Harmonic Analysis of Three-phase Grid-connected Photovoltaic Inverter System

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Abstract - *This paper presents a simple, low cost, and effective technique for hysteresis current regulation to be implemented in three phase PWM grid connected PV inverter. This obtains a substantial reduction in the magnitude and variation of the switching frequency, subsequently improving efficiency, while retaining all of the advantages identified with hysteresis current control. LCL filters have good performances in current ripple mitigation, but they introduce a resonance frequency in the system. The operation and control of the inverter are described, together with simulation. The proposed controller has been verified in simulation using the Simulink package in Matlab. A design procedure of output LCL-filter for three-phase grid-connected Photovoltaic (PV) inverter system is presented in this paper. A comparison between the designed LCL-filter, lc-filter and L-filter based three-phase grid connected PV inverter system is presented in this paper. The comparison results are given to check the theoretical analysis and effectiveness of filters.*

Key Words: (Three phase hysteresis current controllers) LCL-filter, L-filter, grid-connected, Photovoltaic, Power Factor

1. INTRODUCTION

Over the past few decades, the demand for renewable energy has increased significantly due to the disadvantages of fossil fuels and greenhouse effect. Among various renewable energy sources the most popular one is solar energy [1]. Solar energy is plentiful worldwide, and the best way to produce electricity without pollution [2]. We can use solar PV systems for domestic use and store excess electricity in batteries for later use this is a Standalone PV System, or feed into the electricity grid to reduce the electricity bill [3-4]. In standalone PV system power electronic equipment and nonlinear loads are widely used and resulted serious harmonic problems. These harmonics are known as electrical disturbances which are the main cause of the power quality associated harms. Define harmonics is a signal or wave whose frequency is an integral (whole-number) multiple of the frequency of some reference signal or wave. The main problems due to the harmonics are additional power losses in the electrical equipment, irregular function of protective devices, errors in measurement of metering devices and interference with the telecommunication lines. [5]. from another side, mitigation of harmonics and improvement of the power quality is essential under the situation. [6]. in the previous several works have been presented regarding the harmonic mitigation by using different types of filters [7-10]. Filters can be active or passive filter Passive filters have a better stability and can withstand large currents relatively cheaper than active filters Low cost, simple design and high reliability are main advantages of passive filters [11]. LCL filters, which are particularly popular in the renewable energy industry today, are an efficient and economical way of ensuring and improving the quality commonly a high-order LCL filter has been used in place of the conventional L-filter for smoothing the output currents [12-13]. The LCL filter achieves a higher attenuation along with cost savings, given the overall weight and size reduction of the components. LCL filters have been used in grid-connected inverters and pulse-width modulated active rectifiers [12], because they minimize the amount of current distortion injected into the utility grid [14]. Good performance can be obtained in the range of power levels up to hundreds of kW, with the use of small values of inductors and capacitors [13]. The higher harmonic attenuation of the LCL filter allows the use of lower switching frequencies to meet harmonic constraints as defined by standards such as, IEEE-519 [15]. However, it has been observed that there is very little information available describing the systematic design of LCL filters. In order to design an effective LCL filter it is necessary to have appropriate mathematical model of the filter.

Compared with the L filter, the LCL filter is more attractive [16] because it can provide higher high frequency harmonics attenuation with the same inductance value, smaller size and cost, to obtain the same attenuation of commutation harmonics, reduction of electromagnetic interference, low grid current THD and reactive power production, and possibility of using a relatively low switching frequency. It also allows the inverter to operate in both standalone and grid-tie modes, which makes it a universal inverter for distributed generation applications.
The main contributions of this manuscript is to compare several schemes of three phase grid connected PV system with L filter LCL filter and doing harmonic analysis of these filtering methods. The Phase detection control methods are necessary to synchronize the inverter, and a fast and robust phase detector can reduce harmonics and increase the stability of the system.

2. System description

A number of PV cells are connected to form the PV module, which is connected either in series, Ns or parallel, Np to form a PV array. The output of voltage and current depended on the number of PV modules [17], and the solar irradiation level of the PV system respectively [18]. As shown in equation (1), the PV cell equation is used to build the PV module for the simulation model.

$$I=I_{ph}-I_o \{e^{(q\,(V+R\_sI)/AKT-1\}-(V+R\_sI)/Rsh} \quad (1)$$

Where Iph is the insolation current, I is the Cell current, Io is the Reverse saturation current, V is the Cell voltage, Rs is the Series resistance, Rsh is the Parallel resistance, K is the Boltzmann constant, T is the Temperature in Kelvin, q is the Charge of an electron, s is the solar radiation in mW/cm2.

