A BIFUNCTIONAL UTILITY CONNECTED PHOTOVOLTAIC SYSTEM WITH POWER FACTOR CORRECTION AND U.P.S. FACILITY

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Abstract

In this paper, a novel utility connected photovoltaic power generation system with unity power factor and uninterruptable power system facility and its control strategy are proposed. The proposed photovoltaic(PV) system is connected in parallel between utility and load. The PV system provides an uninterruptable voltage to load, a maximum power tracking to solar array, and power factor correction to the utility. The proposed system has the following advantages compared with the conventional utility connected PV system:

1. Harmonic elimination Function
2. Feeding the photovoltaic energy to the utility
3. Providing the uninterruptible power source along battery to the load

In case that the photovoltaic array system is on the poor power generation, the battery and capacitor of the PV system are charged by three phase utility source and the inverter in the PV system only provides the reactive current to eliminate the harmonic current exited on the utility. In the normal operation mode, the PV system supplies active power to load and reactive power to utility in order to maintain the unity power factor and to regulate ac load voltage.

I. Introduction

Power supply reliability and power quality have become important issues for all kind of power electronics systems including photovoltaic systems. Interconnecting a photovoltaic system with utility, it is necessary that the PV system should meet the harmonic standard and the active power supply requirement. Several utility connected photovoltaic systems have been proposed [1,2,3,4,5]. Among these systems, the most common type is the parallel running PV system with the bidirectional power flow to provide unity power factor on the utility line. In this system, an inverter connected to the photovoltaic array supplies the power to the utility, and regulates the magnitude and phase of the photovoltaic system output voltage[3].

This paper presents an alternative approach to the interconnected photovoltaic system above. It employs an inverter connected in shunt between the ac utilities and a load. Fig. 1 shows power circuit of the proposed utility connected PV system. In the normal operation mode, the photovoltaic system provides the active power to the load and utilities. However, if the PV power generation is not enough to supply the demanded power of load, the utility feeds the load directly, and the inverter supplies only a reactive compensating current component that remains after subtracting the inverter output current from the reactive current component. With the utility fail, the power is transferred from the photovoltaic system to the load. Therefore, the proposed system has the following advantages;

1. A near unity power factor
2. UPS function for load
3. Balancing capability for the load

II. Principle of operation

The proposed scheme employs an inverter to have the reactive power compensation, harmonic elimination, and active power supply function; a dc/dc converter to address the maximum power tracking. Furthermore, the proposed system is connected with a utility line through a series inductor allowing the reactive power control. The load is connected at the common coupling point between reactor and inverter through a L-C filter. Under poor generation condition of the photovoltaic system, the ac source supplies the real power to the load directly, and the photovoltaic system only injects the compensating current to eliminate the harmonic components generated by nonlinear load. Therefore, in this mode, the PV system only provides the reactive power to the utility that eliminates the harmonic components generated from the load. In the normal mode, the photovoltaic system mainly provides active power to the load or the utility, and it necessary functions UPS to the load.

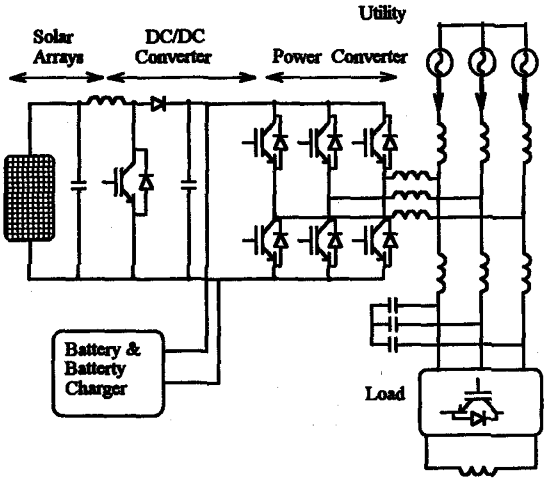


Fig. 1. Proposed Photovoltaic Scheme

II.1. Maximum Power Tracking Control

To achieve the maximum power tracking control from the photvoltaic array, first the output current and the output voltage of the solar array system are controlled to trace the proposed power current profile as shown in Fig 2.

