International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

An Active Power Filter Implemented With a 4-Leg VSI Using Predictive Control Scheme for Improving Power Quality

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Abstract: ***The non- linear loads are connected at the point of common coupling generates the harmonics, which may deteriorate the power quality. The active power filter has been proved to be an effective method to mitigate harmonic currents generated by the non-linear loads as well as to compensate reactive power. The methods of harmonic current compensation play a crucial part in the performance of active power filter. Traditionally, active power filters have been controlled using pre-tuned controllers, such as PI-type or adaptive, for the control of current as well as the dc-voltage loops. PI controllers must be designed based on the equivalent linear model. Predictive controllers use the nonlinear model, which is closer to real operating conditions in order to improve the performance and life of the power switches of voltage source inverter (VSI), reduces its switching frequency. An active power filter implemented with a 4-leg voltage source inverter using a predictive control scheme is presented in this paper. Predictive current control algorithm is based on the system model. The compensation performance of the proposed active power filter and the associated control scheme under steady state and transient operating conditions is demonstrated through simulations using MATLAB/SIMULINK.***

Keywords: Shunt Active Power Filter, 4-Leg VSI, PI, Predictive Current Control, SRF-PLL.

1. Introduction

The electrical energy consumption behavior is random and unpredictable, therefore it may be single- or three-phase, balanced or unbalanced and linear or nonlinear [1]. Nonlinear load contains harmonics to reduce the harmonics uses the filters. Filters are two types passive, active. Passive power filters can filter frequency only the frequencies they were previously tuned for their operation can be limited to a certain load. Resonance problem will be accruing because of the interaction between the passive filters and other loads with unpredictable results [2].

To come out of these disadvantages recent efforts are concentrated in the development of active power filters. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power generated by the non-linear loads [3]. The principle of the shunt active power filter (SAPF) is to produce harmonic currents equal in magnitude but opposite in-phase to those harmonics that are present in the grid. SAPF can compensate reactive power and can also mitigate harmonics and distortions.

I (comp) = I (load) - I (source).

Conventional active power filter implemented with a three-phase three leg topology. In three leg topology the zero sequence currents in the load cannot be compensated and hence the zero sequence currents flow in the neutral wire (Between the system and load). The zero sequence currents thus return to the ac distribution system. If the load is non-linear and contain harmonics then these harmonics also enter ac system thus degrading the power quality.

In three leg inverter, if the load requires a neutral point connection a simple approach is to use the dc link capacitor split in two and ties the neutral point to the midpoint of two capacitors. In this case the unbalanced loads will cause the neutral currents that flow through the fourth wire distorting the output voltage. Another drawback is the need for excessively large dc link capacitors [3]. To overcome these draw backs go for 4-Leg VSI. In this paper 4-Leg VSI using predictive control scheme for effective harmonic compensation.

2. Mathematical Modeling for 4-Leg VSI

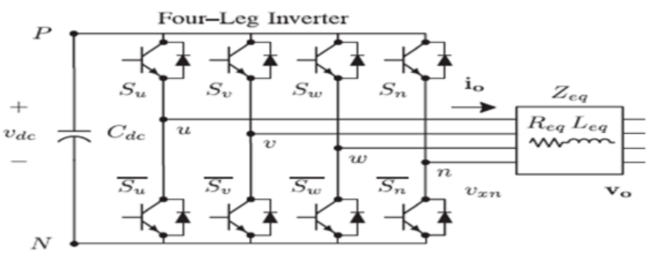

Figure 1: 4-Leg VSI topology

The four-leg PWM converter topology is shown in Figure 1 the converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral wire of the system.

The four- leg increases states of switches from $8(2^3)$ to16 (2^4), improving control flexibility and output voltage quality and is suitable for current unbalanced compensation [1].

