

A Comparative Study of Various Controllers for Static Synchronous Series Compensator Integrated with Superconducting Magnetic Energy Storage System

S. Padma
Asst. Prof., EEE
Sona College of Technology,
Salem, TN, India, 636 005

Dr. M. Rajaram
Vice Chancellor
Anna University of Technology,
Tirunelveli, TN, India

ABSTRACT

A transient stability analysis is done for a multi-area power system with Static Synchronous Series Compensator (SSSC) integrated with Superconducting Magnetic Energy Storage (SMES) system. The SSSC is realized with Voltage Source Inverters (VSI) and the SMES is realized as a coil. The real and reactive power reference values are set constant and a three phase fault is created in one of the transmission lines and the power output from the generator and the load angle of the machine are analysed for three cases: first one with conventional PI controller, the second with fuzzy logic controller and the third with neural network controller. The comparative results are tabulated and it is inferred that the intelligent controllers perform well under transient stability conditions compared to the conventional controller. Matlab 7.0-Simulink software is used as a platform for the simulation.

General Terms

Fuzzy Logic Control, multi-level inverters, neural network control, PI control, FACTS device

Keywords

Back propagation algorithm, Multi-area system, SSSC, Transient stability.

1. INTRODUCTION

Electrical energy transmission and utilization is facing a set of challenges. Numerous changes are introduced continuously in the electrical utility industry due to its ever growing and ongoing expansion. The developing countries are experiencing a rapid growth. Due to this, transmission systems are pushed closer to their stability and thermal limits. When addition of new lines is planned, in addition to the cost, environmental considerations and the public concerns delay the securing of new right-of-ways. The solution to the above problems has to be arrived at in a cost effective way and co-ordinated manner. Series compensation is a means of controlling the power transmitted across transmission lines by altering or changing the characteristic impedance of the line. There are two types of series compensation: the variable impedance type series compensators and the converter type series compensators [1]. Traditionally, series compensation of transmission lines has been performed by thyristor controlled series reactance, either inductive or capacitive, depending on the power system requirement. The switching converter based Static

Synchronous Series Compensator (SSSC) provides another degree of freedom to series compensation, where the Voltage Source Converter (VSC) used for series compensation has the ability to maintain constant compensating voltage in the presence of varying line current. The SSSC can also control the amplitude of the injected compensating voltage independent of the amplitude of the line current [2]. When power system disturbances occur, synchronous generators are not always able to respond rapidly enough to keep the system in a stable condition. The time constant for the turbine governor system is high and if a high speed real or reactive power control is provided, load shedding or generator dropping may be avoided during the disturbances. Recent developments and advances in energy storage and power electronics technologies are making the application of energy storage technologies a viable solution for modern power applications. The storage technologies are batteries, flywheels, ultra capacitors and superconducting energy storage systems [3]. In this proposed work Superconducting Magnetic Energy Storage Systems are used.

For the innovation and development of better control systems, the design and implementation of intelligent systems has become an essential factor. Some of them are fuzzy logic and neural network techniques. These two techniques were applied in the proposed system. Fuzzy logic, which is the logic on which fuzzy control is based, is much closer in spirit to human thinking and natural language than the traditional logical systems. The experiences, preferences and thoughts of human are implemented through membership functions and fuzzy rules in fuzzy logic. A fuzzy logic controller uses a set of control rules and an inference mechanism to determine the control action for a given process state. Fuzzy membership functions can have different shapes depending on the designer's preference and / or experience [4], [5].

Artificial neural network is a replication of our human brain. The understanding, recognising, classifying, clustering, error detection and correction are the sixth sense of human brain and this capability is incorporated with the help of artificial neural network. Situations with incomplete and noisy data are faced in the real world. Back-propagation network is the widely used algorithm [6] for such situations and it is used in this work.

2. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

The Voltage Sourced Converter (VSC) based series compensators - Static Synchronous Series Compensator (SSSC) was proposed by Gyugyi in 1989. The single line diagram of a two machine system with SSSC is shown in Figure 1. The SSSC injects a compensating voltage in series with the line irrespective of the line current. From the phasor diagram, it can be stated that at a given line current, the voltage injected by the SSSC forces the opposite polarity voltage across the series line reactance. It works by increasing the voltage across the transmission line and thus increases the corresponding line current and transmitted power.

