POWER SYSTEM STABILITY IMPROVEMENT VIA STATCOM AND SUPERCAPACITOR

BY

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This thesis is dedicated to:

- My father for his mentorship
- My mother for her blessings
- My wife for her care
- My family for their encouragement

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LIST OF ABBREVIATIONS

STATCOM	:	Static Synchronous compensator
SCESS	:	Super capacitor energy storage system
BESS	:	Battery energy storage system
PSO	:	Particle swarm optimization
FACTS	:	Flexible Alternating current transmission system
AVR	:	Automatic Voltage Regulator
GTO	**:**	Gate Turn-off Thyristor
IGBT	**:**	Insulated Gate Bipolar Transistor
SMIB	**:**	Single Machine infinite bus

LIST OF SYMBOLS

x_q	Generator internal quadrature reactance
x_{tl}	Transmission line reactance between Generator bus and middle bus
x_d'	Generator internal transient direct reactance
x_{lb}	Transmission line reactance between the middle bus and the infinite bus
x_{sdt}	STATCOM transformer reactance
V_{dc}	STATCOM DC link voltage
C_{dc}	STATCOM DC link capacitance
C_{sc}	Super Capacitor's capacitance
L_{sc}	DC/DC converter inductance
P_m	Generator input mechanical power
P_e	Generator output electrical power
v_t	Generator terminal voltage
v_m	Middle bus voltage
v_b	Infinite bus voltage
E_{fd}	Generator field voltage
E_q'	Generator transient internal voltage
E_q	Generator internal voltage
ω_0	Generator synchronous speed
ω	Generator rotor speed
δ_m	Middle bus voltage angle
δ	Rotor angle, also the generator internal voltage angle

D	Generator damping coefficient
M	Generator inertia coefficient
H	Generator inertia constant
T_{do}'	Generator open circuit field time constant
T_C	STATCOM time constant
K_A	Exciter gain
T_A	Exciter time constant
T_w	Power system stabilizer washout time constant
m	STATCOM modulation index
ψ	STATCOM voltage angle
DD	DC/DC converter duty cycle

K_P, T_{P1} - T_{P4}	Excitation PSS gain and time constants
K_m, T_{m1} - T_{m4}	STATCOM magnitude PSS gain and time constants
K_{epsi}, T_{epsi1} - T_{epsi4}	STATCOM angle PSS gain and time constants
K_{sc}, T_{sc}- T_{sc}	SCESS PSS gain and time constants
K_{PDC}, K_{IDC}	STATCOM DC voltage PI controller parameters
K_{PAC}, K_{IAC}	STATCOM AC voltage PI controller parameters

ABSTRACT

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Power system low frequency oscillations became significant in the 1960s during the interconnection of large power systems with weak transmission lines. The most commonly used method for damping those oscillations is the power system stabilizer, but it has its disadvantages such as causing high voltage variations during disturbances. The development of FACTS, or Flexible Alternating Current Transmission Systems, have made them good candidates for enhancing power system dynamic stability. STATCOM, or static synchronous compensator, is a one of FACTS devices, that is connected in shunt to the power system. STATCOMs by their own can exchange reactive power with the power system, but they have limited ability to exchange real power because they don’t include energy storage devices. This limits their ability to improve the power system dynamic stability. In this thesis, supercapacitor energy storage systems "SCESS" is proposed as energy storage for STATCOM. The objective of this thesis is to design and analyze a system consisting of a STATCOM and a supercapacitor to improve power system dynamic stability. The proposed system takes into consideration the coordinated design of generator excitation Power system Stabilizer, STATCOM voltage regulators, and STATCOM damping stabilizers. The design of the control system is formulated as an optimization problem, and Particle Swarm Optimization technique has been utilized to search for the optimum control system parameters. Nonlinear time domain simulations have been carried out to demonstrate the effectiveness of the proposed control strategy in damping low frequency oscillations. The results have shown that the performance of the proposed STATCOM with Supercapacitor in improving power system dynamic stability is superior to that of excitation PSS, or excitation PSS and STATCOM only.

ملخص الرسالة

الاسم الكامل: مصطفى عدنان جعفر الرمضان

عنوان الرسالة: تحسين استقرار نظام الطاقة بواسطة المعوض المتزامن الساكن والمكثف الفائق

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المعوض المتزامن الساكن STATCOM هو أحد أنظمة النقل المرن للتيار المتردد FACTS المعتمدة على ألكترونيات القوى الكهربائية، الذي يتم توصيله بنظام القوى الكهربائية لتبادل القدرة الغير فعالة. الهدف من هذه الرسالة هو تصميم وتحليل نظام متكون من معوض متزامن ساكن ومكثف فائق لتحسين استقرار نظام القوى الكهربائية بزيادة تثبيط التأرجحات المنخفضة التردد. النظام المقترح يأخذ بالاعتبار التصميم المنسق لموازن نظام القوى الكهربائية PSS ومنظمات الجهد لمعوض المتزامن الساكن و موازنات المعوض المتزامن الساكن. تصميم نظام التحكم تم صياغته إلى مسألة حل أمثل، وتم استخدام تقنية تحسين سرب الجسيمات للبحث عن القيم المثلى لمعاملات نظام التحكم. وتم تنفيذ محاكاة نطاق وقتي غير خطية لإظهار فعالية النظام في تثبيط التأرجحات المنخفضة التردد. النتائج بينت أن أداء نظام المعوض المتزامن الساكن مع المكثف الفائق المقترح في تحسين الاستقرار الديناميكي لنظام القوى الكهربائية متفوق بالنسبة لنظام موازن نظام القوى الكهربائية أو موازن نظام القوى الكهربائية مع المعوض المتزامن الساكن فقط.

CHAPTER 1

INTRODUCTION

1.1. Thesis Overview

Power system stability is the field in power system engineering that is concerned with ability of the system to maintain the desired system parameters (voltage, current, power, and frequency) at different operating conditions, and after various disturbances. Power system engineers have to consider power system stability during the design or modification of power system networks. The broad definition of power system stability includes several classifications under its umbrella. One class is power system dynamic stability, which is the ability of power systems to prevent small disturbances from growing up and causing major upset. In particular, power system frequency oscillations have been the concern in this class.

Power system frequency is directly related to the generators' rotor speeds. The rotors of those generators rotate in synchronism as long as they are connected to the same power system network. Ideally, the frequency of a power system shall be constant. In Saudi Arabia, the power system frequency is 60 Hz. However, in real power systems, frequency deviations are experienced, because any deviation in the generator mechanical input power or the electrical output power will cause a deviation in the rotor speed. In fact, a temporary deviation can cause a persistent oscillation in the generator rotor speed because of the nature of 2^{nd} order generator electro-mechanical dynamic relationship. Those oscillations are called power system low frequency oscillations in power system engineering, and the typical frequency range of those oscillations is 0.2 - 3 Hz.

The power system stabilizer needs to be designed to damp the low frequency oscillations. Insufficient damping will cause them to grow up, and eventually the affected generators will lose synchronism with the rest of the system. This is a dangerous situation that will force the protection system to isolate those generators from the rest of the network. This phenomenon has caused some of the historical power failures.

With the non-stopping increase in the electrical demand, electric utilities are motivated to increase the power transfer capacity of transmission lines. While the short transmission lines power transfer is usually limited by the thermal capacity of the lines, the long lines dominant factor is usually the stability of power system. Therefore, Exploring options to improve power system stability can allow more utilization of the long transmission lines, which is an alternative to the costly option of constructing new transmission lines.

Power system stabilizers (PSS), connected to the generation excitation systems, have been the conventional method to damp the low frequency oscillation. STATCOMs “Static synchronous compensators”, which belong to the family of FACTs “Flexible Alternating current Transmission systems” that can installed on transmission lines, have been also proposed to damp the low frequency oscillations. STATCOMs are power electronic devices that are used to control the power flow in power systems to enhance their stability and quality. A STATCOM consists of a DC capacitor and an inverter that converts DC voltage to AC voltage. STATCOMs can be connected in shunt to the transmission line either at the end points or somewhere in the middle.The main purpose of the STATCOM is to control the voltage at the connection point, by exchanging reactive power with the system. STATCOMs can also be used to enhance power system dynamic stability.

STATCOMs by their own can exchange reactive power with the power system, but they have limited ability to exchange real power because they don't include energy storage devices. STATCOMs coupled with energy storage devices such as batteries have been proposed to allow exchanging real power. However, batteries have a limitation in the power they can deliver because of their slow chemical process. The current trend is to use supercapacitor energy storage systems "SCESS" as energy storage for STATCOMS. This is because the supercapacitors have relatively high power interchanging capability.

Supercapacitors were introduced since 1960's, but the interest has grown recently in utilizing them as energy storage systems for STATCOMs. Supercapacitors are also called ultracapacitors or eletrochemical double layer capacitors. They have very large effective surface area and very small dielectric thickness which make their capacitance ,typically in Farads, much higher than conventional capacitors, typically in microfarads. Their power rating is also much higher than a conventional battery because they can release energy quickly, while the chemical process in batteries makes them slower in releasing energy.

STATCOM has not only been the recent trend in literature, but also have been installed in several locations in the world. The use of SCESS system can further improve the performance of STATCOM. Those factors have motivated the development of this thesis.

The thesis consists of threeparts; namely, STATCOM-SCESS system design and power system modeling, control system parameters optimization, and final simulation of the system. In this thesis, a STATCOM-SCESS system has been designed with its controller, and their performance in mitigate power system low frequency oscillations has been shown to be superior compared to STATCOM alone.

1.2. Thesis Objective

The objective of this thesis is to investigate the improvement in the stability of the power system by using STATCOM with Super capacitor. The study includes coordinated design between the power system stabilizer (PSS), STATCOM voltage PI controllers, and STATCOM stabilizers. The control system parameters have been optimized using Particle Swarm Optimization (PSO), and has been implement and tested.The thesis objectives have been met by:

1. Designof the STATCOM-SCESS and its control system.
2. Simulation of the power system with STATCOM-SCESS
3. Investigation of the effectiveness of the proposed STATCOM-SCESS system by comparing it with PSS, and STATCOM only.

1.3. Thesis Contribution

In this thesis, a system consisting of STATCOM and Supercapacitor have been designed and simulated for improving power system dynamic stability. The design of the generator excitation PSS, STATCOM voltage regulators, and STATCOM stabilizers have been coordinated to achieve optimum performance. The design of the controllers is formulated into an optimization problem, and Particle Swarm Optimization technique has been used to select the optimum controllers' parameters. The designed system was tested with nonlinear simulation, and its performance is compared with the performance of the power system with excitation PSS only, and the power system with excitation PSS and STATCOM only.

The three main contributions of this thesis are as follows:

1. A discretized non-linear model has been developed for the single machine infinite bus (SMIB) power system with STATCOM and Supercapacitor system.
2. The design problem of the control system parameters has been formulated as optimization problem, and Particle Swarm Optimization (PSO) technique has been used to search for the optimum solution.
3. A comparison has been made between the performance of the three systems, SMIB, SMIB with STATCOM, and SMIB with STATCOM and Supercapacitor, in improving power system stability.

1.4. Thesis Organization

The following organization has been used in this thesis: Chapter 2 includes the literature survey. The principles of operation of the STATCOM-SCESS system are described in Chapter 3. Chapter 3 also includes the system design and modeling. The control strategy, and the problem formulation are presented in Chapter 4. Particle Swarm Optimization technique is presented in Chapter 4. The simulation results and discussions are included in Chapter 6, while Chapter 7 draws the conclusion and provides the future work.

CHAPTER 2

LITERATURE REVIEW

2.1. Power System Stability

Power system stability refers to the ability of the power system to maintain the desired operating point (voltage, frequency, current, and phase angle), and return to a suitable operating point following a disturbance. Based on the nature the disturbance, the study of power system stability is classified into three categories: steady state stability, transient stability, and dynamic, or small signal, stability. Steady state stability ensures that the gradual changes in the system will not cause the system voltages, currents, and phase angles to go outside the acceptable ranges. Transient stability refers to the ability of the system to reach a stable operating point after a severe disturbance. Dynamic stability refers to the ability of the system to return to the operating point following small signal disturbances [1].

One form of power system stability is the rotor angle stability. Running the generator at a constant speed requires that the mechanical input power equals to the electrical output power plus the generator losses. Disturbances such as faults will reduce the electrical power output. This power unbalance will cause acceleration of the generator rotor. If the fault is not cleared fast enough, the generator will lose synchronism with the rest of the power system, and the out of step protection will take action to trip the generator. A transiently stable system will ensure that he fault is cleared before the generator loses synchronism [1], [2].

This thesis is mainly concerned with the rotor angle dynamic stability, which deals with low frequency oscillations due to insufficient damping torque. The problem of low frequency oscillations became significant in the 1960s during the interconnection of large power systems with weak transmission lines [3] , [4]. The main source of the power system negative damping is the fast acting automatic voltage regulators, which were designed to improve the power system transient stability [2]. The oscillation mode can be a local oscillation modes, which is the oscillation of generation units at one generation station against to the rest of the power system, or an inter-area oscillation mode, which is the oscillation of a group of generators in one part of the power system against a group of generators at another part [1]. An evaluation that was made on the power network at U.S. west coast have brought global attention to this subject, which highlighted the dynamic instability of the system, as generator rotors could survive the first swing upon a three phase fault, but the growing swings that follows the first swing drive them generators out of synchronism [2].

The low frequency oscillations can be avoided by designing the power system with adequate damping, which is a more cost effective option than building new lines or new power generation stations [5], [6]. The most commonly used method to provide the necessary damping is the conventional power system stabilizer, which is a lead lag controller that provides an auxiliary signal to the excitation system's voltage regulation loop [4]. The PSS function is to provide sufficient damping torque in phase with the speed deviation to damp the electromechanical oscillations. However, the PSS have a disadvantage that it may cause undesired voltage variations during disturbances [3]. Other methods for damping low frequency oscillations have been proposed in literature, one of them utilizes STATCOM, which will be discussed further in the next section.

