CHAPTER 2
LITERATURE SURVEY

2.1 GENERAL

The literature survey shows that there has been a lot of work done in the field of FACTS controllers and even then there is a great need to improve the real and reactive power control strategy, voltage control and transient stability enhancement. The application of SSSC in long distance power system has received much attention by researchers in recent years. By virtue of its ability to provide continuous and rapid control of reactive power and voltage, SSSC can enhance several aspects of transmission system performances such as transient stability enhancement, sub synchronous resonance damping and power oscillation damping. The improvement in the performances of the transmission system is effective when FACTS devices are integrated with energy storage systems.

2.2 BACKGROUND STUDY

The works reported in the literature are the application of many FACTS devices such as SVC, TCSC, SSSC, UPFC, SMES etc. in power system network. Conventional PI, PID controllers, Lyapunov energy function approach, multi control and MIMO systems are used as control schemes for FACTS devices. Decoupled techniques for the control of SSSC, internal and external control schemes, chopper control for energy storage systems are also reported in the literature.
Later on the intelligent controllers have been designed for various FACTS devices and they have been very efficient in their performances compared to the general controllers. Fuzzy control schemes, neural networks, genetic algorithm approaches and hybrid controllers are reported in the literature. The energy storage systems play a vital role in the improvement of the power system. Various energy storage systems, their application, modelling for power system network have been reported. Hence, the literature survey carried out has been classified in the following categories:

- FACTS devices
- General control schemes
- Intelligent control schemes and
- Energy storage systems

Around 100 papers have been taken for literature survey in the work and the areas taken can be categorised as in Figure 2.1

![Figure 2.1 Distribution of literature survey](image_url)
2.3 FACTS DEVICES

Due to recent advances in power electronics, FACTS devices have gained good popularity during the last few years. FACTS devices have been mainly used for solving various power system control problems such as voltage regulation, power flow control, and transfer capability enhancement, damping the inter-area modes and enhancing power system stability.

The vision of the FACTS has been formulated by the Electric Power Research Institute (EPRI) in the late 1980s. The various power-electronics based controllers regulate power flow and transmission voltage and mitigate dynamic disturbances. The main objectives of FACTS are to increase the useable transmission capacity of lines and control power flow over designated transmission routes. Hingorani (1988, 1991) and Hingorani and Gyugyi (2000) have proposed the concept of FACTS.

There are two generations for the realization of power electronics-based FACTS controllers: the first generation uses conventional thyristor-switched capacitors and reactors, and quadrature tap-changing transformers and the second generation uses Gate Turn-Off (GTO) thyristor-switched converters as Voltage Source Converters (VSCs). The first generation has resulted in the Static Var Compensator (SVC), the Thyristor-Controlled Series Capacitor (TCSC), and the Thyristor-Controlled Phase Shifter (TCPS). The second generation has produced the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC), and the Interline Power Flow Controller (IPFC). The two groups of FACTS controllers have distinctly different operating and performance characteristics.

The thyristor-controlled set-up has capacitor and reactor banks with fast solid-state switches in shunt or series circuit arrangements. By varying
the on and off periods of the thyristor switches, variable reactance values of the fixed capacitor and reactor banks are obtained.

The voltage source converter (VSC) type FACTS controller set-up has self-commutated DC to AC converters, using GTO thyristors, which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of capacitor or reactor banks. The converter with energy storage device can also exchange real power with the system, in addition to the independently controllable reactive power. Yong Hua Song and Allan T. Johns (1999) have proposed that the VSC can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase shifting, or to control directly the real and reactive power flow in the line.

Bibliography report for the FACTS is published by IEEE working group. Figure 2.2 gives the survey of works done in various FACTS devices for 2007, 2008 and 2009.

![Figure 2.2 Distribution of literature survey according to the IEEE working group for 2007, 2008 and 2009](image-url)
Hanson et al (2002) have described the emergence of second generation FACTS devices as serious alternatives to the conventional devices. The effectiveness of STATCOM to control power system voltage has been presented by Wang et al (2002). UrosGabrijel and Rafael Mihalic (2003) have proposed three methods of transient stability analysis in power systems with FACTS controllers. First is the time domain digital simulations that numerically integrate differential equations and a solution in the form of system trajectory is obtained. The second approach is the direct methods that employ Lyapunov energy functions. The third approach is the hybrid method by combining digital simulation and direct methods.

