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Harmonic Mitigation of Fluctuating Non Linear Load in a Grid connected Photovoltaic system

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***Abstract*-- This paper presents improvement in power quality in a grid connected with non conventional energy source and nonlinear load. Three phase shunt active filter is proposed for improvement in power quality. Harmonic are declining power quality which is to be filtered. Present day energy demand is very high and conventional energy sources are costly and pollute environment. Renewable source of energy are emerging with new technology. This paper presents the model of PV panels connected with voltage source inverter, which are stepped up by transformer and is fed to the grid.**

Here Shunt active filter is implemented with voltage source inverter and dc link capacitor. Synchronous reference frame method is implemented for current control in shunt active filter. Filter can efficiently respond to sudden change in load is depicted in this paper. THD is not much affected with sudden change in load. Active power transfers from PV connected inverter to the grid through transformer.

Index Terms — Photo Voltaic, Power Quality, Shunt Active Filter, Synchronous Reference frame.

I. INTRODUCTION

Electric Energy system is most convenient source of energy transfer. It has been adapted to number of uses. Conventional sources are limited and endanger environment. Hence renewable energy sources like wind energy, solar energy, tidal energy are preferred for electric power generation. Abundant amount of renewable source are available free in atmosphere. Technologies are invented to tap them at its maximum. In the proposed paper PV panels is discussed for tapping solar energy from sun. PV cells can generate electric power from solar energy by use of semiconductor device name photovoltaic cell. Power output of single cell is very low. So series and parallel combination of this individual cell can generate a reasonable output. Such combinations are called PV arrays [1]. These arrays are generating DC power. This DC power cannot be directly used for general purpose. Hence Inverters are implemented to convert DC power to AC power of rated frequency and rated voltage. These inverter either supply directly to the system or voltage is stepped up by transformer and then connected to system. They can be connected parallel to grid or can work in standalone mode. Solar energy is available in abundant and free but its reliability is very less due to atmospheric changes like rain and clouds. So standalone system will stop working during rainy climate. Hence it will become more reliable if connected to grid. Again if these renewable sources are connected in grid, then power exchange is possible using power electronics. Due to power electronic interfacing large amount of harmonics are injected in power system. Moreover major load connected with system is either nonlinear load or power electronic gadgets, which are again sources of harmonics.

Harmonics are integral multiple of fundamental power line frequency. Total Harmonic Distortion is the contribution of all harmonic frequencies to fundamental. This Harmonic distortion is considered genus of pollution in electric system which creates problems if THD level exceeds a definite limit. Due to this harmonics current waveform gets distorted. Voltage distortion is resulted when harmonic current interact with system impedance. When these distortions reach at common point of coupling (PCC) they degrade power quality and cause fatal problems on high precision load. Harmonics severely affects system if not eliminated. There are standards set for evaluating and limiting harmonics by IEEE Standards. According to IEEE 519-1992 standards THD at common point of coupling (PCC) should be or less than 5%. THD can be represented by harmonic spectrum which reveals the dominancy of particular harmonic. Overheating of transformer, blown shunt capacitor fuse, false meter reading, interference are classic examples of faults due to harmonics.

Harmonic filter are used to eliminate harmonics. Passive filters are traditional solutions to filter harmonic content. Passive filters are combination of inductance (L) and capacitor (C) connected in series and parallel are tuned to harmonic of a particular frequency. Moreover due to impedance matching of line with harmonic filter can lead to resonance. Passive filters have high efficiency low cost and simple. With this advantage they do have some limitations. They cannot work effectively with varying load condition which is prior requirement. Construction wise they are bulky and their life span is also less due to load harmonics.

Drawbacks of Passive filters are overcome by Active filters. With invention of high rating power electronic devices Active filter came into existence. It can also improve power factor of system with appropriate control scheme and can eliminate time dependent harmonics in system with variable nonlinear load. An active filter balances unbalanced loading conditions.

