A Robust Fuzzy Sliding Mode Control Design for Current Source Inverter based STATCOM Application

Sangram Keshari Routray, Niranjan Nayak, Pravat Kumar Rout

Department of Electrical Engineering, ITER, S.O.A University, Bhubaneswar-751030, India.

Abstract

This paper presents a robust fuzzy sliding mode control of a CSI based STATCOM. The dq-frame state space model is considered for nonlinear mathematical model for the system and controller design. A nonlinear fuzzy logic enhanced sliding mode controller has been proposed to provide active and reactive power control under various faulted operating conditions. Based upon the time domain simulations in MATLAB/SIMULINK environment the proposed controller is tested and it’s better performance is shown compare with the conventional PI controllers with respect to voltage stability, damping of power oscillations and improving of transient stability.

Keywords: Fuzzy Sliding Mode Controller (FSMC), Static synchronous Compensator (STATCOM), PCC,CSI ;

1. Introduction

Because of rapid development of power electronics technology, the static synchronous compensator (STATCOM) plays a significant role among FACTS devices, in power factor correction, harmonic compensation and for providing required reactive power to the load in modern electric power networks. The fundamental principle of a STATCOM as a shunt compensation device is to generation a controllable ac current source [1]. Theoretically, a STATCOM can be realized by either a voltage-source inverter (VSI) or a current source inverter (CSI) topology [2]. As a shunt compensation device, its performance can be improved when realized by a current-source inverter (CSI), which generates a controllable ac current directly at its output terminals [3]. Operation wise the CSI based STATCOM has some advantages over VSI based STATCOM like fast start-up, high converter reliability, implicit short circuit protection, capability of directly controlling the output current and injects no harmonic into the ac network when it is operating at zero reactive current [4]. Research on STATCOM in past few years mostly focus on VSI based STATCOM and so the capability of reactive power control of CSI based STATCOM is yet to be investigated much. In this paper an attempt has been made to design a fuzzy sliding mode control to enhance the controllability of CSI based STATCOM to damp system oscillations under various transient conditions. Several authors have presented mathematical models and control strategies for CSI-STACOM that include nonlinear fuzzy PID controller [5], feedback linearization based Fuzzy-Neuro controller [6], optimal linear quadratic regulator controller [7] and feedback linearization by pole placement technique [8]. A three phase induction motor [9] along with a reactive load is
connected. The performance of CSI-STATCOM while taking a wide range of faulted operating conditions is studied.

The rest of the paper is organized as follows. In section 2, the time domain mathematical modelling of the CSI-STATCOM is presented. In section 3, the conventional PI controller and robust Fuzzy Sliding Mode Controller are briefly explained. Simulation study that illustrates the effectiveness of the proposed control strategies is discussed in section 4. At last, conclusions are drawn in Section 5.

2. CSI-based STATCOM modeling

Fig.1 shows the basic structure of a six-pulse CSI based STATCOM is connected at the point of common coupling (PCC) at bus (E) and a three phase induction motor with a load to the load bus(Er) in the power system network. Where \( R_s \) represents the ‘ON’ state resistance of the switches including transformer leakage resistance, \( L_s \) is transformer leakage inductance and the switching losses are taken into account by a series dc-side resistance \( R_{dc} \). The filter capacitor is ‘C’ and \( i \) is the secondary side currents of the transformer. A CSI resides at the core of the STATCOM. It generates a balanced and controlled three-phase current \( i \). The current control is achieved by firing angle control of the CSI. The dc-side inductor possesses fixed current \( I_{dc} \) and there is no real power transfer, except for losses.