Haque (2004) has demonstrated the capability of the STATCOM to provide additional damping to the low frequency oscillations by the use of energy function. The STATCOM damping characteristics have also been analyzed and addressed. Different approaches to STATCOM-based damping controller design such as loop-shaping (Rahim et al, 2002), pole-placement (Lee and Sun 2002), multivariable feedback linearization (Sahoo et al 2004), $\text{H}_\infty$ control (Al-Baiyat, 2005) and intelligent control (Morris et al 2003) have been adopted.

The SSSC has been applied to different power system studies to improve the system performance. A comparative study of the STATCOM and SSSC has been investigated for stability study by Haque (2005).

The voltage source inverter for SSSC is initially devised with 3 level inverters. Then 6 pulse, 12 pulse and 24 pulse inverters are designed for the purpose to use in SSSC. Control schemes to enhance the dynamic performance of STATCOM and SSSC have been proposed by Amir H. Norouzi and Sharaf (2005). 24 pulse VSI is designed for STATCOM and SSSC. A new automatic gain controller is proposed to ensure the stable operation of STATCOM under various load conditions. The phase locked
loop has an inherent delay and it has a great influence on the dynamic operation of the SSSC and a new auxiliary regulator is proposed to enhance the dynamic performance of the SSSC. El Moursi and Sharaf (2005) have designed a 48 pulse VSI for the SSSC. Decoupled current control strategy is proposed and the reactive power compensation and voltage stabilization are discussed for both STATCOM and SSSC.

The SSSC as a series compensator has two ways of controlling the magnitude of the compensation, which are the constant quadrature voltage ($V_q$) mode and constant reactance mode ($X_q$). In the $X_q$ mode, the voltage injected by SSSC is proportional to the line current and in $V_q$ mode, the injected voltage of the SSSC is a constant that is in quadrature to the line current. Power oscillation damping, synchronizing power and transient stability limit of a radial power system for the above two modes are discussed by Fawazi Jowder (2005) for the two modes of operation.

Anil Pradhan and Lehn (2006) have presented an analytical formulation of the frequency domain characteristics of the SSSC. Both the $V_q$ control and $X_q$ control of SSSC have been discussed. The influence of the controller parameters on the SSSC characteristics has been investigated.

Ahmadian and Kazemi (2006) have proposed a decoupling technique for improving the vector control model of SSSC. In the indirect control methods, using current control, there is a coupling between d and q axis and therefore a coupling between P and Q is seen. By the decoupling method, an independent control of P and Q is achieved and other control parameters of SSSC are also improved and a faster and more precise response is achieved.

Kumkratug and Laohachai (2007) have proposed a control strategy for SSSC by presenting an energy function of a power system with an SSSC.
The energy function is used for the transient stability analysis. The critical clearing time has been estimated from the proposed energy function and it is compared with the time domain simulation method.

The SSSC constructed with a 48 pulse inverter on the power demand from the grid has been discussed by Taha Selim Ustun and Saad Mekhilef (2010). The compensation achieved by the SSSC and its effects on the line voltage, line current, phase angle and real/reactive power have been analysed. THD analysis is also carried out to see the harmonics content.

Mathematical modelling and control strategy for the transient stability improvement for the SSSC have been presented by Prechanon Kumkratug (2011). Here, the SSSC is represented by variable voltage injection with associate transformer leakage reactance and the voltage source. The swing curves have been presented and analysed.

2.4 GENERAL CONTROL SCHEMES

Designing a controller for the non-linear systems to achieve the adaptiveness, is an emerging field of interest in the research area. Several control methods have been proposed. Initially, owing to their simplicity, conventional control techniques like PI and PID control laws have been proposed. Sunilkumar and Arindam Ghosh (1999) have derived an equivalent circuit model of the SSSC and based on this model a PI controller is proposed. The controller gains are chosen through eigenvalue analysis of the IEEE first benchmark model for SSR analysis.

