Electrical Power and Energy Systems 76 (2016) 129–135

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

DSTATCOM modelling for voltage stability with fuzzy logic PI current controller

Dawood Amoozegar

Electrical Engineering Department, Pasargad University, Shiraz, Iran

ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form 23 August 2015
Accepted 19 September 2015

Keywords:
Power system stability
Damping improvement
D-STATCOM
Fuzzy-logic control

ABSTRACT

In recent years, applications of inverter based power quality conditioners have been growing for reactive power compensation in distribution systems due to their faster response times as compared to the conventional compensators. Distribution Static Synchronous Compensator (D-STATCOM) is an inverter based power quality conditioner device used to improve the power quality issues in distribution systems. Control of D-STATCOM is usually realized by Proportional-Integral (PI) controllers with fixed parameters. However, the overall control performance may be unsatisfactory due to its nonlinear structure. In this paper, Fuzzy-PI controller which has a nonlinear and robust structure is proposed for control of D-STATCOM's direct and quadrature axes currents. The article presents the fuzzy logic control of the D-STATCOM which tries to improve the damping of a power system. Simulation of Fuzzy-PI current controlled D-STATCOM is performed by MATLAB/Simulink software. In simulation study, the dynamic response of D-STATCOM is observed by changing the reference reactive current. A comparison of the simulation results between the proposed technique and the conventional PI controller has been presented.

Introduction

Fixed or switched reactor/capacitor banks and Static VAR Compensators (SVC) have been widely used for reactive power compensation. These types of conventional equipment have some disadvantages such as limited bandwidth, large size, more losses, and slow response times. Today, inverter based power quality conditioners have been proposed for improving power quality in distribution systems because of their fast response, small size and low losses.

Distribution Static Synchronous Compensator (D-STATCOM) is an inverter based power quality conditioner connected in shunt with ac system. It is used for power factor correction, load balancing, voltage regulation and harmonic filtering in distribution systems [2]. D-STATCOM is a power electronic based synchronous voltage source that generates a three-phase voltage from a dc capacitor. By controlling the magnitude of the voltage at D-STATCOM, reactive power exchange between the device and the transmission system can be controlled.

Use of D-STATCOM controller for reactive support of induction generators have also been reported recently. The reactive power is controlled by the ac inductors, dc bus capacitor and solid state commutating devices in the D-STATCOM. In addition to proper control of reactive power exchange, D-STATCOM's can also provide damping support to a power system. In the control system of D-STATCOM, reference values for "*d* and *q*"-axes currents are usually obtained from Proportional-Integral (PI) controllers designed with linear control methods. In the design of PI controllers, linear mathematical model of controlled system is required [1,2,4].

Parameters of these controllers are tuned to obtain the best performance for a particular region of operation and conditions. However the task is difficult and often fails to perform satisfactorily under parameter variation, load disturbance, and nonlinear dynamics of the plant [7].

Most of the control designs are carried out with linearized models. Nonlinear control strategies for D-STATCOM have also been reported recently-STATCOM controls for stabilization have been attempted through complex Lyapunov procedures for simple power system models. Recently, intelligent controllers like Fuzzy Logic Controllers (FLC) and Artificial Neural Network (ANN) as alternative linear and nonlinear control techniques have been used in the control of D-STATCOM. Applications of fuzzy logic and neural network based controls have also been reported [1,8].

The mathematical model of system to be controlled is not needed for these controllers. Moreover, they can provide efficient control over a wide range of system operating conditions, which distinguishes them from conventional linear controllers. Effectiveness of the fuzzy strategies in damping power system oscillations often depends on the choice of inputs to the controller.

E-mail addresses: amoozegar@sutech.ac.ir, amoozegar@pasargad-ihe.ac.ir

http://dx.doi.org/10.1016/j.ijepes.2015.09.017
0142-0615/

In this paper, Fuzzy-PI controller which is a robust controller is proposed for D-STATCOM's *d* and *q*-axes currents control. Models of power system, D-STATCOM, and controller unit are developed in MATLAB/Simulink environment. Two Fuzzy-PI are used for the control of *d* and *q*-axes currents separately. Inputs of Fuzzy-PI controllers are chosen as error values of *d* and *q*-axes currents and the change in these errors. Steady state error is eliminated by using the external integrator in outputs of Fuzzy-PI controllers. Compared results of simulation with Fuzzy-PI controller and the linear PI with fixed parameters are given for the variations in reference reactive current.

Basic operational principle and mathematical modelling of D-STATCOM

A single machine infinite bus system with a D-STATCOM installed at the mid-point of the transmission line is shown in Fig. 1. The D-STATCOM consists of a step down transformer, a three phase Gate Turn Off (GTO)-based voltage source converter, and a DC capacitor. The D-STATCOM is modelled as a voltage Sourced Converter (VSC) behind a step down transformer. Depending on the magnitude the VSC voltage, the D-STATCOM current can be made to lead or lag the bus voltage. Generally, the D-STATCOM voltage is in phase with the bus voltage. Some active power control may be possible through limited variations in the voltage phase angle. This would necessitate a power source behind the capacitor voltage.

In Fig. 1, R_{DC} and R_{SDT} represent switching losses in inverter and winding resistance of coupling inductance respectively.

