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POWER QUALITY IMPROVEMENT WITH IMPROVED ACTIVE POWER FILTER

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Abstract- The control strategies for grid connected inverters incorporating PQ (power quality) solution have been proposed in this paper. This paper presents active power filter implemented with a four leg voltage source inverter that compensates current harmonics and unbalanced currents generated by single phase non linear loads. A predictive control scheme is implemented to control the inverter. The control of the voltage source inverter of the active power filter is carried out by sinusoidal PWM with cost function predictive control. With such a control, the combination of grid interfacing inverter and the 3-phase 4-wire linear/non linear unbalanced load at the point of common coupling point appears as balanced linear load to the grid. The main feature of this control scheme is 1)To anticipate the future behavior of the variable and take control actions accordingly. The controller uses this information to select the optimum switching state that will be applied to the power converter. 2)To allow the current time slots to be optimized by keeping future events in account. This control scheme is an optimization algorithm and has to be developed using discrete mathematics. This new control concept is demonstrated with extensive MATLAB/SIMULINK simulation studies.

Key words: Active power filter, four- leg voltage source inverter, predictive control, current control.

I. INTRODUCTION

The quality of electric power is growing problem seriously, by using extensively high power switching devices, power electronic converters, in commercial, industrial and domestic applications. which causes current harmonics and voltage distortions and also affects power quality. This power electronic converters are non linear in nature. Utilities and users of electric power are increasing day by day and the demand for energy is also increasing. Seventy five percent of total global energy demand is supplied by the burning of fossil fuels which causes air pollution , global warming and increasing cost. So many countries are showing interest on Renewable sources for power generation which does not affect any pollution and also low cost, but shows affect on power quality due to its non linear nature and draws non sinusoidal current and reactive power from the source, which causes voltage distortion that affects the other loads connected at the point of common coupling. The main aim of this paper is to compensate the current harmonics and current unbalance to the grid with the help of new improved active power filters and inject required reactive power to the loads so as to compensate the load reactive power demand. The predictive control algorithm is designed and implemented for this application. Besides the problem of harmonic distortion, there exist also low power factor and unbalanced load currents at the point of common coupling due to the power delivered by the non linear loads. Active power filters are being investigated and developed to solve this problem. The control strategy for a shunt active power filter generates the reference current, that must be provided by the power filter to compensate reactive power and harmonic currents demanded by the load. Most active power filters have been designed on the basis of instantaneous reactive power theory. As the reactive power reduces the power factor improves, which in turn reduces the total harmonic distortion.

Any disruption in the switching of the VSI while connected to the grid system may also disrupt the grid voltage and increases the vulnerability of equipment connected to the system. It is very mandatory to maintain the switching of the VSI with optimal control techniques. The internal voltage of the source is controlled by the discrete 3-Phase Programmable voltage source as the load behaves as constant impedance. The simple mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure implemented in this paper. The proposed scheme achieves comparable reference tracking with the lower switching frequency and similar transient behavior. The effective compensation performance of the control scheme is demonstrated through simulation results.

II. FOUR- LEG CONVERTER MODEL

The proposed system consists of dc- link of a grid-interfacing inverter as shown in fig.1. The voltage source inverter is a key element of a DG system as it interfaces the power generation to the grid and delivers the generated power. The generated power may be a DC source or an AC source with rectifier coupled to DC-link. Usually, the fuel cell and photovoltaic energy sources generate power at variable low DC voltage, Thus, the power generated from these energy sources needs power conditioning(i.e., dc/dc or ac/dc) before connecting on dc- link. An active power filter is connected in parallel at the point of common coupling, it is known as shunt active power filter. The shunt active power filter is a current controlled voltage source inverter consists of compensating currents used to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter, and a first order output ripple filter. This circuit considers the power system impedance Zs, the converter output ripple filter impedance Zf, and the load impedance Zl.

