Fuzzy Logic Control of DSTATCOM for Improving Power Quality and Dynamic Performance

Juan Shi, Amin Noshadi, Akhtar Kalam, and Peng Shi
College of Engineering and Science
Victoria University, Melbourne, Australia
Juan.Shi@vu.edu.au, Amin.Noshadi@live.vu.edu.au, Akhtar.Kalam@vu.edu.au, Peng.Shi@vu.edu.au

***Abstract*—Distribution power system has poor power quality and dynamic performance due to insufficient reactive power support during disturbances. Distribution Static Compensator (DSTATCOM) can improve the power quality and dynamic performance of distribution power system. Proportional and Integral (PI) controllers are often used to control the operation of the DSTATCOM for the distribution power system. However, since the power system is highly nonlinear and subject to various disturbances, the PI controlled DSTATCOM cannot provide optimal performance for different operating points. More robust controllers such as the one based on fuzzy logic approach are required for the DSTATCOM to provide adequate dynamic voltage control and to improve power quality and stability of the distribution power system. This paper presents the design of a fuzzy logic based controller of a 3MVA DSTATCOM for improving the power quality and stability of a distribution power system. Grey Wolf Optimisation (GWO) algorithm has been used to tune the scaling factors of the fuzzy logic controllers. Comparison study of PI controlled and fuzzy logic controlled DSTATCOM for improving the power quality and dynamic performance of a distribution power system is simulated using SimPowerSystem in MATLAB/Simulink environment. The performances of the DSTATCOM controllers are evaluated during grid side voltage sag and load variation. The simulation results in MATLAB/SimPowerSystems show that the fuzzy logic controlled DSTATCOM controller provides better system dynamic response and hence improves power quality and stability for the distribution power system.**

Index Terms*—Distribution Static Compensator (DSTATCOM), Distribution Power System, Fuzzy Logic Control, Grey Wolf Optimisation, Proportional and Integral (PI) Control.

I. Introduction

Low voltage poor power quality can be caused by the demand in reactive power as it loads up the supply system unnecessarily. This can also be due to harmonic pollution and load imbalance as these cause extra stress on the networks and excessive voltage imbalance causing stress on other loads connected to the same network [1]. Flexible AC Transmission Systems (FACTS) devices such as Static Synchronous Compensator (STATCOM) can address the power quality issues related to transmission lines while DSTATCOM can improve the power quality and dynamic performance in a distribution network [2]. A DSTATCOM is a shunt connected bidirectional converter based device which can provide adequate level of reactive power to improve the quality of electrical power featured as the voltage at the point of common coupling (PCC) in distribution network [3]–[5]. Various control structure and algorithms for DSTATCOM converter such as phase shift control with PI controller, carrier based PWM control with PI controller, and carrier less hysteresis control with PI controller have been proposed to address the power quality issues [2]. In the work by Singh and Solanki [6], instantaneous reactive power theory, a synchronous reference frame theory, and an Adaline-based algorithm have been compared for extracting reference current signals. Kora [7] presented fuzzy logic controller for three-phase DSTATCOM to compensate for AC and DC loads. However, the fuzzy logic controller is only proposed for controlling the dc-link voltage based on the energy of a dc-link capacitor. In this paper, carrier-based PWM control with fuzzy controllers are designed for controlling the DC voltage, AC voltage, and current regulators. In [8], a Mamdani type of fuzzy controller was employed whereas a Sugeno type of fuzzy logic controller is designed in this paper. Our previous research results show that a Sugeno type of fuzzy logic controller for STATCOM has many advantages over the Mamdani type [9]–[13]. A Sugeno type of fuzzy logic controller can overcome the computational problem a complex system such as distribution power system encounters in both software simulation and real-time implementation. A Sugeno type fuzzy controller can be analysed and implemented more effectively than the Mamdani type fuzzy controller. In addition, it is more convenient in mathematical analysis and in system analysis for a DSTATCOM equipped with a Sugeno type fuzzy controller as the membership functions for the output are singletons. After designing the fuzzy controller, fine tuning can be made in order to improve the performance of the controller. Tuning can be made either to the membership functions or to the scaling factors (note that it is common to use normalised inputs and outputs for fuzzy controller and hence scaling factors are required to normalise these inputs and outputs). However, as the rule-base conveys a general control policy, it is preferred to keep the rule-base unchanged and the tuning exercise is focused on the scaling factors.In this paper, the scaling factors of the designed fuzzy controllers are tuned using Grey Wolf Optimisation (GWO) algorithm.

