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Power Quality Enhancement by Using Multilevel Shunt Active Power Filter with Renewable Energy Sources

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Abstract-A Multi-Level Inverter (MLI) based Shunt Active Power Filter(APF) is considered in this paper. Single MLI-APF is used as both Interfacing converter that processes and connects generated PV power to grid and also for improvement of power Quality of the Whole system. As Majority of the Renewable systems comprises at least two converters for these tasks, the proposed system may be treated as simple and economical in meeting the same objectives. Use of MLIs reduces stress on power electronic devices because they can be made to operate at low voltages compared to the conventional two level converters. The output voltage provided by MLIs has small voltage steps, that results in good power quality and low-harmonic components. Peak detection method of control strategy is employed in MLI-APF for power quality improvement. The proposed system is simulated using MATLAB/SIMULINK.
Keywords-shunt active power filters (SAPF), power quality (PQ), renewable energy sources (RES).

I. INTRODUCTION

Use of Photo voltaic systems for meeting power crisis has become general interest of system engineers in these days. PV systems supply real power from PV cells and demands reactive and Harmonic power simultaneously through power electronic converters thereby imposes power quality threats on the whole system. Effective power quality improvement methods to maintain the Quality of power is therefore became necessary. Many research efforts have been reported in present days to improve the power quality of PV systems. Usage of Shunt Active Power Filter (SAPF) is a solution for these problems and is responsible for compensation of harmonics and correction of the power factor of the system. Shunt APF operate as controlled current sources injecting current harmonic components to the power is distribution system. The main control objective of SAPF consists of generation of reference current wave form for each phase and driving the inverter by generating gating signals to track this reference wave form. Have presented a review on classification of active filters for power quality improvement based on converter type, topology and the number of phases.

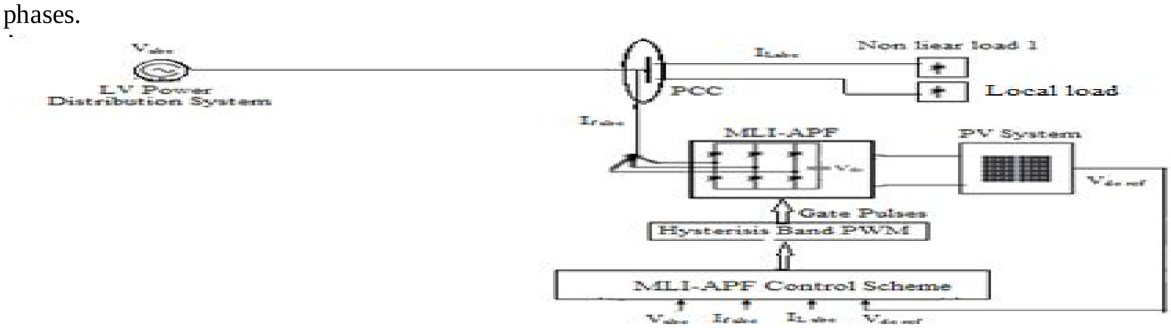

Figure 1: Schematic diagram of the proposed system.

II. SHUNT ACTIVE POWER FILTER (SAPF)

Active filters are special equipments that use power electronic converters to compensate for current and/or voltage harmonics originated by non-linear loads, or to avoid that harmonic voltages might be applied to sensitive loads. There are basically two types of active filters: the shunt type and the series type. It is possible to have active filters combined with passive filters as well as active filters of both types acting together.

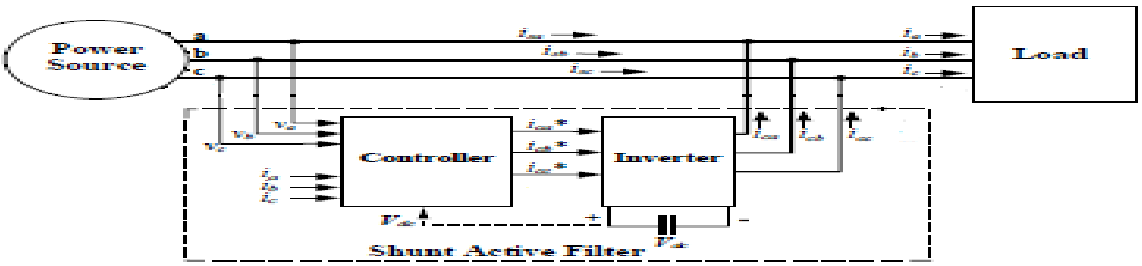

Figure 2: The basic block diagram of three phase three wire shunt active power filter.

