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Enhancement of power quality utilizing photovoltaic fed D-STATCOM based on zig-zag transformer and fuzzy controller

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Abstract. Distribution Static Synchronous Compensator (D-STATCOM) is a shunt compensator in the distribution systems that aims, as one of the most important tasks, to improve the imbalance and reduce and eliminate the nonlinear load harmonics. Distributed generation resources, such as photovoltaic (PV) array, can be used as the DC input of D-STATCOM. In this paper, PV array and DC/DC boost convertor are used to stabilize the DC link voltage of D-STATCOM. The main advantage of the proposed method is that it always provides continuous compensation. Another power quality issue is the neutral current in four-wire systems created due to the harmonics and system imbalance. Zig-zag transformer is one approach to compensating neutral current and providing isolation between the convertor and flow of the fundamental zero-sequence component which contains harmonic neutral current. Role and performance of the distribution shunt compensator in the improvement of power quality indices depends on the performance of its control system. In this paper, the control scheme of synchronous reference frame theory based on fuzzy controller is used for D-STATCOM based on PV and zig-zag transformer. The performance and behavior of the proposed system are examined using MATLAB/Simulink software and the results are presented.

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1. Introduction

Three-phase four-wire distribution systems most often encounter power quality problems due to nonlinear loads of the distribution system. Power quality problems include harmonic currents, high consumption of reactive power, load imbalance, additional neutral current, and so on. Generally, the neutral current in three-phase systems is caused by unbalanced phase current. In response to these problems, some methods for neutral current compensation were presented [1–3]. In four-wire systems, the application of neutral transformer provides zero-sequence current due to voltage and current imbalance and thus, reduces the current passing through neutral in three-phase four-wire systems [5,6]. Further, many solutions have been proposed to overcome other existing challenges and power quality problems in the power industry among which custom power devices including Dynamic Voltage Restorer (DVR) and Distribution Static Synchronous Compensator (D-STATCOM) play an effective role in power

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quality improvement in the distribution systems [7–11]. One of these devices is D-STATCOM that has been designed based on working principles of voltage source convertor or current source convertor. In addition, by injecting current into the system, it compensates harmonics due to the nonlinear loads, allows for the control of reactive power and improvement of load imbalance and power factor correction, and has such abilities as further compensation and very fast response time in comparison with the static Var compensator [12–17].

The D-STATCOM can compensate continuously active and reactive power and harmonic and its DC link should be supported by an energy storage source. In order to provide continuous compensation, it is necessary that the dc link voltage be made available by the energy storage source and remain constant within a certain range. DG sources like photovoltaic (PV) arrays can be used as DC link supply of power quality compensator due to their DC nature. PV array is used for driving the boost converter to step up the voltage and maintain the dc link voltage [17].

In addition to the energy storage issue, the role and performance of the distribution shunt compensator in improving the power quality indices depends on the performance of its control system [18,19]. In [19], various control techniques were employed to control D-STATCOM. Among different control techniques applied to the three-phase four-wire compensators, the synchronous reference frame theory technique is suitable for the control of D-STATCOM [19,20].

In [21], the improvement of power quality and load profile was discussed through a combination of parallel shunt filters and new energy sources as well as heuristic optimization techniques such as particle swarm algorithm and ant colony algorithm. The main drawback of using a metaheuristic algorithm to tune the gains of conventional controllers is that it requires basic data and complex calculations. The compensator implemented in [22] is suitable for three-phase three-wire systems and harmonic compensation and is not able to compensate for neutral current. Reddy et al. [23] investigated the four-leg VSI-based D-STATCOM for compensation of neutral, source current harmonic distortion and compensation of unbalance in current waveform. The studied control system was based on synchronous reference frame theory with the PI controller. Drawback of PI controller is its inability to react to sudden changes of error signal. In [24], controlling study of D-STATCOM based on PSO-PID algorithm was discussed. If PID controller was used instead of PI controller, the oscillations of the system transient response were attenuated, but using PID controller would slow down the system response [25]. In [26], a hybrid D-STATCOM with adaptive dc-link voltage control was proposed to compensate for unbalanced and nonlinear loads in distribution systems. Although this system is suitable for nonlinear and unbalanced loads, it does not have favorable performance due to its structural drawbacks such as not using a proper neutral compensator and energy storage in its structure. In particular, it does not work well in the presence of unbalanced heavy loads.

In order to enhance the performance of D-STATCOM and achieve the required DC link voltage, reduction of neutral current harmonics, reduction of harmonics due to the presence of nonlinear loads, and providing of continuous compensation, it is necessary to make changes in the structure of the power circuit and control circuit of this compensator. In this paper, to achieve these aims simultaneously, a hybrid design with a suitable structure and controller is proposed.

In this paper, the D-STATCOM combined with zig-zag transformer and renewable energy sources and fuzzy logic control scheme is employed to enhance the power quality of distribution systems. The D-STATCOM is employed to compensate for the harmonics caused by nonlinear load as well as unbalanced load current compensation. In the process of controlling this compensator, fuzzy controllers are used instead of PI controllers. The use of fuzzy controller in the proposed compensator leads to further reduction of the total harmonic distortion of the supply current compared to the use of conventional controller. The DC link in this compensator is powered by renewable energy sources such as PV arrays. Also, the zig-zag transformer has been used to reduce the neutral current of the three-phase four-wire distribution system, especially in the presence of unbalanced loads. In short, the use of the proposed scheme enhances the D-STATCOM performance and the compensation capability.

Therefore, the main contribution of this paper is to improve the performance and compensatory capability of D-STATCOM using the proposed hybrid scheme based on solar arrays and zig-zag transformers and employing the fuzzy controller in its control system. The proposed scheme ensures ideal power quality and highly effective compensation of harmonics and neutral currents in four-phase four-wire power distribution networks compared to schemes with the classic structures and based on conventional controllers.

The remainder of this paper is organized as follows: In Section 2, the general structure of D-STATCOM is expressed. In Section 3, compensation of the neutral current using zig-zag transformer is discussed. Then, the PV model and the DC-DC converter connected to it are presented in Section 4. In Section 5, the design of the hybrid scheme of the D-STATCOM, PV, and zig-zag transformer is presented. In Section 6, the proposed scheme control system is expressed. In Section 7, simulation parameters and software simulation results are presented. Finally, in Section 8, the conclusions of the discussions are presented.

2. D-STATCOM

D-STATCOM is one of the power quality improvement devices and the injection of current controls the reactive power of the bus and stabilizes the bus voltage in the common coupling point. Furthermore, fast response and lack of low-frequency harmonics for removing imbalance, compensation of reactive power and negative sequence component, regulation of the AC system voltage, and flicker reduction are the characteristics of the D-STATCOM. Also, this equipment can be used as an Active Power Filter (APF) to eliminate the harmonics.

Figure 1 shows the overall scheme of D-STATCOM [4].

A D-STATCOM generally includes following parts [4]: DC energy storage unit, capacitor, voltage or current inverter, passive low pass filter, parallel injection transformer, and control system.

Batteries, super capacitors, diode convertor with a shunt capacitor, flywheels, super conductor magnetic energy storage, etc. can be used in D-STATCOM as the DC energy storage source. In this case, it is possible to control active power and reactive power. Also, DC voltage source in D-STATCOM can be a capacitor whose voltage can be increased or decreased by controlling the convertor. In doing so, the energy stored in the capacitor is increased or decreased. However, in this case, there is only the possibility of injection or absorption of reactive power. There are various control systems for D-STATCOM and other power quality improvement devices whose common tasks are to detect the fault, calculate and determine the voltage and current required for compensation, and generate trigger pulses for the inverter.

3. Neutral compensation based on zig-zag transformer

The zig-zag transformer is used commonly to create neutral current and to convert a three-phase three-wire system into a three-phase four-wire system. Another application of a zig-zag transformer is to connect in shunt to the load in order to filter the zero-sequence components of the load currents.

