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Design and Implementation of Solar PV for Power Quality Enhancement in Three-Phase Four-Wire Distribution System

Guna Sekar, T† and Anita, R*

Abstract – This paper presents a new technique for enhancing power quality by reducing harmonics in the neutral conductor. Three-Phase Four-Wire (3P4W) system is commonly used where single and three phase loads are connected to Point of Common Coupling (PCC). Due to unbalance loads, the 3P4W distribution system becomes unbalance and current flows in the neutral conductor. If loads are non-linear, then the harmonic content of current will flow in neutral conductor. The neutral current that may flow towards transformer neutral point is compensated by using a series active filter. In order to reduce the harmonic content, the series active filter is connected in series with the neutral conductor by which neutral and phase current harmonics are reduced significantly. In this paper, solar PV based inverter circuit is proposed for compensating neutral current harmonics. The simulation is carried out in MATLAB/SIMULINK and also an experimental setup is developed to verify the effectiveness of the proposed method.

Keywords: Neutral current, Total harmonic distortion, Fuzzy logic, Voltage source inverter, Power quality, Photo voltaic

1. Introduction

Electricity becomes one of the most basic needs in today's world. Many social and economical activities depend on electrical energy quality and efficiency. Due to advancement of information technologies, a large number of computer products and power electronic converters have been connected to power distribution systems. Electric power is distributed through 3P4W system in many industrial and commercial sectors. The 3P4W distribution system can be realized by providing the neutral conductor along with three power lines from the generating station or by utilizing a delta-star transformer at distribution system. Most of loads in the distribution system are connected to one of the phase of three-phase four-wire distribution system, which leads to the unbalanced loading conditions

In U.S, the survey results show that 22.6% of sites in the commercial building have neutral current exceeding phase currents [1]. Due to the presence of non-linear loads, harmonics are injected into the phase and neutral conductor. These harmonic current affects the other linear loads which are connected to the PCC. The power supplies which consist of rectifier with DC smoothening capacitors may generate excessive current harmonics in the neutral [2].

Almost 95% of the harmonic current in the neutral conductor are zero sequence component (3^{rd} order harmonics). In order to reduce neutral current harmonics, various research works on passive, active filters and zigzag transformer have been published [3]. To attenuate these harmonic current in the distribution system, traditionally a passive filters were designed [4, 5] which connected across the non-linear load. But this compensation leads to some of the drawbacks like occurrence of series and parallel resonance which causes an incomplete potential.

To eliminate zero sequence components (third-order harmonics), zigzag transformer based harmonic reduction in neutral conductor was developed [6]. This method offers good attenuation towards harmonics but leads to overheating in windings and increases in the system losses which also lead to an inefficient solution. The neutral current can be compensated by using split capacitor topology or four-leg VSI topology for shunt inverter. But it needs two capacitor and an extra control loop to maintain zero voltage error difference which results more complex to maintain the DC bus voltage at constant level [7-8]. Due to advancement in power electronic technology, active power filters have become most habitual compensation methods.

Shunt active power filters for three-phase three-wire and three-phase four-wire distribution systems have been presented [9-12]. These filter widely used in transmission systems but have fewer effects on the distribution systems. Improved solution to harmonic problem uses a hybrid active filter, consists of shunt active and passive filter or series active and passive filters [13-15]. Recently, in order to improve the power quality and to correct unbalance voltage in the distribution system, a series active power filter which is connected in series with neutral conductor have been proposed [16-19]. The existing methods used

† Corresponding Author: Department. of Electrical and Electronics Engineering, Kongu Engineering College, Erode, India. (gunas.27@gmail.com)
* Department. of Electrical and Electronics Engineering, Institute of Road and Transport Technology, Erode, India. (anita_irtt@yahoo.co.in)
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various controllers like instantaneous reactive power theory [20] and sliding mode control theory. All these theories are able to extract and mitigate harmonics present in neutral under the balanced load conditions only. Fuzzy logic based controller techniques have used in order to mitigate harmonics in phase conductors [21].

In this paper, rotating unit vector is used to extract the harmonic components in the neutral conductor and fuzzy controller is used to generate the triggering pulse to the inverter. Solar PV based controller is given as input to inverter. A series active filter is connected in series with the neutral conductor through coupling transformer for mitigating harmonic currents in the neutral. The rating of proposed series active filter is less than 10% of the harmonic producing loads. The Simulation results based on MATLAB model for parallel RC load with diode rectifier circuit are discussed for unbalanced conditions. An embedded controller based hardware setup is also developed and the results are verified through the power quality fluke analyzer.