D-STATCOM is assumed to be connected at the middle of the line connecting the generator to the network. The network equations excluding the generators and the D-STATCOM are expressed through the relationships,

$$I_{BUS} = Y_{BUS} \times V_{BUS} \tag{1}$$

where

I_{BUS} is the injected current.
V_{BUS} is the node voltages of the Power System.
Y_{BUS} is the Admittance matrix of the Power System.

The D-STATCOM capacitor voltage equation is,

$$\frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} = \frac{m}{C_{DC}}(I_{LOd}\,\mathrm{Cos}\psi + I_{LOq}\,\mathrm{Sin}\psi) \tag{2}$$

where

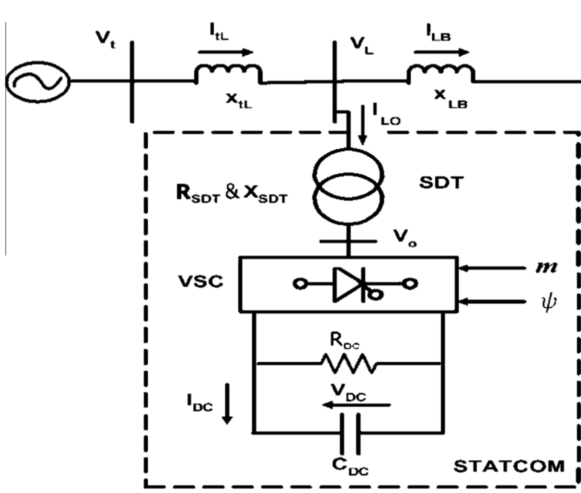

Fig. 1. A single machine system with D-STATCOM [8].

V_{DC} is DC voltage for inverter.
I_{DC} is current of inverter.
I_{LOd} & I_{LOq} are reference values for "*d* and *q*"-axes currents.
C_{DC} is storage capacitor.
m is pulse width modulation index.
ψ is phase angle of the shunt inverter voltage.

Schematic representation of D-STATCOM is shown in Fig. 2. Complete block diagram of D-STATCOM's control algorithm is presented in Fig. 3. D-STATCOM consists of inverter, dc-link capacitance (*C*) supplying the dc voltage for inverter, coupling inductance (L_{SDT}) to exchange reactive power and filter out the current harmonics as well as a control unit to generate Pulse Wave Modulated (PWM) signals for the switches of inverter.

Fuzzy logic control

The Fuzzy Logic Control (FLC) system, shown in Fig. 4, contains four main components – the Knowledge Base (KB), the Fuzzification Interface (FI), the Decision Logic (DL), and the Defuzzification Interface (DI) [9–14]. The KB contains knowledge about all the input and output fuzzy partitions. It includes the term set and the corresponding membership functions defining the input variables to the fuzzy 'Rule-Base' (RB) system and the output or decision variables to the plant.

The crisp stabilizing input signals are converted to fuzzy linguistic variables in the fuzzifier. These are then composed with the fuzzy decision variables. The decision-making logic generates the fuzzified control through various composition rules [15–20]. The fuzzy control is then defuzzified and is used to fire the thyristors in the STATCOM. The following steps are involved in designing the fuzzy STATCOM controller [4,5].

In Fuzzification part, crisp values of input are converted into fuzzy values, so that these values are compatible with the fuzzy set representation in the rule base. The choice of Fuzzification method is dependent on the interference engine. The knowledge base consists of a database of the plant. It provides all the necessary definitions for the Fuzzification process. Rule base is essentially the control method of the system. It is usually obtained from expert knowledge or heuristic as a set of IF-THEN rules. The rules are based on the fuzzy inference. Inference called fuzzy model applies fuzzy reason to rule base to obtain a proper output. Mamadani and Takagi–Sugeno [1] fuzzy systems are the most commonly used fuzzy inference mechanisms. Mamadani is suitable for the systems with slow-changing dynamics while Takagi–Sugeno is suitable for the systems with fast changing dynamics. Results obtained from fuzzy process are converted into crisp values by using any Defuzzification method such as maxima methods and center of area.

Fuzzy-PI controller design for D-STATCOM

Linear PI controller is well established in classical control systems and it is often used as a benchmark against the other types of controllers. This controller is linear, thus unsuitable for strongly nonlinear systems. Fuzzy Logic Controller (FLC) is an alternative to classical PI controllers in such cases. FLC has been widely used in systems with complex structure because it doesn't need mathematical model of controlled system [21–27].

The structure of the Fuzzy-PI controller used in simulation study is shown in Fig. 5. It has two inputs and one output. Inputs of controller are errors of *d* and *q*-axes currents and derivatives of these errors. In addition, an external integrator is used to eliminate the steady state error in the output of FLC.

