Control Algorithm for an SSSC Using Model Based Predictive Control

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Abstract

In this paper, a new control strategy for an SSSC, based on model predictive control (MPC), is presented for power flow control of power systems. Power system installed with SSSC is a nonlinear, indeterminist, multivariable system, and the traditional PI controller has a limited application in some cases because of its non-adaptive parameters. The proposed controller is employed to control the three main parameters affecting the stability of the system: SSSC DC link voltage, real power and reactive power of the power systems. With perfect dynamic characteristics of controller, the real power and reactive power of power systems and also the SSSC DC link voltage are flexibly controlled. Control Mechanism of DC Capacitor Voltage of SSSC is whether controlled independently or can be controlled via MPC strategy of the SSSC. A studying example is carried out to validate feasibility and adaptability of the proposed controller using MATLAB/Simulink software.

1. Introduction

Recent development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems [1]. FACTS controllers are able to change, in a fast and effective way, the network parameters in order to achieve better system performance. FACTS controllers can be categorized into three major groups: shunt devices such as the Static Synchronous Compensator (STATCOM), series devices such as the static synchronous series compensator (SSSC) and series shunt devices such as the unified power flow controller (UPFC) [2]. In addition to steady-state solutions such as power flow and voltage control, an added benefit of FACTS controllers deployed in the transmission system is that they can also effectively control active power oscillations that can damage generators, increase line losses. For the economic reasons, the application research of FACTS was mainly focused on the transmission systems, in order to improve the system stability and enhance the transmitting capability [3]. It has been demonstrated that variable series compensation is highly effective in both controlling power flow in the lines and in improving stability [4, 5].

The voltage source converter based series compensators called static synchronous series compensator (SSSC) provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. Fast power flow control is one of the main functions of SSSC, and choosing a good control method is pivotal to show its effectiveness .The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system. Its various capabilities have been discussed in many papers in areas of power flow control [2, 4], voltage control [6], transient stability improvement [7] and oscillation damping and transient control [8, 9]. As the power systems installed with SSSC are a large-scale nonlinear, indetermination and multivariable system, the structure and parameters of system will change especially when systems failure and load disturbance happens accidentally. Therefore the traditional PI controller has a limited application in some cases because of its non-adaptive parameters and linearity. To overcome these problems the SSSC has been applied in a vast variety of control system investigations, which include Adaptive PI controller [10], adaptive neural network-based controller [11, 12] fuzzy neural network approach [13], sliding-mode and fuzzy controllers [14], and non-linear controller for transient stability [15] are some of the controllers presented in these papers.

Model predictive control (MPC) is an attractive alternative to the classical control methods, due to its several advantages, like fast dynamic response, easy inclusion of nonlinearities and constraints of the system, and the flexibility to include other system requirements in the controller [16]–[18]. MPC is extremely effective in controlling systems with nonlinear cost function, time delay, constraints on the actuator and states. MPC considers a model of the system in order to predict the future behavior of the system over a horizon in time. A cost function represents the desired behavior of the system. MPC is an optimization problem where a sequence of future actuations is obtained by minimizing the cost function.

In this paper, an efficient control strategy for an SSSC based on model predictive control is presented for the power flow control. The SSSC is employed in both capacitive and inductive compensation of a transmission line. Both problems can be rearranged into the problem of tracking a reference reactive power. With perfect dynamic characteristics of **c**ontroller, the real power and reactive power of power systems and also the SSSC DC link voltage are flexibly controlled. A studying example is carried out to validate feasibility and adaptability of the proposed controller using MATLAB/Simulink.

2. Operating Principles of SSSC

Among FACTS devices, the static synchronous series compensator (SSSC) is widely used for series compensation of the transmission lines. A simple schematic of the SSSC is illustrated in Fig. 1. It consists of a voltage source converter (VSC), the control system and the coupling transformer. The

VSC generates a three phase voltage from a DC capacitor bank which is in quadrature with the line current. Therefore, the SSSC acts as an inductor or a capacitor to increase or decrease the overall reactive voltage drop across the line. If the SSSC voltage, E_s, lags the line current, i_s, by 90, a capacitive series compensation is obtained and if leads by 90, an inductive series compensation is obtained. The amount of series compensation can be modified by controlling the magnitude of the injected voltage. In this case, ideally, the SSSC does not exchange any real power with the power system.