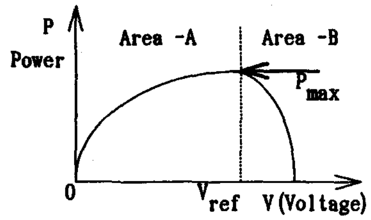


Fig. 2. Power-Voltage Profile for Solar Battery

For the maximum power tracking, the dc/dc converter is operated so that the photovoltaic system is operated on the maximum power point. For a photovoltaic system, a reliable maximum power tracking strategy has been proposed in [2,3,4]. This approach is based on the voltage-power profile that is on the linear transformation of the maximum power quantity into the voltage defined in the reference voltage. Thus reference voltage V_{ref} indicating the maximum power point is established on the power-voltage profile. Since the power output comparison between the previous value P_n and current state P_p is important, it is convenient to consider the following power equation ;

$$P_n = V_n \times I_n \\ P_p = V_p \times I_p \tag{1}$$

where the variable V_n and I_n are the current measured values and the variable V_p and I_p represent the previous measured values. Comparing the P_n to P_p, the operating mode of the system is separated with three different type,

(i) $P_n > P_p$: In this condition, the photovoltaic output parameters are remeasured to check the system state whether the system be on the steady state.
(ii) $P_n = P_p$: This mode represents that the photovoltaic system stands on the p-max point
(iii) $P_n < P_p$: In this mode, if $V_n > V_p$, the operation point of the solar array passes over the p-max point from the area-A into area-B as shown in Fig.2. Thus, the V_{ref} is decreased. In case $V_n < V_p$ that, the operation point passes over the p-max point from the area-B into area-A. Thus, the V_{ref} is increased from the area-A to area-B

II.2. Formulation of the Current Reference

As depicted in Fig 3, the output current generating from the photovoltaic system is formulated from a combination of the capacitor output voltage error between the measured voltage and the command voltage. Thus, the command dc command is decided from the battery voltage specification and the photovoltaic rating voltage. The reference current for the generation operation of the photovoltaic inverter is

$$I_{ref} = K_p(V_c^* - V_c) + K_I \int (V_c^* - V_c)dt - \frac{P_{max}}{V_{ref}} \tag{2}$$

where V_c^* is the reference voltage for UPS specification, V_c^* is the measured voltage, and K_p and K_I, are PI control constants.

K_p, and K_I, are the parameters that determine the trade-off between steady state and transient performance. It can be noted that if K_p and K_I, are large, the photovoltaic output voltage regulation is dominant, and the steady-state output error is low.On the other hand. if K_p and K_I, are small, the transient performance caused by the variation of solar radiation and temperature is small. Therefore, the proper selection of the K_p and K_I, is essentially required to satisfy above two voltage regulator performances. The final term $\frac{P_{max}}{V_{ref}}$ in Eqn. 2 represents the maximum available current from the photovoltaic generation. Te P_{max} and V_{ref} are obtained from Fig. 2. After calculation of the reference signal, the reference signal is summed with the compensating reference current to eliminated harmonic current generated in the nonlinear load. The control equation for the compensating current is derived in the next section. Thus the control scheme of the Eqn. 2 brings the stable d.c. voltage for the UPS system and provides the sinusoidal current waveform 180^o out of phase to the utility voltage so that the photovoltaic inverter supplies the active power to the utility as well as the uninterruptible power to load. The PWM signal is generated by comparing the triangular waveform to the reference waveform;

$$I_{PWM} = I_{ref} + I_c \qquad (3)$$

where I_c is the compensating current to eliminate harmonics existed on the utility

II. 3. Formulation of Reactive Power Compensation

The proposed photovoltaic inverter is controlled to compensate for reactive power and harmonic distortion in addition to provide the active power to utility as described in the previous section. As can be seen from Fig 3, the operation principle is based on the injection of a compensating current that eliminates the reactive component as well as the harmonic current generated by nonlinear load. Thus, a reference waveform for the current to be injected in the utility should be calculated by the control unit, so that the photovoltaic system is required to produce a current as close as possible to the reference waveform.