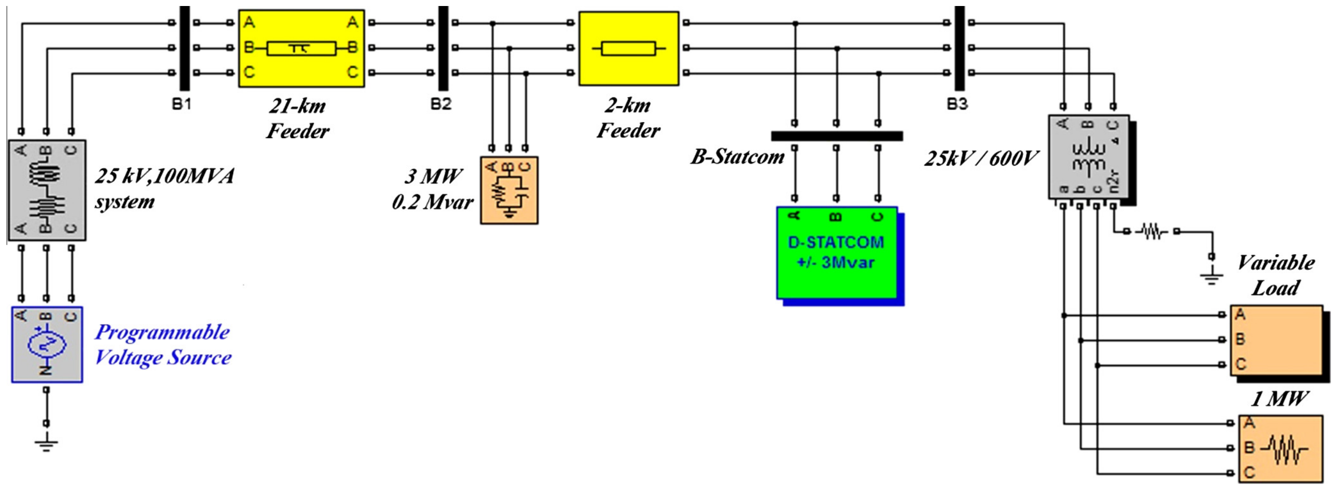

Fig. 2. Schematic presentation of D-STATCOM.

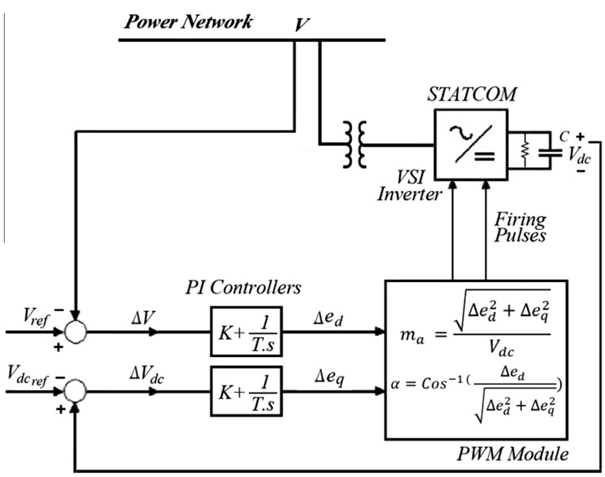

Fig. 3. Complete block diagram of D-STATCOM's control algorithm [5].

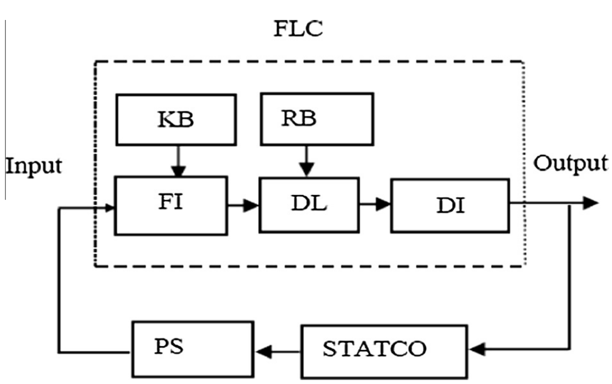

Fig. 4. The fuzzy logic controller configuration [6].

Controller design

The following steps are involved in designing of the fuzzy D-STATCOM controller:

(a) Choose the inputs to the fuzzy D-STATCOM controller. Only two inputs, the error deviation (Δe) and error (e), have been employed in this study. The output or decision variable is

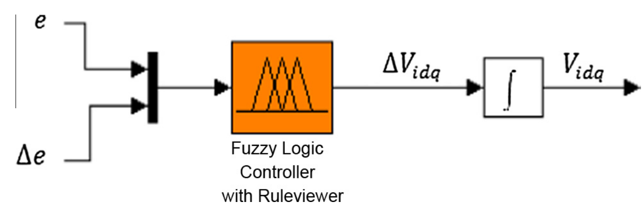

Fig. 5. Structure of Fuzzy-PI controller.

the pulse modulation index 'm' of the D-STATCOM voltage. The symbol 'u' has been synonymously used to represent the output. Since control of phase angle of the shunt inverter voltage 'ψ' is known to provide no additional damping to the system, it has not been considered any further.

(b) Choose membership functions to represent the inputs in fuzzy set notation. Triangular functions are chosen in this work. Fuzzy representation of generator speed change is shown in Fig. 6. Linguistic variables chosen are Positive Big (PB), Positive medium (PM), Zero (Z), medium negative (MN), and Negative Big (NB) at thresholds S_1, S_2, 0, S_3, S_4 respectively. Similar membership functions for the other inputs and the stabilizer output are also defined [3].

(c) A set of decision rules relating the inputs to the output are compiled and stored in the memory in the form of a 'decision table'. The rules are of the form: IF "e" is Negative Big (NB) & "Δe" is Negative Big (NB); then control (u) is Negative Big (NB). The decision table is provided in Table 1.

(d) For N linguistic variables for each of "e" and "Δe", there are N^2 possible combinations resulting into any of M values for the decision variable u. All the possible combinations of inputs, called states, and the resulting control are then arranged in a ($N^2 \times M$) 'fuzzy relationship matrix' (FRM). The fuzzy relationship matrix for all the 25 states and the corresponding membership values of control are tabulated in Table 2.