The classical topological structure is shown in Fig 1. This topology is general use in three-phase PV grid-connected inverters. Where UDC is the voltage of DC bus, dc I is the current of DC bus, S1~S6 six-switch made up three-phase inverter, L1, Cs, L2 made up third-order LCL filter [19].

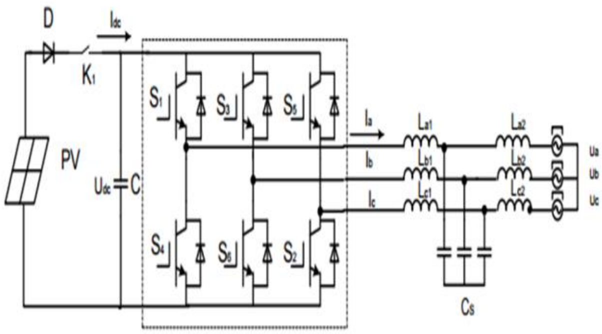

Fig -1: Topological structure of three-phase PV grid-connected inverters with LCL filter

3. Principle of passive filters:

First, grid-connected converters are the interface to connect renewable energy sources to the power system. To reduce the harmonics injected by the converters a high value of input inductance should be used. However, L filter design is easy but in application above several kilowatts it becomes expensive because of using large filter reactor. Moreover, the system dynamic response becomes poor. LC Filter consists of an inductance in series with the inverter and a capacitance in parallel with the grid Fig 2.

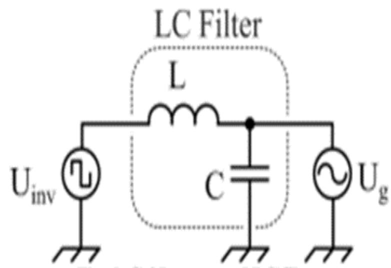

Fig -2: Grid-connected LC filter

By using this parallel capacitance, the inductance can be reduced, thus reducing costs and losses compare with L filter. By using a large capacitance, other problems such as high inrush currents and high capacitance current at the fundamental frequency or dependence of the filter on the grid impedance for overall harmonic attenuation will appear [20].
The LC filter transfer function of grid side voltage and inverter input voltage in grid-connected mode of operation is given in equation (2).

$$G(S) = \frac{U_S}{U_{inv}} = \frac{1}{s^2 LC+1} \quad (2)$$

An alternative and attractive solution of first and second order filter problems is to use an LCL filter as shown in Fig 3. With this solution, optimum results can be obtained in the range of power levels up to hundreds of kilovolt amperes, still using quite small values of inductors and capacitors [21].

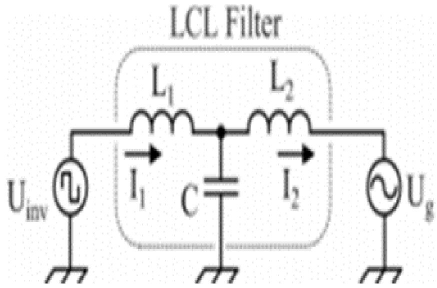

Fig -3: Grid-connected LCL filter

The LCL filter transfer function of line side current and inverter input voltage in grid-connected mode of operation is given in equation (3).

$$G(S) = \frac{I_2}{U_{inv}} = \frac{1}{s^3 L_1 L_2 C + (L_1+L_2)S} \quad \textbf{(3)}$$

The system consists of a PV module as the main component that generates DC power supply, which is built based on the datasheet specification as shown in Table 1 below.