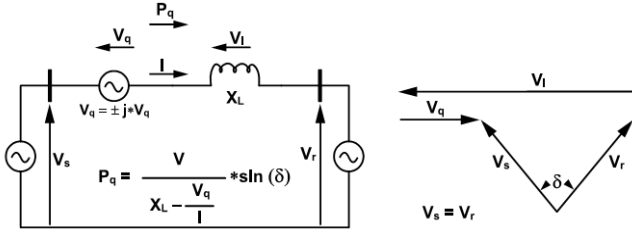


Fig 1: Simplified diagram of series compensation with the phasor diagram.

The compensating reactance is defined to be negative when the SSSC is operated in an inductive mode and positive when operated in capacitive mode. The voltage source converter can be controlled in such a way that the output voltage can either lead or lag the line current by 90° . During normal capacitive compensation, the output voltage lags the line current by 90° . The SSSC can increase or decrease the power flow to the same degree in either direction simply by changing the polarity of the injected ac voltage.

In the present work, 48-pulse VSI is designed and ideal switches and zig-zag phase shifting transformers are used to build a GTO-type VSI. The inverter described is harmonic neutralized. It consists of four 3-phase, 3-level inverters and four phase-shifting transformers. The DC bus is connected to the four 3-phase inverters. The four voltages generated by the inverters are applied to secondary windings of four zig-zag phase-shifting transformers connected in Wye (Y) or Delta (D) [7]. The four transformer primary windings are connected in series and the converter pulse patterns are phase shifted so that the four voltage fundamental components sum in phase on the primary side. Each 3-level inverter generates three square-wave voltages which can be $+V_{dc}$, 0, $-V_{dc}$. The duration of the $+V_{dc}$ or $-V_{dc}$ level (sigma) can be adjusted between 0 and 180 degrees from the sigma input of the firing pulse generator block. Each inverter uses a 3-level bridge block where specified power electronic devices are ideal switches. In this model, each leg of the inverter uses 3 ideal switches to obtain the 3 voltage levels ($+V_{dc}$, 0, $-V_{dc}$). For the input voltage of 20kV at the dc side, the waveforms and THD of the voltage at the ac side of the 48 pulse VSI are shown in Figure 2. The THD is 1.31%.

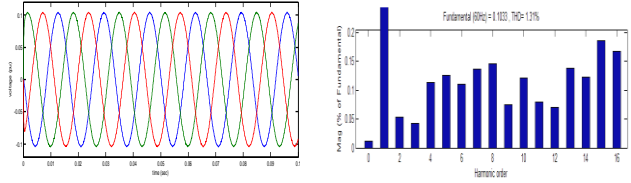


Fig 2: Voltage and THD of the voltage at the ac side of the 48 pulse VSI

3. CONTROL SCHEME PROPOSED

The main function of the SSSC used here is to dynamically control the power flow over the transmission line. There are two types of control schemes for SSSC [8] – voltage control mode and impedance control mode. In the proposed scheme, power references are used in the control strategy [9]. The reference inputs to the controller P_{ref} and Q_{ref} , are to be maintained in the transmission line [2]. The instantaneous power is obtained in terms of d-q quantities of voltages and currents as below:

$$P = V_d I_d + V_q I_q \quad (1)$$

$$Q = V_q I_d - V_d I_q \quad (2)$$

From equations 1 and 2, the required current references are calculated as follows:

$$I_{dref} = (P_{ref} V_d + Q_{ref} V_q) / (V_d^2 + V_q^2) \quad (3)$$

$$I_{qref} = (P_{ref} V_q - Q_{ref} V_d) / (V_d^2 + V_q^2) \quad (4)$$

The desired current references namely I_{dref} and I_{qref} are compared with actual current components I_d and I_q respectively and the error signals are processed in the PI controller. The PI controller parameters set for this process are 0.045 and 16.5 for the proportional and integral gains respectively. Based on these controller parameters set, the required small displacement angle β to control the angle of the injected voltage with respect to the line current has been derived. A Phase Locked Loop (PLL) is used to determine the instantaneous angle θ of the three-phase line voltage V_{labc} . The current components I_d and I_q of the three phase line currents are used to determine the angle θ_r relative to the voltage V_{labc} . Depending upon the instantaneous reactive power with respect to the desired value either $\pi/2$ is added (inductive) or subtracted (capacitive) with β Thus, the required phase angle is derived as in the equation 5.

$$\theta_{ref} = \theta + \theta_r + \beta \pm (\pi/2) \quad (5)$$

4. ENERGY STORAGE SYSTEMS

Electrical energy in an ac system cannot be stored as such (electrically). But it can be stored by converting the electricity and storing it electromagnetically, electrochemically, kinetically or as potential energy. Superconducting Magnetic Energy Storage systems are efficient and fast acting compared to other storage technologies. In the SMES system the energy is stored in the magnetic field generated by the dc current flowing through superconducting coil. The superconducting coil is maintained at cryogenic temperature. A power conversion/conditioning system connects the SMES unit to an ac power system and it is used to charge/discharge the coil. When a superconducting coil is simulated for a purpose of dynamic operation, it is a common practice to represent the coil as an inductor [3].

