**U.Shajith Ali[1,*], V.Kamaraj[2]**

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# Modified incremental conductance algorithm for Z-source inverter based photovoltaic power conditioning systems

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Recently photovoltaic (PV) energy harvesting and its transformation into electrical energy attract substantial pursuits. In this PV power system, it is required to obtain the maximum available power by integrating the maximum power point tracking. Lately, the Z-source inverters are adapted as power conditioning devices, which act as a single stage power conditioner for converting PV array DC voltage into AC output voltage, boost the voltage magnitude and draw out the maximum power. The photovoltaic array output voltage is controlled and the maximum power point tracking is attained by controlling the shoot-through duty cycle. The well known incremental conductance maximum power point tracking algorithm is modified to prevent the bewilderedness during rapidly changing irradiation condition. This algorithm is used along with the shoot-through incorporated pulse width modulation techniques to control the Z-source inverter. Computer simulation and experimental results are rendered to establish the performance of the proposed system.

Keywords: Z-source inverter; photovoltaic; maximum power point; incremental conductance; total harmonic distortion; pulse width modulation

## 1. Introduction

As people are much concerned with the fossil fuel exhaustion and environmental pollution caused by the conventional power generation, renewable energy sources such as solar energy, wind energy, bio mass, etc., are now widely used. Among these renewable energy sources, solar energy draws increasing attention due to free fuel, improvements in photovoltaic (PV) technology, environmental concerns, and little maintenance. Many applications such as solar power generation, solar water pumping, solar vehicle, battery charging, and satellite power systems have been developed employing this technology. One of the most potential and versatile methods for utilizing this vast energy source is its direct conversion into electrical energy with photovoltaic devices. Photovoltaic cells transform energy from an essentially unlimited source – the sun – into useable electricity. Because of the abundant nature of the source it is always desirable to draw as much power as possible from the photovoltaic cells. Over the past few years, PV arrays have been connected to loads by direct coupled method. Unfortunately, direct connection of photovoltaic cells to the utility almost never allows optimum power transfer when the load, irradiation or temperature changes. A PV module can produce the power at a point, called an operating point, anywhere on the current-voltage curve. There is a unique point, called a maximum power point (MPP), at which the module produces the maximum output power. This MPP is the desired operating point for a PV module to get maximum efficiency [1]. Also, in photovoltaic systems, when the solar irradiation changes rapidly, especially the irradiation decreases suddenly, the operating point will be changed simultaneously. This leads to get a mismatch between a PV module and a load requires further over-sizing of the PV array and

[*] Corresponding author: U.Shajith Ali, SSN College of Engineering, Kalavakkam, Chennai, Tamil Nadu, India 603110, E-mail: shajithali@ssn.edu.in

[1], [2] Department of Electrical and Electronics Engineering, SSN College of Engineering, Kalavakkm, Chennai, Tamil Nadu, India -603103

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thus increases the overall cost. To extenuate this problem, a maximum power point tracker (MPPT) can be used to maintain the operating point of PV module at the MPP.

## 2. Power Conditioning Circuits

In order to transfer energy from photovoltaic arrays into utility, power conditioning unit is required to convert the dc voltage obtained from photovoltaic array into ac voltage, to boost the voltage if required and to prevail the maximum power utilization of the photovoltaic array. The conventional power conditioning unit consists of a dc to ac inverter with a line frequency transformer to boost the output voltage. But these line frequency transformers are having many drawbacks like huge in size, produces acoustic noise and high cost. In addition, the inverter is required to be oversized to contend with change in photovoltaic array output voltage. So in order to eliminate the transformer and to minimize the rating of the inverter, a high frequency dc to dc boost converter is used to boost the voltage to a desired level [2]. In this type of power conditioning units, there are two stages of power conversion, i.e. a boost converter followed by a dc to ac inverter. Again this two stage conversion increases the cost and reduces the efficiency of the system.

The recently introduced Z-source inverter is employed as a single stage power conditioning unit, because the DC to AC inversion and boosting function can be achieved in one stage. Fig. 1 shows the main circuit of the Z-source inverter. It employs a unique impedance network coupled between the photovoltaic array and the converter circuit that consists of a split-inductor $L_1$ and $L_2$ and capacitors $C_1$ and $C_2$ connected in X shape. This unique impedance network replaces the dc bus capacitance or inductance so as to overcome the limitaions of the traditional inverters that voltage amplitude can only be boosted or bucked. Also Z-source inverter is highly flexible because its main circuit may be either the voltage-source or current source, so this inverter can be permitted to short or open [3, 4].