The sending end source \( (E_s) \) is assumed to be a strong system with high short-circuits ratio and low impedance. Thus, the source voltage is treated as a constant source irrespective of variations in load current. with \( E_r \) chosen as the reference voltage vector. The dynamic equations governing the instantaneous values of the three-phase voltages across the two sides of STATCOM and the current flowing into it are given by:

\[
(R_s + L_s \frac{d}{dt})i = E - V
\]

(1)

Where, \( i = [i_a \ i_b \ i_c]^T \),

\( E = [E_a \ E_b \ E_c]^T \),

and \( V = [V_a \ V_b \ V_c]^T \)

For a 3-phase AC system the equation (1) can be represented as

\[
R_s i_a + L_s \frac{d}{dt} i_a = V_a - E_a \quad R_s i_b + L_s \frac{d}{dt} i_b = V_b - E_b \quad R_s i_c + L_s \frac{d}{dt} i_c = V_c - E_c
\]

(2)

Also, \( L_s \frac{d}{dt} i_{ab} = L_s \frac{d}{dt} i_{bc} = L_s \frac{d}{dt} i_{ca} \)

Expanding and simplifying equation (3)

\[
L_s \frac{d}{dt} i_{ab} = (V_a - V_b) - (E_a - E_b) + R_s i_{ab}
\]

(4)

\[
L_s \frac{d}{dt} i_{bc} = (V_b - V_c) - (E_b - E_c) + R_s i_{bc}
\]

(5)

\[
L_s \frac{d}{dt} i_{ca} = (V_c - V_a) - (E_c - E_a) + R_s i_{ca}
\]

(6)

Expressing equations (4), (5) and (6) in matrix form

\[
\frac{d}{dt} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{L} \begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} - \frac{1}{R_s} \begin{bmatrix} E_a - E_b \\ E_b - E_c \\ E_c - E_a \end{bmatrix} - \frac{R_s}{L_s} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix}
\]

(7)

Transforming 3-phase AC dynamic equation into orthogonal components in a rotating reference frame. The components are referred to as real and reactive components. Applying Park’s transformation
From principles of power system,

\[ \frac{d}{dt} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{d}{dt} \begin{bmatrix} T^{-1} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{1}{L} T^{-1} V_d - \frac{1}{L} T^{-1} E_d \\ -\frac{1}{L} T^{-1} V_q - \frac{1}{L} T^{-1} E_q \end{bmatrix} \tag{13} \]

Comparing equation (11) with (7),

\[ E_d - \frac{e_d}{n} E_q = 0 \quad \text{and} \quad T \frac{d}{dt} \begin{bmatrix} 0 \\ -\omega \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{14} \]

Multiply T to both sides of equation (13) and applying equation (14),

\[ \begin{bmatrix} \frac{d}{dt} i_{ab} \\ \frac{d}{dt} i_{bc} \\ \frac{d}{dt} i_{ca} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} V_d - \frac{1}{L} E_d \\ -\frac{1}{L} V_q - \frac{1}{L} E_q \end{bmatrix} \]

From circuit principle,

\[ C_d \frac{d}{dt} V_{ab} = i_a - i_a, \quad C_d \frac{d}{dt} V_{bc} = i_b - i_b \quad \text{and} \quad C_d \frac{d}{dt} V_{ca} = i_c - i_c \tag{16} \]

Also,

\[ C_d \frac{d}{dt} V_{ab} = L \frac{d}{dt} V_{ab} - L \frac{d}{dt} V_{bc} \tag{17} \]

The equation (17) can be expanded and simplified as

\[ C_d \frac{d}{dt} (i_a - i_b) = (i_a - i_b) \tag{18} \]

Similarly, representing complete equation (16) in matrix form

\[ \begin{bmatrix} \frac{d}{dt} V_{ab} \\ \frac{d}{dt} V_{bc} \end{bmatrix} = \begin{bmatrix} \frac{1}{L} & \frac{1}{L} & \frac{1}{L} \\ -\frac{1}{c} & -\frac{1}{c} & -\frac{1}{c} \end{bmatrix} \begin{bmatrix} i_a - i_b \\ i_b - i_c \\ i_c - i_a \end{bmatrix} \tag{19} \]

