# Application Of Off Grid Solar PV System for Power Processing Unit

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**Abstract-** In this paper a novel multi-functional power processing unit capable of extracting maximum power from solar photovoltaic panels is described. It employs a combination of a voltage controlled voltage source inverter (VCVSI) and a current controlled voltage source inverter (CCVSI), connected in series on the DC side and in parallel on the AC side. This Power Processing Unit is able to provide an uninterruptible power supply feature, load voltage stabilization, unity power factor operation, maximum power point tracking, and higher efficiency for charging the battery from renewable energy sources and more reactive power support. The experimental results from the proto typed system confirm validity of the proposed topology.

## I. Introduction

Many renewable energy sources (RES), such as photovoltaic (PV) modules, produce maximum power at a DC output voltage that varies widely depending upon the solar insolation levels, ambient temperature and other variables[4,5] . Wind energy, which is often extracted to a DC output using a wind generator (WG)with a rectifier, generally also requires a variable output voltage, to extract the maximum power at any given time or wind speed to obtain the maximum benefit from the equipment capital expenditure[5,7] . Typically, a charge controller is used to transfer power from the PV or WG to a battery. The power from the battery is then converted to AC using a voltage source inverter (VSI) to energize AC loads. A common topology for a stand-alone photovoltaic system with DC output is the series connection of a DC energy source to a battery charger to an inverter [8, 13]. The application of PV assisted uninterruptible power supply systems for poor quality utility power grids has been reported [6, 10-24]. Where a bi-directional inverter is used in an “in-line” configuration as shown in Fig. 1. Energy not intended for the battery must then be converted again, resulting in a system where the cost and efficiency have not been optimized.

## Ii. The Multi-Function Power Processing Unit

In the Multi-Functional Power Processing Unit [1-3] (Fig. 2). the CCVSI is connected in series with a combination of the battery and VCVSI on the DC side in order to regulate the difference in voltage between the battery and the PV and hence provide the Maximum Power Point Tracking; MPPT operation. The CCVSI is connected directly across the AC grid and is able to supply a controlled current to the AC bus. In the absence of PV input, it can provide rated reactive power support or active filtering of the line current to minimize the harmonic distortion. The VCVSI is connected to the battery, providing bi-directional power (both rectification and inversion) flow capability. The VCVSI is connected through the decoupling inductor ($x_m$)and produces a constant output voltage across the load. In extended periods of grid failure, a backup diesel generator can be used to provide the AC supply. The CCVSI only needs to operate in inverter mode (active power .flow from DC to AC), while the VCVSI has fully hi-directional real power flow.