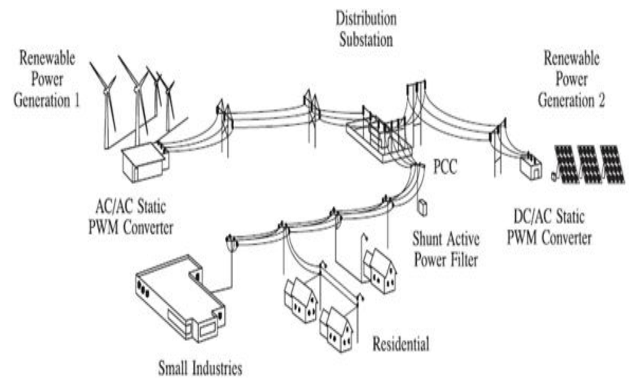

Fig.1. Stand alone hybrid power generation system with a shunt active power filter

The three- phase four wire system is more preferable if the load is unbalanced, because for unbalanced load 3-phase supply are not equal. This happens only when the phases area loaded by separate single phase appliance connected across a typical 3-phase input. Incorrect and correct balanced return currents are always returned via neutral conductor.

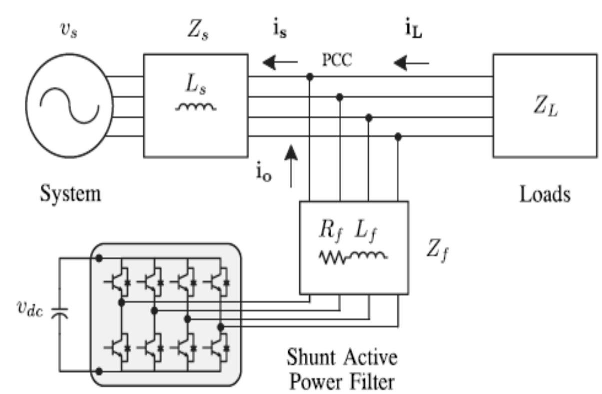

Fig.2. Three-phase equivalent circuit of the proposed shunt active power filter

The four-leg PWM converter topology, the fourth leg increases its switching states from 8 to 16 , it improves control flexibility and output voltage quality and is suitable for current unbalanced compensation. The fourth leg provides path for zero sequence currents present at the load. The fourth leg deals with the unbalanced currents and maintains sinusoidal output voltage waveform. The output voltage waveform is obtained by changing the inverter switching states from one state to another. The switches of any leg x cannot be switched on simultaneously that would lead to short circuit. The four-leg PWM- VSI topology is shown in fig.3.

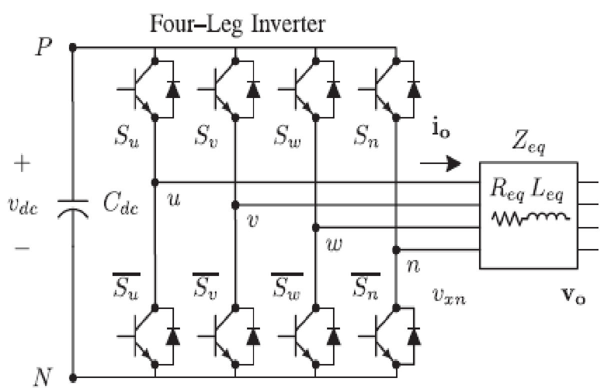

Fig.3. Two-level four leg PWM-VSI topology

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

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

The mathematical model of the filter derived from the equivalent circuit shown in fig is

$$V_o = v_{xn}\text{-}\ R_{eq} i_o \text{-} L_{eq}\frac{d_{i_o}}{dt} \qquad (2)$$

Where R_{eq} and L_{eq} are the 4L- VSI output parameters expressed as Thevenin impedances at the converter output terminals Z_{eq}. Therefore, the Thevenin equivalent impedance is determined by a series connection of the ripple filter impedance Z_f and a parallel arrangement between the system equivalent impedance Z_s and load impedanceZ_L.