The voltage in any leg *x* of the converter, measured from the neutral point (*n*), can be expressed in terms of switching states as follows

$$v_{un} = s_u - s_n v_{dc} \quad (1)$$

The mathematical model of the filter derived from the equivalent circuit shown in Figure 1

$$v_0 = v_{un} - R_{eq} i_0 - L_{eq} \frac{di_0}{dt} \quad (2)$$

Where in Eq. (2) R_{eq} and L_{eq} are the 4-Leg VSI output parameters used in thevenin impedance (Z_{eq}) at the converter output terminals. Therefore the equivalent impedance is determined by a series connection of the ripple filter impedance *Z* and a parallel arrangement between the system equivalent impedance Z_S and the load impedance Z_L as shown in Figure 2.

$$Z_{eq} = \frac{Z_S Z_L}{Z_S + Z_L} + Z_f \approx Z_S + Z_f \quad (3)$$

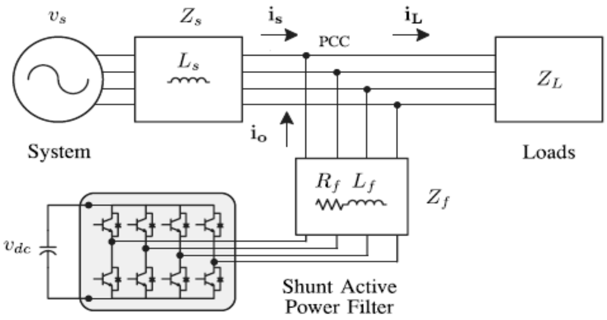

Figure 2: Three-phase equivalent circuit with the shunt active power filter

For this model, it is assumed that $Z_s >> Z_L$ that the resistive part of the system's equivalent impedance is neglected, and that the series reactance is in the range of 3–7% p.u., which is an acceptable approximation of the real system. Finally in Eq. (3) $R_{eq} = R_f$ and $L_{eq} = L_f + L_S$.

3. Proposed Predictive Control Method

The proposed predictive control strategy is based on the fact that only a finite number of possible states of switches can be generated by a static power converter and that models of the system can be used to predict the behavior of the variables for each state of switching. Then selected the appropriate state of switching can be applied to next interval state. This selection criteria is expressed as a quality function that will be evaluated for the predicted values of the variables to be controlled. The main characteristic of predictive control is the use of the system model to predict the future behavior of the variables to be controlled. This information is given to the controller to select the optimum switching state that will be applied to the power converter according to obtained optimization criteria. The predictive control algorithm is easy to implement and to understand.

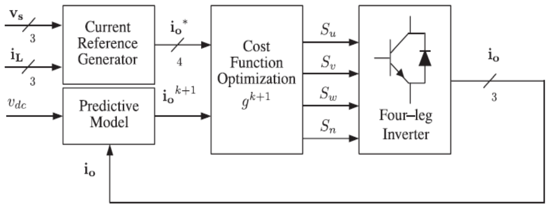

Figure 3: Predictive current control block diagram

Current Reference Generator: This unit is designed to generate the required current reference that is used to compensate the undesirable load currents. Here, the dc converter voltage, load currents and the system voltages are measured, while the source neutral current and neutral load current are generated directly from these signals.

3.1 Prediction Model

The converter model is used to predict the output converter current. Here the controller operates in discrete time, such that the controller and the system model must be represented in a discrete time domain. The model consists of recursive matrix equations that represent this prediction system. This means that for a given sampling time T_s, that the converter switching states and control variables at instant kT_s, such that it is possible to predict the next states at any instant $[k + 1]T_s$. The algorithm calculates all 16 values associated with the possible combinations that the state variables can achieve. The prediction model is used to predict the output converter current. A sufficiently accurate first-order approximation of the derivative is considered as

$$\frac{di_0(k)}{dt} = \frac{i_0[k+1] - i_0[k]}{T_{ts}} \quad (4)$$

From Eq. (4) rewritten as

$$T_s \left[\frac{di_0}{dt}\right] + i_0(k) = i_0(k+1) \quad (5)$$

From Eq. (2)

$$\frac{di_o(k)}{dt} = \frac{v_{un}[k] - v_o(k) - Ri_0[k]}{L} \quad (6)$$

Substituting the Eq. (5) in Eq. (6) get the Eq. (7). The 16 possible output current predicted values can be obtained from Eq. (7)

$$i_0[k+1] = \frac{T_s}{L_{eq}}(v_{xn}[k] - v_0[k]) + \left(1 - \frac{R_{eq} T_s}{L_{eq}}\right) i_0[k] \quad (7)$$

3.2 Cost Function Modeling:

The cost function optimization is a quality function evaluates the error between reference and predicted currents in the next sampling interval. The voltage which value minimizes the current error is selected and applied to the load.