As mentioned before, the phase and the magnitude of the injected voltage can be altered by proper control of the VSC. Therefore, two degrees of freedom can be defined for the SSSC. The phase of the injected voltage is commonly allocated for controlling the DC link voltage and the magnitude of the injected voltage determines the amount of series compensation. The magnitude of the injected voltage can be used to control the active or reactive power flow through the transmission line.

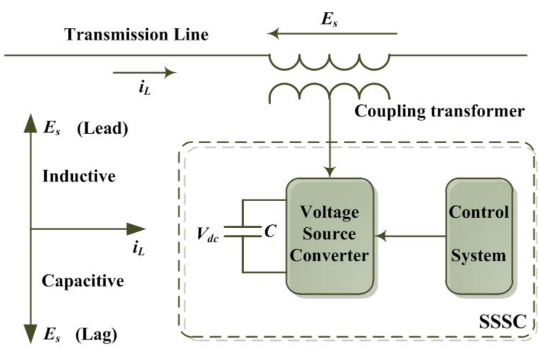

Fig. 1. Static synchronous series compensator

3. Power System Equipped with SSSC

Fig. 2 shows the test power system single machine infinite bus installed with SSSC. By using the SSSC, the power flowing from the transmission line can be controlled. In order to simplify the analysis of the SSSC, the generators dynamics are neglected and the generator is modeled as a voltage source. Also, the coupling transformers turn ratio is considered to be 1:1.

According to the single line diagram of the test system shown in Fig. 2, the following equation can be obtained.

$$\begin{bmatrix} \frac{di_{sa}}{dt} \\ \frac{di_{sb}}{dt} \\ \frac{di_{sc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} V_{sa} - V_{ra} - E_{sa} \\ V_{sb} - V_{rb} - E_{sb} \\ V_{sc} - V_{rc} - E_{sc} \end{bmatrix} \quad (1)$$

Where L is the sum of L_s and L_r, and R is the sum of R_s and R_r. For the converter side of the circuit, the following equation can also be written as:

$$\begin{bmatrix} \frac{di_{sa}}{dt} \\ \frac{di_{sb}}{dt} \\ \frac{di_{sc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_T}{L_T} & 0 & 0 \\ 0 & -\frac{R_T}{L_T} & 0 \\ 0 & 0 & -\frac{R_T}{L_T} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{1}{L_T} \begin{bmatrix} E'_{sa} - E_{sa} \\ E'_{sb} - E_{sb} \\ E'_{sc} - E_{sc} \end{bmatrix} \quad (2)$$

Using the previous equations (1) and (2), the following equation can be written as:

$$\begin{bmatrix} \frac{di_{sa}}{dt} \\ \frac{di_{sb}}{dt} \\ \frac{di_{sc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_{eq}}{L_{eq}} & 0 & 0 \\ 0 & -\frac{R_{eq}}{L_{eq}} & 0 \\ 0 & 0 & -\frac{R_{eq}}{L_{eq}} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{1}{L_{eq}} \begin{bmatrix} V_{sa} - V_{ra} - E'_{sa} \\ V_{sb} - V_{rb} - E'_{sb} \\ V_{sc} - V_{rc} - E'_{sc} \end{bmatrix} \quad (3)$$

Where L_{eq} is the subtraction of L from L_T (L-L_T) and R_{eq} is the subtraction of R from R_T (R-R_T). The equation (3) describes the dynamic behavior of the power system equipped with an SSSC. The input control parameter of the system is the output voltage of the inverter (E'_S). By proper control of the phase and magnitude of the inverter output voltage, power flowing from the transmission line can be controlled.

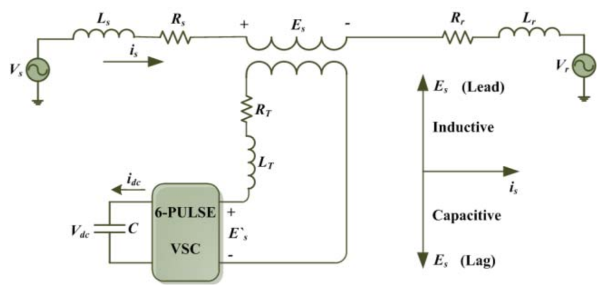

Fig. 2. Single line diagram of the test system

4. Predictive Controller Design

The model predictive controller aims to estimate the future behavior of the controlled variables so that proper control actions could be determined. The finite state characteristics of the power converters makes the model predictive control a suitable and efficient method to control them.

