM, *IEEE Transactions on Power Delivery*, 21(3): 1398--1405, July 2006.

[31] S. Panda, Differential evolution algorithm for SSSC-based damping controller design considering time delay, *Journal of the Franklin Institute*, 348(8): 1903--1926, October 2011.

[32] S. Panda, Robust coordinated design of multiple and multi-type damping controller using differential evolution algorithm, *International Journal of Electrical Power & Energy Systems*, 33(4):1018--1030, May 2011.

[33] E. Rashedi, H. N. Pour and S. Saryazdi, Filter modeling using gravitational search algorithm, *Engineering Applications of Artificial Intelligence*, 24(1): 117--122, February 2011.

[34] C. Li C and J. Zhou. Parameters identification of hydraulic turbine governing system using improved gravitational search algorithm, *Energy Conversion and Management*, 52(1):374--81, January 2011.

[35] L. Gyugyi, C. D Schauder and K. K. Sen, Static synchronous series compensator: a solid state approach to the series compensation of transmission lines, *IEEE Transactions on Power Delivery*, 12(1): 406--417, January 1997.

[36] S. Panda, Multi-objective evolutionary algorithm for SSSC-based controller design, *Electrical Power System Research*, 79(6): 937-- 44, June 2009.

[37] R. Mihalic and I. Papic, Static synchronous series compensator – a mean for dynamic power flow control in electric power systems, *Electrical Power System Research*, 45(1): 65--72, April 1998.

[38] S. Panda, S. C. Swain, P. K. Rautray, R. Mallik and G. Panda, Design and analysis of SSSC based supplementary damping controller, Simulation *Modelling Practice and Theory*, 18(9): 1199--1213, October 2010.

[39] H. F. Wang, Static synchronous series compensator to damp power system oscillations, *Electrical Power System Research*, 54(2): 113--119, May 2000.

[40] S. Panda, Design and analysis of SSSC-based supplementary damping controller, *Simulation Modelling Practice and Theory*, 18(9): 1199--1213, October 2010.

[41] E. S. Ali and S. M. A. Elazim, Coordinated design of PSSs and TCSC via bacterial swarm optimization algorithm in a multi-machine power system, *International Journal of Electrical Power & Energy Systems*, 36(1): 84--92, March 2012.

[42] L. J. Cai and I. Erlich, Simultaneous coordinated tuning of PSS and FACTS damping controller in a large power system, *IEEE Transactions on Power Systems*, 20(1):294--300, February 2005.

[43] S. M. A. Elazim and E. S. Ali, Coordinated design of PSSs and SVC via bacteria foraging optimization algorithm in a multi-machine power system, *International Journal of Electrical Power & Energy Systems*, 41(1):44--53, October 2012.

[44] S. Ray, G. K. Venayagamoorthy and E. H. Watanabe, A computational approach to optimal damping controller design for a GCSC, *IEEE Transactions on Power Delivery*, 23(3):1673--1681, July 2008.

[45] S. Panda, N. K. Yegireddy and S. K. Mohapatra, Hybrid BFOA–PSO approach for coordinated design of PSS and SSSC-based controller considering time delays, *International Journal of Electrical Power & Energy Systems*, 49: 221--233, July 2013.

[46] C. J. A. B. Filho, D. A. R. Chaves, F. S. F. E. Silva, H. A. Pereira and J. F. M. Filho, Wavelength Assignment for Physical-Layer-Impaired Optical Networks Using Evolutionary Computation, *Journal of Optical Communications and Networking*, 3(3): 178--188, March 2011.

[47] S. Panda and R. N. Patel, Damping of power system oscillations by genetically optimized PSS and TCSC controller, *International Journal of Energy Technology and Policy*, 5(4):457--474, January 2007.

[48] J. Kennedy, Particle swarm optimization. *In: Encyclopedia of Machine Learning, Springer*, 760--766, 2010.

[49] S. Panda, N. P. Padhy and R. N. Patel, Robust coordinated design of PSS and TCSC using PSO technique for power system stability enhancement, *Journal of Electrical System*, 3(2): 109--123, 2007.