For the integration of SSSC with SMES, a multiphase GTO chopper is modelled as in [10]. In FACTS / SMES application,

the dc-dc chopper is connected to a FACTS device through a link capacitor maintaining a constant dc voltage. The control scheme that is proposed coordinates the control subsystems of the chopper and the VSI of the SSSC. The control scheme of the dc-dc chopper uses the control algorithms proposed by [10] and [11] as the basis. The duty cycle D is estimated from the active power ratings that the SSSC should inject ($V_{ac} \cdot I_{pr}$), from the voltage at the dc bus (V_{dc}) and from the current stored into the superconducting magnetic coil I_{SMES} . This estimated value (D_{est}^*) is adjusted through a closed loop control whose function is to eliminate the voltage error between the calculated and the real voltage ratings at the dc bus through an integral controller. The operating mode selector selects the proper mode for the charging and discharging of the SMES coil. The value of K_i is set through a trial and error method and the value is fixed as 25.

5. FUZZY LOGIC CONTROLLER FOR THE PROPOSED WORK

Fuzzy logic controller is designed for the current controller of SSSC. The input variables are the error and change in error in the dq current and the output variable is the dq component of the voltage. The universe of discourse for the input and output variables are partitioned into five intervals. The linguistic variables are NEGATIVE LARGE (NL), NEGATIVE SMALL (NS), ZERO (Z), POSITIVE SMALL (PS) and POSITIVE LARGE (PL). The triangular membership function taken for the inputs and output variables are defined as in Figure 3. The rule base is formed for the PI like controller. The heuristic rules are formed. There are totally 25 rules and they are represented with the FAM table as below. Fuzzy approximate reasoning is applied to the inputs and in the aggregation of fuzzy outputs 'and' operation is performed on the rule outputs. Centroid method of defuzzification is used.

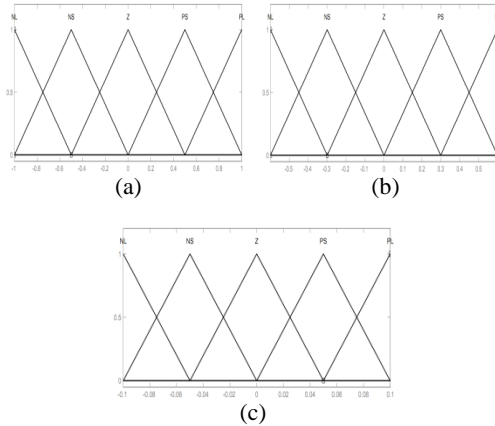


Fig 3: Membership functions for the proposed work (a) input error (b) input change in error and (c) control output

Table 1 FAM Table

e/Δe	NL	NS	Z	PS	PL
NL	NL	NL	NL	NS	Z
NS	NL	NL	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PL	PL
PL	Z	PS	PL	PL	PL

6. BACK-PROPAGATION NETWORK (BPN) FOR THE PROPOSED WORK

The BPN architecture is multi-layer feed-forward. But during learning process, it is a feedback network. Delta learning rule is used in the training phase. In this work, the layers used are three. The inputs used are the error and change in error (e and Δe) of the currents. The output is the dq voltages for proper fixing of the dc link voltage of the capacitor and reactive power compensation. In the hidden layer, there are four neurons. The off line training data of the neural network has been obtained using the results of the PI controller. Mean Square Error (MSE) is the performance criterion that evaluates the network according to the mean square of the error between the target and computed output. Learning occurs with a learning factor of 0.01 and momentum factor of 0.9. The hyperbolic tansigmoid function is used as activation function for the output of the hidden layer and linear function for the output layer.

7. SIMULATION RESULTS AND DISCUSIONS

A three area four bus system is taken for analysis and it is shown in figure 4. The transient stability of the system is analysed with the application of a three phase to ground fault in line 2. The real and reactive power references are fixed at 11 pu and -0.67 pu respectively. Fault is applied at 0.2 sec and cleared at 0.3 sec and the results are analysed.