Figure:2 presents the electrical scheme of a shunt active filter for a three-phase power system. which, can both compensate for current harmonics and perform power factor correction. Furthermore, it allows load balancing. The power stage is, basically, a voltage-source inverter with only a single capacitor in the DC side (the active filter does not require any internal power supply), controlled in a way that it acts like a current-source. From the measured values of phase voltages (*va*, *vb*, *vc*) and load currents (*ia*, *ib*, *ic*), the controller calculates the reference currents (*ica**, *icb**, *icc**) used by the inverter to produce the compensation currents (*ica*, *icb*, *icc*). This solution requires 6 current sensors and 4 voltage sensors, and the inverter has 4 legs (8 power semiconductor switches). For balanced loads without 3rd order current harmonics (three-phase motors, three-phase adjustable speed drives, three-phase controlled or non-controlled rectifiers, etc) there is no need to
compensate for the current in neutral wire. These allow the use of a simpler inverter (with only three legs) and only 4 current sensors. It also eases the controller calculations.

III. CONTROLLER FOR SAPF

The proposed control system consists of reference current control strategy using SRF method and triangular periodical current modulator for switching signals of cascaded VSI.

A. SRF Control Strategy

The synchronous reference frame theory is developed in time-domain based reference current generation techniques. The SRF is performing the operation in steady-state or transient state as well as for generic voltage and current; it's capable of controlling the active power filters in real-time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The block diagram of the synchronous reference frame controller is shown in Fig 4.

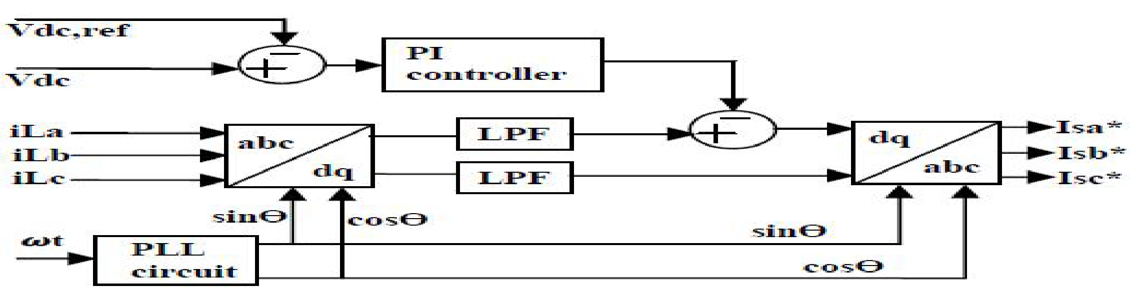

Figure3: synchronous reference frame theory.

The basic structure of SRF methods consists of direct (d-q) and inverse (d-q)-1 park transformations, which allow the evaluation of a specific harmonic component of the input signals. The reference frame transformation is formulated from a three-phase *abc* stationery system to the two-phase direct axis *(d)* – quadratic axis *(q)* rotating coordinate system. In a-b-c stationary axes are fixed on the same plane and separated from each other by 120º. These three phase space vectors stationary coordinates are easily transformed into two axis d-q rotating reference frame. This proposed algorithm derivate from a three phase stationary coordinate load current iLa, iLb, iLc are convert to id-iq rotating coordinate current, as follows

$$i_d = \frac{2}{3}\left[i_{La}\sin(\omega t) + i_{Lb}\sin\left(\omega t - \frac{2\pi}{3}\right) + i_{Lc}\sin\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (1)$$

$$i_q = \frac{2}{3}\left[i_{La}\cos(\omega t) + i_{Lb}\cos\left(\omega t - \frac{2\pi}{3}\right) + i_{Lc}\cos\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (2)$$

