Power Quality Improvement on 11kV/440V Distribution System using DSTATCOM

S.R.REDDY[1], P.V.PRASAD [2], G.N.SRINIVAS [3]
[1]EEE Department, GNITC, Ibrahimpatnam, Hyderabad, INDIA
[2] EEE Department, CBIT, Gandipet, Hyderabad, INDIA
[3]EEE Department, JNTUH, Hyderabad, INDIA

Abstract: - At the PCC and source side, current and voltage harmonics are compensated by utilizing a distribution static compensator. In this work, we also compensated for voltage control and reactive power correction. An improved reference current switching signal is suggested using a synchronous reference frame control technique. The analysis is done on an 11kV/440V three-phase four-wire unbalanced nonlinear load distribution system. The DC link voltage and harmonic reduction of the suggested distribution system performance is compared with the PI and fuzzy logic controllers. Harmonic distortion is reduced, and reactive power is successfully compensated with the suggested method. These simulation results are obtained by MATLAB/SIMULINK software.

Key-Words: Harmonic distortion, proportional integral (PI) controller, fuzzy logic controller, hysteresis current controller, and distribution static compensator (DSTATCOM).

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1 Introduction

Electrical power devices have become increasingly popular in the industrial sector in the past decade due to their ability to transmit power more efficiently [1]. Disturbances in power quality, such as harmonic problems, unbalanced load flows, and reactive power issues, have occurred due to the increased use of electronic power electronic equipment's and non-linear loads. This power quality affects motors and transformers overheat, sensitive devices fail, power factor decreases,, effectiveness of system decreases etc. [2, 3]. Another issue with power quality is a voltage unbalance in the supply due to an unbalanced load. It decreases the torque of an electric machine drive system and causes negative sequence currents [4, 5]. Unbalanced and nonlinear load increases the risk of high neutral current and other power quality issues. Custom power devices such as distribution static compensators (DSTATCOM), dynamic voltage restorers (DVR) and unified power quality conditioners (UPQC) are utilized to compensate for these power quality issues. Static distribution compensators outperform compared to other custom power devices when it comes to correcting reactive power, reducing harmonics, unbalancing loads, voltage fluctuations, and current harmonics in the distribution network [6]. Power quality issues and neutral current correction can be solved with topologies based on transformers and inverters. DSTATCOM employs transformer-based methods that can include, among other configurations, a VSI with three legs and a zigzag transformer [7], a T connection [8], or star-delta topology. Similar studies can be found in [9], [10]

. The zero-sequence part of the current is eliminated by using a transformer, and positive and negative currents are compensated for using three-leg VSIs. The inverter-based DSTATCOM incorporates a three-leg VSI with a split-stage capacitor, a four-leg VSI, and a three-leg VSIs with split-phase capacitor. There are merits and demerits associated with each of these approaches. In This design utilizes a three-legged VSI with a split-phase capacitor. To regulate the correct DC interface voltage, a proportional-integral (PI) controller is an integral part of the SRF control method. Inaccurate outcomes may be produced by the PI controller if it is exposed to changes in input parameters, load, etc. [11-13], and the controller needs precise mathematical model values, which can be difficult to acquire. The use of a fuzzy logic processor in DSTATCOM is currently a subject of considerable interest. Fuzzy logic controllers are preferable to PI controllers because they are more forgiving of imperfect input values and do not necessitate precise values for the mathematical models they are based on. For SRF-controlled DSTATCOM, the mamdani form of fuzzy logic processor is most commonly used because it produces the best outcomes. The fuzzy logic controller provides better compensation as compared to the proportional integral (PI) controller in DSTATCOM [14, 15, 16]. In this work, an SRF-controlled DSTATCOM with split-phase capacitor

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VSI is proposed and developed. Unbalanced nonlinear load circumstances are simulated, and the suggested DSTATCOM's harmonic reduction and DC link voltage control capabilities are evaluated.

2 Configuration of the System

The arrangement of the static distribution compensator system (DSTATCOM) for a three phase, four-wire distribution system with an unbalanced nonlinear load is shown in Figure 1. Before being connected to the unbalanced nonlinear load, the 11kV three-phase source voltage is brought down to 400V through the use of 11/0.4kV three phase transformers. Harmonics are introduced at the PCC by the connected unbalanced nonlinear load.