2. Analysis of Neutral Current and Proposed System Configuration

2.1 Neutral current for diode rectifier nonlinear load

The diode bridge rectifier loads are the source of non-linear currents which affects the distribution system and is shown in the Fig.1.

The input AC voltage is applied to diode bridge rectifier with filtering capacitor which results in the distorted phase and neutral currents. An unbalanced load connected to this distribution system causes the flow of neutral current in which zero sequence components becomes predominant. These excessive harmonic current causes problems like over loading of the neutral conductor, increases the size of the neutral conductor, de-rating distribution transformer and overheating of the distribution transformer. Also the THD analysis of phase and neutral current is given by,

$$I_{ph} = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_f} \tag{1}$$

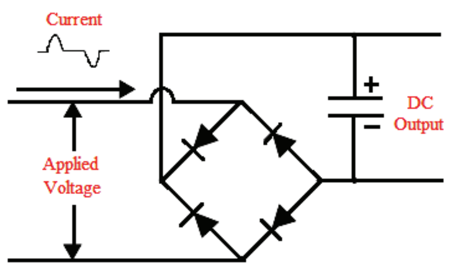

Fig. 1. Diode bridge rectifier non linear load

$$I_n = \frac{\sqrt{3\sum_{h=2}^{n} I_h^2}}{I_f} \tag{2}$$

Where I_h is the harmonic component and I_f is the fundamental component of neutral conductor and n is the order of harmonics. In the above analysis, the magnitude of the neutral current (I_n) is 1.73 times of the phase current (I_{ph}) which cause the significant total harmonic distortion in the distribution system.

2.2 Description of proposed system

The proposed block diagram and scaled model of the system is shown in Figs. 2 and Fig. 3. In this proposed system, three single phase loads are connected to the three phase source. In each phase, a diode rectifier with parallel RC loads with different values are connected which leads to the flow of neutral current. The diode rectifier acts as a non-linear load in this scheme. Due to this, a zero sequence component which is dominant in third order harmonics flows in the neutral conductor.

This phenomenon affects the distribution transformer. In order to attenuate the above effect, a series active filter is connected in series with the neutral conductor. The neutral current has both fundamental and harmonic components. The fundamental component is due to the unbalance loading condition and harmonic component is due to the non-linear property of the load. This neutral current is

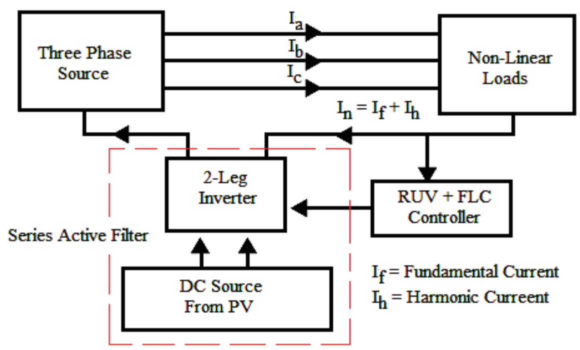

Fig. 2. Block diagram of the system

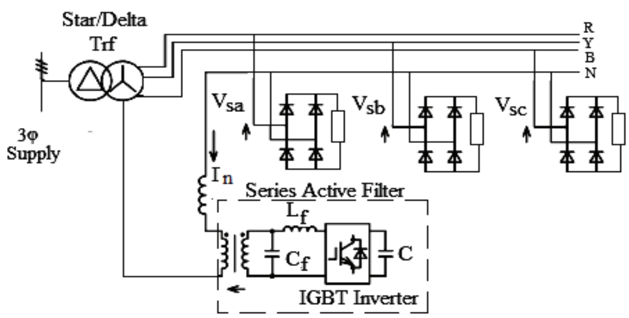

Fig. 3. Scaled model of the system

sensed and harmonic component in the neutral conductor is extracted and then given to the controller circuit which generates the gate pulse to the IGBT based inverter of series active filter. The series active filter injects the harmonic compensation in anti direction and it reduces the distortion effect in the neutral conductor and phase conductor.

