Design of a Photovoltaic Panel connected to the Grid System using a Zeta Converter

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Abstract— **This paper introduces the design of a photovoltaic panel which is connected to the grid system using the zeta converter. Here we have designed a circuit to explain the system along with the mathematical analysis as well as the functions of the zeta converter. The inverter circuit has been designed in such a way that it employs the 180º modulation, so that the zeta converter switches can operate in low frequency. Therefore, the switching losses can be considered negligible and maximizes the energy produced by solar panels.**

Index Terms— **Zeta converter, Photovoltaic panel, Energy conversion system, Full-Bridge inverter, Harmonic distortion**

I. INTRODUCTION

In recent years many researchers have been working on renewable energy such as solar energy and photovoltaic panels [1], [2]. Most of these works were done by using Zeta converter. They have described the applications of zeta converter and designed different kinds of AC-DC and AC-AC converter using zeta topology. Some researchers have developed the ideas for the connection of photovoltaic panels (PVs) to the power grid [3], analyzed the photovoltaic energy and equivalent conventional power [4] and also designed some PV panels using low frequency transformers between the inverter and the power grid [5]. Many of this research works are based on the zeta DC-DC control system [6] which includes the Buck pulse-width modulation [7] and Maximum power point tracking system [8]. In this study we have designed a grid connected PV panels using the zeta converters applications and developed a power system which can be used in the grid connection of renewable energy sources to the power grid using a zeta converter. This system is associated with a full bridge inverter operating at low frequency and discontinuous conduction mode. This study shows the process of generating a rectified sinusoidal current to be injected in the grid and reducing the switching losses of the system using an inverter which operates at low frequency.

II. PRINCIPLE OF OPERATION

The Zeta converter, operating in discontinuous conduction mode (DCM), plays the main role in this procedure. The sinusoidal current waveform synchronized with the electric grid and it is a combination of the full-bridge inverter and the Zeta converter. This combination gives a DC-AC conversion inverting the current in each half cycle. A modular system, synchronized with the electric grid which is able to inject low harmonic content, providing galvanic insulation between the solar panels and the grid.

a. Proposed Energy Conversion System:

Our proposed energy conversion system composed of three stages shown in Fig 1.

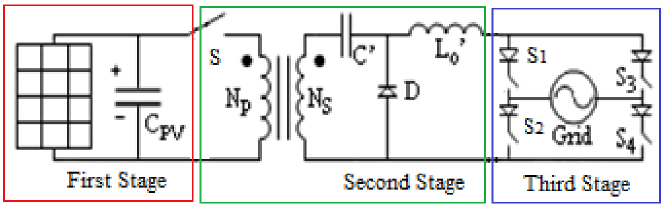

Fig. 1 Proposed energy conversion system

The first stage consists of two series connected solar panels, in parallel with a bulky capacitor C_{PV} [9]. We have,

$$C_{PV} = \frac{P_{PV}}{2\pi\omega_{Grid} V_{PV} \hat{V}_{PV}}$$

Where, P_{PV} is rated power of PV array, V_{PV} is rated voltage of PV array, $\hat{V}_{PV}$ is rated voltage ripple (< 8.5 %), in Volts and ω_{Grid} is rated grid frequency (in Hz).

The second stage consists of an isolated Zeta converter operating in DCM at a switching frequency of 20 kHz (Approx.) and the third stage consists of a full bridge inverter operating in the utility frequency. This circuit is responsible for reversing the output current i_{L_0} of the Zeta converter at every 180°. The Theoretical waveforms of the different stages of the proposed arrangement are shown in Fig 2.