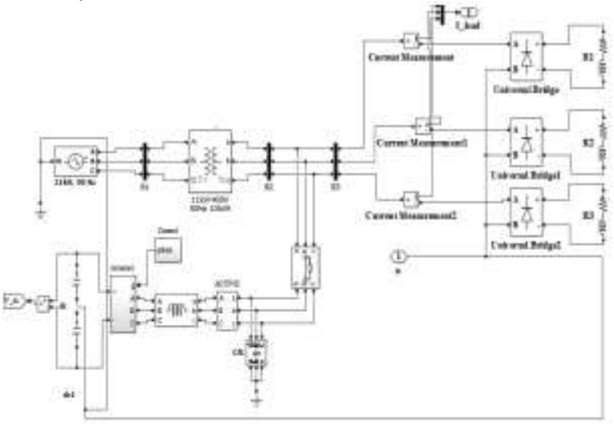


Figure.1. System configuration

A split-phase capacitor connected to DSTATCOM at the PCC can reduce harmonics and prevent unbalanced loading at the PCC and the load. It is possible to improve load balancing, power factor correction, and line voltage regulation by connecting on the bus.
The DSTATCOM consists of a dc-link voltage regulator, three leg voltage source inverter, Interface Inductor (Lf), and a split phase capacitor. Connecting three phase ripple filters of resistance (rf) and capacitor (Cf), switching and voltage transients caused by DSTATCOM are eliminated. The SRF and hysteresis band current control are used to generate the modified control switching signals that are sent to switching of the VSI based DSTATCOM.

3 Control strategy

The proposed SRF control algorithm block diagram is shown in Figure 2. The control method is used to obtain the fundamental switching reference control signals for switching of VSI-based DSTATCOM, for harmonic and reactive power correction under unbalanced nonlinear load situation.

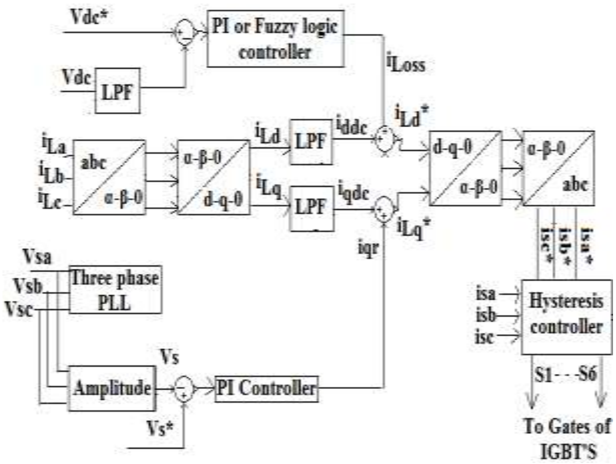


Figure.2. Block diagram of the suggested control method.

In a three-phase system, non-linear load currents divided into active current, reactive current, and the harmonic current. For compensation reasons, in this method, the reactive current and harmonic current are separated. Separation is achieved by applying Clark's transformation equation (1). To covert the three-phase load currents into a two-phase fixed α-β-0 line

$$\begin{bmatrix} i_{L0} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (1)$$

A Using the below park transformation condition, the present α-β-0 current axis components are changed to d-q-0 (d-direct axis, q-quadrature axis parts).equation-(2)

$$\begin{bmatrix} i_{L0} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{L0} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \qquad (2)$$

The transformation angle denoted by the symbol θ here. The cos θ and sin θ are derived from the voltage source's three-phase PLL block (phase-locked loop) when voltage and current are synchronized.
The terms i_{Ld} and i_{Lq}, which stand for instantaneous active and reactive load currents, are used after their reactive components of current have been isolated. As shown in equations (3) & (4), both the average (dc) and fluctuating (ac) values of the two components can be calculated.

$$i_{Ld}=i_{ddc}+i_{dac} \quad (3)$$
$$i_{Lq} = i_{qdc}+i_{qac} \quad (4)$$

The $i_{d\,dc}$ is average or DC part of i_{Ld}, while $i_{d\,ac}$ and fluctuating or AC part of i_{Lq}. For this situation, the fluctuating part is to appear as a ripple. The active and reactive current parts are given as Equations (5) and (6), separately, after the fluctuating current part has been eliminated utilizing a low pass filter.

$$i_{Ld}=i_{ddc} \quad (5)$$
$$i_{Lq}=i_{qdc} \quad (6)$$

The i_{Loss} current component is added to the average active reference current part i_{ddc} of the d-axis in a d-q frame. The i_{Loss} current component is obtained from the PI or fuzzy logic controllers, which is used to maintain and keep a constant DC bus voltage and supply losses in DSTATCOM. For this reason, the active reference current is given in Equation (7)

$$i_{Ld}^{*}=i_{ddc}+i_{loss} \quad (7)$$

For the adjustment of the harmonic and power factor, the direct axis reference current (i_{Ld}*) is used.
In Likewise, the reactive current (i_{qr}) should be provided by the source to keep a steady voltage at the PCC. In the same manner as for the direct current axis component, this current is added to the average reference part (component) of the current (i_{qdc}) of the q axis in the d-q frame. The ensuing portion of the reactive reference current is given by Equation (7).

$$i_{Lq}^{*}=i_{qdc}+i_{qr} \quad (8)$$

The output of the PI controller is the reactive current (i_{qr}), and the input of the PI regulator is the value of the voltage Vs, which can be subtracted from the reference voltage Vs*. An illustration of the PCC voltage magnitude is provided below. Output of the PI controller is given equation-(9)

$$Vs = \sqrt{2/3\,(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\,)} \quad (9)$$

