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# PSS and STATCOM Controller Design Using Fuzzy Logic Controller and Teaching-Learning Based Optimization

**Ahmad Rouhani[a], Mahmood Joorabian[b], S.Saeedollah Mortazavi[c]**
[a] Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
a-rouhani@stu.scu.ac.ir
[b] Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
mjoorabian@scu.ac.ir
[c] Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran
mortazavi_s@scu.ac.ir

**Abstract.** STATCOM is one of the most significant devices in FACTS technology which is used in parallel compensation, enhancing the transient stability, limiting the low frequency oscillations and etc. designing a proper controller is effective in operation of STATCOM. In this paper a method is presented for the design of STATCOM and Power System Stabilizer (PSS) controllers in order to enhance the damping of the low frequency oscillations in power systems. The equations that describe the proposed system have been linearized and a Fuzzy Logic Controller (FLC) has been designed for the PSS. Then, the Teaching-Learning Based Optimization (TLBO) is employed to search for the optimal STATCOM controller parameters. The proposed controllers are evaluated on a single machine infinite bus power system with the STATCOM installed in the midpoint of the transmission line. Moreover, a system performance analysis under different operating conditions and some performance indices studies show the effectiveness of the proposed controller.

**Keywords:** FACTS, FLC, PSS, STATCOM, TLBO.

## 1 INTRODUCTION

One of the most important issues in power system analysis is power system stability (Gholipour & Nosratabadi, 2015). Dynamic stability is based on small amplitude oscillations that can be initiated by sudden changes in the load or the network (Afzalan & Joorabian, 2013). Therefore, there will be limit on the maximum power to be transmitted on tie-lines. Two types of oscillations are usually known. One is referred to inter-area modes resulted from swinging one generation area with respect to other areas. The second one is associated with swinging of generators existed in one area against each other and is known as local mode (Khodabakhshian & Morshed, 2013).

So far, conventional Power System Stabilizer (PSS) is still used as an effective and economical facility to tackle the problem (Tse & Tso, 1993) which are generally most effective in damping the local modes. However, in certain cases they are not fully effective in damping the inter-area oscillations. Thus, development of most effective method of damping the inter-area mode of low-frequency oscillation for enhancing the power system security is still a major area of research today. (Pant, Das & Bhargava, 2012). Reference (Kundur, Klein, Rogers & Zywno, 1989) shows that the appropriate selection of PSS parameters can achieve satisfactory performance during system upsets. However, it has been recognized that a set of PSS parameters which works well under a certain operating condition may no longer yield satisfactory results when there is a drastic change in system operating conditions and configurations (Abido, 2000).

To achieve better utilization of the existing power grid, power electronic device based equipment, commonly known as Flexible AC Transmission Systems (FACTS) controllers are being increasingly implemented nowadays in various parts of the world (Safari Tirtashi, Mazlumi & Rouhani, 2010; Raouf, Rouhani, Abedini, Rasooli Anarmarzi, 2013). The conception of FACTS as a total network control philosophy was first introduced by N.G. Hingorani (Hingorani, 1988) from the Electric Power Research Institute (EPRI) in the USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that. Some of the FACTS devices are Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC), Unified Power Flow Controller (UPFC), Inter-phase Power Flow Controller (IPFC), Static Synchronous Series Controller (SSSC), Convertible Series Compensator (CSC), Thyristor Controlled Series Compensator (TCSC), Thyristor Controlled Phase Shifting Transformer (TCPST), Super Conducting Magnetic Energy Storage (SMES).The devices may be connected so as to provide either series compensation or shunt compensation depending upon their compensating strategies (Wang, 2003).