The proposed model consists of three-phase supply, step-down transformer, non-linear diode rectifier and series active filter. The proposed system configuration is shown in Fig.3. V_{sa}, V_{sb} and V_{sc} are the three-phase source voltages. C_f and L_f are the coupling reactors. The analysis of the neutral current is follows. The neutral point voltage before compensation is given by,

$$V_n = V_{nd} + V_{nq} \tag{3}$$

Where $V_{nd} = -RI_n$ is a direct axis component and $V_{nq} = j(\omega L_n)$ is a quadrature axis component.

Compensating active filter voltage is given by,

$$V_{AF} = K.j(V_{nq}) \tag{4}$$

Then the neutral point voltage after compensation is given by,

$$V_n = -R.I_n + j[\omega / (1+K).I_n] \tag{5}$$

Similarly, neutral current before and after compensation is given in Equ (4) and Equ (5) respectively,

$$I_n = V_n / [R + j(\omega L)] \tag{6}$$

$$I_n = V_n / [R + j(\omega L + K)] \tag{7}$$

Where, R and L are the resistance and inductance of delta-star transformer and ω is the third harmonic angular frequency. Thus by selecting the higher value of gain K, better performance can be achieved in the system

3. Generation of Reference Signal and Implementation of Fuzzy Logic Controller

3.1 Extraction of reference signal

The Rotating Unit Vector (RUV) controller is used to extract the fundamental component from the neutral current. It is the modified version of Synchronous Reference Frame Controller (MSRF) and is shown in Fig. 4.

In order to extract the harmonic component of neutral current, it is converted into a DC component by multiplying with sinωt and cosωt. Low pass filter is applied to extract DC component and then multiplied by sinωt and cosωt respectively and summed to synthesize the fundamental component ($I_{n,f}$). Then the fundamental

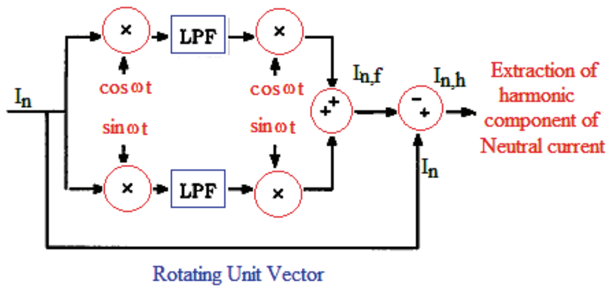

Fig. 4. Extraction of harmonic component

component of the neutral current is subtracted from the neutral current I_n to get the harmonic component of the neutral current $I_{n,h}$.

3.2 Fuzzy logic controller

The extracted harmonic current is taken as error signal and its derivatives are given as input to the fuzzy logic controller. The fuzzy control scheme is shown in Fig. 5.

The desired triggering pulses for the inverter circuit are determine according to the error in filter current using fuzzy logic controller. The switching frequency is chosen as 20 KHz and is desired by,

$$f_s = \frac{V_{dc}.\Delta I_{rms}}{3L\Delta I_{rms\_ref}} \tag{8}$$

Where f_s is the switching frequency, V_{dc} = DC input voltage to the inverter of 120 V, L = Filter inductance of 0.2mH and $\frac{\Delta I_{rms}}{\Delta I_{rms\_ref}}$ is the ration of RMS value of the neutral current to its reference value.

In this proposed method, the harmonic component in the neutral conductor acts as an error signal to the fuzzy logic controller. Mamdani fuzzy interference system model is used in this paper. There are two inputs to the fuzzy logic

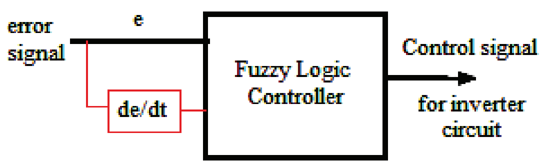

Fig. 5. Fuzzy logic controller

Table 1. Fuzzy set rules

Change in Error/Error	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	PB	PM	PB	PB	PB	PB

controller, one is error (e) and another one is change in error (de/dt) and an output which is the command signal to the PWM of inverter circuit. Two inputs use the Gaussian membership function while the output uses the triangular membership function. The Rule table is constructed based on the inputs and output which consists of 49 rules as shown in Table 1.