The $V_{te(n)}$ $=V^{*}_{s}$ (reference voltage amplitude) - Vs(n)(actual terminal voltage amplitude) at time nth. K_{pq} (proportional) and K_{iq} (integral) gain of the PI controller. The n^{th} time PI controller is calculated by using Equation (10)

$$V_{qr(n)}=V_{qr(n-1)}+K_{pq}(V_{te(n)}-V_{te(n-1)})+K_{iq}V_{te(n)} \quad (10)$$

The part of the reference current known as the reactive current (i_{Lq}*) is used to rectify reactive power and regulate ac voltage.
Active and reactive reference current parts (i_{Ld}*, i_{Lq}*) can be completely changed to the α-β-0 frame by utilizing inverse Park condition (transformation) using equation (11).

$$\begin{bmatrix} i_{s0}^{*} \\ i_{s\alpha}^{*} \\ i_{s\beta}^{*} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{L0}^{*} \\ i_{Ld}^{*} \\ i_{Lq}^{*} \end{bmatrix} \quad (11)$$

Inverse Clark's equation is used to transform the reference current to three-phase currents (a, b, c) by equation (12).

$$\begin{bmatrix} i_{sa}^{*} \\ i_{sb}^{*} \\ i_{sc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 0 & 1 & 0 \\ 0 & -1/2 & \sqrt{3}/2 \\ 0 & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{s0}^{*} \\ i_{s\alpha}^{*} \\ i_{s\beta}^{*} \end{bmatrix} \quad (12)$$

The hysteresis band controller analyses the got three phase reference currents (I sa*, I sb*, and isc*) to the actual compensating filter currents in order to improve VSI switching with IGBTs. The main advantages of this hysteresis band controller's main advantages are its simplicity, increased stability, and quick response time. The primary disadvantage of the carrier-based controller compared to the hysteresis band controller is the strain that its varying switching frequency places on switching devices [17].

4 DC VOLTAGE REGULATION

The accuracy with which the adjusting reference current is generated, which is a process heavily influenced by the voltage control of the dc bus, is essential for the performance and accuracy of DSTATCOM. To meet the demands of the compensating current, the voltage across the dc bus (Vdc) either increases or decreases. The dc side of the inverter should remain steady at a predetermined reference value to work VSI properly [17]. VSI is able to compensate for the power losses caused by its filters and switches by maintaining a stable dc-link voltage. In rotating frame theory, a controller must add the average active current component (id dc) to manage or maintain a constant dc-link voltage. This section includes a comparison of two controller devices.

- PI controller.
- Fuzzy logic controller

4.1 PI controller

Figure 3 shows the structure of the PI controller block. It shows the how the internal framework functions inside. While compensating losses of DSTATCOM and filters, the source should likewise give the active reference current part (i_{Ld}) and the losses reference current part (i_{LOSS}). At the nth sampling moment, VSI obtained current loss reference component (i_{LOSS}) is found by comparing the reference dc bus voltage Vdc* to the actual dc bus voltage Vdc (Vdc1+Vdc2=Vdc). (i_{LOSS}).

$$V_{de(n)}=V_{dc^*(n)}- \quad V_{dc(n)} \qquad (13)$$

The loss component (i_{Loss}) at the nth testing moment can be computed using the contrasted error signal Vde(n), which is specified as

$$i_{Loss(n)} = i_{loss(n-1)} + k_{pd} \, (V_{de(n)} - V_{de(n-1)})+k_{id} \, V_{de(n)} \qquad (14)$$

The kpd = 0.6, and kid = 0.09 are proportional and integral values of the PI controller. For the DSTATCOM, the PI controller created the loss reference part (i_{Loss}). When managing the active reference current (i_{Ld}*), it is important to add the loss reference current part (i_{Loss}) to the average active reference current (i_{Ld}).A hysteresis band controller is needed for improved VSI switching with IGBTs. In this paper, the predicted reference current component and the actual compensating filter currents are compared.

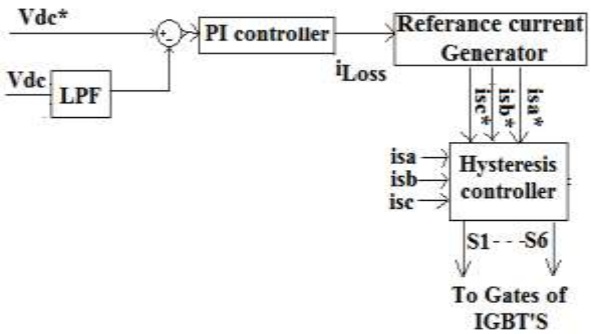


Figure.3. Diagram of the PI controller block DSTATCOM.

4.1 Fuzzy *logic controller*

The proposed internal circuit of the fuzzy logic controller as shown in Figure.4 Compares the reference voltage of the dc bus capacitance with the actual dc bus voltage and generate error signal. A fuzzy logic controller processes this error signal.