2.2. STATCOM

STATCOM “Static synchronous compensator” belongs to the family of FACTS “Flexible AC Transmission systems”, which are defined in [7] as alternating current transmission systems incorporating power electronic based and other static controllers to enhance controllability and increased power transfer capability. The flow of real and reactive power through the transmission line without the FACTS devices is called the natural flow, and it depends on the receiving and sending ends voltage amplitudes and angles in addition to the transmission line impedance. FACTS control the real and reactive power flow through the transmission line using at least one of the three methods; namely, voltage regulation, phase angle regulation, and reactance regulation. An overview of the types and characteristics of FACTS devices is presented in [6] and [8]. An overview of several actual installations of different FACTS devices at U.S. is presented in [9]. The FACTS devices that are connected in shunt to the power system for voltage regulation are: Switched Inductor/Capacitor, Static Var Compensator (SVC), and STATCOM, which is the seconds generation of SVC. Those devices are well explained in [7], [8], and [10]. An analysis of the advantages and limitations of installing SVC or STATCOM installed on a power network in China is presented in [11]. STATCOM has several advantages compared to SVC such as maintaining the rated required reactive power support even at reduced A/C voltage, improving the transient stability margin for the power system, and allowing the controlled exchange of active power if an energy source used [12], [13]. The later advantage could be used to improve the power system dynamic stability, since injecting real current at one of ends of the transmission lines improves the power system dynamic stability more than injecting reactive current of the same magnitude at the middle bus [12].

STATCOM is a shunt static device that generates a set of three phase voltages at the power system frequency with controllable amplitude and phase. STATCOM typically consists of a voltage sourced converter (VSC) connected to an AC voltage bus through a reactance [14]. By varying the magnitude of the electronically generated voltage, the STATCOM can inject a capacitive or inductive reactive power into the main power system [15]. The voltage sourced converters consists of a dc link capacitor and an inverter which is controlled by power electronic switches. The power electronic switches can be either GTOs "Gate Turn off thyristors" in case of low frequency switching, or IGBTs "insulated gate bypolar transistors" in case of high frequency switching. A thyristor based STATCOM design, which can only absorb reactive power, is also presented in [16].

Some of the early versions of STATCOM, before it was called STATOM, are presented STATCOM in [17] and [18]. Mathematical Modeling and analysis of STATCOM is available in [19]. STATCOMs utilizing current sourced converters instead of VSC were also proposed [20]. Developed prototype STATCOMs are presented in [21] and [22]. Some real world applications of STATCOM in power systems are presented in [8], [23], [24], and [25].

The authors in [26] discussed different topologies of STATCOMs, including multi-pulse and cascade STATCOMs. The voltage sourced converter can provide a sinusoidal voltage, but with the addition of harmonics, and the main purpose of designing multi-pulse or cascade STATCOMs is to help to mitigating those harmonics. Filters can also be installed on the STATCOM A/C bus to mitigating the harmonics, and the authors in [27] describe the design of passive filters for harmonics mitigation for inverters connected to power distribution systems. The design of LC filters for distribution STATCOMs is also discussed in [28]. High frequency switching techniques such as the Selective harmonic elimination had also been used minimize the STATCOM harmonics [29].

STATCOM requires a controller to control the real and reactive power flow for power system compensation. The controller can either regulate the flow of reactive power or to the point of common coupling (PCC) or the AC voltage at the PCC. There are many control methods that can be utilized for STATCOM control. The control system described in [7] utilizes a PI controller. It consists of a quadrature current control loop inside a line voltage magnitude control loop. The output of the inner quadrature current control loop is the angle difference between voltage at the point of common coupling and the VSC generated voltage. This angle will cause real power flow and a change in the voltage of the VSC dc link capacitor. Consequently, the quadrature current will be adjusted. The reference quadrature current is the output of the outer line voltage control loop. Adjusting the quadrature current will cause adjustment of the line voltage. At steady state, VCS generated voltage is synchronized with the power system line voltage, except for a small phase difference [7].

The authors in [30] propose another control method for the STATCOM by decoupling the direct current control and the quadrature current control, utilizing a PI controller for each. This allows independent control of the VSC voltage amplitude and phase. The advantage of this control method over the previous one is the possibility of real power exchange with the power system as shown in the next section. Another control method is also presented in [31], which employs PI controllers to control VSC voltage amplitude and angle directly from the PCC voltage amplitude and capacitor dc voltage without inner current control loops, and in addition to a stabilizer for power system frequency damping.

STATCOM controller designs different from the conventional PI controllers are available in literature. STATCOM controllers based on pole placement control, and linear quadratic regulation are presented in [14]. Robust STATCOM controllers based on loop shaping techniques are presented in [32], [33], and [34]. On-line control of STATCOM is presented in [35].

Besides voltage amplitude regulation, the control system shall also detect the main power system frequency and phase to synchronize the output of the VSC. The common method used for frequency and phase detection is the synchronous reference frame phase locked loop (SRF-PLL). Special designs of PLL for STATCOM have also been presented, such as the instantaneous phase locked loop in [36], which detects negative sequence voltage, and the PLL with moving average filter, which eliminates the effect of harmonics on the PLL [37].

2.3. Energy Storage Systems

The authors in [38] describe many methods of energy storage for power system applications; namely, batteries, flywheels, super capacitors, compressed air, hydraulic systems, and superconducting magnetic energy storage systems. Battery energy storage system is used in many locations but its disadvantages are the limited discharge rate and the degradation with time. Hydraulic storage systems are also widely used but require large amount of land, and take long time to construct. Both super capacitor and superconducting magnetic energy storages do not have those disadvantages. They have fast response to electrical disturbances, and they can deliver high amount of power. The advantage of super capacitor energy storage system over the superconducting magnetic energy storage system is that it does not need the cooling and the sophisticated structure which is required by the superconducting magnetic energy storage system [38].

The super capacitors have been known since 1960's. A super capacitor is an electrochemical double layer capacitor. Super capacitors are highly temperature and vibration resistive. They have a high discharge cycle, and they are able to provide high power. Super capacitor banks currently have a rated voltage up to 1.5 kV. However, the disadvantage of super capacitor is that they store low amount of energy compared to batteries. Therefore, they are suitable for applications where energy is needed for short time [38]. A typical super capacitor can store 5% of the energy of a typical battery of the same weight, but can provide 50 times more power [38] .The authors in [39] applied impedance spectroscopy on a supercapacitor, and have came up with a four parameters model that describes the supercapacitor more accurately than the typical 2-parameters RC model, especially in highly dynamic applications.

Besides power system networks application, the major application for super capacitors is in electrical transportation systems. The authors in [40] propose a design of super capacitor energy storage system for a Metro-vehicle. In this application, the kinetic energy is not completely wasted during breaking. Regenerative breaking is used to store the kinetic energy into a super capacitor for later re-use. This method does not only save energy, but also helps to stabilize the power system voltage. Designs of supercapacitor energy storage systems (SCESS) for hybrid electric vehicles have been proposed in [41] and [42]. The design in [42] includes also a battery system, to combine the benefits of the battery high energy storage, and the super capacitor high rate of energy exchange.

The designs in the previously mentioned references in [40], [41] and [42] all include bidirectional DC/DC converters in the super capacitor energy storage. Those references mention the benefits of converters; namely: (1) the supercapacitor usually have lower voltage rating than the system voltage, (2) It is desired to fix the output voltage while the supercapacitor voltage decreases as it discharges, and (3) it is allows to control the output current of the SCESS system. The authors in [43] describe the typical bidirectional buck-boost DC/DC converters, and the associated separate controllers for buck and boost mode which is the mostly used configuration for those controllers. They also propose a unified controller that controls both the buck and the boost mode, solving the problem of the saturation in the typical converters when transferring from buck mode to boost mode and vice versa.

The authors in [44] proposed utilizing super capacitor energy storage system for electronic power transformers. Electronics power transformers have the same functions of conventional power transformers with additional features. They consist of three stages: input AC/DC converter, isolation medium frequency transformer, and output DC/AC converter. The SCESS consists of supercapacitor and DC/DC converter to allow the electronic power transformer to ride through momentary interruptions.

2.4. Using Energy Storage Systems with STATCOMs

There are proposals in the literature for connecting an energy storage system to the STATCOM to improve its performance. Reference [45] includes modeling and simulation of ESTATCOM, consisting of STATCOM and energy storage system, the model in [45] is general and can be applied to either for battery or supercapacitor energy storage systems. However, the model did not consider the DC/DC converter. The authors in [45] used their model to design a control system from damping low frequency oscillations. Their simulation results have shown that the ESTATCOM ability to exchange active power has led to stronger oscillations damping compared to a STATCOM alone. Similar design with the similar conclusion has been presented in [46] utilizing a STATCOM with battery energy storage system, also without a DC/DC converter.

The authors in [47] presents a dynamic model of battery energy storage systems BESS that consists of 6 parameters. They used their model to analyze a BESS installed at the generator output bus, for the main purpose of peak load leveling. They have shown using their model that the BESS can improve the dynamic stability of the system by damping the torsional oscillations. However, their system did not have a DC/DC converter, and a DC/AC converter is used to couple the BESS to the power system, which is a simpler version of STATCOM that does not have a voltage regulation controller sine it is not designed for reactive support.

The authors in [48] propose a STATCOM with supercapacitor to be used for wind power generation system to compensate for the fluctuations that result from wind speed variations. They have shown that the system also helped to stabilizer the system voltage and current during a remote fault. Reference [49] highlights a problem with using distribution systems STATCOMs without energy storage systems that they cannot regulate their DC voltage and may even trip during disturbances in the distribution system such as a remote single line to ground fault. The authors presented a STATCOM-SCESS system that is able to maintain the DC link voltage during various disturbances in the distribution system. Their system did not include a DC/DC converter.

A STATCOM with superconducting magnetic energy storage (SMES) has also been proposed in [50]. The design in [50] includes a DC/DC converter that controls the charging and discharging of the SMES. The configuration of this DC/DC converter is different from the DC/DC converter associated with SCESS system, since the SMES system stores energy as current, and it is charged, or discharged by the voltage across the coil of the SMES. The model was developed for the power system with STATCOM/SMESS, and the simulations results have shown that STATCOM-SMES has provided stronger damping to low frequency oscillations compared to STATCOM alone. The authors also has shown that the damping is stronger when the STATCOM-SMES is placed at the generation side of the transmission line, compared to the middle of the line.

The use Supercapacitor with DC/DC converters for STATCOMs have been explored in [15] and [51]. In those references, the authors have designed the SCESS, and developed a control system through small signal model. They run a simulation where their system is connected to a load bus. Their results illustrated that their system prevented voltage sags, and frequency drops associated with high load switching by the real power exchange from the STATCOM-SCESS. However, the authors did not address the capability of their system to enhance the damping of low frequency oscillations. In [52], a STATCOM-SCESS with DC/DC converter was presented for D-STATCOM. The authors have shown that their system was able to eliminate the A/C voltage sag due to high load switching, to provide real power for certain amount of time, and to eliminate harmonics from a nonlinear load from traveling to the utility power supply. However, the authors did not address the capability this design to damp low frequency oscillations.

The design of the SCESS system in [15] and [51], and in [52] consist of the super capacitor, the DC/DC converter, and the dc link capacitor which is common between the SCESS and the STATCOM. The DC/DC converter is a bi-direction buck/boost converter which consists of two transistors which for the buck and the boost action. A controller is required to control the operation of the DC/DC converter. A typical control scheme used in this application is the peak current control mode which is described in details in [53].

CHAPTER 3

POWER SYSTEM MODELNG

3.1. STATCOM Principles of Operation

The STATCOM consists of a DC/AC inverter with a capacitor on the DC side, and a reactance connecting the A/C side to the power system A/C bus as shown in Figure 3-1. The reactance, X_{sdt}, could be the leakage reactance of a transformer. The inverter can be made of gate turn off thyristors, GTO, or insulated gate bipolar transistors, IGBTs. A 2-levels, 6-pulses inverter is shown in the diagram for simplicity, but higher level/pulse number inverter is typically used to reduce the harmonics. The gates of the switching devices are connected to gate pulse generators, which controls the sequence of switching and the firing angles, so that a 120^{o} phased three phase A/C output is produced from the inverter, whose angle and magnitude is controllable. Thus, the equivalent circuit for the STATCOM is as shown in Figure 3-2, consisting of voltage source with controllable magnitude and angle, connected to the STATCOM A/C bus through a reactance.

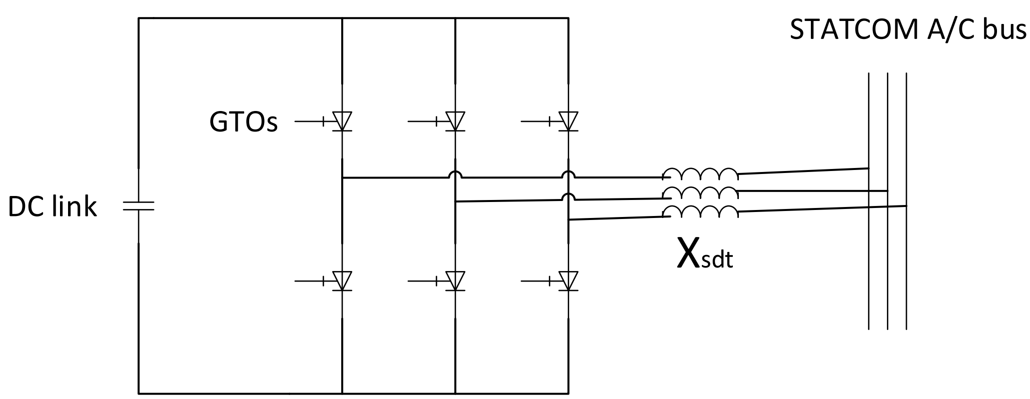

Figure 3-1 STATCOM components

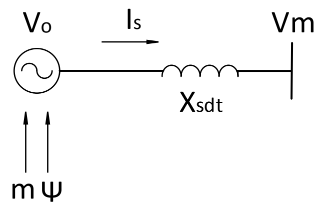

Figure 3-2 The equivalent circuit for STATCOM

The real and reactive power flow from STATCOM depends on magnitudes and angles of the V_O and V_m and X_{sdt}, where V_O is the output voltage of the inverter, V_m is the voltage of the bus to which STATCOM is connected, here called STATCOM bus, and X_{sdt} is the reactance between the inverter output and STATCOM bus. The equations for output active P and reactive power Q from the STATCOM are given in Equations (1) - (3).

$$P = \frac{V_O\, V_m}{X_{sdt}} \sin\psi \tag{1}$$

$$Q = \frac{V_O\, (\, V_O - \, V_m\, \cos\psi)}{X_{sdt}} \tag{2}$$

$$\text{Where } V_O = \, m\, V_{DC} \tag{3}$$

where ψ voltage angle of the inverter output relative to STATCO bus voltage, m is the modulation index of the inverter, and V_{DC} is the dc link voltage. It can be seen from the equations that singe of the angle ψ determines the direction of active power flow. If ψ = 0, there will be no active power exchange between the STATCOM and the power system. The direction of the reactive power flow is mainly determined by the sign of $(\, V_O - \, V_m\, \cos\psi)$. In case magnitude ψ = 0, reactive power flows from the STATCOM to the power system if $V_O > V_m$, and flows from the power system to the STATCOM if $V_O < V_m$. Therefore, the real and reactive power flow can be controlled by controlling ψ and m.