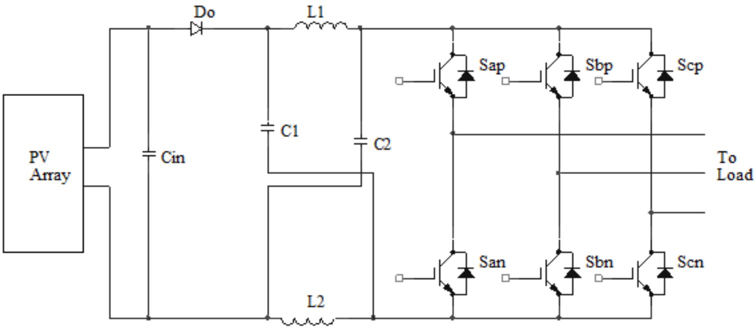


Fig.1. Z-source inverter

The output peak phase voltage of the Z-source inverter is derived as

$$V_{ac} = \frac{MBV_s}{2} \tag{1}$$

where $M$ is the modulation index, B is the boost factor and $V_s$ is the DC voltage across impedance network.

The boost factor is given as

$$B = \frac{1}{1 - 2\frac{T_o}{T}} \tag{2}$$

where $T_o$ is the shoot-through time period and $T$ is the switching time.

To vary the output voltage and to improve the performance of the traditional inverters many pulse-width modulation (PWM) control methods are developed [5]. The traditional voltage source inverter has six active vectors when the dc voltage is impressed across the load and two zero vectors when the load terminals are shorted through either the lower or upper three switches. These total eight switching states and their combinations have spawned many PWM control schemes [6, 7, 8]. On the other hand, Z source inverter has additional shoot-through switching states that are forbidden in the traditional voltage source inverters, both switches of any phase leg can never be gated on at the same time or a short circuit (shoot through) would occur and destroy the inverter. The Z-source inverter (ZSI) advantageously utilizes the shoot through state to boost the dc bus voltage by gating on both upper and lower switches of a phase leg and produce a desired output voltage that is greater than the available dc bus voltage. The reliability of the inverter is also greatly improved because the shoot through due to misgating can no longer destroy the circuit. Thus it provides reliable, a low-cost, and high efficiency single stage circuit for buck and boost power conversion.

## 3. Photovoltaic Array and MPPT

Photovoltaic cell consists of a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted electricity through photovoltaic effect. The simplest equivalent circuit of a photovoltaic cell consists of a photo current ($I_p$), a diode ($D_j$), a parallel resistor ($R_{sh}$) expressing a leakage current, and a series resistor ($R_s$) describing an internal resistance to the current flow, is shown in Fig. 2(a).Since a single photovoltaic cell produces very small power and output voltage, many cells must be connected in series-parallel configuration on a module to produce enough high power. A photovoltaic array is a group of several modules which are electrically connected in series and parallel circuits to generate the required current and voltage [9]. Photovoltaic system naturally exhibits a non-linear I-V and P-V characteristics shown in Fig. 2(b) which vary with the radiant intensity and cell temperature.

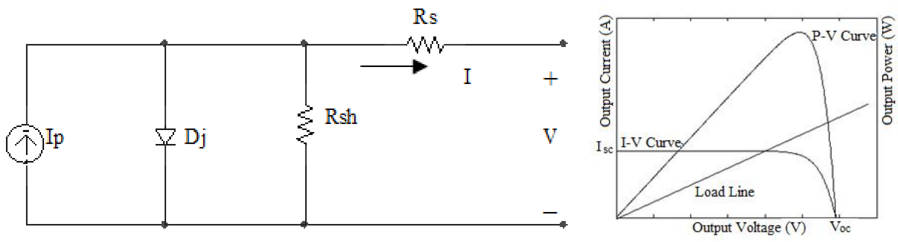



Fig.2. Photovoltaic cell (a) Equivalent circuit (b) Typical I-V and P-V characteristics