The fuzzy logic controller output is combined with fundamental active current to provide active power for dc-bus voltage regulation and VSI losses compensation. An error signal is generated when the calculated compensating current is compared with the measured compensating current in the filter hysteresis region. The error signal runs the VSI.

The Fuzzy Inference System (FIS) is made up of the defuzzification module, the Rule Proofreader, the rule Viewer, the Surface viewer, and the Membership Function Editor. [18 -20].

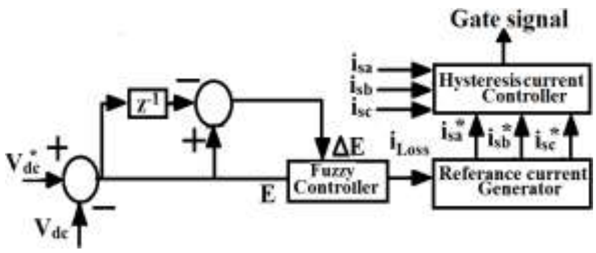


Figure. 4(a). Fuzzy logic controller block diagram

This work presents the fuzzy interface system, we developed as

- The input-output analysis (2 inputs and 1output).
- Membership functions (seven).
- Type of Implication (maximum Mammalian operation).
- Defuzzification method (centroid of area method).
- Rules Count: (49 rules).
- Function of input membership (Gaussian)
- What is the input membership function (triangular)

This decision each input and output pair has N linguistic variables, for a total of N2. These N2 pairs can produce any one of the M potential values for the decision variables. States encompass every conceivable permutation. The total number of fuzzy matrixes is (N2 * M) =49. Membership duties are controlled by these 49 states.

Fuzzy logic controller has a greater reaction and enhances DSTATCOM behavior than the other controller.

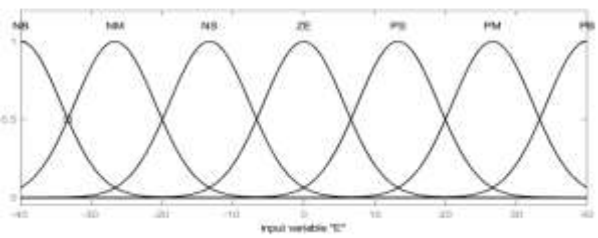


Figure.4 (b). The function of Gaussian memberships for the input variable E.

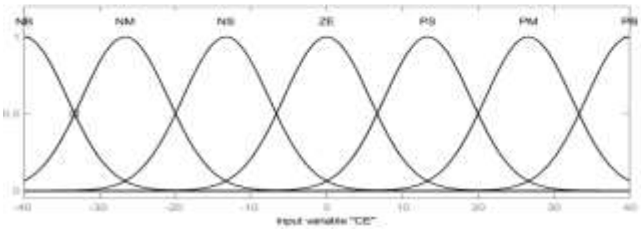


Figure 4 (c). It can be shown that change in input Variable (ΔE) Membership Function

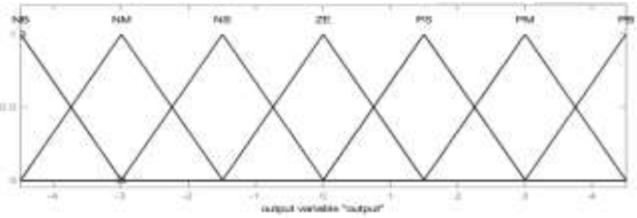


Figure. 4(d). The function of a triangular output variable's membership

Table.1. summary of decision rules

E/ΔE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

5 RESULTS AND DISCUSSION

The MATLAB/SIMULINK implementation of the suggested DSTATCOM model is controlled by the PI and FUZZY logic controllers with synchronous reference frame control method. An unbalanced non-linear load is used to test the model's accuracy. The suggested model is utilized for voltage control, power factor adjustment, and harmonic mitigation at the PCC. The analysis is done by comparison of the PI and FUZZY logic controller. The simulation time was observed between 0.2 and 0.3 seconds to obtain a clearer picture. The following cases are used to evaluate the effectiveness of DSTATCOM:

- Unbalanced nonlinear load without DSTATCOM
- PI-Controlled DSTATCOM
- Fuzzy-logic controlled DSTATCOM
- THD analysis

5.1 Unbalanced nonlinear load without DSTATCOM

The unbalanced nonlinear load introduces harmonics in the source current waveform (Bus-1) as shown in Figure 5(b). At the PCC, the voltage and current waveforms are distorted due to harmonics introduced by the unbalanced nonlinear load (bus-2) observed from figures 5(c) and (d). The load voltage and load current are observed in Figs. 5(e) and 5(f). Fig.5 (g). PCC current waveform of phase-A, unbalanced nonlinear load without DSTATCOM.