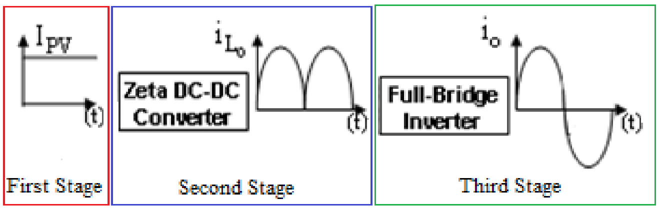

Fig. 2 Theoretical waveforms of the proposed arrangement

b. Stages of Operation of the Zeta Converter:

The operation of the Zeta converter will be analyzed further by assuming that,

1. All semiconductors are ideal;
2. The transformer has an unitary ratio ($N_S / N_P = 1$) and is represented by its magnetizing inductance L_m

iii. The voltage of electric grid V_0 is considered constant within a high frequency switching period.

iv. The solar panels in parallel with the C_{PV} capacitor sets up the voltage source E.

The operations of different stages in DCM are as follows

1) First stage ($0 < t < t_c$): The switch S is closed and the voltage E is applied to inductors L_m and L_0, shown in Fig 3. This currents i_{L_m} and i_{L_0} grow linearly with slopes E/L_m and E/L_0, respectively.Thus, the current in the switch S, which is the sum of currents i_{L_m} and i_{L_0}, grows at the rate of E/L_{eq}, where:

$$L_{eq} = \frac{L_m L_0}{L_m + L_0}$$

The diode D is reverse polarized and remains blocked throughout this stage.

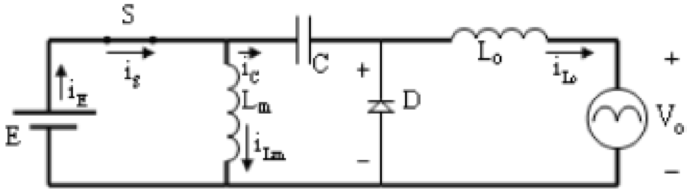

Fig. 3 Operation of DC-DC Zeta converter for the first stage.

2) Second stage ($t_c < t < t_d$): The switch S is open and diode D enters into conduction, shown in Fig 4. The voltage $-V_0$ is applied to inductors L_m and L_0. L_m transfers the energy stored in the previous step for the coupling capacitor C, in a similar way L_0 enables the connection to the grid, acting as a current source. The currents i_{L_m} and i_{L_0} decrease linearly with slope $-V_0/L_m$ and $-V_0/L_0$ respectively. The current i_D in diode D is the sum of the current i_{L_m} and i_{L_0}, and decreases linearly with slope $-V_0/L_{eq}$.

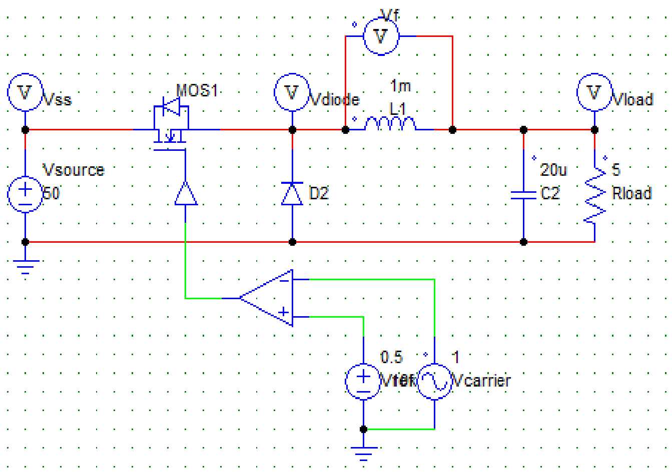

Fig. 4 Operation of the DC-DC Zeta converter for second stage.