Similar to the Ziegler Nichols method, Basilio and Matos (2002) have suggested a systematic adjustment of gains in PI and PID controllers in order to meet the transient performance specifications where the tuning needs only the parameters obtained from the plant step response.
Xiao and Ping Zhang (2003) have described multi control functional model of SSSC for power flow analysis which can be used for steady state control of active and reactive power flows on the transmission lines, the voltage at the bus and the impedance of the transmission lines. The model can also take into account the voltage and current constraints of SSSC.

Farsangi et al (2004) have proposed methods to select the input signals for both single and multiple FACTS devices in small and large power systems. Different input – output controllability analyses have been used to assess the most appropriate input signals for the SVC, SSSC and UPFC for achieving good damping of the interarea oscillations.

Haque (2004) has proposed a control strategy for the shunt FACTS devices to improve the first swing stability limit of a simple power system. It is shown that the speed based bang-bang control is unable to use the entire decelerating area in maintaining stability. The proposed control strategy improves the stability limit first by maximizing the decelerating area and then fully utilizing it in counter balancing the accelerating area.

FACTS damping control is superimposed on FACTS normal control functions and hence its effectiveness can be hampered by the interactions between FACTS normal control and damping control function. Hence, Relative Gain Array (RGA) method is proposed by Wang et al (2004) for the effective design of FACTS damping controller and it is effectively demonstrated using UPFC.

Later on, MIMO controller is designed by Ghaisari et al (2005) to increase the power oscillation damping and the dc link voltage is also regulated. Since SSSC in power system results in a multivariable system with effective interactions among its state variables, multivariable control strategies and techniques are expected to improve its performance.
Li-Jun Cai and Istvan Erlich (2005) have proposed a method for the simultaneous co-ordinated tuning of FACTS devices and power system stabilizers in multi-machine power system. The proposed method is effective for the tuning of multi-controllers in large power systems.

2.5 INTELLIGENT CONTROL SCHEMES

The lack of intelligence, learning, and adaptation capability in the control methods discussed in general control scheme, reveal the need for continuous expert intervention for the control of non-linear systems. Hu et al (1997) have described an optimal design of a fuzzy PI controller based on theoretical fuzzy analysis and genetic based optimization. The proposed controller is very simple in structure and it consists of a single input variable, three rules and four design parameters. But for the power system transient stability problems with such a simple controllers, it is not possible to obtain efficient controllers.

Singh et al (1999) have discussed the dynamic response of SSSC with sliding mode fuzzy controllers for SSSC and current controlled voltage source inverter is used as a SSSC. Kwang Lee et al (2000) have designed model free intelligent controller for the power system application. The controller is designed only with the input and output data. The idea of free model is from the Taylor series approximation. The free model developed is controllable, observable and robust. The accuracy of the free model approximation can be improved by increasing the observation window and the order of the free model.

Dingguo Chen et al (2000) address the power system stability issue involving the regular generator angle transient stability and load driven voltage instability. Transient stabilization of simplified power systems equipped with the FACTS device, the TCSC, is studied with consideration of
unknown loads. They computed off line time optimal trajectories based on the switching times variation methods and developed a robust near time neural controllers for the application in power system networks equipped with FACTS devices.

Dash et al (2000) have devised a hybrid controller for FACTS devices in a multi machine power system. The hybrid controller has been realized with an incremental fuzzy logic controller in place of proportional term in a conventional PI controller. The controller has provided a wide variation of controller gains in a non linear manner and the controller has been tested for FACTS devices like UPFC, TCSC and TCPST etc. in damping multi-modal oscillations in a multi-machine environment.

Wang et al (2000) have designed an optimal PI controller for the enhancement of transient stability of a single machine infinite bus power system with SVC using genetic algorithm approach. The application of this controller is concerned with the damping of oscillations of a synchronous generator as well as to control the system voltage.

Feng Zheng et al (2001) have suggested a Takagi-Sugeno fuzzy model with parameter uncertainties to approximate the non linear systems. A numerically tractable algorithm based on the technique of iterative linear matrix equalities is developed to design a proportional controller which is suitable for transient stability analysis.

