A Single-Phase Grid-Connected PV System
With Active Power Filter

Denizar C. Martins and Kleber C. A. de Souza

Abstract—In this paper a single-phase active power filter based in a two stages grid-connected photovoltaic system is presented. The proposed system can not only inject PV power into utility but can act always as an active power filter to compensate the load harmonics and reactive power such that the input power factor is unity independently of the solar radiation. In sunny days, the system processes all the reactive and active load power and the excessive power from the PV module can be fed to the utility. On the other hand, on cloudy days for instance, if the PV power is not enough, the system processes all the reactive load power and the shortage of load active power is supplemented by the utility. Besides, just using one current sensor, the control strategy is simpler and of easy practical implementation.

Keywords—Active power filter, grid-connected, power factor, PV systems, single-phase systems, THD.

I. INTRODUCTION

PHOTOVOLTAIC (PV) solar energy as an alternative resource has been becoming feasible due to enormous researches and development work being conducted over a wide area (Bahu, 1996), (Chiang, 1998), (Hirachi, 1996) and (Yamaguchi, 1994).

Some researchers spent efforts in developing PV inverter systems with grid connection and active power filtering features using sensors to measure the load current (Wu, 2005), (Kim, 1996), (Cheng, 1997) and (Kuo, 2001).

This paper presents a single-phase topology, without load current sensor, composed by a dc-dc converter in cascaded with an inverter, as shown in Fig. 1. The system aims transferring the photovoltaic (PV) power to the ac load and paralleled with the utility. The dc-dc converter is used to boost the PV voltage to a level higher than the peak of the voltage utility such that the inverter can provide the ac voltage without requiring the transformer. The dc-dc converter is also responsible for tracking the maximum power point (Koutroulis, 2001) and (Zhang, 200) of the PV modules to fully utilize the PV power. The shortage of load power from the PV module is supplemented by the utility. On the contrary, the excessive power from the PV module to the load can be fed to the utility. The balance of power flow is controlled through the inverter. The inverter also is used to act always as an active power filter to compensate the load harmonics and reactive power such that the input power factor is unity (Fig. 2).

II. PROCEDURE FOR PAPER SUBMISSION

The dc-de converter power structure used to boost the PV voltage and for tracking the maximum power point of the PV modules to fully utilize the PV power was the Half-Bridge Zero Voltage Switching Pulse Width Modulation (DC-DC HB ZVS-PWM) asymmetrically driven converter (de Souza, 2006) shown in Fig.3.

The HB ZVS-PWM has been designed considering the reduction of losses and mainly the volume of the magnetic and the right value of the capacitors Ce1 and Ce2 can be determined by (1) and (2).

\[ Ce_1 = \frac{P_o \cdot f_s \cdot \Delta V_{in}}{f_i \cdot V_i \cdot D} \] (1)

\[ Ce_2 = \frac{P_o \cdot f_s \cdot \Delta V_{in}}{f_i \cdot V_i \cdot D} \] (2)

Fig. 1 Single-phase two stages Active Power System PV system.

Fig. 2 Power flow of the system with nonlinear load.
Fig. 3 Half-Bridge Zero Voltage Switching.

Fig. 4 Full bridge inverter.

Fig. 5 Four equivalent circuits of the switching modes.

In Fig. 6 the energy flow is controlled by the current $I_L(t)$. However, this current is defined by the difference of voltage between the sources $V_i(t)$ and $V_o(t)$, applied across the impedance. In this case, as the impedance is a pure inductance, the current will be equal the integral of the voltage across it. As $V_o(t)$ is known, once it is the utility voltage itself, $V_i(t)$ is imposed and therefore $V_L(t)$, in a convenient form, in a way to obtain the output current desired across the inductor. Thus:

$$V_L(t) = V_i(t) - V_o(t) \quad (3)$$

In this manner, the structure of the converter shown in Fig. 4 can be represented, without loss of generality, as the controlled voltage source $V_i(t)$, presented in Fig. 6 where the link inductors are represented by the inductor $L$, $V_o(t)$ is the utility voltage and $I_L(t)$ is the output PV system current.
amplitude is defined by the modulation, added to harmonic components of frequencies that are multiples of the switching frequency. Ignoring the effect of the harmonic components of the switching frequency on voltage $V_{r}(t)$, once the inductor works as a low pass filter for the current, the voltage imposed across the inductor is represented simply by (3). Fig. 7 shows the manner in which the converter allows the voltage to be imposed across the inductor, as shown in the equivalent circuit of Fig. 6.

$$V_{o}(t) = V_{r}(t) + \sum V_{L}(t) - \frac{1}{L} \int V_{L}(t) \, dt - i_{r}(t)$$

Fig. 7 Block diagram of the simplified equivalent circuit.

