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Improved Active Power Filter Performance with Four Leg Voltage Source Inverter for Renewable Power Generation Systems

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Abstract: Renewable generation special effects on power quality problems due to its nonlinearity, in view of the fact that solar generation plants and wind power generators are interconnected to the grid through high power static converters. The non-linear loads also produce harmonics that deteriorates power quality problems of the system. The active power filter has been proves the effective method to mitigate harmonic currents. In this paper an active power filter with four leg voltage source inverter using predictive control scheme is implemented, which will compensate current harmonic components and unbalanced current generated by single phase non-linear loads. A simple mathematical model of the active power filter is designed with the help of predictive control algorithm. The compensation performance of the proposed active power filter and the connected control scheme under steady state and transient operating conditions is demonstrated through simulation results using MATLAB/SIMULINK.

Index Terms: Active power filter, current control, four-leg converters, predictive control.

1. INTRODUCTION

The non-uniform life of power generation directly affects on the voltage regulation and creates voltage distortion in power system. Providing of uninterrupted supply of power with voltage, frequency within the nominal values is called power quality. Renewable power generation plants such as solar and wind are connected to the grid by static converters of high power. Both these type of generation units use static dc/ac and ac/ac PWM converters for voltage transformation. And for storage of energy they use battery banks. In power system, the non-uniform nature of generation has an impact on voltage regulation and hence causes voltage distortion. Presence of the static converters, constituting power electronic devices, introduces non-linearity and affects power quality. In addition to this, with the development of technology, there is rapid increase in the usage of power electronics based loads (such as switch mode power supplies, adjustable speed drives) in power system to increase controllability and efficiency and hence attracting the increase of harmonic distortion levels. These static devices introduce harmonic currents into the system and deteriorate power quality. Filters are used to reduce harmonics.

Conventionally, passive filters were used to eliminate harmonics. Passive filters can filter the frequencies that they are earlier tuned for their operation. Use of the passive filters creates resonance that depends on system circumstances. They need to be hyped for potential harmonic absorption. The rating should be coordinated with load reactive power necessities. Hence, they suffer from disadvantages of tuning problems, large size, resonance and fixed compensation features.

MODELING OF CASE STUDY

2. FOUR-LEG CONVERTER MODEL

Renewable sources, such as sun light and wind, are used here used to produce electricity for small industries and residential customers. Both types of power generation use dc/ac and ac/ac static PWM converters for voltage conversion and also battery banks for storage of energy over long term. Maximum possible energy is extracted from sun and wind by these converters through maximum power point tracking. The nature of electrical energy consumption is unpredictable and random, and therefore, it may be three- or single-phase, unbalanced or balanced, and linear or nonlinear. At the point of common coupling, the active power filter is connected in shunt to compensate current unbalance, current harmonics, and reactive power. It is incorporated with a four-leg PWM inverter, a first-order output ripple filter and an electrolytic capacitor, Fig .2. This circuit considered with converter ripple filter impedance Z_f which is connected at its output, impedance of load Z_L and resultant impedance of the power system Z_s.
Fig. 1 shows the configuration of a typical power distributions system with renewable power generation. It consists of different categories of loads and different categories of power generation units.

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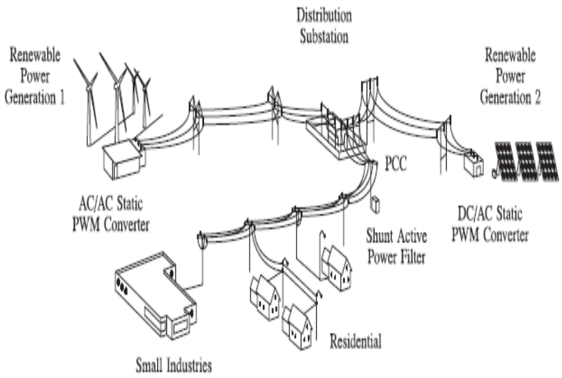

Fig. 1. Stand-alone hybrid power generation system with a shunt active power filter

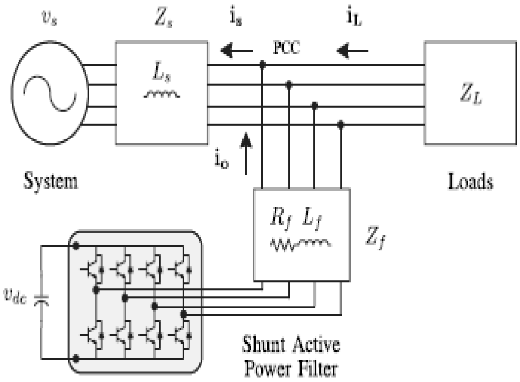

Fig. 2.Three-phase equivalent circuit of the proposed shunt active power filter.