Table -1: The Specification of PV module at STC (25℃, A.M 1.5, 1000 W/M2)

Parameter	Multi-Crystalline SPR-415E-WHT-D
Maximum Power ,Pmax	414.8 W
Voltage at Pmax, Vmpp	72.9V
Current at Pmax, Impp	5.69 A
Open-circuit Voltage, Voc	85.3 V
Short-circuit Current, Isc	6.09 A
Temperature Coefficient of Voc, KVoc	-0.229 mV/℃
Temperature Coefficient of Isc, KIsc	0.030706 A/℃

4. Three Phase (Grid-Connected PWM PV System) with LCL Filter:-

LCL filters is getting increasing attention in recent years for grid-connected inverters, mainly because of its greater attenuation of high frequency harmonics. LCL filters are mainly used for grid-connected inverters to meet the grid interconnection standards So LCL filter has come into wide use in the inverter

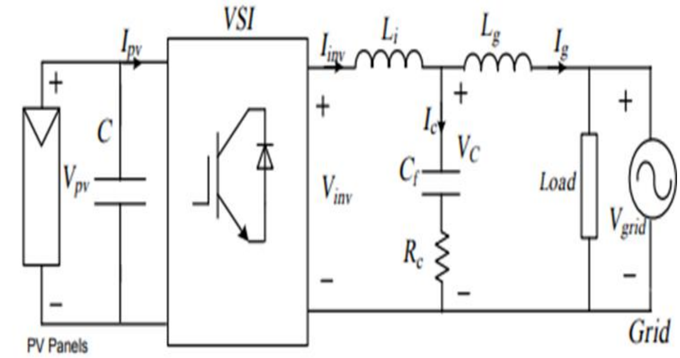

Fig -4: Equivalent circuit of grid-connected with LCL filter

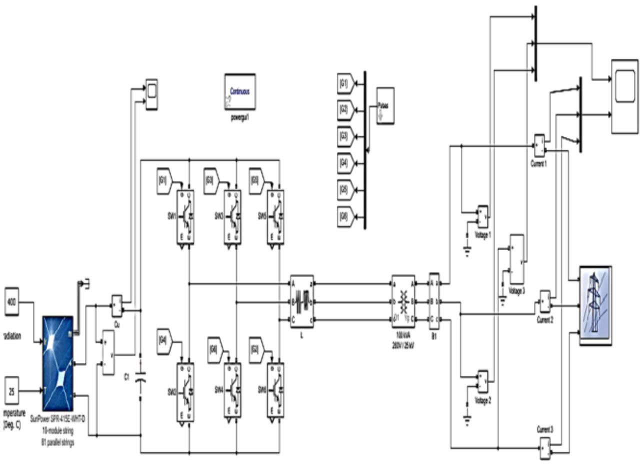

Fig -5: Simulink model of three phase Grid-connected inverter with L filter

5. Simulation results:-

The performance of the proposed structure is assessed by a computer simulation that uses MATLAB Software. In this paper, two models for L filter and LCL filter evaluation have been analyzed using Matlab® and Simulink® Power System ToolBox simulation environment as shown in Fig.5 and Fig.6