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

For this model, it is assumed that $Z_L \gg Z_S$, that the resistive part of the system's equivalent impedance is neglected, and an acceptable approximation of the real system. Finally, in (2) R_{eq}= R_f and L_s+ L_f

III. CURRENT REFERENCE GENERATION

The current reference generator scheme is used to obtain the active power filter current reference signals. The complexity of any calculation performed with abc can be reduced to dq transformation. Here the dq- current reference scheme is used to generate the current reference signals. In this case the load currents, system voltage and dc voltage converter is measured. This control scheme presents a fast and accurate signal tracking capability and the current reference generator scheme is used to obtain the active power filter current reference signals. The complexity of any calculation performed with abc can be reduced to dq transformation. Here the dq- current reference scheme is used to generate the current reference signals. In this case the load currents, system voltage and dc voltage converter is measured. This control scheme presents a fast and accurate signal tracking capability and also avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance. The current reference signals are obtained from the corresponding load currents as shown in fig.4.This module calculates the reference factor ($\sin\emptyset_{(L)}$) and the maximum total harmonic distortion of the load THD_L defines the relationships between the apparent powers required by the active power filter, with respect to the load, as shown

$$\frac{S_{APF}}{S_L} = \frac{\sqrt{\sin\emptyset_{(L)} + THD_{(L)^2}}}{\sqrt{1 + THD_{(L)^2}}} \quad (4)$$

Where the value of THD_L includes the maximum compensable harmonic current, defined as double the sampling frequencyf_s.

The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency. DQ method is also known as synchronous reference frame. Here the reference frame d-q (direct axis, quadrature axis) is determined by the angle θ with respect to the α-β frame used in the p-q theory. The d-q- based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the sin (wt) and cos (wt) signals. By using dq- transformation, the d current component is synchronized with the corresponding phase- to neutral system voltage and the q current component is phase- shifted by 90 ^{0}. The sin(wt) and cos(wt) synchronized reference signals are obtained from a synchronous reference frame(SRF)PLL. The SRF- PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted. The SRF- PLL are designed to avoid phase voltage unbalancing, harmonics and voltage distortions. PLL used to measure the frequency and also used to generate signals locked on the variable frequency system voltage. The matrix equation represented below shows the park and Clark transformation

$$\begin{bmatrix} f_a \\ f_b \end{bmatrix} = \frac{2}{2}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\emptyset & \sin\emptyset \\ -\sin\emptyset & \cos\emptyset \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \end{bmatrix} \quad (5)$$

A low- pass filter (LPF) extracts the dc component of the phase currents i_d to generate the harmonic reference components$-i_d$ .The reactive corresponding ac and dc components of i_q by 180^0 . 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. The proposed method achieves comparable reference tracking with lower switching frequency and transient behavior.

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \begin{bmatrix} \cos(\emptyset) & -\sin(\emptyset) \\ \sin(\emptyset) & \cos(\emptyset) \end{bmatrix} \times \begin{bmatrix} f_d \\ f_q \end{bmatrix} \quad (6)$$

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase- currents, phase- shifted by180^0, as shown next

$$i^{*}_{on} = -(i_{Lu} + i_{Lv} + i_{Lw}) \quad (7)$$

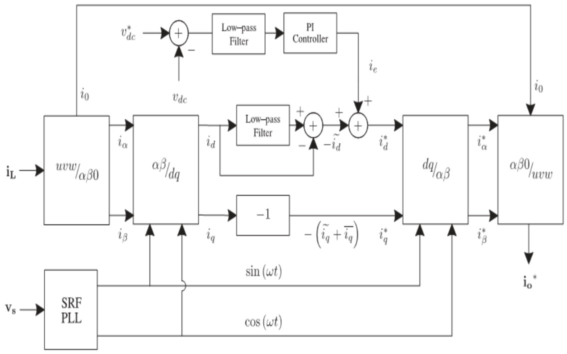

Fig. 4.DQ- Based Current Reference Generator Block Diagram.

IV. PREDICTIVE DIGITAL CURRENT CONTROL

Predictive model control is the advanced method of process control that has been in use power system balancing models. The main advantage of predictive control is the fact that it allows the current time slots to be optimized, while keeping the future time slots in account. It has the ability to anticipate the future events and take control actions accordingly.