This paper presents the design of fuzzy logic based controller of a 3MVA DSTATCOM for improving the power quality and stability of a distribution network. A comparative study of the PI controlled and the fuzzy logic controlled DSTATCOM for improving the power quality and dynamic performance of a distribution power system is simulated using SimPowerSystem in MATLAB/Simulink environment. The performances of the DSTATCOM controllers are evaluated during grid side voltage sag and large load variations.

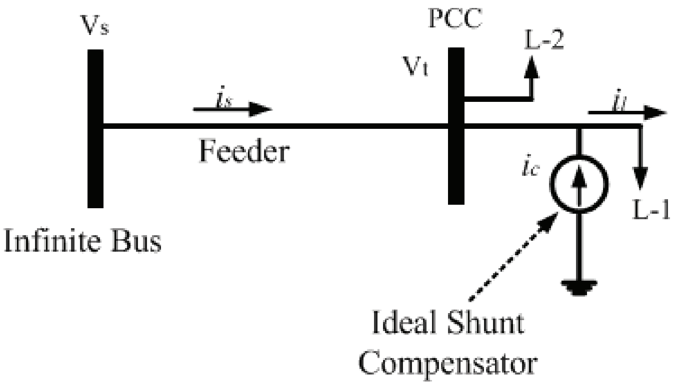

Figure 1. Schematic diagram of load compensation [2].

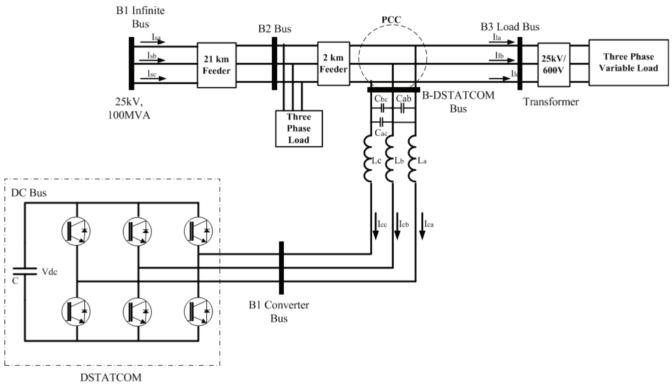

Figure 2. System configuration of a distribution network.

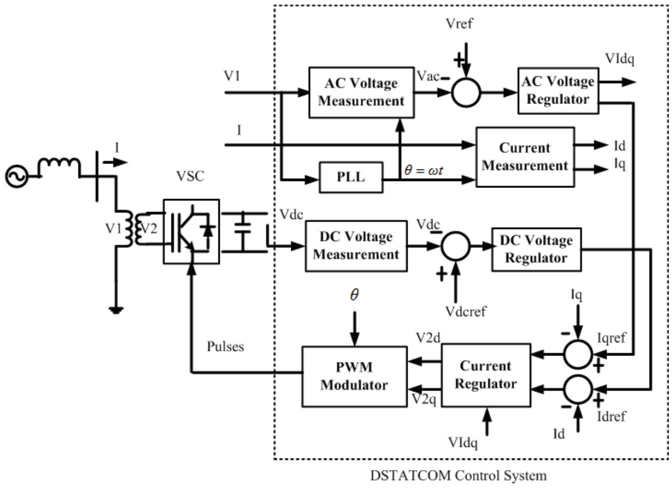

Figure 3. DSTATCOM control system block diagram.