Case (a) is discussed for the system integrated with SSSC and SMES for PI controller, case (b) is discussed for the fuzzy logic controller and case (c) is discussed for the neural network controller.

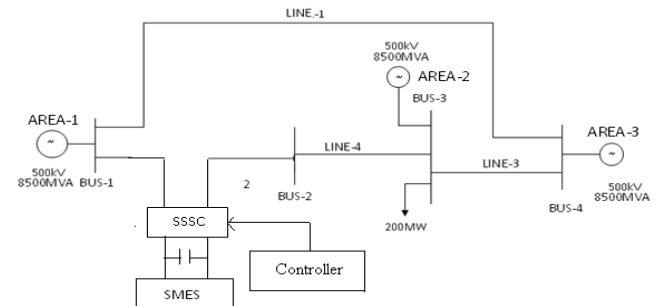


Figure 4: Single line diagram of the test system with SSSC.

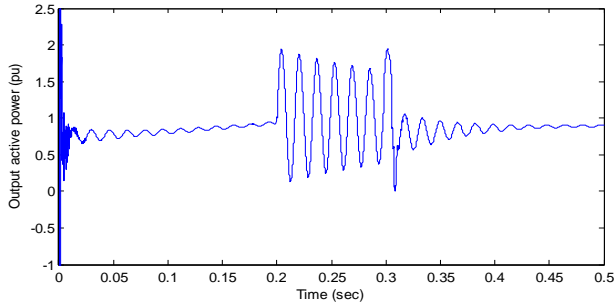


Figure 5: Electrical power output from generator 1 for case (a)

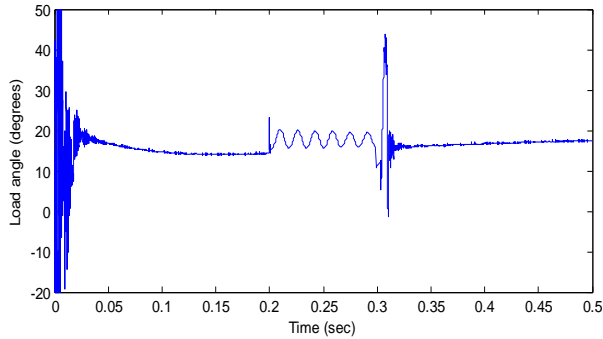


Figure 6: Load angle of machine 1 for case (a)

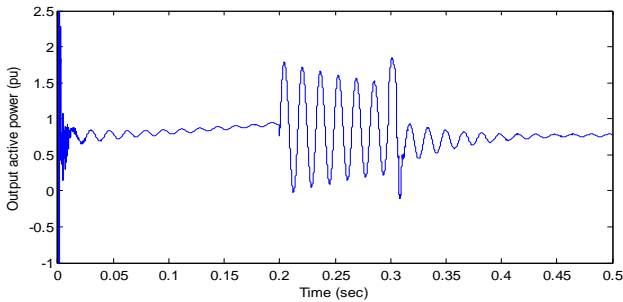


Figure 7: Electrical power output from generator 1 for case (b)

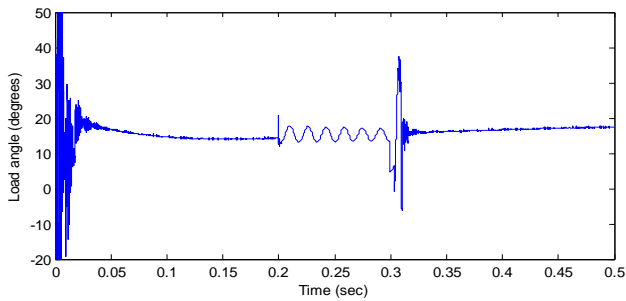


Figure 8: Load angle of machine 1 for case (b)

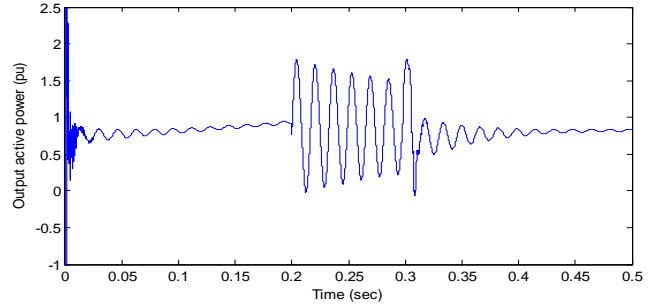


Figure 9: Electrical power output from generator 1 for case (c)