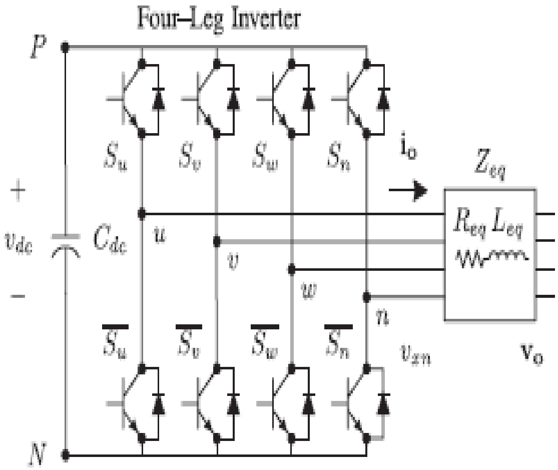

Fig. 3. Two-level four-leg PWM-VSI topology

From fig.3. The 4- leg converter topology is shows. This converter topology is similar to the conservative 3-phase converter with the fourth leg connected to the neutral-bus of the system. The fourth leg increases switching-states from 8 (2^3) to 16 (2^4), getting better voltage quality at output and also flexibility in control and is appropriate for compensation of current unbalance.

$$v_{xn} = S_x - S_n v_{dc}, x = u, v, w, n \qquad (1)$$

$$v_o = v_{xn} - R_{eq} i_o - L_{eq} \frac{di_o}{dt} \qquad (2)$$

Where L_{eq} and R_{eq} are the output parameters of 4L-Voltage Source Inverter and is expressed in terms of Thevenin's impedances Z_{eq} at the output terminals of converter. Therefore, a parallel organization between the load impedance Z_L, equivalent impedance of the source Z_s and series connected ripple filter impedance Z_f, determine the Thevenin's equivalent impedance Z_{eq} as shown below.

$$Z_{eq} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f \qquad (3)$$

Finally, in (2)

$$R_{eq} = R_f \text{ and } L_{eq} = L_s + L_f.$$

3. PROPOSED DIGITAL PREDICTIVE CONTROL SCHEME

The proposed predictive current control scheme block diagram is shown in Fig. 5.4. Being an optimization algorithm, this could be implemented in a microprocessor. To account for extra limits such as approximations and time delays, the analysis is to be done using discrete mathematics. In this predictive control, the system model is considered to expect the hope performance of variables that are to be embarrassed. With this information the controller selects the optimum switching state to apply the same to power converter, according to predefined criteria of optimization. The proposed control scheme is easy to understand and implement. It can be implemented with three main blocks

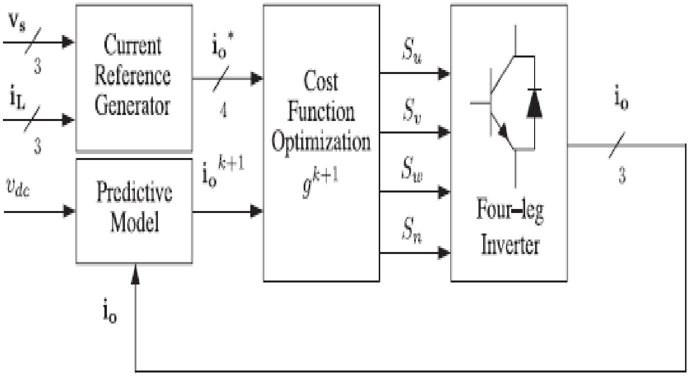

Fig. 4.Proposed predictive digital current-control structure

3.1 Current Reference Generator: In the direction of compensate the unwanted apparatus of load current, the needed current reference is generated by this unit. In this case, the dc-voltage of inverter, the system voltages and the load currents are calculated, at the same time as the load neutral-current and output neutral-current are in a straight line produced commencing these signals.**3.2 Prediction Model:** The predict the output of the current converter, the prediction model of converter is used. The system model and controller are to be representing in discrete time domain as controller operates in this domain. The discrete model comprises a recursive matrix-equation to represent this prediction scheme. By expressive the manage variables and converter switching states at any instant kT_s, for a prearranged sampling time T_s, it is possible to forecast the next states at any other instant$[k + 1]T_s$. The model described by the state equations of first-order nature and hence first-order approximation is considered here