3) Third stage ($t_d < t < T$): The switch S remains open and the diode D is also open when it is required because of the extinction of its current i_D. The current in the capacitor C is constant and equal to the inductor current L_0, depicted in Fig. 5. The current $i_{L_0}(0)$ has the opposite direction of the current $i_{L_m}(0)$ of the inductor L_m, causing the voltage at the inductors to be equal zero. The relations L_m/L_0 and $I_{E_{med}}/I_0$ is,

$i_{L_m}(0) < 0 < i_{L_0}(0)$

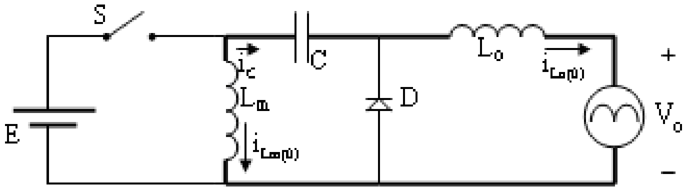

Fig. 5 Operation of the DC-DC Zeta converter of the third stage.

The general waveforms of zeta converter are shown in Fig 6. We have done the simulation works using matlab and the results show that the waveform of this study is identical to the general waveforms of Zeta converter.

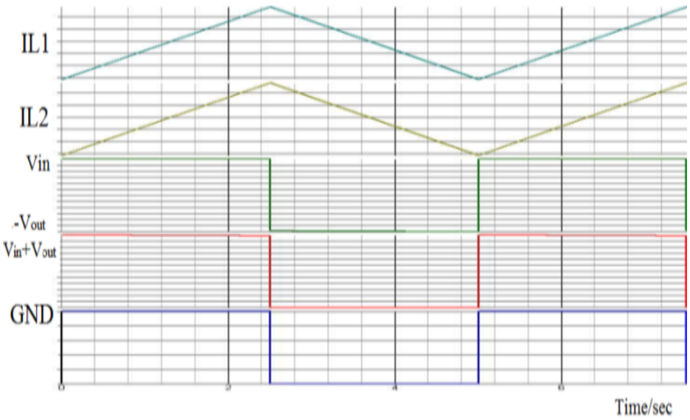

Fig. 6 Simulation results of Zeta converter.

III. MATHEMATICAL ANALYSIS

A. Static Gain: The instantaneous static gain g(t) of the Zeta converter in DCM can be expressed as,

$$g(t) = \frac{V_0(t)}{E} = \frac{R i_{L_0}(t)}{E} = \frac{d(t)}{\sqrt{K_1}} \tag{1}$$

The conduction time of diode D (t_D), in this mode of operation, is constant when there is no variation of the load R in the converter.

$$\frac{1}{\sqrt{K_1}} = \sqrt{\frac{R}{2fL_{eq}}} = \frac{T}{t_D} = D_1 \tag{2}$$

Where, V_0 (t) is instantaneous output voltage of the power grid, $i_{L_0}(t)$ is the instantaneous output current, d(t) is the instantaneous duty cycle, g(t) is instantaneous static gain, E is input voltage, R is load resistance, f is switching frequency in Hz, T is switching frequency period, t_D is conduction time within a high frequency switching period of the diode D.

If a waveform is forced on the duty-cycle d(t) (from a null value up to a maximum value D_{max}) the waveform of the output current $i_{L_0}(t)$ will take the same shape imposed by d(t) (from a null value up to a maximum value $I_{L_0\,max}$). To keep the normal behaviour of the converter it would not be the continuous conduction mode (CCM) and that the input voltage E and the K_1 remains constant within a low frequency. Since the objective of the DC-DC Zeta converter on the proposed system is to generate an output current $i_{L_0}(t)$ that is sinusoidal in absolute value, the following relation shall be assumed as

$$d(t) = D_{max}|\sin(\omega t)| \tag{3}$$

By transforming (1) in (4) we get,

$$G_{max}|\sin(\omega t)|=\frac{RI_{L_0\,max}}{E}|\sin(\omega t)|=\frac{D_{max}}{\sqrt{1}}|\sin(\omega t)| \tag{4}$$