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Active filters are designed with different topologies depending on the types of configurations and supply system. Table I shows classification of Active filter based on different criteria.

TABLE I. Active Filter Classification

Converter based classification	• VSI (Voltage Source Inverter) • CSI (Current Source Inverter)
Topology base classification	• Shunt APF • Series APF • UPQC: Shunt APF + Series APF • Hybrid APF: Series or Shunt Active Filter with Passive Filter
Supply system based classification	• Two wire APF • Three wire APF • Four wire APF

In this paper Shunt Active Filter with Voltage source inverter topology is implemented. Shunt active filter is less bulky than series active filter and is reliable for low to medium KVA load. Moreover it form power factor displacement problem. Load or supply inductance (L) does not affect its compensation capabilities and has simple control implementation. Protection and sequencing is quite easy and expensive switchgears are least necessitate.

Many control strategies are implemented for the control of filter. These control systems are either time domain or frequency domain. It is very essential to have suitable controller designed for shunt active filter. There are few methods like Instantaneous reactive power theory, direct control method, hysteresis current control method, Fuzzy controllers, synchronous reference frame theory, dead beat control method, d-q method are used for controlling Shunt active filter. In this paper we have discussed synchronous reference frame theory. This method is more efficient as it can easily extract both reactive and active power and can generate a sinusoidal reference current signals that has to be injected in the SAPF. It also regulates and balance dc link capacitor voltage.

II. PHOTOVOLTAIC PANELS AND INVERTER SYSTEM

2.1.PV Panels

PV panels are made of single unit of photovoltaic cell. This cell is a Semiconductor p-n junction diode. Heat and Light radiated from sun generate free electrons in proportion to the light intensity. Electromotive force is generated at their terminals. Current flow in cell depends on number of free electrons which depend on sun radiation.

Single PV cell can generate power up to 2W at 0.5 volt. This power being very low series and parallel combination of PV cells is done to generate enough power. PV panels are group of several modules. Matlab simulation of PV panels is discussed in this paper with mathematical equation and parameters. PV module with constant current and constant insolation is considered [3]. Mathematical equations and circuit with characteristics are shown in Fig.1.Simulink model of single PV panel with PV and VI characteristics is shown in Fig.2, Fig.3, and Fig.4. Electrical parameter and radiation data along with inverter design parameter are shown in Table II.

$$I_{pv} = I_p - I_D - I_{sh} = 0 \quad (1)$$

$$V_{PVcell} = V_D - R_S I_{PV} \quad (2)$$

$$I_{sh} = \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (3)$$

$$I_D = I_0 (e^{\frac{q(V_{pv}+R_s I_{pv})}{NkT}} - 1) \quad (4)$$

I_p = Light generated current
V_{pv} = Terminal voltage of the cell
I_D = Diode current
I_o = Saturation current
I_{sh} = Shunt current

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q = Electron charge
k = Boltzmann constant
T = Temperature
R_s = Series Resistance R_{sh} = Shunt Resistance