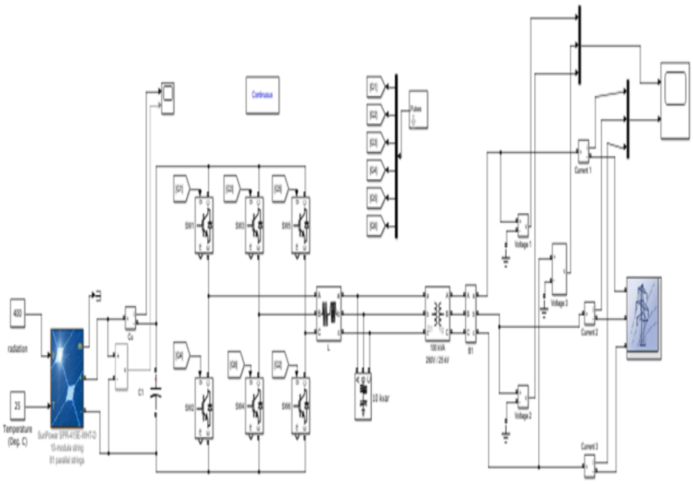

Fig -6: Simulink model of three phase Grid-connected inverter with LC filter

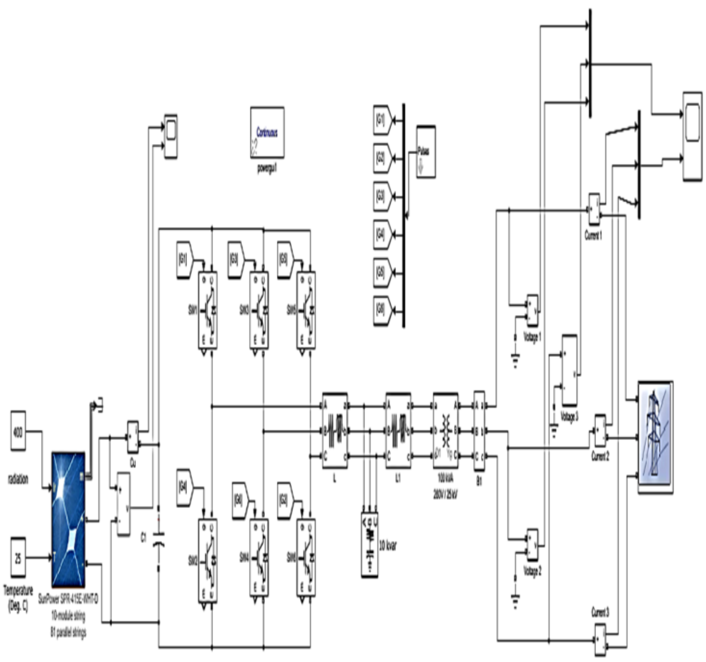

Fig -7: Simulink model of three phase Grid-connected inverter with LCL filter

Where, the system rated power is 100 kW, the line voltage is 260V, the switching frequency is 1.08 K, the fundamental frequency is 50Hz. Then the values of parameters could be calculated. The L1 and L2 are 270uH, C is 470 uF, and the damping resistor R is 2 mΩ. The presented simulation results were obtained. The harmonic current waveforms of Ia are shown in fig.8, 9 and fig.10.