Also,

\[ \begin{bmatrix} \frac{d}{dt} V_{ab} \\ \frac{d}{dt} V_{bc} \end{bmatrix} = \begin{bmatrix} 0 & -\omega & V_d \\ 0 & 0 & V_q \end{bmatrix} + \begin{bmatrix} \frac{1}{c} & \frac{1}{c} & \frac{1}{c} \\ \frac{1}{c} & \frac{1}{c} & \frac{1}{c} \end{bmatrix} \begin{bmatrix} i_d \\ i_d \\ i_d \end{bmatrix} \tag{20} \]

CSI under tri-level SPWM control behaves as a 3-phase linear power amplifier can be modelled as:

\[ i_a = m_a I_{dc} \quad i_a = m_b I_{dc} \quad i_a = m_c I_{dc} \]

\[ L_{dc} \frac{d}{dt} (I_{dc}) + R_{dc} I_{dc} = -m_a v_a - m_b v_b - m_c v_c \tag{21} \]
Where, \( m_a, m_q \) and \( m_c \) are the modulating signals of the 3-Phases normalized to the peak of the triangular carrier signal. The modulating signals can be transformed into \( d-q \) axis,
\[
I_{id} = M_d l_{dc} \quad \text{and} \quad I_{iq} = M_q l_{dc}
\]
\[
L_{dc} \frac{d}{dt} (I_{dc}) + R_{dc} I_{dc} = -M_d V_d - M_q V_q
\]  
(22)

The dynamic equations from the converter to the secondary side of the transformer are:
\[
\frac{d}{dt} (I_{dc}) = -\frac{R_{dc}}{L_{dc}} I_{dc} - \frac{M_d V_d}{L_{dc}} - \frac{M_q V_q}{L_{dc}}
\]  
(23)
\[
\frac{d}{dt} (I_d) = -\frac{R_s}{L_s} I_d + \omega I_q - \frac{1}{L_s} E_d + \frac{1}{L_s} V_d
\]  
(24)
\[
\frac{d}{dt} (I_q) = -\frac{R_s}{L_s} I_q - \omega I_d + \frac{1}{L_s} V_q
\]  
(25)
\[
\frac{d}{dt} (V_d) = -\frac{1}{C} I_d + \omega V_q + \frac{1}{C} M_d I_{dc}
\]  
(26)
\[
\frac{d}{dt} (V_q) = -\frac{1}{C} I_q - \omega V_d + \frac{1}{C} M_q I_{dc}
\]  
(27)

The above system is nonlinear, where \( I_{dc}, I_d, I_q, V_d \) and \( V_q \) are the state variables. \( i_{id} \) and \( i_{iq} \) are the input variables. \( R_s, L_s, L_{st1}, R_{st1}, L_{rt1}, C, R_{dc}, L_{dc}, R_s \) and \( \omega \) are system parameters and considered as constants. The output variables are \( I_{dc} \) and \( Q_{st} \), which are chosen according to the control objectives of the STATCOM. A common method to deal with the nonlinearity is to linearize the equations of system around a steady-state operating point.

3. Control structure of the STATCOM

A fuzzy sliding mode controller and PI controller is briefly explained. This acts as the basis for the digital simulations performed in the next section.

3.1. Fuzzy Sliding Mode Controller

Robust Fuzzy Sliding Mode Controller (RFSMC) can be employed to be a basis to ensure the stability of the controller of nonlinear and linear systems [11]. A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, and switching among different functions is determined by plant state that is represented by a switching function. Since the sliding surface and switching do not depend upon the system operating point, circuit parameters and converter dynamics, it offers good robustness. For controlling CSI based STATCOM, SMC is used here to obtain new control input for \( I_{dc} \) and \( Q_{st} \). The general equation proposed earlier to determine the desired sliding surface \( \sigma(x) \) is as follows:
\[
\sigma(x) = \left( \frac{d}{dx} + k_t \right)^{q_n+1} er(x)
\]  
(28)