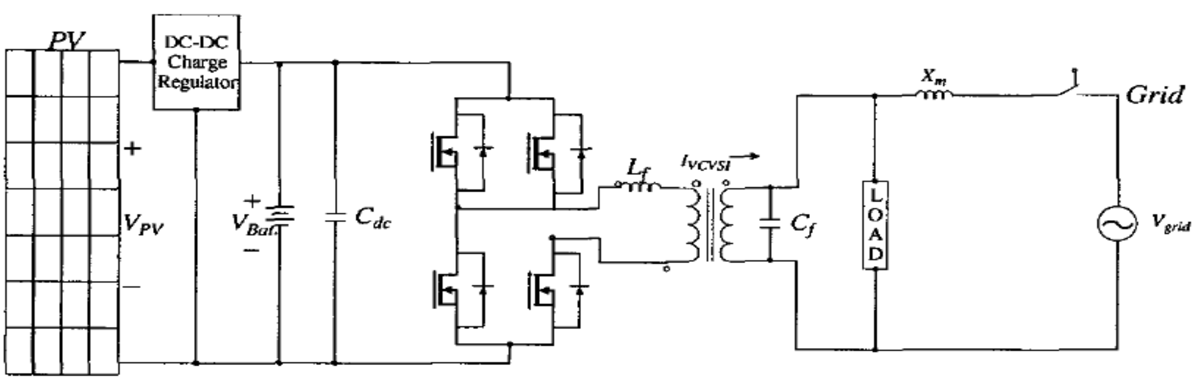


Fig. 1 Conventional grid-connected PV assisted UPS

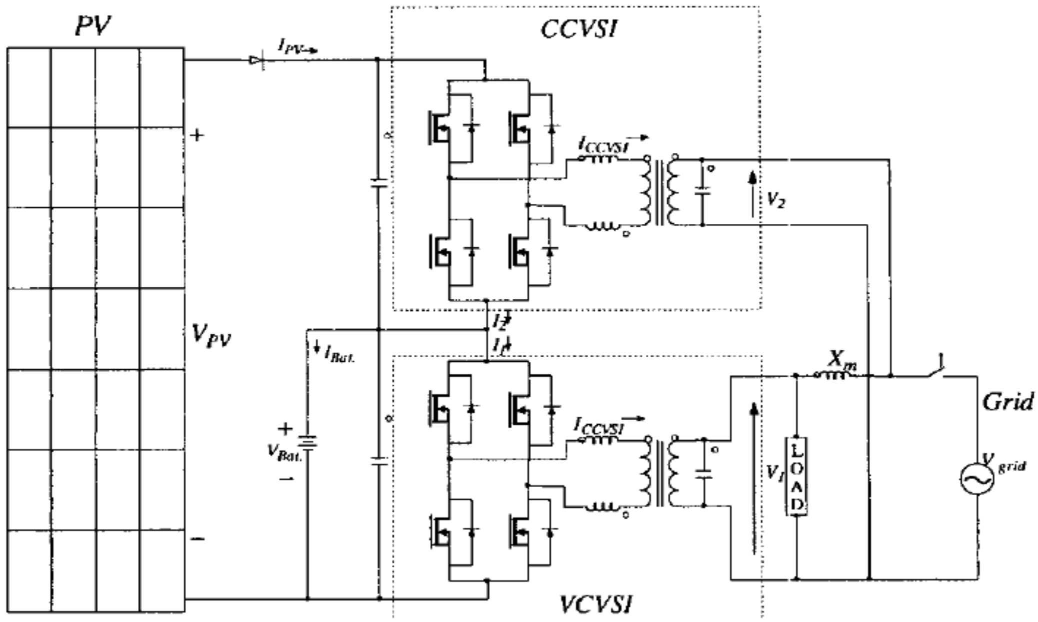


Fig. 2. Power circuit diagram of the proposed Power Processing Unit

### *A. Performance Enhancement*

The series DC configuration of the two VSI**s** provides improved MPPT efficiency to charge the battery. Moreover, the parallel AC configuration of the output of the Power Processing Unit offers more reactive power support and unity power factor operation to the system. Moreover, with proper sizing of the VSI**s** in Power Processing Unit, the size reduction compare to Conventional UPS with DC-DC series charge controller is possible.

**1) Reactive Power Support Improvement and Unity Power Factor operation**

Fig. 3 shows the simplified equivalent electric circuit diagram of the Power Processing Unit in grid-connected mode. The CCVSI is connected directly across the grid and is able to supply a controlled current to the grid. In the absence of RES input, it can provide rated reactive power support or active filtering of the line current to minimize the harmonic distortion. As the VCVSI cannot provide effective reactive power support to the grid and the grid power factor is not controllable in the conventional UPS, the CCVSI in the Power Processing Unit can rectify this deficiency by providing reactive power to the AC side.

It is shown that he reactive power support from the CCVSI can given also to the VCVSI in the power processing unit to achieve the unity power factor operation from the grid point of view . It is shown that if the PV voltage is set at 160% of $V_{bat}$, leaving the DC voltage across the CCVSI at 60% of $V_{bat}$ the CCVSI should be able to handle 60% of the VCVSI capacity. In the maximum power angle ($\sigma = 30^0$), the maximum reactive power flow from the grid to the: VCVSI is about 0.4 per unit [25]. Therefore, assuming that only 50% of reactive power demanded is supported by the CCVSI in different conditions (e.g., during the daytime when PV energy is available), the power factor can be improved to unity for $v_{ccvsi}$<1 .1 (Fig. 4). Therefore, the size of the CCVSI should be defined based on the amount of required reactive power support while supplying the required active power.

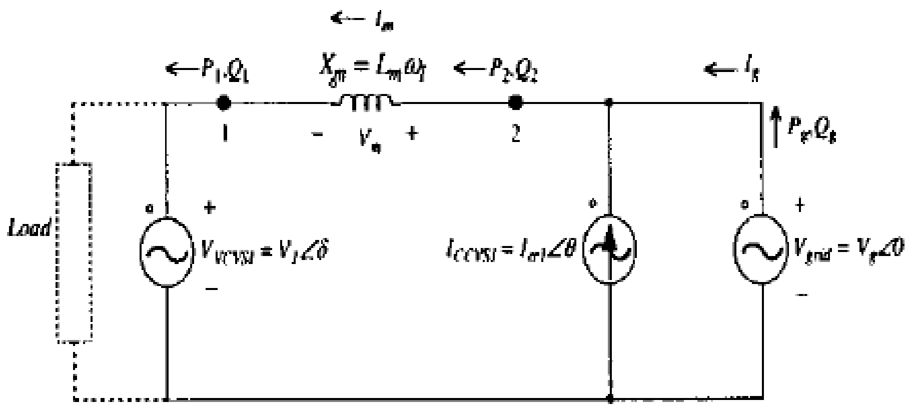


Fig. 3. The simplified equivalent electric circuit diagram of the Power Processing Unit in grid-connected mode