Figure 2 shows the structure of the zig-zag transformer, and Figure 3 shows the connection of a zig-zag

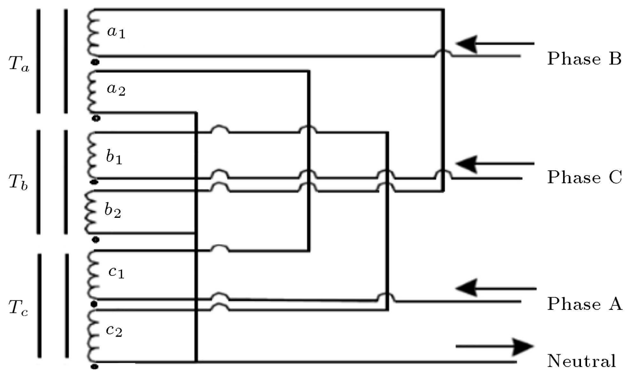


Figure 2. Zig-zag transformer for compensation of the neutral current [5,6].

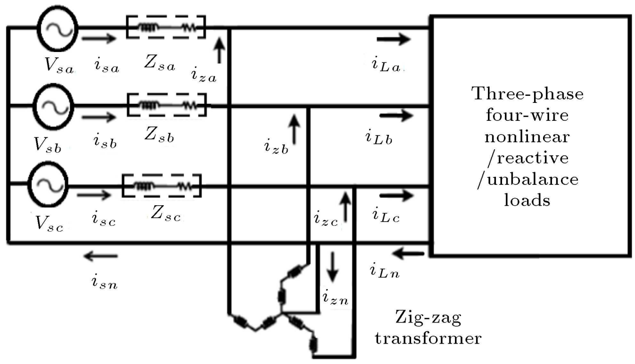


Figure 3. System configuration with a zig-zag transformer for compensation of the neutral current [5,6].

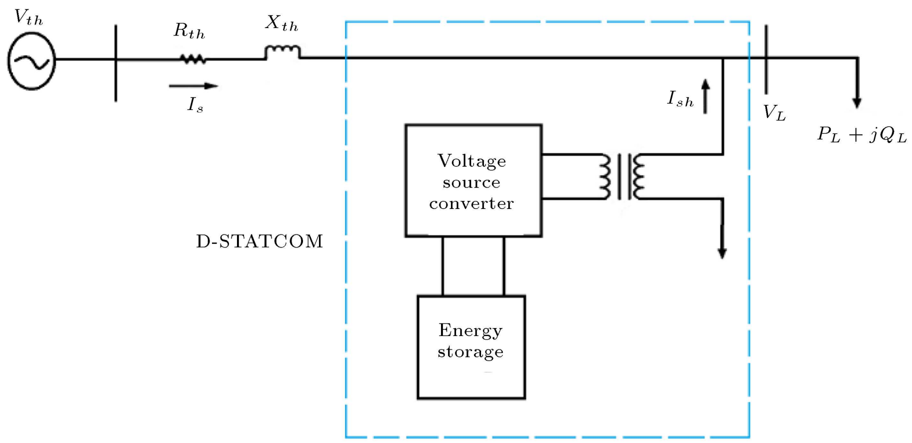


Figure 1. Circuit diagram of the D-STATCOM [4].

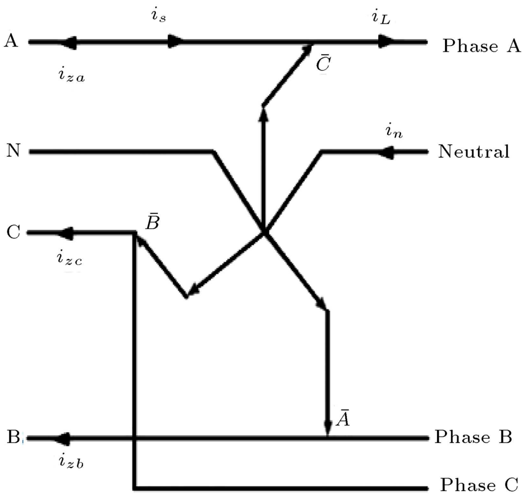


Figure 4. Diagram showing the flow of currents in zig-zag transformer for compensation of neutral current [6].

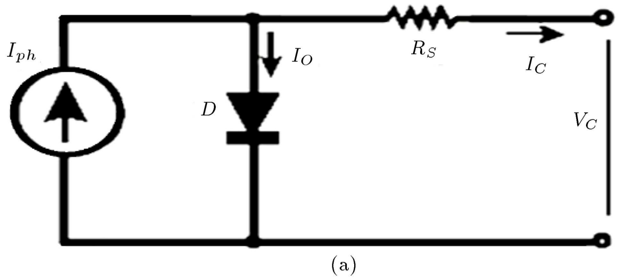
transformer in the system. A zig-zag transformer is a special connection of three single-phase transformer windings or three-phase transformer windings [5,6].

Figure 4 shows the phasor diagram of the zig-zag transformer. The currents flowing through the utility side of these three transformers are the same and equal. Thus, the zig-zag transformer can be regarded as open-circuit for the negative-sequence and positive-sequence currents. Therefore, the currents flowing through the zig-zag transformer only contain the components of the zero sequence [6].

Zig-zag transformer is a special connection of three-phase transformer windings or three single-phase transformer windings. Zig-zag transformer is commonly used to create neutral current and turn a three-phase three-wire system into a three-phase four-wire system. Use of an independent zig-zag transformer in a three-phase four-wire system has the advantage of reducing load imbalance and also neutral current on the source side. However, there is an inherent defect, that is, the performance of the system depends on the location of zig-zag transformer, which is close to the load. In addition, when the source voltage is distorted or unbalanced, reducing the neutral current by D-STATCOM on the side of the source affects the amplitude of the source current [6]. Instead of zig-zag transformer, a star-delta transformer can be used and both systems are the same in terms of performance [17]. Also, instead of zig-zag transformer, a T-connected transformer is used [27,28].

4. PV model

A PV cell is basically an optical diode whose p-n connection is exposed to light. PV arrays or panels are made by a combination of series/parallel PV solar cells [29,30]. PV cell is presented by a simplified



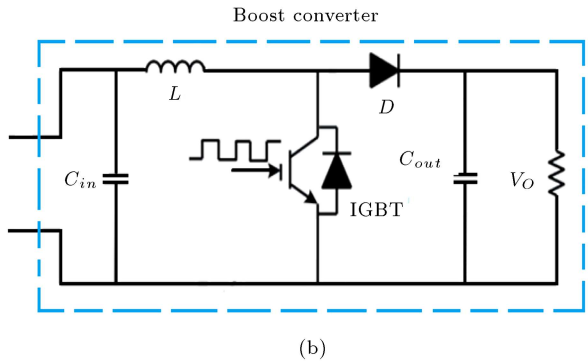


Figure 5. (a) Simplified equation circuit of the PV cell [30,31] and (b) block diagram of the DC-DC convertor connected to the PV array [33].

equation circuit as given in Figure 5(a) and expressed as Eq. (1) [30,31].

Output voltage of the PV cell is a function of photo current that is determined basically by the load current depending on the solar radiation area during the performance [30,31].

$$V_c = \frac{AKT_C}{q} \ln\left(\frac{I_{ph} + I_O - I_C}{I_O}\right) - R_S I_C, \quad (1)$$

where q is electron charge (1.602×10^{-19}c), K Boltzmann constant (1.38×10^{-23}J/°K), I_C output current of the cell in Amperes, I_{ph} photo current that is a function of radiation area and connection temperature, I_O reverse saturation current of diode, R_S series resistance of the cell, T_C reference working temperature of the cell, and V_c output voltage of the cell in volts.

