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Input and Output Distortions in the Operation of Stand alone Solar PV Inverters and Method for Compensation

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Inverter and power conditioning circuit is the most important part of solar PV system which is responsible for providing the AC output as per the requirement of the application. The presence of AC harmonics and DC ripples in the inverter is still an unavoidable drawback, even though it has reduced to a great extent in past two decades. This paper presents a detailed study of distortions in the AC and DC sides of commercial standalone single phase Solar PV inverter and the effect of the same in the application. The harmonic content is evaluated by loading the inverter using electronic loading. The reduction in distortions in the AC and DC sides by utilization of a high impedance network on the DC side of the inverter is also evaluated by simulation. A comparative study of harmonics and DC ripples in the inverter under test and the simulated impedance source inverter is also presented.

Keywords: *Harmonics, Stand alone Solar PV inverters, DC ripples, Impedance network*

1.0 INTRODUCTION

Solar PV systems are being widely used in domestic and industrial applications to bring down the consumption from utility grid. Inverter is the most important part of the Solar PV system which is designed based on the application. The design and features vary according to, whether the inverter is to be used for supplying domestic loads, industrial loads, grid or specific types of loads like machines.

Standalone solar PV systems are becoming very popular in house hold and industrial applications especially in rural areas where obtaining power from grid is difficult and not reliable. In urban areas also standalone SPV systems are used as a supplementary power source without connecting to the grid. Large number of researchers are working in this area for performance improvement of standalone systems especially in inverters [1][2][3]. Reduction of harmonics, Improved protection, transformer less design, Integration of maximum power point tracking etc are some of the key areas of research and development. Out of these reduction of harmonics is a matter of prime importance since the performance of the load devices depends upon the quality of the power supplied [4][5][6]. Here a detailed study of the output and input waveforms and harmonics of commercial Solar PV inverter is presented with a method of reducing AC and DC distortions

2.0 STAND ALONE SOLAR PV INVERTERS

The output from standalone SPV inverter is directly given to the load without connecting to the grid. Here there is no problem of synchronization and islanding but the response of inverter under various loads is of prime importance. Since most of the stand alone inverters are of smaller ratings,

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the presence of harmonics will result in increase in losses, temperature rise and performance degradation of load equipment.

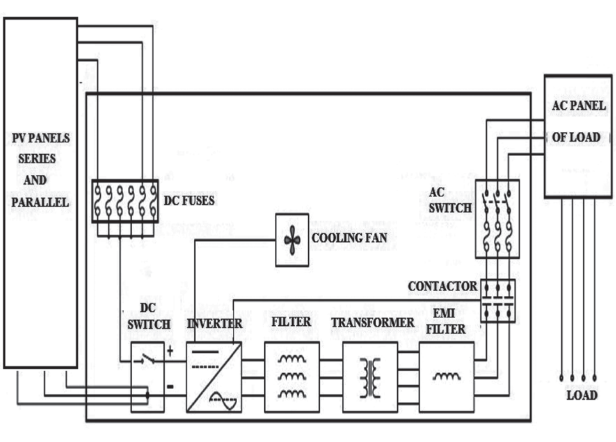

FIG. 1 SCHEMATIC OF STAND ALONE SOLAR PV INVERTER

Different types of multilevel inverters are developed with the aim of reducing harmonics, which can give better sinusoidal output. But increase in number of switches will cause increase in switching losses which is not very feasible for low power applications. Also higher level logics which can be implemented using simulation is very difficult practically. In most of the commercial SPV inverters, Sinusoidal PWM or modified Sinusoidal PWM scheme is used for basic full bridge converter along with suitable LCL filters on the AC side as shown in Figure 1.

The transformer also helps in smoothening the AC output to some extent. But transformer causes increase in weight and losses. Another option is to go for high frequency transformers or transformer less design which requires a complex electronic circuitry. A statistical comparison of inverter weight for with transformer and without transformer design for standalone SPV inverters is shown in Figure 2.