In order to obtain the maximum static gain $G_{max}$with respect to the average input $I_{E\,med}$ and output $I_{L_0 med}$ currents, the definition of an average value is applied, according to (3) in a semi-cycle of the power grid, resulting in

$$G_{max}=\frac{I_{E\,med}}{I_{L_0 med}}\frac{4}{\pi} \tag{5}$$

B. Currents of the system: The average current on the switch S in a commutation period of the converter $I_{S\,med}(t)$ is equal to the average input current at the same period $I_{E\,med}(t)$. Both can be expressed by: (Fig 4)

$$I_{E\,med}(t) = I_{S\,med}(t) = \frac{E}{2fL_{eq}}(d\,(t))^2 \tag{6}$$

Considering (3) and a commutation period of the inverter, it is possible to apply the concept of average value (6) in the interval of a semi-cycle of the electric grid, obtaining the average input current on the switch S ($I_{E\,med}$ and $I_{S\,med}$).

$$I_{E\,med} = I_{S\,med} = \frac{ED^2{}_{max}}{4fL_{eq}} \tag{7}$$

Thus, the average power input P_E can easily be obtained as follows:

$$P_E = \frac{E^2D^2{}_{max}}{4fL_{eq}} \tag{8}$$

Depending on the desired waveform, the instantaneous output power $P_0(t)$ of the Zeta converter is defined by:

$$P_0(t)= V_{0\,max}|\sin(\omega t)|I_{L_0 max}|\sin(\omega t)| \tag{9}$$

Where $V_{0\,max}$ and $I_{L_0 max}$ are the maximum voltage and current, respectively at the output of the DC-DC converter. Considering a low frequency, the average output voltage P_0 can be obtained by applying the definition of average value in (9), resulting in:

$$P_0=\frac{V_{0\,max}I_{L_0 max}}{2} \tag{10}$$

The method used to obtain (7), is employed to determine the expressions of the average current in the magnetizing inductance $I_{L_m\,med}$ (equal to $I_{E\,med}$) and of the average current at the output inductor $I_{L_0\,med}$ (equal to current injected into the mains $I_{0\,med}$).

$$I_{E\,med} = I_{L_m\,med} = \frac{ED_{max}T}{L_m}\left(\frac{D_{max}}{4}+\frac{D_1}{\pi}\right)+I_{L_m(0)\,min}\frac{2}{\pi} \tag{11}$$

$$I_{0\,med} = I_{L_0\,med} = \frac{ED_{max}T}{L_0}\left(\frac{D_{max}}{4}+\frac{D_1}{\pi}\right)+I_{L_0(0)\,min}\frac{2}{\pi} \tag{12}$$

Where, $I_{L_m(0)\,min}$ is minimum value of the current on the magnetizing inductance when d(t) = D_{max} and $I_{L_0(0)\,min}$ is minimum value of the current on the output inductor when d(t) = D_{max}. The values of $I_{L_m(0)\,min}$ and $I_{L_0(0)\,min}$ are defined by:

$$I_{L_m(0)\,min}=\frac{ED_{max}}{8f}\left(\frac{\pi D_{max}}{L_{eq}}-\frac{(\pi D_{max}+4D_1)}{L_m}\right) \tag{13}$$

$$I_{L_0(0)\,min}=\frac{ED_{max}}{8f}\left(\frac{(\pi D_{max}+4D_1)}{L_m}-\frac{\pi D_{max}}{L_{eq}}\right) \tag{14}$$

IV. DESIGN CRITERION

A. Maximum Duty Cycle: In order to minimize the magnetizing inductance (L_m) it is important to design the duty cycle which occurs when the electric grid voltage is in its peak value.

$$D_{max}=\frac{V_{0\,max}}{E+V_{0\,max}} \tag{15}$$

Where, E is defined by supply voltage and expressed as (16), V_{mpp} is the maximum power point voltage, N_D is the number of blocking diodes in series and N_S is the total number of PV panels in series.