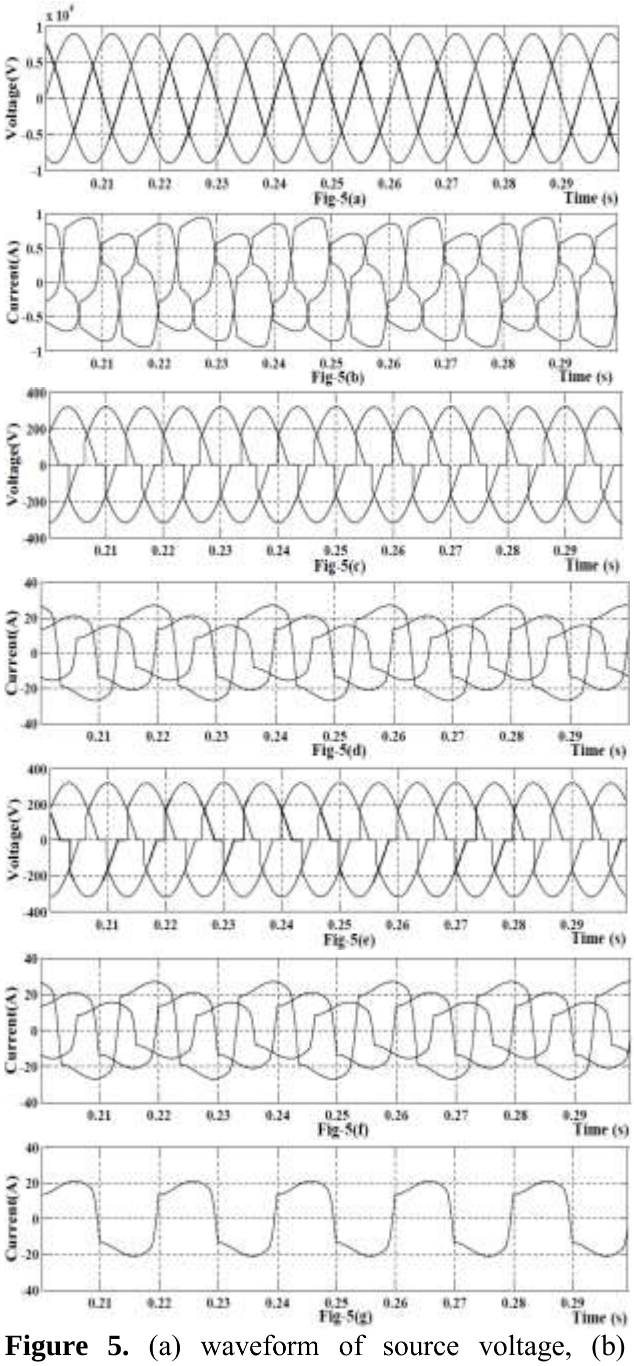
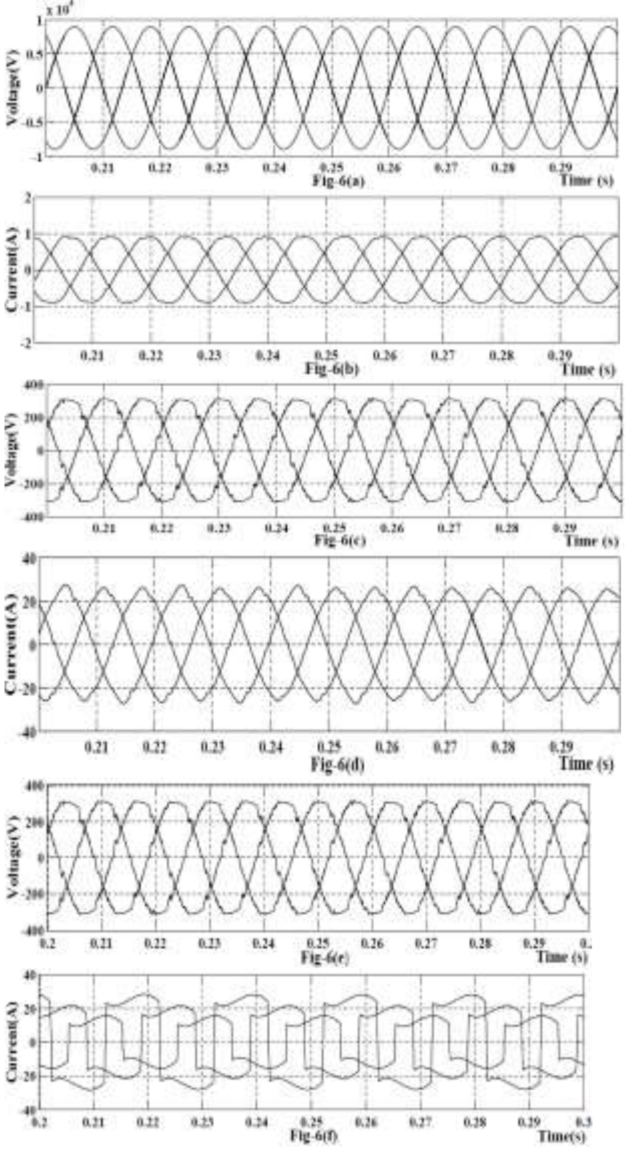


Figure 5. (a) waveform of source voltage, (b) waveform of the source current, (c) PCC (Bus-2) voltage waveform, (d) PCC (Bus-2) current waveform, (e) load voltage waveform, (f) waveform of the load current (g) per phase of the PCC current

waveform, unbalanced non-linear load without DSTATCOM.