So other alternatives of reduction in harmonics can help in avoiding transformer by providing boosting on the DC side. This will make the inverter very compact but will require extra protection on DC side since there is no galvanic isolation [7].

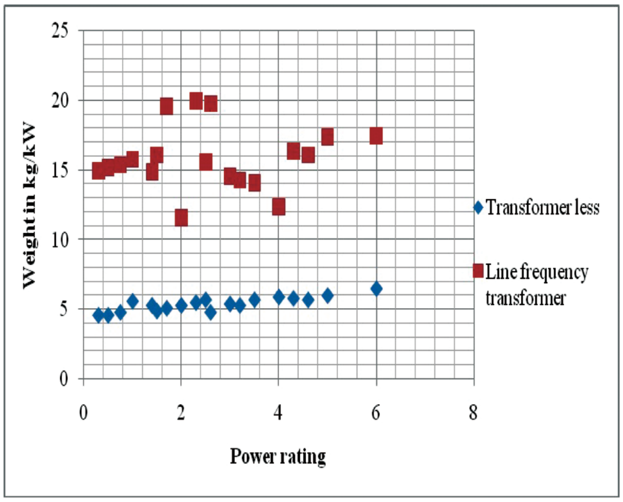

FIG. 2 COMPARISON OF INVERTER WEIGHT FOR WITH TRANSFORMER AND TRANSFORMERLESS DESIGN

2.1 Origin of harmonics

In any application presence of harmonics in the waveform affects the utility end in the form of losses, unwanted noises and abnormalities in operation. A harmonic of a wave is a component wave that is an integer multiple of the fundamental frequency of the wave. Any periodic signal can be expressed as a combination of sinusoidal waves with frequencies that are integer multiples of fundamental frequency.

If an inverter gives square wave output, the waveform can be expressed as equation (1)

$$f(\omega t) = \sum_{n=1}^{\infty} [a_n \sin(n\omega t) + b_n \cos(n\omega t)] \quad ....(1)$$

Where,

$$a_n = \frac{1}{\pi} \int_0^{2\pi} f(\omega t) \sin(n\omega t) d(\omega t)$$
$$b_n = \frac{1}{\pi} \int_0^{2\pi} f(\omega t) \cos(n\omega t) d(\omega t) \quad ....(2)$$

n=0 gives fundamental component and and higher values of n gives harmonics of corresponding order.

Assuming that the periodic waveform has Half-wave symmetry

$$f(\omega t) = f(\omega t + \pi) \quad ....(3)$$

The symbols used are conventional where t is the time, ω is the angular frequency, and a_n and b_n are constants.

With half wave symmetry, the discrete form of constants a_n and b_n can be expressed as

$$a_n = \frac{4}{n\pi}\left[1+\sum_{k=1}^{2M}(-1)^k \cos n\alpha_k\right] \qquad ....(4)$$

$$b_n = \frac{4}{n\pi}\left[-\sum_{k=1}^{2M}(-1)^k \sin n\alpha_k\right]$$

Where, M is the number of chops in one half cycle.

Any distortion in pure sinusoid results in presence of harmonics. Total Harmonic distortion is a general term used to specify the extent of variation of the waveform from pure sinusoid [8][9].

$$V_{THD} = \frac{\sqrt{V_1 + V_2 + V_3 + ...V_n}}{V_1} \qquad ....(5)$$

Where, V_1 is the fundamental component and V_n is the of magnitude n^{th} order harmonic.

3.0 EXPERIMENTAL ANALYSIS

In order to analyze the harmonics and distortion in the AC and DC side of Solar PV inverter, an experimental setup is utilized as shown in Figure 3 [10]. The Solar PV inverter under study is of rating 1kVA with 24V DC input. The output is Sinusoidal AC of rms value 230 V, 50Hz. An adjustable electronic load is used for analyzing the output and input waveforms at various power levels. Power analyzer used is of 0.05% accuracy and frequency bandwidth of 0.5 Hz to 150 kHz.