4. Photo Voltaic Charging Capacitor

The DC input to the inverter of series active filter is fed through the charging capacitor. The voltage across the capacitor may discharge which leads to incomplete operation of inverter circuit. In this paper, solar PV panel based capacitor is used with lead acid battery as a backup. The proposed configuration is shown in the Fig. 6.

Capacitance C_i across solar PV panel is used to remove the ripples from the solar source and inductance L_i is used to smoothen the waveform before giving to the lead acid battery. The voltage across the inverter is maintained constant of 100V as shown in Fig. 7. The Fig. 8 shows the equivalent model of PV cell. I_{ph} represents the maximum solar PV current, R_s and R_{sh} represents the series resistance and shunt resistance, I_D and I_{sh} represents the diode current, and shunt resistance current respectively.

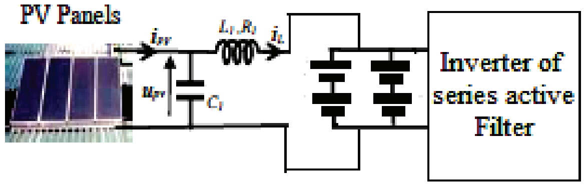

Fig. 6. PV system configuration

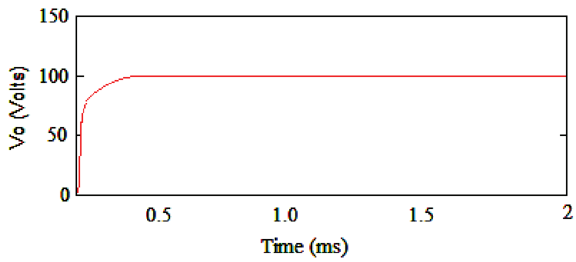

Fig. 7. Voltage/Time characteristics of capacitor

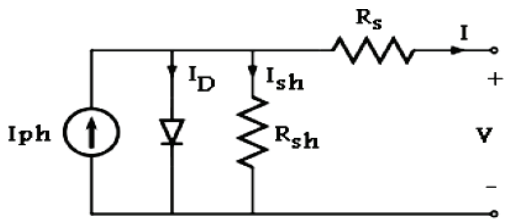

Fig. 8. Equivalent model of PV

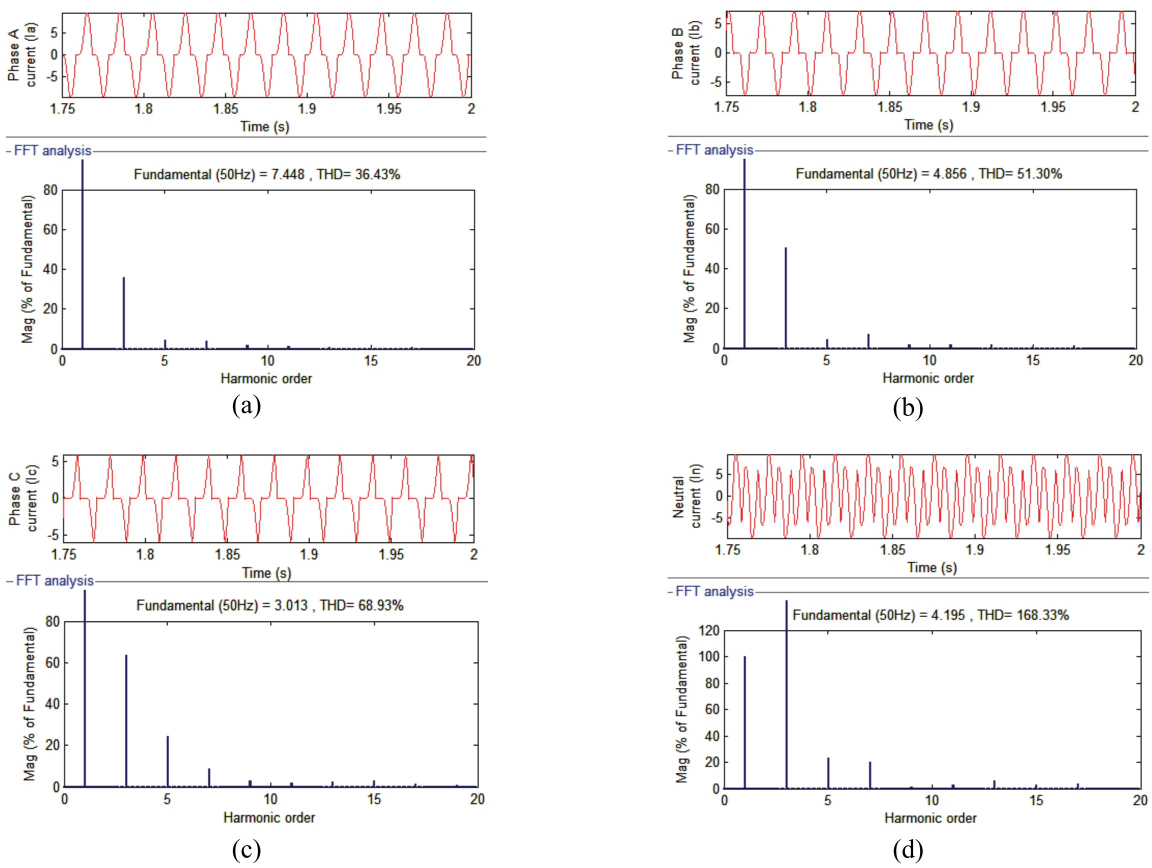

Fig. 9. Waveform and THD analysis before filter

5. Simulation Results and Experimental Setup

5.1 Simulation and hardware setup results

The solar photovoltaic panel model is simulated using MATLAB/SIMULINK. The simulation model of 240V/120 V with parallel RC diode bridge rectifier of three-phase four-wire distribution system is taken for simulation. The simulation parameters are given in Appendix. Due to the use of diode bridge rectifier, a non-linear component of current gets added with the phase conductor through the neutral point. To make