

Power Quality Improvement In Distribution Networks Using a New Fuzzy Controlled DSTATCOM

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ABSTRACT

In this paper, a new fuzzy controller for a three-phase and three-wire distribution static compensator (DSTATCOM) is presented to improve power quality. A three-leg voltage source converter based DSTATCOM is used to control the harmonic currents for two nonlinear loads. In this control system, gate pulses for IGBT switches are provided by a hysteresis controller, using samples of source voltages and currents. The derived reference currents, obtained by the direct method of reference current estimation with two PI and Fuzzy control models are simulated in a MATLAB/Simulink environment and each performance is analyzed. Comparisons show that the fuzzy controller performs better than a classic PI controller.

KEYWORDS: DSTATCOM, Power Quality, Fuzzy Controller.

1. INTRODUCTION

The meaning of power quality is quite wide and any problem that can cause a change in voltage, current, frequency of the system or can damage and malfunction equipments, can be categorized as a power quality issue. Power quality problems are not new concepts in the power systems. The concepts existed since the beginning of the power industry, but greater attention on this subject these days is because of an increase in the nonlinear loads and the distortions produced on the network and also extension of sensitive loads to distortions. DSTATCOM is a modern flexible AC transmission system device with fast response, continuous absorption of reactive power control, harmonic currents and low losses in small size compared to conventional reactive power compensation devices. Numerous researches have been done on the design of DSTATCOM control.

Analysis of the external voltage direct current control method, the internal structure of a static VAR generator and control simulation are investigated in [1]. The cause and the solution of high-voltage of the capacitor, when the compensator emits a pure capacitive reactive power has been provided in [2]. The simulation of the inductive and reactive current waveforms of the voltage of capacitor using direct current control system also has

been presented in this paper. Some studies show that the active and reactive power can be controlled using power-time equation of the switches and simulations illustrate effectiveness of the control system [3]. A Fuzzy controller is designed to enhance the interlinked power system stability in order to increase transient stability and transmission margins in [4]. DSTATCOM is designed for power quality improvement using Mamdani fuzzy control method for a three-phase, four-wire distribution system [5]. A three-phase, four-wire DSTATCOM and a T-connected transformer are used to improve power quality and to neutralize current compensations using synchronous reference frame control theory [6]. Other studies describe a unified approach to reduce voltage sag and voltage flicker using the DSTATCOM [7]. DSTATCOM can also be adopted for load compensations in a weak AC voltage system, using state feedback control method [8]. Due to the large number of parameters and the complexity of the control method in the studies indicated above, control systems are difficult to design. The ease up this difficulty, this paper uses a new direct control method based on the Mamdani fuzzy logic controller, in a three-phase distribution system. This method is supposed to be less complicated in design and

performance which leads to a better compensation characteristics than the previous studies.

2. THE PRINCIPLE OPERATION OF DSTATCOM

The Performance of a DSTATCOM is similar to a current control loop. DSTATCOM controller works in a closed loop mode and determines the reference compensator in a real time. This controller generates gating pulses in order that its output currents remain around the reference waveform. On the other hand, the reference waveform generating part determines the ideal output reference current waveform of the filter. Thus, DSTATCOM's expected performance goals must be provided by the reference waveform generated part. The main idea of using these devices is to replace the eliminated portion of the sinusoidal wave in the nonlinear load current. Therefore, while the load current is distorted, the power system currents will be close to sinusoidal mode. This harmonics elimination method will form the basis of DSTATCOM. In addition to limiting harmonics, DSTATCOM also can correct system's power factor.

3. THREE-LEG DSTATCOM CONFIGUREURATION

Single line diagram of distribution system and DSTATCOM are shown in Figure 1. V_M represents three phase voltage sources as for step-down transformer, L_S represents a distribution line and transformer inductor and R_S represents effective resistance of line and transformer [10]. As shown in Figure 1, DSTATCOM is installed at the end bus of the distribution line. Figure 1.b shows the system phasor diagram for the unity power factor (UPF). Injected reactive current of DSTATCOM (i_c) will be injected to cancel the reactive component of the load currents until the source current only has an active component. These currents are adjusted dynamically to maintain unity power factor under variable loads.