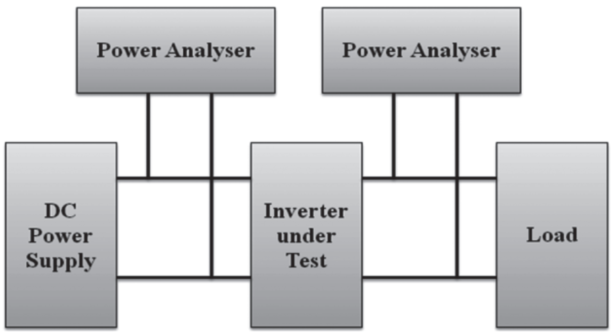

FIG. 3 EXPERIMENTAL SETUP TO ANALYSE THE INPUT AND OUTPUT WAVEFORM OF SPV INVERTER

The voltage and current waveforms on the input and output side of the inverter for resistive loading of 75% is shown in Figure 4. The current waveform on the DC side is found to be oscillating.

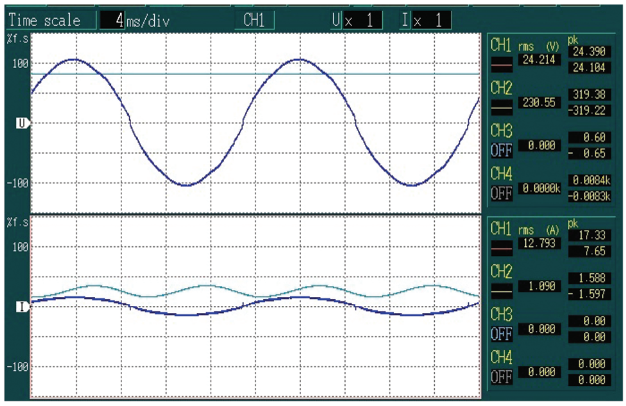

FIG. 4 THE AC AND DC SIDE VOLTAGE AND CURRENT WAVEFORMS OF SPV INVERTER

3.1 AC side distortions

In inverters with large power rating, the output waveform is more sinusoidal compared to those of smaller ratings. Also, the amount of harmonics is more at lower loading. The distortion in the output waveform for a resistive load at 25% loading for a commercial inverter is shown in Figure 5.

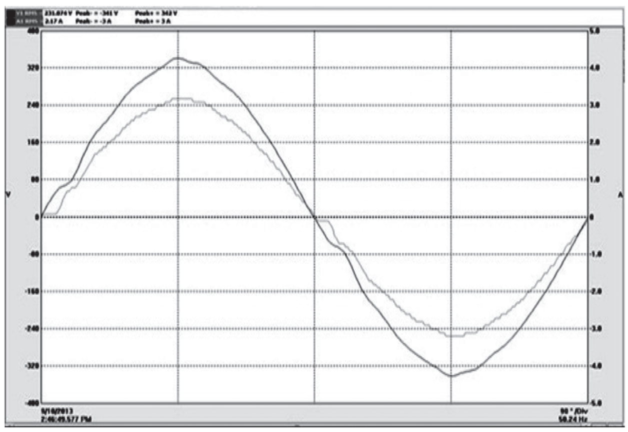

FIG. 5 OUTPUT WAVEFORM FOR 25% LOADING

A comparison of harmonics at 25% loading and 75% loading for the inverter under study is also shown in Figure 6. The black lines indicates voltage harmonics and grey lines indicates current harmonics. The magnitude of harmonic component decreases with the order.

3.2 DC side distortions

Ideally the DC voltage should be stable and current ripples should be within permissible limits. The operation of the switches introduces a ripple voltage onto the terminal of the PV array [11] [12]. From the experimental setup, the DC side current is found to have large amount of ripples and distortion due to the operation of the inverter.