The 16 predicted values obtained for $i_o[k+1]$ are compared with the reference currents using a cost function .The output current predictive block $i_o[k+1]$ is equal to the reference $i_0^*[k+1]$ when g = 0. Therefore, the optimization goal of the cost function is to achieve a g value close to zero. During each sampling state, the switching state that generates the minimum value of *g* is selected from the 16 possible function values.

4. dq-Base Current Reference Generator Modeling

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. The dq-base scheme has fast accurate, response and signal tracking capability.

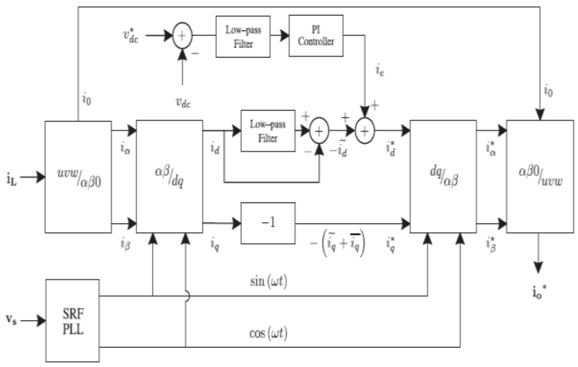

Figure 4: dq-based current reference generator block diagram

dq- based current reference generator scheme characteristic avoids voltage fluctuations that deteriorate the current reference signal performance of compensation. The reference current signals are obtained from the corresponding load currents as shown in Figure 4.

The dq-based scheme operates in rotating reference theory. The currents measured must be multiplied by the sin(*wt*) and cos(*wt*) signals. By using dq-transformation, the d-axis current component is synchronized with the corresponding phase-to-neutral system voltage, and the q-axis current component is phase-shifted by 90◦. The sin(*wt*) and cos(*wt*) synchronized reference signals are obtained from a synchronous reference frame (SRF). The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. Tracking errors are eliminated.

The dq-transformation, transforms the three-phase stationary coordinate system to the dq rotating coordinate system.

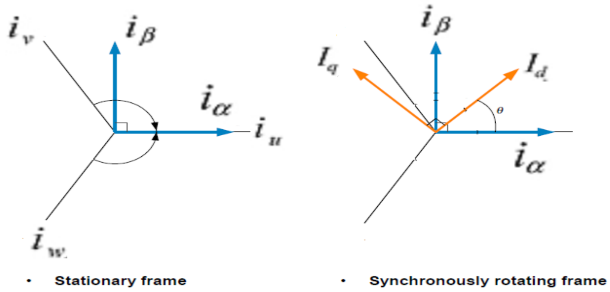

Figure 5: Vector representation of abc to dq transformation

This transformation is done two steps:

1) The three-phase stationary transformation of coordinate system to the two-phase so-called αβ stationary coordinate system and
2) A transformation from the αβ stationary coordinate system to the αβ rotating coordinate system [5].
3) Figure 5. Vector representation of abc to dq transformation to transform the abc to αβ using Clark transformation shown in Eq. (10)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

αβ to dq using park transformation in Eq. (10)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (10)$$

the transformation from abc to dq in Eq.(11)

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (11)$$

A low-pass filters (LFP) using in Figure 4 to extracts the dc component of the phase currents i_d to generate the harmonic reference components $-i_q$. The reactive reference components of the phase-currents are obtained by phase-shifting the corresponding ac and dc components of $-i_q$ by 180◦. In order to keep the dc-voltage constant the amplitude of the converter reference current must be modified by adding an active power reference signal i_e with the d-component. The resulting signals i_d^* and i_q^* are transformed back to a three-phase system by applying the inverse Park and Clark transformation as shown in Eq.(12)

$$\begin{bmatrix} i_u^* \\ i_v^* \\ i_w^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin wt & -\cos wt \\ 0 & \cos wt & \sin wt \end{bmatrix} \begin{bmatrix} i_0 \\ i_d^* \\ i_q^* \end{bmatrix} \quad (12)$$