3.2. Power System Model

3.2.1. Overall Power System

For the purpose of study, the power system can be modeled by a single machine infinite bus (SMIB) system [47]. It is enough to consider the power system reactances while the resistances can be neglected for this study [3]. The overall Power System under study with STATCOM and Super capacitor is shown in Figure 3-3. The STATCOM is connected at the middle of the transmission line. Hence, the reactances x_{tl} and x_{lb} are equal.

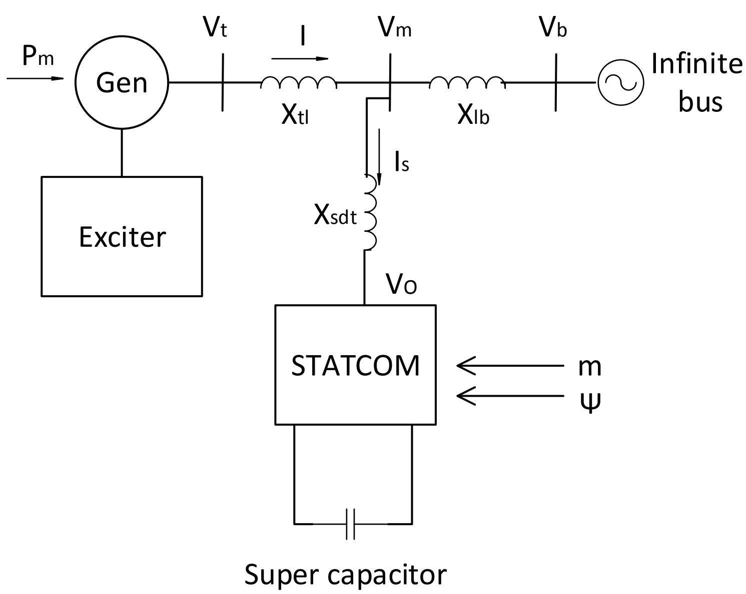

Figure 3-3 Overall power system with STATCOM and Super capacitor

3.2.2. Generator and Exciter Model

The generator third order model is used, where the generator equations are given by (4) - (6).

$$\dot{\delta} = \omega_0 \, (\omega - 1) \tag{4}$$

$$\dot{\omega} = \frac{P_m - P_e - D \, (\omega - 1)}{M} \tag{5}$$

$$\dot{E}'_q = \frac{E_{fd} - E_q}{T'_{do}} \tag{6}$$

where δ is the rotor angle relative to a synchronously rotating frame, which has the same value as the generator internal voltage angle relative to the infinite bus,

ω is the generator rotor speed,

ω_0 is the generator synchronous speed,

D is the generator damping coefficient,

P_m is the generator input mechanical power,

P_e is the generator output electrical power,

M is the generator inertia coefficient,

E_{fd} is the generator field voltage,

E'_q is the generator internal transient voltage,

E_q is the generator internal voltage,

and T_{do}' is the generator open circuit field time constant.

For the excitation system, IEEE Type-ST1 excitation system has been used, which is modeled by equation（7）.

$$\dot{E_{fd}} = \frac{K_A\left(v_{t,ref} - v_t + u_{PSS}\right) - E_{fd}}{T_A} \tag{7}$$

where v_t is the generator terminal voltage,

u_{PSS} is power system stabilizer auxiliary signal,

K_A is the exciter gain,

and T_A is the exciter time constant

3.2.3. Power System Model without STATCOM

The remaining algebraic relations for the power system without the STATCOM are given by Equations (8) - (14).

$$i_q = \frac{E_q' - v_b \cos\delta}{x_d' + x_{tl} + x_{lb}} \tag{8}$$

$$i_q = \frac{v_b \sin\delta}{x_q + x_{tl} + x_{lb}} \tag{9}$$

$$v_t = \sqrt{\left[x_q i_q\right]^2 + \left[E_q' - x_d' i_d\right]^2} \tag{10}$$

$$E_q = E_q' + (x_d - x_d')i_d \tag{11}$$

$$P_e = E_q' i_q + \left(x_q - x_d'\right)i_d i_q \tag{12}$$

$$v_m = \sqrt{\left[\left(x_q + x_{tl}\right)i_q\right]^2 + \left[E_q' - (x_d' + x_{tl})i_d\right]^2} \tag{13}$$

$$\delta_m = \cos^{-1}\left[\frac{E_q' - (x_d' + x_{tl})i_d}{v_m}\right] \tag{14}$$

Where i_d is the generator output direct current,

i_q is the generator output quadrature current,

v_b is the infinite bus voltage,

x_q is the generator internal quadrature reactance,

x_{tl} is the transmission line reactance between Generator bus and middle bus,

x_d' is the generator internal direct transient reactance,

x_d is the generator internal direct reactance,

x_{lb} is the transmission line reactance between the middle bus and the infinite bus,

v_m is the middle bus voltage,

and δ_m is the generator internal voltage angle relative to the middle bus voltage angle.

3.2.4. Power System Model with STATCOM

If a STATCOM is installed in the middle bus, one more state is added for the DC link voltage, given by Equation (15).

$$\dot{V_{DC}} = \frac{m\left(I_{sd}\cos\epsilon + I_{sq}\sin\epsilon\right)}{C_{DC}} \tag{15}$$

In addition, Equations (8) - (9) for the power system model are replaced with Equations (16)-(20).

$$i_d = \frac{(x_{lb} + x_{sdt})E_q' - x_{lb}mV_{DC}\sin\epsilon - x_{sdt}v_b\cos\delta}{Z_d} \tag{16}$$

$$i_q = \frac{x_{lb} m V_{DC} \cos\epsilon + x_{sdt} v_b \sin\delta}{Z_q} \quad (17)$$

$$\epsilon = \frac{\pi}{2} - (\psi + \delta_m) \quad (18)$$

$$I_{sd} = \frac{E'_q - (x'_d + x_{tl}) i_d - m V_{DC} \sin\epsilon}{x_{sdt}} \quad (19)$$

$$I_{sq} = \frac{m V_{DC} \cos\epsilon - (x_q + x_{tl})\, i_q}{x_{sdt}} \quad (20)$$

where V_{dc} is the STATCOM DC link voltage,

C_{sc} is the Super Capacitor's capacitance,

M is the STATCOM modulation index,

ψ is the STATCOM output voltage angle relative to the middle bus voltage angle,

ϵ is the STATCOM output voltage angle relative to the generator rotor direct access,

I_{sd} is the direct current drawing by the STATCOM,

I_{sq} is the quadrature current drawing by the STATCOM,

and Z_d and Z_q are given by equations (21) and (22).

$$Z_d = x_{sdt} (x'_d + x_{tl}) + x_{lb} (x'_d + x_{tl} + x_{sdt}) \quad (21)$$

$$Z_q = x_{sdt} (x_q + x_{tl}) + x_{lb} (x_q + x_{tl} + x_{sdt}) \quad (22)$$

In addition, two state equations are introduced to represent the he time constant between the change of in input signals of the voltage angle and modulation index to the STATCOM, and the actual change taken in place the STATCOM. The two state equations are given by (23) and (24).

$$\dot{m} = \frac{m' - m}{T_C} \tag{23}$$

$$\dot{\psi} = \frac{\psi' - \psi}{T_C} \tag{24}$$

where m' is the STATCOM modulation index input signal,

ψ' is the STATCOM output voltage angle input signal,

and T_C is the STATCOM time constant.

CHAPTER 4

PROPOSED CONTROL STRATEGY

4.1. Excitation System Power System Stabilizer

A conventional lead lag controller is used for the Power System Stabilizer for the excitation system as shown in Figure 4-1 Excitation system power system stabilizer (PSS)The excitation system equations are given by (25) - (27):

$$\dot{x} = \dot{\omega} - \frac{x}{T_w} \tag{25}$$

$$\dot{u'}_{PSS} = \frac{1}{T_{P2}}[K_P(x + T_{P1}\dot{x}) - u'_{PSS}] \tag{26}$$

$$\dot{u}_{PSS} = \frac{1}{T_{P4}}\left[\left(u'_{PSS} + T_{P3}\dot{u'}_{PSS}\right) - u_{PSS}\right] \tag{27}$$

Where T_w is the power system stabilizer washout time constant,

K_P, and T_{P1} - T_{P4} are the PSS gain and time constants.

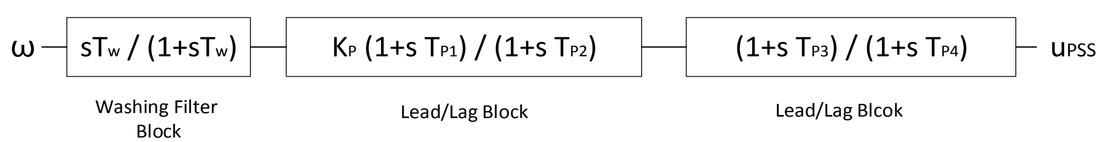

Figure 4-1 Excitation system power system stabilizer (PSS)

4.2. STATCOM Voltage Regulators

The STATCOM control system consists of two voltage regulation loops as shown in Figure 4-2, each one is a PI controller. The DC link voltage error signal is used to drive STATCOM voltage angle, while the STATCOM bus A/C voltage is sued to drive the STATCOM modulation index. There also two auxiliary signals, one for each PI controller, coming from the STATCOM stabilizers. The time domain equations for this control system are given by (28) and (29).

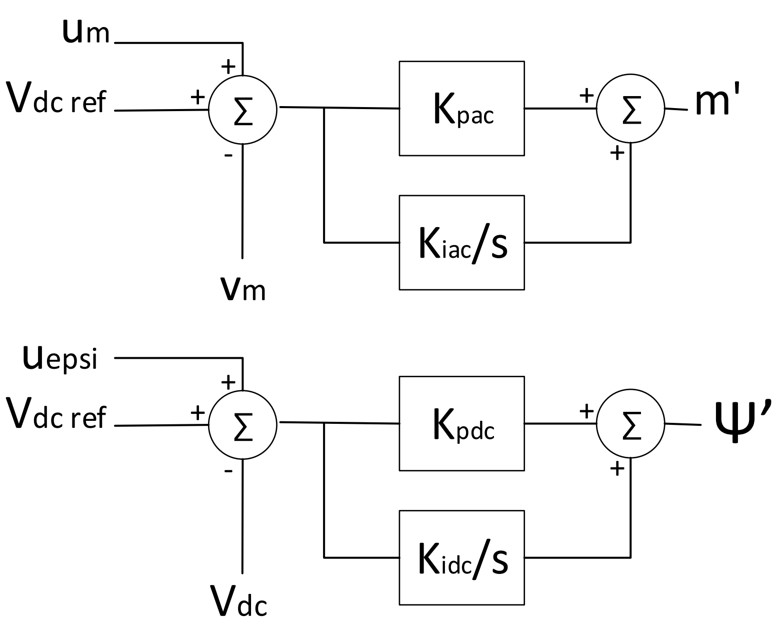

Figure 4-2 STATCOM voltage controllers

$$\dot{m}' = -K_{pac}\dot{v_m} + K_{iac}\,(v_m^{ref} - v_m) \tag{28}$$

$$\dot{\psi}' = -K_{pdc}\dot{V_{DC}} + K_{idc}\,(V_{DC}^{ref} - V_{DC}) \tag{29}$$

where K_{PDC}, K_{IDC} are the STATCOM DC voltage PI controller parameters,

K_{PAC}, K_{IAC} are the STATCOM AC voltage PI controller parameters,

u_m is the STATOM modulation index stabilizer auxiliary signal, and u_{epsi} is the STATOM voltage angle stabilizer auxiliary signal.

4.3. STATCOM Damping Stabilizers

Each one of the two STATCOM stabilizers consist of a conventional lead/lag controller as shown in Figure 4-3. The input signal is the rotor angle speed, filtered by a washing filter block to remove the steady state value.

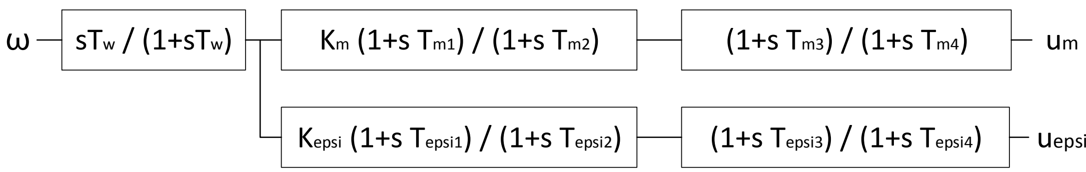

Figure 4-3 STATCOM damping stabilizers

The time domain equations for STATCOM damping stabilizers are given by (30) - (34)

$$\dot{x} = \dot{\omega} - \frac{x}{T_w} \tag{30}$$

$$\dot{u_m'} = \frac{1}{T_{m2}}[K_m(x + T_{m1}\dot{x}) - u_m'] \tag{31}$$

$$\dot{u_m} = \frac{1}{T_{m4}}[(u_m' + T_{m3}\dot{u_m'}) - u_m] \tag{32}$$

$$\dot{u_{epsi}'} = \frac{1}{T_{epsi2}}[K_{epsi}(x + T_{epsi1}\dot{x}) - u_{epsi}'] \tag{33}$$

$$\dot{u_{epsi}} = \frac{1}{T_{epsi4}}[(u_{epsi}' + T_{epsi3}\dot{u_{epsi}'}) - u_{epsi}] \tag{34}$$

where K_m, T_{m1} - T_{m4} are the STATCOM modulation index PSS gain and time constants, and K_{epsi}, T_{epsi1} - T_{epsi4} are the STATCOM voltage angle PSS gain and time constants.

4.4. Problem Formulation

During the design of the control system, some of the control system parameters have been kept fixed at the pre-specified values shown in Appendix A, while the others have been varied to search for the optimum solution.