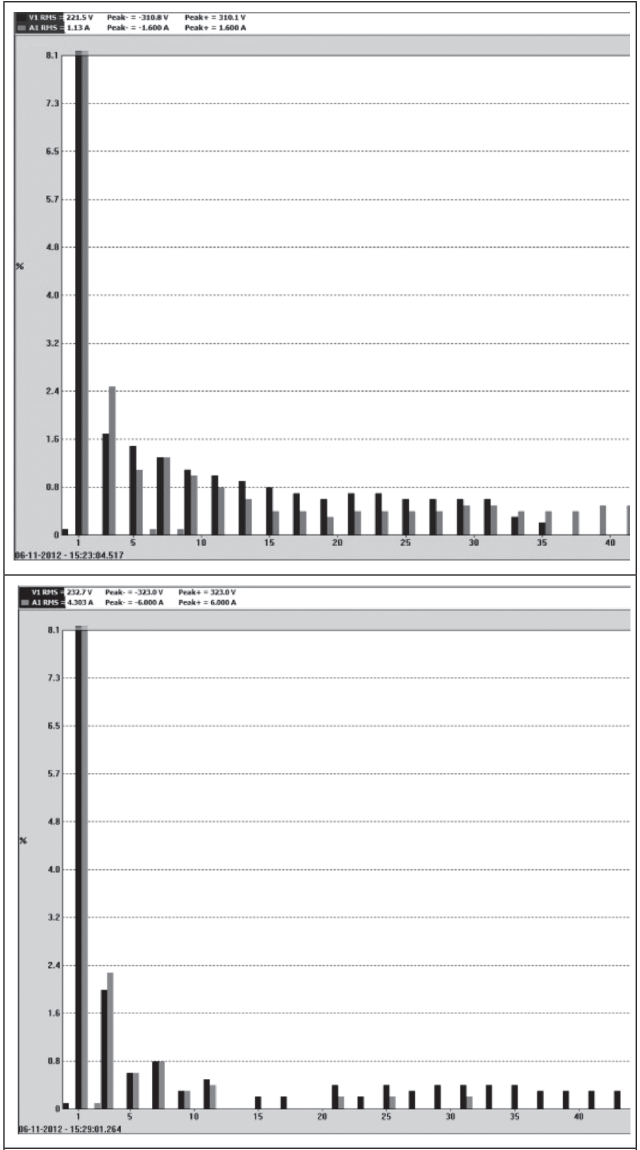

FIG. 6 COMPARISON OF HARMONICS FOR 25% AND 75% LOADING

The voltage and current waveform obtained is shown in Figure 7. Its is plotted from array of data indexed in x axis. The amplitude of the voltage ripple is determined by the switching frequency, PV voltage, bus capacitance, and filter inductance as shown in equation 6.

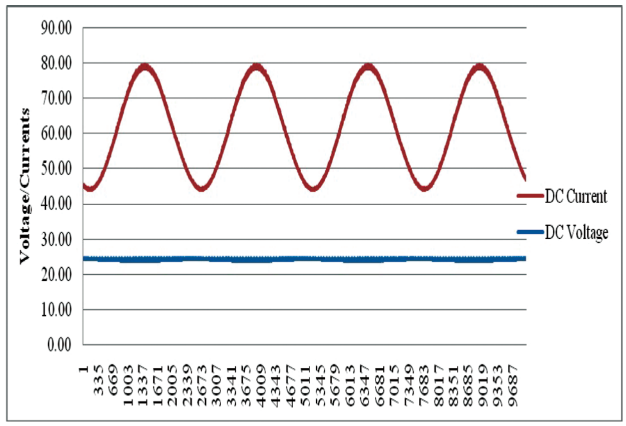

FIG. 7 VOLTAGE AND CURRENT WAVEFORM ON THE DC SIDE OF SPV INVERTER

$$V_{\text{P-P ripple}} = \frac{V_{PV}}{32.C_{bus}.L.f_s^2} \quad ....(6)$$

$$\text{Repple Factor} = \frac{V_{Ripple(rms)}}{V_{PV}} \quad ....(7)$$

Where,

V_{PV} is the solar panel DC voltage,

C_{bus} is the capacitance of the bus capacitor,

L is the inductance of the filter inductors,

f_s is the switching frequency.