a system as unbalance, different types of loads are connected to each phase of the three-phase system. The neutral current carries both fundamental and harmonic components. In order to eliminate the harmonic component of neutral conductor, series active filter is connected with neutral conductor through the coupling transformer. The waveform of phase and neutral current along with the FFT analysis of THD before compensation is shown in Fig. 9.

The above analysis indicates that due to non-linearity of the load, waveforms of neutral and phase currents are distorted and THD measures are very high. The waveform of the phase and neutral current along with the FFT analysis of THD after compensation is shown in Fig. 10.

The analysis after compensation shows that by single installation of active filter in series with the neutral conductor, the harmonic effects reduced much in neutral as well as in phase conductor. The comparison of THD without and with filter of neutral is shown in Fig. 11.

The line voltage and the frequency of the utility for experimental setup are 120V and 50Hz respectively. The parameters of the single-phase power converter and the active filter are same as used in simulation. A three single-phase step-down transformer is used to provide a three-phase four-wire experimental setup. Single-phase loads are connected between one of the three phase and the neutral conductor. The DC sides of the rectifiers are connected in parallel to a resistor and capacitor. The active filter consists of a single-phase voltage-fed PWM inverter using four IGBTs and is connected to the neutral conductor via a single-phase matching transformer and coupling inductance. A switching ripple filter with a cutoff