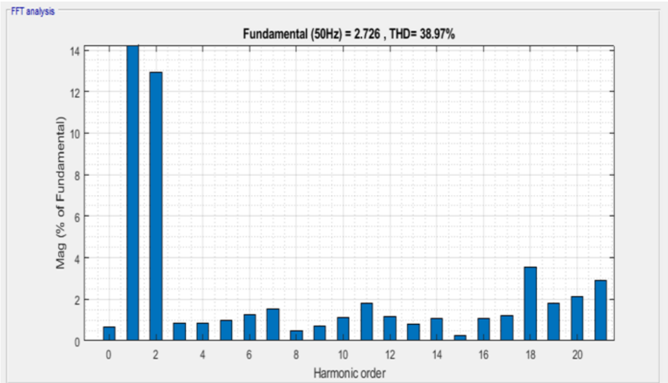

Fig -8: Harmonic diagram of L filter output current wave form

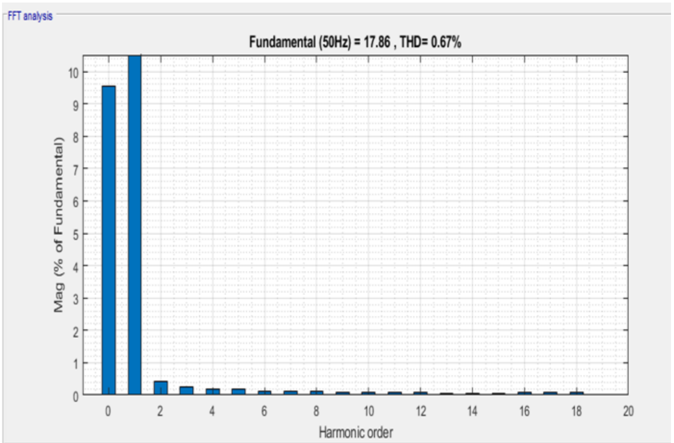

Fig -9: Harmonic diagram of LC filter output current wave form

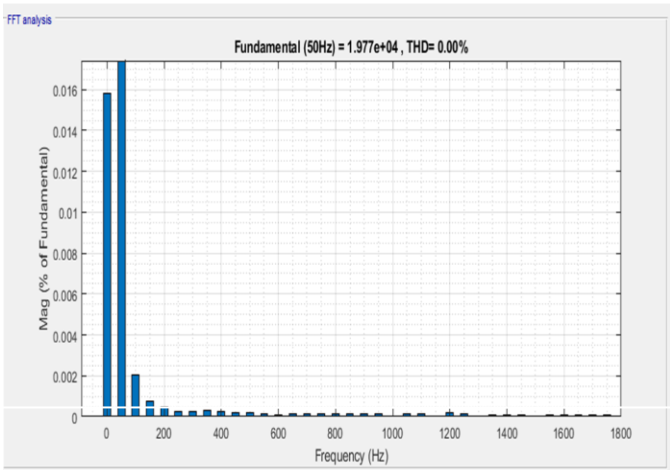

Fig -10: Harmonic diagram of LCL filter output current wave form

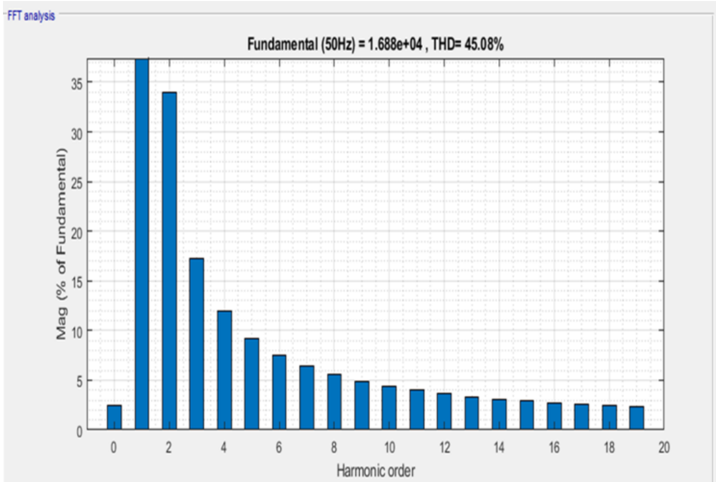

Fig -11: Harmonic diagram of L filter output voltage wave form

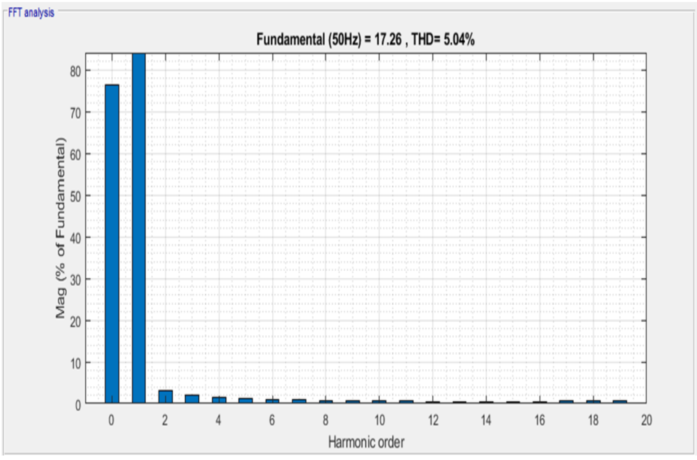

Fig -12: Harmonic diagram of LC filter output voltage wave form

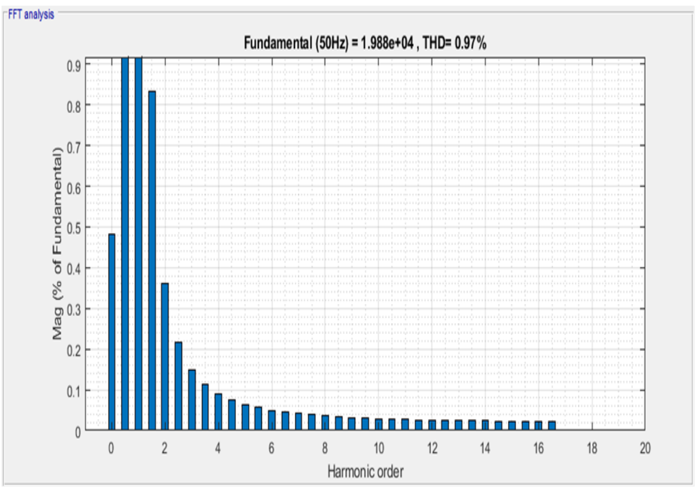

Fig -13: Harmonic diagram of LCL filter output voltage wave form

Table -1: comparison between L, LC and LCL filters

	L filter	LC filter	LCL filter
Current harmonics	100 kVA	100 kVA	100 kVA
Voltage harmonics	260V	260V	260V
Current THD	38.97	0.67	0.00
Voltage THD	45.08	5.04	0.97