Khan et al (2004) have discussed the power system stability of a single machine infinite bus system with SVC using fuzzy set theory. Sze et al (2004) have proposed an intelligent fuzzy controlled SSSC for stability enhancement where he used machine angle and electrical power as the input signals. Tamer Abdelazim and Malik (2006) have developed an adaptive fuzzy controller to control the output of an SSSC to damp power system
oscillations. The adaptive controller consists of recursive least squares identifier and a fuzzy controller that adapts itself based on the identifier parameter.

A fuzzy logic controller has been designed for SSSC by Chandrakar and Kothari (2004) for transient stability improvements. The fuzzy logic approach is applied to coordinate the two control inputs: in phase voltage and quadrature voltage of SSSC. The real power flow, damping of first swing and improvement in transient stability margin of a single machine infinite bus system have been analysed.

Pavel Zuniga Haro and Juan M Ramirez (2006) have presented a control for SSSC by a B-spline neural network in order to regulate the active power flow on a transmission line. Such control drives the phase of the series source to the desired value so as to achieve the reference power flow. B-spline neural network control presents an adaptive performance.

A novel fault-tolerant optimal neuro control scheme for SSSC connected to a multi-machine benchmark power system has been proposed by Wei Qiao et al (2008). A set of fault-tolerant measurements to the SSSC controllers were obtained and guarantees fault tolerant control for the SSSC.

Neural network controller for SSSC has been used by Pavel Zuniga Haro and Juan Ramirez (2006) to regulate the power flow. Using fuzzy controller damping of power system oscillation with SSSC has been discussed by Tamere Abdelazim and Malik (2006). Transient stability assessment has been carried out by Kumkratug and Laohachai (2007) using energy function approach.

Geethalakshmi et al (2008) developed a fuzzy logic based SSSC controller for enhancing the transient stability of a single machine infinite bus
power system. The SSSC is realized using a 48-pulse voltage source inverter. Fuzzy logic controllers are designed to operate the SSSC in the automatic power flow control mode.

Optimal tuning of SSSC based controller for stability enhancement has been discussed by Sidartha Panda (2010). A systematic procedure for modelling, simulation and optimally tuning the parameters of a Static Synchronous Series Compensator (SSSC) controller in a multi-machine system for power system stability enhancement is presented. By minimizing a time-domain based objective function, in which the modal oscillations of the power system are involved, stability performance of the power system is improved.

2.6 ENERGY STORAGE SYSTEMS

The objectives of using energy storage devices in power system are as follows: ability to absorb harmonics, provide load levelling, provide damping of inter-area oscillations, help in damping transient stability, and provide effective and fast control power flow along a transmission line corridor. The various energy storage technologies adopted are the battery energy storage, flywheel energy storage, advanced super capacitors, superconducting magnetic energy storage systems etc. The key factors in selecting an energy storage system depend upon the amount of energy that can be stored in the device and the rate at which the energy can be transferred into or out of the storage device. Integration of energy storage technologies with FACTS and custom power devices are the advanced power applications utilizing energy storage.

Advances in both superconducting technologies and the necessary power electronics interface have made SMES a good technology for high power utility applications. The power industry’s demands for more flexible,
reliable and fast active power compensation devices make the ideal opportunity for SMES applications.

The number of technical issues and trade-offs resulting from the design optimization process for SMES have been discussed by Karasik et al (1999). The conductor design options, system configuration, current/voltage levels and insulation issues for a low temperature superconducting coil, the power electronics interface are discussed. Finally, consideration is given to the impact of new business environment, potential markets and overall cost. The design of +/-100MW peak and +/-50MW oscillatory power with 100MJ of stored energy SMES is given. The base line for the coil design assumes a cable in conduit conductor with rated voltage of 24kV and operating at nominal temperature of 4.5K.

Issarachai NGAMROO et al (1999) have proposed a sophisticated application of SMES to load frequency control in an interconnected power system. The SMES is coordinated with a solid state phase shifter to enhance load frequency. They have proved the economical advantage of MJ capacity of SMES.

Bikash Paul et al (2000) have designed a robust damping controller on a weighted and normalized eigen value-distance minimization method employing several superconducting magnetic energy storage devices. These controllers are aimed at enhancing the damping of multiple inter-area modes in large power systems.