[50] K. Y. Chan, T. S. Dillon and E. Chang, An Intelligent Particle Swarm Optimization for Short-Term Traffic Flow Forecasting Using on-Road Sensor Systems, *IEEE Transactions on industrial electronics*, 60(10): 4714--4725, October 2013.

[51] N. A. El-Hefnawy, Solving Bi-level Problems Using Modified Particle Swarm Optimization Algorithm, *International Journal of Artificial Intelligence*, 12(2): 88--101, February 2014.

[52] K. M. Passino, Biomimicry of bacterial foraging for distributed optimization and control, *IEEE Control System*, 22(3); 52--67, June 2002.

[53] E. S. Ali and S. M. Abd-Elazim, Bacteria foraging optimization algorithm based load frequency controller for interconnected power system, *International Journal of Electrical Power & Energy Systems*, 33(3): 633--638, March 2011.

[54] S. Panda, Multi-objective non-dominated shorting genetic algorithm-II for excitation and TCSC-based controller design, *Journal of Electrical Engineering*, 60(2):87--94, March 2009.

[55] R. Quan, J. B. Jian and Y. D. Mu, Tighter relaxation method for unit commitment based on second-order cone programming and valid inequalities, *International Journal of Electrical Power & Energy Systems*, 55: 82--90, 2014.

[56] H. F. Wang and F. J. Swift, Multiple Stabilizer Setting in Multi machine Power Systems by the Phase Compensation Method, *International Journal of Electrical Power & Energy Systems,* 20(4): 241--246, May 1998.

[57] R. E. Precup, R. C. David, E. N. Petriu, S. Preitl and M. B. Radac, Fuzzy logic-based adaptive gravitational search algorithm for optimal tuning of fuzzy-controlled servo systems, *IET Control Theory & Applications*, 7(1): 99--107, January 2013.

[58] S. Jiang, Z. Ji and Y. Shen, A novel hybrid particle swarm optimization and gravitational search algorithm for solving economic emission load dispatch problems with various practical constraints, *International Journal of Electrical Power & Energy Systems*, 55: 628--644, February 2014.

[59] S. Mirjalili and S. Z. M. Hashim, A New Hybrid PSOGSA Algorithm for Function Optimization, *International conference on In Computer and information application (IEEE-ICCIA)*, 374--377, December 2010.

[60] S. Mallick, S. P. Ghoshal, P. Acharjee and S. S. Thakur, Optimal static state estimation using improved particle swarm optimization and gravitational search algorithm, *International Journal of Electrical Power & Energy Systems*, 52: 254--265, November 2013.

[61] SimPowersystem 5.2.1 User's guide. *http://www.mathworks.com/ products/simpower*/ >

[62] F. Damien, N. K. Nguyen, P. Wira, G. Sturtzer, D. O. Abdeslam and J. Mercklé, A self-learning solution for torque ripple reduction for nonsinusoidal permanent-magnet motor drives based on artificial neural networks, *Industrial Electronics, IEEE Transactions on*, 61(2), 655--666, February 2014.

[63] J.L Rueda, J.C Cepeda and I. Erlich. Probabilistic approach for optimal placement and tuning of power system supplementary damping controllers, *IET Generation, Transmission & Distribution*, 8(11):1831--42, May 2014.

[64] D. Das, Reactive power compensation for radial distribution networks using genetic algorithm, *International journal of electrical power & energy systems*, 24(7): 573--581, October 2002.

[65] A. R Phadke, F. Manoj and K. R. Niazi, A new multi-objective fuzzy-GA formulation for optimal placement and sizing of shunt FACTS controller, *International Journal of Electrical Power & Energy Systems*, 40(1):46--53, September 2012.

[66] N. Gupta, A. Swarnkar, K. R. Niazi and R. C. Bansal, Multi-objective reconfiguration of distribution systems using adaptive genetic algorithm in fuzzy framework. *IET generation, transmission & distribution*, 4(12): 1288--1298, December 2010.

[67] S. Sridhar, H. K. Khalil, Output feedback control of nonlinear systems using RBF neural networks, *IEEE Transactions on neural Networks*, 11(1): 69--79, January 2010.

[68] D. Das, A fuzzy multi-objective approach for network reconfiguration of distribution systems. *IEEE Transactions on power delivery*, 21(1): 202--209, January 2006.