The utility voltage and load current is defined as

$$E(t) = \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} V_m \sin(\omega t) \\ V_m \sin(\omega t - 120^\circ) \\ V_m \sin(\omega t + 120^\circ) \end{bmatrix} \qquad (4)$$

$$I_L(t) = \begin{bmatrix} I_m \sin(\omega t) + I_{reactive,a} \\ I_m \sin(\omega t - 120^\circ) + I_{reactive,b} \\ I_m \sin(\omega t + 120^\circ) + I_{reactive,c} \end{bmatrix} \qquad (5)$$

where the $I_{reactive,a}$ is defined as current component that remains after subtracting the active currents(I_m sin(wt)) from the I_L(t). Furthermore, the instantaneous power flow in the network is defined as;

$$p = v(t) \times i(t) = \begin{bmatrix} \frac{V_m I_m}{2} + Harmonic\ terms \\ \frac{V_m I_m}{2} + Harmonic\ terms \\ \frac{V_m I_m}{2} + Harmonic\ terms \end{bmatrix} \qquad (6)$$

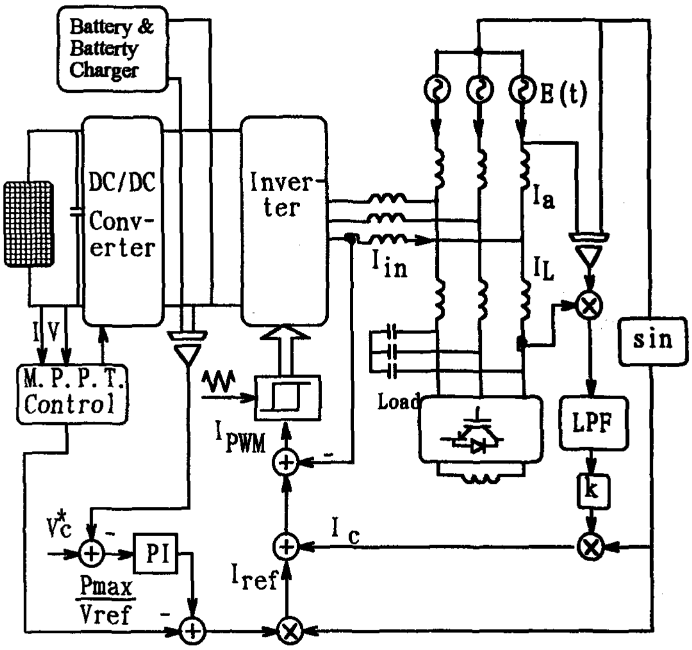


Fig. 3. Block Diagram of Photovoltaic System Control

Taking a low pass filtering for the above instantaneous power as shown in Eqn. 6, the harmonic components of the instantaneous power can be eliminated and the pure dc power component($P_{dc}=V_m I_m/2$) is obtained. After taking multiplication $\frac{V_m}{2}$ with P_{dc}, the peak value I_m of the active current is obtained, and then the compensating reference current is calculated as follows;

$$I_{in}(t) = \begin{bmatrix} I_{L,a}(t) - I_m \sin(\omega t) \\ I_{L,b}(t) - I_m \sin(\omega t - 120^o) \\ I_{L,c}(t) - I_m \sin(\omega t + 120^o) \end{bmatrix} \quad (7)$$

From the above equations, it is clear that the reference current contains the reactive current components at the fundamental frequency as well as the higher harmonic frequency since the load current I_L have higher harmonics.

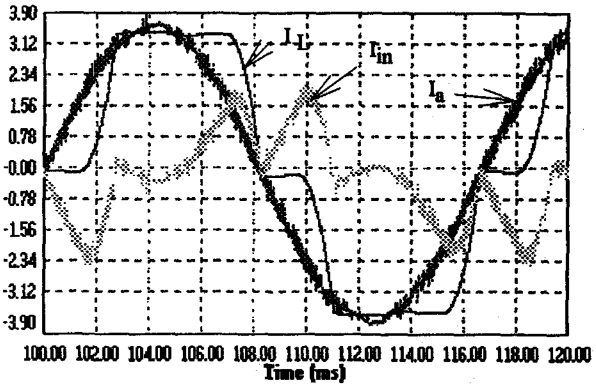
The current control utilizing a ramp comparison controller is employed for the photovoltaic inverter. The resulting PWM frequency has a duty cycle that is proportional to the current error. When the current error exceeds the triangular waveform, the inverter switch is turned off and when the error is less than the triangular waveform, the inverter switch is turned on.