Reactive power compensation is an important issue in electrical power systems and STATCOM plays an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and angle stability (Safari Tirtashi, Rouhani & Noroozian, 2010). Among the various FACTS controllers, STATCOM is one of the most prominent equipment, which is basically a shunt-connected equipment with the main objective of controlling the bus voltage (Pant, Das & Bhargava, 2012). While most of the control designs are carried out with linearized models, nonlinear control strategies for a STATCOM have also been reported recently (AL-Baiyat, 2005 & Liu, et al, 2003). Reference (Pant, Das & Bhargava, 2012) presents the design of a damping controller for a STATCOM using periodic output feedback technique. A new concept of Primary frequency control (PFC) based on incorporating a STATCOM coupled with a SMES device is presented in (Molina & Mercado, 2013). A new multi-objective function as an optimization problem is proposed for coordination process in (Abido, 2000). The seeker optimization algorithm (SOA) is used to design the parameters of PSS and STATCOM coordinately to improve more stability of power system in (Afzalan, & Joorabian, 2013). The design method of a nonlinear control technique, named zero dynamics is given in (Khodabakhshian, & Morshed, 2013) to design the controllers of STATCOM and excitation systems coordinately for multi-machine power systems. Also Seeker Optimization Algorithm (SOA) based on Pareto optimum method used as a strategy to solve this optimization problem. To coordinate the dual action of both SSSC and PSS devices a Genetic algorithm Tuning Controller is applied in (Ghanbari Jolfaei, & Sharaf, 2016). In (Safari, Ahmadian & Golkar, 2013) a novel methodology for tuning STATCOM based damping controller is presented and the optimization problem solved by a Honey Bee Mating Optimization (HBMO) algorithm.

This article investigates the stability enhancement problem of a power system considering a STATCOM. A Fuzzy Logic Controller (FLC) has designed for PSS controller and a Teaching Learning Based Optimization (TLBO) is employed to search for the optimal STATCOM controller parameters. The proposed modelling is implemented in the MATLAB/Simulink environment.

The remainder of the paper is organized as follows; Section II describes the mathematical model of proposed system and the STATCOM connected in the distribution system. Power system linearized model is presented in Section III. The TLBO method and the design of the proposed FLC is detailed in Section IV and V, respectively. The computer simulation results are presented and discussed in Section VI. Finally Section VII concludes this paper. The various para-meters of the system and controllers are listed in Appendix A.

## 2 MATHEMATICAL MODEL OF PROPOSED SYSTEM

### 2.1 Synchronous generator and exciter

A synchronous machine with an IEEE type-ST1 excitation System connected to an infinite bus through a transmission Line has been selected to demonstrate the derivation of simplified linear models of power system for dynamic stability analysis. The single-machine infinite-bus power system shown in Fig. 1 comprises a synchronous generator connected to the infinite bus through a transmission line. The STATCOM is located at the middle of the transmission line. Transmission line has impedance of $Z = R_e + jX_e$ for both sections. The equations that describe the generator and excitation system have been represented in following equations:

$$\dot{\delta} = \omega_b(\omega - 1) \tag{1}$$

$$\dot{\omega} = \frac{P_m - P_e - D(\omega - 1)}{M} \tag{2}$$

Where $P_m$ and $P_e$ are the input and output powers of the generator, respectively; $M$ and $D$ the inertia constant and damping coefficient, respectively; $\omega_b$ the synchronous speed; $\delta$ and $\omega$ are the rotor angle and speed, respectively. The output power of the generator can be expressed in terms of the d- and q-axis components of the armature current, $i$, and terminal voltage, $v_t$, as

$$P_e = V_{td} I_d + V_{tq} I_q \tag{3}$$

The internal voltage, $E'_q$, equation is

$$\dot{E}'_q = \frac{E_{fd} - (X_d - X'_d)id - E'_q}{T'do} \tag{4}$$

Where $E_{fd}$ is the field voltage; $T'_{do}$ the open circuit field time constant; $X_d$ and $X'_d$ are the $d$-axis reactance and the $d$-axis transient reactance of the generator, respectively.

The excitation System can be expressed as

$$\dot{E}_{fd} = \frac{K_A(V_{ref} - V_t) - E_{fd}}{T_A} \tag{5}$$

Where $K_A$ and $T_A$ are the gain and time constant of the excitation system, respectively; $V_{ref}$ is the reference voltage. The terminal voltage, $V_t$, can be expressed as

$$V_t = V_{td} + jV_{tq} \tag{6}$$

$$V_{td} = X_q I_q \tag{7}$$

$$V_{tq} = E'_q - X'_d I_d \tag{8}$$

Where $X_q$ is the $q$-axis reactance of the generator.