$$\frac{dx}{dt} \approx \frac{x[k+1] - x[k]}{T_s} \qquad (4)$$

The predicted values of 16 possible output currents are obtained from (2) and (4) as

$$i_o[k+1] = \frac{T_s}{L_{eq}}(v_{xn}[k] - v_o[k]) + \left(1 - \frac{R_{eq} T_s}{L_{eq}}\right) i_o[k] \qquad (5)$$

As shown in Eq.(5), at any instant $(k + 1)$, to forecast the output current $\mathbf{i_o}$, the values of converter output voltage v_{xn} and the input voltage $\mathbf{v_o}$ are required. The16 values allied with the achievable combination of state variables can be calculated by the algorithm.

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3.3 Cost Function Optimization*:* The most favorable switching state to be functional toward the power-converter can be selected by comparing the 16 predicted morals acquired for **io**$[k+1]$ through the reference by means of a cost function g, as follows:

$$g[k+1] = (i^*_{ou}[k+1] - i_{ou}[k+1])^2 + (i^*_{ov}[k+1] - i_{ov}[k+1])^2 + (i^*_{ow}[k+1] - i_{ow}[k+1])^2 + (i^*_{on}[k+1] - ionk+12 \qquad (6)$$

4. CURRENT REFERENCE GENERATION

From figure.5 to acquire the active power-filter current-reference signals a *dq*-based on

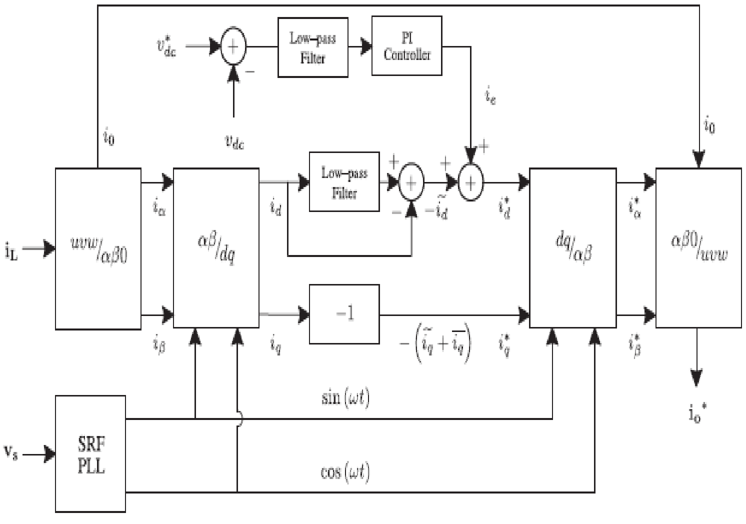

Fig. 5.*dq*-based current reference generator block diagram.

current-reference generator system is used. This system offers a quick and precise signal tracking ability. This avoid voltage fluctuations which cause deterioration of the current-reference signal that affects compensation performance. As shown in Fig.5.5, the current reference signals are acquired from equivalent load-currents. Reference signal currents necessary for the converter are calculated by this module to compensate current harmonic, reactive power, and current imbalance. The *dq*-based technique operate in a rotating reference-frame and hence calculated currents should be multiplied by sin *wt* and cos *wt* synchronized reference signals obtain as of a SRF and PLL. The SRF-PLL produces a pure sinusoidal-wave-form though the voltage of the system is cruelly distorted. Equation (7) show the connection stuck between the real currents $i_{Lx}(t)$ ($x = u, v, w$) and the linked dq components ($i_d$and i_q)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} i^*_{ou} \\ i^*_{ov} \\ i^*_{ow} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\omega t & -\cos\omega t \\ 0 & \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} i_0 \\ i^*_d \\ i^*_q \end{bmatrix} \qquad (8)$$

$$i^*_{on} = -(i_{Lu} + i_{Lv} + i_{Lw}) \qquad (9)$$

5. DC-VOLTAGE CONTROL

A traditional PI-controller is a easy and efficient substitute to control the dc voltage of the converter. Slow dynamic response capacitor voltagewill not disturbs the current-transient response. The dc voltage leftovers unaltered awaiting the active-power captivated by the converter falls to a intensity anywhere it is not able to recompense for its own losses.