[69] R. K. Misra and S. P. Singh, Steady State Security Analysis using Artificial Neural Network, *Electric Power Components and Systems*, 32(11),1063--1081, November 2004.

[70] Y. H. Song, Flexible AC Transmission Systems (FACTS), *the Institution of Electrical Engineers*, London, 1999.

[71] L. H. Leo, A. P. Hu and G. A. Covic, A direct AC–AC converter for inductive power-transfer systems, *IEEE Transactions on power electronics*, 27(2): 661--668, February 2012.

[72] P. A. Reddy, G. Amer and S.S. Rao, An Improved current sharing method for paralleled DC/DC converter using fuzzy logic control, *Journal of Electrical Engineering*, 10 (2): 33--41, June 2010.

[73] A. R. Phadke, S. K. Bansal and K. R. Niazi, A comparison of voltage stability indices for placing shunt FACTS controllers, *First International Conference on In Emerging Trends in Engineering and Technology (IEEE-ICETET)*, 939--944, 2008.

[74] Y. L. A. Magid and M. A. Abido, Robust coordinated design of excitation and TCSC based stabilizers using genetic algorithms, *International Journal of Electrical Power & Energy Systems*, 69(2): 129--141, May 2004.

[75] S. Dutta and S. P. Singh, Optimal Rescheduling of Generators for Congestion Management Based on Particle Swarm Optimization, *IEEE Transactions on Power Systems*, 23(4): 1560--1569, November 2008.

[76] S. Selleri, M. Mussetta, P. Pirinoli, E. Zich and L. Matekovits, Differentiated meta-PSO methods for array optimization, *IEEE Transactions on Antennas and Propagation*, 56(1):67--75, January 2008.

[77] E. Grimaldi, A. F. Grimaccia, M. Mussetta, P. Pirinoli and R. E. Zich, A new hybrid genetical-swarm algorithm for electromagnetic optimization, *3rd International Conference on in Computational Electromagnetics and Its Applications, (IEEE-ICCEA)*, 157--160, 2004.

[78] F. Grimaccia, M. Mussetta and E. R. E. Zich, Genetically swarm optimization: Self-adaptive hybrid evolutionary algorithm for electromagnetics, *IEEE Transactions on Antennas and Propagation*, 55(3):781--785, March 2007.

[79] H. H. Zeineldin, A. F. Zobaa, Particle swarm optimization of passive filters for industrial plants in distribution networks, *Electric Power Components and Systems*, 39(16):1795--1808, October 2011.

[80] P. W. Sauer and M. A. Pai, Power System Dynamics and Stability, *Pearson education Pvt. Ltd., Singapore*, 2002.

[81] S. Panda, S. C. Swain and S. Mahapatro, A hybrid BFOA–MOL approach for FACTS-based damping controller design using modified local input signal, *International Journal of Electrical Power & Energy Systems*, 67: 238--51, May 2015.

[82] S. Poitout and P. J. C. Branco, Theoretical modeling and experimental tests of an electromagnetic fluid transportation system driven by a linear induction motor, *IEEE Transactions on Magnetics*, 42(9): 2133--2151, September 2006.

[83] D. Sabaripandiyan, G. Aarthi, H. H. Sait, and S. A.Daniel, Maximum Power Point Tracking using ANFIS, *International Journal of Applied Engineering Research*, 10(51): 1--6, 2015.

[84] Z. A. Faheem and S. H. E Aleem. A new approach for harmonic distortion minimization in power systems supplying nonlinear loads, *IEEE Transactions on Industrial Informatics*, 10(2): 1401--1412, May 2014.

[85] A. Juraj, J. Michalik, B. Dobrucky, and L. H. Viet. Single-phase power active filter using instantaneous reactive power theory: theoretical and practical approach, *Electrical Power Quality and Utilization*, 11 (1):33--38, 2005.

[86] G. Panda and P. K. Rautraya, Designing of SSSC-based damping controller using bacterial foraging algorithm to improve power system stability, *International Journal of Modelling, Identification and Control*, 21(2):172--183, January 2014.

Appendix

The default User's Manual [40] of Sim-Power Systems represents a complete list of parameters used for our study. Unless otherwise specified all the data are in pu only.