### 2.2 Synchronous static compensator (STATCOM)

The STATCOM is represented by a first order differential equation relating the STATCOM DC capacitor voltage and current. As shown in Fig. 1, the STATCOM consists of a step-down transformer with a leakage reactance of $X_t$, a three phase gate turn-off (GTO)-based voltage source converter (VSC) and a dc capacitor. The STATCOM model used in this study is found good enough for the low frequency oscillation stability problem (Wang, 1999). The VSC generates controllable ac voltage $V_o$ given by

$$V_o = CV_{dc}\angle\psi \tag{9}$$

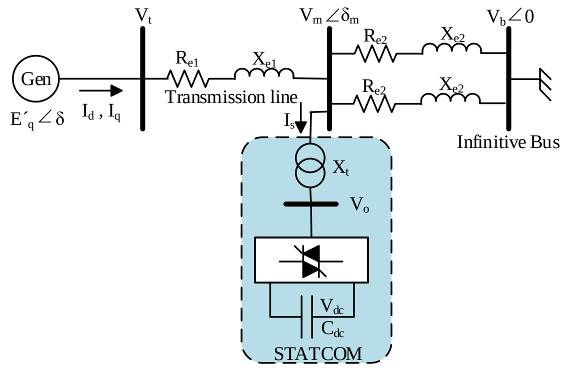


Fig. 1. SMIB system model with a STATCOM.

where $C = mk$, $m$ the modulation ratio defined by pulse width modulation (PWM), $k$ the ratio between the ac and dc voltage depending on the converter structure, $V_{dc}$ the dc voltage, and $\Psi$ is the phase defined by PWM. The magnitude and the phase of $V_o$ can be controlled through $m$ and $\Psi$, respectively. By adjusting the STATCOM ac voltage $V_o$, the active and reactive power exchange between the STATCOM and the power system can be controlled through the difference between $V_o$ and the STATCOM-bus voltage $V_m$. The dc voltage $V_{dc}$ is governed by

$$\dot{V}_{dc} = \frac{I_{dc}}{C_{dc}} = \frac{C}{C_{dc}}\left(I_{sd}\cos\psi + I_{sq}\sin\psi\right) \tag{10}$$

Where $C_{dc}$ is the dc capacitor value and $I_{dc}$ is the capacitor current while $i_{sd}$ and $i_{sq}$ are the *d*- and *q*-components of the STATCOM current $I_s$, respectively. The *d*- and *q*-axis components of the $I_d$ can be expressed as

$$I_d = \frac{c_1 E'_q - c_2 CV_{dc}\sin\psi - v_b\cos\delta}{c_1 X'_d + c_3} \tag{11}$$

$$I_q = \frac{c_2 CV_{dc}\cos\psi + v_b\sin\delta}{c_1 X_q + c_3} \tag{12}$$

Where $c_1$, $c_2$, and $c_3$ are constants.

Fig. 2 illustrates the block diagram of STATCOM ac and dc voltage PI controller. The proportional and integral gains are $K_{pac}$, $K_{iac}$ and $K_{pdc}$, $K_{idc}$ for ac and dc voltages, respectively. The excitation system of the generator consists of a simple AVR along with a supplementary PSS. The complete AVR and PSS control system with FLC used in this paper is shown in Fig. 3.

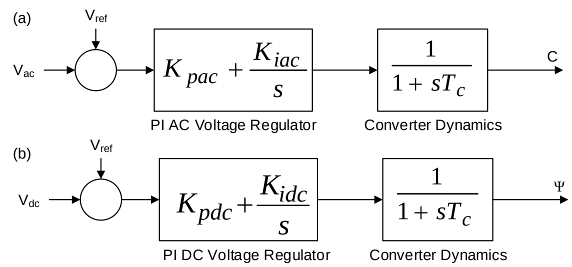


Fig. 2. STATCOM PI controller for (a) ac voltage and (b) dc voltage.

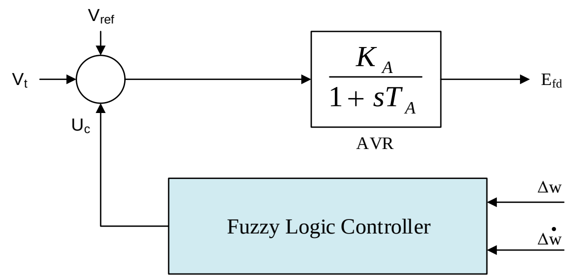


Fig. 3. Model of generator AVR and PSS control system with FLC.