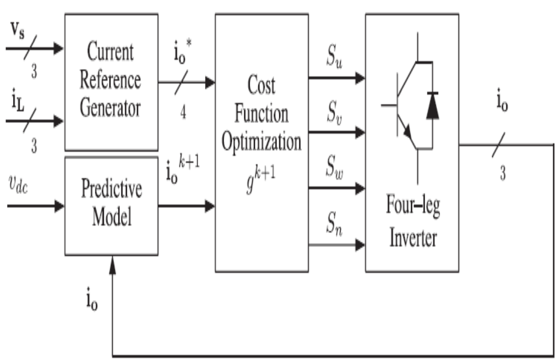

Fig.5. Proposed Predictive Digital Current Control Block Diagram.

This control scheme is basically an optimization algorithm and it is digital control method used to implement the control scheme. The analysis has to be developed using discrete mathematics considering time delays and approximations. The main characteristics of predictive control are the use of the system model to predict the future behavior of the system for each switching states of the inverter. The sampling state that minimize the given quality function g is selected and applied during the next sampling interval. The predictive control is used to evaluate the behavior of the current error for each sampling state. The predictive control algorithm is easy to implement and to understand.

The prediction model is used to predict the output converter current. Since the controller operates in discrete time, both the controller and the system model operate in discrete time. The discrete time consists of recursive matrix equation that represents this prediction system. This means that for a given sampled time T_S, knowing the converter switching states and control variables t instant (k+1)T_S, it is possible to predict the next state at any instant(k+1)T_s.

The first order nature of the state equation is as follows

$$\frac{dx}{dt} \approx \frac{x[k+1] - x[k]}{T_s} \quad (8)$$

From equation 2 and 8 we get equation 9

$$i_o[k+1] = \frac{T_s}{L_{eq}}\left(v_{xn}[k] - v_o[k]\right) + \left(1 - \frac{R_{eq}T_s}{L_{eq}}\right) i_o[k] \quad (9)$$

As shown in (9), in order to predict the output current **io** at the instant (k + 1), the input voltage value **vo** and the converter output voltage *vxN*, are required. The algorithm calculates all16 values associated with the possible combinations that the state variables can achieve.

V. COST FUNCTION OPTIMIZATION

The cost function is used as criterion in selecting the switching state that will be applied during the next sampling state. The optimal switching state that minimizes the cost function g is selected and applied during each sampling state. The selected switching state must be applied to the power converter, the16 predicted values obtained for **io**[*k* + 1] are compared with the reference using a cost function *g*, as follows:

$$g[k+1] = (i^*_{ou}[k+1] - i_{ou}[k+1])^2 + (i^*_{ov}[k+1] - i_{ov}[k+1])^2 + (i^*_{ow}[k+1] - i_{ow}[k+1])^2 + (i^*_{on}[k+1] - i_{on}[k+1])^2 \quad (10)$$

The output current (**io**) is equal to the reference (**io**) when *g* =0.Therefore, the optimization goal of the cost function is to achieve a *g* value close to zero. The voltage vector **vxN** that minimizes the cost function is chosen and then applied at the next sampling state. During each sampling state, the switching state that generates the minimum value of *g* is selected from the16 possible function values. The algorithm selects the switching state that produces the minimal value and applies it to the converter during the *k* + 1 state. The control of the voltage source inverter of the active power filter is carried out by sinusoidal PWM with cost function predictive control.

VI. PROGRAMMABLE VOLTAGE SOURCE

A programmable load is simply a programmable power supply that applies a voltage but sinks current rather than sourcing it. By changing the current direction, the programmable load electrically looks like a programmable resistor rather than a programmable (Thevenin) voltage source. A programmable load is a type of test equipment or instrument which emulates DC or AC resistance loads normally required to perform functional tests of batteries, power supplies or solar cells. By virtue of being programmable, tests like load regulation, battery discharge curve measurement and transient tests can be fully automated and load load changes for these tests can be made without introducing switching transient that might change the measurement or operation of the power source under test.