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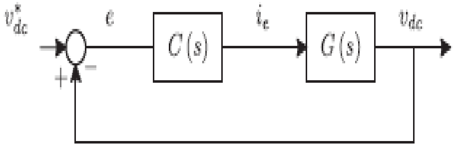

Fig. 6. DC-voltage control block diagram

Adjustment of amplitude of the active-power reference-signal i_e controls the active power of the converter as shown in fig .6.

$$G(s) = \frac{v_{dc}}{ie} = \frac{3}{2}\frac{K_p v_s \sqrt{2}}{C_{dc} v_{dc}^*} \qquad (10)$$

$$C(s) = K_p\left(1 + \frac{1}{T_i.s}\right) \qquad (11)$$

6. SIMULATION RESULTS

Table I. Specification of parameters

1	V_s	Source voltage	55V
2	F	System frequency	50Hz
3	V_{dc}	dc-voltage	162V
4	C_{dc}	dc capacitor	2200µF
5	L_f	Filter Inductor	5.0mH
6	R_f	Internal resistance within L_f	0.6Ω
7	T_s	Sampling time	20µs

A simulation model for the three-phase four-leg PWM converter is designed with the parameters shown in Table I. It has been developed in MATLAB-Simulink. The simulation block diagram of proposed shunt active power filter is shown in Fig. 7.

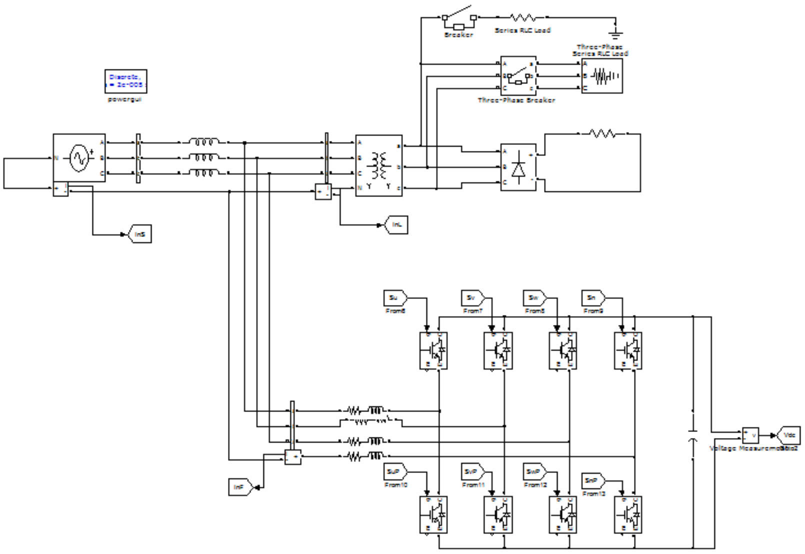

Fig. 7.Simulation Block diagram

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Case 1: Active power filter-Single phase results

Single phase (A-phase) sinusoidal source voltage is shown in Fig. 8(a). Single phase non-linear load current is exposed Fig.8(b). An exposed in Fig.8(c), the active power filter commences to compensate at 0.04sec and injects an output current. During compensation single phase source current demonstrate sinusoidal-waveform with low down THD as shown in Fig.8(d).The non-linear load increases at 0.1sec. This makes the load current to increase in magnitude as shown in Fig. 8(b). This also cause an increase in magnitude of the source current duly maintaining sinusoidal shape with low distortion level as exposed in Fig.8(d).