## 3 LINEARIZED MODEL

A linear dynamic model is obtained by linearizing the nonlinear model round an operating condition ($P_e = 0.8$, $Q_e = 0.28$). The linearized model of proposed power system is given as follows:

$$\Delta\dot{\delta} = \omega_b \Delta\omega \tag{13}$$

$$\Delta\dot{\omega} = \frac{\Delta P_m - \Delta P_e}{M} \tag{14}$$

$$\Delta\dot{E}'_q = \frac{\Delta E_{fd} - (X_d - X'_d)\Delta i_d - \Delta E'_q}{T'_{do}} \tag{15}$$

$$\Delta P_e = k_{p\delta}\Delta\delta + k_{peq}\Delta E'_q + k_{pdc}\Delta V_{dc} + k_{pc}\Delta c + k_{p\psi}\Delta\psi \tag{16}$$

$$\Delta V_t = k_{v\delta}\Delta\delta + k_{veq}\Delta E'_q + k_{vdc}\Delta V_{dc} + k_{vc}\Delta c + k_{v\psi}\Delta\psi \tag{17}$$

$$\Delta\dot{V}_{dc} = h_{\delta}\Delta\delta + h_{eq}\Delta E'_q + h_{dc}\Delta V_{dc} + h_c\Delta c + h_{\psi}\Delta\psi \tag{18}$$

$$\Delta V_{ac} = f_{\delta}\Delta\delta + f_{eq}\Delta E'_q + f_{dc}\Delta V_{dc} + f_c\Delta c + f_{\psi}\Delta\psi \tag{19}$$

Where *k*, *h*, and *f*, are linearization constants. In short, the linearized model of the power system installed with the STATCOM is

$$\dot{X} = AX + BU \tag{20}$$

Where the state vector $X$ is $[\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}, \Delta V_{dc}]^T$ and the control vector $U$ is $[\Delta C, \Delta\Psi]^T$.

## 4 TEACHING–LEARNING-BASED OPTIMIZATION

This optimization method is based on the effect of the influence of a teacher on the output of learners in a class. It is a population based method and like other population based methods it uses a population of solutions to proceed to the global solution (Rao, Savsani & Vakharia, 2012). A group of learners constitute the population in TLBO. In any optimization algorithms there are numbers of different design variables. The different design variables in TLBO are analogous to different subjects offered to learners and the learners' result is analogous to the 'fitness', as in other population-based optimization techniques. As the teacher is considered the most learned person in the society, the best solution so far is analogous to Teacher in TLBO. The process of TLBO is divided into two parts. The first part consists of the "Teacher phase" and the second part consists of the "Learner phase". The "Teacher phase" means learning from the teacher and the "Learner phase" means learning through the interaction between learners. In the sub-sections below we briefly discuss the implementation of TLBO (Rao, Savsani, & Vakharia, 2012; Rao & Savsani, 2012). More detail of proposed TLBO is shown in Fig. 4.

### 4.1. Initialization

Following are the notations used for describing the TLBO

*N*: number of learners in class i.e. "class size"

D: number of courses offered to the learners

MAXIT: maximum number of allowable iterations

The population X is randomly initialized by a search space bounded by matrix of *N* rows and *D* columns.

The *jth* parameter of the *ith* learner is assigned values randomly using the equation

$$x^0_{(i,j)} = x^{min}_j + rand \times (x^{max}_j - x^{min}_j) \quad (21)$$

where *rand* represents a uniformly distributed random variable within the range (0,1), $x^{min}_j$ and $x^{max}_j$ represent the minimum and maximum value for *jth* parameter. The parameters of *ith* learner for the generation *g* are given by

$$x^g_{(i)} = \left[x^g_{(i,1)}, x^g_{(i,2)}, x^g_{(i,3)}, \ldots, x^g_{(i,j)}, \ldots, x^g_{(i,D)}\right] \quad (22)$$

### 4.2. Teacher phase

The mean parameter *Mg* of each subject of the learners in the class at generation *g* is given as

$$M^g = \left[m^g_1, m^g_2, m^g_3, \ldots, m^g_j, \ldots, m^g_D\right] \quad (23)$$

The learner with the minimum objective function value is considered as the teacher $X_g^{Teacher}$ for respective iteration. The Teacher phase makes the algorithm proceed by shifting the mean of the learners towards its teacher. To obtain a new set of improved learners a random weighted differential vector is formed from the current mean and the desired mean parameters and added to the existing population of learners.

$$Xnew^g_{(i)} = x^g_{(i)} + rand \times (x^g_{Teacher} - T_F \times M^g) \quad (24)$$

$T_F$ is the teaching factor which decides the value of mean to be changed. Value of $T_F$ can be either 1 or 2. The value of $T_F$ is decided randomly with equal probability as,

$$T_F = round[1 + rand(0,1)] \quad (25)$$

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Where $T_F$ is not a parameter of the TLBO algorithm. The value of $T_F$ is not given as an input to the algorithm and its value is randomly decided by the algorithm using (Joorabian, Razzaz, Ebadi, & Moghaddasian, 2008).