Where \( k_t \) is a positive constant which describes the control bandwidth, \( er(x) \) is the output error, and \( q_n \) is the relative degree of the state variable taken as the output state. The sliding surface is chosen by using a positive scalar Lyapunov cost function \( v(x) > 0 \) as
\[
v(x) = \frac{\sigma^T(x) \sigma(x)}{2}
\]  
(29)

The necessary condition for the minimization of the function is \( \sigma(x) \sigma(x) < 0 \). The fuzzy sliding mode control is consists of an equivalent control and a switching fuzzy control and is given by
\[
u(t) = u_{eq}(t) + u_f(t)
\]  
(30)
The inputs to the fuzzy controller to calculate \( u_f \) are the sliding surfaces \( \sigma \) and its derivative \( \dot{\sigma} \). The membership values \( \mu_p(\sigma) \) and \( \mu_n(\sigma) \) and \( \mu_p(\dot{\sigma}) \) and \( \mu_n(\dot{\sigma}) \) are obtained using similar membership functions as given below:

\[
\mu_p(\sigma) = \begin{cases} 
0 & \sigma < -L \\
\frac{6+L}{2L} & -L \leq \sigma \leq L \\
1 & \sigma > L 
\end{cases} \tag{31}
\]

\[
\mu_n(\sigma) = \begin{cases} 
1 & \sigma < -L \\
\frac{-6+L}{2L} & -L \leq \sigma \leq L \\
0 & \sigma > L 
\end{cases} \tag{32}
\]

The fuzzy rule base used is:

- **R1:** if \( \sigma \) is P and \( k\dot{\sigma} \) is P, then \( u_1 = k_1(\sigma + \lambda k\dot{\sigma}) \)
- **R2:** if \( \sigma \) is P and \( k\dot{\sigma} \) is N, then \( u_2 = k_2u_1 \)
- **R3:** if \( \sigma \) is P and \( k\dot{\sigma} \) is P, then \( u_3 = k_3u_1 \)
- **R4:** if \( \sigma \) is P and \( k\dot{\sigma} \) is N, then \( u_4 = k_4u_1 \)

The effective control \( u_f \) is obtained using a centroid defuzzifier,

\[
\frac{\sum_{i=1}^{4} u_i \mu_i}{\sum_{i=1}^{4} \mu_i} \] which when simplified yields,

\[
u_f = k_{eff}(\sigma + \lambda k\dot{\sigma}) \quad \text{and} \quad k_{eff} = \frac{k_1u_1+k_2u_2+k_3u_3+k_4u_4}{u_1+u_2+u_3+u_4}\]

The values of \( \lambda, k, k_1, k_2, k_3 \) and \( k_4 \) are chosen as 0.3, 0.0166, 1, 0.1, 0.1 and 0.5 respectively for this study. The complete block diagram for FSMC is shown in Fig.2.

### 3.2. PI Controller Design

This control system is based on a decoupled strategy or d-q transformation that makes it possible to control the reactive current flow between the STATCOM and the transmission system. The dual control objectives are met by generating appropriate current references for d- and q-axis then by regulating these currents in STATCOM. Fig.3 shows the schematic diagram of the method of finding the inputs \( u_1 \) and \( u_2 \) from the difference between \( I_{dc\text{ref}} \) and measured value of \( I_{dc} \) and \( Q_{st\text{ref}} \) with the measured value of \( Q_{st} \).