$$E=N_SV_{mpp}-0.7N_D \tag{16}$$

B. Output Inductance: The output inductor L_0 should be designed to produce an excellent filtering when the converter is connected directly to the power grid. The maximum inductor current ripple L_0 ($\Delta I_{L_0 max}$) occurs when the duty cycle is maximum d(t) = D_{max}, using this parameter it is possible to minimize EMI (electromagnetic compatibility) problems. We have,

$$\Delta I_{L_0 max} = \frac{\pi}{D_1}\frac{L_{eq}}{L_0}I_{L_0\,med} \tag{17}$$

It is desirable that the time constant τL_0 (equal to L_0/R) is tuned to a frequency higher than twice the frequency of network ω_{grid}, because it is depending on the value of L_0 and load R, the low-pass filter formed by these components can be distorted causing the waveform of the rectified current by the attenuation of the low frequency component. If the time constant τL_0 is tuned approximately one decade above the low frequency component, its mitigation will be minimized. There is a restriction on the highest possible value of the output inductor L_0 according to the peak voltage of the network $V_{o\,max}$, maximum power to be injected in the network $P_{o\,max}$ and frequency of network ω_{grid} in Hz:

$$L_0 \le \frac{V_{0\,max}^2}{80\pi P_{0\,max}\omega_{grid}} \tag{18}$$

C. Coupling Capacitor: Similarly, to design the output inductor it is desirable that the time constant τC (equal to RC) is tuned to a frequency greater than twice of the network frequency ω_{grid} because it depends on the value of C and load R, the low-pass filter formed by these components can be distorted. The value of the coupling capacitor C capacitance is also limited according to the peak voltage $V_{o\,max}$, maximum power to be injected in the network Po and network frequency ω_{grid} in Hz:

$$C = \frac{P_{0\,max}}{20\pi V_{0\,max}^2\omega_{grid}} \tag{19}$$

V. SAMPLE DESIGN

A sample design of the Zeta converter has been represented below within the context of this paper.

A. Specifications: The sizing of the converter is done from the technical specifications below. We have considered a critical point at the temperature of 60°C and irradiance of 1000 W/m². Here low voltage and maximum current are obtained from the system. Let,

$P_E = 82$ Wpk;
$P_{E\,max} = 96$ Wpk;
$E = 2 \times (14.6V) - (0.7V) \times 2 = 27.8$ V;
$V_{0\,max} = 180$ V;
$f = 20$ kHz;
$\omega_{grid} = 60$ Hz

B. Calculus: The duty cycle D_{max} maximum is determined by (15),

$$D_{max} = \frac{V_{0\,max}}{E + V_{0\,max}} = \frac{180\text{ V}}{207.8\text{ V}} = 0.87$$

The equivalent inductance L_{eq} can be obtained by (8). We know that, the power of entry P_E and input voltage E.

$$L_{eq} = \frac{E^2 D^2{}_{max}}{4fP_E} = \frac{(27.8)^2 \times (0.87)^2}{4 \times 20\text{ kHz} \times 82\text{Wpk}} = 89\ \mu\text{H}$$

The maximum ripple current $\Delta I_{L_0 max}$ depends on L_0. Considering, $P_E = \frac{P_0}{\eta}$ and a yield of $\eta = 80$ %, we get the maximum value of L_0 from (18):

$$L_0 \le \frac{V_0^2{}_{max}}{80\pi P_{0\,max}\omega_{grid}} = \frac{(180\text{ V})^2}{80\pi \times (96\text{W} \times 80\%) \times 60\text{ Hz}}$$

$\therefore L_0 \le 28$mH

It is possible to determine the value of the ripple of output current iL_0 with the combination of (2), (4), (5), (10) and (17). From these equations, we get,

$$\Delta I_{L_0 max} = \frac{\pi}{D_1}\frac{L_{eq}}{L_0} I_{L_0\,med} = \frac{\pi}{0.15} \times \frac{89\ \mu\text{H}}{28\text{mH}} \times 0.71\text{A} = 4.7\%$$