During the optimization process, the power system is simulated with a disturbance of 100% increase in the mechanical input power for a duration of 10 ms. The applied objective function is a discretized form of the Equation (35), where all values are in per unit, except the time is in seconds. T_f is the overall duration of the simulation, which is set at 2 seconds in this case. Increasing T_f will cause more computational effort and time for the optimization, so it should be kept as small as practically possible, without affecting the quality of the search.

$$J = \int_{t=0}^{t=T_f} t \times \left(|\omega(t) - \omega_0| + \left|v_m(t) - v_{m,ref}\right| + 10\left|V_{dc}(t) - V_{dc,ref}\right| \right) dt \tag{35}$$

The constraints of the optimization problems are the minimum and maximum values of the control system parameters. The design of the control system parameter can be formulated into the following optimization problem:

Minimize J, given by (35) subject to the following constraints:

$$K_{pac}^{min} < K_{pac} < K_{pac}^{max}$$

$$K_{iac}^{min} < K_{iac} < K_{iac}^{max}$$

$$K_P^{min} < K_P < K_P^{max}$$

$$T_{P1}^{min} < T_{P1} < T_{P1}^{max}$$

$$K_m^{min} < K_m < K_m^{max}$$

$$T_{m1}^{min} < T_{m1} < T_{m1}^{max}$$

$$K_{epsi}^{min} < K_{epsi} < K_{epsi}^{max}$$

$$T_{epsi1}^{min} < T_{epsi1} < T_{epsi1}^{max}$$

CHAPTER 5

PARTICLE SWARM OPTIMIZATION

5.1. Overview of Particle Swarm Optimization Technique

The use of intelligent optimization techniques have been proposed to set the optimum parameters of the controllers of PSS and STATCOM [54]. In this work, the Particle Swarm Optimization is used to select the control system parameters.

The particle swarm optimization technique emulates life organisms such as the swarming of a group of bees, or the flocking of birds. It is a technique that is easy to use and efficient. The optimization starts with a group of particles positioned randomly in the search space, each having a random initial speed. Each particle represents a solution. Each particle move in the search space memorizing the optimum solution it encounters, and the group as a whole memorize the best global solution encountered the group. At the end the group adjust the direction of their movement towards the global best solution, which is updated if any individual encounters a better solution [54].

Particle Swarm Optimization Terminology is as follows [54]:

1. The search space: an m-dimensional space, where each dimension corresponds to parameter being optimized.
2. Particle: a member that searches for the optimum solution by changing its position and velocity in the search space.
3. Position: the location of every particle in the search space.

4. Population: the number of particles performing the search.
5. Individual best solution: the best solution found so far by a specific particle
6. Global best solution: The best solution every found by the group as a whole. This value is communicated to every member, as it affects how they update their velocities.
7. Number of iterations: The number of times the particles change their position while searching for the optimum solution.
8. The stopping criteria: The conditions which will end the search if at least on of them is met. The conditions are typically the specified total number of iterations, and a specified number of iteration with no update on the global best solution.

The algorithm of the PSO code is as follows

1. Set the population size, number of iterations, the weight w, the factor α, the stopping criteria, and the minimum and maximum values of each parameter.
2. Place the initial positions of the particle X_j by selecting a random value for every parameter $x_{i,j}$ between the minimum x_{min} and maximum value x_{max}.
3. Place the Initial Velocity of the particle X_j by selecting random velocity for every parameter $v_{i,j}$ between the minimum v_{min} and maximum velocity v_{max}
4. Calculate the objective function for every particle at the initial position, and set it as the best individual solution J_j, and the position is the best individual position.
5. Set the minimum global solution J_{glob} to be the minimum of J_j.
6. Move the particles to the next position by the equation (36):

$$X\ (n+1) = X\ (n) + V(\mathrm{n}) \tag{36}$$

The new position is bounded by x_{max} and x_{min}.

7. Calculate the new individual objective functions, and compare it with the best individual objective function so far, if the new one is better, update the individual best objective function and position.
8. Update the best global solution and position.
9. Break the search if the stopping criteria is met
10. Adjust the weight and the velocities of the particles as shown in equations (37), (38):

$$w(n+1) = \ \alpha\ \times w(n) \tag{37}$$

$$V\ (n+1) = w(n) \times V(n) + R_1\ \times [\ X_{ind} - X(n)] + R_1\ \times \left[\ X_{glob} - X(n)\right] \tag{38}$$

where R_1 and R_2 are random values.

5.2. Using PSO to Design a PSS

5.2.1. Base Case Study

A disturbance in the generator input mechanical power as shown in Figure 5-1 was applied to a single machine infinite bus system with an AVR. The rotor speed and rotor angle responses shown in Figure 5-2 and Figure 5-3 indicate that the power system is dynamically instable, which is expected since automatic voltage regulators cause negative damping in the power system, if it is not equipped with a power system stabilizer.

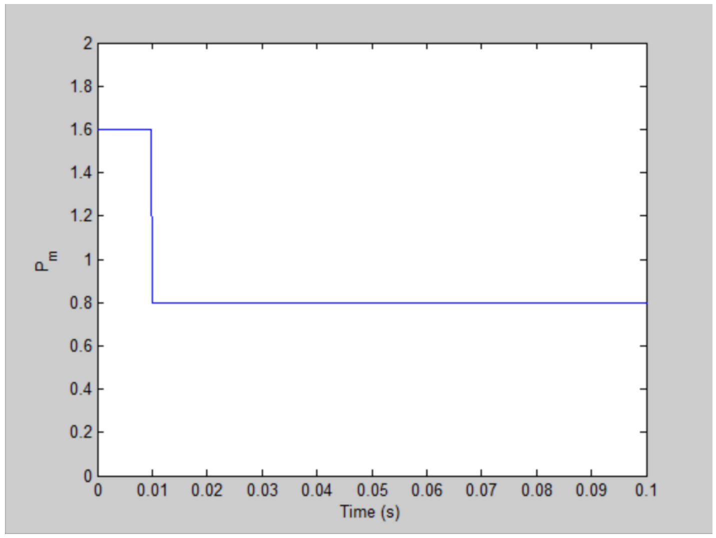

Figure 5-1 Applied mechanical power disturbance

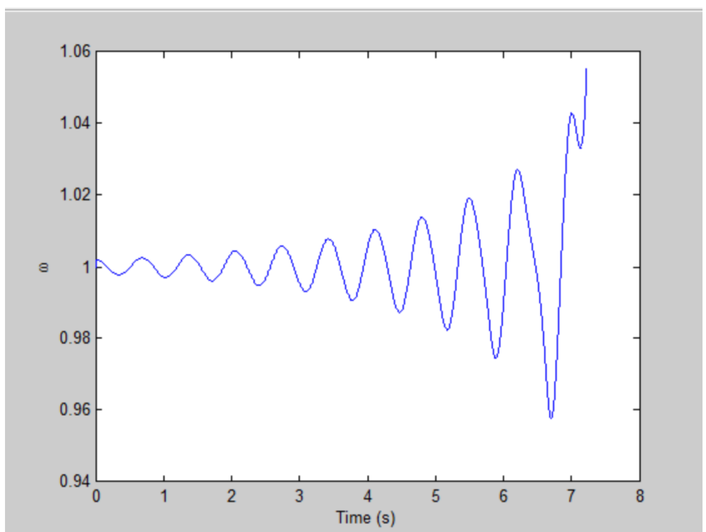

Figure 5-2 Rotor speed (SMIB)

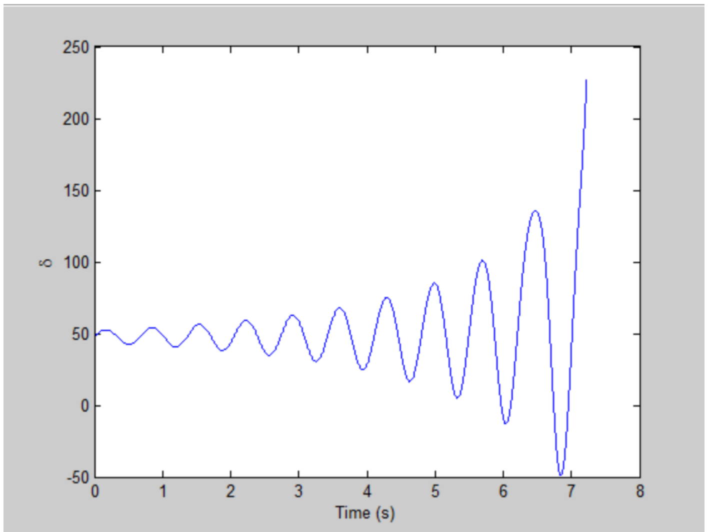

Figure 5-3 Rotor angle profile (SMIB)

5.2.2. The Design of PSS

A PSS was designed for the same power system in section 5.2.1using PSO with the objective function shown in (39), which resulted in $J_{\omega} = 0.1922$. The convergence curve is shown in Figure 5-4. The optimized PSS parameters are shown in Table 5-1.

$$\boldsymbol{J_{\omega} = \int t \times |\omega - \omega_b| \, dt} \tag{39}$$

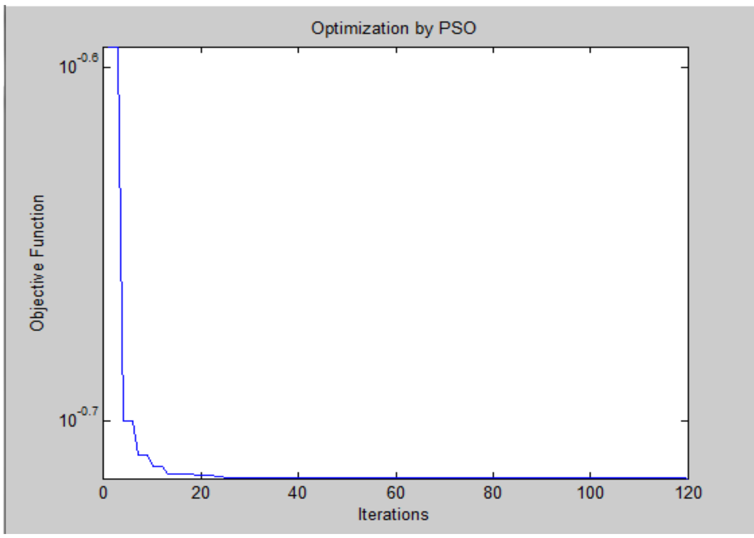

Figure 5-4 Jω convergence curve (SMIB with PSS)

Controller	Parameter	Value
PSS	K_P	350.6777
	T_{P1}	0.0666s

Table 5-1 PSS parameters (SMIB with PSS)

5.2.3. Simulation of the Power System with PSS

The same disturbance in Figure 5-1 has been applied to the power system with PSS. The rotor speed and angle responses shown in Figure 5-5 and Figure 5-6 indicate that the system is now stable. This is expected since addition of the power system stabilizer produces positive damping to the electromechanical oscillations. The PSS also introduced high frequency oscillations that are quickly damped after 5 cycles, which does not harm the system. The rotor angle deviation in the first swing is also smaller, and the rotor angle return smoothly to the initial angle within 5 seconds.

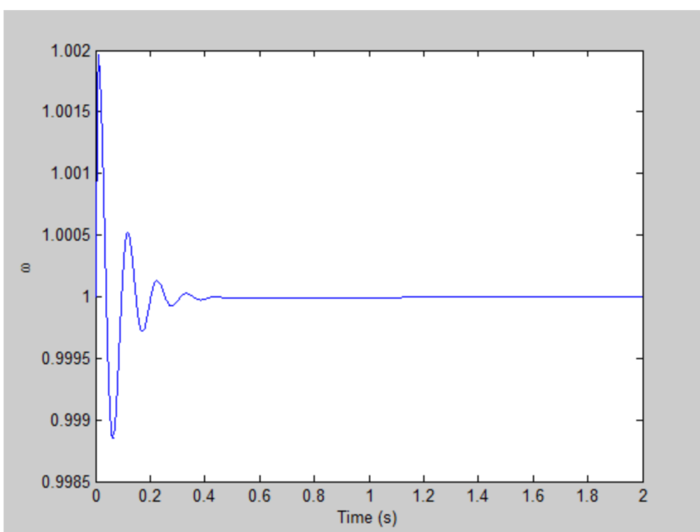

Figure 5-5 Rotor speed profile (SMIB with PSS)

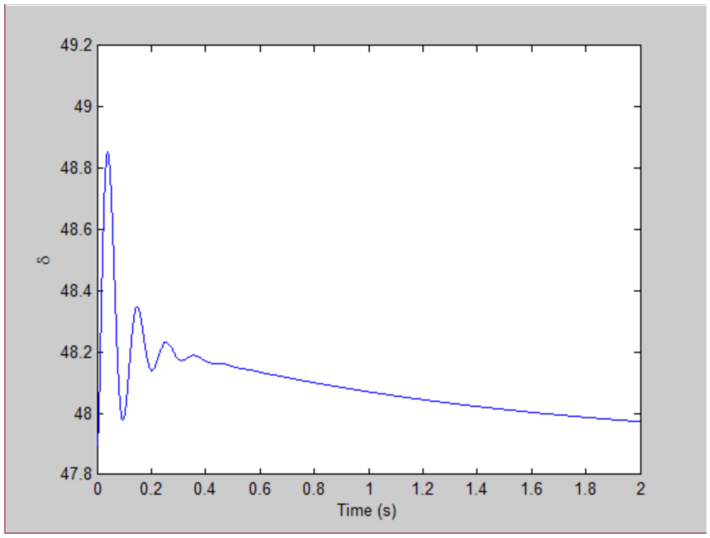

Figure 5-6 Rotor angle profile (SMIB with PSS)

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1. The Power System with STATCOM

6.1.1. Case 1: Power System with No Damping Stabilizers

The STATCOM controllers were designed using PSO with the objective function shown in Equation (40). The optimized values of the controllers' parameters are shown in Table 6-1. For the mechanical power disturbance shown in Figure 6-1, the rotor angle response shown in Figure 6-2 indicate that the system is instable, which is expected since the system does not include PSS that produces positive damping to the electromechanical oscillations, and the STATCOM cannot perform this function without damping stabilizers.

$$J = \int t \times \left[|\omega - \omega_b| + \left|V_m - V_{m,ref}\right| + 10\left|V_{dc} - V_{dc,ref}\right| \right] dt \tag{40}$$

Controller	Optimized Parameter	Value
STATCOM PI Voltage Regulators	K_{PDC}	902.6216
	K_{IDC}	65.75136
	K_{PAC}	113.5277
	K_{IAC}	1000

Table 6-1 STATCOM parameters (SMIB-STATCOM)