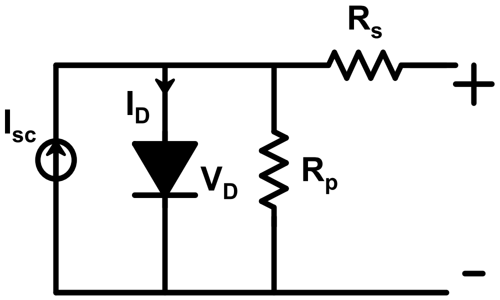

Fig.1. PV Cell internal circuit

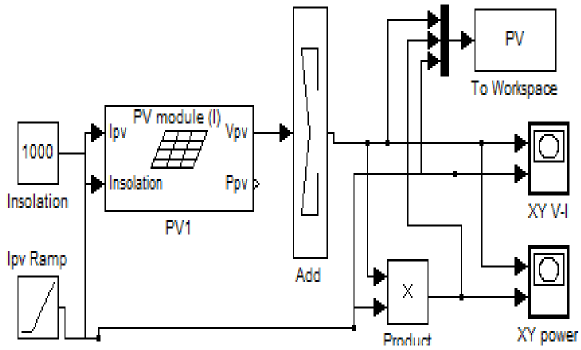

Fig.2. Matlab model of single PV array

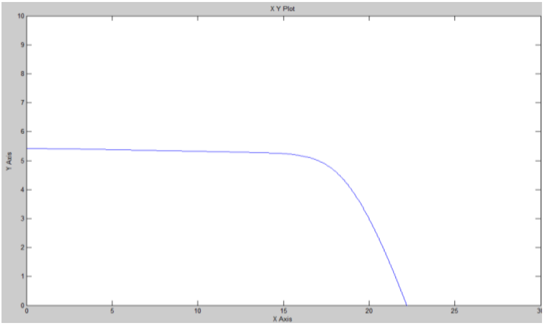

Fig.3. V-I Characteristics of single PV array

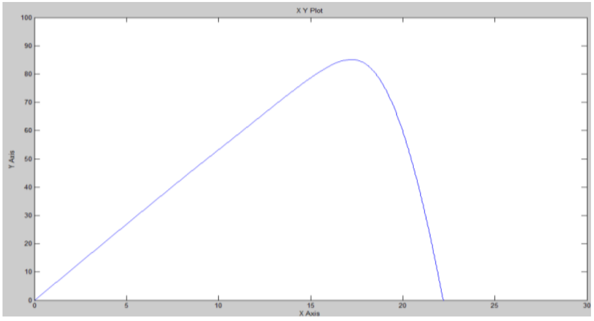

Fig.4. PV characteristics of single PV array

2.2.PV connected Inverter.

PV arrays are connected in series to build up voltage level. DC Voltage generated from PV arrays. This voltage is converted to AC using Inverter topologies. High efficiency inverter module is desired to be utilized in PV system since power loss in inverter is power not supplied to grid. In this paper simulink model of Voltage sourced discrete PWM inverter is considered with three phase IGBT based bridge configuration. Output of inverter is filtered using LC filters. This filtered output is fed to transformer [2]. Output of transformer is then connected to grid. Single line diagram of PV system connected with inverter and grid is shown in Fig.5.

Table II Parameters for simulink model of PV Panel connected with inverter

No of PV panels	20 panels
Insolation	1000 w/m^2
V_{oc} per panel	35
I_{sc} per panel	7
Total V_{dc}	400
Filter Inductor	60 mH
Frequency	50 Hz
Grid voltage	415 Vrms
Total Peak power	15 kW

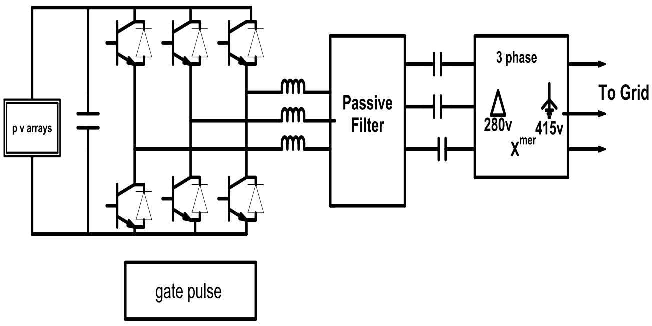

Fig.5. PV system connected to grid with 3-ph inverter

III. SHUNT ACTIVE FILTER AND CONTROL STRATEGY

In this paper shunt active filter is discussed as harmonic filtering tool. Harmonics as discussed distorts waveforms and leads to malfunction of several equipments. SAPF is connected in parallel with the load. Generally filters are placed near load end for better results. Inverse harmonic current is generated by shunt active filter is injected in the line which nullifies harmonic current generated from the load end [4]. In other words load harmonic current is injected with 180^0 phase shift by shunt active filter. Simulink model of shunt active filter connected to grid with non linear load is discussed in this paper.