The d-q transformation output signals depend on the load currents (fundamental and harmonic frequency components) and the performance of the phase locked loop. The PLL circuit of rotation speed (rad/sec) of the rotating reference frame ωt set as fundamental frequency component. The PLL circuit is providing sinθ and cosθ for synchronization. The id-iq current passed through low pass filter (LPF) for filtered the harmonic components and allows only the fundamental frequency components. The LPF design is based on Butterworth method and the filter order is 2. The band edge frequency is selected the fundamental of 50 Hz for eliminate the higher order harmonic components. Proportional Integral (PI) controller is used to eliminate the steady state error of the DC-component of the cascaded multilevel inverter and maintains the dc-side capacitor voltage constant. The dc capacitor voltage is sensed and compared with reference voltage for calculate the error voltage. These error voltages involved the P-I gain (KP=0.1 and KI=1) for regulate the capacitance voltage in the dynamic conditions. In accordance to the PI controller output is subtracted from the direct axis (d-axis) of harmonic component for eliminate the steady state error. The algorithm is further developed to the desired reference current signals in *dq* rotating frame is converted back into *abc* stationery frame. The inverse transformation from *dq* rotating frame to *abc* stationery frame is achieved by the following equations

$$i_{sa}^* = i_d \sin\omega t + i_q \cos\omega t \quad (3)$$

$$i_{sb}^* = i_d\left[\sin(\omega t - {}^{2\pi}/_3)\right] + i_q\left[\cos(\omega t - {}^{2\pi}/_3)\right] \quad (4)$$

$$i_{sc}^* = i_d\left[\sin(\omega t + {}^{2\pi}/_3)\right] + i_q\left[\cos(\omega t + {}^{2\pi}/_3)\right] \quad (5)$$

The reference frame is rotates synchronous with fundamental currents. Therefore, time variant currents with fundamental frequencies would be constant after transformation. Thus, currents would be separated to DC and AC components. AC components of d-axis and in q-axis current are used for harmonics elimination and reactive power compensation. In recent years, multilevel converters have shown some significant advantages over traditional two-level converters, especially for high power and high voltage applications. In addition to their superior output voltage quality, they can also reduce voltage stress across switching devices. Since the output voltages have multiple levels, lower d*v/dt* is achieved, which greatly alleviates electromagnetic interference problems due to high frequency switching. Over the years most research work has focused on converters with three to five voltage levels, although topologies with very high number of voltage levels were also proposed. In general, the more voltage levels a converter has the less harmonic and better power quality it provides. However, the increase in converter complexity and number of switching devices is a major concern for multilevel converter.

There are several topologies available, being the Neutral Point Clamped, Flying Capacitor and Cascaded H-bridge inverter the most studied and used. In recent years many variations and combinations of these topologies have been reported, one of them is the cascaded H-bridge.

IV. MULTILEVEL INVERTER

A. Cascade Inverter Configuration

1) Single-Phase Structure: To synthesize a multilevel waveform, the ac output of each of the different level H-bridge cells is connected in series. The synthesized voltage waveform is therefore, the sum of the inverter outputs. The number of output phase voltage levels in a cascaded inverter is defined by

$$m = 2s + 1 \quad (6)$$

Where *s* is the number of dc sources. For example, a nine-level output phase voltage waveform can be obtained with four-separated dc sources and four H-bridge cells. Figure 4 ,shows a general single-phase *m*-level cascaded inverter. From Figure 4, the phase voltage is the sum of each H-bridge outputs and is given as

$$V_{AN} = V_{dc1} + V_{dc2} + V_{dcs} + \cdots + V_{dc(s-1)} \quad (7)$$

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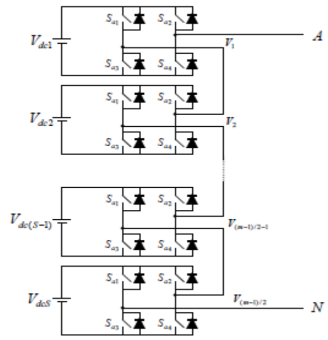

Figure4:single phase configuration of an m-level cascaded inverter.