The voltage-current characteristic equation of the array becomes as follows:

$$I = N_p I_p - N_p I_s (\exp\left[q\left(\frac{\frac{V}{N_s}+\frac{IR_s}{N_p}}{kT_c A}\right)\right]-1)-\left(\frac{\frac{N_p V}{N_s}+IR_s}{R_{sh}}\right) \qquad (3)$$

where $I_p$ is the photocurrent, $I_s$ is the saturation current, $A$ is the diode ideality factor, $V$ is the photovoltaic output voltage**,** $k$ is a Boltzmann's constant (=1.38x10$^{-23}$J/K), $R_s$ is the series resistance, $R_{sh}$ is the shunt resistance, $q$ is an electron charge (=1.6x10$^{-19}$ C), $T_c$ is the cell's working temperature, $N_p$ is the number of cells connected in parallel and $N_s$ is the number of cells connected in series.

The photo current mainly depends on the solar radiant intensity and cell's temperature, which is given as

$$I_p = [I_{sc} + K_i (T_c - T_{ref})]\lambda \qquad (4)$$

where $I_{sc}$ is the short circuit current of PV cell, $K_i$ is the cell's short circuit temperature coefficient, $T_{ref}$ is the cell's reference temperature and $\lambda$ is the solar irradiance.

The cell's saturation current varies with cell temperature is described as

$$I_s = I_{rs}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_G\left(\frac{1}{T_{ref}}-\frac{1}{T_c}\right)}{kA}\right] \qquad (5)$$

where $I_{rs}$ is the reverse saturation current and $E_G$ is the band-gap energy of the semiconductor.

Since the Z-source inverter based photovoltaic system is directly connected to the load, the photovoltaic system is controlled to transfer maximum power from the photovoltaic array to the load circuits continuously. Because of the non-linear characteristics of photovoltaic modules, the maximum power cannot be achieved by directly connecting the photovoltaic models [10, 11, 12, 14]. Incremental conductance algorithm is one of the widely used MPP tracking [13]. Here the terminal voltage variation for PV modules by measuring and comparing the incremental conductance and instantaneous conductance of PV modules is determined. If the value of incremental conductance is equal to that of instantaneous conductance, it represents that the maximum power point is found [15, 16]. This algorithm shows best performance under rapidly varying environmental conditions as compared to perturbation and observation method. In this paper, the conventional incremental conductance algorithm is modified based on the power calculation, which can improve both dynamic and steady state performances. In this new method an additional measurement of power in the middle of the MPPT sampling period [17] without any perturbation is computed as shown in fig.3. The change in power between $P_x$ and $P_{k+1}$ ponders only the change in power due to the atmospheric changes, as no action has been made by the MPPT. The difference between the powers contains the change in power caused by the perturbation of the MPPT plus the irradiation change. If the rate of change of irradiation is constant over one sampling period of the MPPT, the change in power $dP$ is calculated as

$$dP = dP_1 - dP_2 = (P_x - P_k) - (P_{k+1} - P_x) = 2P_x - P_{k+1} - P_k \qquad (6)$$

Fig.4 shows the flow chart of improved incremental conductance algorithm. This improved algorithm differs the conventional one by having additional block to calculate the $dP$. In the Z-source inverter, higher output voltage can be achieved by increasing the shoot-through time. Because the output of the photovoltaic array is given as the input to the Z-source inverter, the output voltage and the operating point are controlled by varying the shoot-through time interval.

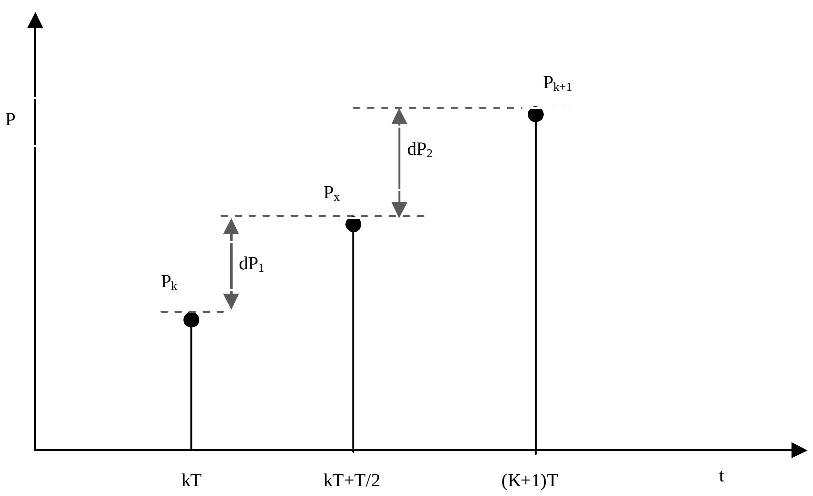



Fig. 3.Measurement of Power between two sampling instances

## 4. Simulation and Experimental Results

The Solkar PV module is chosen for modelling, simulation and implementation, because this module is well suited to traditional stand-alone photovoltaic applications. The Solkar PV module provides 37W of nominal maximum power, and has 36 series connected monocrystalline silicon cells. The key specifications are shown in Table 1.