Advanced DC programmable loads offer additional test capabilities with internal controls that can detect oscillations within a fraction of a second and immediately stabilize the load profile. By eliminating the effects of oscillation and current spikes a programmable load can protect against damage to your mission critical electronics.

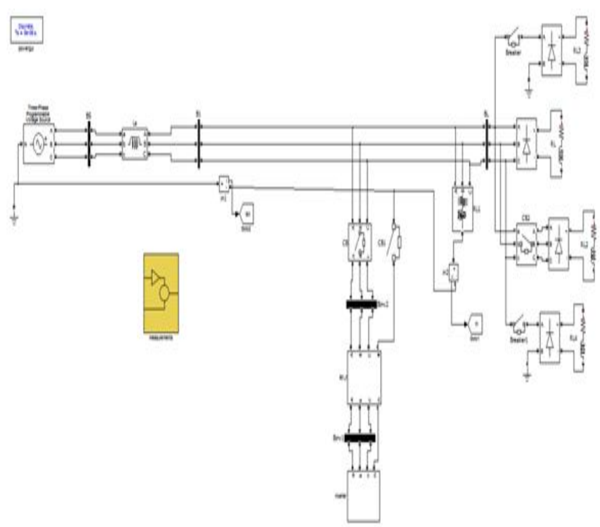

Fig.6.Three- Phase Programmable Voltage Source With SAPF

VII. SIMULINK RESULTS

A simulation model for the three-phase programmable voltage source four- leg PWM converter with the parameters shown in Table 1 has been developed using matlab/simulink. The objective is to verify the current harmonic compensation effectiveness of the proposed control scheme under different operating conditions.

In simulated results shown in fig below the active filters starts to compensate at t=t_1. At this time, the active power filter injects an output current i_{ou} to compensate current harmonic componenets, current unbalanced, and neutral current simultaneously. At t=t_2, a three- phase balanced load step change is generated from 0.6 to 1.0 p.u. Fig below shows the simulated results of the proposed control scheme. FFT analysis shows the total harmonic distortion of the line current is reduced from 28.09% to 1.78%.

Table.1. Specification Parameters

variable	Description	Value
V_s	Source voltage	55[v]
f	System frequency	50[Hz]
V_{dc}	dc-voltage	162[v]
C_{dc}	dc capacitor	2200[μF] (2.0 pu)
L_f	Filter inductor	5.0[mH] (0.5 pu)
R_f	Internal resistance with L_f	0.6[Ω]