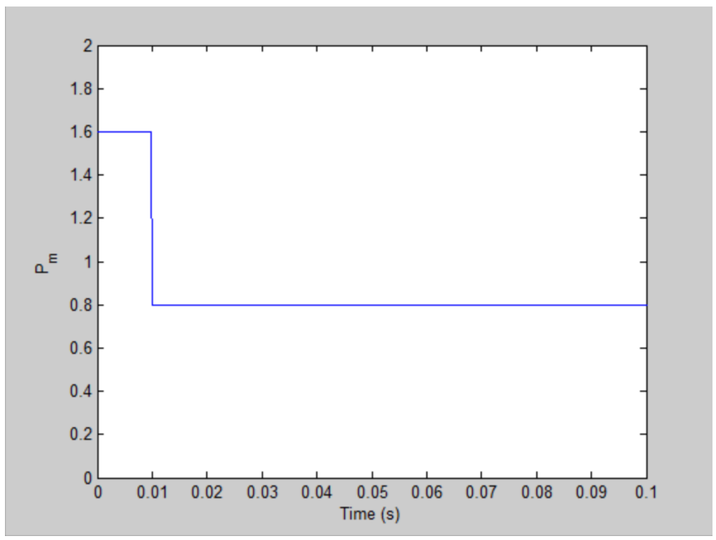

Figure 6-1 Applied mechanical power disturbance

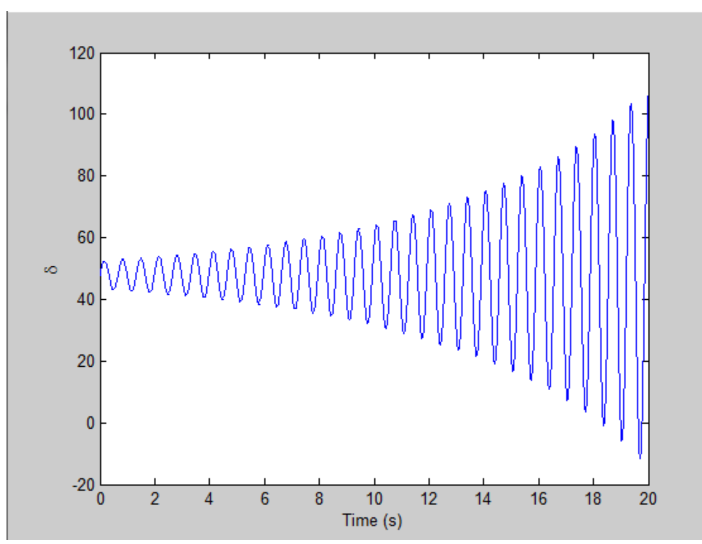

Figure 6-2 Rotor angle response (SMIB-STATCOM)

6.1.2. Case 2: Power System with Excitation PSS

6.1.2.1. Design of STATCOM Controllers and PSS

STATCOM controllers and excitation PSS have been designed using PSO with the objective function shown in Equation (40). The best objective function obtained by the PSO is J = 1.2083. The optimized parameters values are shown in Table 6-2 STATCOM and PSS parameters (STATCOM-SMIB with PSS).

Controller	Optimized Parameter	Value
STATCOM PI Voltage Regulators	K_{PDC}	586.224
	K_{IDC}	590.8342
	K_{PAC}	113.5251
	K_{IAC}	1000
PSS	K_P	356.8528
	T_{P1}	0.0672

Table 6-2 STATCOM and PSS parameters (STATCOM-SMIB with PSS)

6.1.2.2. Simulation of the Power System with STATCOM and Excitation PSS

The same disturbance shown in Figure 6-1 has been applied to the power system with STATCOM and excitation PSS. The rotor speed, rotor angle, middle bus voltage, and STATCOM DC voltage responses shown in Figure 6-3 - Figure 6-6 indicate that a stable response. This is expected since the introduction of PSS has produced positive damping to the system.

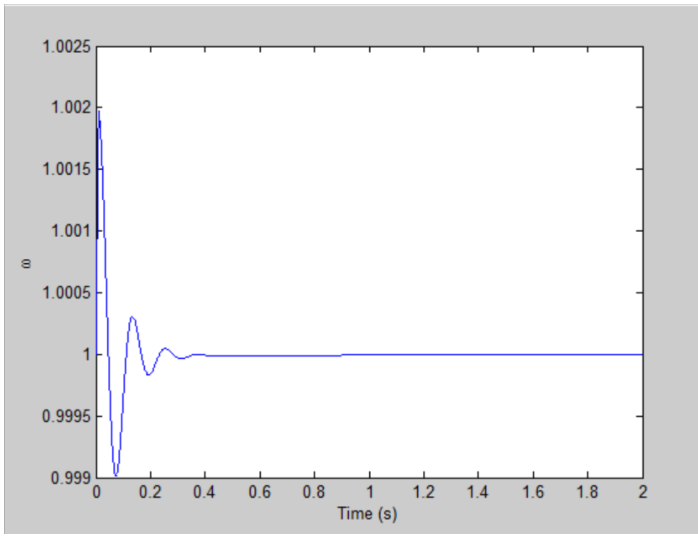

Figure 6-3 Rotor speed response (STATCOM-SMIB with PSS)

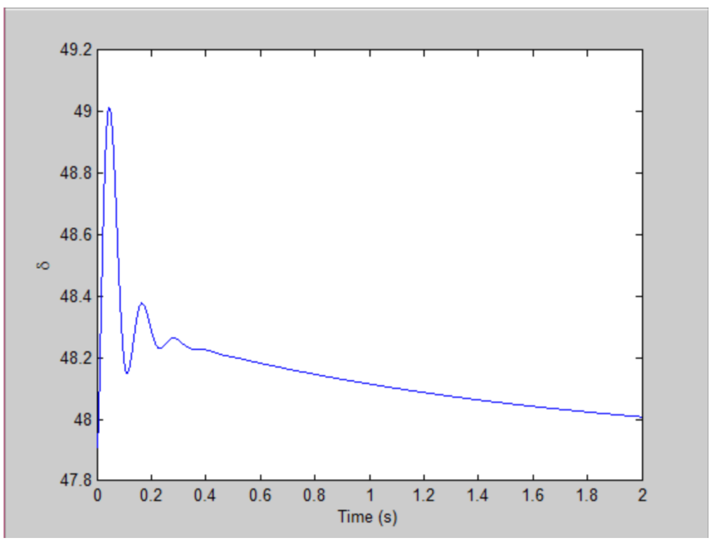

Figure 6-4 Rotor angle response (STATCOM-SMIB with PSS)

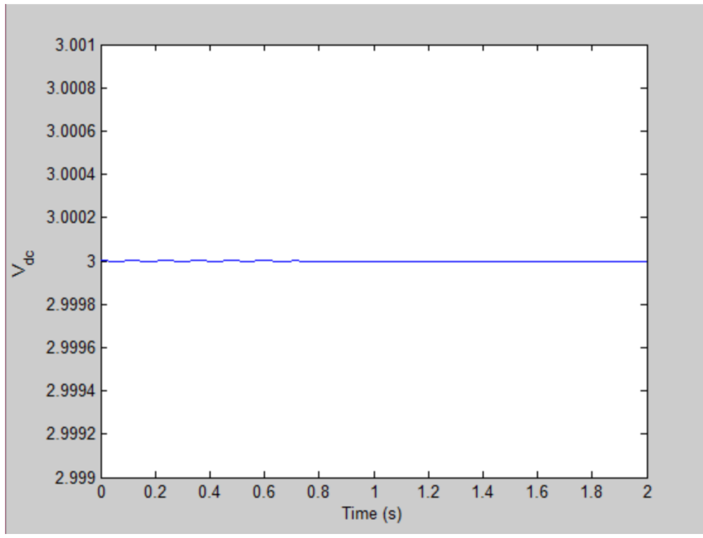

Figure 6-5 DC voltage response (STATCOM-SMIB with PSS)

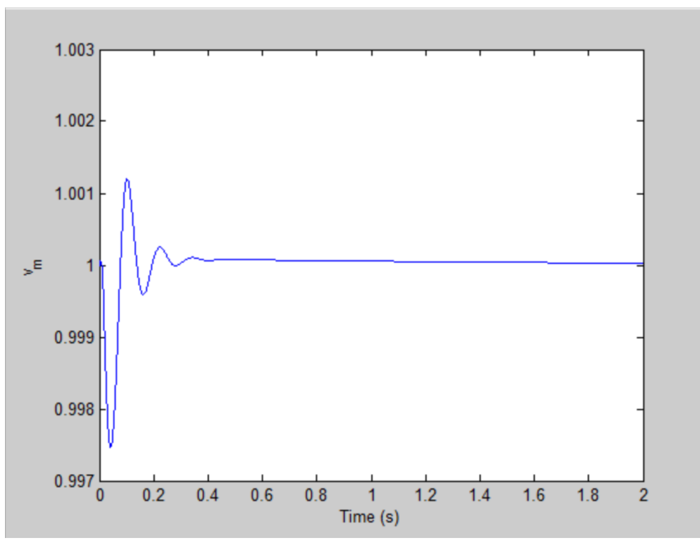

Figure 6-6 Middle bus voltage response (STATCOM-SMIB with PSS)

A 1% step increase in the reference DC voltage reference was applied on the STATCOM controller. The DC voltage and middle bus voltage responses shown in Figure 6-7 - Figure 6-10 indicate that the system is stable. The DC link voltage reached the new set point within 6 seconds. It can be seen that energy that was drawn by the STATCOM from the power system has caused a temporary dip in the rotor angle, which is also expected. The middle bus voltage also shows a deviation that has been corrected by the A/C voltage regulator, this is expected since the increase in the DC link voltages causes an increase in the output reactive power, and it is then counteracted by reducing the modulation index m.

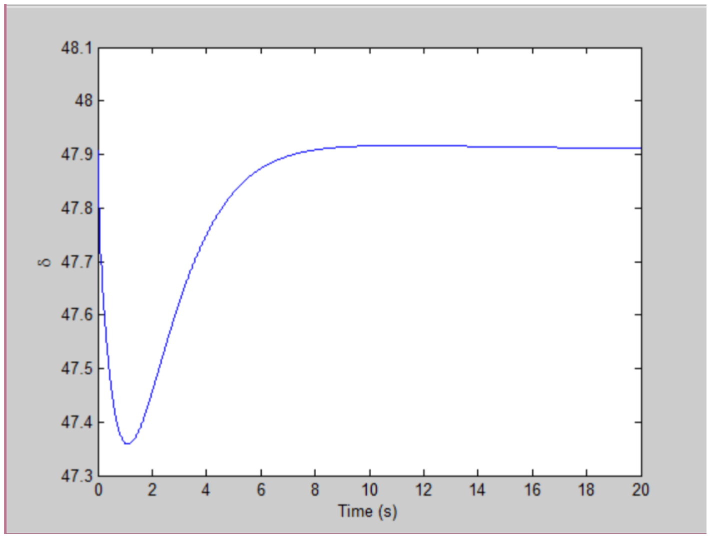

Figure 6-7 Rotor angle response to step in reference V dc (STATCOM-SMIB with PSS)

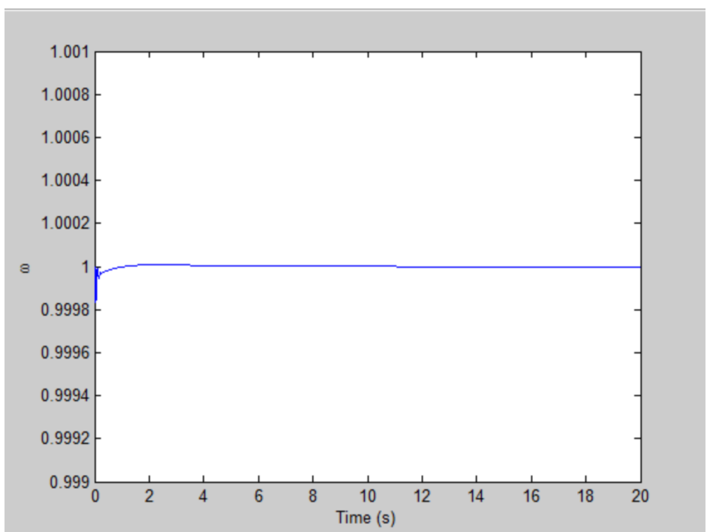

Figure 6-8 Rotor speed response to step in reference V dc (STATCOM-SMIB with PSS)

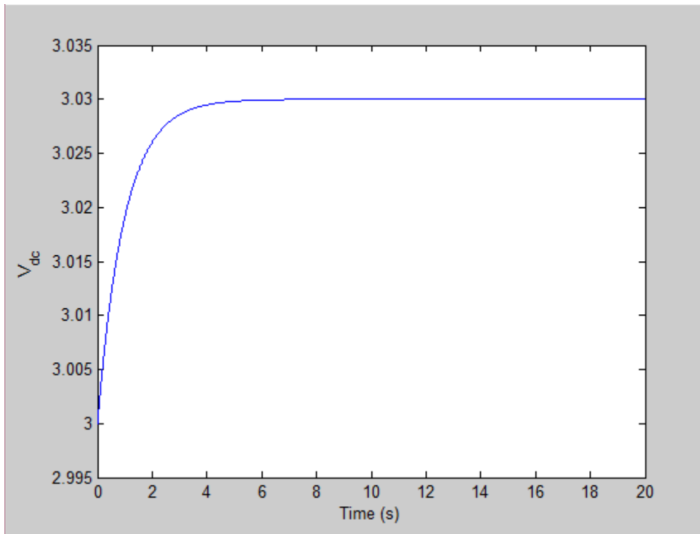

Figure 6-9 DC voltage response to step in reference V dc (STATCOM-SMIB with PSS)

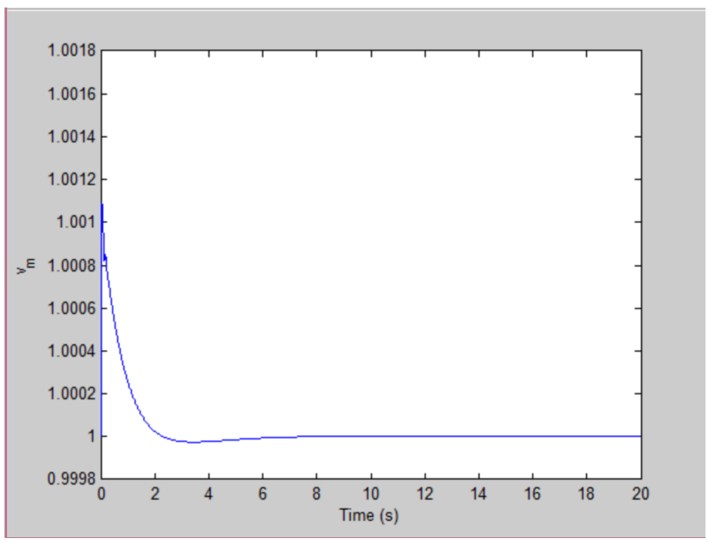

Figure 6-10 Middle bus voltage response to step in reference V dc (STATCOM-SMIB with PSS)

6.1.3. Case: 3: Power System with Excitation and STATCOM Damping Stabilizers

6.1.3.1. Design of STATCOM controllers and damping stabilizers

STATCOM controllers, excitation PSS, and STATCOM stabilizers have been designed using PSO with the objective function shown in Equation (40). The best objective function obtained by the PSO is J =1.0155. The optimized parameters values are shown in Table 6-3.