II. The Operating Principle Of Load Compensation DSTATCOM And System Configuration

Fig. 1 shows a schematic diagram for load compensation using an ideal shunt compensator like a DSTATCOM by inject current i_c at the PCC to cancel the reactive, nonlinear and unbalanced load current i_l [2], [7].

Fig. 2 shows a configuration of a network where DSTATCOM is used to regulate the voltage on a 25-kV distribution power system [14]. 21 km and 2 km feeders are used to transmit power to loads at buses B2 and B3. A variable load producing continuously changing currents and voltage flicker is connected to bus B3 through a 25kV/600V transformer. The DSTATCOM uses Voltage Source Converter (VSC) to regulate voltage at PCC by absorbing or generating reactive power using power electronics to regulate three phase sinusoidal voltage at its terminal. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesise the voltage on the secondary side of the coupling transformer from a DC voltage source [14], [15]. A DSTATCOM with VSC using IGBT-based PWM inverters has been used in this study. Fig. 3 depicts a single-line diagram of the DSTATCOM and the control system block diagram of DSTATCOM.

In Fig. 3, PLL represents the phase-locked loop used to synchronize on the positive sequence component of the three phase (3Φ) primary voltage V_1. The output of the PLL is $\theta = \omega t$ and it is used to compute the direct-axis and quadrature-axis components of the AC (3Φ) voltage (V_d and V_q) and currents (I_d and I_q). The DC measurement system in Fig. 3 provides the measurement of the DC voltage V_{dc}. The AC voltage measurement and current measurement systems in Fig. 3 measure the d and q components of AC positive-sequence voltage and currents to be controlled, respectively.

The AC voltage regulator and DC voltage regulator form the outer regulation loop of the DSTATCOM control system. The current regulators form the inner current regulation loop. The output of the AC voltage regulator is the reference current I_{qref} for the current regulator where I_q is the current in quadrature with voltage which controls the reactive power flow. The output of the DC voltage regulator is the reference current I_{dref} for the current regulator where I_d is the current in phase with voltage which controls the active power flow. The current regulator produces V_{2d} and V_{2q} based on the current difference in $(I_{dref} - I_d)$ and $(I_{qref} - I_q)$. In addition, a feed forward type regulator which predicts V_{2d} and V_{2q} from V_{1d} and V_{1q} and the transformer leakage reactance is used to assist the current regulator. The PWM modulator generates pulses to control the IGBT in the VSC based on V_{2d} and V_{2q} in synchronization with the output of the PLL θ.

III. Fuzzy Logic Controller Design For The DSTATCOM

A fuzzy logic controller (FLC) consists of four elements. These are a fuzzification interface, a rule base, an inference mechanism, and a defuzzification interface [16]. A FLC has to be designed for the DC voltage regulator, AC voltage regulator, and the current regulator. The design of the FLC for DC voltage regulator is described in detail first. The design of the fuzzy controllers for the AC and current regulators follows similar procedure. The PI-like FLC designed for DC voltage regulator has two inputs and one output. The error $e(t)(e = V_{dcref} - V_{dc})$ and the rate of change of error $(\dot{e}(t))$ are the inputs and the output of the FLC is ΔI_d. In fact, ΔI_d is integrated to produce I_{dref}. Fig. 4 shows the block diagram of the DC voltage regulator where *GE*, *GCE*, and *GCU* are the scaling factors for the inputs and output, respectively.

The linguistic variables for error $e(t)$, the rate of change of error $(\dot{e}(t))$ and the controller output ΔI_d will take on the

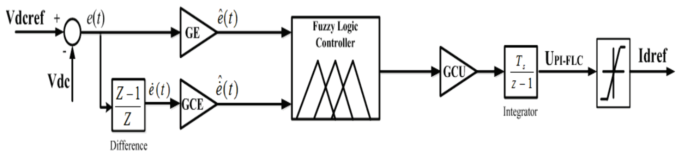

Figure 4. DSTATCOM control system block diagram.

following linguistic values:

NL = Negative Large
NM = Negative Medium
NS = Negative Small
ZO = Zero
PS = Positive Small
PM= Positive Medium
PL = Positive Large.