5.2. DSTATCOM with PI Controller

When a DSTATCOM controlled by an SRF controlled algorithm is connected at the PCC, it supplies the reactive power expected to compensate for source current harmonics and voltage & current harmonics at the PCC. The DC-interface voltage is regulated by a PI controller. Figures 6(b) and 6(c) show the compensated source and PCC harmonic waveforms. The controlled and adjusted voltage at the PCC in Fig. 6(c). As can be seen in Fig.6 (e). The load voltage is also regulated. The waveform of the load current is shown in Fig. 6(f). Figure 6(g) depicts the DC link voltage wave form, Figure 6(h) shows the load current waveform represented per phase, and Figure 6(i) depicts the PCC current waveform (i). Fig.6 (J) shows a waveform of voltage and current



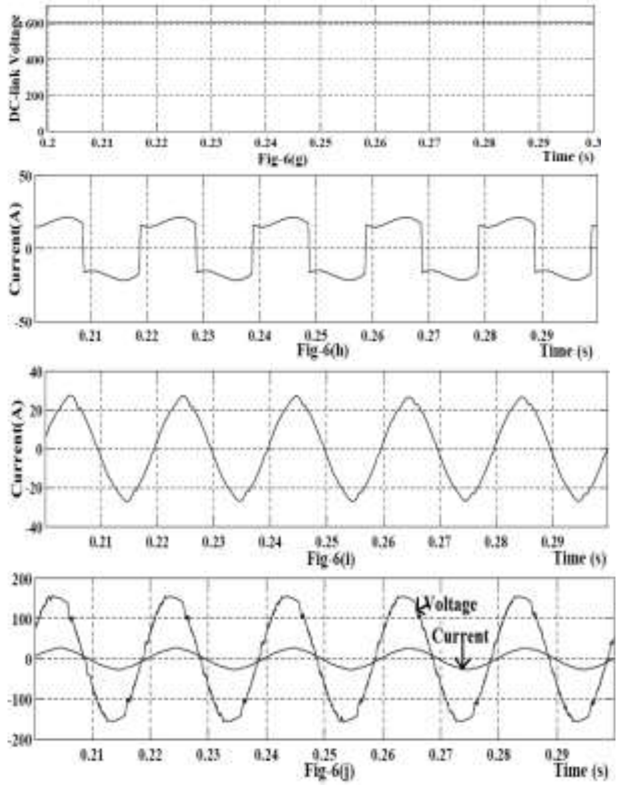
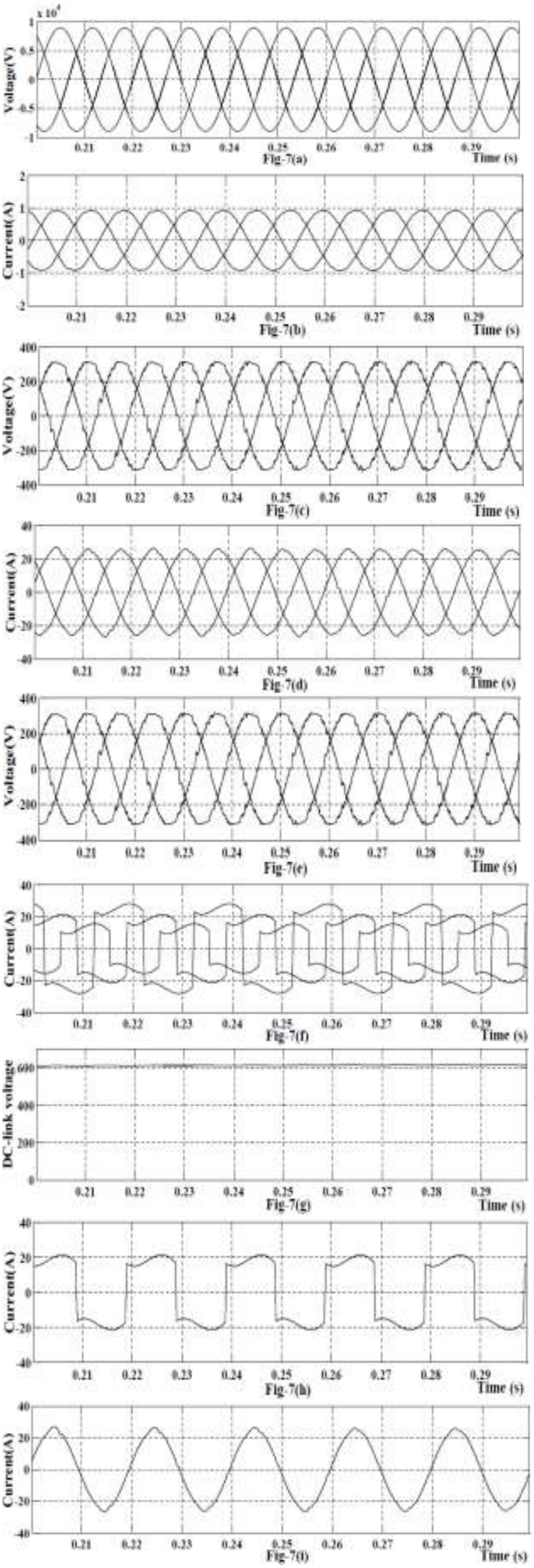