Indeed, the output current is desired to be a mirror of $V_{o}(t)$ as expressed in (4). Nevertheless, according to (5), the inductor voltage is the derivative of the current across itself. Therefore, equation (6) describes the voltage $V_{r}(t)$, which, in effect, is defined by the control loop, should present a sine, in order to annul the effect of $V_{o}(t)$, and a cosine, which, by composition, will be the resulting voltage imposed across the inductor, therefore, guaranteeing a sinusoidal current. In practice, at the frequency of the mains, the inductor is a very small reactance, causing the voltage drop across the inductor to be much smaller than the voltage of the mains. In other words, the sine of $V_{r}(t)$ dominates the cosine, demonstrating that the demand on the current loop is much more in favor of annihilating the "disturbance" of the output voltage rather than to effectively control the output current.

$$I_{r}(t) = I \cdot \sqrt{2} \cdot \sin(\omega t)$$ (4)

$$V_{L}(t) = L \cdot \frac{dI_{r}(t)}{dt} = L \cdot I \cdot \sqrt{2} \cdot \omega \cdot \cos(\omega t)$$ (5)

$$V_{r}(t) = L \cdot I_{ref} \cdot \sqrt{2} \cdot \omega \cdot \cos(\omega t) + V_{ref} \cdot \sqrt{2} \cdot \sin(\omega t)$$ (6)

In the classic control strategy, an internal current loop and an external loop to control the input voltage are implemented. The voltage loop defines the amplitude of the reference current by multiplying its control signal by a "waveform", which can be a sample of the output voltage or a digitally generated sinusoid, generating the output current reference. Fig. 8 demonstrates how the classic control strategy is implemented, in which $V_{r}(t)$ is determined by the current error signal passing through the compensator and the error signal is the difference between a sample of the current and its reference. Fig. 9 shows the same block diagram simplified.

$$\frac{d}{dt} e(t) = 0 = \frac{d}{dt} i_{ref}(t) - \frac{d}{dt} i_{r}(t)$$ (10)

$$v_{control}(t) = L \cdot \frac{d}{dt} i_{ref}(t) + \frac{1}{k} V_{o}(t)$$ (11)

As the disturbance is measurable, the utility voltage disturbance controller $G_{cd}$ is used to reduce de disturbed voltage component. The new block diagram that contains this feed-forward controller is presented in Fig.10. From Fig.10, it can be seen that:

$$i_{r} = \frac{k \cdot C_{i}}{sL + k \cdot C_{i}} \cdot i_{ref} + \frac{k \cdot (G_{cd} - 1/k)}{sL + k \cdot C_{i}} \cdot V_{o}$$ (12)

From (12), when $G_{cd} = 1/k$, the disturbance from $V_{o}$ can be eliminated, and if $kC_{i} >> |sL|$, than $I_{r} = I_{ref}$ identifying accurate current control effect for $I_{ref}$.

Repeating the same analysis, but now considering the connection of any load between the system and the commercial electric grid, a new configuration, presented in
Fig. 11, is obtained. It can be observed that now the inductor current is the load current plus the utility current. Again, as sinusoidal current to the utility line is a designed goal, adding a sample of the load current to the inductor current reference it is possible to control the inductor current and still guarantee a sinusoidal utility current. A new block diagram representing the system is shown in Fig. 11.

However, in this case, besides the current sensor used to sample the current in $L$, it is the necessary another sensor to sample the current in the load. Another disadvantage in this configuration is that as the control is done monitoring the load current ($I_L$), when the system is operating Active Power Line Conditioner Mode (low sun light), is necessary before to extract the fundamental component of the load current for later to find the reference current. So, it is necessary to observe a period of the grid at least.

Thus, to control the output current in phase with the voltage utility and, to obtain a unity power factor, even with the connection of a load between the grid and the system, it is enough to observe only the AC mains current. In this case, besides doing use of just a sensor one, the control strategy is simpler and of easy practical implementation.

III. EXPERIMENTAL RESULTS

To demonstrate the feasibility of the discussed PV system, a prototype was designed and implemented. The specifications of the system (Figure 15 and Figure 16) are shown below.

Solar array:
- Number of PV Module: 20;
- Rated power: 1002W;
- Rated voltage: 83.5V;
- Rated current: 12A;
- Short-circuit current: 12.4A;
- Open-circuit voltage: 107V.

DC-dc power converter:
- Output voltage: 400V;
- Switching frequency: 100kHz;
- $C_{in}$ and $C_{HF}$: 1000μF;
- $C_{e1}$ and $C_{e2}$: 10μF and 5μF;
- $L_{HF}$ and $L_{r}$: 50μH and 680nH;
- $C_o$ : 1000μF.

Inverter:
- Switching frequency: 20kHz;
- $C_{LF}$: 1000μF;
- $L_{LF}$: 1.6mH;
- $L_{o1}$ and $L_{o2}$: 1.2mH;
- Output voltage: 220V, 60Hz;
- Load: 400VA (Capacitive).

In the proposed system, a LC filter ($L_{HF}$ and $C_{HF}$) is connected with the PV array output to filter the high frequencies drained by the dc-dc converter, and a series LC filter ($L_{LF}$ and $C_{LF}$) is connected between the converters to support the second-order component (120Hz) presented in the input inverter current.
IV. CONCLUSION

This paper presents a single-phase topology for transferring the photovoltaic (PV) power to the ac load and paralleled with the utility. The proposed PV system has the advantage of acting always as an active power filter to compensate the load harmonics and reactive power such that the input power factor is unity.

The simplicity in the strategy of the output current control, in other words, current injected in the electric system, is another advantage of the study, because besides doing use of just one current sensor, it is of easy practical implementation.

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REFERENCES


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Figure 18. Utility current ($I_u$) and utility voltage ($V_{\text{Utility}}$) with load (Ch1 1A/div and Ch2 100V/div).

Fig. 19. Waveforms of utility current ($I_u$) and Inverter current ($I_o$) (Ch1 2A/div and Ch2 2A/div).

Fig. 20. Waveforms of grid current ($I_g$) and utility voltage ($V_{\text{Utility}}$) without load. (Ch1 2A/div and Ch2 100V/div)