After conducting a number of experiments on many benchmark functions it is concluded that the algorithm performs better if the value of $T_F$ is between 1 and 2. However, the algorithm is found to perform much better if the value of $T_F$ is either 1 or 2 and hence to simplify the algorithm, the teaching factor is suggested to take either 1 or 2 depending on the rounding up criteria given by (Joorabian, Razzaz, Ebadi, & Moghaddasian, 2008).

If $Xnew^g_{(i)}$ is found to be a superior learner than $X^g_{(i)}$ in generation $g$ , than it replaces inferior learner $X^g_{(i)}$ in the matrix.

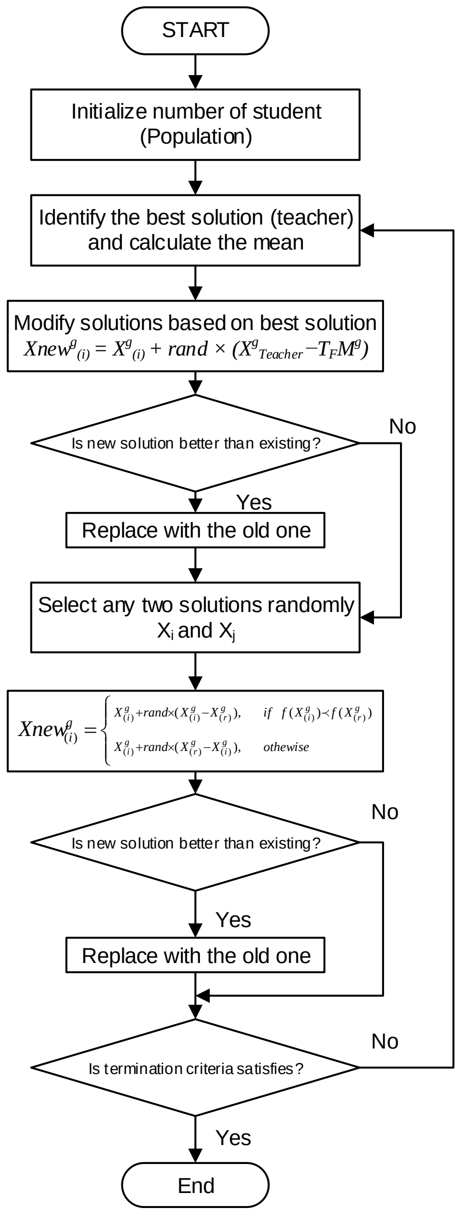


Fig. 4. TLBO flow chart.

### 4.3. Learner phase

In this phase the interaction of learners with one another takes place. The process of mutual interaction tends to increase the knowledge of the learner. The random interaction among learners improves his or her knowledge. For a given learner $X^g_{(i)}$, another learner $X^g_{(r)}$ is randomly selected ($i \neq r$). The *ith* parameter of the matrix *Xnew* in the learner phase is given as

$$Xnew^g_{(i)} = \begin{cases} X^g_{(i)} + rand \times (X^g_{(i)} - X^g_{(r)}), & if \;\; f(X^g_{(i)}) \prec f(X^g_{(r)}) \\ X^g_{(i)} + rand \times (X^g_{(r)} - X^g_{(i)}), & othewise \end{cases} \tag{26}$$

The convergence of the algorithms to obtain the optimal STATCOM controller parameters is shown in Fig. 5.

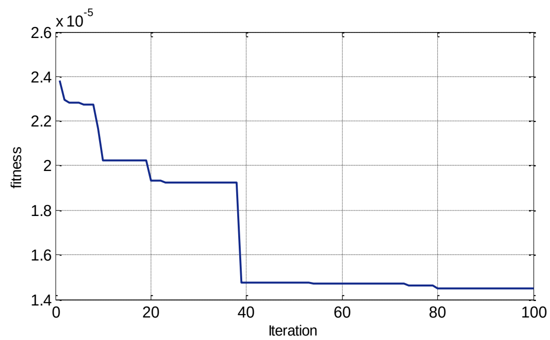



Fig. 5. Convergence of TLBO.