The above linguistic quantification has been used in this paper to specify a set of rules or a rule-base. The rules are formulated from practical experience. For the FLC with two inputs and seven linguistic values for each input, there are $7^2 = 49$ possible rules with all combination for the inputs. The tabular representation of the FLC rule base (with 49 rules) of the fuzzy control based DC voltage regulator is shown in Table I.

TABLE I. 7 × 7 FLC RULE-BASE IN TABULAR FORM

$e(t)$ \ $\dot{e}(t)$	**NL**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PL**
PL	ZO	PS	PM	PL	PL	PL	PL
PM	NS	ZO	PS	PM	PL	PL	PL
PS	NM	NS	ZO	PS	PM	PL	PL
ZO	NL	NM	NS	ZO	PS	PM	PL
NS	NL	NL	NM	NS	ZO	PS	PM
NM	NL	NL	NL	NM	NS	ZO	PS
NL	NL	NL	NL	NL	NM	NS	ZO

The membership functions to be employed for the inputs are of the triangular type where the membership functions for the output are singletons. The membership functions for the inputs and the output of the fuzzy controller for the DC voltage regulator are shown in Figs. 5, 6, and 7, respectively.

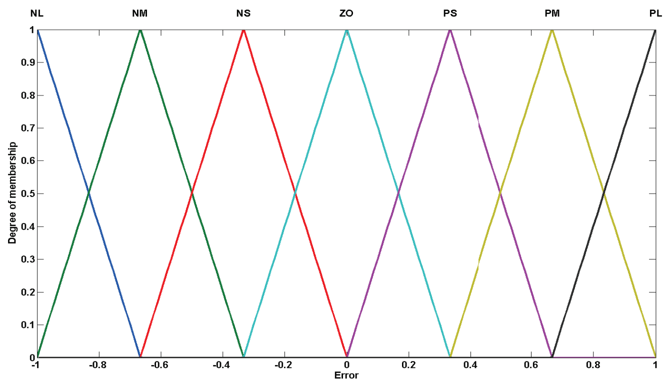

Figure 5. Membership functions of the input error $e(t)$.

Figs. 8 and 9 illustrate the block diagram of the fuzzy controllers as the AC voltage regulator and current regulator

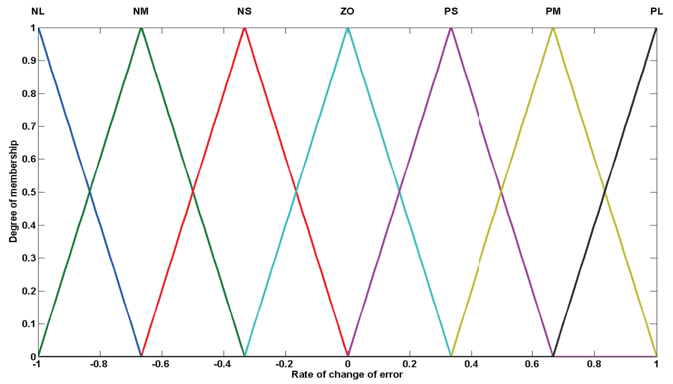

Figure 6. Membership functions of the input the rate of change of error ($\dot{e}(t)$).

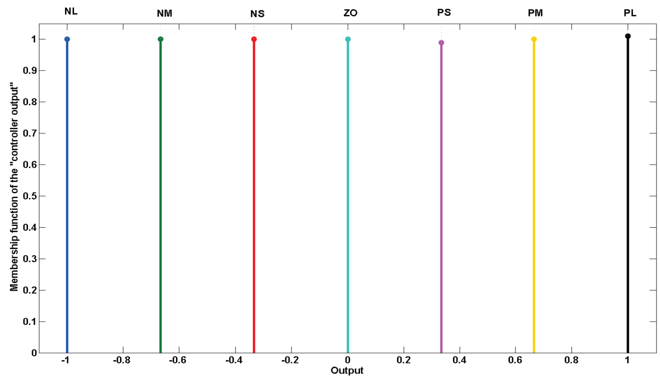

Figure 7. Membership functions of the output of fuzzy logic controller.

which has similar structure of the FLC DC voltage regulator. Again GE, GCE, and GCU are the scaling factors for the inputs and output, respectively.