Because zero voltage is common for all inverter outputs, the total level of output voltage waveform becomes 2*s*+1. An example phase voltage waveform for a nine-level cascaded inverter and all H-bridge cell output waveforms are shown in Figure.5 In this thesis, all dc voltage are assumed to be equal. That is

$$V_{dc1} = V_{dc2} = \cdots V_{dc(s-1)} = V_{dcs} = V_{dc} \qquad (8)$$

V. PV SYSTEM

Solar energy is the radiant energy that is produced from the sun.every day the sun radiates,or sends enormous amount of energy.The sun radiates more energy in one second than people have used since the beginning of the time. The common denominator of PV cells is that a p–n junction, or the equivalent, such as a Scotty junction, is needed to enable the photovoltaic effect Understanding the p–n junction is thus at the heart of understanding how a PV cell converts sunlight into electricity. Photons of light with energy higher than the band-gap energy of PV material can make electrons in the material break free from atoms that hold them and create hole electron pairs, These electrons, however, will soon fall back into holes causing charge carriers to disappear. If a nearby electric field is provided, those in the conduction band can be continuously swept away from holes toward a metallic contact where they will emerge as an electric current. The electric field within the semiconductor itself at the junction between two regions of crystals of different type, called a p-n junction [4, 8].

Mathematical modeling of a PV cell:

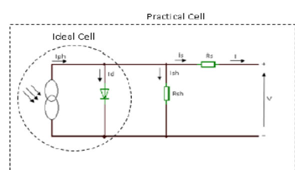

Figure: 5 General model of PV cell in a single diode model.

Photovoltaic module is formed by connecting many solar cells in series and parallel. Considering only a single solar cell; it can be modeled by utilizing a current source, a diode and two resistors. This model is known as a single diode model of solar cell. Two diode models are also available but only single diode model is considered here . The same modeling technique is also applicable for modeling a PV module. The equivalent electric circuit diagram of PV cell is shown in Figure:5 which consists of a photocurrent source, a diode, a parallel resistor. Also called shunt resistor (Rsh) expressing a leakage current and a series resistor (Rs) describing internal resistance to the current flow.The PV cell‘s electrical characteristic under solar Irradiance (S) is given in terms of PV cell output current (I) And PV cell voltage (V). Refers to figure:5.

A. Ideal Solar Cell Characteristics:

An ideal solar cell can be represented by a current source connected in parallel with a rectifying diode, as shown in the equivalent circuit of Figure 5. The corresponding I-Characteristic is described by the Shockley solar cell equation

$$I = I_{ph} - I_d = I_{ph} - I_0\left(e^{\frac{qV}{kT}} - 1\right) \qquad (9)$$

$$I = I_{ph} - I_d - I_{sh} \qquad (10)$$

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Where

$$I_{\square}{}_{ph} = I_{\downarrow}{}_{scr} + [k_{\downarrow}i\,(T - T_{\downarrow}r)](s/r) \quad (11)$$

$$I_d = I_0\left[\frac{\exp V_d}{V_t} - 1\right] \quad (12)$$

$$I = I_{\downarrow}(0,r)\,(\square T/T_{\downarrow}r)\square^{\uparrow}3\,\exp[(qE_{\downarrow}g)/nk(1/T_{\downarrow}r - 1/T)] \quad (13)$$

$$E_g = E_{g0} - \frac{\propto T^2}{T + \beta} \quad (14)$$

$$V_t = \frac{nkT}{q} \quad (15)$$

$$T_v = (T_{v1} - 32) + 273 \quad (16)$$

$$V_{sh} = V_d \; and \; V_d = V + IR_s \quad (17)$$

$$I_{sh} = \frac{V_{sh}}{R_{sh}} = \frac{V_d}{R_{sh}} = \frac{V + IR_s}{R_{sh}} \quad (18)$$

Then;

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{\frac{nkT}{q}}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (19)$$

VI. SIMULATION AND RESULTS

The experimental analysis for the three phase three wire system without SAPF,with SAPF and with multi level shunt active power filters are given below simulation using SIMULINK/MATLAB.