(e) The membership values for the condition part of each rule are calculated from the composition rule as follows:

$$\mu(x_i) = \mu(\text{"}e\text{" is PM}, \textit{and } \Delta e \textit{ is } \text{NM}) = \min[\mu(\text{"}e\text{" is PM}), \mu(\Delta e \textit{ is } \text{NM})]; \quad i = 1, 2, \ldots, N^2 \tag{3}$$

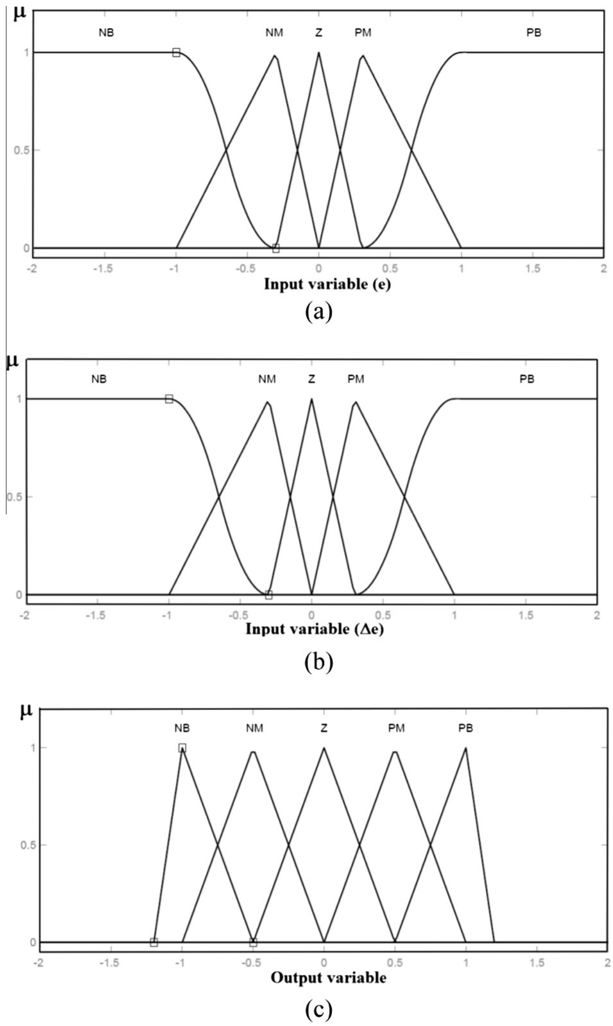

Fig. 6. Triangular membership functions, (a) and (b) are for input variables, (c) for the output variable.

where
x_i is the ith value of the N^2 possible states (input-combinations) in the FRM.
N is number of variable for each of "e" and "Δe".
$\mu(x_i)$ is membership function of x_i state.

(f) The membership values for the output characterized by the 'M' variables are then obtained from the intersection of the N^2 values of membership function $\mu(x_i)$ with the corresponding values of each of the decision variables in the FRM. For example, for the decision NB $\subset$ NM and for state x_i, we obtain

$$\mu_u(x_i, \mathrm{NB}) = \min[\mu(x_i, \mathrm{NB}), \mu(x_i)] \quad i = \quad 1, 2, \ldots, N^2 \tag{4}$$

Table 1
Decision table.

e	Δe NB	NM	Z	PM	PB
NB	NB	NB	NB	NB	M
NM	NB	NB	MN	MN	Z
Z	NB	MN	Z	PM	PB
PM	MN	MN	Z	PM	PB
PB	MN	Z	PM	PB	PB

where
x_i is the ith value of the N^2 possible states (input-combinations) in the FRM.
N is number of variable for each of "e" and "Δe".
$\mu(x_i)$ is membership function of x_i state.

The final value of the stabilizer output 'NB' can be evaluated as the union of all the outputs in Eq. (4) given by the relationship

$$\mu_u(\mathrm{NB}) = \max[\mu_{us}(x_i, \mathrm{NB})] \text{ for all } x_i \tag{5}$$

where
μ_u and μ_{us} are the fuzzy outputs.
The membership values for the other M − 1 variables are generated in a similar manner.

(g) The fuzzy outputs $\mu_u(\mathrm{NB}),\ \mu_{us}(x_i, \mathrm{NB})$ etc. are then defuzzified to obtain crisp u. The popular methods of Defuzzification are the centroid and the weighted average methods. Using the weighted average method, the output of the FLC is then written as,

$$u = \sum_{i=1}^{M} \frac{\mu_u(x_i) \times \text{threshold values of } x_i}{\sum \mu_u(x_i)} \tag{6}$$

The expert knowledge is employed in the general fuzzy D-STATCOM design to stabilize a power system. Exertion of large control is required to bring the states to the origin if they are far from it. Polarity of the control is roughly decided by the quadrants. Since a "$e - \Delta e$" based control is generally known to damp transients, given enough time to iterate, this type of method will eventually converge [3].

In this study, normalized triangular membership functions are preferred for input variables and output variable as shown in Fig. 6. Rule base for Fuzzy-PI controller consists of 25 rules and are given in Table 1.

Fuzzy-PI controller designed as described above is replaced with PI controller used in control of d and q-axes currents. Complete block diagram of Fuzzy-PI current controlled D-STATCOM is shown in Fig. 7.