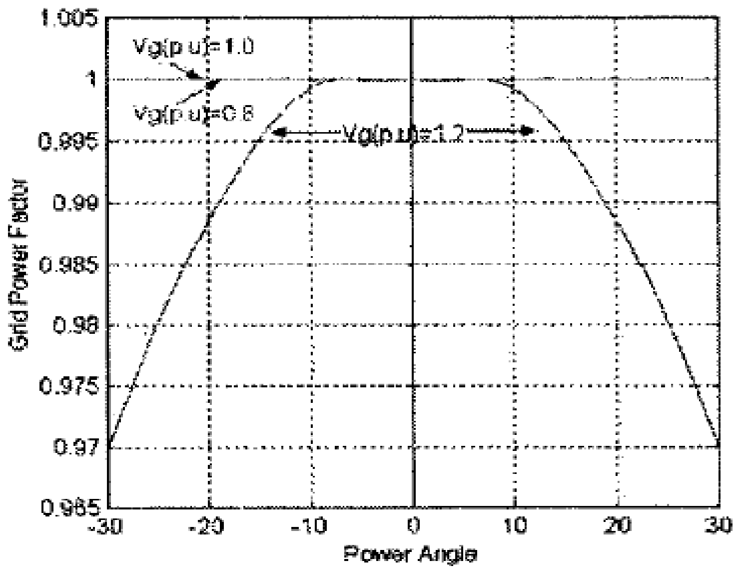


Fig. 4. Grid power factor improvement by Power Processing Unit (only 0.2 per unit reactive power support by CCVSI)

**2) MPPT Efficiency Improvement for Battery Charging**

Since the battery is directly connected to the DC side of the VCVSI, that portion of the PV power can he delivered to the battery with no conversion losses and can ,be described as follow:

$$\tilde{\eta}_{Total} = ( V_{Bat}(1+(V_{PV}- V_{Bat}).\tilde{\eta}_{VCVSI}.\tilde{\eta}_{CCVSI})/V_{PV}$$

$$\Rightarrow \quad \tilde{\eta}_{Total}=(1+\tilde{\eta}_{VCVSI}.\tilde{\eta}_{CCVSI}((V_{PV}/V_{Bat})-1))/(V_{PV}/V_{Bat})$$

Fig. *5* shows assuming the CCVSI has an efficiency rate of 90 percent the($\tilde{\eta}_{ccvsi}$=90%), the total captured efficiency of the Power Processing Unit is higher than the efficiency of a single VCVSI when the PV voltage is less than twice the battery voltage. It means that, compared to the conventional grid-connected PV assisted *UPS* scheme, assuming the DC-DC charge regulator efficiency is also 90% (similar to the$\tilde{\eta}_{ccvsi}$=90%), the proposed power processing unit can charge batteries at a higher efficiency. This is an attractive feature for photovoltaic applications.

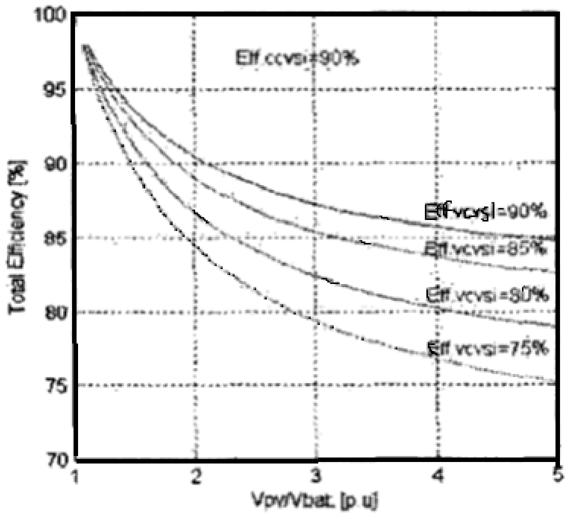


Fig. 5. Overall Efficiency improvement of Power Processing Unit for charging battery at MPPT

### 3) Size Reduction Comparing a Conventional UPS with DC-DC Series Charge Controller

Assuming the RES is a PV array with a required MPPT voltage range from 120 to 160 volts, the VCVSI and battery may have a DC voltage of 100 volts, and the CCVSI may be designed to vary between 20 volts and 60 volts DC. Hence, the inverter power ratings for the VCVSI and CCVSI would be ($P_{CCVSI} = P_{DCmax}$X 6oV/160V and $P_{VCVSI} = P_{DCmax}$ X 100V/120V) This would give an aggregate Power Processing Unit power rating of 121% of $P_{DCmax}$. However, to transfer the same power via conventional UPS with DC-DC series charge controller, a power rating of 200% of $P_{DCmax}$is required. Therefore, the Power Processing Unit makes it possible to reduce the overall size of the power conditioner.