A. Case 1:Simulation For System Without SAPF

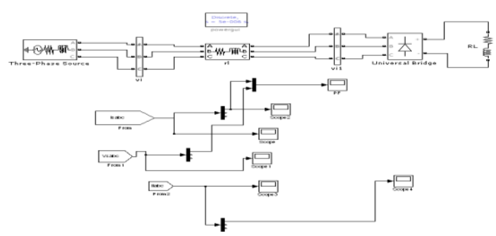
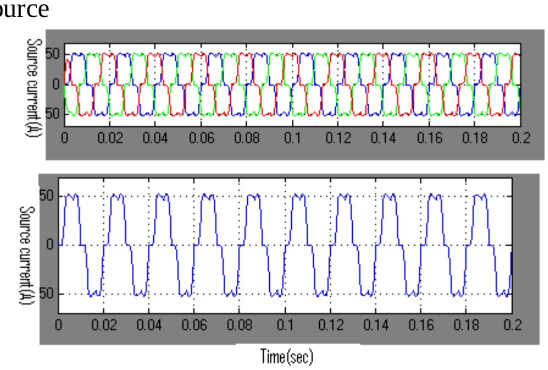


Figure:6 Simulation diagram for system without shunt active power filter.

Figure:6 shows the simulation diagram for three phase three wire system without shunt active power filter.Here the source is three phase supply source.The voltage is 415volts consider as input. Here universal bridge is consider as inverter and RL load is connected to it.Figure10.a shows the source



7a Source currents of three phase and single phase without SAPF.

current wave forms for three phase and single phase respectively.10.b shows the load current wave forms for three phase and single phase respectively.

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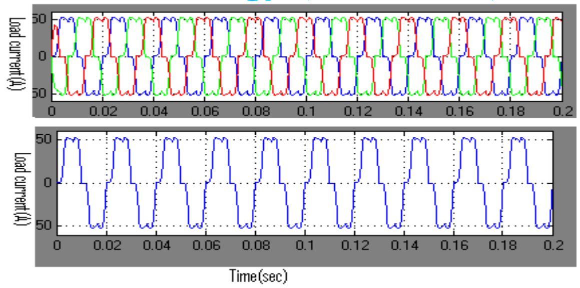
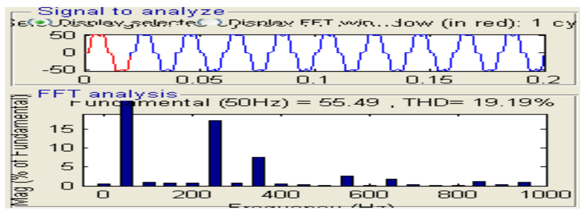


7.b Load currents of three phase and single phase without SAPF.



7.c FFT analysis of phase A.

Figure:7 simulation results for system without shunt active power filter and FFT analysis for source current of phase A.

Figure 7.c shows the FFT analysis of source current for phase A. The total harmonic distortion of the system without shunt active power filter is 19.19%.For reducing this total harmonic distortion percentage different levels in shunt active power filters are consider. Among different levels in this paper two level and five levels shunt active power filters are used.

B. Case 2: System with Two Levels SAPF

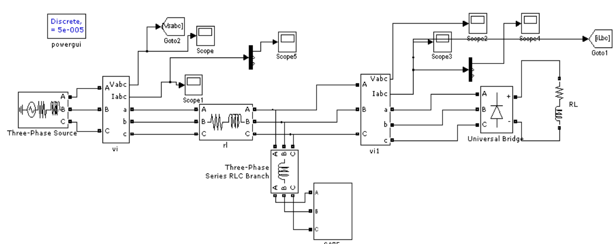
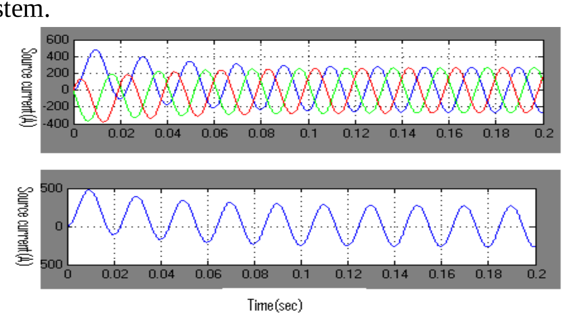


Figure: 8 Simulation diagram for system with two levels SAPF.