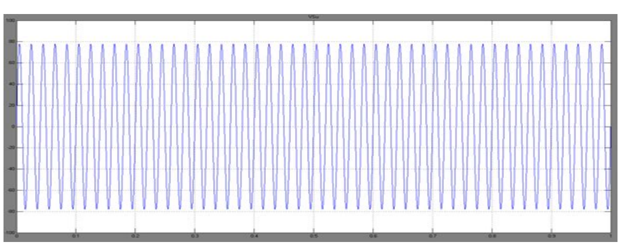

Fig:7 Phase To Neutral Source Voltage

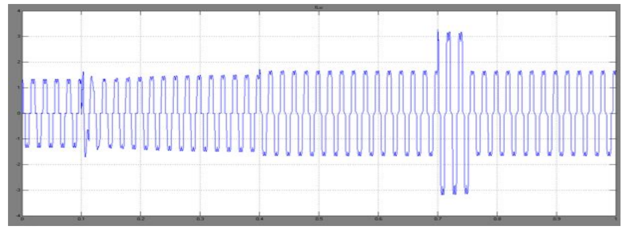

Fig:8 Load Current

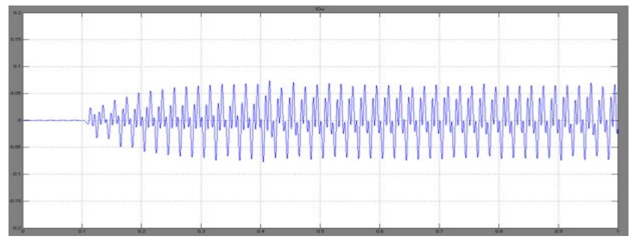

Fig:9 APF Output Current

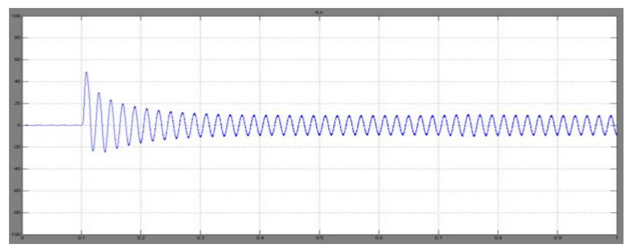

Fig:10 Load Neutral Current

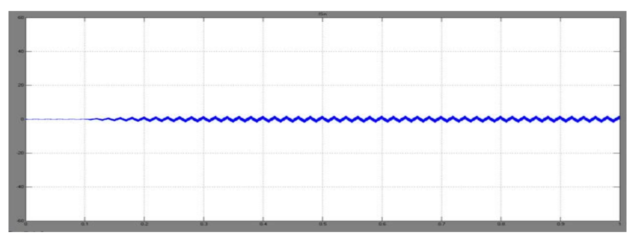

Fig.11: System Neutral Current

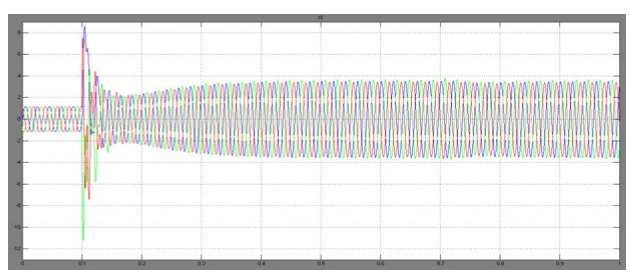

Fig12: System Currents

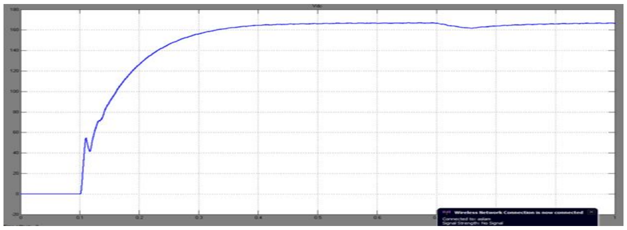

Fig13: Dc Voltage Converter

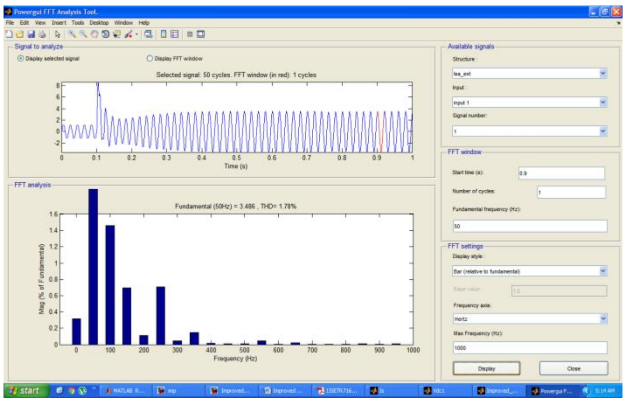

Fig14: FFT analysis of the source current after APF connection

VIII. CONCLUSION

The quality of electric power in power distribution system is improved by compensating current harmonics and current unbalance and reactive power compensation. The use of a predictive control algorithm for the converter current loop proved to be an effective solution for active power filter applications, improving current tracking capability, and transient response. The predictive current control algorithm is a stable and robust solution. Programmable voltage source in power generation system detects oscillations and current spikes and stabilizes the load profile. Simulated results have shown the compensation effectiveness of the proposed active power filter.

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