III. Simulation Results

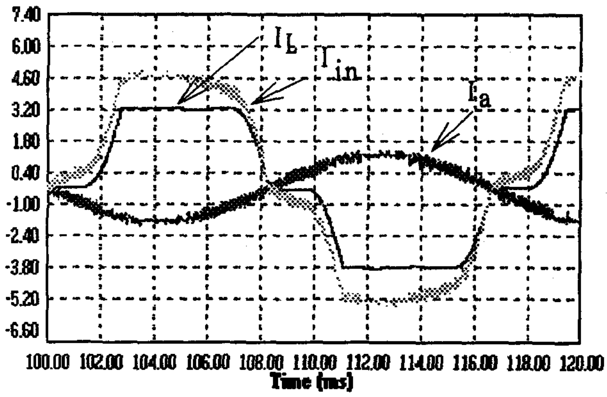
The analytic expressions in the previous section shows the various control operation of the proposed photovoltaic system. In order to further verify the proposed scheme, simulations for a three phase and a single phase power system are performed using PSIM software.

First, a simulation for a three phase system is performed. The major parameters used in the simulation are as follows: line to line voltage=240(V); photovoltaic output voltage = 350(V); DC side capacitor = 5500(μF); inductor L=7(mH); the switching frequency=20(kHz). Rectifier is used for the nonlinear load. Fig 4(a) shows the simulation results for the proposed control scheme without photovoltaic generation. It is seen that the utility input current has a sinusoidal shape. It shows that compensating current successfully eliminates the harmonic current generated by nonlinear load. Fig 4(b) shows the simulation results for the photovoltaic system that provides the active power to utility and load. It is seen that the utility input current waveform is close to a sinusoidal waveform and is 180° out of phase to the utility voltage. It means that the photovoltaic inverter supplies the active power to the utility as well as the uninterruptible power to load.

Second, a simulation for a single phase system is performed. The major parameters used in the simulation are as follows: line voltage=120(V); photovoltaic output voltage = 260(V); DC side capacitor = 3500(μF); inductor L=7(mH); the switching frequency=20(kHz). Rectifier is used for the nonlinear load.Fig 5(a) shows the simulation results for the proposed control scheme without photovoltaic generation case. It is seen that the utility input current has a sinusoidal shape.



(a) Without photovoltaic generation

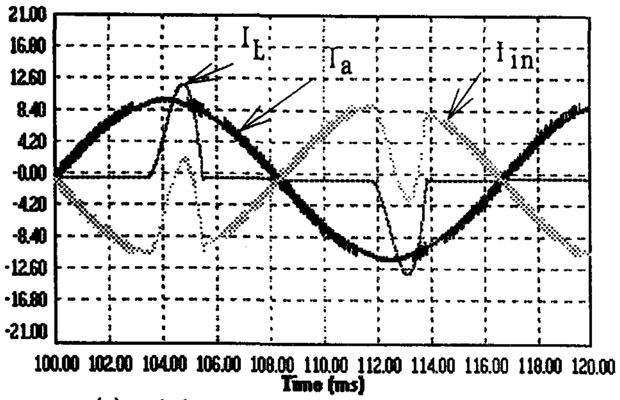


(b) With Photovoltaic Generation

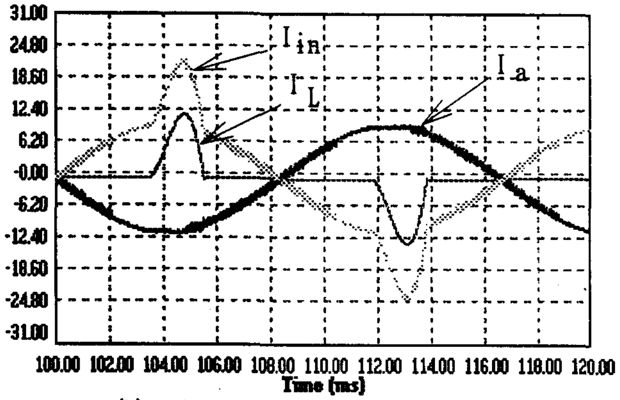
Fig. 4. Photovoltaic System Current Waveform

It shows that compensating current successfully eliminates the harmonic current generated by nonlinear load. Fig 5(b) shows the simulation results for the photovoltaic system that sucessfully provides the active power to utility and load. It is seen that the utility input current waveform is close to a sinusoidal waveform.