A ripple of 4.7% represents a good filtration. This value of L_0 should be maintained. The value of the magnetizing inductance L_m can be found by,

$$L_{eq} = \frac{L_m\, L_0}{L_m + L_0}$$

$$\frac{1}{L_m} = \frac{1}{L_{eq}} - \frac{1}{L_0} = \frac{1}{89\,\mu H} - \frac{1}{28mH} = 89\ \mu\text{H}$$

$\therefore L_m = 89\ \mu$H

The value of the coupling capacitor C is obtained by (19):

$$C = \frac{P_{0\,max}}{20\pi V_0^2{}_{max}\omega_{grid}} = \frac{(96\text{W} \times 80\%)}{20\pi \times (180\text{ V})^2 \times 60\text{ Hz}} = 628\ \eta\text{F}$$

The value of the C_{PV} capacitor is obtained by,

$$C_{PV} = \frac{P_{PV}}{2\pi\omega_{Grid}V_{PV}\hat{V}_{PV}}$$

Here we assume a ripple smaller than 8.5 %. In this case we assume it as 5.0 %

$$C_{PV} = \frac{P_{PV}}{2\pi\omega_{Grid}V_{PV}\hat{V}_{PV}} = \frac{96\text{ W}}{2\ \pi \times 60\text{Hz} \times 34\text{V} \times 1.7\text{V}} = 4400\mu\text{F}$$

VI. ZETA DC-DC CONTROL

A feed forward control is an alternative, when the input/output relation of the PWM converter is linear. It reduces the effects of disturbances of the source voltage [7].
In this kind of control, usually the peak voltage of the triangular high frequency waveform is proportional to the source voltage, but it is possible to modulate a reference voltage proportional to the source, keeping the triangular waveform peak fixed [8]. Fig. 7 shows the block diagram of the reference-voltage modulation feed forward control strategy for the grid-tied zeta converter.

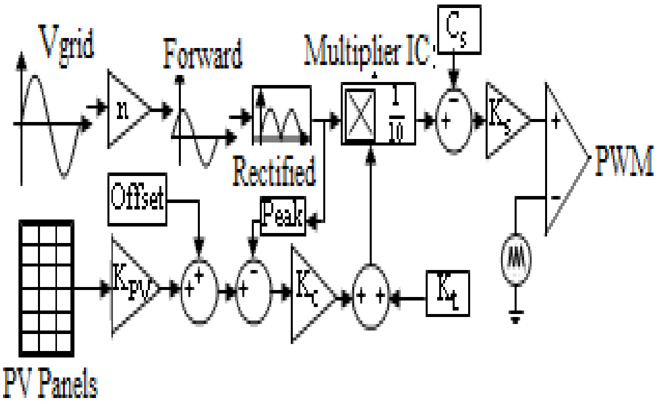

Fig. 7 Feed forward control block diagram for the Zeta converter.

The voltage in the solar panel is reduced by a gain K_{PV} and combined with an "Offset". This compensate de irradiance effects, building a linear relation between the maximum power voltage V_{mpp} and maximum power current I_{mpp}, like a table, extracting the maximum power of PV's [9]. The resultant signal is reduced by a sinusoidal peak rectified value, so that any change in the peak value of the network is compensated. A gain K_C appropriates the signal to the maximum value supported by the IC multiplier (10 V). To compensate the temperature dependence, a temperature sensor with linear mV/°C relation (K_t) was used, changing the best operation point to V_{mpp} and I_{mpp} when temperature changes. This control is a very simple and low cost maximum power point tracker algorithm which will be present in future paper.
A sample of grid voltage is obtained through a transformer with *n* relation. This sample is advanced through an all-pass filter to compensate the lag caused by the inductor (L_0). Irradiance and temperature compensation combined with peak detector composes the scale factor. The multiplication of scale factor by the network sample results in a signal of 0V to 10 V, which is the reference that the current output $iL_0(t)$ will follow. This signal must have an offset C_S and a gain K_S so that it varies within the limits of the triangular wave. The values of the constants involved in the control can be seen in Table 1.