Controller	Optimized Parameter	Value
STATCOM PI Voltage Regulators	K_{PDC}	113.5535
	K_{IDC}	338.8988
	K_{PAC}	7.5231
	K_{IAC}	37.1368
PSS	K_P	1000
	T_{P1}	0.5063
STATCOM Damping Stabilizers	K_m	297.5061
	T_{m1}	0.4310
	K_{epsi}	0.0007
	T_{epsi_1}	0.5767

Table 6-3 Optimized values for control system parameters (PSS & STATCOM stabilzers)

6.1.3.2. Simulation of the Power System with PSS and STATCOM Damping Stabilizers

The same disturbance shown in Figure 6-1 has been applied to the power system with STATCOM and excitation PSS. The rotor speed, rotor angle, middle bus voltage, and STATCOM DC voltage responses shown in Figure 6-11 Figure 6-14 indicate that a stable response. This is expected since the excitation PSS and the STATCOM PSS produces positive damping to the system.

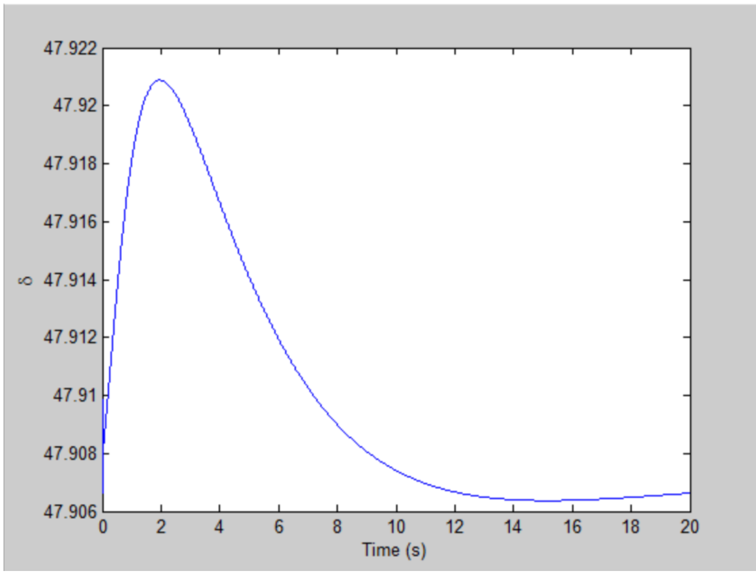

Figure 6-11 Rotor angle response (PSS & STATCOM stabilzers)

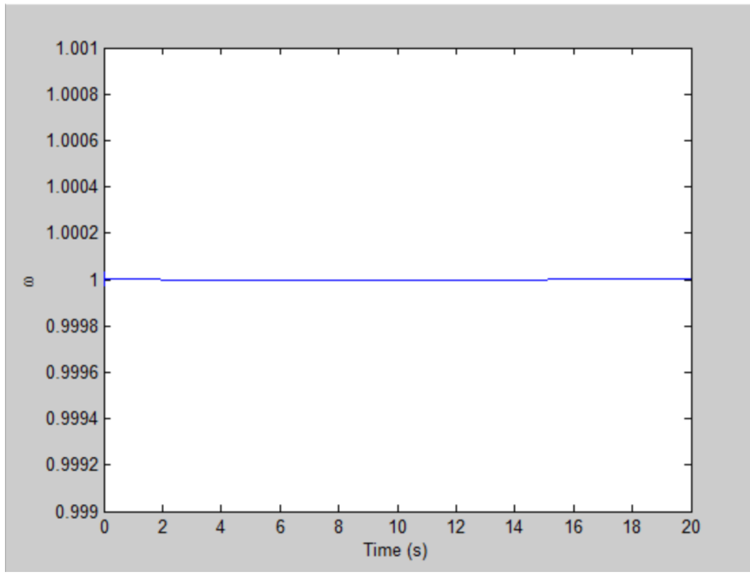

Figure 6-12 Rotor speed response (PSS & STATCOM stabilzers)

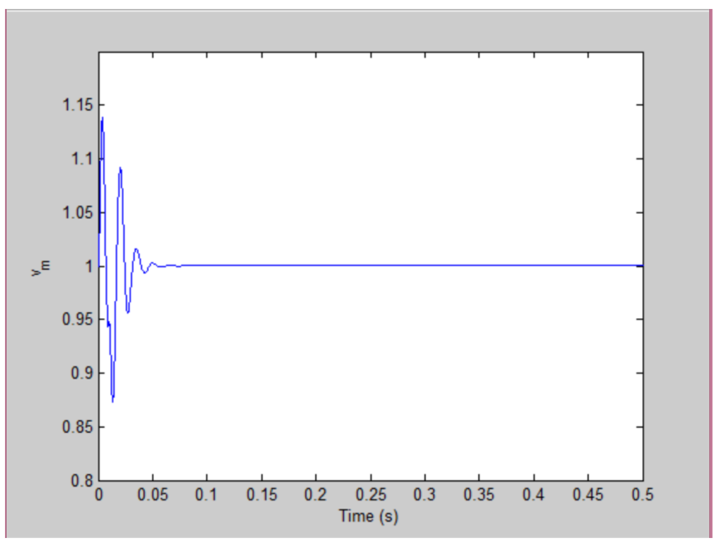

Figure 6-13 middle bus voltage response (PSS & STATCOM stabilzers)

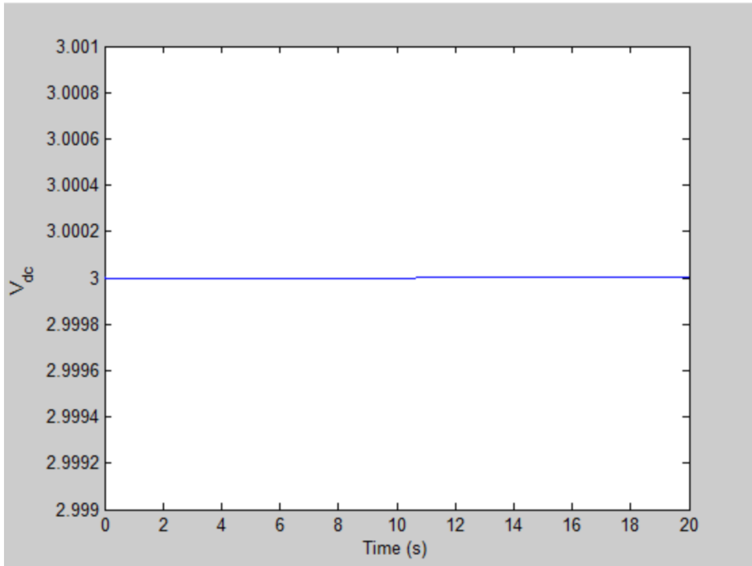

Figure 6-14 DC link voltage response (PSS & STATCOM stabilzers)

6.2.Power System with STATCOM and Supercapacitor

6.2.1. Design of STATCOM and Supercapacitor

PSO was used to design the parameters of STATCOM, excitation PSS, and STATCOM stabilizers using the objective function shown in Equation (40). The best value of J obtained from the PSO was J = 38.3893. The convergence curve of the objective function is shown in Figure 6-15, and the optimized parameter are shown in Table 6-4.

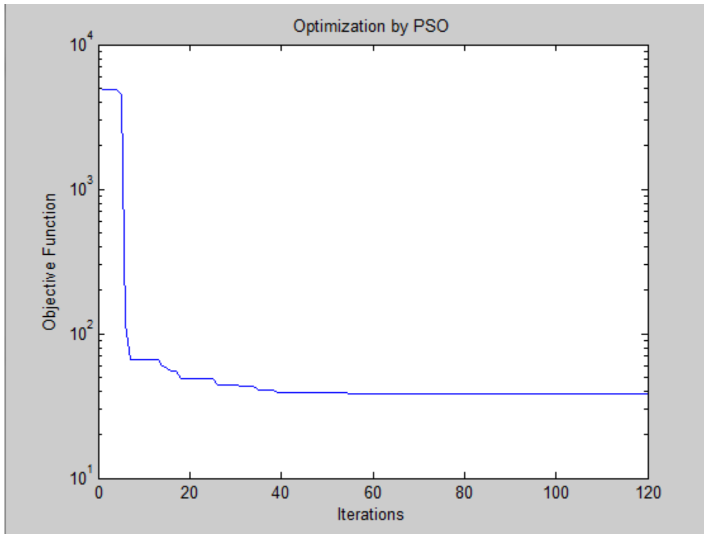

Figure 6-15 Objective funxrion convergence curve (STATCOM & Super capacitor)

Controller	Parameter	Optimized value
STATCOM PI Voltage Regulators	K_{pac}	104.558
	K_{iac}	944.3855
PSS	K_{P}	953.4982
	T_{P1}	0.460363
STATCOM Damping Stabilizers	K_{m}	524.0065
	T_{m1}	0.4084
	K_{epsi}	398.0446
	T_{epsi_1}	0.9639535

Table 6-4 Optimizaed values for control system parameters (STATCOM & Super capacitor)

6.2.2. Simulation of STATCOM and Supercapacitor

A disturbance in the input mechanical power as shown in Figure 6-1, but with a pulse of 10% increase instead of 100%, was applied on the power system with STATCOM and Super capacitor. The rotor angle, rotor speed, STATCOM DC voltage, and middle bus AC voltage responses shown in Figure 6-16 - Figure 6-19. This is expected since the PSS and the STATCOM-SCESS stabilizers are providing positive damping to low frequency oscillations.

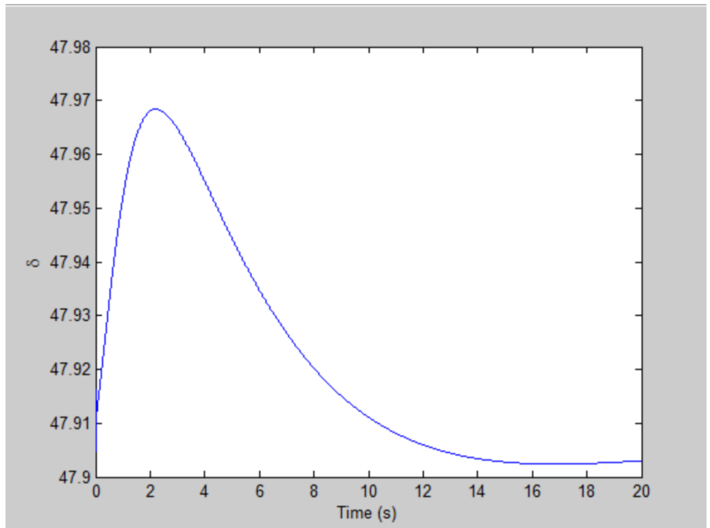

Figure 6-16 Rotor angle response (STATCOM & Super capacitor)

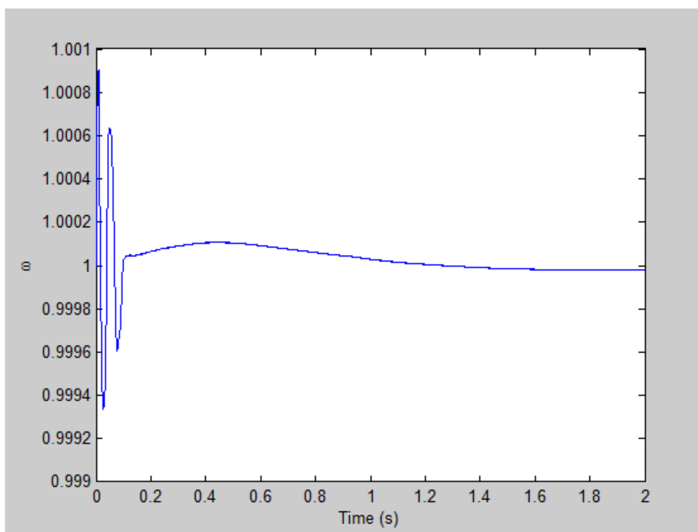

Figure 6-17 Rotor speed response (STATCOM & Super capacitor)

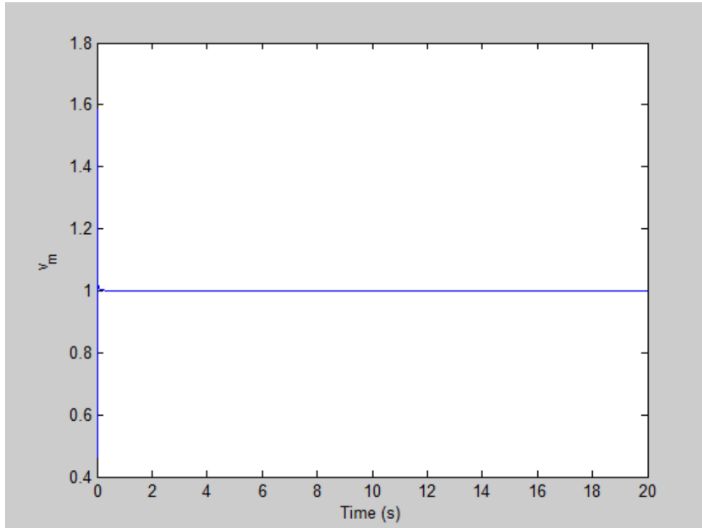

Figure 6-18 Middle bus voltage response (STATCOM & Super capacitor)

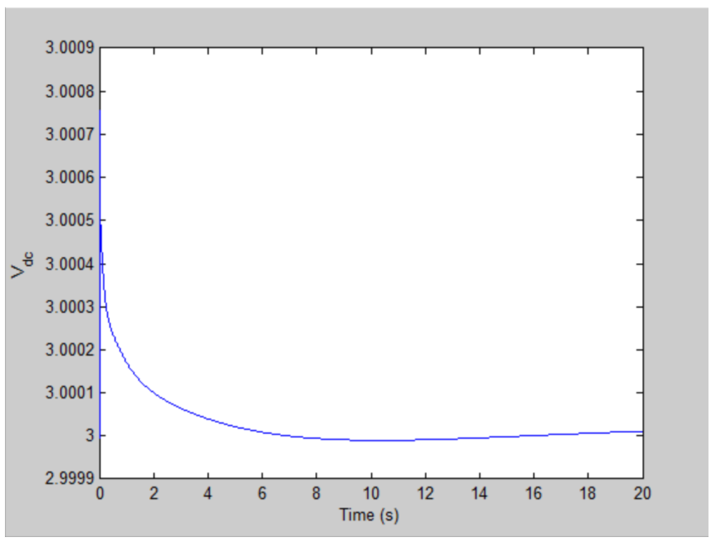

Figure 6-19 DC link voltage response (STATCOM & Super capacitor)

6.3. Comparison of Different Systems' Responses to Mechanical Power Disturbances

The performances of the previously describes systems are compared in Table 6-5 based on the value of J_ω obtained by Equation (39). It can be seen that the STATCOM with super capacitor damps the low frequency oscillations more than the PSS alone or the PSS with

STATCOM only, which is expected since STATCOM angle is only controlled to damp the low frequency oscillations. Figure 6-20 compares the speed responses of the three systems to the disturbance in input mechanical power shown in Figure 6-1.