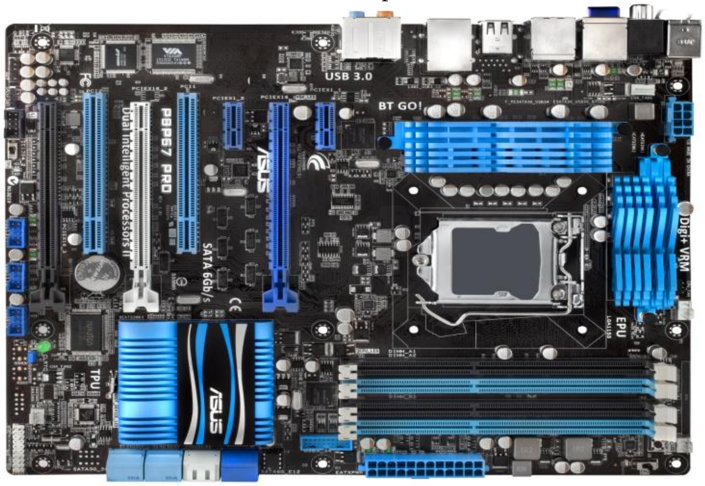

**Fig.6 The Prototyped Power Processing Unit**

## III. Experimental Results:

To evaluate the validity of the proposed power conditioner, the Power Processing Unit was prototyped (Fig. *6)*. In our experimentation, importance was placed on the operation of the Power Processing Unit at different modes rather than the optimization of control algorithms. For clarity of the experimentation the results were obtained in the eight different modes. The result of eight different modes of operation confirms the validity of the proposed multi-functional power processing unit for a hybrid power system.

A block diagram of the system components is shown in Fig. 7, which shows how the two VSIs, the battery, PV and grid are connected. The top inverter in the block diagram is a CCVSI whose performance is shown in Fig. 8. This inverter has a built-in MPPT algorithm, and therefore, after synchronization to the grid and connection to the grid. it tries to track the Maximum Power Point; MPP of the connected solar array.

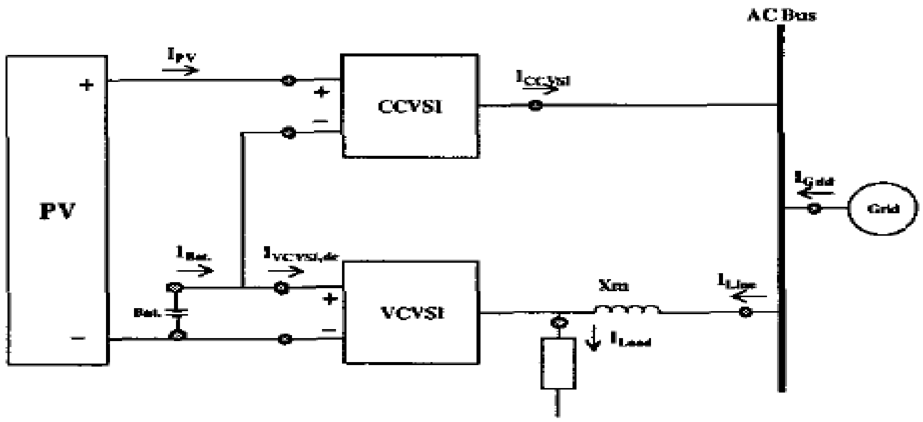


**Fig. 7. Block diagram of the parallel hybrid system using the Power Processing Unit**

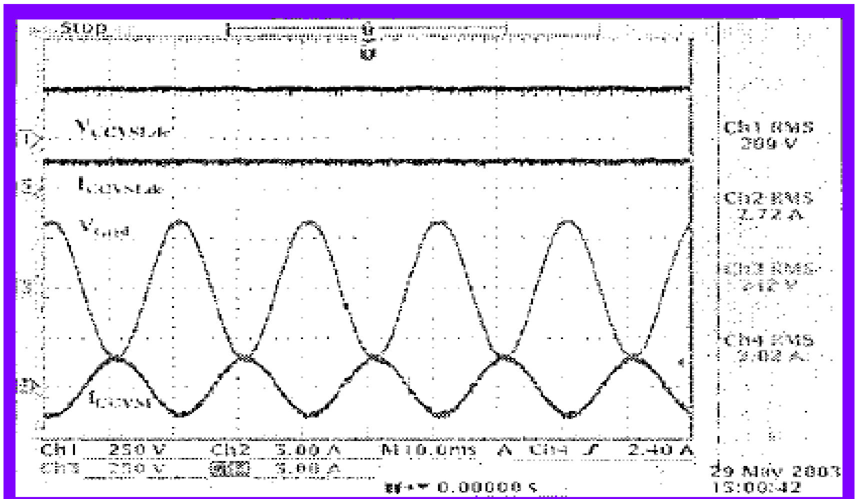


**Fig. 8. DC & AC measurement in CCVSI – ( $P_{PV} \rightarrow P_{Grid}$ ).**

In Fig. 8, the first two waveforms are the voltage ( $V_{ccvsi,DC}$) and current ( $I_{ccvsi,dc}$) of the PV is the input for the inverter and the second two waveforms are the AC output voltage (V$_{Grid}$and current ( $I_{CCVSI}$). The c c v s l is equipped with a DC filter to damp 100 *Hz* ripple of the voltage at DC side to be able to extract the maximum power of the PV at higher efficiency. This figure shows a $180^0$degree phase shift between the output voltage and current, which means that power is transferred from the PV panel tothe AC grid ( $P_{pv} \rightarrow P_{Grid}$).