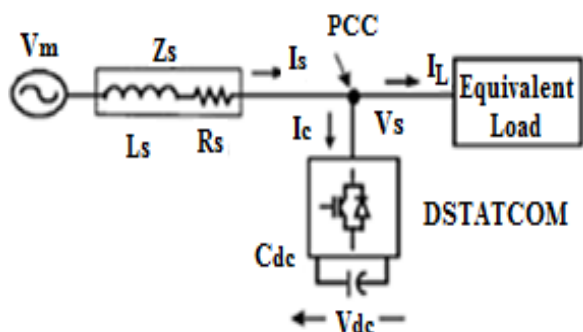


Fig. 1.a. The single line diagram of distribution system and DSTATCOM

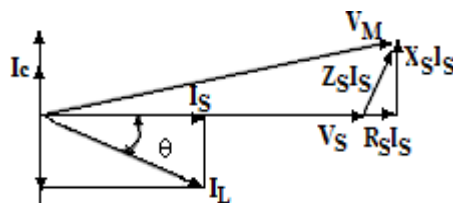


Fig. 1.b. The phasor diagram for UPF

Figure.2 shows the schematic diagram of three-leg DSTATCOM connected to the distribution system. The three-phase power system is realized by using three voltage sources connected in star and a ground point. Three-phase non-linear loads and three-phase three-wire DSTATCOM are connected at PCC. DSTATCOM includes 3-leg IGBT switches VSC, three interface inductors and a capacitor.

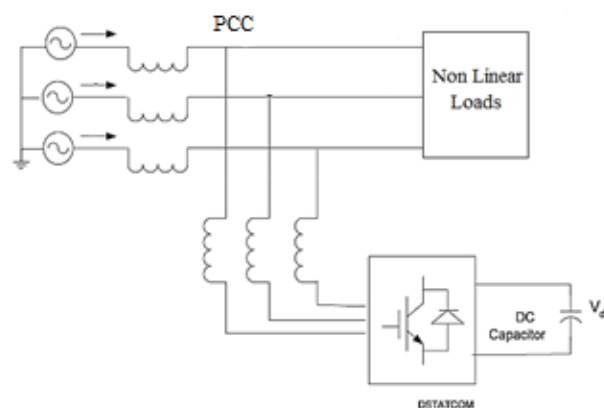


Fig. 2. The schematic diagram of three-leg DSTATCOM connected to the distribution system

3.1. Selection of design parameter and other features

Design parameter of DSTATCOM is an important factor to achieve better compensation performance. The main compensator component is the switches. IGBT is an appropriate choice in the medium capacity while GTO is used at higher rates. Series isolation inductor (L_f) is located between the PCC and voltage source converter. The inductor size is critical in the performance of DSTATCOM. If a small value of L_f is selected, the large amount of current ripple is injected to the supply current at the switching frequency. The large value of L_f will not provide proper tracking of compensation current close to the desired values. An optimal selection of L_f is essential for obtaining appropriate performance of DSTATCOM. The value of DC link of DSTATCOM is another important parameter. Small C_{dc} causes excessive ripples in steady state and transient fluctuations in the DC bus voltage. Large C_{dc} reduces ripple fluctuations of the DC bus voltage, but increases the cost and size of the system.

The following steps describe the procedure and criteria for the selection of design parameters. [12, 13]:

DC Bus Voltage

The minimum DC bus voltage of VSC of DSTATCOM should be greater than twice the peak of the phase voltage of the system. The DC bus voltage is calculated as:

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (1)$$

Where:

m: Modulation index and its value is taken as 1

V_{LL} : AC line output voltage of DSTATCOM.

DC Bus Capacitor:

The design of the DC capacitor is governed by the reduction in the DC bus voltage upon the application of load and rise in the DC bus voltage on removal of the load. Using the principle of energy conservation, the equation governing C_{DC} is as follow:

$$\frac{1}{2}C_{dc}[(V_{dc}^2) - (V_{dc1}^2)] = 3V(al) \quad (2)$$

Where:

V_{DC} : is reference voltage

V_{DC1} : is the minimum voltage level of the DC bus voltage

a: is the overloading factor

V: is the phase voltage

I: is the phase current of the VSC

t: is the response time of the DSTATCOM

In summary, capacitor duty is to provide a large enough fixed voltage to create a proper current in the inverter output in order to compensate harmonic currents of nonlinear load and improve power quality. In addition, the capacitor must be large enough such that the ripple on the capacitor, in steady state and transient conditions, does not exceed the permitted limit.