Simulation results

In this study, the model of power system, D-STATCOM and controller are developed in MATLAB/Simulink environment and shown in Fig. 8.

Here, the power system is three-phase and assumed balanced. AC side and DC side mathematical models of D-STATCOM are used to obtain d and q-axes currents and DC average voltage value respectively. The DC bus voltage is controlled by a PI controller with fixed parameter to compensate for active power losses in the transformer and inverter. Reference value for d-axis current is obtained from output of this controller. Reference value for q-axis current is given as step command. Firstly, the d and q-axes currents are controlled by a PI controller with fixed parameter and then these PI controllers are replaced with Fuzzy-PI controllers. The outputs of the d and q-axes current controllers

Table 2
Part of the fuzzy relationship matrix.

FLC Input x_i	FLC Output $(e, \Delta e)$	Membership values NB	NM	Z	PM	PB
x_1	(NB, NB)	1	0.5	0	0	0
x_2	(NB, MN)	1	0.5	0	0	0
…	…	…	…	…	…	…

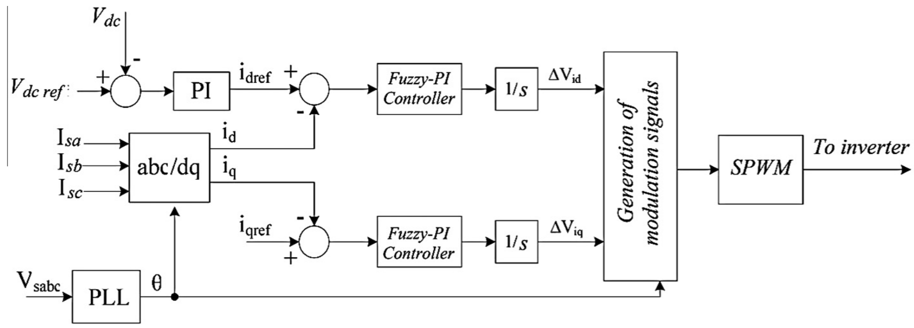

Fig. 7. Complete block diagram of Fuzzy-PI current controlled D-STATCOM.

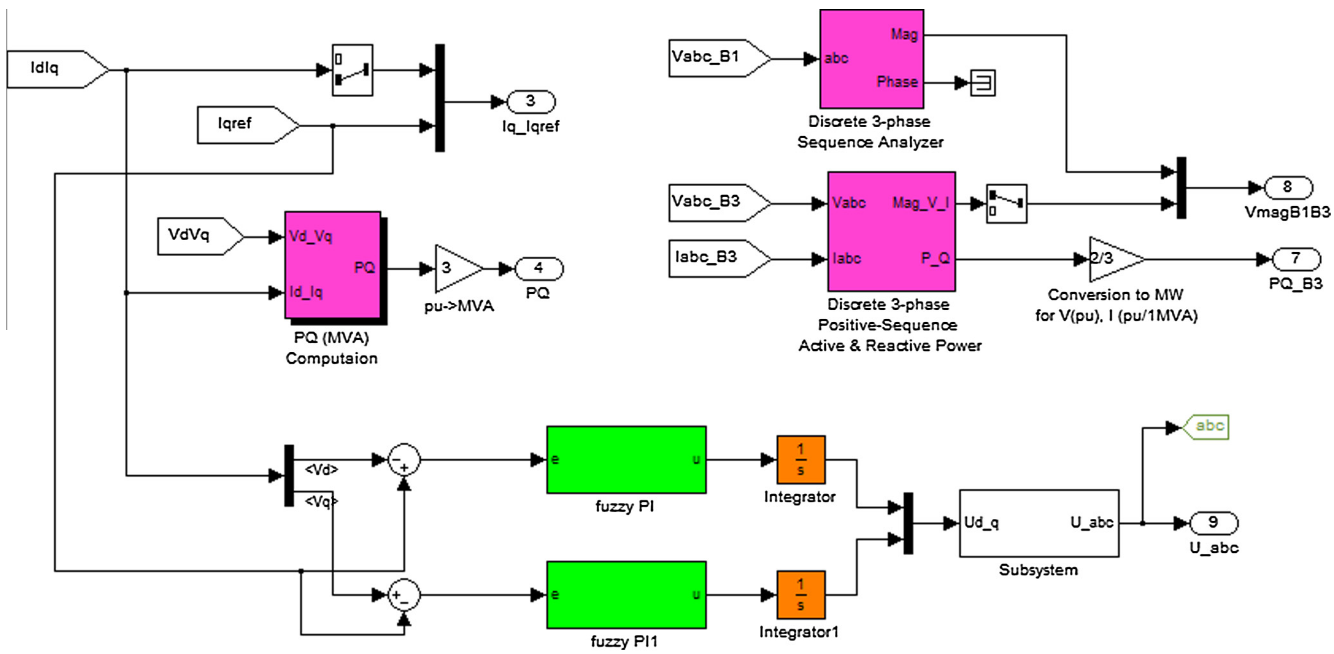

Fig. 8. Simulink model of Fuzzy-PI current controlled D-STATCOM.

are the desired *d* and *q*-axes voltages to be generated by the inverter. These voltages are converted to three-phase in order to generate modulation signals required for control of inverter. Phase Locked Loop (PLL) is used to synchronize the inverter output voltage with power system voltage [28–30].