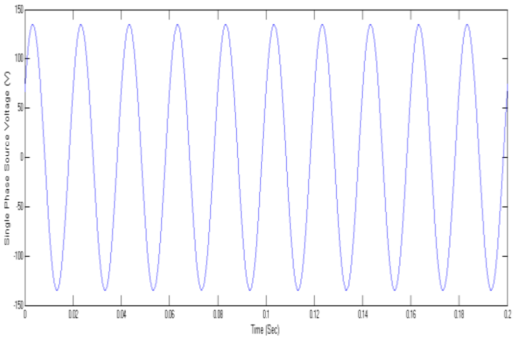

Fig.8(a). Phase to neutral source voltage

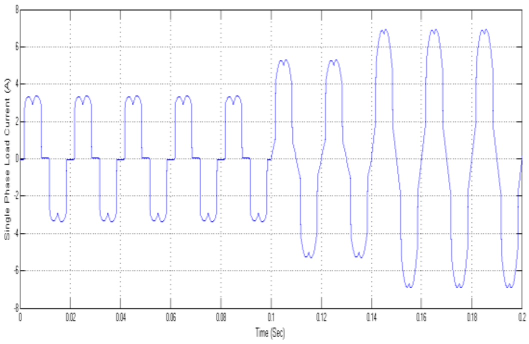

Fig.8(b). Single phase load current

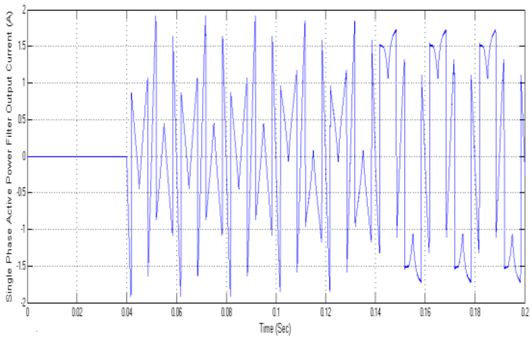

Fig.8(c). Single Phase filter output current

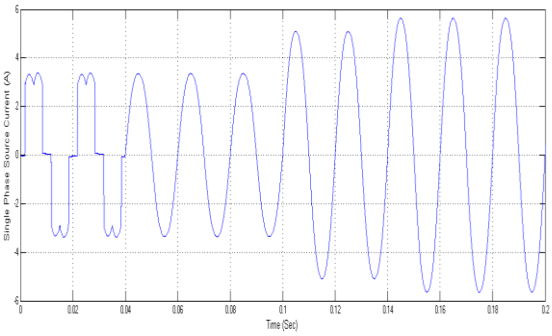

Fig.8(d).Single phase source current.

Case 2: Active power filter-Three phase results

The three phase sinusoidal source voltages of 3-phases A, B and C are exposed in Fig.9(a). Three phase non-linear load currents are shown in Fig.9(b).

At 0.04 sec, the active power filter starts to compensate and commence to inject current harmonic components, neutral current and current unbalance simultaneously as shown in Fig. 9(c). During compensation, the source currents in three phases show sinusoidal waveforms with low THD=3.91% as shown in Fig.9(d).

At 0.1sec a 3- phase balanced step load change is applied. This causes effective increase in non-linear load on the power system there by increasing the magnitudes of load currents and also source currents as shown in Fig. 9(b) and Fig. 9(d) respectively. However, the source currents remain sinusoidal despite of change in the magnitude of load current.

At 0.14sec, a 1-phase load step change is applied to introduce current imbalance. This causes neutral-current to flow in the neutral-conductor on load side as shown in Fig. 9(e). But on the source side, it is observed that neutral current does not flow as shown in Fig.9(f).