## 5 FUZZY LOGIC

In 1965, Zadeh proposed Fuzzy logic; it has been effectively utilized in many field of knowledge to solve such control and optimization problems (Zadeh, 1965). FLC is a good mean to control the parameters when there isn't any direct and exact relation between input and output of the system, and we only have some linguistic relations in the If-Then form (Joorabian, Razzaz, Ebadi, Moghaddasian, 2008). The use of fuzzy logic has received increased attention in recent years because of its usefulness in reducing the need for complex mathematical models in problem solving (Ng, Salama & Chikhani, 2000). In power system area, it has been used to stability studies, load frequency control, unit commitment, and to reactive compensation in distribution network and other areas. Fuzzy control system is made from different blocks such as numeral quantity converter to fuzzy quantities (fuzzifier interface) block, the fuzzy logical decision maker section, knowledge base section, and defuzzier interface block.

The following steps are involved in designing the fuzzy STATCOM controller (Toliat, Sadeh & Ghazi, 1996):

1) Choose the inputs to the FLC. As shown in Fig. 3, only two inputs, the generator speed deviation ($\Delta\omega$) and generator speed derivative deviation ($\Delta\dot{w}$), have been employed in this study. The symbol $U_c$ has been synonymously used to represent the output or decision variable of FLC.

2) Choose membership functions to represent the inputs in fuzzy set notation. Triangular functions are chosen in this work. Fuzzy representations of generator speed change, acceleration, and output variable have been illustrated in Fig. 6. Similar membership functions for the other inputs and the stabilizer output are also defined.

3) A set of decision rules relating the inputs to the output are compiled and stored in the memory in the form of a "decision surface". The decision surface is provided in Fig. 7.

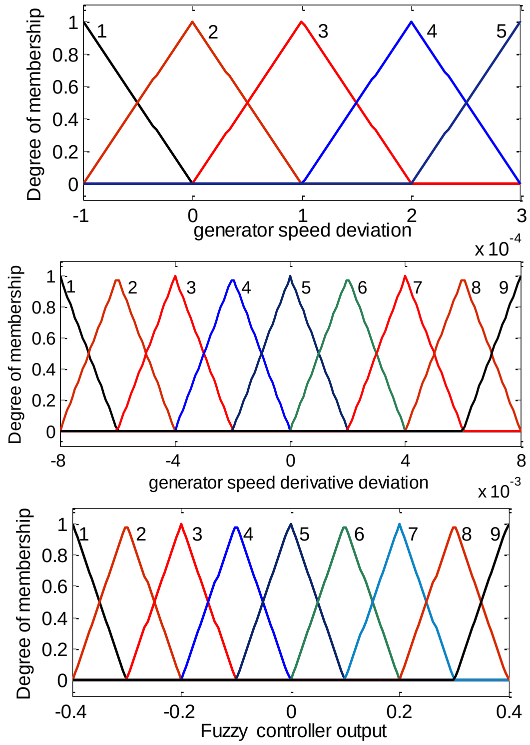



Fig. 6. Membership functions of inputs and output.

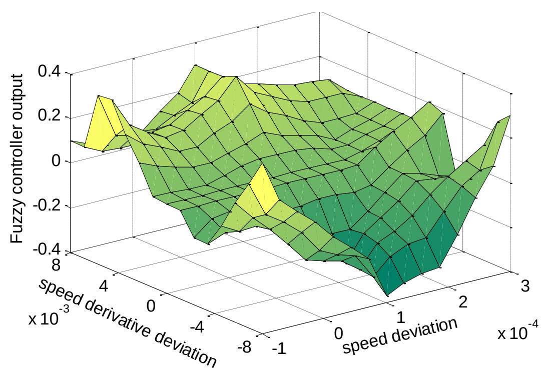



Fig. 7. Decision surface of proposed FLC.

## 6 SIMULATION RESULTS

The performance of the PSS controller (with FLC strategies) for stabilization of synchronous generator is evaluated by computer simulation studies. The SMIB system was tested with the FLC for various operating conditions. The system data is given in the appendix A. The transient performance of the rotor speed variation, rotor angle variation, terminal voltage variation, and DC capacitor voltage variations are compared in Fig. 8 for the nominal operating point following 3% disturbance on mechanical generator power input for a three-cycles fault duration. It is clearly seen that with the inclusion of FLC, electromechanical damping characteristics of the system is improved.