TABLE I
CONSTANTS FOR FEED FORWARD CONTROL

Constants	Value
n= N_S/ N_P	50.3
K_{PV}	0.35
Offset	6.93
K_C	1.50
C_S	2.61
K_S	5.76
K_t	177 mV/°C

An example of control behavior is show in Fig. 8. Initially the PV panel operates under 1000 W/m² irradiance at 0°C temperature (A). The irradiance decrease to 500 W/m² keeping the same temperature, linear approximation *AMVL* makes PV panel operates like an irradiance sensor, reducing V_{mpp} and extracting adequate current (B). After, temperature increases from 0°C to 60°C keeping the irradiance. Temperature sensor place *AMVL* straight line at necessary position to MPP at 60°C, *AMVL'* (C). Skew straight line and current are the same when the operating point was point B. Finally, irradiance increase to 1000 W/m², which keeps the same temperature, increases V_{mpp} and extracts more current (D).

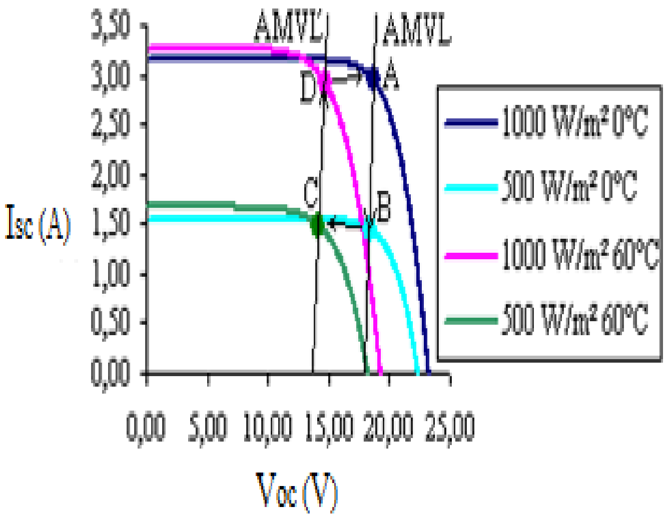

Fig. 8 Control dynamics of the Zeta MPPT.

VII. EXPERIMENTAL RESULTS

TABLE II
COMPONENTS VALUES OF ZETA CONVERTER

Component	Value
C_{PV}	4400 µF
L_m	89 µH
L_0	28 mH
C	680 ηF
N= N_S/ N_P	1

The waveforms of injected current i_0 and grid voltage V_0 are shown in Fig. 7. It shows that the maximum power of the PV panels generates 100 W_{pk} approximately. It is also found that the phase opposition indicates the drained power by grid utility depicted in Fig 9.

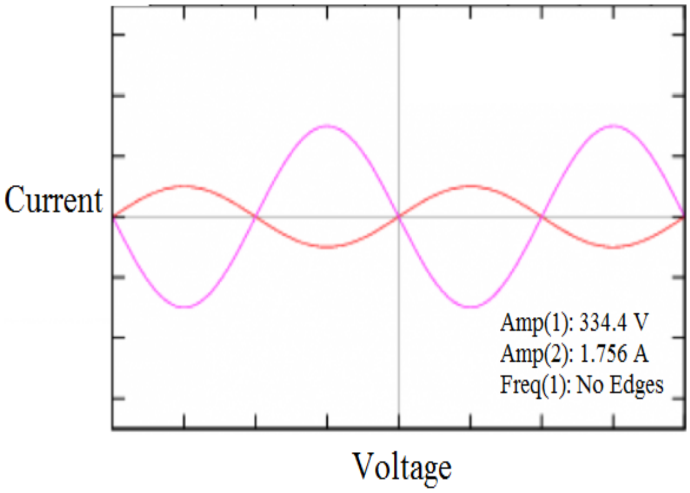

Fig. 9 Waveforms of grid voltage V_0 and grid injected current i_0.