### 4.1 Simulation Results

The model of the photovoltaic module is implemented using Matlab/Simulink. The model parameters are evaluated based on the Shockley diode equation listed on the previous section. The developed model takes solar irradiation and cell temperature as input parameters and outputs the I-V and P-V characteristics under various conditions. Fig.5 and Fig.6 show I-V and P-V characteristics of the photovoltaic module with various solar irradiation and temperature.

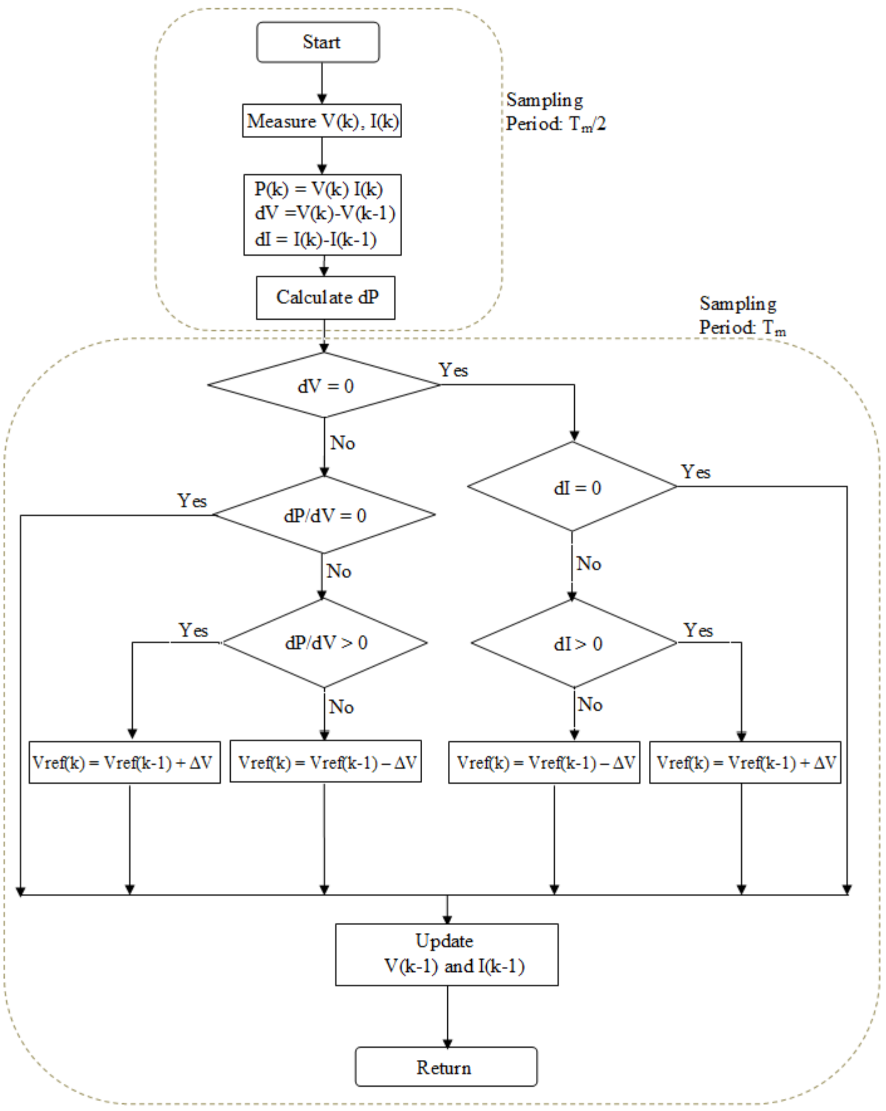



Fig. 4.Flow chart of modified incremental conductance algorithm

Table 1: Typical electrical characteristics of Solkar PV module

| Parameter | Variable | Value |
|---|---|---|
| Maximum power | $P_m$ | 37.08 W |
| Voltage at maximum power | $V_m$ | 16.56 V |
| Current at maximum power | $I_m$ | 2.25 A |
| Short circuit current | $I_{sc}$ | 2.55 A |
| Open circuit voltage | $V_{oc}$ | 21.24 V |
| Series resistance | $R_s$ | 0.47 Ω |
| Shunt resistance | $R_{sh}$ | 145.62 Ω |
| Diode ideality factor | A | 1.5 |