TABLE 1
TABULATION OF AC AND DC SIDE DISTORTIONS

Loading	AC Side THD		DC Side ripple	
	V(%)	I(%)	V(%)	I(%)
10%	5.7	8.9	6.4	22.4
25%	4.6	5.7	7.2	28.9
50%	3.2	4.5	8.6	32.4
75%	3.1	4.7	9.1	36.5
100%	3.6	4.9	9.9	42.4

The DC ripples affects the operation of the PV system, as the average voltage applied to the terminals should be held at the maximum power point. The presence of voltage ripple on the PV terminals will oscillate the power extracted from the system [12], causing a lower average power output. DC bus capacitor is added onto the bus in order to smooth out the voltage ripple [13]. But the size of DC capacitor is limited by safety issues and circuit complexity. The average THD and DC ripple for various loading of the inverter under test is shown in Table 1.

4.0 METHOD FOR REDUCTION OF AC AND DC DISTORTIONS

Methods to reduce harmonics in the output side of the inverter are under study for many decades. Multilevel topologies and advanced filters are developed for this purpose. The higher reduction in harmonics is achieved, the higher is the cost and complexity of the inverter and controller. Here the reduction of DC side ripple and AC side harmonics by utilizing a Z source network on the DC side of the inverter is evaluated by simulation.

Normally Voltage source inverters are used for Solar PV applications because of better dynamic response and simpler circuitry. Current source inverters are used only for specific high power applications like machine loads. Z source inverters are still under development to find its application in commercially used converters. It consists of a network of inductors and cross connected capacitors on the DC side of the inverter. Here the VSI in PV inverter is replaced by impedance source and the performance is evaluated [14].

5.0 SIMULATION AND RESULTS

The complete simulation model using MATLAB is shown in Figure 8. Impedance source network is modeled using time domain equations and converter is modeled as 1kVA sinusoidal PWM modulated inverter similar to the tested inverter. The L-C-L filter values and other passive component values are taken same as that in the inverter under test.

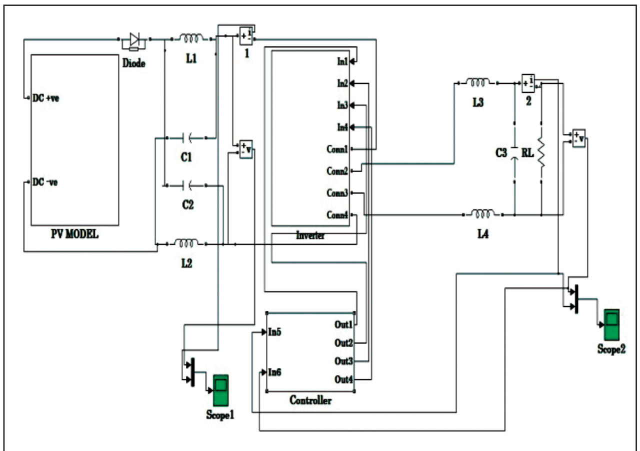

FIG 8. SIMULATION MODEL

The DC input and AC output waveform of the inverter with impedance source network is shown in Figure 9.