To obtain the discrete model of the system, the Euler approximation is applied to the equation (3). The discrete model of the system can be written as follows:

$$\begin{bmatrix} i_{sa}(k+1) \\ i_{sb}(k+1) \\ i_{sc}(k+1) \end{bmatrix} = K_1 \begin{bmatrix} i_{sa}(k) \\ i_{sb}(k) \\ i_{sc}(k) \end{bmatrix} + K_2 \begin{bmatrix} V_{sa}(\mathrm{k}) - V_{ra}(\mathrm{k}) - E'_{sa}(\mathrm{k}+1) \\ V_{sb}(\mathrm{k}) - V_{rb}(\mathrm{k}) - E'_{sb}(\mathrm{k}+1) \\ V_{sc}(\mathrm{k}) - V_{rc}(\mathrm{k}) - E'_{sc}(\mathrm{k}+1) \end{bmatrix} \quad (4)$$

$$K_1 = \frac{L_{eq}}{L_{eq} + T_s R_{eq}} \quad (5)$$

$$K_2 = \frac{1}{\frac{L_{eq}}{T_s} + R_{eq}} \quad (6)$$

Where T_s is the sampling time. It is also considered that the mains voltages V_s and V_r are constant during a sampling time T_s ($V_s(k+1) = V_s(k)$ and $V_r(k+1) = V_r(k)$).

The voltage source converter employed in the SSSC is shown in Fig. 3. There are eight possible switching states for a two-level inverter as follows:

$$S = \left\{ \begin{bmatrix}0\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}, \begin{bmatrix}0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\1\\1\end{bmatrix}, \begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}1\\0\\1\end{bmatrix}, \begin{bmatrix}1\\1\\0\end{bmatrix}, \begin{bmatrix}1\\1\\1\end{bmatrix} \right\}$$

According to Fig. 3, converter output phase voltages can be obtained as follows:

$$\begin{aligned} E'_{sa} &= \frac{V_{dc}}{3}(2S_1 - S_3 - S_5) \\ E'_{sb} &= \frac{V_{dc}}{3}(2S_3 - S_1 - S_5) \\ E'_{sc} &= \frac{V_{dc}}{3}(2S_5 - S_3 - S_1) \end{aligned} \quad (7)$$

Where S_1, S_3 and S_5 are equal to 1 if the corresponding device is on, 0 if the device is off. To predict the future behavior of the currents (i_s) for all switching states according to equation (4) at time instant $K+1$, it is required to know the V_s, V_r and i_s at time instant K. The instantaneous active and the reactive power flowing through the transmission line can also be predicted as follows:

$$P(k+1) = \begin{bmatrix} V_{sa} & V_{sb} & V_{sc} \end{bmatrix} \begin{bmatrix} i_{sa}(k+1) \\ i_{sb}(k+1) \\ i_{sc}(k+1) \end{bmatrix} \quad (8)$$

$$Q(k+1) = \frac{1}{\sqrt{3}} \begin{bmatrix} V_{sbc} & V_{sca} & V_{sab} \end{bmatrix} \begin{bmatrix} i_{sa}(k+1) \\ i_{sb}(k+1) \\ i_{sc}(k+1) \end{bmatrix} \quad (9)$$

The prediction of the DC link voltage is also necessary. As it is shown in Fig. 3, the DC link current can be expressed as:

$$i_C = i_{inv} - \frac{V_{dc}}{R_C} \quad (10)$$

$$i_C = C\frac{dV_{dc}}{dt} \quad (11)$$

The discrete model of the equations can be given as:

$$V_{dc}(k+1) = V_{dc}(k) + \frac{T_s}{C} i_c(k+1) \quad (12)$$

$$i_{inv}(k+1) = \begin{bmatrix} S_1 & S_3 & S_5 \end{bmatrix} \begin{bmatrix} i_{sa}(k+1) \\ i_{sb}(k+1) \\ i_{sc}(k+1) \end{bmatrix} \quad (13)$$

Substituting equations (10, 12, and 13) and simplifying yields to:

$$V_{dc}(k+1) = \frac{1}{1 + \frac{T_s}{R_C C}} \left(V_{dc}(k) + \frac{T_s}{C} \left\{ \begin{bmatrix} S_1 & S_3 & S_5 \end{bmatrix} \begin{bmatrix} i_{sa}(k+1) \\ i_{sb}(k+1) \\ i_{sc}(k+1) \end{bmatrix} \right\} \right) \quad (14)$$

Then a cost function must be minimized to determine the switching state at next time instant.