K and T_C must have the same temperature unit: Kelvin or Celsius. The curve fitting factor A is used to adjust the current-voltage characteristics of the cell obtained from Eq. (1) to the actual characteristics obtained by the experiment and test.

Eq. (1) gives the voltage of a single solar cell and then, this value is multiplied by the number of cells connected in series to calculate the total voltage of the array. Since the array current is the sum of the currents flowing from the cells into the parallel branches, the cell current I_C is obtained by dividing the array current into the number of cells connected in parallel before being used in the equation.

Given that the intended voltage for the DC link in the D-STATCOM must be a specified and constant value, in the case of using PV array to supply the DC link, it is necessary to use a DC-DC boost convertor to increase the DC output voltage of PV.

DC-DC convertor used in the PV output is a boost convertor that is designed to increase the generated power of the PV and send it to the capacitor of DC link [32,33]. The block diagram of this converter is shown in Figure 5(b) [33].

The convertor includes inductors, diodes, and capacitors. The capacitor C_{PV} serves to limit the output voltage of PV and, also, to filter high-frequency ripples of the solar cell in the output. Continuous output voltage of the convertor can be obtained by connecting a large capacitor between the cathode and the ground so that as the capacitance increases, the output voltage raises. The convertor output voltage comprises a reference value and the error signal is applied to a PI controller. Output signal of the controller acts as the input for PWM switching to set the duty cycle. Output voltage of the convertor must be greater than the source voltage, and the voltage across the capacitor of DC link increases by changing duty cycle D. When $D = 0$, the output voltage equals the source voltage. Recently, reactive power resources of solar plants include static synchronous compensators that are static reactive power compensation devices and PV inverters can also perform dynamic reactive power compensation.

To extract maximum power from the PV array, the maximum power tracker can be used as presented in [33–35] for the PV system. This paper does not focus on this issue.

When weather is cloudy or at night time, the power of PV array is not available; thus, a battery bank is also used. In addition to battery, in order to support the DC-link, another power source like wind turbines can be paralleled with the PV array and battery [36]. This plan is not presented in this paper.

5. Combination of D-STATCOM, PV array, and zig-zag transformer

The proposed compensator is a combination of three-phase Voltage Source Converter (VSC) and a zig-zag transformer as a D-STATCOM, a PV array, and a boost convertor. This compensator allows the neutral current compensation with load voltage regulation, harmonic currents elimination, reactive power compensation, and load balancing. The scheme of the proposed system is shown in Figure 6. Zig-zag transformer connected to the load terminal provides a circulating path for the fundamental component and zero-sequence component current.

Compensation of the neutral current along with

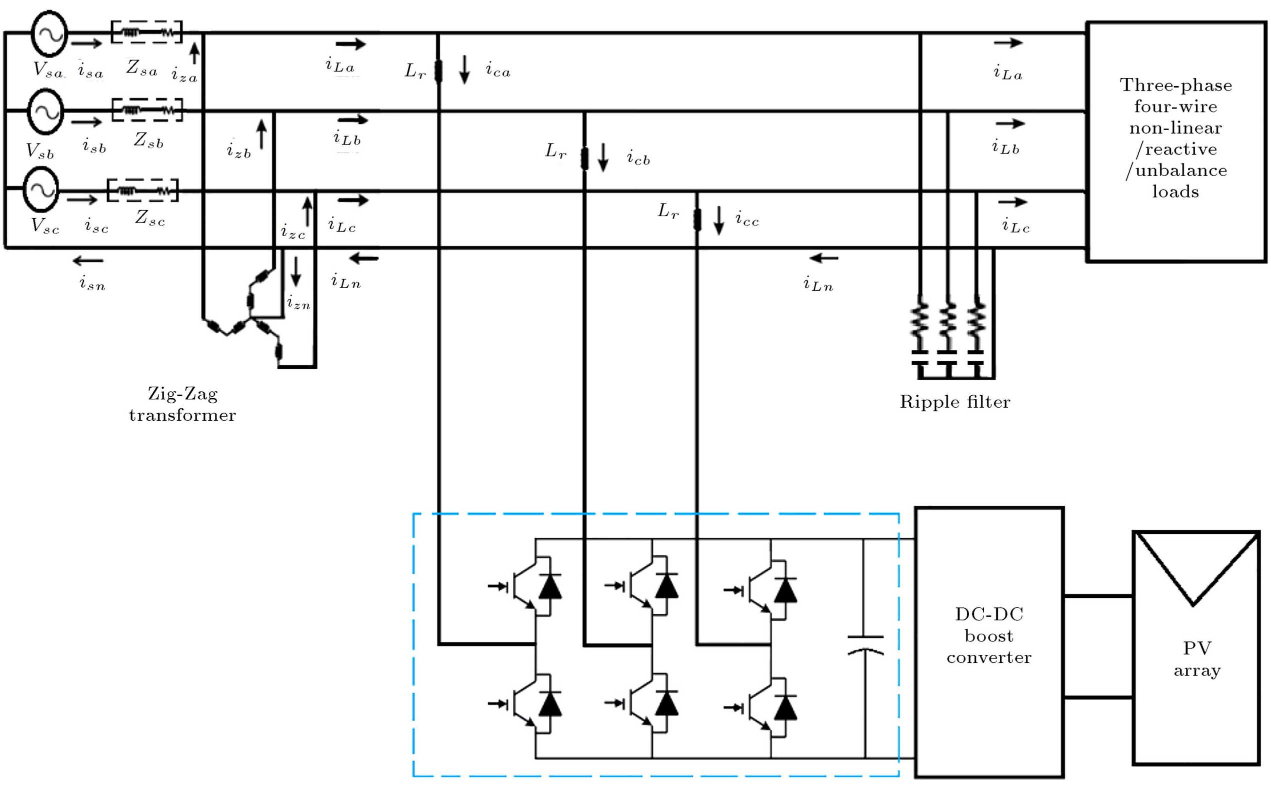


Figure 6. Scheme of D-STATCOM based on photovoltaic and zig-zag transformer.

harmonics, reactive power compensation, and load balancing are achieved using the proposed scheme for the three-phase four-wire systems.

6. Scheme of fuzzy control system

Various techniques including instantaneous reactive power theory, synchronous reference frame theory, unit power factor, instantaneous symmetrical components, and so on are used to generate reference voltage for controlling the inverter in D-STATCOM.

Here, the method of synchronous reference frame theory based on fuzzy controller is used for harmonic compensation and its scheme is shown in Figure 7.

In the simulated control scheme, load current and voltage of common coupling point (V_{PCC}) of the D-STATCOM and bus voltage are sampled as feedback signals. Load currents are transformed from abc to d-q-0. DC values are extracted by passing the current through a low-pass filter and similarly, non-DC values are separated from the reference signal. Fuzzy logic controller regulates the DC bus voltage and the line voltage. Fuzzy logic is based on the rules that are obtained by the empirical knowledge gained from the system behavior and does not follow any mathematical model or computational systems [37]. First, the capacitor voltage is sampled and is comprised of the reference value.

Two inputs of the fuzzy logic controller are error or (e) and change in error or de/dt (Δe), as shown in Figure 8(a) [38].

Input variables of the fuzzy controller, difference or error of the capacitor voltage (e), and its variations (Δe) in the stage k are as follows [39]:

$$e(k) = \alpha(Vdc(k) - Vdcref), \tag{2}$$

$$\Delta e(k) = \beta\left(e(k) - e(k-1)\right), \tag{3}$$

where α and β are the input scaling coefficients.