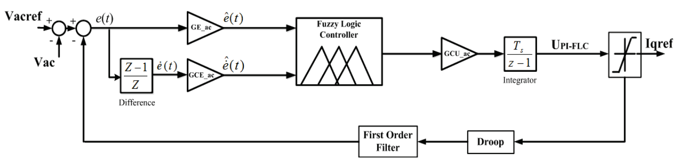

Figure 8. Block diagram of the fuzzy logic based AC voltage regulator.

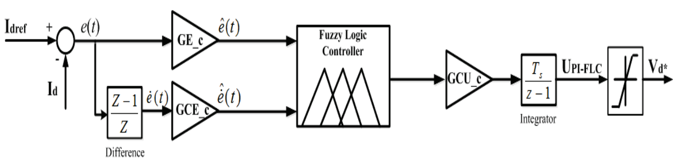

Figure 9. Block diagram of the fuzzy logic based current regulator.

Note that there are two fuzzy logic based current regulators producing V_{2d} and V_{2q}, respectively, based on the current difference in $(I_{dref} - I_d)$ and $(I_{qref} - I_q)$.

IV. Tuning the Scaling Factors of the Fuzzy Logic Controller Using Grey Wolf Optimisation Algorithm

Grey Wolf Optimisation (GWO) is a very recent meta-heuristic algorithm based on the natural hunting behavior of grey wolves [17], [18]. In GWO, the solution candidates are made up of four different types of wolves (agents) (α, β, δ and ω). α, β and δ can be considered as the first, second, and third best solutions. There is only one agent within each of α, β and δ dimensions, however, the ω can consist of multiple agents (wolves). Similar to all other meta-heuristic algorithms, the algorithm starts with randomly generated solutions (wolves). All candidates are considered as ω at the start of the algorithm. Upon the end of first iteration, the three agents (α, β, and δ) is assigned to the best three solutions. The optimiser then continues to move the search agents towards the best scoring solution (α), as well as random placement of some agents throughout the search space to promote exploration. The optimiser continues with an "encircling prey" algorithm, which focuses on the surrounding of the prospective best solution. The encircling algorithm can be formulated as in (1) and (2) [17].

$$\overrightarrow{D} = |\overrightarrow{C} \times \overrightarrow{X_p}(t) - \overrightarrow{X}(t)| \tag{1}$$

$$\overrightarrow{X}(t+1) = \overrightarrow{X_p}(t) - \overrightarrow{A} \times \overrightarrow{D} \tag{2}$$

where X_p is the position of the prey, $X(t)$ and $X(t+1)$ represent the current and the future positions of a grey wolf. $\overrightarrow{A}$ and $\overrightarrow{C}$ are given in (3) and (4).

$$\overrightarrow{A} = 2.\overrightarrow{a}.\overrightarrow{r_1} - \overrightarrow{a} \tag{3}$$

$$\overrightarrow{C} = 2.\overrightarrow{r_2} \tag{4}$$

In (3) and (4), r_1 and r_2 are random set of vectors between $[0, 1]$. The parameter a is used to mathematically model the attacking stage when the prey stops moving. In fact, a decreases linearly from 2 to 0 over the course of iterations. GWO continues the algorithm by storing the best three solutions and updating their positions according to (5)-(7), and the iteration continues until the stopping criteria are reached.