1. Single-Machine Infinite Bus Power System:

Generator: S_B = 2100 MVA, H = 3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544e-3, X_d = 1.305, X'_d= 0.296, X''_d= 0:252, X_q = 0.474, X'_q= 0.243; X''_d=0.18, T_d = 1.01 s, T'_d =1.01 s, T''_{q0} = 0.1 s.

Load at Bus2: 250 MW.

Transformer: 2100 MVA, 13.8/500 kV, 60 Hz, R_1 = R_2 = 0.002, L_1 = 0, L_2 = 0.12, D_1/Y_g connection, R_m = 500, L_m = 500.

Transmission line: 3-Ph, 60 Hz, Length = 300 km each, R_1 = 0.02546 X/km, R_0 = 0.3864 X/km, L_1 = 0.9337 e-3 H/km, L_0 = 4.1264e-3 H/km, C_1= 12.74e-9 F/km, C_0= 7.751e-9 F/ km.

Hydraulic Turbine and Governor: K_a = 3.33, T_a = 0.07, G_{min} = 0.01, G_{max} = 0.97518, V_{gmin} = -0.1 pu/s, V_{gmax} = 0.1 pu/s, R_p = 0.05, K_p = 1.163, K_i = 0.105, K_d = 0, T_d = 0.01 s, β=0, T_w = 2.67 s.

Excitation System: T_{LP} = 0.02 s, K_a = 200, T_a = 0.001 s, K_e = 1, T_e = 0, T_b = 0, T_c = 0, K_f = 0.001, T_f = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0.

Conventional Power System stabilizer Parameters: Gain K_{PS} = 30, Washout time constant T_W = 10 s,

Lead-lag structure time constants: T_{1CP} = 0.05s, T_{2CP} = 0.02s, T_{3CP} = 3s, T_{4CP} = 5.4 s,

Output limits of V_S= ± 0.15.

2. Three-Machine Power System:

Generators: S_{B1} = S_{B2} = 2100 MVA, S_{B3} = 4200 MVA, H = 3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e-3, X_d = 1.305, X'_d =0.296, X''_d = 0.252, X_q = 0.474, X'_q=0.243, X''_d=0.18, T_d = 1.01 s, T'_d=1.01 s; T''_{q0} =0.1 s.

Loads: Load1 = Load2 = 25 MW, Load3 = 7500MW+ 1500 MVAR, Load4 = 250 MW.

Transformers: S_{BT1} = S_{BT2} = 2100 MVA, S_{BT3} = 4200 MVA, 13.8/500 kV, f = 60 Hz, $R_1 = R_2$ = 0.002, L_1 = 0, L_2 = 0.12, D_1/Y_g connection, R_m = 500, L_m = 500.

Transmission lines: 3-Ph, 60 Hz, Line lengths: L1 = 175 km, L2 = 50 km, L3 = 100 km, R_1 = 0.02546 Ω/km, R_0 = 0.3864 Ω/km, L_1 = 0.9337e-3 H/km, L_0 = 4.1264e-3 H/km, C_1 = 12.74e-9 F/km, C_0 = 7.751e-9 F/km.

SSSC: Converter rating: S_{nom} = 100 MVA; System nominal voltage: V_{nom} = 500 kV; Frequency: f = 60 Hz; Maximum rate of change of reference voltage (V_{qref}) = 3 pu/s;

Converter impedances: R = 0.00533, L = 0.16; DC link nominal voltage: V_{DC} =40 kV; DC link equivalent capacitance C_{DC} =$375*10^{-6}$ F;

Injected Voltage regulator gains: K_P =0.00375, K_i =0.1875;

DC Voltage regulator gains: K_P =$0.1*10^{-3}$, K_i =$20*10^{-3}$;

Injected voltage magnitude limit: V_q = ± 0.2.

Initial operating conditions: Machine 1: Pe_1 = 1280MW (0.6095 pu); Qe_1 = 444.27 MVAR (0.2116 pu), Machine 2: Pe_2 = 880MW (0.419 pu); Qe_2 = 256.33 MVAR (0.1221 pu), Machine 3: Pe_3 = 3480.6MW (0.8287 pu); Qe_3 = 2577.2 MVAR (0.6136 pu).