Fuzzy controller output, variations of the adjustment current (ΔI_{ad}), and actual value of the adjustment current are given below [39]:

$$I_{ad}(k) = i_{ad}(k-1) + \gamma.\Delta I_{ad}(k), \tag{4}$$

where γ is the output scaling coefficient. This

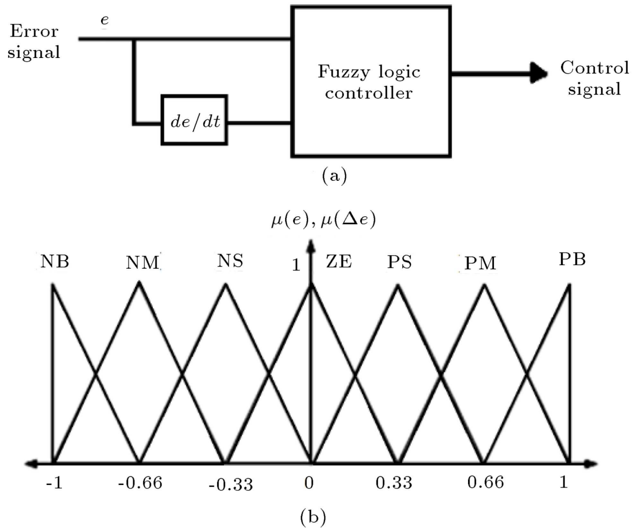


Figure 8. (a) Fuzzy logic controller and (b) membership functions for the inputs e and Δe.

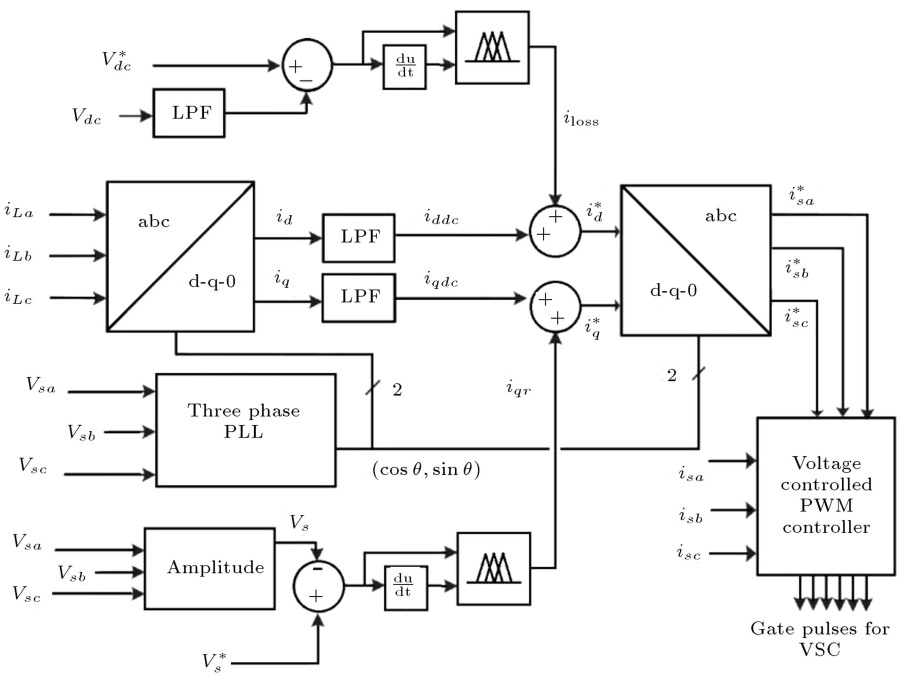


Figure 7. D-STATCOM control system.

Table 1. Fuzzy rules used in the fuzzy blocks of the control system.

$e/\Delta e$	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	ZE
NM	PB	PM	PM	PS	PS	ZE	NS
NS	PM	PM	PS	PS	ZE	NS	NS
ZE	PM	PS	PS	ZE	NS	NS	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NS	NS	NM	NM	NB
PB	ZE	NS	NS	NM	NM	NB	NB

adjustment current is considered as i_{loss} and it finally affects the output reference current. The rules of the fuzzy controller are shown in Table 1 and triangular membership functions used for the inputs and outputs are shown in Figure 8(b) [39].

The disadvantage of PI controller is its inability to respond to sudden changes in the error signal (e), because it can only detect instantaneous value of the error signal and is not able to consider rising or falling edge of the error signal that equals the error signal derivative (Δe). A fuzzy controller has been presented to solve this problem. All fuzzy subsets of the variables for the inputs e and Δe are defined by (NB, NM, NS, Z, PS, PM, PB).

Fuzzy logic controller has a number of linguistic variables of the inputs namely Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

In the decision-making process of a system, there are rules that communicate between input (error signal) and output signals. In the simulated control scheme, load current and voltage of common coupling point (V_{PCC}) of D-STATCOM and bus voltage are sampled as the feedback signals. Using Park transformation, the load currents are transformed from abc to d-q-0 which is a DC quantity. Net DC quantities are extracted by passing through a low-pass filter and similarly, non-DC quantities are separated from the reference signal. The value of fuzzy controller output current (i_{loss}) is considered as deviation of the DC bus voltage from its reference value aimed at fixing the DC bus voltage in the case of small changes in the active power of the AC system, thereby maintaining the power factor in the unit and reducing the harmonics. Like the previous fuzzy controller, in order to control the reactive power and fix the voltage, there is also a fuzzy controller whose output is combined with i_{qr} and the reference current is obtained. In other words, amplitude deviation of the voltage V_{PCC} is another input of the controller. i_{qr} is the output of this controller if the power factor is equal to zero. After the combination of currents i_{loss} and i_{qr} with the currents d-q, i_d and i_q are achieved as the reference currents. Eventually, by transforming them into the abc, final reference currents are obtained and applied to the pulse generator of PWM to generate switching signals for the switches of D-STATCOM. The overall block diagram of the proposed model is shown in Figure 9.

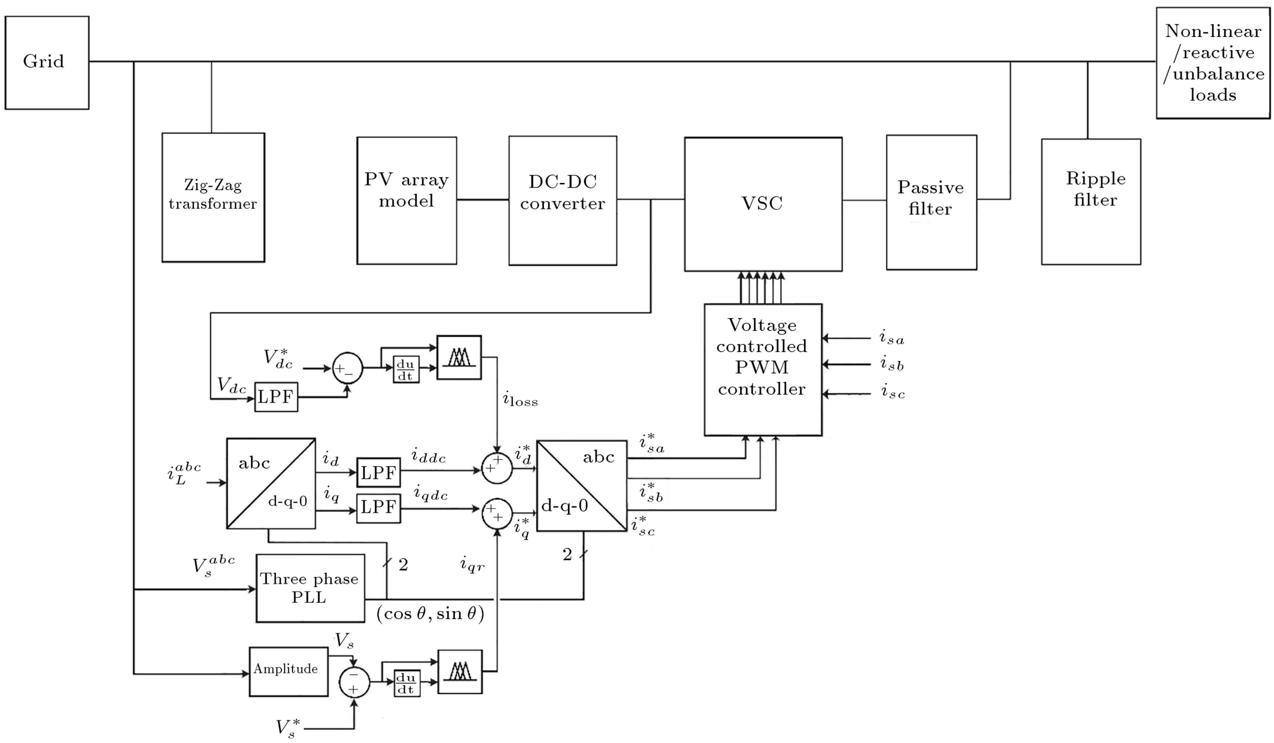


Figure 9. Overall block diagram of the proposed model.