$$\overrightarrow{D_\alpha} = |\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \overrightarrow{X}|,\ \overrightarrow{D_\beta} = |\overrightarrow{C_2}.\overrightarrow{X_\beta} - \overrightarrow{X}|,\ \overrightarrow{D_\delta} = |\overrightarrow{C_3}.\overrightarrow{X_\delta} - \overrightarrow{X}| \tag{5}$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1}.\overrightarrow{D_\alpha},\ \overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2}.\overrightarrow{D_\beta},\ \overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3}.\overrightarrow{D_\delta} \tag{6}$$

$$\overrightarrow{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \tag{7}$$

GWO is employed to find the optimal values of the tuning parameters used in the fuzzy logic controllers. The integral time absolute of error (ITAE) between the reference DC voltage V_{dcref} and the measured DC voltage V_{dc} is employed as the optimisation objective for optimising the scaling factors of the fuzzy DC voltage regulator. Similar fitness functions are used for the fuzzy AC regulator, and fuzzy current regulators as shown in (8).

$$J = \int_0^\infty t.|e(t)|dt \tag{8}$$

The convergences of the objective functions using GWO for the FLCs as the DC voltage regulator, AC voltage regulator, and current regulators are depicted in Figs. 10-12.

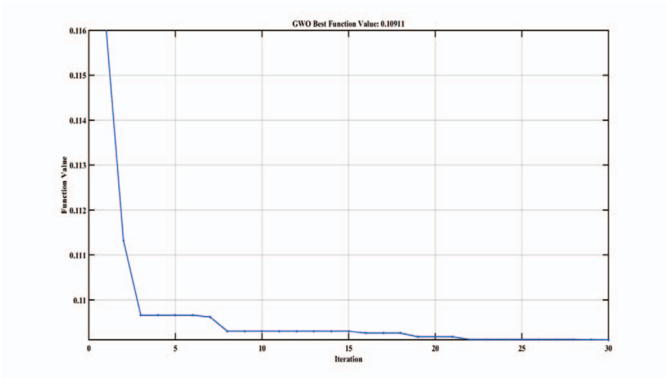

Figure 10. Tuning of the fuzzy DC Voltage regulator parameters using GWO.

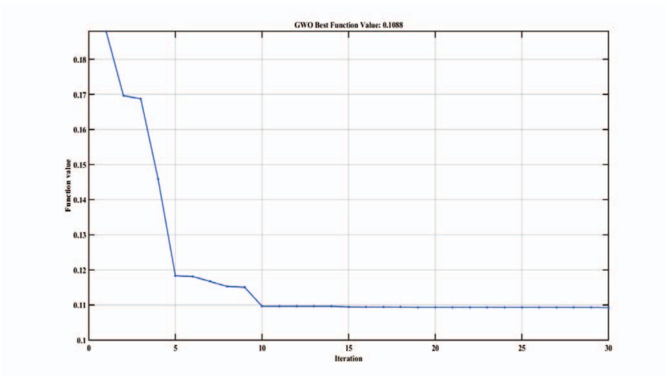

Figure 11. Tuning of the fuzzy AC Voltage regulator parameters using GWO.

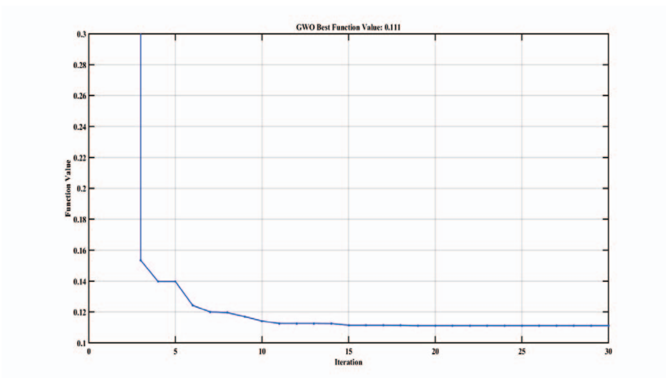

Figure 12. Tuning of the fuzzy current regulator parameters using GWO.