These simulation results for a single phase and a three phase system show that the proposed photovoltaic system successfully accomplishes the unit power factor correction and the active power generation for the utility and load with and without photovoltaic generation.



(a) Without photovoltaic generation



(b) With photovoltaic generation

Fig. 5. Photovoltaic System Current Waveform

IV. Experimental Results

Fig 6 shows the block diagram of the proposed scheme for the experiment. A digital signal processor (DSP56001) manufactured by Motorola is used in the implementation of the reference current formulation and switching pulse generation. The DSP56001 includes two separate memory spaces for data, which can be simultaneously accessed during a single instruction cycle. Since the DSP can multiply two 24bit numbers, execute 10.25 million instructions per second (MIPS), add 48 bit result to a 56-bit accumulator, and access both memories in one instruction cycle, it is very powerful to implement the proposed scheme.

The load current, solar array output current and the inverter output current are measured through current sensor. The A/D converter ADC 678 and the sample and holder ADG 529 are used to convert and sample the analog signal. The dc voltages(V,V_{dc}) is isolated from the signal processing unit by voltage isolator (AD202) for noise immunization.

To verify the performance of the proposed scheme, a prototype was developed and tested in a single phase power system connected with 120(V). The major parameters used in the experiment are as follows: photovoltaic output voltage = 260(V); DC side capacitor = 3500(μF); inductor L=7(mH); the switching frequency=20(kHz). Rectifier is used for the nonlinear load. Fig. 7(a) shows the utility voltage and the load current for poor photovoltaic power generation state. Fig 7(b) shows the utility AC line current compensated from the proposed scheme implemented using a DSP 56001. From these figures, it can be seen that the utility current is pure sine wave, the utility voltage is in phase with the utility current, and the waveforms is coincided with the simulation result as shown in Fig.5(a). It shows the proposed scheme performs unity power factor correction during the poor power generation of the photovoltaic system.

Fig 8(a) and(b) shows the experimental results for the photovoltaic system that provides the active power to utility and load. It is seen that the utility input current waveform is close to a sinusoidal waveform and the waveform is coincided with the simulation result as shown in Fig.5(b). This experimental results show that the proposed photovoltaic system successfully accomplishes the unit power factor correction and the active power generation to the utility and load.

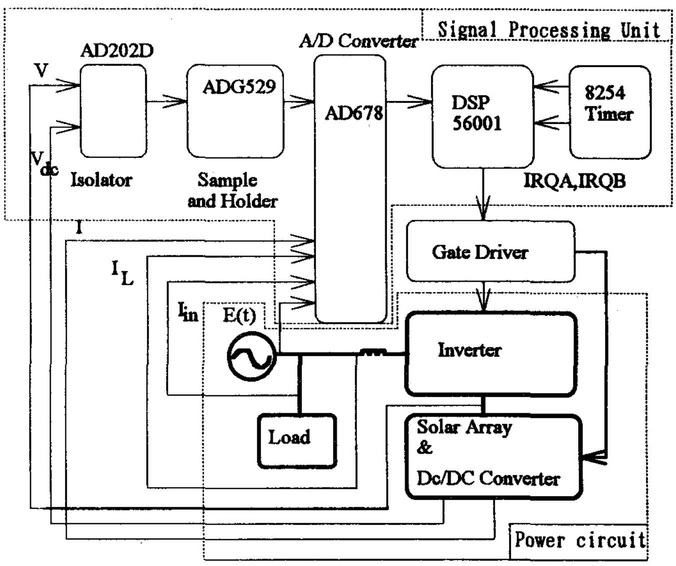


Fig. 6 Block Diagram of the proposed scheme for experiment

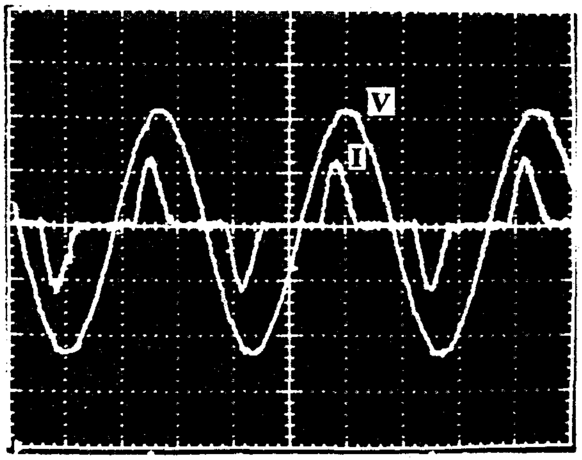


Fig. 7 (a) Line Voltage and load current (10 A/Div)