Figure 8 shows the power system with non-linear load along with two level shunt active power filter. The inverter consists of RL load and the inverter along with RL load consider as a non-linear load. Using two level shunt active power filter we can get out put which is harmonic free compared with previous one. Figure 12.a shows the source current wave forms after the connection of two level shunt active power filter to the system.



9.a Source currents of three phase and single phase with SAPF.

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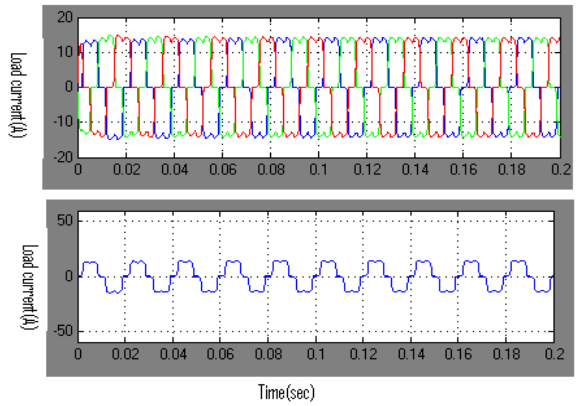
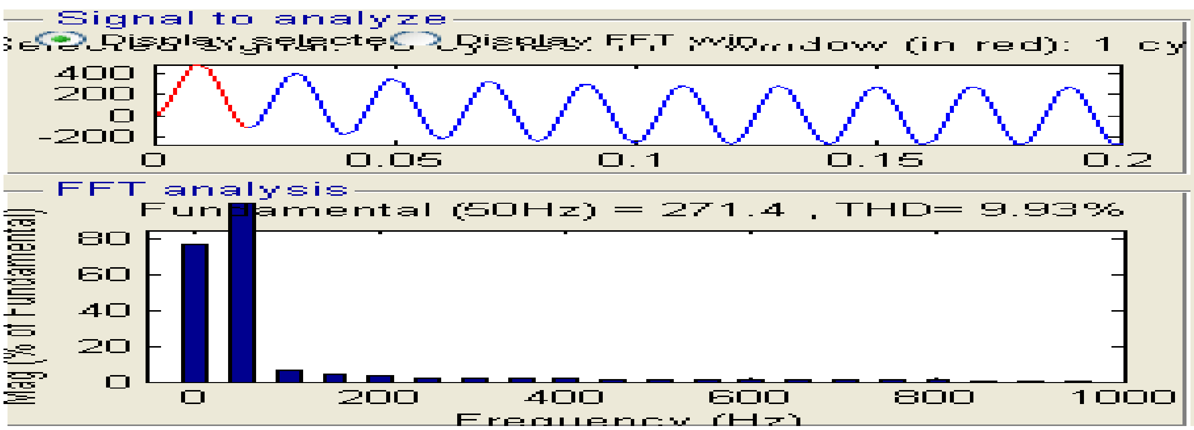
For reducing total harmonic distortion (THD) percentage two levels shunt active power filter is used. Harmonics in source can be reduced using this two levels shunt active power filter.



9. b Load currents of three phase and single phase with two level SAPF.

Figure 9.c shows the load current wave forms for the system with two levels shunt active power filter. Here harmonics in load side are common due to non –linear loads. So for reducing harmonics at source side shunt active power filters are used. Figure 12.c shows the total harmonic distortion percentage with two levels shunt active power filter. The total harmonic distortion percentage occurs is 9.93%.which is less than system without shunt active power filter.



9. c FFT analysis of two level SAPF for phase A.

Figure: 9 simulation results for system with shunt active power filter and FFT analysis for source current of phase A.

C. Case 3: System Of Five Level SAPF With PV Array

Figure 10 shows the simulation diagram for system with five levels shunt active power filter along with PV array.