V. Comparative Study of the Performance of the PI and Optimal Fuzzy Logic Controllers for the DSTATCOM

The power system used in the simulation study is shown in Fig. 2 in Section II. System parameters are shown in Table II. The control parameters of the DSTATCOM such as the PI DC and AC voltage regulators gains, and the PI current regulator gains as well as the scaling factors of the fuzzy controllers of the DSTATCOM are provided in Table III. Note that the parameters of the PI controllers are provided in the examples in MATLAB/SimPowerSystems, hence, the PI controllers are fine tuned for their optimal performance. However, the PI-FLC scaling factors of the designed fuzzy controllers are tuned using *GWO*.

Alternatively, Multi-Objective Genetic Algorithm (MOGA) is used in [19] to find the optimal tuning factors used in the PID-FLC controllers. However, the shortcoming with the GA is that the performance of the algorithm is not consistent. In fact, the algorithm has to be repeated multiple times to ensure that the optimal values are obtained [20], [21]. From the best of our knowledge, GWO shows more consistent behaviour, at least in this particular problem, and similar results are obtained if the algorithm is executed multiple times.

TABLE II. System Parameters

Parameter	numerical value
Source Voltage	$25KV$
Distribution Line Voltage	$25KV$
Frequency	$60Hz$
Feeder resistance R	$0.1153\Omega/Km$
Feeder inductance L	$1.048mH/Km$
Feeder capacitance C	$11.33nF/Km$
Fixed load at bus 2	$3.007MVA$ with power factor = 0.998
Fixed load	$1MVA$ with power factor = 1
Variable load	Nominal: $1.8MVA$ with power factor= 0.9, Modulation: $1.2MVA$ with frequency of $5Hz$
DC link capacitor	$10mF$
DC voltage set point	$2400V$

TABLE III. Control Parameters

Parameter	Numerical Values
DSTATCOM DC Voltage Regulator Gains	$Kp = 0.001$; $Ki = 0.15$
DSTATCOM AC Voltage Regulator Gains	$Kp = 0.55$; $Ki = 2500$
DSTATCOM Current Regulator Gains	$Kp = 0.8$; $Ki = 200$
FLC Scaling Factors for the DC Voltage Regulator	$GE = 0.00319$; $GCE = 1.7778$; $GCU = 0.53559$
FLC Scaling Factors for the AC Voltage Regulator	$GE = 1.2229$; $GCE = 4.1472$; $GCU = 2450$
FLC Scaling Factors for the Current Regulator	$GE = 0.1223$; $GCE = 5.7638$; $GCU = 1060$

A. Dynamic Response of the Fuzzy Controlled DSTATCOM

The dynamic response of a DSTATCOM corresponding to initial system transient, step changes in source voltage at the infinite bus, and load variation is observed without the DSTATCOM, with the conventional PI controlled DSTATCOM, and with the fuzzy controlled DSTATCOM. Fig. 13 shows the voltage at B3 when the source voltage has been changed by successively increasing the source voltage by 6%, decreasing it by 6% and bringing it back to its initial value at $0.2s$, $0.3s$, and $0.4s$. Fig. 13 also shows the dynamic response of the system when extra load variation is applied at $1.0s$ and removed at $1.5s$. It is observed that the voltage at the PCC has improved dramatically when the distribution system is equipped with the DSTATCOM. The fuzzy controlled DSTATCOM has the lowest overshoot and fastest dynamic response during the initial system transient period. In addition, the fuzzy controlled DSTATCOM has improved the voltage dynamic response more at PCC by providing less overshoot and faster settling time in comparison with the response with the PI controlled DSTATCOM. Fig. 14 provides a close-up view of the voltage at B3 subject to grid voltage variation.

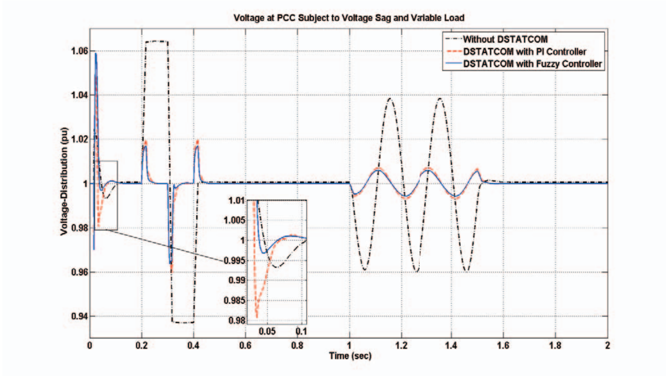

Figure 13. Dynamic response of the fuzzy controlled DSTATCOM and conventional PI controlled DSTATCOM.