Figure.6. (a) voltage waveform at the source, (b) waveform of the source current, (c) compensation of voltage at the PCC (Bus-2), (d) current waveform at the PCC (Bus -2), (e) waveform of the load voltage, (f) waveform of load current, (g) DC bus voltage, (h). The load current waveform is shown individually phase A (i) displaying the waveform of the current at the PCC of phase-A, (j), the voltage and current waveforms at the PCC (BUS- 2), with PI controlled DSTATCOM.

5.3. DSTATCOM with Fuzzy logic controller

When the DSTATCOM operated by the SRF controlled is connected to the PCC, it compensate for voltage and current harmonics caused by the unbalanced non-linear load. The DC bus voltage is controlled by the fuzzy logic controller. Figure.7 shows the harmonic and reactive power compensation by DSTATCOM controlled by fuzzy logic. The fuzzy logic controller consequences provide better compensation as compared to the PI controller. The R-C filters are connected to the PCC. The rectified PCC and source current waveform are shown in Figs. 7(b) and 7(d) Figure (c). Shows the compensated PCC voltage waveform, Figure. 7(e). The voltage at the load is also compensated, figure.7 (f). Shows the load current waveform, Figure7(g) for the DC link voltage wave form, Figure 7(h) for the load currents per phase representation, and Figure 7(i) for the PCC current wave form . Figure 7(j): Voltage and current waveforms.



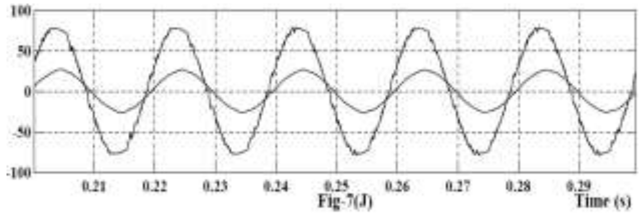


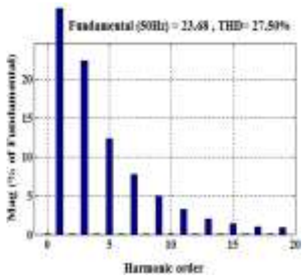
Figure.7 (a). Source voltage waveform, (b) source current waveform, and (c) voltage waveform at the PCC (Bus- 2), (d) current waveform at the PCC (Bus-2) (e) load voltage, and (f) the waveform of load current; (g) DC bus voltage, (h) The load current wave shape is shown individually for each phase, (i) displaying the wave shape of the current at the PCC on a phase-by-phase basis, (j) PCC (BUS-2) voltage and current waveform, DSTATCOM with fuzzy logic controller.

5.4. TOTAL HARMONIC DISTORTION ANALYSIS (THD)

At the source and PCC, we investigate how DSTATCOM affects the suggested system's overall harmonic distortion. This THD analysis of proposed system is done with PI and fuzzy logic controllers.

5.4.1. Unbalanced nonlinear load without DSTATCOM

Figure 8. Shows the overall harmonic distortion introduced into the system when a non-linear load is connected but without DSTATCOM. Harmonic distortion at the PCC Current is 27.50% and at the PCC voltage is 12.92% shown in figure 8(a) &8(b). Figure 8 (c), the harmonic distortion in the source current is 16.32%.



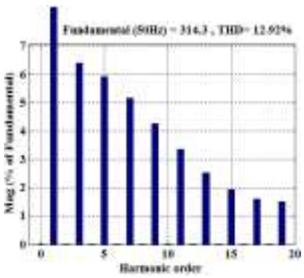


Figure.8(a). **Figure 8 (b).**

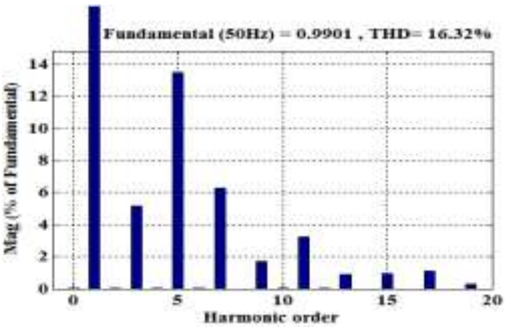
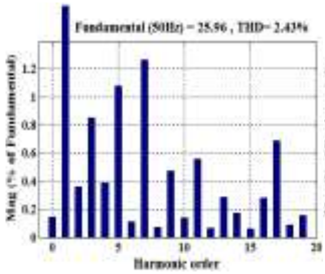


Figure. 8(c).