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Grid is fed with a Voltage source and solar power plant. Effect of sudden change in load on filter is also discussed in this paper. Fig. shows single line diagram of a shunt active filter connected with load and solar power plant connected to grid. Proposed simulink model of shunt active filter comprises of IGBT based three phase Voltage source inverter having bridge configuration. Bridge rectifier with RL load is seen as non linear load. Synchronous reference frame theory is implemented as current control technique to generate reference current and gating signals for VSI. Fig.7 shows line diagram of Shunt Active Filter connected to RL load [5]. Filter design parameters are shown in table III

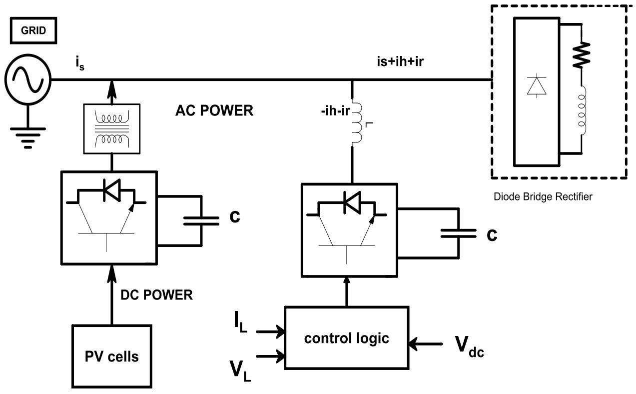

Fig.7. Proposed model of SAPF with PV system

Equation for power drawn by nonlinear load connected to grid is

$$P_L(t) = P_F(t) + P_h(t) \quad (5)$$

Compensated power supplied by active filter

$$P_c(t) = P_h(t) + P_{loss}(t) \quad (6)$$

Instantaneous AC voltage equation is

$$V_s(t) = V_m \sin wt \quad (7)$$

Equation for supply current with compensation

$$i_s(t) = i_l(t) + i_c(t) \quad (8)$$

Load current with fundamental current component and several harmonics of odd and even order is represented and Fourier series [6].

$$i_L(t) = \sum_{n=1}^{\infty} \sin(nwt + \emptyset_n) \quad (9)$$

$$i_L(t) = I_1 \sin(wt + \emptyset_1) + \sum_{n=2}^{\infty} \mathrm{I}_n \sin(nwt + \emptyset_n) \quad (10)$$

Here first part is fundamental component and rest part is harmonic current which is to be filtered.

In this proposed model synchronous reference frame theory is implemented for reference current generation. This control technique is based on co ordinate transformation which separates harmonic component from load current. This separated harmonic component is inverted by VSI and is fed to line. Co ordinate transformation implements Clark's Transformation and Park's Transformation. Load current extraction is achieved implementing low pass filter [7].

In reference frame transformation stationary three phase which are displaced 120^0 apart are transformed to rotating two phase named direct axis (d-axis) and quadratic axis (q-axis)

$$i_d = \frac{2}{3}\left[i_{La}\sin(\omega t) + i_{Lb}\sin(\omega t - \frac{2\pi}{3}) + i_{Lc}\sin(\omega t + \frac{2\pi}{3})\right] \quad (11)$$

$$i_q = \frac{2}{3}\left[i_{La}\cos(\omega t) + i_{Lb}\cos(\omega t - \frac{2\pi}{3}) + i_{Lc}\cos(\omega t + \frac{2\pi}{3})\right] \quad (12)$$

Rotation of this component is made possible using PLL circuit which provides sin component to direct axis and cos component to quadratic axis for synchronization.

This current then passes through low pass filter to filter harmonic component. Butterworth filter of 2^{nd} order is implemented for LPF to eliminate higher order harmonics. Block diagram representing synchronous reference frame theory is shown in Fig 8.