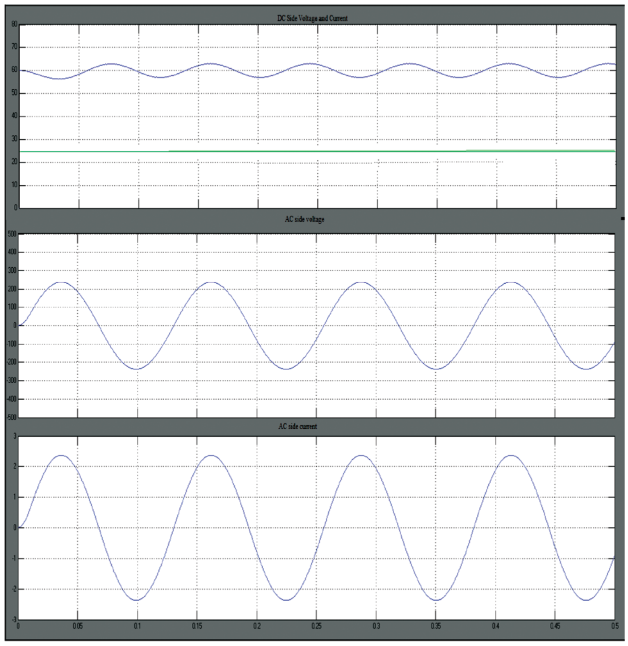

FIG 9. VOLTAGE AND CURRENT WAVEFORMS OF DC LINK AND AC OUTPUT

The waveform, THD and ripple factor are verified for different values of loading and are compared with the inverter under study. The DC ripples and AC harmonics are found to be reduced with the addition of impedance source network. Comparative studies are shown in Figure 10 and 11.

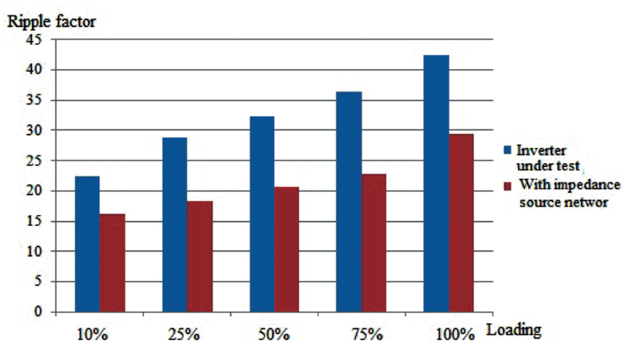

FIG 10. COMPARISON OF CURRENT RIPPLE FACTOR IN THE INVERTER UNDER TEST AND THE IMPEDANCE SOURCE TOPOLOGY

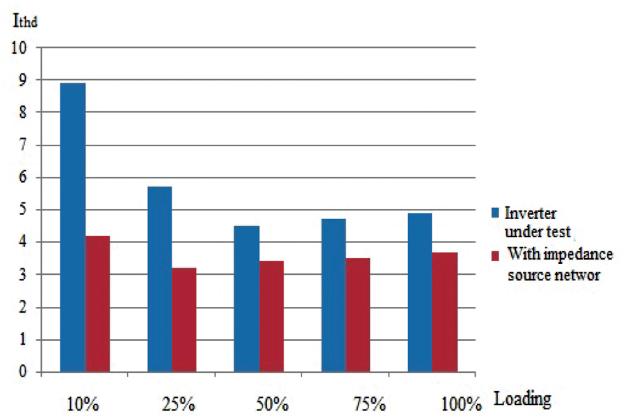

FIG 11. COMPARISON OF THD OF CURRENT IN THE INVERTER UNDER TEST AND THE IMPEDANCE SOURCE TOPOLOGY

An important advantage of impedance source network is DC boosting during shoot through state [15][16]. But this work is considering only the effect of the network on DC ripples and AC harmonics. The most pronounced disadvantage of impedance source is that the presence of inductor reduces the dynamic response of the system and makes it bulky.

6.0 CONCLUSIONS

The input and output waveforms of some commercial solar PV inverters are analyzed to obtain the amount of harmonics induced by the power electronic converter.

- Commercial Solar PV inverters mainly use Voltage source inverter topology with Sinusoidal PWM or modified Sinusoidal PWM method.
- The amount of voltage harmonics is around 3-4% and current harmonics is around 5-6% at optimum loading
- By utilization of impedance source network, the V_{thd} and I_{thd} are reduced both at low loading and high loading.
- One drawback of this topology is that the circuit will become comparatively bulky.

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