3. Four-Machine Power System:

Generators: S_{B1} = S_{B2} = S_{B3} = S_{B4} = 2100 MVA, H = 3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e-3, X_d = 1.305, X'_d =0.296, X''_d = 0.252, X_q = 0.474, X'_q=0.243, X''_d=0.18, T_d = 1.01 s, T''_{q0} =0.1 s.

Loads: Load: P=11670MW, Q_L=1000 MVAR, Q_c=3070 MVAR;

Load2 P=92350MW, Q_L=1000 MVAR, Q_c= 5370 MVAR;

Transformers: S_{BT1} = S_{BT2} = S_{BT3} = S_{BT4} =2100 MVA, 13.8/500 kV, f = 60 Hz, R1 = R2 = 0.002, L1 = 0, L2 = 0.12, D1/Yg connection, Rm = 500, Lm = 500.

Transmission lines: 3-Ph, 60 Hz, Line lengths: L_1 = 50 km, L_2 = 20 km, L_3 = 220 km, R_1 = 0.02546 Ω/km, R_0 = 0.3864 Ω/km, L_1 = 0.9337e-3 H/km, L_0 = $4.1264e^{-3}$ H/km, C_1 = $12.74e^{-9}$ F/km, C_0 = $7.751e^{-9}$ F/km.

SSSC: Converter rating: S_{nom} = 100 MVA; System nominal voltage: V_{nom} = 500 kV; Frequency: f = 60 Hz; Maximum rate of change of reference voltage (Vqref) = 3 pu/s;

Converter impedances: R = 0.00533, L = 0.16; DC link nominal voltage: V_{DC} =40 kV; DC link equivalent capacitance C_{DC} =375*10^{-6} F;

Injected Voltage regulator gains: K_P =0.00375, K_i =0.1875;

DC Voltage regulator gains: K_P =0.1*10^{-3}, K_i =20*10^{-3};

Injected voltage magnitude limit: Vq = ± 0.2. Initial operating conditions: Machine 1: P_{e1} = 1567.5MW (0.74645 pu); Q_{e1} = 115.2 MVAR (0.05486 pu), Machine 2: P_{e2} = 1567.8MW (0.7466 pu); Q_{e2} = 146.96 MVAR (0.06998 pu), Machine 3: P_{e3} = 1576.6 MW (0.7507 pu); Q_{e3} = 316.51 MVAR (0.1507 pu). Machine 4: P_{e3} = 1735 MW (0.8262 pu); Q_{e3} = 305.88 MVAR (0.14567 pu).

Dissemination

International Journal Articles

[1] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy. Time delay approach for PSS and SSSC based coordinated controller design using hybrid PSO-GSA algorithm. *International journal of power and energy system (IJEPES) – Elsevier,* Volume 71, pp. 262–273, March 2015.

[2] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy. A new hybrid GA-GSA algorithm for designing a unified power flow controller. *International journal of power and energy system (IJEPES) – Elsevier,* vol. 73, pp. 1060-1069, July 2015.

[3] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy. A Hybrid Gravitational Search and Pattern Search Algorithm for Tuning Damping Controller Parameters for a Unified Power Flow Controller: - A Comparative Approach. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields.* (Submitted in revised format).

[4] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy. Design of a Novel Modified Local Input Signal for the SSSC Based Damping Controller. *IET Generation, Transmission & Distribution* (Under Review).

Conference Publications

[1] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy, "Gravitational search algorithm for the static synchronous series compensator based damping controller design," *IEEE TechSym, IIT Kharagpur*, pp. 356-361, DOI: 10.1109/TechSym.2014.6808075, Feb. 28-March 2, 2014.

[2] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy, "Unified Power Flow Controller based Damping Controller Design:-A Hybrid PSO-GSA Approach," *IEEE ICEPE, NIT, Meghalaya,* pp. 1-6, DOI: 10.1109/EPETSG.2015.7510143, June 12-13, 2015 (Best Poster of the conference).

[3] Rajendra Kumar Khadanga and Jitendriya Kumar Satapathy, "Co-Ordinated Design of PSS and SSSC Based Damping Controller Using Evolutionary Algorithms," *IEEE Indicon-2015*, pp. 1-6, DOI: 10.1109/INDICON.2015.7443667, Dec. 17-20, 2015.