DC bus PI controller is implemented to regulate dc voltage of capacitor constant to its reference value. DC voltage of capacitor s compared with reference voltage and error is calculated under dynamic condition. Error signal is fed to d-axis

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to extract harmonic component. After extraction of harmonic component d-q rotating axis is converted back to a-b-c stationary frame using inverse transformation.

$$i_{sa}^{*} = i_d \sin(\omega t) + i_q \cos(\omega t) \quad (13)$$

$$i_{sb}^{*} = i_d \sin(\omega t - 2\pi/3) + i_q \cos(\omega t - 2\pi/3) \quad (14)$$

$$i_{sc}^{*} = i_d \sin(\omega t + 2\pi/3) + i_q \cos(\omega t + 2\pi/3) \quad (15)$$

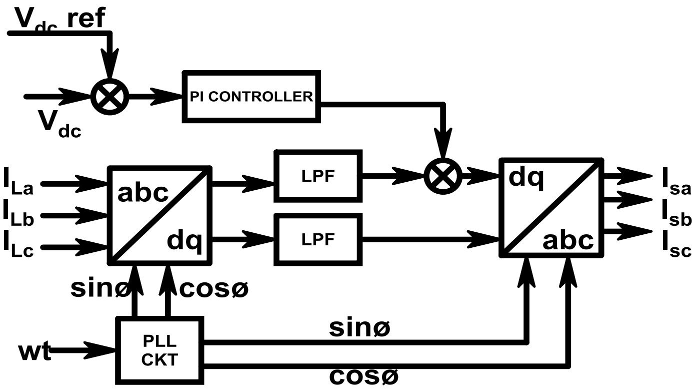

Fig.8. Block diagram of SRF control algorithm

IV. SIMULATION

Performance of the above discussed model of PV system and shunt active filter with SRF control logic is evaluated using Matlab simulink power tool. It includes shunt active filter, load, and PV inverter. Waveform of load current is shown in Fig 11, Fig 12 and Fig 13 shows filtered source current with rated load and with sudden change in load respectively. Compensated current generated from shunt active filter is shown in Fig 14. Voltage across DC link capacitor is shown in Fig.15.