Fig. 9 shows the performance of the VCVSI used in the system. The first two waveforms are the voltage ($V_{Bat}$)and Current($I_{vcvsi,Dc}$)of the battery, which is the input for the inverter and the second two waveforms are the AC output voltage ($V_{Load}$) and load current ($I_{Load}$). As expected because of single-phase operation of the inverter, 100 *Hz* ripple appears in both the battery voltage and the current waveforms. The PWM of the inverter is controlled to provide a sinusoidal voltage at the rated value for the load. Therefore, the battery supplies the load in stand-alone mode

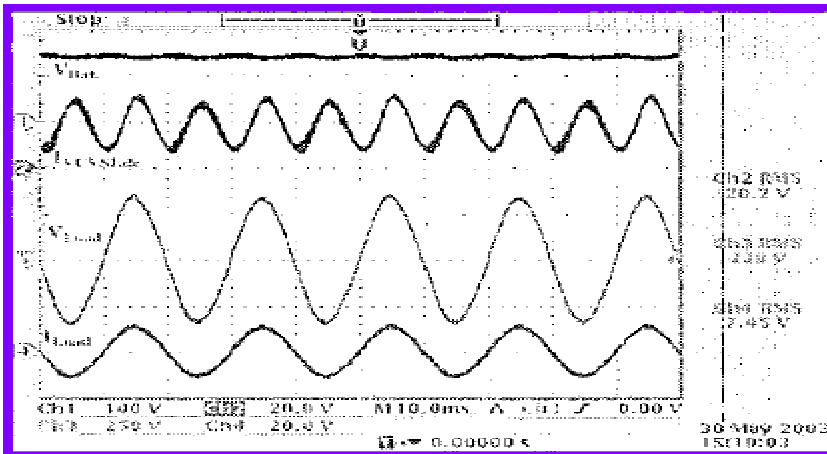


Fig. 9. DC & AC measurements in VCVSI in stand-alone mode
( $P_{Bat.} \rightarrow P_{Load}$ ).

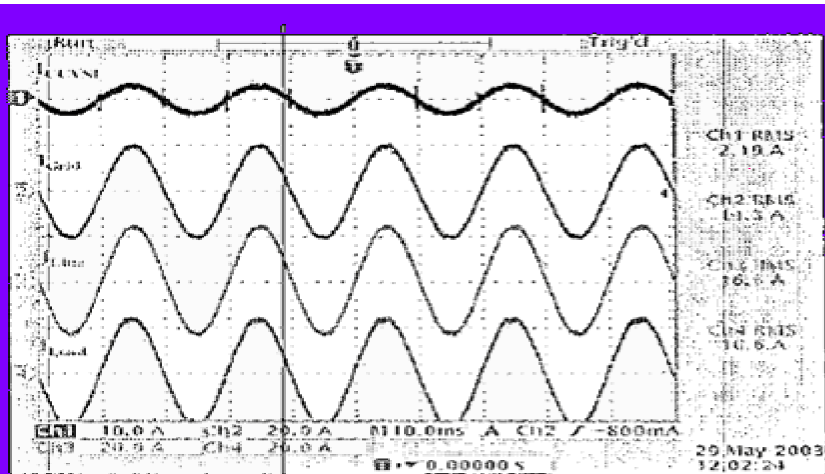


Fig. 10. AC currents flow in Power Processing Unit –mode 1
( $(P_{CCVSI} + P_{Grid}) \rightarrow P_{Load}$ & $(P_{PV} - P_{CCVSI}) \rightarrow P_{Bat.}$ ).

Fig. 10 shows that the CCVSI transfers the power received from the pv to the grid and the extra power demand by the load supply from the grid $((P_{ccvsi}+ P_{Grid}) \rightarrow P_{Load})$. The rest of the power from the pv will be given to the battery ( $((P_{pv}- P_{ccvsi})\rightarrow P_{Bat})$. Therefore, although the VCVSI is synchronized and connected to the grid, it is possible to put the whole load demand on the grid and partially on PV. In this case the line current is equal to the load current, which confirms that the whole load demand is met from the AC bus in AC coupling of hybrid system.

Fig. 11shows the situation when there is no system loads. In this mode of operation the available PV at maximum power will be extractcd by the CCVSI. A portion of the PV power of the PV *goes to* the grid $(I_{ccvsi}= -I_{Grid})$ and the rest of the power flows from the DC bus direct to the battery. Therefore this configuration can increase the efficiency of charging battery from PV ($P_{ccvsi} \rightarrow P_{Grid}$and ( $P_{Pv}- P_{ccvsi}) \rightarrow P_{Bat}$).