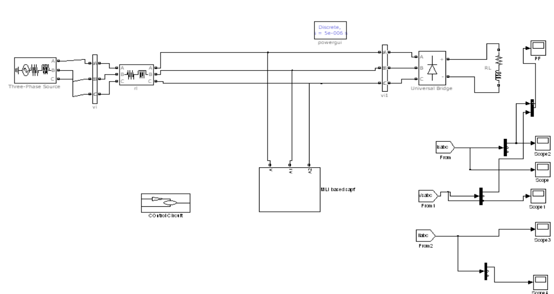


Figure: 10 Simulation diagram for system with five level shunt active power filter with PV array.

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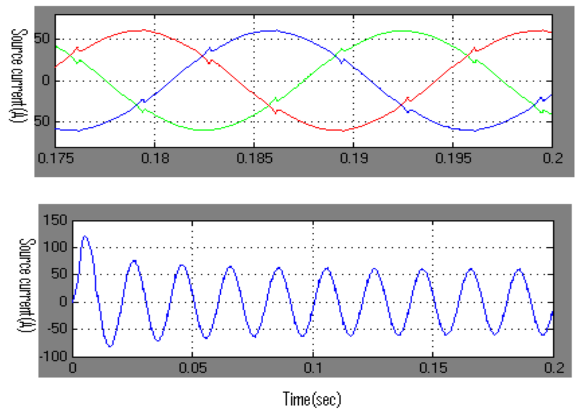
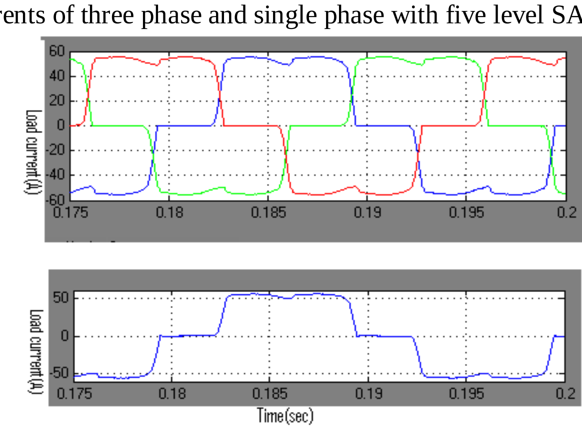
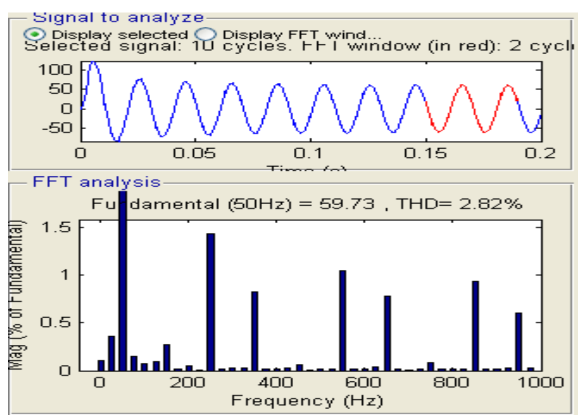
In five level shunt active power filter increasing number of levels reduces the harmonics and total harmonic distortion percentage. In the system without shunt active power filter total harmonic distortion percentage is high. In the system having two levels shunt active power filter some percentage of total harmonic distortion is reduced due to two levels shunt active power filter compared with system without shunt active power filter. Figure 11.c shows the source current wave forms for three phase and single phase respectively. Here total harmonic distortion is less due to increasing number of levels. Figure 11.b shows the load current wave forms for three phase and single phase. Figure 11.c shows the FFT analysis for five levels shunt active power filter of phase A. Here total harmonic distortion is reduced due to increased number of levels. The total harmonic distortion is 2.82%.which is less than the total harmonic distortion percentage of system with two levels shunt active power filter.



11.a Source currents of three phase and single phase with five level SAPF and PV system.



11.b Load currents of three phase and single phase with five level SAPF and PV system.



11.c FFT analysis of five level SAPF for phase A.

Figure: 11 simulation results for system with five level shunt active power filter ,PV array and FFT analysis for source current of phase A

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VII. CONCLUSION

The shunt active power Filter presented is capable to use energy from a renewable source and in the same time to improve the power quality indicators on grid. Proposed system eliminates the usage of Separate converters for connection of PV cells and Compensation of current harmonics. To make a move towards the improvement of harmonic performance, the existing two level converter of PV system has been replaced by Multi Level Inverter. The results obtained reveals that for the same operating conditions of PV system the THD of source currents is improved considerably in five level converter compared to two level.