Definition of the cost function plays a major role in Model predictive control constraining the deviations of the controlled variables from their references so the cost function is given as follows:

$$\begin{aligned} J(S(k+1)) = {} & \lambda_1 \frac{1}{V_{dcR}} \left| V_{dc}(k+1) - V^*_{dc}(k+1) \right| + \\ & \lambda_2 \frac{1}{P_R} \left| P(k+1) - P^*(k+1) \right| + \\ & \lambda_3 \frac{1}{Q_R} \left| Q(k+1) - Q^*(k+1) \right| \end{aligned} \quad (15)$$

Where * indicates reference values, P_R, Q_R and V_{dcR} are respectively rated values of active power reactive power and dc link voltage, λ_1, λ_2, and λ_3 are the weighting factors that allow a proper balance among deviations in voltage, active and reactive power. The cost function assures the tracking of V_{dc}, P, and Q from the reference values. For each sampling sequence the cost function is evaluated for all the switching states. Comparison of cost function for different switching states determines the control actions for the following time instant.

It is worth noting that if the DC link voltage is supplied and controlled from outside such as another feeder, both the active and reactive power flowing through the transmission line can be controlled independently. Otherwise, the active or the reactive power along with the DC link voltage will be regulated.

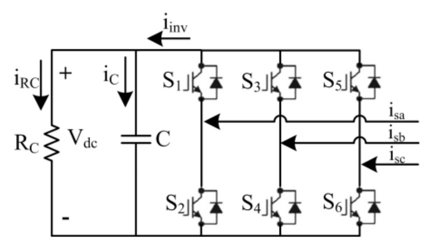

Fig. 3. The voltage source converter

5. Simulation Results

To verify the efficient operation of the presented scheme simulations have been carried out by Matlab/Simulink software. According to Fig. 2, the simulated system includes a two level voltage source converter, coupling transformers and the transmission line. The SSSC is installed on a 220 kV transmission line. The impedance of the transmission line is considered to be 0.1 P.u. with the S_{base}=100MVA. The coupling transformer impedance is taken 0.05 P.u. The DC link capacitor is 200 μF. The sampling time is also 20 μs. Fig .4 shows the DC link voltage. The reference value is given 35 kV with a step change at t=6s to 40 kV. As it is shown in Fig. 4, the reference value is well tracked. The reactive power flowing through the transmission line is shown in Fig. 5. The reference value is given -0.9 MVar with a step change at t=3s to -0.5 MVar. In this case, the control strategy is applied on the DC link voltage and the reactive power flow. As a result, the real power flow is determined by the characteristics of the system. The real power flow of the system is also depicted in Fig. 6.

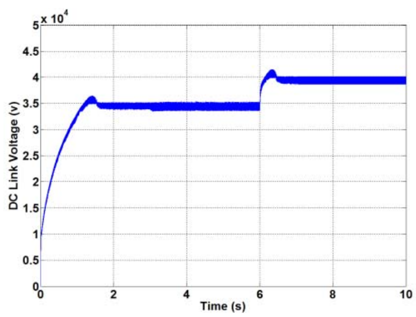

Fig. 4. DC link voltage (reference step change at t=6s)

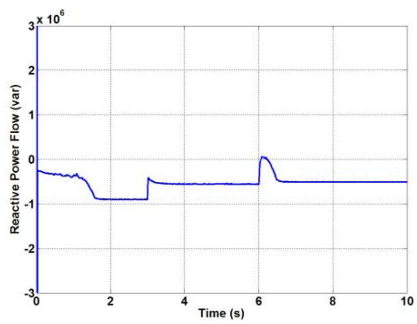

Fig. 5. Reactive power flow (reference step change at t=3s)