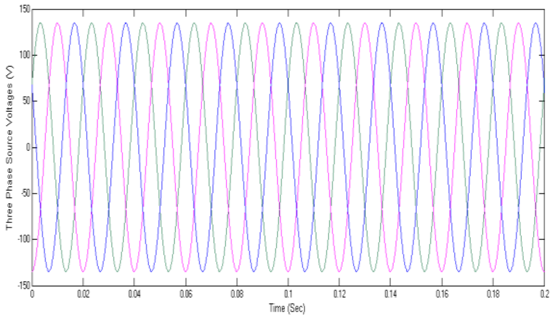

Fig 9(a). Three phase source voltages

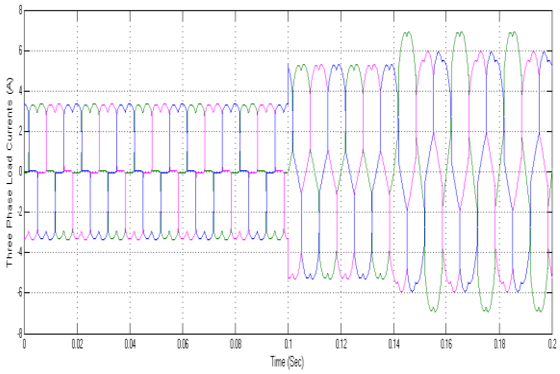

Fig.9(b). Three phase load currents

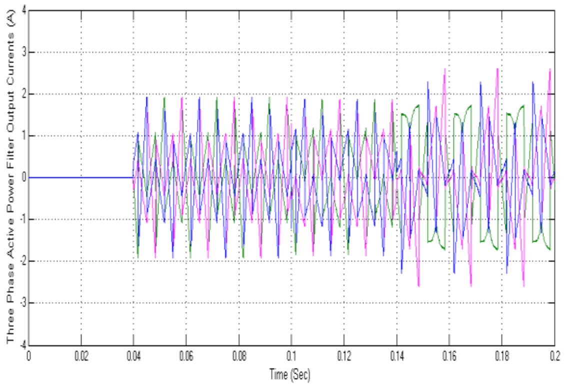

Fig. 9(c). Three phase filter output currents

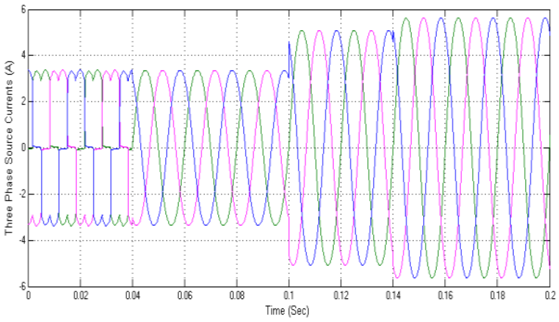

Fig.9(d). Three phase source currents

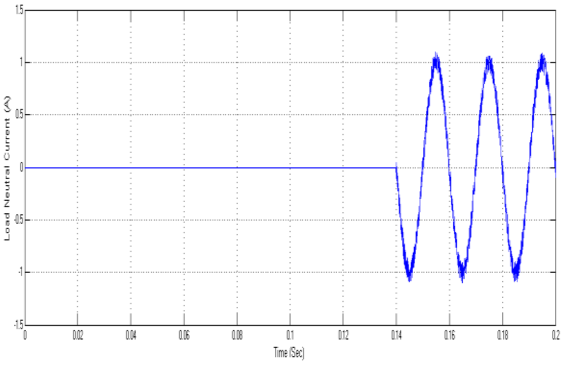

Fig.9(e): Load neutral current

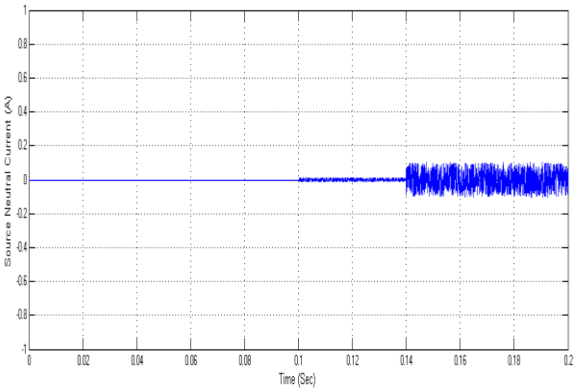

Fig.9(f). Source neutral current

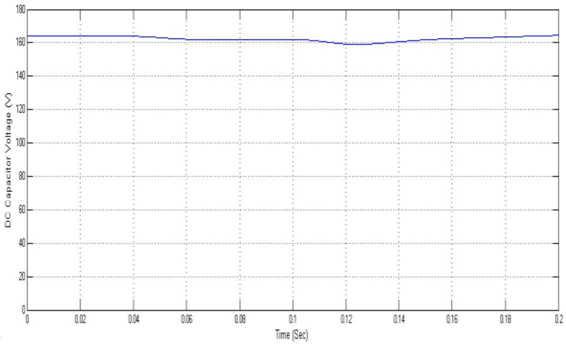

Fig 10. DC voltage of converter

Additionally, as shown in Fig.10, the dc-voltage of the voltage source inverter remains stable during the period of whole active power filter operation.