Active and reactive power measurement equations for D-STATCOM are:

$$P = V_d \times I_d + V_q \times I_q \quad (7)$$

$$Q = V_q \times I_d - V_d \times I_q \quad (8)$$

where

P is active power.
Q is reactive power.
V_d is voltage of *d* axes.
I_d is current of *d* axes.
V_q is voltage of *q* axes.
I_q is current of *q* axes.

Eqs. (7) and (8) are schematically represented in Fig. 9.

The subsystem of control for *d* and *q*-axes currents in Fig. 8 is shown in Fig. 10. It includes two Fuzzy-PI controllers that control the *d* and *q*-axes currents and generation of modulation signals.

The subsystem of Fuzzy-PI used in *d*-axis is shown in Fig. 10 and it is identical with Fuzzy-PI used in *q*-axis. Here, Fuzzy-PI controllers have two inputs and one output. Inputs to Fuzzy-PI controller used in control of *d*-axis current are error and change in error of *d*-axis current. Similarly inputs to Fuzzy-PI controller used in control of *q*-axis current are error and change in error of

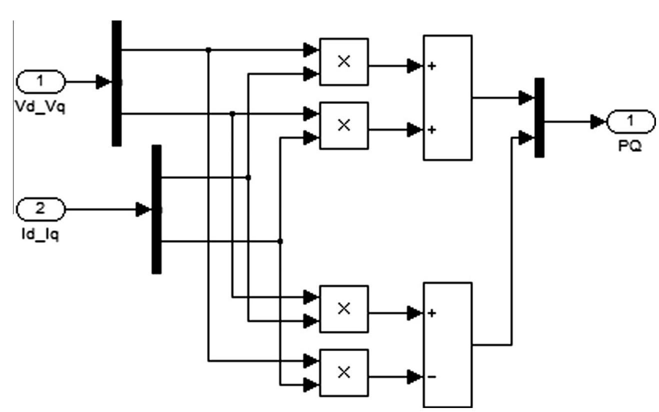

Fig. 9. Active and reactive power measurement equations for D-STATCOM.

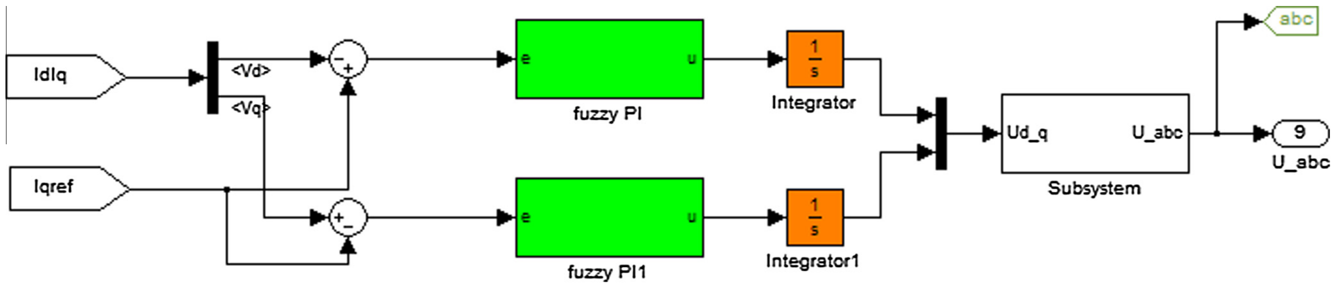

Fig. 10. Subsystem of d and q-axis currents control.

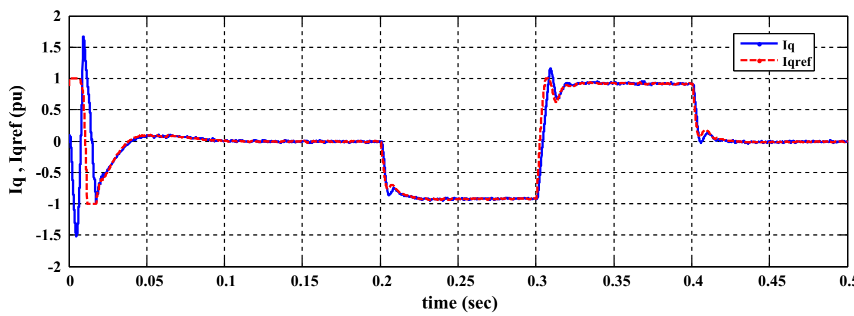

Fig. 11. Simulation result for variation of I_q and I_{qref} without Fuzzy-PI.

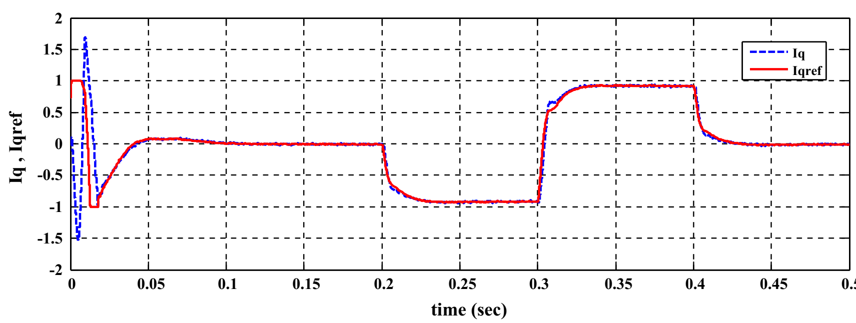

Fig. 12. Simulation result for variation of I_q and I_{qref} with Fuzzy-PI.