5. DC-Voltage Control

The dc-voltage remains constant, until the active power absorbed by the converter decreases to a level where it is unable to compensate for its losses. In the block diagram shown in Fig.6the dc-voltage v_{dc} is measured and then compared with a constant reference value v_{dc}

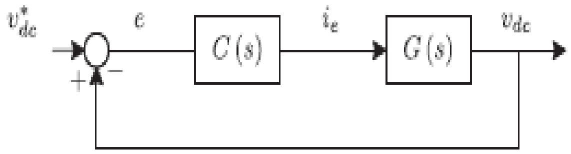

Figure 6: DC voltage control block diagram

The error (*e*) is processed by a PI controller, with two gains, $k_p$and k_i. both gains are calculated according to the dynamic response requirement. Fig.6.shows that the output of the PI controller is fed to the dc-voltage transfer function G(s), which is represented by a first-order Eq. (13).

$$G(s) = \frac{v_{dc}}{i_e} = \frac{3k_p v_s \sqrt{2}}{2c_{dc}v^*_{dc}} \tag{13}$$

6. Flow Chart for Predictive Controller

The Figure 7 shows the flow chart of the predictive control method. The input values taken as the i_0, S[t_k] predefined values of the compensating current and switching state. Based on these values the predictive control block calculates the i_0[k+1] value, repeat the process until 16 predictive values.

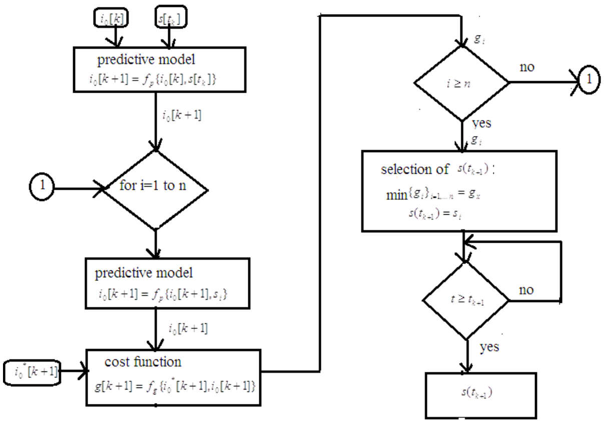

Figure 7: Flow chart for predictive controller [6],[7],[8]

Reference current values calculates from dq- base reference current method and compare those values predictive values using Eq. (9).which have minimum error value select the particular switching state then apply to the VSI.

7. Simulation Results

Table 1: Specification of parameters

S. No	*Variable*	*Description*	*Value*
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	50mH
6	R_f	Internal resistance with in L_f	0.6Ω
7	T_s	Sampling time	20µs

A simulation model for the three-phase four-leg PWM converter designed using Table 1 parameters; it has been developed in MATLAB/SIMULINK. A six-pulse rectifier was used as a nonlinear load. Simulation of proposed shunt active power filters shown Figure 8, predictive controller shown in Figure 9 and Reference current generator shown Figure 10.