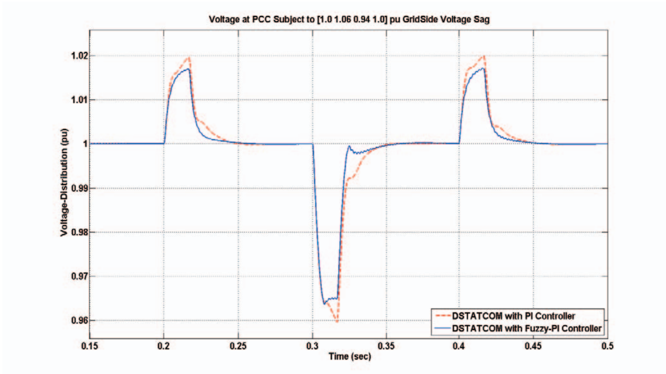

Figure 14. Dynamic response of the fuzzy controlled DSTATCOM and conventional PI controlled DSTATCOM.

B. Mitigation of Voltage Flicker

The mitigation of voltage flicker with the fuzzy logic controlled and conventional PI controlled DSTATCOM can be observed when the load is varied. Fig. 15 shows the voltage at B3 with the fuzzy controlled DSTATCOM and conventional PI controlled DSTATCOM. It can be observed in Fig. 13 shown previously that voltage at B3 varies between 0.96 pu and 1.04 pu ($\pm 4\%$ variation) without DSTATCOM. It is observed in Fig. 15 that the voltage fluctuation at bus B3 is reduced to $\pm 0.7\%$ with the PI controlled DSTATCOM. The voltage fluctuation at bus B3 is further reduced to $\pm 0.6\%$ with the fuzzy controlled DSTATCOM as indicated in the solid line shown in Fig. 15.

VI. Conclusion

This paper has presented the design of fuzzy controller for a DSTATCOM to improve power quality and dynamic

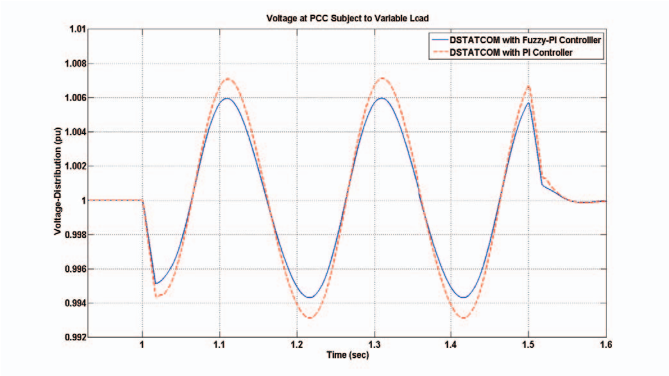

Figure 15. Mitigation of voltage flicker with the fuzzy controlled DSTATCOM and conventional PI controlled DSTATCOM.

performance of a distribution power system. A metaheuristic optimisation algorithm called grey wolf optimisation (GWO) is utilised to find the optimal values of the tuning parameters used in the fuzzy logic controllers. Comparison study of the PI controlled and the optimal fuzzy logic controlled DSTATCOM for improving the power quality and dynamic performance of a distribution power system has been simulated using SimPowerSystem in MATLAB/Simulink environment. The performances of the DSTATCOM controllers are evaluated during grid side voltage sag and load variations. The simulation results obtained in MATLAB/SimPowerSystems show that the fuzzy logic controlled DSTATCOM provides better system dynamic response and hence improves power quality and stability for the distribution power system.

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