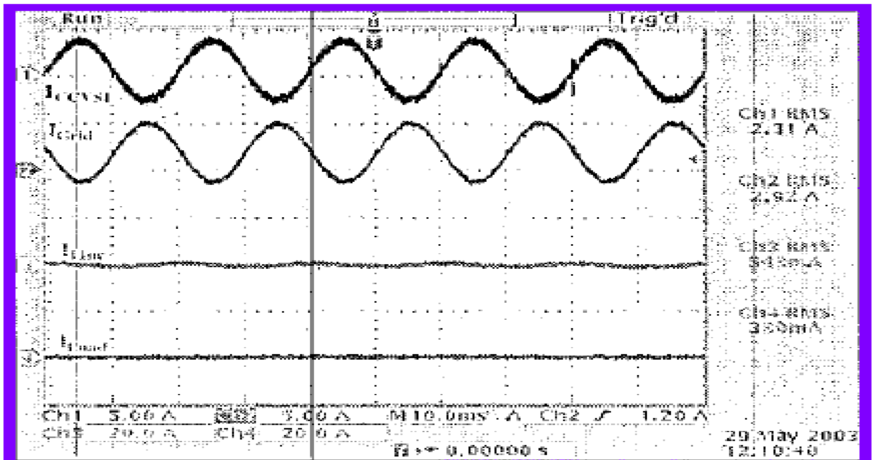


Fig. 11. AC currents flow in Power Processing Unit –mode 2
( $P_{CCVSI} \rightarrow P_{Grid}$ & $(P_{PV} - P_{CCVSI}) \rightarrow P_{Bat.}$ )

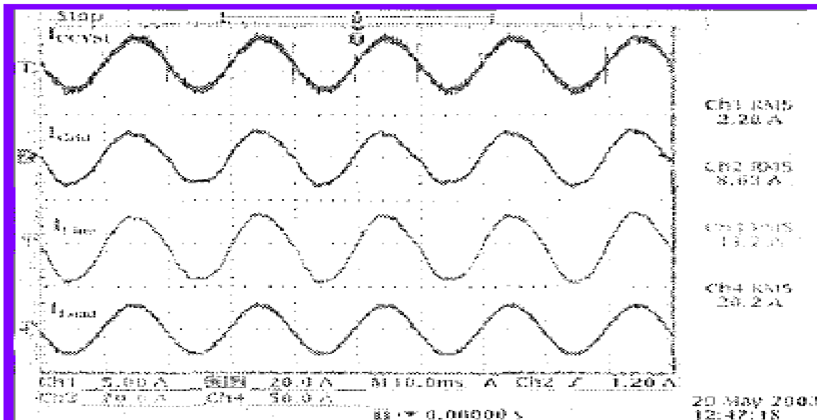


Fig. 12. AC currents flow in Power Processing Unit –mode 4
( $P_{PV} + P_{Grid} + P_{Bat.} \rightarrow P_{Load}$ ).

Fig. 13 shows the situation when the Power Processing Unit does have a load and wants to supply the load through the battery and part of the PV energy. In this mode the CCVSI injects part of the PV power to the grid *($I_{ccvsi}$= -$I_{Grid}$)* and the rest of the power is used to directly charge the battery or extract to the load. In this case, as the load demand is high, the battery has to contribute in supplying the load, therefore ( $P_{CCVSI} \rightarrow P_{Grid}$ and ( $P_{Bat} + P_{Pv} - P_{CCVSI}) \rightarrow P_{Load}$)

Fig. 12 shows the situation when peak load occurs. In this mode all sources of energy will contribute to supplying the load. As a resistive load bank is used for this experiment all currents are in phase (Fig. 12). In this mode all the energy of the PV is used for supplying the load. The rest *of* the demand is compensated by the battery and the grid $P_{pv} + P_{Grid} + P_{Bat} \rightarrow P_{Load}$.
Fig. 15 shows the situation when the system load is low and the available power from the AC grid (or diesel) is usedfor battery charging. In this mode PV and grid contribute to supply the load and charge the battery $((Ppv + P_{Grid}) \rightarrow (P_{load} \& P_{bat}))$. There is a phase shift between the current of the CCVSI and the grid. As the CCVSI delivers its current at unity power factor pure sinusoidal to the grid, the existing phase shift between the voltage and current of the grid shows the reactive power flow to or from grid. This phase shift is small because a small change in phase shift creates a huge amount of power from the grid to the inverter and vice versa. As a resistive load bank is used for this experiment, the currents are in phase with the load voltage (Fig. 15). As the load current is purely sinusoidal, the load or VCVSI voltage is also good quality sinusoidal. The line current, which is equal to the summation of the CCVSI and grid current, is not purely sinusoidal because the grid voltage is not fully sinusoidal and the voltage differences between the grid and VCVSI will drop across the decoupling inductor. Therefore the grid is forced to supply the non-sinusoidal current. Hence even in this mode, although the VCVSI is not equipped with a wave shaping controller, the quality of supply is guaranteed.