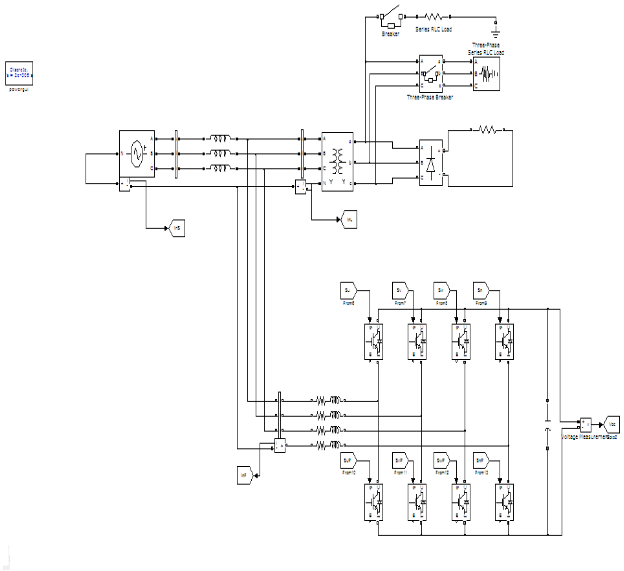

Figure 8: Simulink block diagram

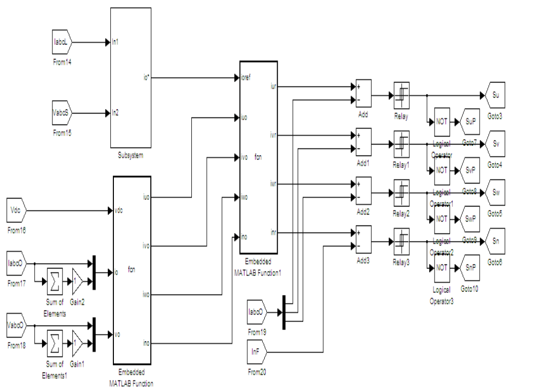

Figure 9: Simulink diagram of the controller

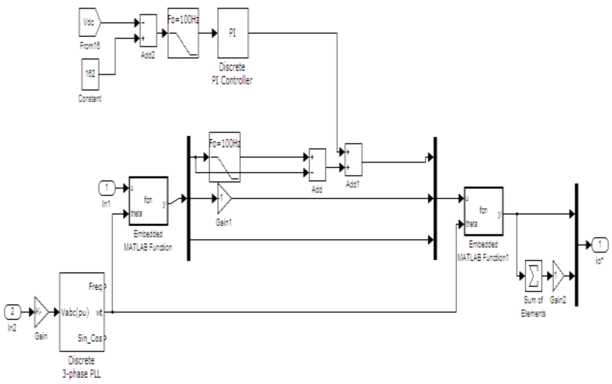

Figure 10: Reference current generation simulation block

Case 1: Single Phase results of proposed shunt active power filter

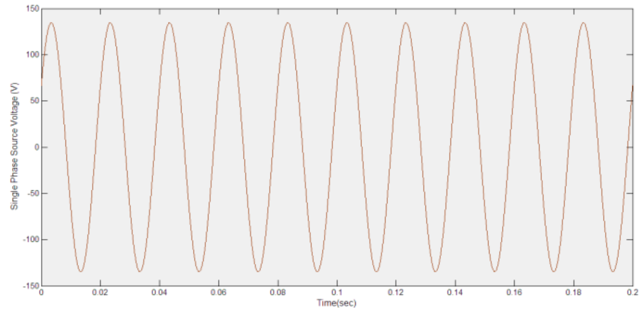

Figure 11 (a): Phase to neutral source voltage

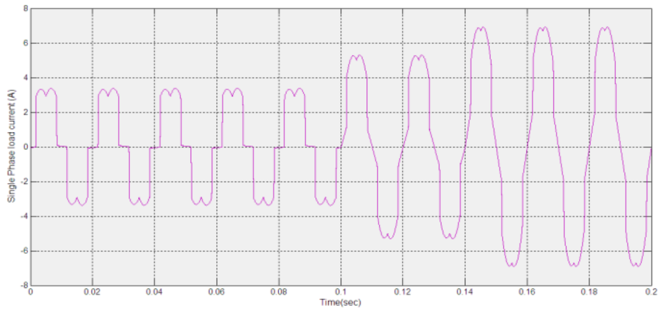

Figure 11 (b): Single phase load current

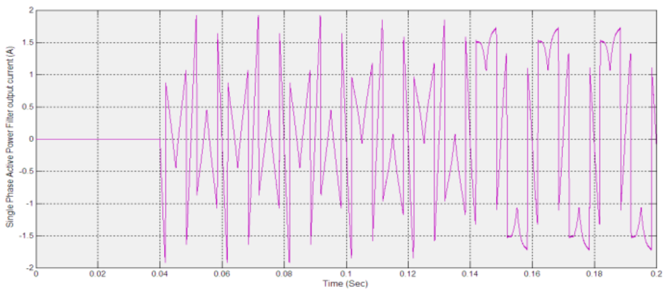

Figure 11(c): Single phase filter output current

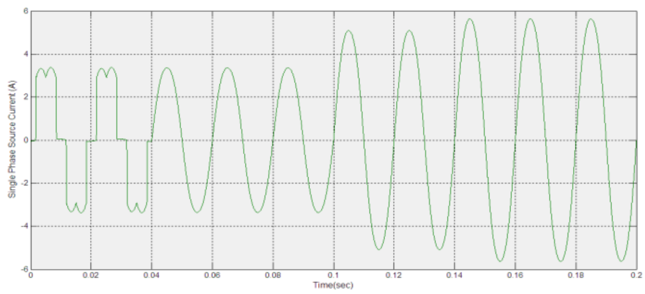

Figure 11 (d): Single phase source current

In Figure 11 (a) shows the constant u-phase source voltage. Figure 11 (b) shows the u-phase non-linear load currents, the filter starts to compensate at t=0.04sec shown Figure 11(c), at t=0.1sec the non-linear load increases even though the source current contains no harmonics maintain pure sinusoidal wave shown in Figure 11(d) without filter source currents contains harmonics shown source current wave t=0sec to t=0.04sec.

Case2: Three Phase results of proposed shunt active power filter.

Three phase constant source voltages u, v and w shown in Figure 12(a).The non-linear load currents shown Figure 12(b) t=0.1sec the three phase balanced step load change even though the source currents remain constants shown in Figure 12(d).again at t=0.14sec in u-phase single phase unbalanced load is applied the source voltage maintain pure sinusoidal wave.