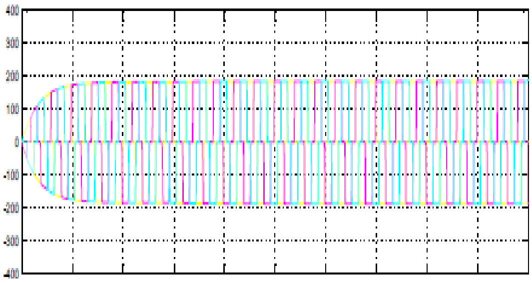

Fig.11. Load Current waveform with rated load

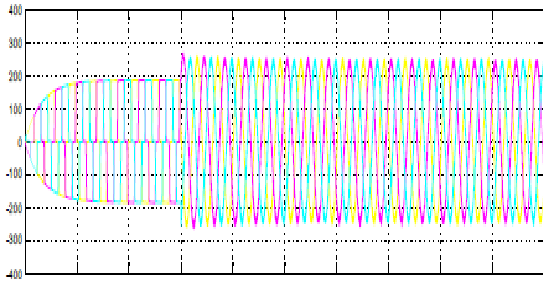

Fig.12. Source current waveform after filtering with rated load

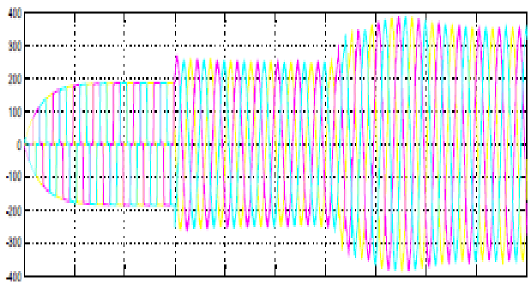

Fig.13. Source current with sudden change in load

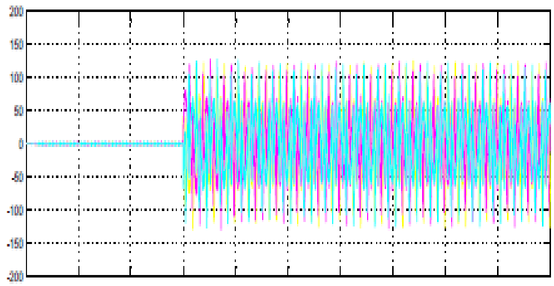

Fig.14. Compensating current

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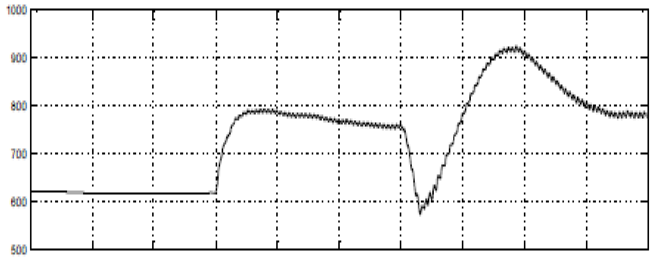

Fig.15. Voltage across capacitor

Fast Fourier Transform is tool to evaluate harmonic content with respect to fundamental frequency. Order of harmonic in system before filtering is shown in Fig.16. After compensation and with sudden change in load is shown in Fig.17 and Fig.18.There is minor effect with sudden increase in load during filtering but THD level remains within IEEE limits.

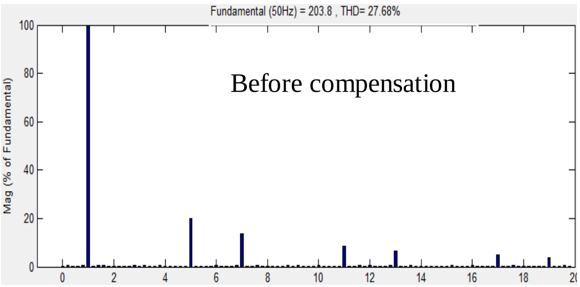

Fig.16. THD in source current before filtering (27.66%)

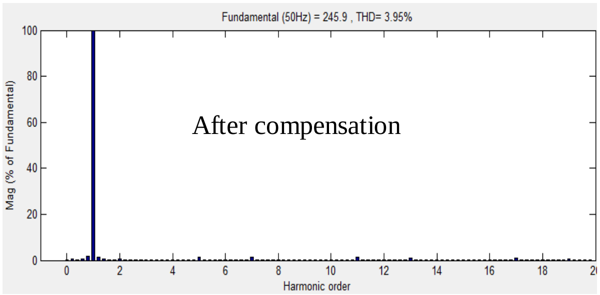

Fig.17. THD in source current after filtering (3.95%)

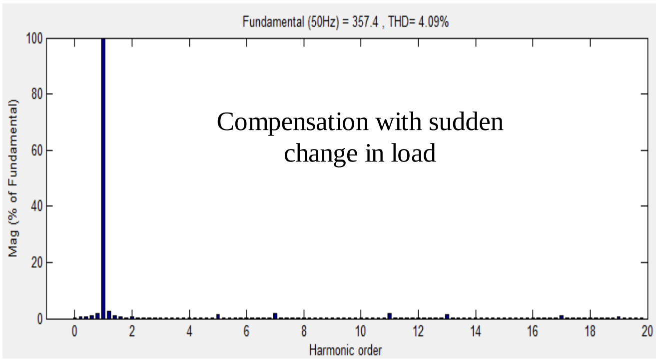

Fig.18. THD in source current with increase in load during filtering (4.09%)

V. CONCLUSION

This paper identifies the need of harmonic filtering when grid is loaded with nonlinear load and interfacing with renewable energy sources. Here solar panels are connected with grid as renewable energy source. Using Shunt Active harmonic filter total harmonic distortion can be brought within limits.Synchronous reference frame is used as control techniques for reference current generation which generates precise gating signals for the VSI of SAPF.

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