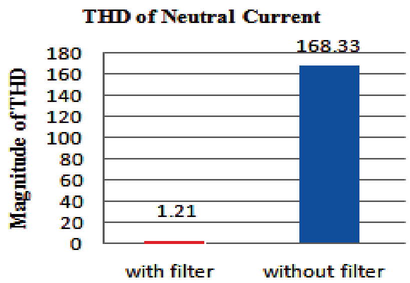

Fig. 11. Comparison of THD simulation

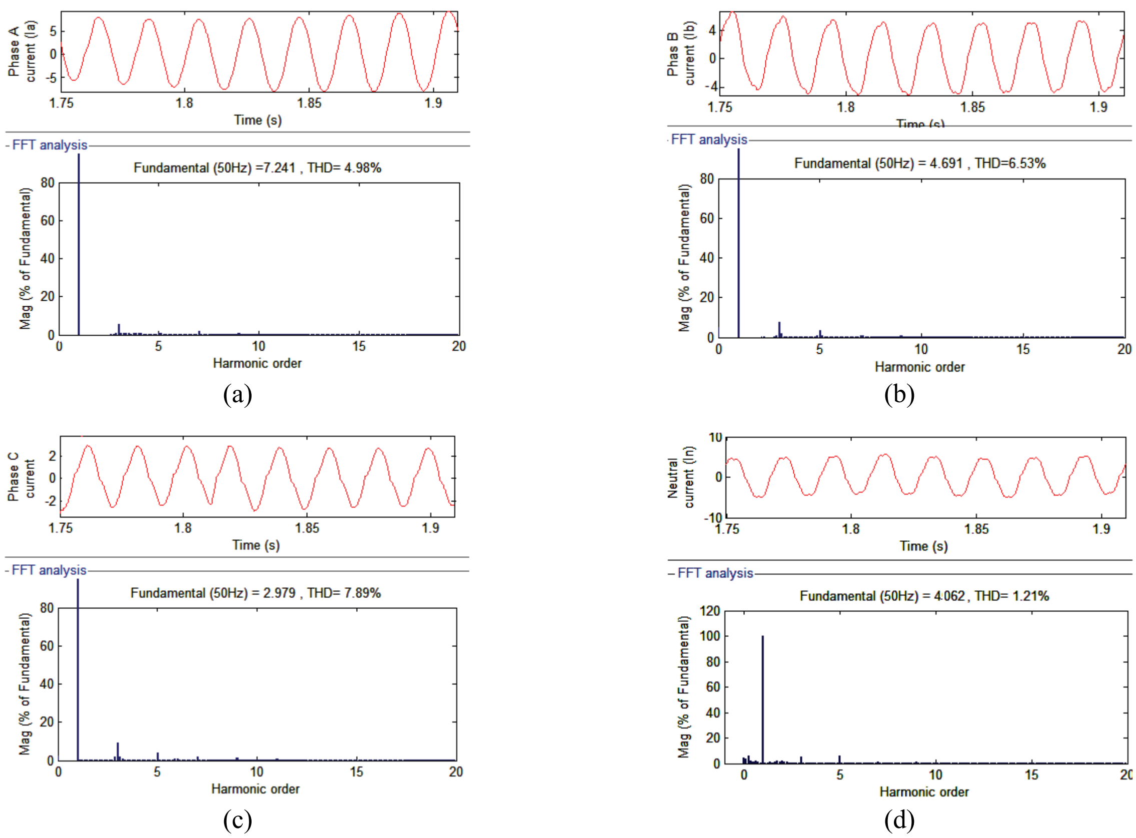

Fig. 10. Waveform and THD analysis after filter

frequency of 20 kHz is inserted between inverter and the matching transformer.

The DC voltage to the active filter is fed using solar PV panel as shown is Fig. 12 which maintains the constant voltage of nearly 100V. The embedded digital DSPIC microcontroller consists of an A/D unit which is used for the measurement of neutral voltage and neutral current. The harmonic extraction is achieved by using phase detector in the measured signal. The extracted harmonic component is given to the controller which generates the pulses equivalent to the harmonic component. The gate pulses thus obtained is given to two-leg IGBT of active filter which injects the harmonic components in the anti-direction into the neutral conductor. This effect suppresses the harmonic content in the neutral conductor thereby indirectly reduce the harmonic effect of phases also. The waveform of the neutral current is measured using power quality fluke meter analyzer. The waveform without filter is shown in Fig. 13.

The frequency of 149.82Hz displayed in the waveform indicates the effect of third order harmonic (zero sequence components) in the neutral conductor. The neutral current waveform after adding active filter in series with neutral conductor is shown in Fig. 14.

After adding filter circuit, harmonic content in neutral conductor reduced significantly and the frequency remains nearly 50Hz. The comparison of THD without and with filter of neutral using hardware setup is shown in Fig. 15.

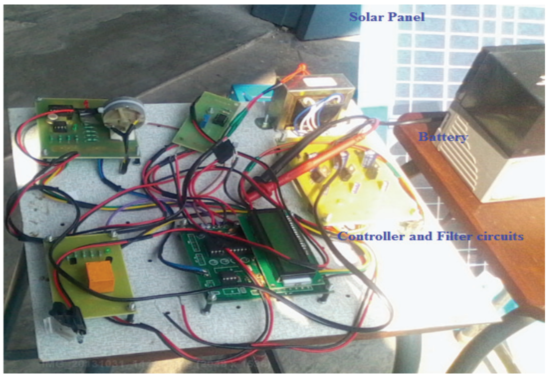

Fig. 12. Hardware model of PV system

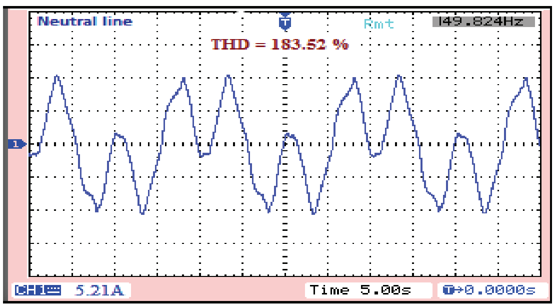

Fig. 13. Waveform of neutral current without filter (Experimental)