Table 2. Parameters of the compensator system.

Parameters	Values
Type of switches	IGBT
Switching frequency	10 kHz
Type of D-STATCOM inverter	Three-phase two-level six-switch
Ripple filter resistance	5 Ω
Ripple filter capacitance	5 μF
Passive filter resistance	0.05 Ω
Passive filter inductance	1e-6 H
DC bus voltage	680 V
Zig-zag transformer voltage	150/150V
Zig-zag transformer power	5 kVA

Table 3. Parameters of the system and nonlinear load.

Parameters	Values
Nominal voltage	415 V
System frequency	50 Hz
X/R ratio of the system	5
Line resistance	0.01 Ω
Load power factor	0.8
Load active power	20 kW

7. Simulation results

7.1. Parameters of simulation

The case study system shown in Figure 6 is simulated in MATLAB/Simulink using fuzzy controller scheme and the following parameters (Tables 2 to 4), and related results are presented.

7.2. Compensation of linear load current imbalance and neutral current

In the system presented in Figure 6, at interval times 0.2 sec to 0.45 sec, one phase of the three-phase balanced linear load is disconnected while another phase is disconnected at 0.3 sec to 0.4 sec. Simulation results are shown in Figures 10 to 14.

The current drawn by unbalanced load is shown in Figure 10(a). According to the simulation results of the unbalanced load, with the setup of the proposed D-STATCOM, in the presence of unbalanced load, the source current is sinusoidal and balanced. Installing the proposed D-STATCOM in parallel with the system allows compensating for the reactive power and the imbalance of three-phase power line currents. Moreover, through zig-zag transformer, the neutral current caused by imbalance of currents reduces to a very small amount. Zig-zag transformer provides a low impedance path for zero-sequence currents. Hence, when connected in parallel, a path is created for neutral current and it, therefore, weakens the neutral current on the side of source.

Total Harmonic Distortion of the current (THD_I) is obtained as follows:

Table 4. Parameters and characteristics of the photovoltaic.

Parameters	Abbreviations	Values
Charge of electron	q	1.602×10^{-19}c
Boltzmann constant	K	1.38×10^{-23} J/°K
Photo current	I_{ph}	5 A
Reverse saturation current of diode	I_O	2e-4 A
Series resistance of the cell	R_S	0.001 Ω
Reference working temperature of the cell	T_C	20 C
Output voltage of the cell	V	160 V
Capacitor of the boost convertor	C	2 mF
Inductance of the boost convertor	L	1 mH

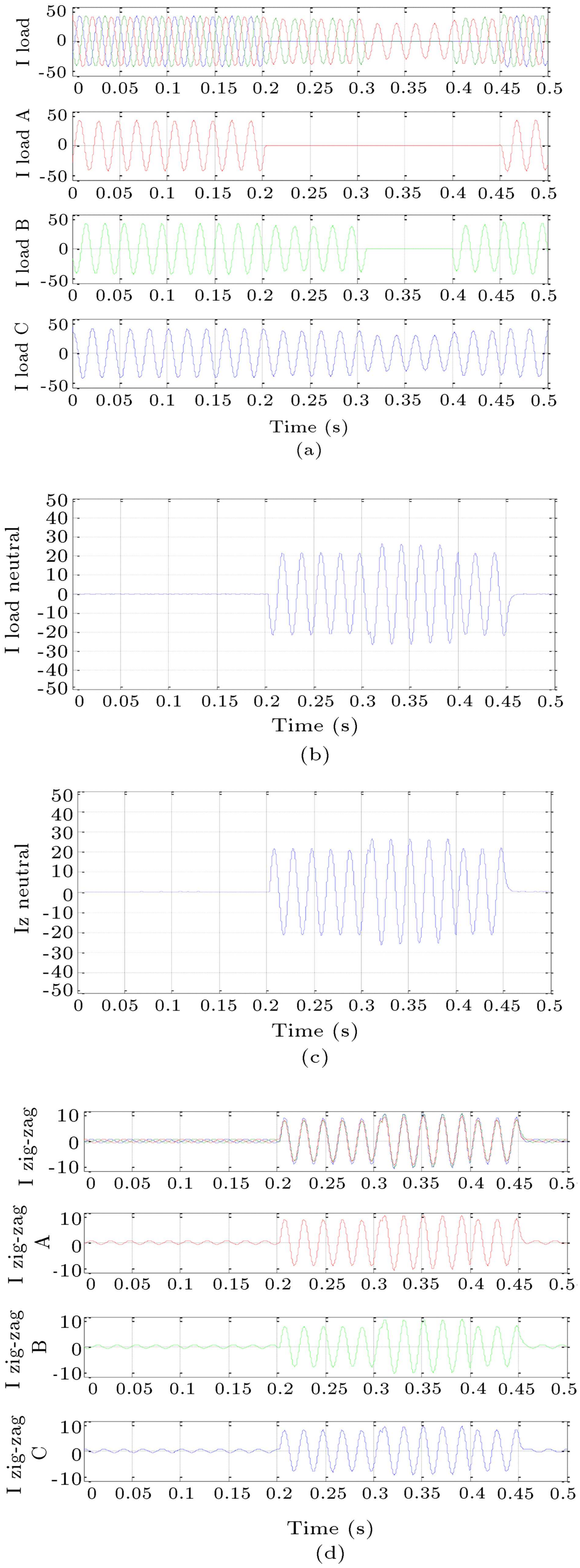


Figure 10. (a) Unbalanced load current, (b) neutral current of the load, (c) neutral current of the zig-zag Transformer, and (d) phase currents of the zig-zag transformer.

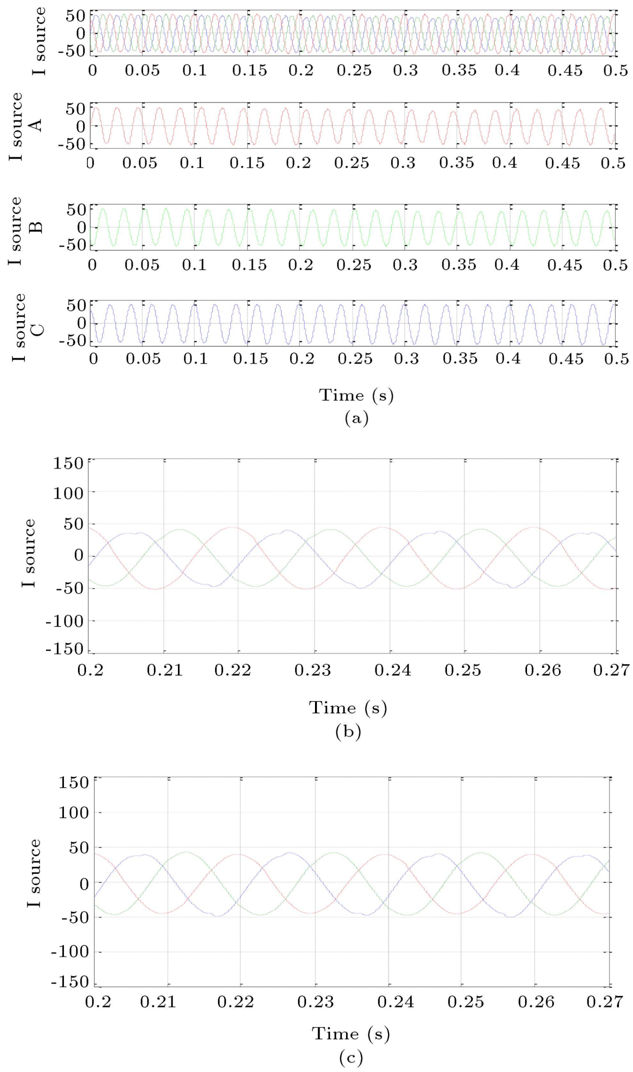


Figure 11. (a) Source current, (b) magnification of source current by applying conventional PI controller, and (c) magnification of source current by applying proposed controller.

$$THD_i = \frac{\sqrt{\sum_{h=2}^{n} I_{Gh^2}}}{I_{G1}} \times 100\%, \tag{5}$$

where I_{G1} is the fundamental component of the system current and I_{Gh} is the harmonic components of the current.