![Fig.2. Block Diagram of the RFSMC system.](image)

The expression for DC current and controllers are obtained from equation (23), (26) and (27) respectively.

\[
I_{dc} = -\sqrt{(I_{sd}V_{std} + I_{sq}V_{stq})/(R_{dc})} \tag{33}
\]

\[
u_1 = (I_{sd} - wCdcV_{stq})/I_{dc} \tag{34}
\]

\[
u_2 = (I_{sq} - wCdcV_{std})/I_{dc} \tag{35}
\]

The dc current \( (I_{dc}) \) and reactive power \( (Q_{st}) \) are taken as the outputs and can be written as:
4. Simulation results

The proposed robust fuzzy sliding mode controller is simulated in MATLAB. The performance of the RFSMC is tested under various operating conditions in a wide neighborhood of the initial operating condition and compared with PI controller. Different plots like dc current input to STATCOM \( I_{dc} \), active power at PCC (\( P_e \)), reactive power at PCC (\( Q_e \)), inverter output power (\( P_{st} \)), inverter output reactive power (\( Q_{st} \)) and receiving end bus voltage(\( E_r \)) are plotted for comparison from Fig. 4 to Fig. 7.

4.1 50% increase in load torque of induction motor for 10 cycles.

The system is simulated with a 10 cycle 50% increase in load torque of induction motor. Due to the fault the STATCOM voltage (V) is decreased to a critical level. The performance of the proposed controller restores the system earlier, than the conventional PI controller. The improvement with the new controller shown in Fig.4 clearly indicates the superiority of the proposed controller.

4.2 6-cycle LLLG fault at point of common coupling (PCC):

A 6-cycle LLLG fault at point of common coupling bus (E) is simulated and shown in Fig.5.
4.3. Change in system frequency

A 10% change in the system frequency for 10 cycles on input side as shown in Fig.6.

4.4. Variation of the transmission line impedance parameters

The value of resistance and inductance at both the sides of PCC are increased by 50% is shown in Fig.7.

5. Conclusion

In this paper, a systematic procedure for modeling the nonlinear controller based on robust fuzzy sliding mode for a CSI based STATCOM is proposed. The sliding mode control takes into account the parametric uncertainties and cancels the nonlinearities. The proposed controller is found to be robust and improves damping and overshoots for a variety of operating conditions that include torque variation, short circuit, and variation of frequency and line parameters.
References

1. N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of flexible AC Transmission Systems. New York: IEEE Press, 2000.
2. K. K. Sen, “STATCOM—STATIC synchronous Compensator: Theory, Modeling, and applications,” in Proc. 1999 IEEE Power Engineering Society, Winter Meeting, pp. 1177–1183.
3. Yang Ye, M Kazerani,” Current-source converter based STATCOM: Modeling and control IEEE Transaction on Power Delivery, vol. 20, pp. 795–800, April 2005.
4. Dong Shen, P.W.Lehn, “Modeling, Analysis, and Control of a CSI based STATCOM,” IEEE Transaction on Power Delivery, vol. 17, pp. 1730–1735, Nov. 2002.
5. S. Morris, P.K. Dash, K.P. Basu, A fuzzy variable structure controller for STATCOM, Electric Power System Research. 65 (No. 1) (2003) 23–34.
6. Boniface H.K.Chia,S. Morris, P.K. Dash,” A feedback Linearization Based Fuzzy-Neuro Controller for current Source Inverter based STATCOM”, Power Engineering Conference, 2003. PECon 2003. Proceedings. National . Dec. (2003) 172–179.
7. S Fukuda ,”LQ control of sinusoidal current PWM rectifiers Electric Power Applications, IEE Proceedings-, March ,1997,95-100.
8. N.C. Sahoo, B.K. Panigrahi, P.K. Dash, G. Panda,” Application of a multivariable feedback linearization scheme for STATCOM control” Electric Power System Research June 2002, pp. 81-91.
9. PW Sauer, M A Pai ,” Development and comparative study of induction machine based dynamic P, Q load models, IEEE Transaction on Power Systems, 10 (1)(1995)182-191.
10. Y.W. Liao, E. Levi, Modelling and simulation of a stand-alone induction generator with rotor flux oriented control, Electric Power System Research, 46 (1998) 141–152.
11. Rong-Jong Wai, Chih-Min Lin, Chun-Fei Hsu,” Adaptive fuzzy sliding-mode control for electrical servo drive” May 2003, Elsevier ,Fuzzy Sets and Systems 143 (2004) 295–310.