Fig. 10 shows the waveforms of injected current i_0 vs grid voltage V_0 when the power is increased. It is observed that the injected current gives us a pure sine wave and when PV panels increases power and the control dynamics, the frequency of the injected current waveform was also increased.

When the PVs' power increases from 60 W_{pk} to 100 W_{pk}, we get,

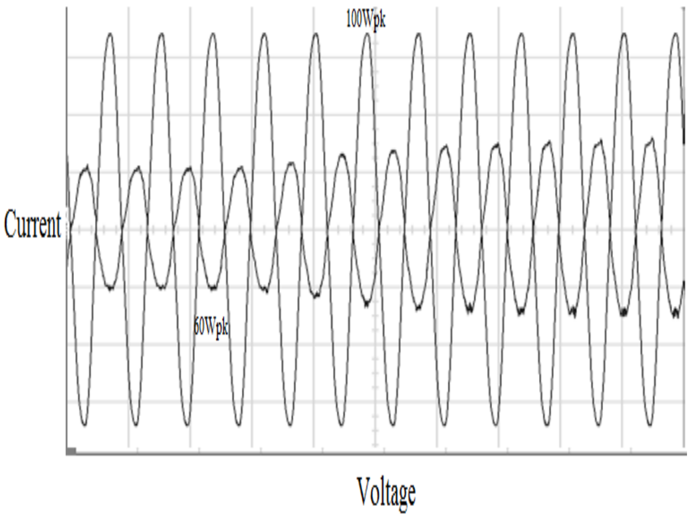

Fig. 10 Waveforms of grid voltage V_0 and grid injected current i_0 when PV panels increase power.

The harmonic content of grid voltage and injected current i_0 is shown in Fig. 11. The voltage grid sample is used to generate the injected current, so the harmonic content of the injected current is similar to the grid voltage. The total harmonic distortion of grid voltage is 3.4 % which is below the total harmonic distortion of 9.4 % and the reactive power is about 13.5 VAR.

From the Fig. 9 we can see that for the 3rd and 5th harmonic, the distortion is higher than the others. As the order of harmonic components increases, the percentage rate of harmonic current and harmonic grid voltage decreases.

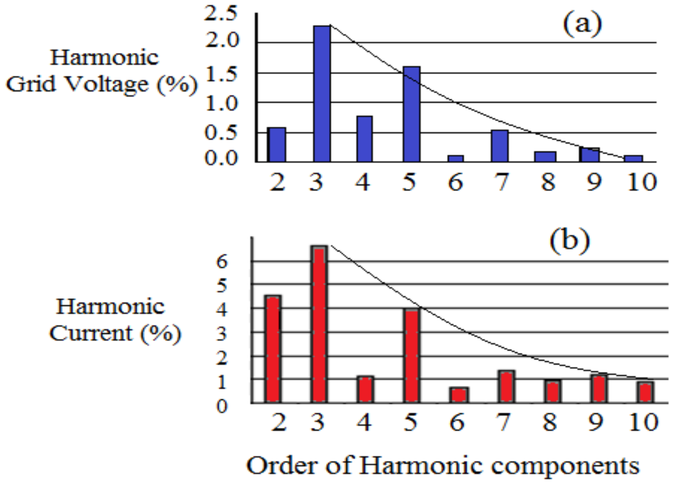

Fig. 11 Harmonic content of (a) grid voltage V_0 and (b) injected current i_0

VIII. CONCLUSION

In this paper we have studied the design of a Photovoltaic Panel connected to the Grid System using a Zeta Converter working in DCM, producing the output of a sinusoidal current waveform from a set of solar panels. From the control strategy of this study, we obtained a clear waveform of the current injected into the grid. The necessary lag of 180º between the network voltage and the current waveform injecting into the grid was also obtained. The losses are reduced by the Zeta converter switch which operates at low frequency. However the switching losses are considerable at high frequency. Thus, the total harmonic distortion is higher in injected current witch is better for the system.

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