AC Inductor

The selection of the AC inductance of VSC depends on the current ripple $i_{cr(p-p)}$, switching frequency (f_s), DC bus voltage (V_{dc}); then, L_f is given as:

$$L_f = \frac{\sqrt{3}mV_{dc}}{12af_s i_{cr(p-p)}} \quad (3)$$

All parameters are defined in the above equations.

4. COMPENSATION IN THE THREE-PHASE DISTRIBUTION SYSTEM

Control strategy plays a vital role in the overall performance of the compensating device. The control of a compensating device is realized in three stages. In the first stage, the essential voltage and current signals are sensed using power transformers (PT's), CT's and Hall-effect sensors to gather accurate system

information. In the second stage, compensating commands in terms of current or voltage levels are derived based on different control methods and device configurations. In the third stage of control, the gating signals for the solid-state devices are generated. Figure 3 shows the compensation basic idea of DSTATCOM. In this paper i_s , i_L and i_C are source, load and compensator currents respectively. V is the source voltage and i indicates the reference current generated by the controller.

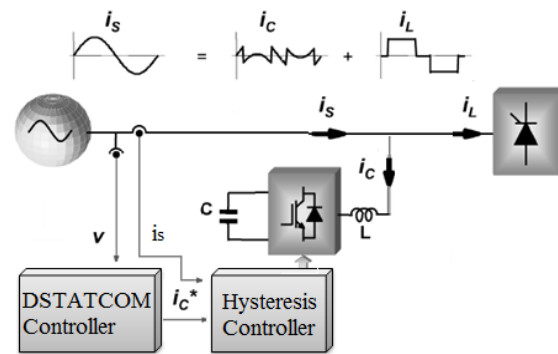


Fig. 3. The configuration of distribution static var compensator

5. CONTROL METHOD OF DSTATCOM

There are two general types of DSTATCOM control methods: direct control and indirect current control [14]. Indirect current control considers DSTATCOM as a voltage source and controls AC side of current indirectly by controlling the amplitude and phase of AC voltage generated by the inverter. By adjusting the phase difference δ of the output voltage and the system voltage, or in combination with the control pulse width θ to compensation system, direct control uses the hysteresis of the instantaneous current value to feedback control. As a result, the indirect method is relatively easy to control, but has no high control accuracy and response speed; while the direct current control has a high response speed and control precision. Therefore, the latter method can achieve a better results compared to the indirect control method [15]. Therefore, in this paper direct current control method is used.

5.1. Estimation of reference current for DSTATCOM controller

In this paper, the control design method is based on the injection of current into the network by the hysteresis current controller. Using these techniques, the controller keeps the control system variables beyond the boundaries of the hysteresis band and sends the switching signals to the inverter. Generated switching signals control scheme is shown in figure 4.

The control algorithm is required to measure several variables such as three phase source currents i_{Sabc} , DC voltage (V_{DC}) and inverter currents (i_{iabc}) using sensors. In a current controller, the sensed i_{Sabc} and reference supply currents i_{Sabc}^* are compared.

In a balanced three-phase system, the amplitude of the voltage source is calculated from source phase voltage in the sampling frequency and expressed as a sample template [17]:

$$V_{sm} = \left\{ \frac{2}{3} (V_{sa}^2 + V_{sb}^2 + V_{sc}^2) \right\}^{1/2} \quad (4)$$