Figure. 8. (a) The current THD at PCC is, (b) THD (Voltage) at the point of Common Coupling (PCC), (c). THD of the source current waveform (BUS-1).

5.4.2. DSTATCOM with PI Controller

DSTATCOM, when connected into the suggested system, decreases the current and voltage harmonics at the PCC to 2.43 % and 3.49 %, respectively, shown in figure. 9 (a) &9 (b). As is the same as is noticeable in Figure 9 (c), the harmonic distortion of the source current has been decreased to 2.02%.



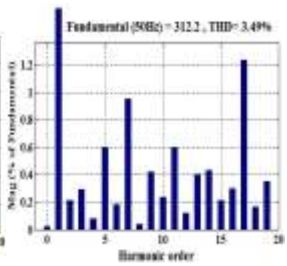


Figure.9 (a). **Figure 9.9 (b).**

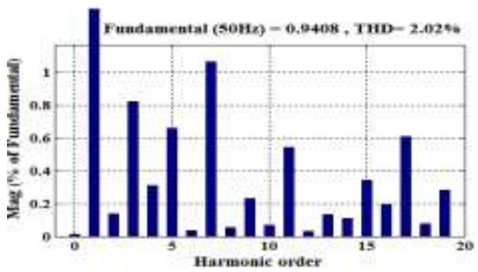
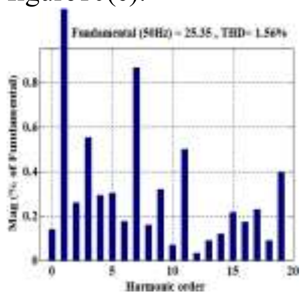


Figure.9(c).

Figure .9 (a). PCC current THD, (b) THD voltage at PCC, (c). THD of source current (BUS-1).

5.4.3. With a Fuzzy-Logic-Controlled DSTATCOM

DSTATCOM controlled by fuzzy logic with a lower current harmonic distortion at the PCC from 27.50 % to 1.56 %, and a lower voltage harmonic distortion at the PCC from 12.92 %, to 2.84 % as shown in figure 10 (a) &10(b). The figures clearly show that the amount of harmonic distortion in the source current also reduced to 1.55 %. It is shown in figure10(c).



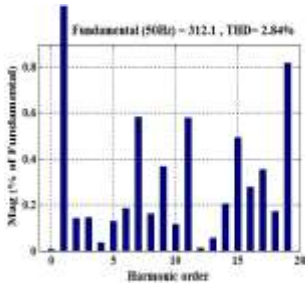


Figure.10(a). **Figure.10 (b).**

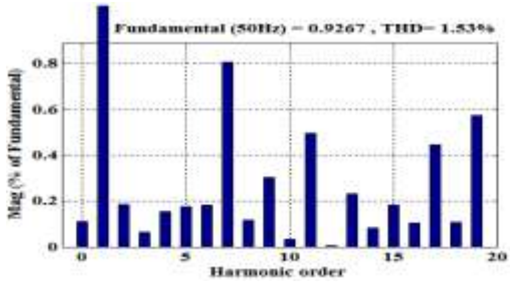


Figure.10(c).

Figure.10 (a) Current THD at PCC, (b) THD (Voltage) at the Point of Common Coupling (PCC), (c) THD at the source current (BUS-1)

The above total harmonic distortion research shows that the DSTATCOM fuzzy logic controller is more effective at reducing harmonic distortion than the PI controller DSTATCOM.

6 Conclusions

This research investigates the effectiveness of VSI-based DSTATCOM in balancing reactive power, lowering harmonics, and controlling voltage in a three-phase, three-wire, unbalanced non-linear load distribution system by utilizing the synchronous reference frame control technique. The proposed control method is easy to understand and effectively compensates for an unbalanced nonlinear load distribution system. The proposed system simulation results are analyzed and compared with the PI and Fuzzy logic controller. By combining their efforts, both processors are able to keep the dc bus voltage stable regardless of external disturbances. While both controllers are effective at compensating for unbalanced non-linear loads, the fuzzy logic controller provides better compensation in unbalanced non-linear load distribution system. MATLAB/SIMULINK is used to run the simulations and get the results. The results show that, compared to a PI-controlled DSTATCOM, one with fuzzy logic control offers a more dynamic reaction from the system, which in turn leads to improved transient behavior and power quality.

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