Harmonic spectrum and THD of the source current are presented in Figure 12(a) and (b), respectively.

Since the current generated by the compensator is based on pulse width modulation and high frequency switching, the current injected by the compensator is not purely sinusoidal. This problem leads to the appearance of various orders of harmonic components in the source current waveform and consequently, as the current is compensated, the THD of the source current increases.

Therefore, it is necessary to use a suitable controller in the hybrid compensator control system to

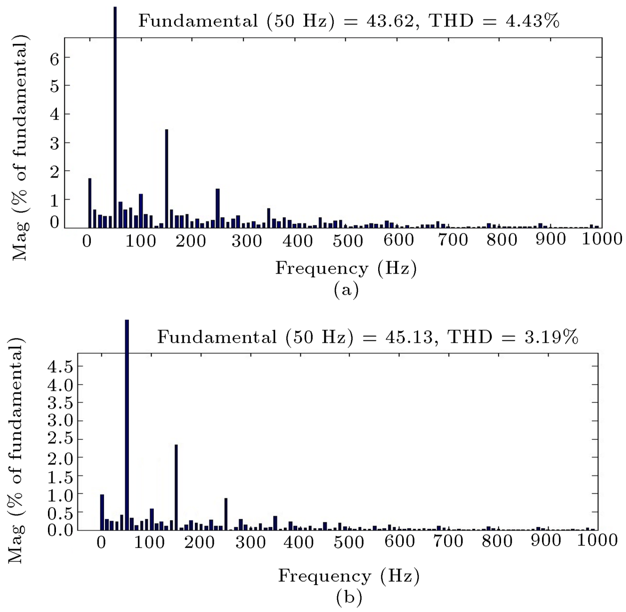


Figure 12. Harmonic spectrum of the source current and percentage of THD: In the presence of compensator based on (a) PI controller and (b) fuzzy controller.

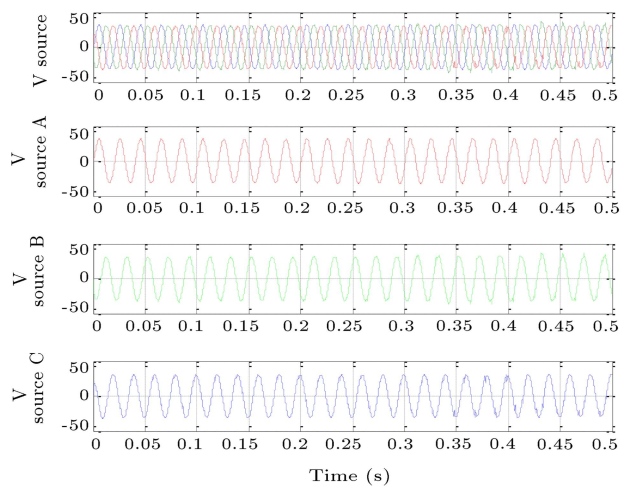


Figure 13. Instantaneous voltage of three phases of the source and instantaneous voltage of each phase.

improve its performance. In this paper, fuzzy control is used instead of conventional controllers and the simulation results are presented.

As can be seen from the results, the proposed scheme not only compensates source current more completely, but also reduces harmonic contents and THD. In this scenario, with the presence of the compensator based on the fuzzy controller, the THD value of the source current is 3.19% and with the presence of the compensator based on a conventional PI controller, the THD value of the source current is 4.43%. Therefore, the use of the proposed controller in the compensator control system is superior to the conventional PI controller, and the proposed controller-based compensator

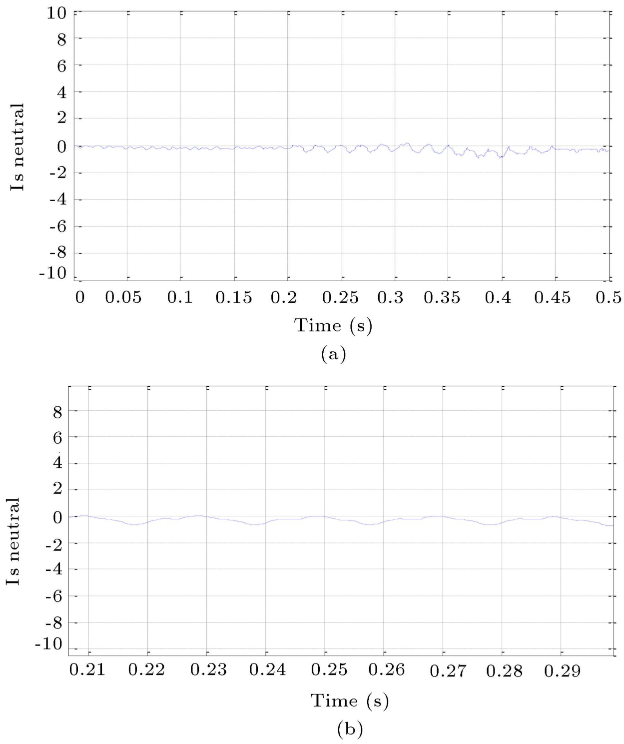


Figure 14. (a) Source neutral current and (b) magnification of source neutral current.

performs better than the conventional PI controller-based compensator.

7.3. Compensation of current harmonics and neutral current

In the system shown in Figure 6, three single-phase nonlinear loads of diode rectifier are placed in the circuit from the beginning of the simulation and simultaneously, two phases out of three-phase balanced linear load are also disconnected. The results obtained from this case are shown in Figures 15 to 20.

The current drawn by unbalanced-nonlinear load is shown in Figure 15(a)–(c) and its harmonic spectrum and THD of the current are presented in Figure 15(d).

Based on the simulation results, the current is completely harmonic. In the absence of the proposed D-STATCOM, the current waveforms are impure and non-sinusoidal on both sides of the system (on the side of the load and source). While using the proposed D-STATCOM, the harmonics of the load side are not transferred to the source side and the source current is nearly sinusoidal.