The System	J_ω
PSS	0.1922
PSS and STATCOM	0.1840
PSS and STATCOM with Supercapacitor	0.0196

Table 6-5 Comparison of different systems performances

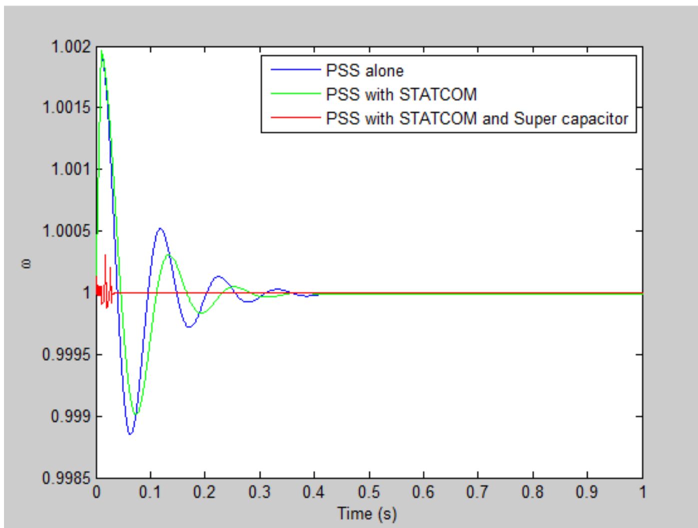

Figure 6-20 Comparison of the speed response of the three systems

6.4. Performance of STATCOM with Super Capacitor at Reduced Generator Output Power

To see the effectiveness of the system at different operating point, the same disturbance shown in Figure 6-1 has been applied to the power system with STATCOM and Supercapacitor, but the generator output power has been reduced by 50%. The rotor speed, rotor angle, middle bus voltage, and STATCOM DC voltage responses shown in

Figure 6-21 - Figure 6-24 indicate that a stable response, which shows that the proposed system has good performance at different operating points.

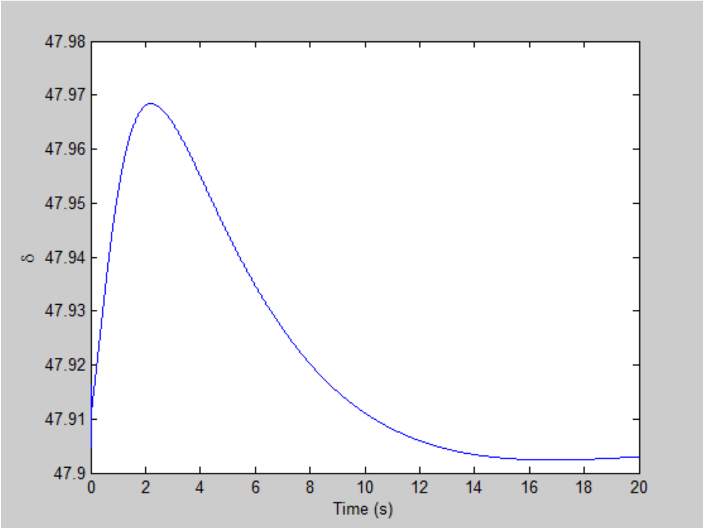

Figure 6-21 Rotor angle response (STATCOM & Supercapacitor at half load)

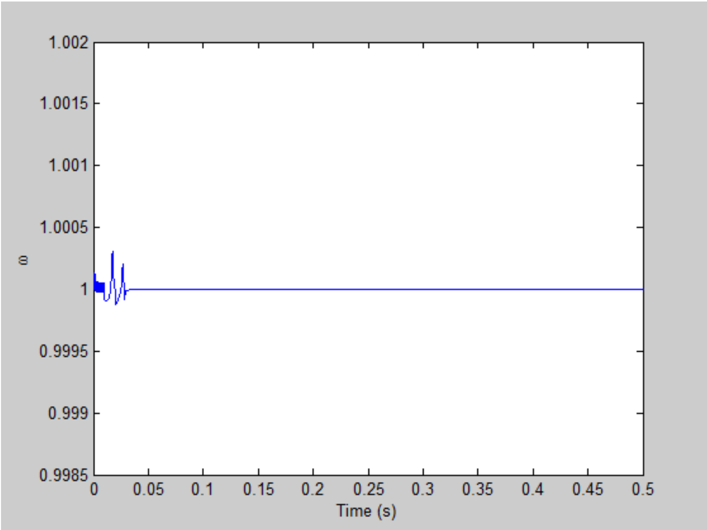

Figure 6-22 Rotor speed response (STATCOM & Super capacitor at half load)

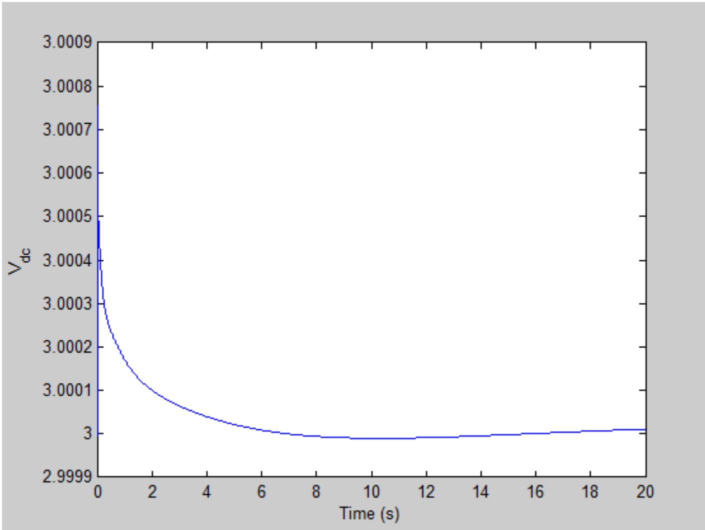

Figure 6-23 DC link voltage response (STATCOM & Supercapacitor at half load)

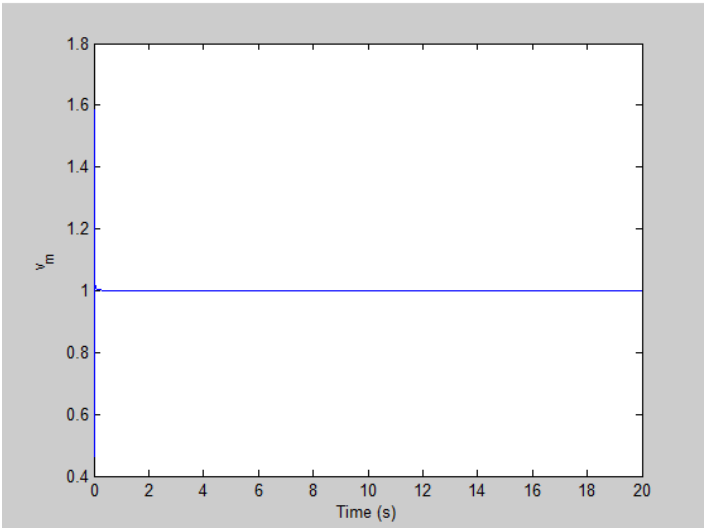

Figure 6-24 Middle bus voltage response (STATCOM & Supercapacitor at half load)

6.5. Performance of the STATCOM with Super capacitor with Reduced Generator Inertia

To see the effectiveness of the system for different generator inertia, the same disturbance shown in Figure 6-1 has been applied to the power system with STATCOM and Supercapacitor, but the generator inertia has been reduced by 50%. The rotor speed, rotor angle, middle bus voltage, and STATCOM DC voltage responses shown in Figure 6-25 - Figure 6-28 indicate that a stable response, which shows that the proposed system has good performance for different generator inertia.

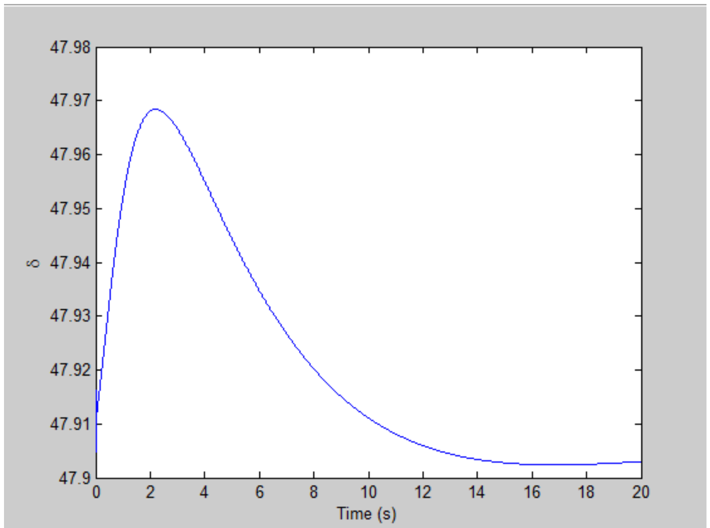

Figure 6-25 Rotor angle response (STATCOM & Super capacitor at half machine constant)

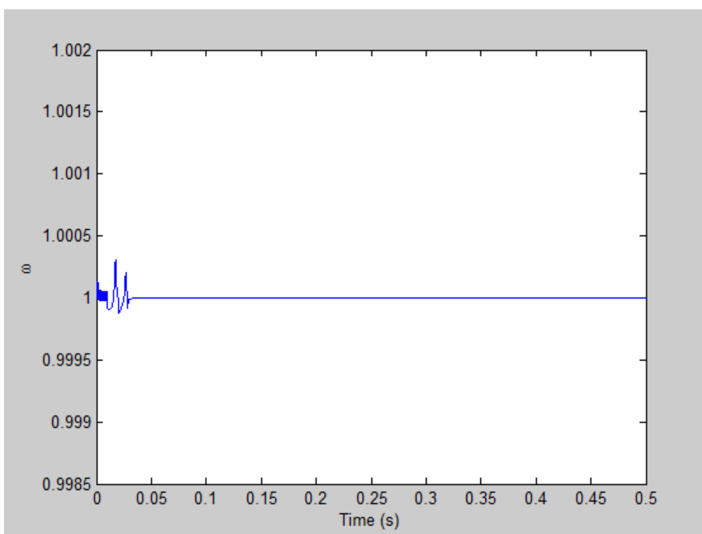

Figure 6-26 Rotor speed response (STATCOM & Super capacitor at half machine constant)

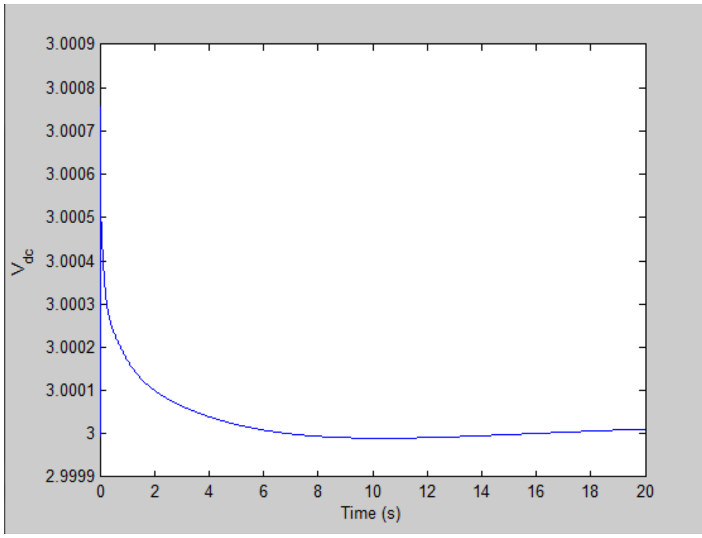

Figure 6-27 DC link voltage response (STATCOM & Super capacitor at half machine constant)

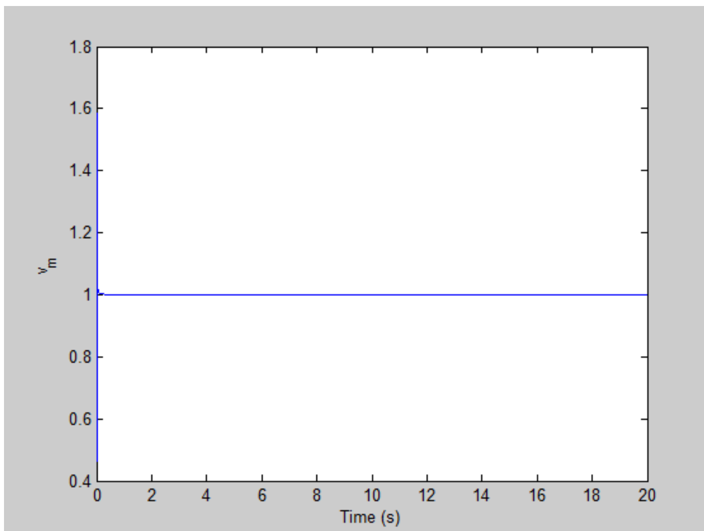

Figure 6-28 Middle bus voltage response (STATCOM & Super capacitor at half machine constant)

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1. Conclusion

In this thesis, a system consisting of STATCOM and Super capacitor has designed to enhance the dynamic stability of the power system. The design of the generator excitation PSS, STATCOM voltage regulators, and STATCOM damping stabilizers have been coordinate to reach the optimum performance in reactive power support and low frequency oscillations damping. The design of the controllers the PSS and STATCOM-SCESS has been formulated into an optimization problem. Particle Swarm Optimization technique has been applied to search for the optimum parameters of the controllers, using an objective function that ensures adequate system dynamic stability and voltage regulation.