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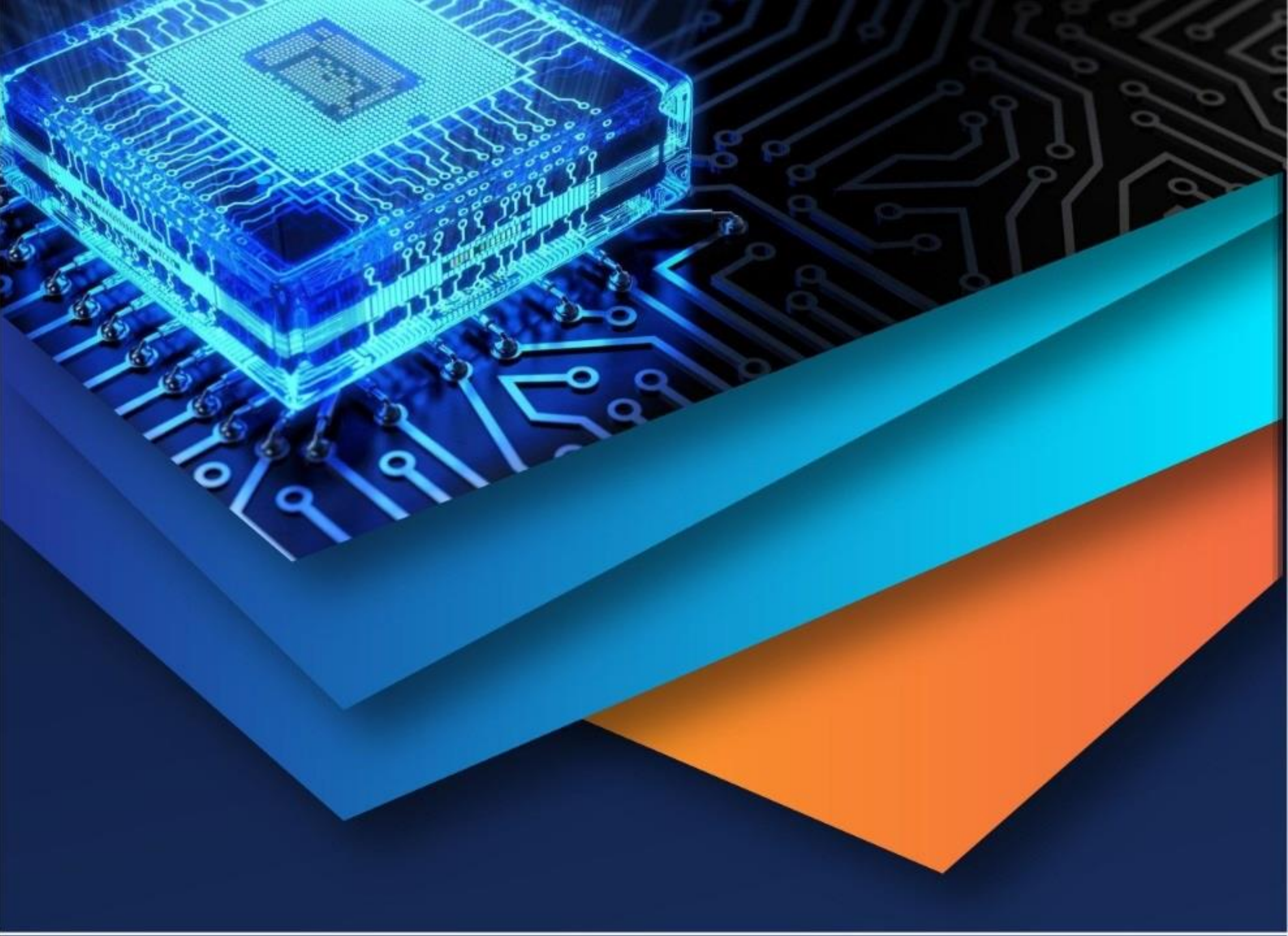

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