The percentage of total harmonic distortion of the nonlinear load is 31.28% which indicates harmonic load, but this value is reduced to 5.38% and 3.59% in the presence of D-STATCOM based on PI controller and fuzzy logic controller, respectively. From the simulation results of the unbalanced load, it is determined that by using the proposed D-STATCOM, the source current is balanced and sinusoidal in the presence of

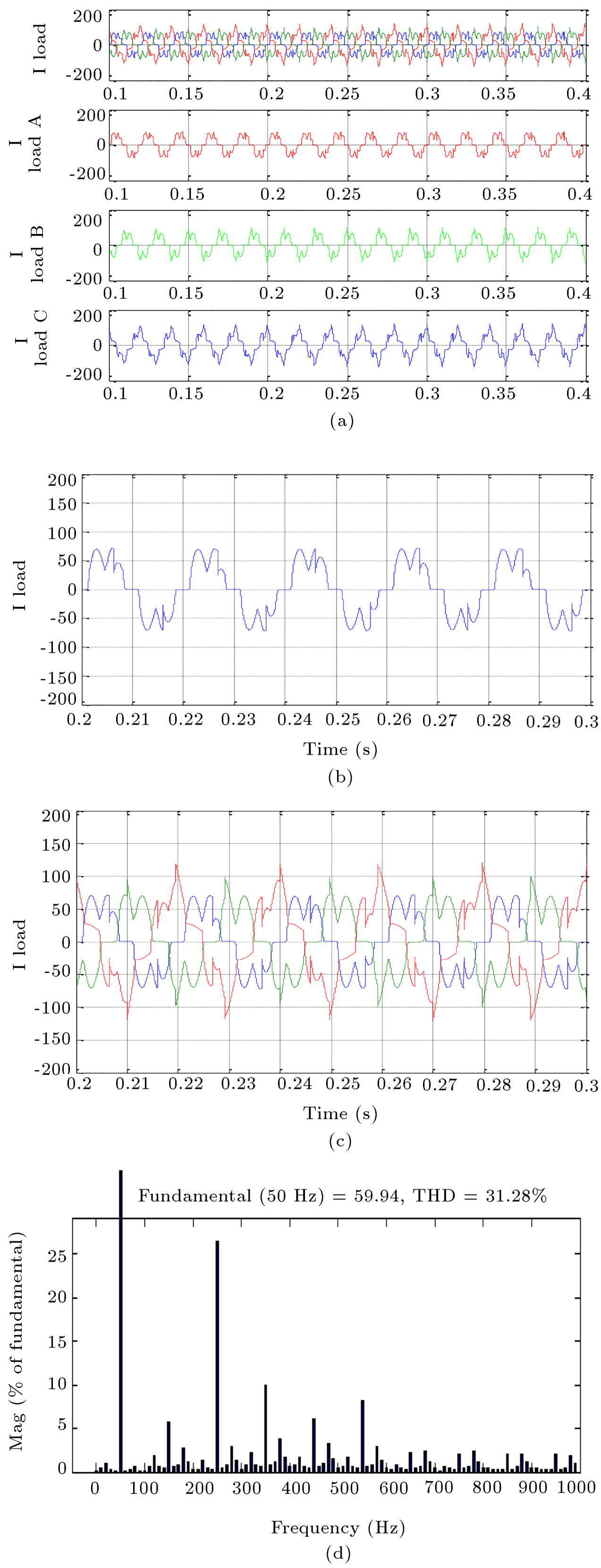


Figure 15. (a) Unbalanced and nonlinear load current. (b) Magnification of load current- phase A. (c) Magnification of load 3-phase current. (d) Harmonic spectrum of the load current and percentage of THD.

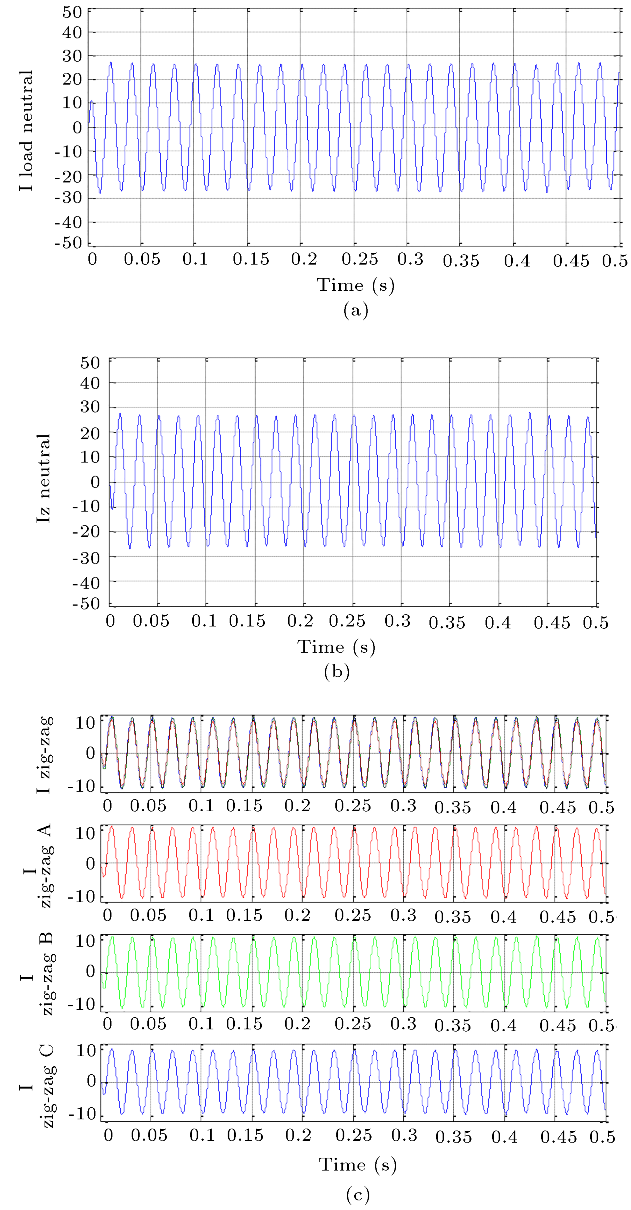


Figure 16. (a) Neutral current of the load. (b) Neutral current of the zig-zag transformer. (c) 3-phase currents of the zig-zag transformer.

unbalanced load. In the simulations performed on the four-wire system, although the D-STATCOM based on the PV is able to compensate the source current, it cannot compensate the neutral current of the source alone. For this reason, a zig-zag transformer was used to compensate for the neutral current. Based on the results, with the use of the zig-zag transformer, the neutral current of the source is compensated and it reaches a negligible value. In the absence of zig-zag transformer, the neutral current of the source equals the neutral current of the load, but the zig-zag transformer connected to the load terminal provides a circulating current for the fundamental component and zero-sequence harmonic component; hence, it is

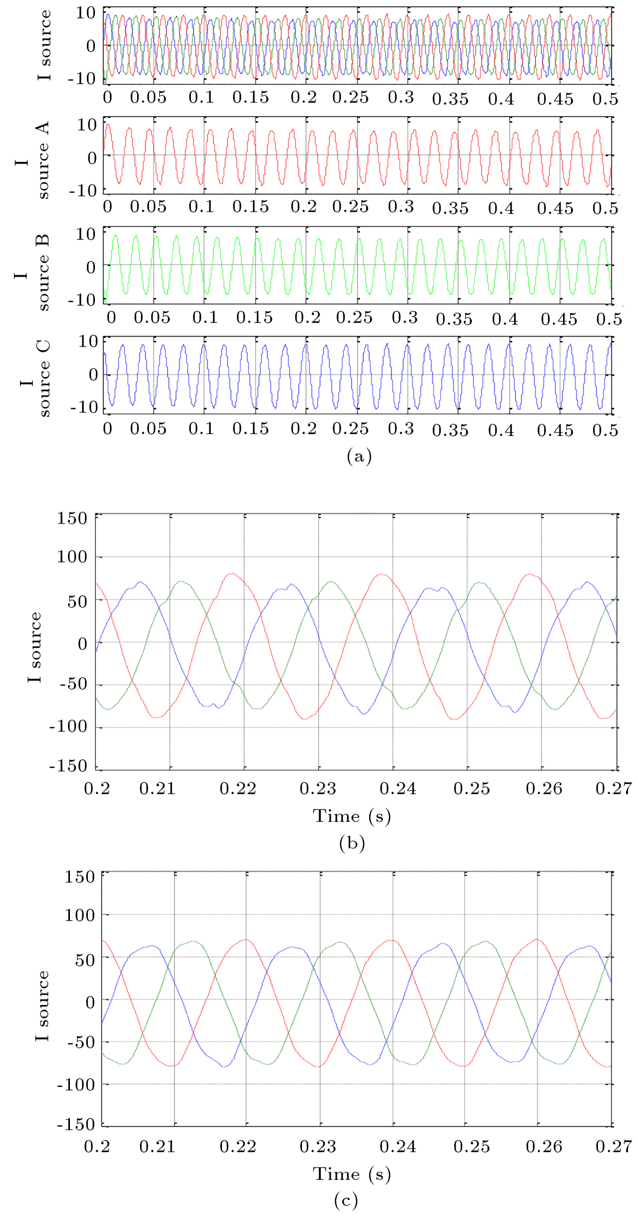


Figure 17. (a) Source 3-phase current. (b) Magnification of source current by applying conventional PI controller. (c) Magnification of source current by applying proposed controller.

the reason why the current does not pass through the source neutral or the current passing through the neutral is negligible.