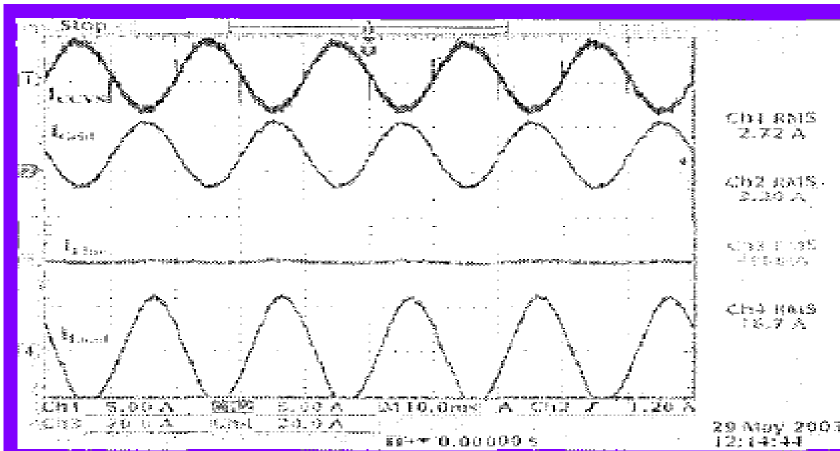


Fig. 13. AC currents flow in Power Processing Unit –mode 3
$(P_{CCVSI} \rightarrow P_{Grid} \;\&\; (P_{Bat.} + P_{PV} - P_{CCVSI}) \rightarrow P_{Load})$.

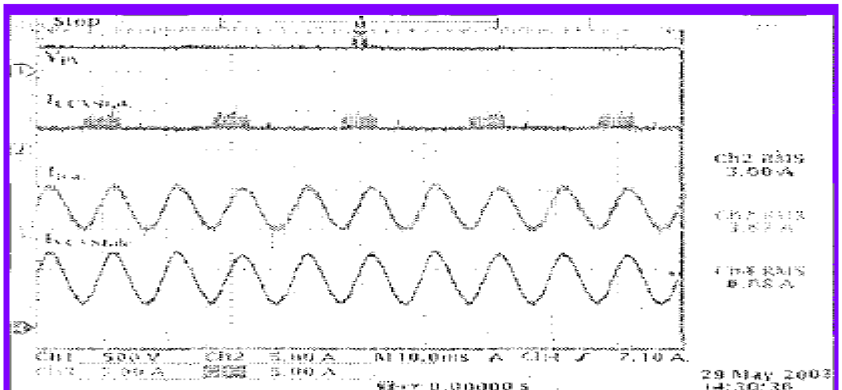


Fig. 14. DC measurement in Power Processing Unit –mode 6
$(P_{CCVSI} \rightarrow P_{Grid} \;\&\; (P_{Bat.} + P_{PV} - P_{CCVSI}) \rightarrow P_{Load})$

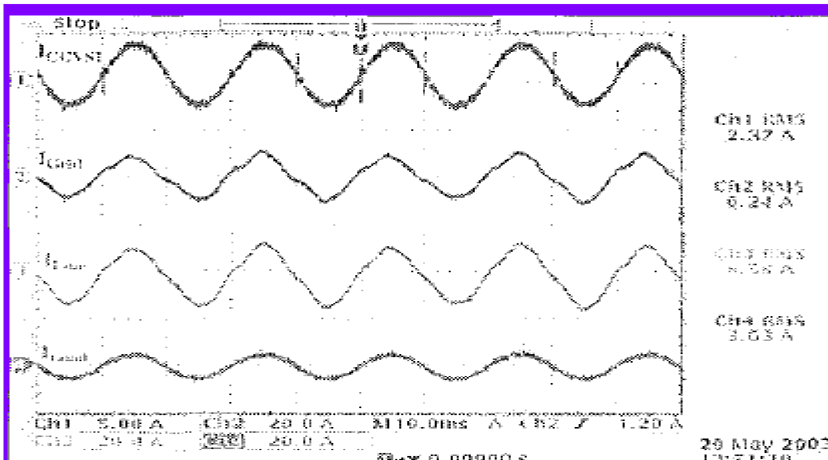


Fig. 15. AC currents flow in Power Processing Unit –mode 5
$((P_{PV} + P_{Grid}) \rightarrow (P_{Load} \;\&\; P_{Bat.}))$

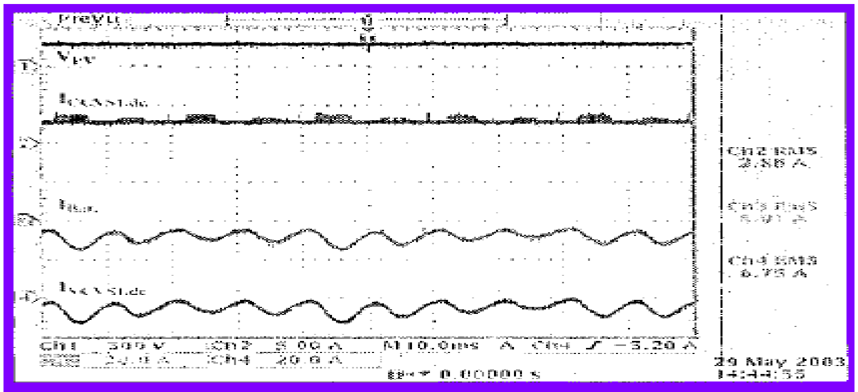


Fig. 16. DC measurement in Power Processing Unit –mode 8
$((P_{PV} + P_{Grid}) \rightarrow P_{Bat.} \ \& \ P_{Grid} \rightarrow P_{Load})$.