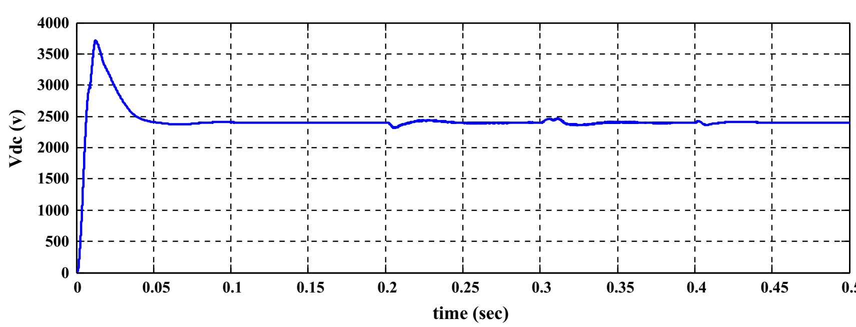

Fig. 13. Variation of average dc voltage with PI controller.

q-axis current. Outputs of these controllers are the d and q-axes voltages u_d and u_q which have to be generated by inverter [1].

Simulation result for variations of I_q and I_{qref} are shown in Figs. 11 and 12. Note that the over shoot between I_q and I_{qref} shown by Fig. 12, is less with fuzzy-PI controller as compared to the one without the fuzzy-PI controller.

Variations of average dc voltage are shown in Figs. 13 and 14 in case of using the PI and Fuzzy-PI controllers having fixed parameters in control of d and q-axes currents. With fuzzy-PI controller rise time and peak time are slightly larger than with PI controller.

Concluding remarks

In some cases, the type of controller might be more complex or more general, like PID instead PI or PD, to improve the control system performance. In all cases, the tuning problem must be satisfactorily resolved. On the other hand, fuzzy control has made possible the establishment of intelligent control. However, Fuzzy Logic Controllers (FLC) are only used in simple configurations and their analytic knowledge is still poor. In this paper, a Fuzzy-PI current controlled D-STATCOM has been proposed and realized in

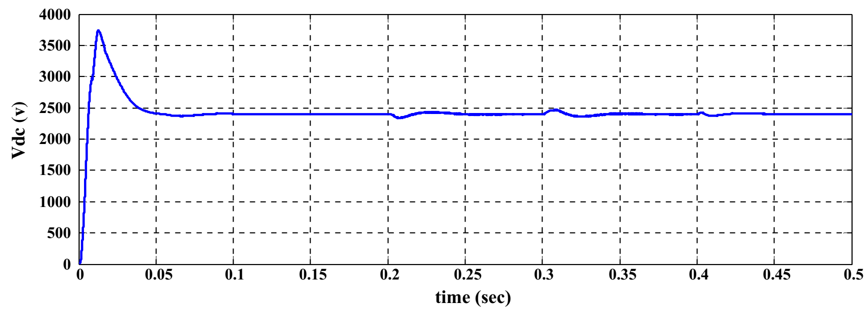

Fig. 14. Variation of average dc voltage with Fuzzy-PI controller.

MATLAB/Simulink environment. Simulation results have been compared with a conventional PI controller and presented. The results show that Fuzzy- PI controller provides a better response in changes of reference reactive current over the conventional PI controller. In addition, the Fuzzy-PI controller is easily designed without the need for a complex mathematical model of the system to be controlled. These features of the fuzzy controller make it a more attractive choice over the conventional PI alternative. Fuzzy-PI controller is employed for the better performance and the transient stability. Further, the work can be done by using neuro-fuzzy control.