As shown in Fig. 8, FFT analysis of inverter output current, the current using L filter THD is 38.97% using a LC filter THD is 0.67 as shown in Fig. 9, after using LCL filter this value of THD will be zero, Fig.10, this not happens when using L filter. The FFT analysis for the inverter output voltage in case of using L filter is shown in Fig11, the voltage THD is 45.08% this value will decrease to 5.04% when using LC filter when using LCL filter this value will decrease to 0.97% with the same inductance, 270 u H [22], Fig. 13.

6. Control scheme

Fig. 14, shows a schematic block diagram of 3-phase AC grid connection of PV cell through a PWM voltage source inverter (PWM-VSI). In this Figure, each ideal switch of the PWM-VSI represents a semiconductor device (IGBT) with a reverse diode in antiparallel. Here, the PWM-VSI uses a hysteresis current control, also known as adaptive current control. With this control, the inverter upper and lower switches are turned on and off in such a way as to keep the output currents tracking with a very small amplitude error or phase delay.

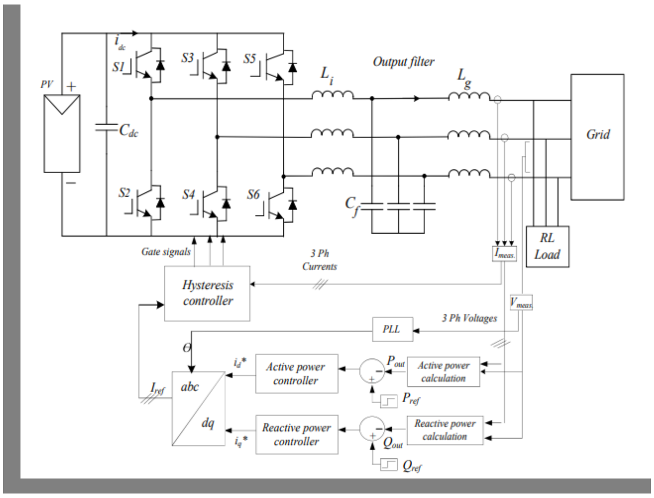

Fig -14: Proposed three-phase PV power system

In order to overcome the inverter losses while supplying the required power, the inverter needs to draw some active power from the grid. The control strategy enables PV inverters to absorb little active power from the grid when the PV losses, regulates the DC bus voltage to keep it within limits, and operates the inverters in VAR mode. This eventually extends the utilization of PV inverters beyond active power generation and helps improving grid stability and voltage regulation.

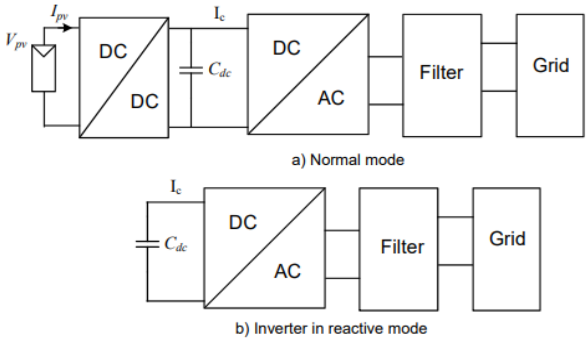

Fig -15: block diagram of inverter operation modes

7. CONCLUSION

This paper has investigated the design procedures for LCL filter used with grid connected PV inverters in distributed generation system. The filter design is based on achieving the standard level determined by IEEE519 for harmonics limits. The proposed controller has been verified in simulation using the Simulink package in Matlab. Various types of filters are used in this study. A comparison between the designed LCL-filter and L, LC-filter based three-phase grid-connected PV inverter system is carried out. The comparison results are given to validate the theoretical analysis and effectiveness of filters. The output voltage across the load is almost sinusoidal in waveform as recorded for different load demand values. The THD of the inverter output voltage during day and night hour's are 38.97% and 45.08% respectively (without LC filter). With the use of the filter, the THD for these waveforms is 6.85% and 7.2% respectively.

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