Vitae

Name	:	Rajendra Kumar Khadanga
Date of Birth	:	23rd September 1986
Permanent Address	:	S/O Simanchala Khadanga Balunki Peta Street, Aska Road, Berhampur, Ganjam, Odisha, 760006.
E-mail	:	rajendra697@gmail.com

Academic Qualifications:

- Pursuing **Ph. D** in Electrical Engineering, National Institute of Technology, Rourkela.
- **M.Tech** in Electrical Engineering, Biju Patnaik University of Technology, Rourkela, Odisha, India.
- **B.Tech** in Electrical and Electronics Engineering (EEE) from N.I.S.T, Berhampur, under B.P.U.T. Rourkela, Odisha, India.

Electrical Power and Energy Systems 73 (2015) 1060–1069

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new hybrid GA–GSA algorithm for tuning damping controller parameters for a unified power flow controller

Rajendra Ku Khadanga *, Jitendriya Ku Satapathy

Department of Electrical Engineering, National Institute of Technology (NIT), Rourkela, Odisha 769008, India

ARTICLE INFO

Article history:
Received 4 June 2014
Received in revised form 20 May 2015
Accepted 9 July 2015
Available online 20 July 2015

Keywords:
Flexible AC transmission systems (FACTS)
Unified power flow controller (UPFC)
Modified Heffron–Phillips (P–H) model
Damping controller
Hybrid Genetic–Gravitational Search Algorithm (hGA–GSA)

ABSTRACT

Tuning of damping controller parameters for optimal setting, such as gain and signal wash out block parameters, has major effects on its performance improvement. Estimation of optimum values for these parameters requires reliable and effective training methods so that the error during training reaches its minimum. This paper presents, a suitable tuning method for optimizing the damping controller parameters using a novel hybrid Genetic Algorithm–Gravitational Search Algorithm (hGA–GSA). The primary purpose is that the FACTS based damping controller parameter can be optimized using the proposed method. The central research objective here is that, how the system stability can be improved by the optimal settings of the variables of a damping controller obtained using the above proposed algorithm. Extensive experimental results on different benchmarks show that the hybrid algorithm performs better than standard gravitational search algorithm (GSA) and genetic algorithm (GA). In this proposed work, the comparison of the hGA–GSA algorithm with the GSA and GA algorithm in term of convergence rate and the computation time is carried out. The simulation results represent that the controller design using the proposed hGA–GSA provides better solutions as compared to other conventional methods.

Introduction

The Flexible AC Transmission Systems (FACTS) is a new technology that acts as a promising tool for power system application during the last decade. A critical and versatile member of the FACTS family is the Unified power flow controller (UPFC) which typically comprises of voltage source converter (VSC). The basic advantage of UPFC is that it can control all the parameters of the system like line impedance, voltage, and the phase angle thus justifies the name as "unified". The key function of this device is to control the transmission line power as well as to improve the transient stability of the system. The UPFC can offer voltage support and alleviate the system oscillation of the power system while it is subjected to changes in ambient conditions [1].

In the power system stability studies, preference is always given to lead–lag controllers. The online tuning of the parameters of these controllers is always a challenge to the power engineers and development of suitable soft-computing techniques for tuning of these controller for better stability have been reported [2]. Over the years, in order to carry out the power system study (small signal stability study) the linear Phillips–Heffron model has been used [3] that can be utilized for analyzing the low frequency oscillation of the power system [4–6].

In this study a UPFC based lead–lag damping controller is used for the stability analysis of power system. Tuning of the damping controller of the UPFC is an uphill task as the structure is highly complex [7,8]. The literature study shows that the conventional techniques are very time consuming, convergence rate is slow, being iterative, requires substantial computational burden [9–11].

Genetic algorithm (GA) is the most widely used method of finding a damping control parameters [12]. This algorithm is commonly used for function approximation and pattern classifications [13]. GA algorithm is likely to reach local minima especially in case that the error surface has multiple minima, thus it is a suitable choice for the parameter estimation [14,15]. Although, Genetic Algorithm is an option for finding the optimum parameters but due to its exploration and exploitation properties, it suffers from the mutation problem leading to premature convergences and needs more time to converge to an optimum solution comparing to the other algorithms like particle swarm optimization [16].