Tables 5 and 6 present the results of the two scenarios discussed (for source current) by applying two different control techniques, respectively.

It should be noted that due to the symmetry of the obtained waveforms, the content of even harmonics in the harmonic spectrum is minor and is, therefore, not presented in the tables.

In Tables 5 and 6, the value of the unbalanced percentage is calculated based on the proposed formula of the IEEE standard. This value is calculated as the

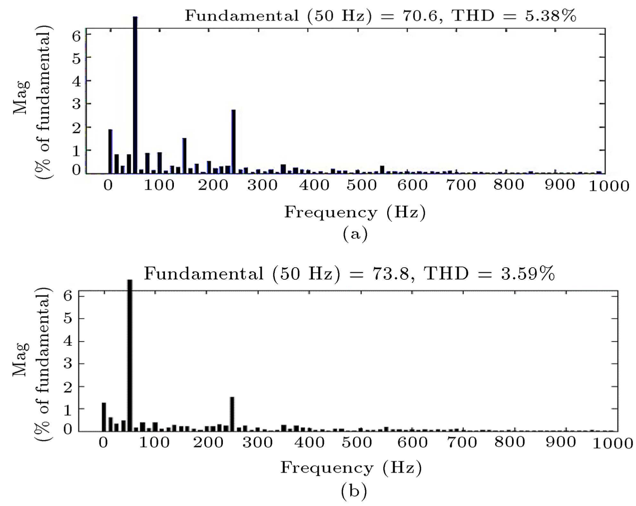


Figure 18. Harmonic spectrum of the source current and percentage of THD in the presence of compensator based on (a) PI controller and (b) fuzzy controller.

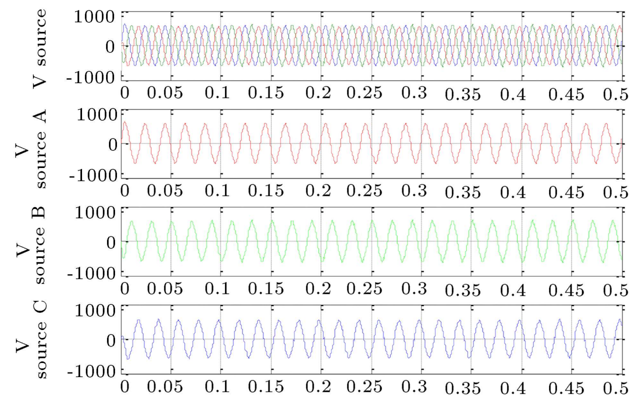


Figure 19. Instantaneous voltage of three phases of the source and instantaneous voltage of each phase.

maximum difference between the effective value and mean value of the currents divided by the mean value of the currents.

According to the results, it can be mentioned that the use of the proposed hybrid compensator reduces the unbalanced percentage of waveforms, harmonic content, and the THD% value of current and voltage.

Table 5. Comparison of results obtained from Scenario 1 (for source current) by applying two different control techniques.

Index	With classic PI controller	With fuzzy controller
Imbalance (%)	4.25	2.37
DC harmonic (%)	1.8	1
h3 (%)	3.5	2.4
h5 (%)	1.3	0.9
h7 (%)	0.5	0.3
THD (%)	4.43	3.19

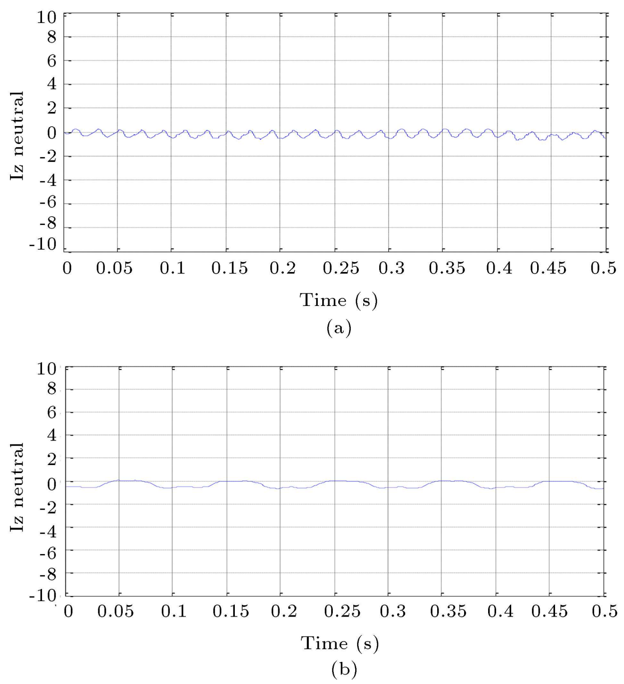


Figure 20. (a) Source neutral current. (b) Magnification of source neutral current.

Table 6. Comparison of results obtained from Scenario 2 (for source current) by applying two different control techniques.

Index	With classic PI controller	With fuzzy controller
Imbalance (%)	6.35	3.39
DC harmonic (%)	1.9	1.3
h3 (%)	1.6	0.3
h5 (%)	2.8	1.7
h7 (%)	0.4	0.3
THD (%)	5.38	3.59

Therefore, the purity of the waveform is higher than other conventional schemes and is closer to ideal.

8. Conclusions

Distribution Static Synchronous Compensator (D-STATCOM) is a shunt compensator in the distribution systems that aims, as one of the most important tasks, to reduce and eliminate the harmonics of the nonlinear loads and to prevent them from penetrating the system. This equipment is necessary for eliminating the harmonics in the distribution systems. In this paper, the fuzzy logic controller was used in the control system of D-STATCOM. The fuzzy logic controller does not require a mathematical model of the system and this is an important advantage for applying the controller. In addition, the Photovoltaic (PV) array was applied to support the DC link and a zig-zag transformer was used to reduce the neutral current. The proposed combined D-STATCOM based on fuzzy controller represents a better option for solving the power quality problem in the distribution systems with unbalanced, nonlinear, and harmonic loads, has a better performance in the transient conditions, and yields good results. Implementation and simulation of the system in the presence of D-STATCOM based on PV array and zig-zag transformer were performed using MATLAB/Simulink software.

Nomenclature

q	Charge of electron
K	Boltzmann constant
I_{ph}	Photo current
I_O	Reverse saturation current of diode
R_S	Series resistance of the cell
T_C	Reference working temperature of the cell
V	Output voltage of the cell
C	Capacitor of the boost convertor
L	Inductance of the boost convertor
α, β	Input scaling coefficients
γ	Output scaling coefficient
e	Error
$de/dt(\Delta e)$	Change in error
V_{PCC}	Voltage of common coupling point
I_{ad}	Adjustment current
ΔI_{ad}	Variations of the adjustment current
NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big
Vdc	Voltage of DC bus
$Vdcref$	Reference voltage of DC bus
THD_I	Total Harmonic Distortion of the current
I_{G1}	Fundamental component of the system current
I_{Gh}	Harmonic components of the current

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