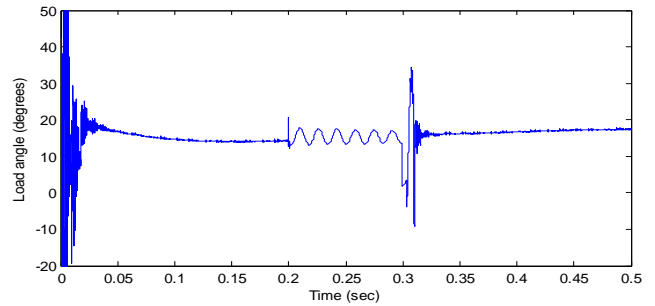


Figure 10: Load angle of machine 1 for case (c)

Figures 5 and 6 show the electrical power output from generator 1 and load angle of machine 1 respectively for case (a). Figures 7 and 8 show the results for case (b) and figures 9 and 10 show the results for case (c). From the waveforms the analysis has been produced in table 2.

Table 2 Comparative results for the integrated SSSC-SMES system with PI controller, Fuzzy Logic Controller and neural network controller

		PI Controller	Fuzzy Logic Controller	Neural Network Controller
Electrical power output from generator 1	Peak value (pu)	1.94	1.85	1.79
Load angle in generator 1	Peak value (degree s)	44	37.5	34.5

8. CONCLUSION

The dynamic performance of SSSC without and with SMES is analyzed with PI, fuzzy logic and neural network controllers using Matlab/Simulink, where the SSSC is connected to a multi-area system. The SSSC is realized with 48 – pulse inverter and it

generates symmetrical output voltages of desired magnitude and phase angle with very low harmonic components. It is inferred from the results that the intelligent controllers perform effectively for the SSSC system with SMES compared to the PI controller for the set reference values of real and reactive power for a three phase to ground fault.

9. ACKNOWLEDGMENTS

We sincerely thank the Management, Secretary and Principal of Sona College of Technology, Salem for their complete support in doing this research work.

9. REFERENCES

- [1] Hingorani, N.G., Role of FACTS in a Deregulated Market, *Proc. IEEE Power Engineering Society Winter Meeting*, Seattle, WA, USA, 2006, 1-6.
- [2] Padma S and Rajaram M, Fuzzy Logic Controller for Static Synchronous Series Compensator with Energy Storage System for Transient Stability Analysis, *Journal of Computer Science*, Vol. 7, Issue 6, pp 859 – 864.
- [3] IEEE Task Force on Benchmark Models for Digital Simulation and Custom Power Controllers, T&D Committee (2006), ‘Detailed Modeling of Superconducting Magnetic Energy Storage (SMES) Systems’, *IEEE Transactions on Power Delivery*, Vol.21, no. 2, pp 699-710
- [4] Kaufman A and Gupta M.M, *Introduction to Fuzzy Arithmetic: Theory and Applications*, Van Nostrand Reinhold Co., New York.
- [5] Padma S and Lakshmipathi R, Power Flow Regulation of a Multi-Area System with Fuzzy Gain Scheduled PI (FPGI) Controller for Static Synchronous Series Compensator with Superconducting Magnetic Energy Storage System (SMES), *International Journal of Computer Applications*, Vol. 7, No. 2, 2010, pp. 15-20.
- [6] Sivanandam S.N and Deepa S.N, *Principles of Softcomputing*, Wiley India Pvt. Ltd., New Delhi.
- [7] Padma S, Rajaram M and Madhubalan S, Intelligent Controller in Transient Stability Analysis of Static Synchronous Series Compensator, *European Journal of Scientific Research*, Vol. 49, No. 1 (2011), pp. 110-119.
- [8] Anil C Pradhan and Lehn P.W., Frequency Domain Analysis of the static synchronous series compensator, *IEEE Transaction on Power Delivery*, Vol. 2, pp. 440-445.
- [9] B. Geethalakshmi and P. Dananjayan, Investigations of Performance of UPFC without DC link capacitor, *Electric Power Systems Research*, vol. 78, Issue 4, pp. 736-746, April 2007.
- [10] Marcelo G Molina, Pedro E Mercado and Edson H Watanabe, Dynamic performance of a static synchronous compensator with superconducting Magnetic Energy Storage, *IEEE*, 2005, pp. 224-230.
- [11] Lasseter R.H. and S. G. Lalali, “Dynamic Response of Power Conditioning Systems for Superconductive Magnetic Energy Storage,” *IEEE Trans. On Energy Conversion*, 6, 3, 1991, pp. 388-393.