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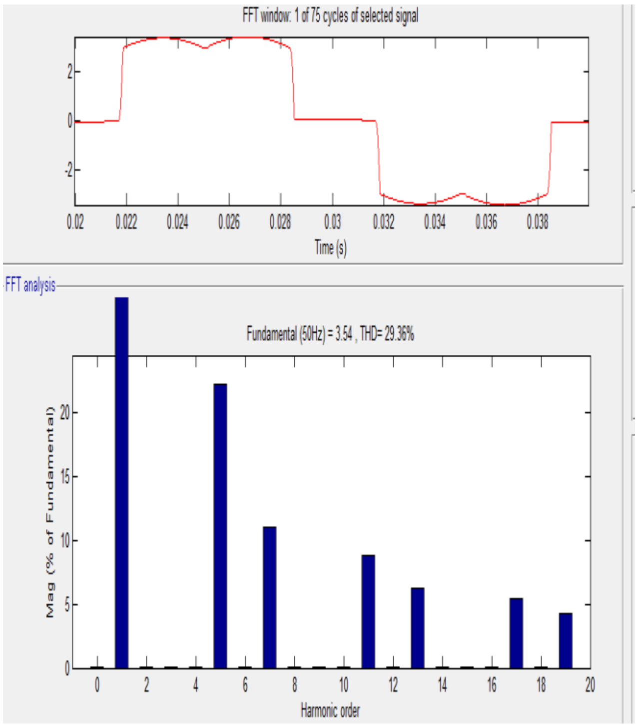

Fig. 11(a): Harmonic spectrum of the source

Current (Before compensation)

As shown in Fig.11(a), without active power filter, the total harmonic distortion(THDs) in the three phase source currents is 29.36%. As shown in Fig.11(b), after compensation i.e. with active power filter operation, the THD of source-current is compact to 3.91%. It is evident from the simulation results that the proposed three phase four-leg voltage source inverter implemented with the proposed control scheme can be utilised effectively for compensation of current harmonics and unbalanced currents.

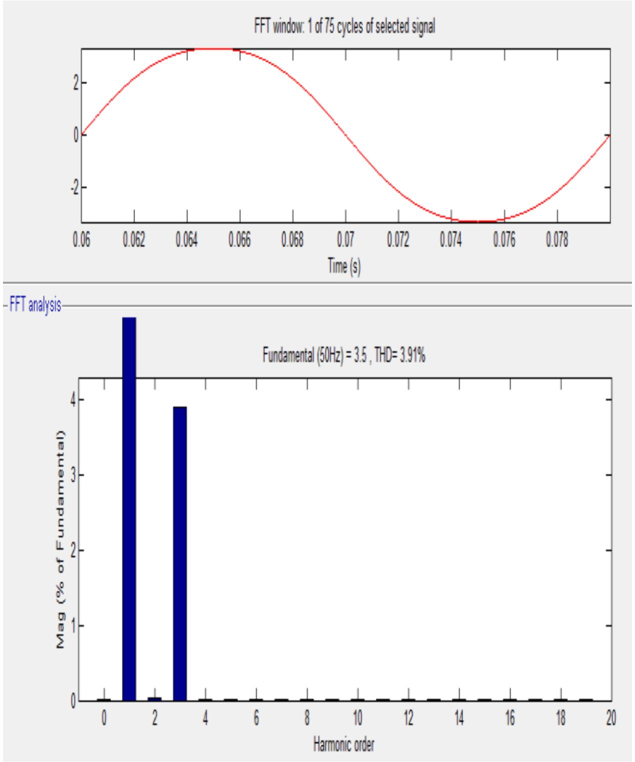

Fig.11(b): Harmonic spectrum of the source current(After compensation)

7. CONCLUSION

The power distribution system incorporated with renewable generation units is considered and a compensation scheme is proposed for reimbursement of current harmonics and unbalanced currents and reactive-power in order to enhance the current-quality of the distribution system. Benefits of the scheme with four-leg voltage source inverter are related to its modeling, ease and execution. The predictive control approach for the converter current loop evidenced to be an effective outcome for active power filter applications, innovative improvement in current tracking capability and also transient response. It is a noble alternative to classical linear control approaches. From results, it is observed that THD is reduced from 29.36% to 3.91% by installing an active power filter. Simulated results have depicted the compensation efficacy of the proposed active power filter.

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