References

[1] Coteld Resul, Danddl Besir, Fikret ATA. Fuzzy-PI current controlled D-STATCOM. Gazi Univ J Sci 2014;24(1):91–9.
[2] Hingorani NG, Gyugyi L. Understanding FACTS, concepts and technology of flexible AC transmission systems. New York: IEEE; 1999. ISBN 0-7803-3455-8.
[3] Dong LY, Zhang L, Crow ML. A new control method for the unified power flow controller. In: IEEE power engineering society winter meeting, New York, NY, USA, January 27–31, 2002, vol. 1. p. 562–6.
[4] Masand D, Jain S, Agnihotri G. Control strategies for distribution static compensator for power quality improvement. IETE J Res 2008;54(6):421–8.
[5] Miller TJE. Reactive power control in electric systems. Toronto (Ontario, Canada): Wiley; 1982.
[6] Mathur RM. Static compensators for reactive power control. Winnipeg (Canada): Contexts Publications; 1984.
[7] Singh B, Mittal AP, Gupta JRP. Modelling and control of DSTATCOM for three-phase, four- wire distribution systems. In: Industry applications conference, 2005. Fortieth IAS annual meeting, conference record of the 2005, vol. 4; 2005. p. 2428–34.
[8] Venayagamoorthy GK, Harley RG. Computational intelligence techniques for control of FACTS devices. In: Applied mathematics for restructured electric power systems optimization, control and computational intelligence; 2005. p. 201–37.
[9] Soltanpour Mohammad Reza, Khooban Mohammad Hassan, Niknam Taher. A robust and new simple control strategy for a class of nonlinear power systems: induction and servomotors. J Vib Control 2014. http://dx.doi.org/10.1177/1077546314543729.
[10] Khooban Mohammad Hassan, Niknam Taher. A new intelligent online fuzzy tuning approach for multi-area load frequency control: self adaptive modified bat algorithm. Int J Electr Power Energy Syst 2015;71:254–61.
[11] Veysi Mohammad, Soltanpour Mohammad Reza, Khooban Mohammad Hassan. A novel self-adaptive modified bat fuzzy sliding mode control of robot manipulator in presence of uncertainties in task space. Robotica; 2012. p. 1–20.
[12] Abadi Davood Nazari Maryam, Khooban Mohammad Hassan, Siahi Mehdi. A novel automated fuzzy model for diabetes mellitus. In: 2011 2nd International Conference on Control, Instrumentation and Automation (ICCIA). IEEE; 2011. p. 350–4.
[13] Soltanpour Mohammad Reza, Khooban Mohammad Hassan, Khalghani Mohammad Reza. An optimal and intelligent control strategy for a class of nonlinear systems: adaptive fuzzy sliding mode. J Vib Control 2014. http://dx.doi.org/10.1177/1077546314526920.
[14] Soltanpour Mohammad Reza, Otadolajam Pooria, Khooban Mohammad Hassan. Robust control strategy for electrically driven robot manipulators: adaptive fuzzy sliding mode. IET Sci Meas Technol 2014;9(3):322–34.
[15] Khalghani Mohammad Reza, Khooban Mohammad Hassan. A novel self-tuning control method based on regulated bi-objective emotional learning controller's structure with TLBO algorithm to control DVR compensator. Appl Soft Comput 2014;24:912–22.
[16] Khooban Mohammad Hassan, Taher Niknam. A new and robust control strategy for a class of nonlinear power systems: adaptive general type-II fuzzy. Proc Inst Mech Eng I: J Syst Control Eng 2015;229(6):517–28.
[17] Abadi Davood Nazari Maryam, Khooban Mohammad Hassan, Alfi Alireza, Siahi Mehdi. Design of optimal self-regulation Mamdani-type fuzzy inference controller for type I diabetes mellitus. Arab J Sci Eng 2014;39(2):977–86.
[18] Khooban Mohammad Hassan, Abadi Davood Nazari Maryam, Alfi Alireza, Siahi Mehdi, et al. Optimal type-2 fuzzy controller for HVAC systems. računarstvo i komunikacije 2014;55(1):69–78.
[19] Ghaemi Mostafa, Hosseini-Sani Seyyed Kamal, Khooban Mohammad Hassan. Direct adaptive general type-2 fuzzy control for a class of uncertain non-linear systems. IET Sci Meas Technol 2014;8(6):518–27.
[20] Shamsi-Nejad Mohammad Ali, Khalghani Mohammad Reza, Khooban Mohammad Hassan. Determination of optimum hysteresis bandwidth to improve the operation of electric machines. J Power Technol 2013;93(4).
[21] Khooban Mohammad Hassan, Soltanpour Mohammad Reza, Abadi Davood Nazari Maryam, Esfahani Zahra. Optimal intelligent control for hvac systems. J Power Technol 2012;92(3):192–200.
[22] Niknam Taher, Khooban Mohammad Hassan, Kavousifard Abdollah, Soltanpour Mohammad Reza. An optimal type II fuzzy sliding mode control design for a class of nonlinear systems. Nonlinear Dyn 2014;75(1–2):73–83.
[23] Niknam Taher, Khooban Mohammad Hassan. Fuzzy sliding mode control scheme for a class of non-linear uncertain chaotic systems. IET Sci Meas Technol 2013;7(5):249–55.
[24] Khooban Mohammad Hassan, Abadi Davood Nazari Maryam, Alfi Alireza, Siahi Mehdi. Swarm optimization tuned Mamdani fuzzy controller for diabetes delayed model. Turk J Electr Eng Comput Sci 2013;21(1):2110–26.
[25] Khalghani Mohammad R, Shamsi-Nejad Mohammad A, Farshad Mohsen, Khooban Mohammad H. Modifying power quality's indices of load by presenting an adaptive method based on Hebb learning algorithm for controlling DVR. AUTOMATIKA: časopis za automatiku, mjerenje, elektroniku, računarstvo i komunikacije 2014;55(2):153–61.
[26] Khooban Mohammad Hassan. Design an intelligent proportional-derivative PD feedback linearization control for nonholonomic-wheeled mobile robot. J Intell Fuzzy Syst: Appl Eng Technol 2014;26(4):1833–43.
[27] Soltanpour Mohammad Reza, Khooban Mohammad Hassan, Soltani Mahmoodreza. Robust fuzzy sliding mode control for tracking the robot manipulator in joint space and in presence of uncertainties. Robotica 2014;32(03):433–46.
[28] Hosseini SH, Rahnavard R, Ebrahimi Y. Reactive power compensation in distribution networks with STATCOM by fuzzy logic theory application. In: CES/IEEE 5th International Power Electronics and Motion Control conference, IPEMC 2006; 2006. p. 1–5.
[29] Shen D, Lehn PW. Modelling, analysis and control of a current source inverter-based STSTCOM. IEEE Trans Power Deliv 2002;17(1):248–53.
[30] Rao P, Crow ML, Yang Z. STATCOM control for power system voltage control applications. IEEE Trans Power Deliv 2000;15(4):1311–7.