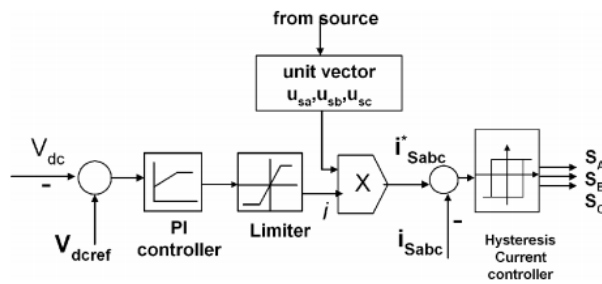


Fig. 4. Gate signals generating scheme for DSTATCOM switches

Per unit vectors are calculated from AC source phase voltage and RMS value of unit vector u_{sa}, u_{sb}, u_{sc} as follows:

$$u_{sa} = \frac{V_{sa}}{V_{sm}}, u_{sb} = \frac{V_{sb}}{V_{sm}}, u_{sc} = \frac{V_{sc}}{V_{sm}} \quad (5)$$

Per-unit Generated reference currents is evaluated using per-unit voltage term as follow:

$$i_{sa}^* = i \cdot u_{sa}, i_{sb}^* = i \cdot u_{sb}, i_{sc}^* = i \cdot u_{sc} \quad (6)$$

Where i is proportional to the filtered voltage source. The output taken from PI controller ensures that the current source is controlled to be sinusoidal. Unit vector plays a key role in coordinating the inverter. Compared to other methods, this method is very simple, robust and desirable [16].

5.2. Generating gate signals for DSTATCOM switches

Hysteresis based current controller is implemented on the control scheme. Reference current generated by equation (6) and the sensed current identified by current sensors are subtracted to calculate the current error for the hysteresis controller. ON/OFF switching signals for IGBTs are resulted from hysteresis controller. When the sensed current is greater than the reference current, it is essential that the corresponding switches change to achieve negative inverter output voltage and then the output current decreases and reaches the reference current. In the other words, if the measured current is less than the reference, switches change to achieve the positive output voltage of the inverter in order that the output current increases and

reaches the reference current. As a result, the output current will be in a band around the reference current. S_A switching function for phase "a" is expressed as follows:

$$\begin{aligned} i_{sa} > (i_{sa}^* + HB) &\Rightarrow S_A = 1 \\ i_{sa} < (i_{sa}^* - HB) &\Rightarrow S_A = 0 \end{aligned} \quad (7)$$

Where HB is the hysteresis band width, the switching functions of S_B and S_C are obtained for phases B and C respectively.

Inverter current control mode injects the current into the network; therefore, the source current will not contain harmonics and the current phase angles are in phase with the voltage source angles. The injected current, eliminates the harmonics and reactive components of the load current and improves the quality of current source at PCC. Hysteresis current control implementation is not costly. The hysteresis current control is working properly and responds quickly to the sudden changes in the reference current, because current control has a negligible delay and inertia.

6. SIMULATION

In this paper, the performance of DSTATCOM is investigated in order to reduce the source current harmonics and improve the power factor. The model is studied under variable loads and without turbulence supply conditions. Simulation is done in two cases of lagging power factor nonlinear load and a DC motor. The data required for simulation study the are shown in Table 1.

Table 1. The data required for simulation studies

Line impedance	$R_s = 1\mu\Omega, L_s = 10^{-5}H$
bridge rectifier (Three-phase)	$R_s = 10^{-5}\Omega, C_s = 10^{-12}F$ $R_{on} = 10^{-3}\Omega$
Load 1	$R_1 = 10\Omega, R = 20\Omega,$ $L = 10^{-4}H$
Load 2	$R = 30\Omega, L = 0.5H,$ DC Voltage Source = 60
Dc link capacitor	2000 μF
DSTATCOM impedance	$R = 1m\Omega, L_s = 2mH$
Voltage source	415V, 50 Hz

6.1. Control of DSTATCOM using a classic PI controller

The proportional gain (K_p) determines the dynamic response of the DC link capacitor voltage and the integral gain (K_i) determines the settling time and steady state error of DC link capacitor voltage. In the conventional methods, trial and error method is used to determine the values of the PI coefficients.

In this paper, genetic algorithm is used to calculate the optimal coefficients of the PI. The obtained PI coefficients are used to improve the controller parameters such as performance improvement and error reduction. Table 2 presents the results of the genetic algorithm which are used to determine the coefficients of PI controller.