Tsang and Sutanto (2000) have designed a fuzzy and neural network controlled Battery Energy Storage System to improve the stability of the power systems. Detailed model of the BESS is used for accurate dynamic assessment. The model takes into account the switching actions of the converter as well as the battery characteristics. Hysteresis technique is used
to control the output current of BESS. The neural network uses back propagation algorithm. Yang et al (2001) have integrated the battery energy storage system with STATCOM and proved the flexibility in mitigating the transmission level power flow problems.

Paulo Ribeiro et al (2001) have discussed the various energy storage systems for advanced power applications. Battery technologies have improved significantly in order to meet the challenges of practical electric vehicles and utility applications. Flywheel technologies are used in advanced non polluting uninterruptible power supplies. Advanced capacitors are being considered as energy storage for power quality applications. Superconducting energy storage systems are nowadays receiving attention for utility applications.

FACTS devices which handle both real and reactive power to achieve improved transmission system performance are multi-MW proven electronic devices and are now being introduced in the utility industry. In this environment, energy storage is a logical addition to the expanding family of FACTS devices. As deregulation takes place, generation and transmission resources will be utilized at higher efficiency rates leading to tighter and moment-by-moment control of the spare capacities. Energy storage devices can facilitate this process, allowing the maximum utilization of resources.

A combined control of superconducting magnetic energy storage with series phase compensator for the stabilization of a power system is proposed by Duangkamol Kamolyabutra et al (2001). By the use of series compensator, the SMES becomes capable of absorbing the generator accelerating power during a short circuit fault. In addition, the fault current is limited by the energy absorption as well as by the leakage reactance of a series transformer. A new control scheme for damping control of the
generator swing has been proposed that is suitable for an SMES with series configuration.

Marcelo Molina et al (2005) have integrated the STATCOM with Superconducting Magnetic Energy Storage system for controlling the frequency of large power systems. The chopper control scheme is also well discussed.

Sadeghzadeh and Ansarian (2006) have proposed an adaptive controller for SSSC and SMES based on the neural networks and fuzzy control for the improvement of tie line loadability and transient stability of power system. The proposed neuro fuzzy controllers combine the advantages of fuzzy controller and quick response and adaptability nature of ANN. The SSSC and SMES are separately included in the power system and their operating capabilities are discussed.

IEEE Task Force on Benchmark Models for Digital Simulation of FACTS and Custom Power Controllers, T&D Committee (2006) have presented a detailed model for simulation of a Superconducting Magnetic Energy Storage system. SMES technology has the potential to bring real power storage characteristic to the utility transmission and distribution systems. A detailed SMES system benchmark model is given.

A bidirectional dc/dc converter suitable for energy storage system with an additional function of galvanic isolation has been addressed by Shigenori Inoue and Hirofumi Akagi (2007). An energy storage device is directly connected to one of the dc buses of the dc/dc converter without any chopper circuit.

Energy cache control which enables fast compensation of stochastic power fluctuations through the use of Superconducting Magnetic Energy
Storage (SMES) connected to the DC bus of Distributed Generation (DG) has been discussed by Henry Louie and Kai Strunz (2007). The term energy cache control is chosen to reflect its analogy to the utilization of the data cache in computers. The SMES provides an energy cache for other types of storage with a higher capacity of energy but also longer response times.

Sheikh et al (2010) have presented novel control strategies of self tuned fuzzy proportional integral controller and fuzzy frequency controller for automatic generation control with SMES in a power system. Primary frequency control is better with SMES.

2.7 CONCLUSION

A detailed literature survey has been made in the areas of FACTS devices, General control schemes, intelligent control schemes and Energy storage systems. It is clear from the literature survey, that SSSC is having wide applications in the areas of power flow control, transient stability enhancement, voltage stability, power oscillation damping and sub-synchronous oscillation damping. Many works in the general and intelligent control schemes have been discussed. PI controller is effective for the linear systems where mathematical models are available and the intelligent controllers such as fuzzy logic, neural networks, neuro-fuzzy controllers etc. provide a good performance for the non-linear and dynamic systems. The various energy storage systems are discussed and the recent development is the superconducting magnetic energy storage system. FACTS devices integrated with energy storage system is an emerging technology today and lesser works have been reported in the literature survey.