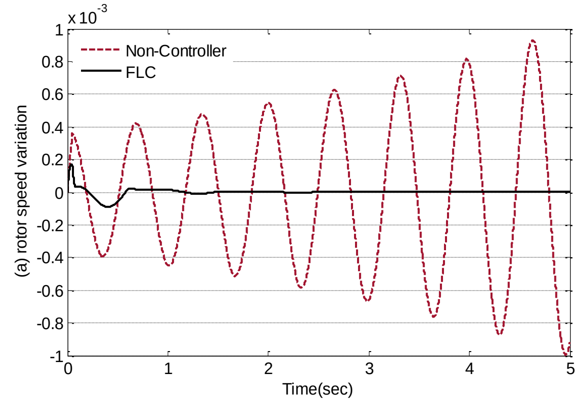
The robustness of the controller was tested by applying the fuzzy strategy to a number of operating conditions. Fig. 9 shows the system dynamic response for a three-cycle fault disturbance for rotor speed variation, rotor angle variation, terminal voltage variation, and DC capacitor voltage variations for the following 3 loading conditions;

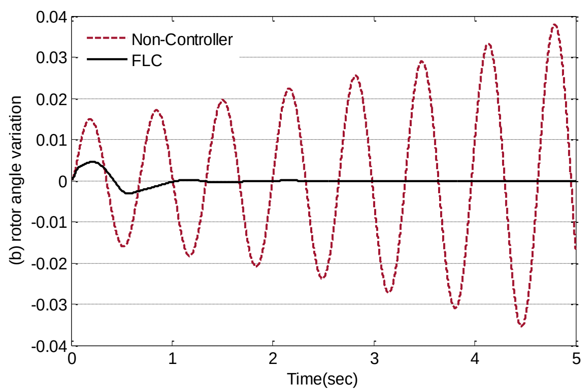
a) Nominal loading: $P_e = 0.8$ p.u. and $Q_e = 0.28$ p.u.;

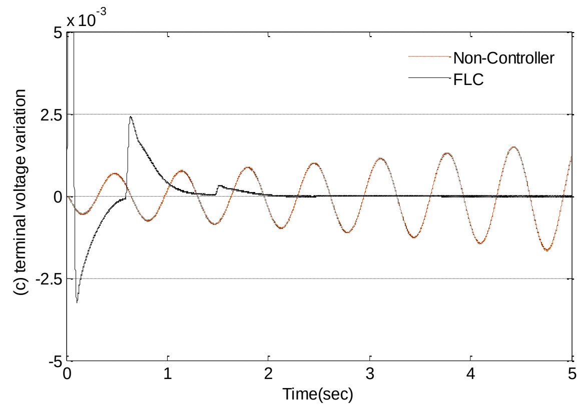
b) Heavy loading: $P_e = 1$ p.u. and $Q_e = 0.34$ p.u.;

c) Light loading: $P_e = 0.6$ p.u. and $Q_e = 0.26$ p.u.;

It can be observed the fuzzy control scheme gives very good damping profile over a range of operating conditions even for severe fault conditions.



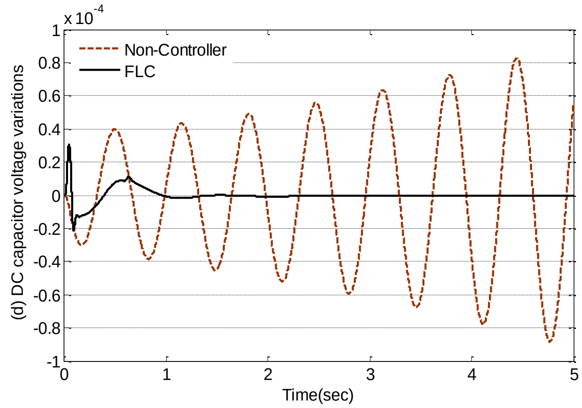
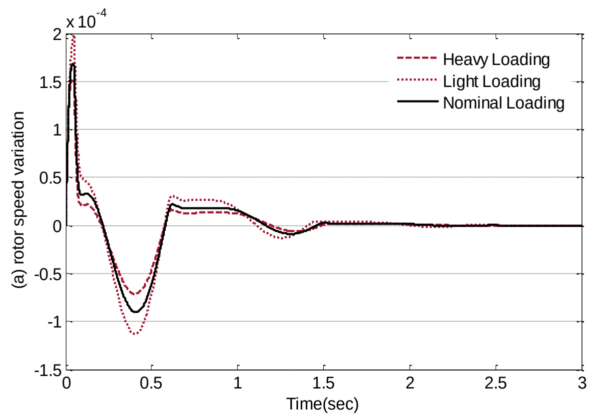
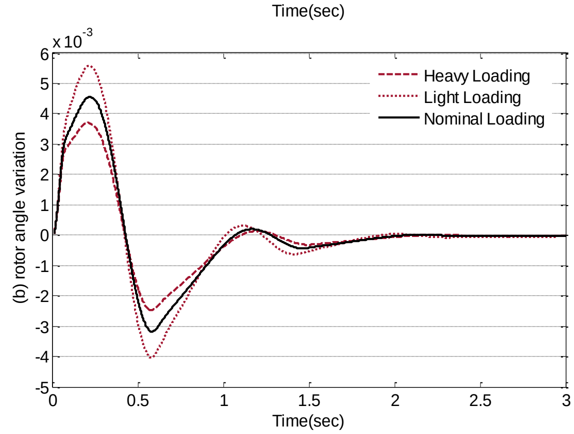