The dynamic performance of DSTATCOM under lagging power factor nonlinear load and direct current control system and hysteresis method of switching using PI₁ controller is shown in figure 5. Load current (I_L), the source current (I_S) and DSTATCOM injected current ($I_{DSTATCOM}$) are demonstrated in figure 5.

Table 2. The PI controller coefficients obtained from genetic algorithm

controller /coefficients	K_p	K_i
PI controller for regulation of DC voltage for Load 1 (PI ₁)	0.8	10
PI controller for regulation of DC voltage for Load 2 (PI ₂)	0.1	3

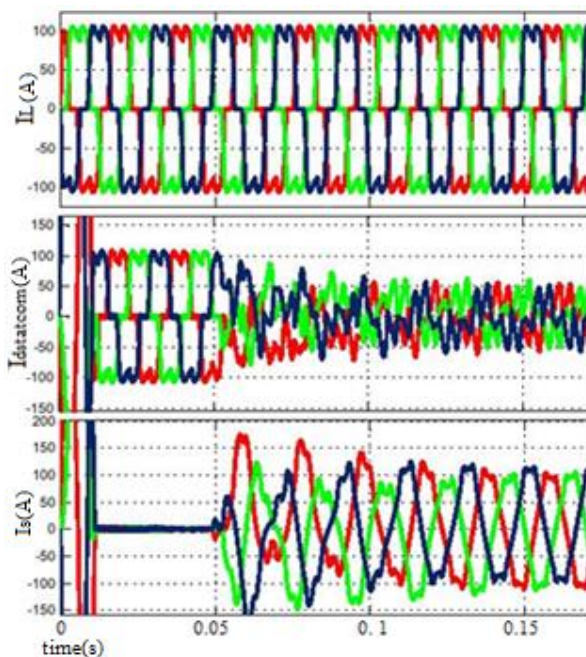


Fig. 5. The DSTATCOM performance using PI₁ controller under nonlinear lagging power factor load condition

It is observed that the source current under lag nonlinear load becomes sinusoidal at 0.15 s. This is achieved by injecting suitable current by DSTATCOM. The performance of DSTATCOM under DC motor load and direct current control system and hysteresis method of switching using PI₁ controller is shown in figure 6. Load current (I_L), the source current (I_S) and DSTATCOM injected current ($I_{DSTATCOM}$) are

demonstrated in figure 6. As it is shown, the coefficients of the designed PI controller under the load harmonic distortions have not been able to compensate harmonics of the source current and it is needed to adjust the new PI controller coefficients.

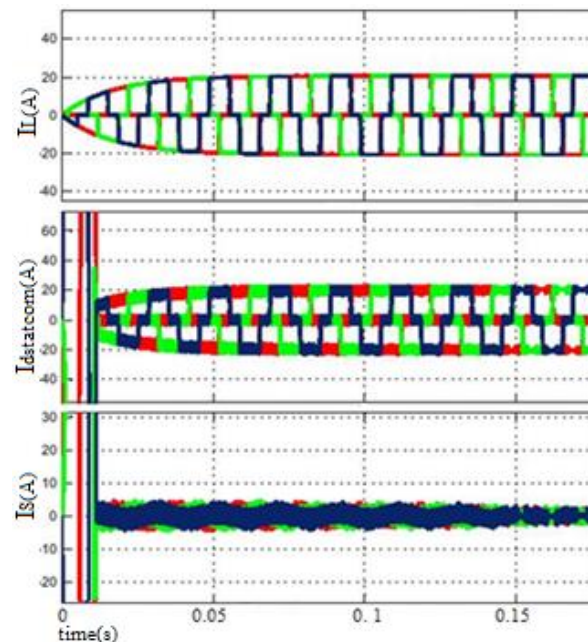


Fig. 6. The DSTATCOM performance using PI₁ controller under DC motor load condition

The performance of DSTATCOM under DC motor load and direct current control system and hysteresis method of switching using PI₂ controller is shown in figure 7. Load current (I_L), the source current (I_S) and DSTATCOM injected current ($I_{DSTATCOM}$) are presented in figure 7. It is observed that the source currents under DC motor load becomes balanced and sinusoidal. This is achieved by injecting the proper current by DSTATCOM.