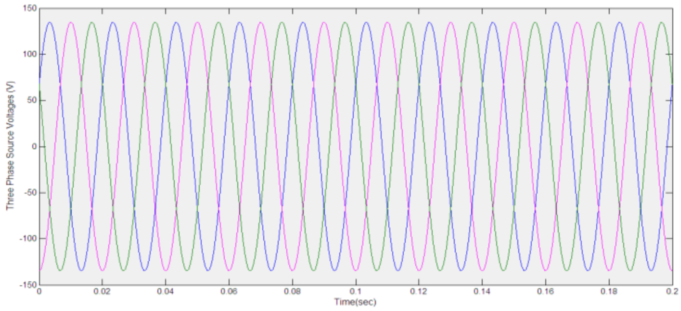

Figure 12(a): Three phase source voltages

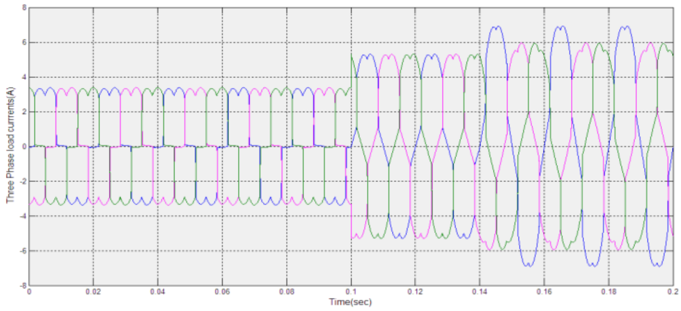

Figure 12(b): Three phase load currents

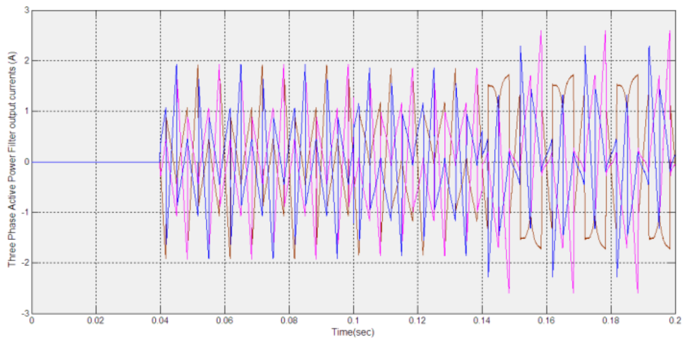

Figure 12(c): Three phase filter output current

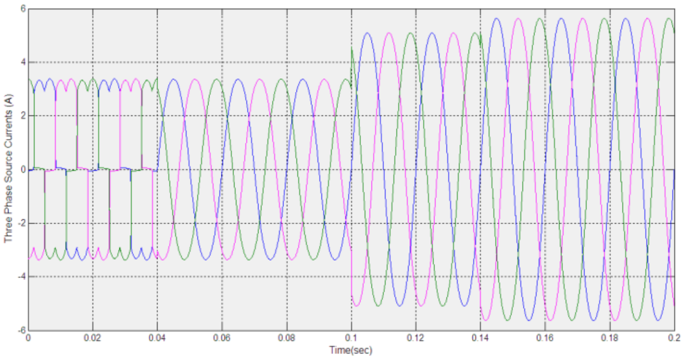

Figure 12(d): Threephase source currents

At t=0.14sec the single phase unbalance load is applied which is equalient to11% current unbalance at thattime load side neutral currentis presented shown in Figure 12(f) at that time no neutral current flow through the source neutral wire shown Figure 12(e).

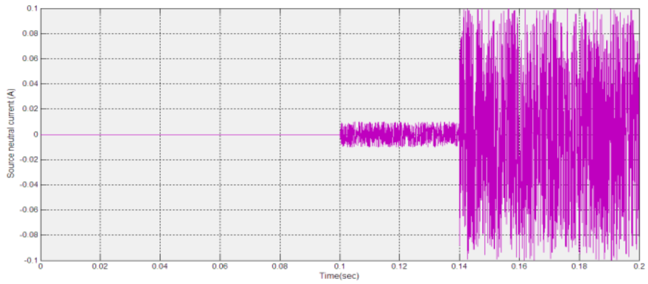

Figure 12(e): Source neutral current