The performance of the STATCOM-SCESS system has be verified by simulation using discretized non-linear equation equations. The performance of the STATCOM-SCESS system in damping low frequency oscillations have been compared with the power system that contains only excitation PSS, and the power system that contains only the excitation PSS and the STATCOM. It has been demonstrated that the addition of the supercapacitor has enhanced the dynamic stability of the power system.

7.2. Future Work

This research on the use of STATCOM and supercapacitor to improve power system stability can be extended in following directions:

- A prototype model can be physically implemented and tested on scaled power system. This will provide the opportunity to test the system before implementation in a real power system.
- An investigation of the system performance on a multi-machine system to damp inter-area oscillation can be conducted.
- In this thesis, the input signal to the stabilizers was the rotor speed, which is equivalent to system frequency. A system that uses other input signals such as the electric power flow through the transmission line could be designed and evaluated.
- In this thesis, the STATCOM-SCESS system was placed at the middle of the transmission line. The performance of the same system installed at other locations through the line could be evaluated to find the optimum location. Both the reactive support and the low frequency oscillation damping need to be evaluated since the optimum location of the STATCOM could potentially present a trade off between the two.
- Different control strategies other than the conventional controller could be designed and tested for the control of STATCOM-SCESS. For example, a robust controller could be designed using loop shaping technique is a potential approach.
- Different optimization techniques other than PSO could also be investigated. Objective functions other than the one used here could also be evaluated to achieve the best system performance.

APPENDIX

THE SYSTEM'S DATA

The below power system data were used for the case studies. All quantities are in per unit unless otherwise noted. The system's data, other than the dc link capacitance, have been taken from [54].

Reactances, Capacitances:
$x_q = 0.6$ $x_{tl} = 0.3$ $x_d' = 0.3$ $x_{lb} = 0.3$ $x_{sdt} = 0.5$
$V_{dc} = 3.0$ $C_{dc} = 0.0003$
$C_{SC} = 6$

Steady-state power, frequency, and voltages:
$P_m = 0.8$ $v_t = 1.05$ $v_m = 1.0$ $v_b = 1.0$ $\omega_0 = 377$ Rad/s

Generator parameters:
D=0 H = 8.0 M=H/2 $T_{do}' = 5.044$ s

STATCOM Time Constant:
$T_C = 0.01$s

Fixed Control system parameters for excitation system and STATCOM-SCESS:
$K_A = 50.0$ $T_A = 0.05$s
$T_w = 10$s $T_{P2} = 0.01$s $T_{P4} = T_{P2}$
$T_{m2} = 0.1$s $T_{m4} = T_{m2}$
$T_{epsi2} = 0.1$s $T_{epsi4} = T_{epsi2}$

REFERENCES

[1] P. Kundur, Power System stability and Control, McGraw-Hill, 1994.

[2] L. L. Grisbi, Power System Stability and Control, Floreda: CRC Press, 2012.

[3] M. A. Abido, "Analysis And Assessment of STATCOM-Based Damping Stabilizers for Power System Stability Enhancement," in *Electricl Power Systems Researches 73*, 2005.

[4] M. Abido, "Power System Stability Enhancement Via Coordinated Design of Excitation and STATCOM-Based Controllers," 2003.

[5] S. M. Bamasak, "FACTS-Based Stabilizers for Power System Stability Enhancement," Thesis presented to King Fahd University of Petroleum and Minerals, 2005.

[6] J. Paserba, "How FACTS controllers-benefit AC transmission systems," in *Transmission and Distribution Conference and Exposition*, 7-12 Sept. 2003.

[7] K. K. Sen and M. L. Sen., Introduction to FACTS Controllers; Theory, Modeling, and Applications, Wiley-IEEE, 2009.

[8] N. G. Hingorani and L. Gyugyi, Understanding FACTS; Concepts And Technology of Flexible AC Transmission Systems, New York: IEEE Press, 2000.

[9] A. Edris, "FACTS technology development: an update," in *IEEE Power Engineering Review*, 2000.

[10] L. Gyugyi, "Power electronics in electric utilities: static VAR compensators," in *Proceedings of the IEEE, vol.74, No.4*, Apr 1988.

[11] D. Lijie, L. Yang and M. Yiqun, "Comparison of High Capacity SVC and STATCOM in Real Power Grid," in *International Conference on Intelligent Computation Technology and Automation*, 11-12 May 2010.

[12] E. Larsen, N. Miller, S. Nilsson and S. Lindgren, "Benefits of GTO-based compensation systems for electric utility applications," in *IEEE Transactions on Power Delivery, vol.7, no.4*, Oct. 1992.

[13] L. Gyugyi, "Dynamic compensation of AC transmission lines by solid-state synchronous voltage sources," in *IEEE Transactions on Power Delivery, vol.9, no.2*, Apr. 1994.

[14] P. Rao, M. L. Crow and Z. Yang, "STATCOM control for power system voltage control applications," in *IEEE Transactions on Power Delivery, vol.15, no.4*, Oct. 2000.

[15] P. Srithorn, M. Sumner, L. Yao and R. Parashar, "A STATCOM with supercapacitors for enhanced power system stability," in *4th IET Conference on Power Electronics, Machines and Drives*, 2008.

[16] J. Chen, S. Song and Z. Wang, "Analysis and Implement of Thyristor-based STATCOM," in *Power System Technology International Conference*, 22-26 Oct. 2006.

[17] Y. Sumi, Y. Harumoto, T. Hasegawa, M. Yano, K. Ikeda and T. Matsuura, "New Static Var Control Using Force-Commutated Inverters," in *IEEE Transactions on Power Apparatus and Systems-100, vol.9*, 1981.

[18] L. Gyugyi, "Reactive Power Generation and Control by Thyristor Circuits," in *IEEE Transactions on Industry Applications*, Sept. 1979.

[19] K. Padiyar and A. Lakshmi Devi, "Control and simulation of static condenser," in *Applied Power Electronics Conference and Exposition, Ninth Annual*, 13-17 Feb 1994.

[20] A. Ajami and M. Younesi, "Modeling and state feedback controller for current source inverter based STATCOM," in *nternational Conference on Control, Automation and Systems*, 14-17 Oct. 2008.

[21] C. Edwards, K. Mattern, E. Stacey, P. Nannery and J. Gubernick, "Advanced state VAr generator employing GTO thyristors," 1988.

[22] H. Masdi, N. Mariun, S. Bashi, A. Mohamed and S. Yusuf, "Construction of a Prototype D-Statcom for Voltage Sag Mitigation," *European Journal of Scientific,* vol. 30, no. 1, pp. 112-127, 2009.

[23] S. Mori, K. Matsuno, T. Hasegawa, S. Ohnishi, M. Takeda, M. Seto, S. Murakami and F. Ishiguro, "Development of a large static VAr generator using self-commutated inverters for improving power system stability," in *IEEE Transactions on Power Systems, vol.8, no.1*, 13-15 Aug. 1993.

[24] Y. H. Song and A. T. Johns, Flexible AC Transmission Systems (FACTS), London: IEE, 1999.

[25] G. Reed, J. Paserba, T. Croasdaile, M. Takeda, Y. Hamasaki, T. Aritsuka, N. Morishima, S. Jochi, I. Iyoda, M. Nambu, N. Toki, L. Thomas, G. Smith, D. LaForest, W. Allard and D. Haas, "The VELCO STATCOM based transmission system project," in *Power Engineering Society Winter Meeting*, 2001.

[26] Q. Yu, P. Li, W. Liu and X. Xie, "Overview of STATCOM technologies," in *Proceedings of the 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, 5-8 April 2004.

[27] K. H. Ahmed, S. J. Finney and B. W. Williams, "Passive Filter Design for Three-Phase Inverter Interfacing in Distributed Generation," in *Compatibility in Power Electronics*, May 29 2007-June 1 2007.

[28] C. Wang, X. Yin, M. Wen, J. Liu, Q. Xiong and B. Zhang, "Structure and parameters design of output LC filter in D-STATCOM," in *International Conference on Power System Technology (POWERCON)*, 24-28 Oct. 2010.

[29] A. Cetin and M. Ermis, "VSC-Based D-STATCOM With Selective Harmonic Elimination," in *IEEE Transactions on Industry Applications, vol.45, no.3*, May-June 2009.

[30] C. Shauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," July 1993.

[31] M. Zarringhalami and M. A. Golkar, "Analysis of Power System Linearized Model with STATCOM Based Damping Stabilizer," in *Third International on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, 2008.

[32] A. M. Abdurrahim, S. Al-Baiyat and F. Kandlawala, "A robust STATCOM controller for power system dynamic performance enhancement," in *Power Engineering Society Summer Meeting*, 2001.

[33] M. F. Kandlawala, *Investigation of Dynamic Behavior of Power System Installed With STATCOM,* A thesis submitted to King Fahd University of Petroleum and Minverals, 2001.

[34] S. F. Faisal, *Damping Enhancement of Multimachine Power System Through STATCOM Control,* A thesis submitted to King Fahd University of Petroleum and Minverals, 2005.

[35] M. B. Abbas, *On-line Identification And Control of Power System With STATCOM,* A thesis submitted to King Fahd University of Petroleum and Minverals, 2005.

[36] Z. Xi and S. Bhattacharya, "STATCOM Control with Instantaneous Phase-locked Loop for Performance Improvement under Single-line to Ground Fault," in *34th Annual Conference of IEEE Industrial Electronics*, 2008.

[37] L. Shi and M. Crow, "A novel phase-locked-loop and its application in STATCOM," in *North American Power Symposium (NAPS)*, 26-28 Sept. 2010.

[38] S. Smith, P. Sen and B. Kroposki, "Advancement of energy storage devices and applications in electrical power system," in *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 20-24 July 2008.

[39] S. Buller, E. Karden, D. Kok and R. D. Doncker, "Modeling the Dynamic Behavior of Supercapacitors Using Impedance Spectroscopy," in *IEEE Transactions on Industry Applications, vol.38, no.6*, 2002.

[40] Z. Yi-cheng, W. Lu-lu, Z. Xue-jun and L. Hai-quan, "Design of Supercapacitor-based Energy Storage System for Metro Vehicles and Its Control Rapid Implementation," in *IEEE Vehicle Power and Propulsion Conference*, Harbin, China, September 3-5, 2008.

[41] W. Lhomme, P. Delarue, P. Barrade, A. Bouscayrol and A. Rufer, "Design and Control of a Supercapacitor Design Storage System for Traction Applications," in *Fourtieth Industry Applications Conference*, 2-6 Oct. 2005.

[42] N. S. Zhai, Y. Y. Yao, D. L. Zhang and D. and Xu, "Design and Optimization for a Supercapacitor application System," in *International Conference on Power System Technology*, 3-5 Sept. 2008.

[43] J. Zhang, J. Lai and W. Yu, "Bidirectional DC-DC Converter Modeling and Unified Controller with Digital Implementation," in *Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition*, 24-28 Feb. 2008.

[44] H. Liu, C. Mao, J. Lu and D. Wang, "Electronic power transformer with supercapacitors storage energy system," *Electric Power Systems Research,* no. 79, p. 1200–1208, 2009.

[45] K. Kobyashi, M. Goto, K. Wu, Y. Yokomizu and T. Matsumura, "Power System Stability Improvement by Energy Storage Type STATCOM," in *IEEE Power Tech Conference Proceedings*, Bologna, 23-26 June 2003.

[46] Z. Yang, C. Shen, L. Zhang, M. L. Crow and S. Atcitty, "Integration of a StatCom and Battery Energy Storage," in *IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 16, NO. 2*, 2001.

[47] C. F. LU, C. J. WU and C. C. Liu, "Dynamic modelling of battery energy storage system and application to power system stability," in *IEE Proceedings in Generation, Transmission, and Distribution, Vol. 142, No. 4*, 1995.

[48] C. Banos, M. Aten, P. Cartwright and T. C. Grenn, "Benefits and control of STATCOM with energy storage in wind power generation," in *IEEE Power Electronics Specialists Conference*, 2006.

[49] Z. Xi, B. Parkhideh and S. Bhattacharya, "Improving Distribution System Performance with Integrated STATCOM and Supercapacitor Energy Storage System," in *IEEE Power Electronics Specialists Conference*, 2008.

[50] A. Arsoy, Y. Liu, P. Ribeiro and F. Wang, "StatCom-SMES," *Industry Applications Magazine,* vol. 9, no. 2, pp. 21- 28, Mar/Apr 2003.

[51] P. Srithorn, M. Sumner, L. Yao and R. Parashar, "Power System Stabilization using STATCOM with Supercapacitors," in *IEEE Industry Applications Society Annual Meeting*, 2008.

[52] M. Molina and P. Mercado, "Dynamic modeling and control design of DSTATCOM with ultra-capacitor energy storage for power quality improvements," in *Transmission and Distribution Conference and Exposition*, Latin America, 13-15 Aug. 2008.

[53] P. T. Kerin, Elements of Power Electronics, Oxford university Press, 1998.

[54] M. A. AbdulMalik and M. A. Abido, "Statcom based controller design Using Paricle Swarm Optimization for Power System Stability Enhancement," in *IEEE International Syposium on Industrial Power Electronics*, 2009.

[55] S. Hosseini, A. Nazarloo and E. Babaei, "Super-Capacitor based D-STATCOM applied in IEEE 13-bus industrial distribution system," in *8th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, 17-19 May 2011.

[56] K. Patra, "Design of STATCOM Controllers with Energy Storage System Using GEA," 2005.

[57] M. J. Basler and R. C. Schaefer, "Understanding Power System Stability," in *IEEE*, 2005.

[58] A. T. Al-Awami, "Design of Robust PSS and FACTS-Based Controllers for Stability Enhancement of Power Systems," Thesis presented to King Fahd University of Petroleum and Minerals, 2004.

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