Figure 8 shows the performance of DSTATCOM under lagging power factor nonlinear load and direct current control system and hysteresis method of switching using PI₂ controller. Load current (I_L), the source current (I_S), and DSTATCOM injected current ($I_{DSTATCOM}$) are demonstrated in figure 8. As can be seen, the determined coefficients of the PI controller under the nonlinear with harmonic distortions load conditions are not able to compensate harmonics of the source current.

6.2. DSTATCOM control using fuzzy control algorithm

Practically, the topology of the distribution system varies with time according to network and load changes. This change leads to an uncertainty in the model of the distribution system and lack of optimal

performance of compensators with linear controllers. On the other hand, the parameters of the linear controller are depending on the distributed system topology. Thus, it is admirable to replace the conventional controller with robust controllers. Fuzzy logic controllers in some cases are used as an alternative to the classical PI controller.

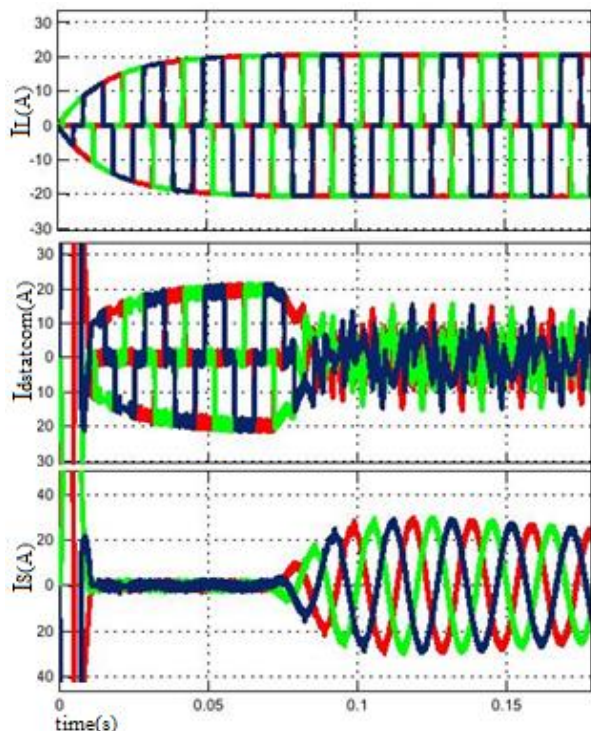


Fig. 7. The DSTATCOM performance using PI₂ controller under DC motor load condition

Fuzzy logic controller (FLC) is used with complex structure in systems. In this case, fuzzy controller can be used to improve the performance of DSTATCOM. Fuzzy controller can also be used instead of linear PI controllers. In this paper, fuzzy logic is used as a powerful computational algorithm for the optimization of the DC voltage. In fact, compared to PI controller, fuzzy controller is a nonlinear adaptive controller that has a robust performance against the changing of the parameter of linear and nonlinear processes. Optimizing DC voltage is one of the key aspects of harmonic compensation.

DSTATCOM performance is entirely dependent on the capacitor voltage. In fact, it affects the generation of reference current [19]. In the simulation study, the structure of the fuzzy controller is shown in figure (9).

To convert fuzzy variables in each fuzzy controller, fuzzy sets are defined as follows:

Very High Negative (VHN), Medium Negative (MN), Small Negative (SN), Zero (Z), Small Positive (SP), Medium Positive (MP), Very High Positive (VHP).