Fig. 8. Comparison of transient response for a three-cycles fault disturbance with and without FLC.



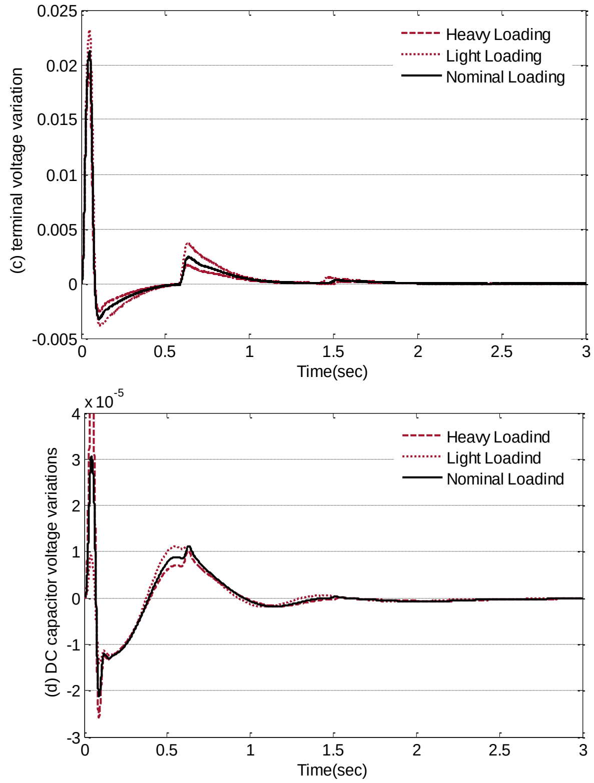



Fig. 9. System transient response for a three-cycles fault disturbance with nominal, light, and heavy loading.

## 7 CONCLUSIONS

A design of STATCOM and PSS controllers in order to enhance the damping of the low frequency oscillations in power systems is presented. A fuzzy logic controller has designed for the PSS and Teaching-Learning Based Optimization is employed to search for the optimal STATCOM controller parameters in a SMIB system with a STATCOM located at the midpoint of the transmission line. The optimal design of control has been implemented on a proposed system for operation of the power system at nominal, light, and heavy load. It has been observed that the damping controller is capable of enhancing the system damping substantially for all the operating conditions. Effective damping, fast dynamic response, and high accuracy for various disturbance conditions demonstrate the robust-ness of the fuzzy PSS controller.

## APPENDIX A: PARAMETERS OF THE STUDIED SYSTEM

SMIB and STATCOM parameter values

| | |
|---|---|
| Generator | $M = 4$ *MJ/MVA*; $T'_{do} = 5.044$ *s*; $D = 0$; $w_b = 120\pi$ *rad/s*; $X_d = 1$; $X_q = 0.6$; $X'_d = 0.3$; |
| Excitation System | $k_A = 50$; $T_A = 0.01$; |
| Transformer | $X_t = 0.5$; |
| Transmission Lines | $X_{e1} = 0.3$; $R_{e1} = 0$; $X_{e2} = 0.6$; $R_{e2} = 0$; |
| STATCOM Parameters | $V_{dc} = 2$; $C_{dc} = 1$; $T_c = 0.01$; |

| | |
|---|---|
| Operating Condition | $V_t = 1.05$; $V_m = 1.0$; $V_b = 1.0$; $P_e = 0.8$; $Q_e = 0.28$; |

## Acknowledgments

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