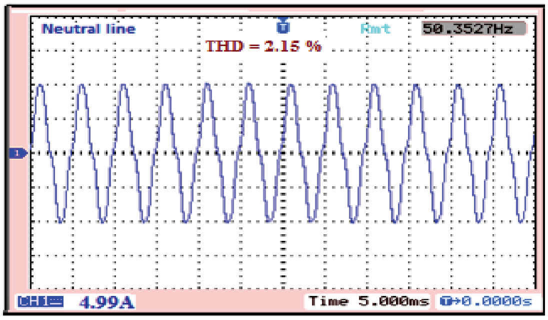

Fig. 14. Waveform of neutral current with filter (Experimental)

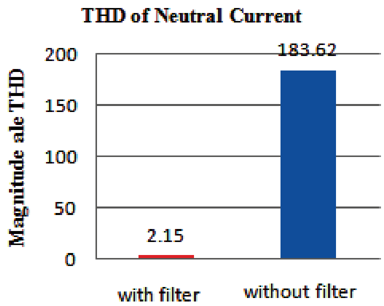

Fig. 15. Comparison of THD Hardware

5.2 Distribution system experimental setup

The experimental setup of the distribution system with filter and controller circuit is visualized as shown in Fig. 16.

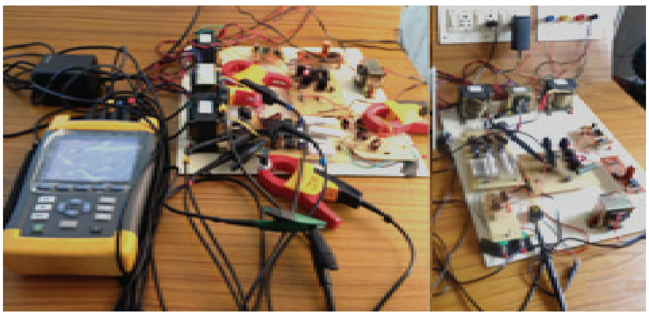

Fig. 16. Experimental setup of distribution system

The real-time visualization of the simulation circuit is experimented. The THD values obtained from the simulation and experimental results are much similar. The THD value of neutral current from the experimental setup is slightly greater than the simulation result which is due to the real time implementation.

6. Conclusion

This paper presented a novel control strategy for eliminating the neutral current harmonic components in three-phase four-wire distribution system. A new technique based on solar PV panel for inverter input was implemented and analyzed. The simulation was carried out using MATLAB/SIMULINK software tool and also the results of waveform and THD of neutral and phase currents were discussed. The experimental setup was also implemented and the simulation results were validated. The power quality of the distribution system was enhanced by implementing the above proposed method.

Appendix

Parameters	Values
Line to neutral voltage	120 V
Frequency of the system	50 Hz
Leakage reactance of the distribution transformer	0.35 mH
Switching frequency	20 KHz
Filter inductance	0.2 mH
Filter capacitance	1 μF
Capacitance voltage V_{DC}	100 V
Load Values at rectifier side	R_A=15Ω, R_B=25Ω, R_C=50Ω C_A=C_B=C_C =1000 μF

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T. Guna Sekar He received his B.E in Electrical and Electronics Engineering from Bharathair University, Coimbatore and M.E. in Power System Engineering from College of Engineering, Guindy, Anna University, Chennai, India. He has published 10 papers in International journals and conferences. His areas of interest include Power Systems, Power Quality Engineering, Active filters and Electrical Machines.

R. Anita Professor and Head, Department of Electrical and Electronics Engineering, Institute of Road and Transport Technology, Erode, India. She received her Ph.d degree from Anna University, Chennai, India. She published several papers in International Journals and conferences. Her areas of interest include Control system, Optimization Techniques and Intelligent Controllers.