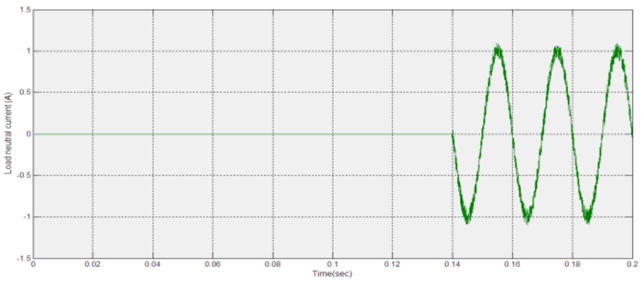

Figure 12(f): Load neutral current

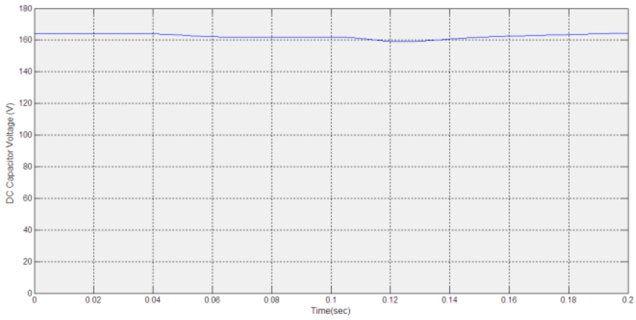

Figure 13: DC voltage of converter

DC voltage of the VSI shown in Figure 13.its maintain constant through out the inverter operation.A stepload chage was appiled to evaluate the transient response of the dc-voltage loop.

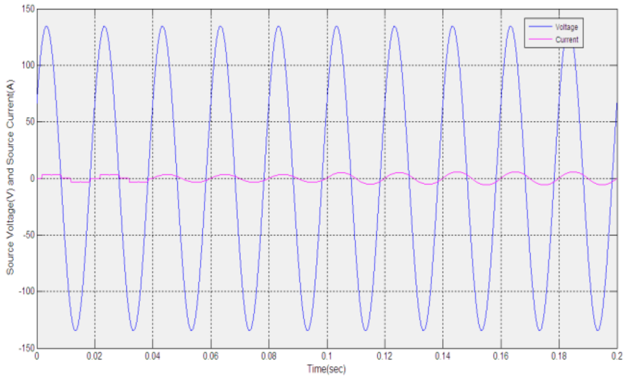

Figure 14: Source voltage and Source current

At t=0sec to t=0.04sec source current not inphase with the source voltage because there is no operation of the filter shown in Figure 14.the filter start to operate at t=0.04sec the source current inphase with the source voltage.