Fig. 14 shows the DC measurement in the Power Processing Unit. This mode (six) is similar to mtde three - the CCVSI is grid-connected, however, the VCVSI is'in stand-alone mode. In this mode the Power Processing Unit supplies the load partly from the battery and partly from the PV. The PV power at the MPP is given to the grid and

The rest of the PV power and battery contribute to supply the load
( $P_{CCVSI} \rightarrow P_{Grid}$ and ( $P_{Bat} + P_{PV} - P_{CCVSI}) \rightarrow P_{Load}$).The first two waveforms are the PV voltage and current. As the CCVSI is in series with the PV, the PV and CCVSI currents are equal. The current of the VCVSI is equal to the summation of the CCVSI and battery currents and it is positive. It means that the DC power is flowing from the DC bus of the VCVSI to the AC bus to supply the load. As this system is single-phase the 100 *Hz* ripple in the battery current can be observed.

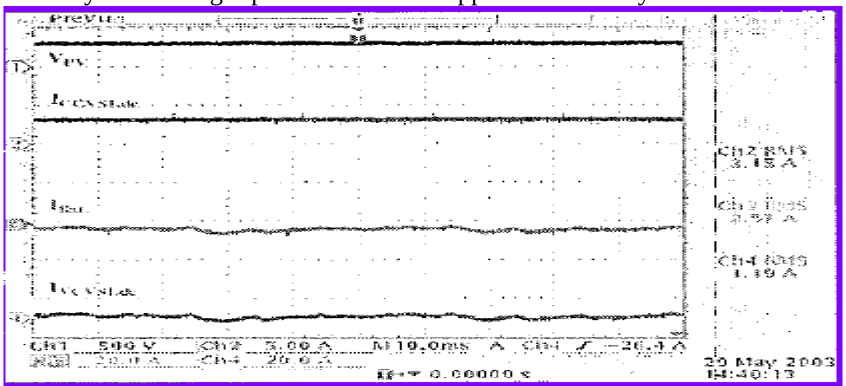


Fig. 17. DC measurement in Power Processing Unit –mode 7
$((P_{CCVSI} + P_{Grid}) \rightarrow P_{Load} \ \& \ (P_{PV} - P_{CCVSI}) \rightarrow (P_{Load} \ \& \ P_{Bat.}))$

Fig. 17 shows the DC measurement in the Power Processing Unit when the load is fed from the AC bus and the battery charged from the PV. In this mode, both the CCVSI and VCVSI are grid-connected and the grid supplies the load. The PV power at the MPP is extracted to the grid through the CCVSI. The rest of the PV power is fed directly to the battery ( $(P_{CCVSI} + P_{Grid}) \rightarrow P_{Load}$ and ( $P_{PV} - P_{CCVSI}) \rightarrow (P_{Load}$ and $P_{Bat}$) ). The top two waveforms are the PV voltage and current. As the CCVSI is in series with the PV, the PV and CCVSI currents are equal. The current of the VCVSI is equal to the summation of the CCVSI and battery currents and it is positive. It means that the DC power is flowing from the DC bus of the VCVSI to the AC bus to supply the load. As this system is single-.phase, the 100 *Hz* ripple is a major component in the battery current.

Fig. 16 shows the DC measurement in the Power Processing Unit when a small load and battery are feeding from the AC bus. 'When there is a huge demand for charging the battery, power from the PV is not sufficient, therefore the grid supplies the demand through the VCVSI. In this mode both the CCVSI and VCVSI are grid connected. The PV power at the MPP is extracted to the grid through the CCVSI. The rest of the PV power is given directly to the battery ( $(P_{PV} + P_{Grid}) \rightarrow P_{Bat}$ and $P_{Grid} \rightarrow P_{Load}$ ). The first two waveforms are the PV voltage and current. As the CCVSI is in series with the PV, the PV and CCVSI currents are equal. The current of the VCVSI is equal to the summation of the CCVSI and battery currents and is negative. It means that the DC power is flowing from the AC bus of the VCI'SI to the AC bus for charging the battery. The 100 *Hz* ripple in the battery current is not identical, because of' change in the power angle in the control system.

## IV. Conclusion

In this paper the fundamental concept and experimental results of a novel power conditioner for extracting maximum available energy of different renewable energy sources are described. The proposed power conditioner employs two voltage source inverters connected in series on the DC side and in parallel on the AC side. The power conditioner provides unity power factor and maximum power point tracking as well as more reactive power support in all modes of operation through control of the instantaneous output parameter of inverters. It has demonstrated that the proposed Power Processing Unit is an innovative solution to power conditioning for a weak grid, and suitable for application such as in hybrid power Systems.

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