Also and then algorithm known as gravitational search algorithm (GSA) has been reported. The said algorithm utilizes the concept of the law of gravity, the mass interactions [17]. GSA is a simple concept, and this can be easily implemented and is also

* Corresponding author.
E-mail addresses: rajendra697@gmail.com (R.K. Khadanga), jitendriya@gmail.com (J.K. Satapathy).

http://dx.doi.org/10.1016/j.ijepes.2015.07.016
0142-0615/

Electrical Power and Energy Systems 71 (2015) 262–273

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Time delay approach for PSS and SSSC based coordinated controller design using hybrid PSO–GSA algorithm

Rajendra Ku Khadanga *, Jitendriya Ku Satapathy

Department of Electrical Engineering, National Institute of Technology (NIT), Raurkela, Odisha 769008, India

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form 9 February 2015
Accepted 17 March 2015
Available online 31 March 2015

Keywords:
Static synchronous series compensator (SSSC)
Power system stability
Power system stabilizer (PSS)
Gravitational search algorithm (GSA)
Particle swarm optimization (PSO)
Multi-machine power system

ABSTRACT

In this work we present a novel approach in order to improve the power system stability, by designing a coordinated structure composed of a power system stabilizer and static synchronous series compensator (SSSC)-based damping controller. In the design approach various time delays and signal transmission delays owing to sensors are included. This is a coordinated design problem which is treated as an optimization problem. A new hybrid particle swarm optimization and gravitational search algorithm (hPSO–GSA) algorithm is used in order to find the controller parameters. The performance of single-machine infinite-bus power system as well as the multi-machine power systems are evaluated by applying the proposed hPSO–GSA based controllers (PSS and damping controller). Various results are shown here with different loading condition and system configuration over a wide range which will prove the robustness and effectiveness of the above design approach. From the results it can be observed that, the proposed hPSO–GSA based controller provides superior damping to the power system oscillation on a wide range of disturbances. Again from the simulation based results it can be concluded that, for a multi-machine power system, the modal oscillation which is very dangerous can be easily damped out with the above proposed approach.

Introduction

The major problem associated with an interconnected power system when connected by a weak line is the low frequency oscillation. If the damping of the system is not adequate, then these oscillation leads to system separation. In industries to damp out these oscillations, generally PSS are used [1]. However the application of PSS is insufficient in some cases in order to provide sufficient damping when the loading of a transmission line increases over a long distance. For this purpose other alternatives which may be effective are needed which can be applied in addition with PSS.

Recently the power engineer's uses FACTS controllers for the power system applications. The main objective of the FACTS controller is to control the system parameter at a very fast rate, which can improve the system stability [2]. The SSSC is considered to be a member of the FACTS family. The SSSC has a unique capability that it can change reactance from capacitive to inductive [3]. An auxiliary stabilizing signal is used here which can improve the system stability in a significant manner. This auxiliary signal is basically used in the control function of the SSSC [4]. The application of SSSC to improve stability and to damp out the system oscillation is discussed in [5–9].

The performance of a power system can be enhanced by designing a PSS and a FACTS based damping controller which can be operated in a coordinated manner. A lot of research has been carried out in this coordinated process work [10–14].

Generally a FACTS device is installed far way from the generator. On the other hand PSS is installed near to the generator. Thus a transmission delay is observed due to various signal transmission and sensors used in the powers system [15]. These delays should be included when designing a FACT/PSS based damping controller design. However in the above literature study these time delays have not been considered. Also the literature includes various algorithms such as residue method, linear matrix inequality technique, eigenvalue-distance minimization approach, and multiplemodel adaptive control approach, for the coordinated controller's damping enhancement. The key issue which need to be discussed in the coordinated design technique is to verify the robustness of the design approach. Very efficient and effective techniques are highly beneficial in order to design the robust controller which can change according to the system configurations.

* Corresponding author.
E-mail addresses: rajendra697@gmail.com (R.K. Khadanga), jitendriya@gmail.com (J.K. Satapathy).

http://dx.doi.org/10.1016/j.ijepes.2015.03.014
0142-0615/