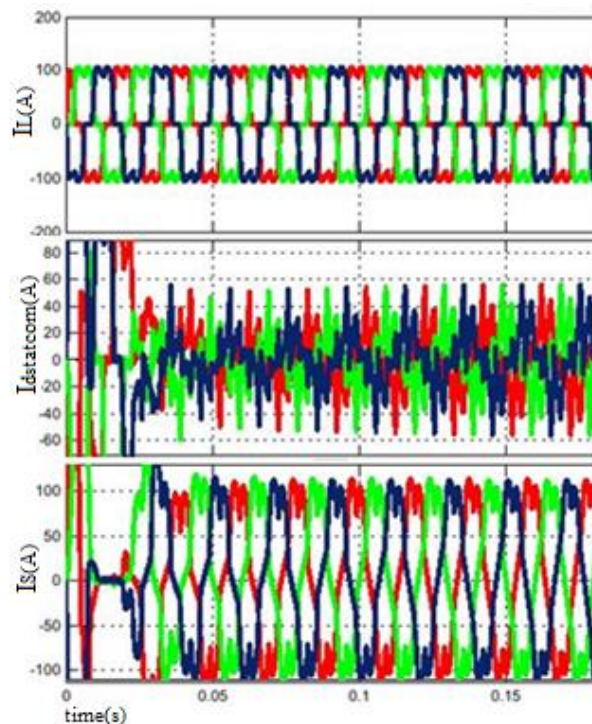


Fig. 8. The DSTATCOM performance using PI₂ controller under nonlinear lagging power factor load condition

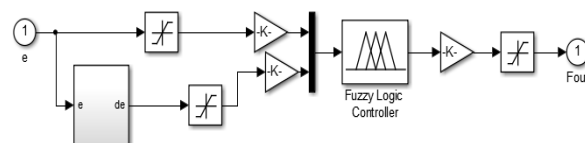


Fig. 9. The fuzzy regulator diagram

A fuzzy set form determines how a fuzzy system estimates control rules as well as a function. Triangle-shaped membership functions are the most common form of membership functions to estimate the nonlinear function. In this paper, the same method is used. Herein, the difference between capacitor voltage and its reference value are defined as an error and the error variation are defined as inputs to the controller. As fuzzy controller utilizes two variables, controlling rules can be summarized as shown in table3. Membership functions and rules are obtained by understanding the behavior of DSTATCOM. Table 3 shows the details of 49 rules for optimal control of DC link voltage of DSTATCOM and each rule represents the operating conditions of the system. Totally, 49 control laws can guarantee the acceptable and desirable control. For fuzzy controller using Mamdany method, the relationship between inputs and outputs are simulated.

For a better comparison of fuzzy and PI controller, in Table (4.a) and (4.b) comparisons between load and source currents in terms of the amount of THD is demonstrated. It is observed that, in the case of using a fuzzy controller and conventional hysteresis switching method, the best response in terms of total harmonic distortion for both loads is obtained.

7. CONCLUSION

Initially, the proportional integral controller is used in the control systems, which operate linearly. Optimal PI coefficients are calculated using genetic algorithms.

Selected PI controller coefficients are practically optimized for system specific point of operation. The calculation of these values is time consuming and complicated. It was shown that with the changing of loads, each determined PI coefficient was not able to compensate the harmonics. To overcome this issue, a fuzzy controller is used. It is observed that the DSTATCOM performance becomes better using this intelligent controller for power quality improvement and DSTATCOM can compensate various loads.

Table 3. The fuzzy rules

e	ce						
	VHN	MN	SN	ZE	SP	MP	VHP
VHN	VHN	VHN	VHN	VHN	MN	SN	ZE
MN	VHN	VHN	VHN	MN	SN	ZE	SP
SN	VHN	VHN	MN	SN	ZE	SP	MP
ZE	VHN	MN	SN	ZE	SP	MP	VHP
SP	MN	SN	ZE	SP	MP	VHP	VHP
MP	SN	ZE	SP	MP	VHP	VHP	VHP
VHP	ZE	SP	MP	VHP	VHP	VHP	VHP

Table 4.a. The THD Comparison of source currents under load 1 condition

LOAD 1				
3 Phases	Load current	Source current		
		PI ₁ controller	PI ₂ controller	Fuzzy controller
THD%				
phase A	23.88	4.65	7.51	0.70
phase B	23.88	4.63	7.49	0.67
phase C	23.88	4.69	7.53	0.71

Table 4.b. The THD Comparison of source currents under load 2 condition

LOAD 2				
3 Phases	Load current	Source current		
		PI ₁ controller	PI ₂ controller	Fuzzy controller
THD%				
phase A	26.55	14.60	3.45	0.54
phase B	26.52	14.91	2.18	0.57
phase C	26.52	15.89	3.52	0.54

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