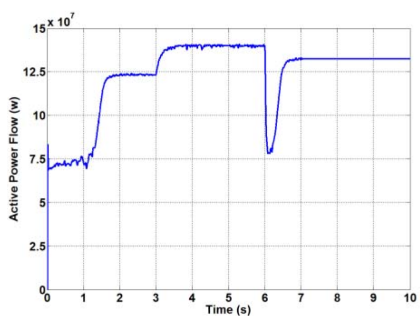

Fig. 6. Real power flow

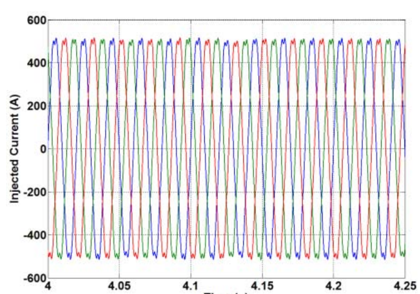

Fig. 7. Injected current of the VSC

The injected current of the VSC is also shown in Fig. 7. The results indicate the effective control of the DC link voltage and the reactive power flow.

It is also considered that the DC link voltage is supplied and controlled independently for instance, it can be supplied from other feeders. In this case, both the active and reactive power can be controlled independently. The DC link voltage is regulated at 50 kV. Fig. 8 shows the active power flow. The reference value is given 70 MW with a step change at t=0.25s to 75 MW. The reactive power flowing through the transmission line is shown in Fig. 9. The reference value is given 0 MVar with a step change at t=0.5s to -5 MVar and a step change at t=0.75s to 5 MVar. As it is shown in Figs .8, 9, the active and reactive power is controlled independently. Fig. 9 shows that the SSSC can operate both in capacitive and inductive modes. The injected current of the VSC is also shown in Fig. 10.

Simulation results indicate the effectiveness of the control strategy in power flow control using an SSSC.

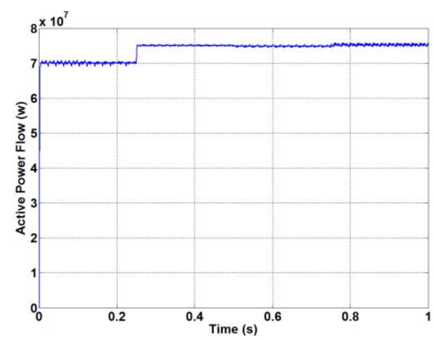

Fig. 8. Real power flow (reference change at t=0.25s)

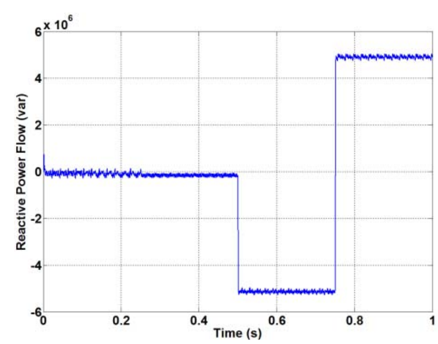

Fig. 9. Reactive power flow (reference change at t=0.5, 0.75s)

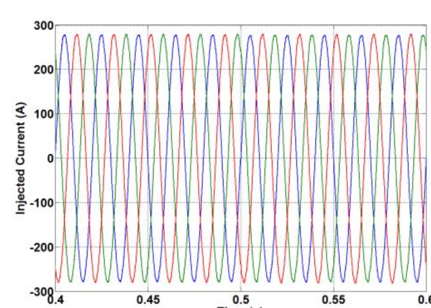

Fig. 10. Injected current of the VSC

6. Conclusions

In this paper, model based predictive control scheme is applied to a power system equipped with SSSC. The DC link voltage of the SSSC, active and reactive power flow through transmission line is predicted for future time instants. A cost function is defined and minimized in order to obtain the best switching state for the next time instant. The system is studied in two cases when the DC link voltage of the SSSC is supplied and controlled independently and when the DC link voltage is controlled via MPC strategy of the SSSC. In both cases, simulation results indicate fast dynamic response of the system, adaptability and the feasibility of the presented control scheme.

7. References

[1] A. Laka,J.A. Barrena, J. Chivite-Zabalza, M.A.Rodriguez, "Analysis and Improved Operation of a PEBB-Based Voltage-Source Converter for FACTS Applications", *Power Delivery, IEEE Transactions on.,* vol. 28,no. 3,pp. 1330 – 1338, July, 2013.