The total harmonic distortions (THDs) of without filter in phase u, v and w source current are noticed as 29.35% respectively shown in Figure 15 (a). After compensation the source current THDs is reduced to 3.94% for u, v and w phases respectively which is shown in Figure 15 (b). Thus from the simulation results it is evident that the three phase four leg current controlled voltage source inverter can be effectively utilized to compensate current harmonics and also enables the source to supply sinusoidal power at UPF.

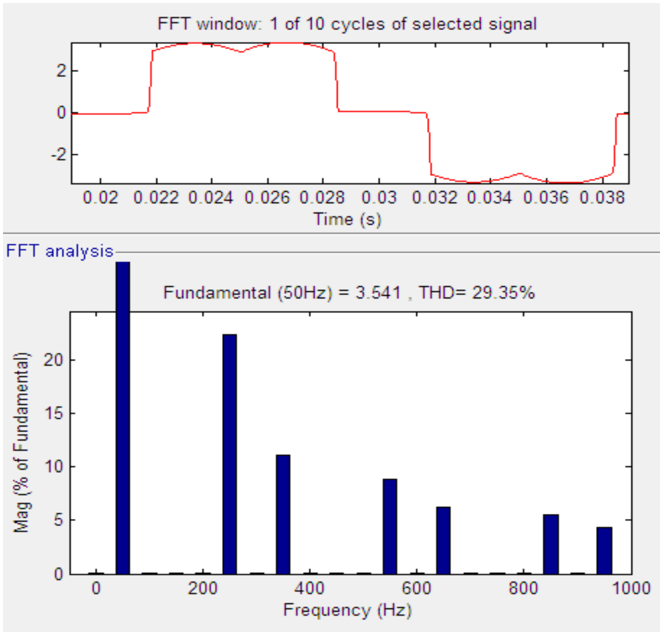

Figure 15(a): Harmonic spectrum of the souce current (before compensation)

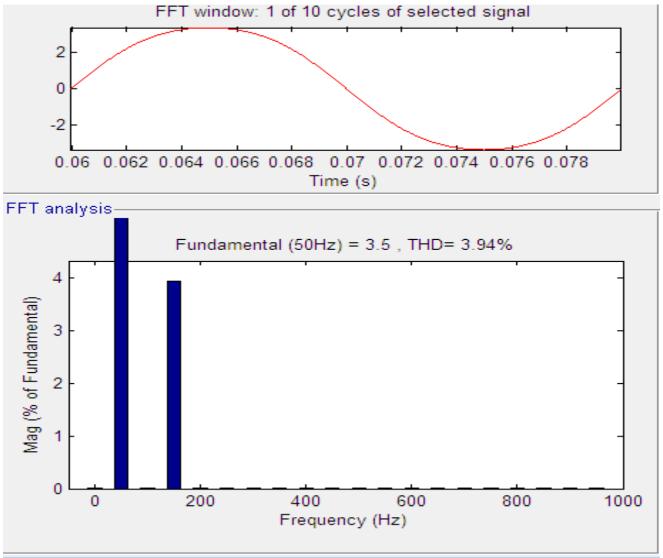

Figure 15(b): Harmonic spectrum of the souce current (after compensation)

8. Conclusion

The proposed SAPF control scheme advantages are related to its simplicity, implementation and modeling. The use of a predictive control algorithm for the converter current loop proved to be an effective solution for improving current quality of the distribution system. The system tracking capability and transient response is improved. The predictive current controller is a stable and robust solution. The proposed algorithm mitigates the system harmonic currents and reactive power compensation simulated results have been shows the compensation effectiveness of the proposed active power filter

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Author Profile

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