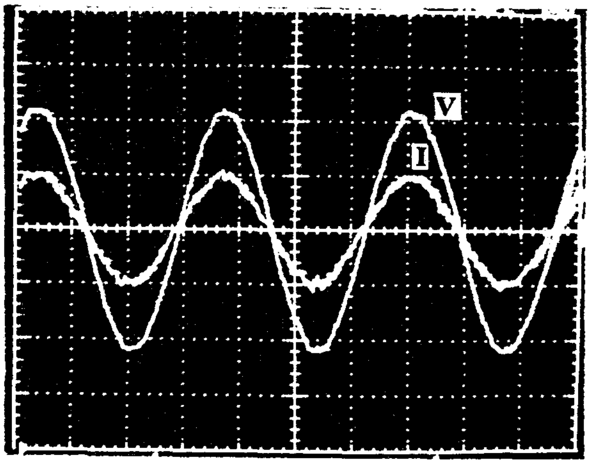


Fig. 7 (b) Line Voltage and line current (10 A/Div)

Fig. 7 Current and voltage waveform without photovoltaic power generation

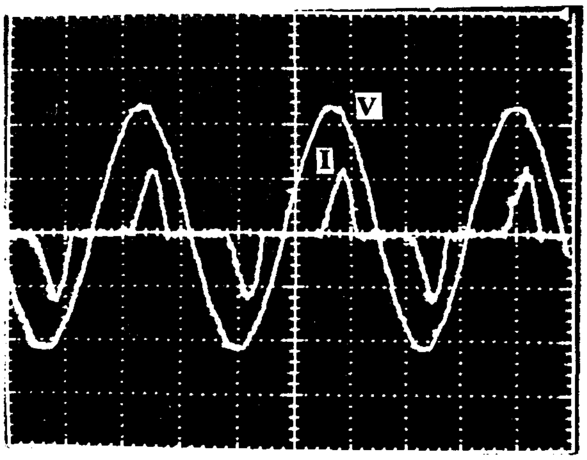


Fig. 8 (a) Line Voltage and load current (10 A/Div)

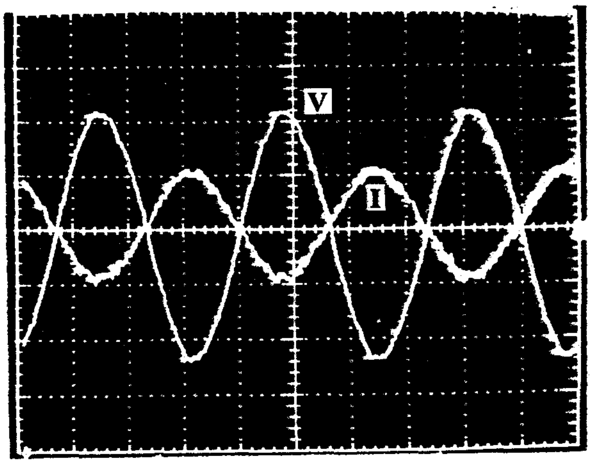


Fig. 8 (b) Line Voltage and line current (10 A/Div)

Fig. 8 Current and voltage waveforms with photovoltaic power generation

V. Conclusion

In this paper, the bifunctional photovoltaic system is proposed in the three phase power system. The proposed approach employs a three phase inverter and a dc/dc converter. A suitable current and voltage control strategy are proposed to control the switches in order to provide the maximum power tracking and the reactive power compensation. Furthermore ,active power generated by the photovoltaic system is supplied to utility and load. The analytical and experimental results demonstrate that the reactive power compensation and harmonic elimination is achieved with a maximum power tracking condition.

References

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