[2] X. Jiang, "Operating modes and their regulations of voltage-sourced converter based facts controllers ", Ph.D. thesis, Faculty of Rensselaer Polytechnic Institute., Troy., New York, 2007.

[3] R. Grunbaum, "FACTS for dynamic load balancing and voltage support in rail traction ", European *Conference on Power Electronics and Applications*, Aalborg,. EPE. 2007, pp. *1-10*.

[4] M. Noroozian , L. Angquist, M. Ghandhari, G. Andersson, "Improving power system dynamics by series-connected FACTS devices ", *Power Delivery, IEEE Transactions on*, vol. *12*, no. *4*, pp. *1635 - 1641*, Oct ,1997.

[5] N. Gaidi , H. Shijie , W. Yue , Y. Lei , W. Zhaoan, "Design of distributed FACTS controller and considerations for transient characteristics ", *Power Electronics and Motion Control Conference*, Shanghai,. IPEMC. 2006, pp. *1-5*.

[6] L. Jingsheng, H. Sepahvand, M. Ferdowsi, "The design of nonlinear control strategy for SSSC based on constant voltage control", *2nd International Conference on Computing, Control and Industrial Engineering,* CCIE. Wuhan, 2011, pp.30-32.

[7] S. Amara, H.A. Hsan, "Power system stability improvement by FACTS devices: A comparison between STATCOM, SSSC and UPFC", *First International Conference on Renewable Energies and Vehicular Technology,* REVET. Hammamet, 2012, pp.360-365.

[8] V.K. Chandrakar, A.G. Kothari, , "Fuzzy logic based static synchronous series compensator (SSSC) for transient stability improvement ", *Proc of the IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, DRPT.2004, pp. 240-245.

[9] K.R. Padiyar, K. Uma Rao, "Discrete control of series compensation for stability improvement in power systems", *Electrical Power & Energy Systems*, vol. 19, no. 5, pp.311-319, 1997.

[10] W. Jiekang, J. Cheng, H. Junfeng, Z. Yunan, Z. Nan, "Adaptive PI Algorithm of SSSC Controller for Power Flow of Power Systems Based on Neural Networks", *Asia-Pacific Power and Energy Engineering Conference,* APPEEC*,* 2009, pp.1-4.

[11] Q. Wei, R.G. Harley, G.K. Venayagamoorthy, "Investigation on hybrid cascaded multilevel inverter with Neural-network-based intelligent control for improving dynamic performance of FACTS devices", *Bulk Power System Dynamics and Control Revitalizing Operational Reliability, iREP Symposium*, Wuhan, 2007, pp.1-9.

[12] P.Z. Haro, J.M. Ramirez, "SSSC's Adaptive Neural Control", 6th International Joint Conference on Neural Networks, IJCNN ,Vancouver, BC 2009, pp. 2267 - 2273.

[13] S.R. Khuntia, "Simulation study of a SSSC-based neuro-fuzzy controller for improvement of transient stability in a three-machine power system", *Energytech*, Cleveland, OH, 2012, pp.1-9.

[14] B.N. Singh, A. Chandra, k. Al-Haddad, B. Singh, " Performance of sliding-mode and fuzzy controllers for a static synchronous series compensator ", *IEE proc of Generation, Transmission and Distribution,* vol.*146*, no.*2*, pp.*200-206*, August, 2002.

[15] T.R. Jyothsna, K. Vaisakh, "Design of a decentralized non-linear controller for transient stability improvement under symmetrical and unsymmetrical fault condition: A comparative analysis with SSSC", 9th *Power Systems Conference and Exposition,* PSCE. Seattle, WA.2009, pp.1-9.

[16] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model predictive control - a simple and powerful method to control power converters", IEEE Transactions on Industrial Electronics, vol. *56* , no. *6*, pp. *1826-1838*, May, 2009.

[17] J. Rodriguez, J. Pontt, C.A. Silva, P. Correa, P. Lezana, P. Corster, and U. Ammann, "Predictive current control of a voltage source inverter", *IEEE Transactions on Industrial Electronics*, vol . *54*, no. *1*, pp. *495-503*, Feb, 2007.

[18] S. Koul, S. Tiwari, "Model predictive control for improving small signal stability of a UPFC equipped SMIB system", *University International Conference on Engineering,* NUiCONE*,* Nirma, 2011, pp.1-6.