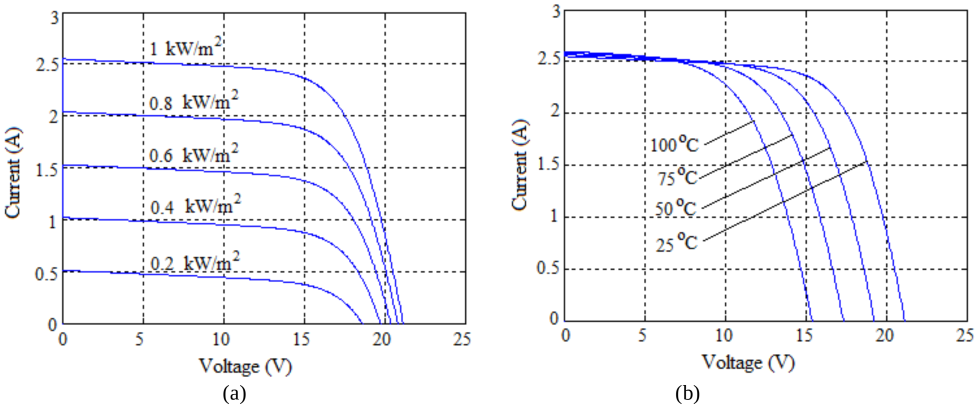



Fig.5.I-V output characteristics of PV module with different (a) solar irradiation (b) temperature

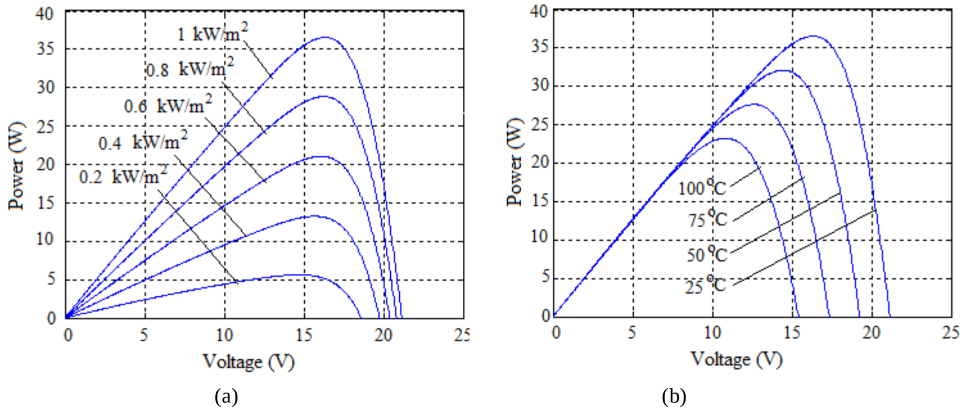
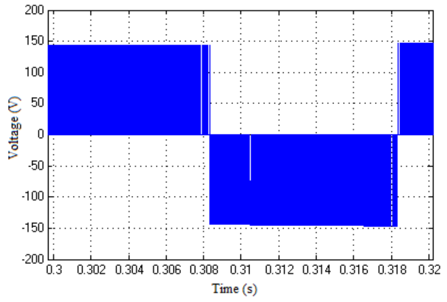
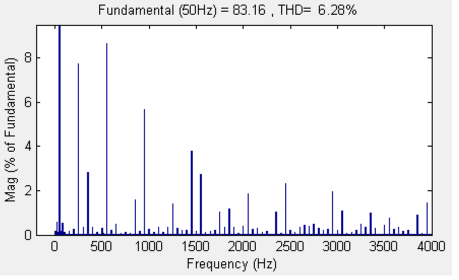



Fig.6. P-V output characteristics of PV module with different (a) solar irradiation (b) temperature

The photovoltaic output voltage changes mainly with temperature, while the photovoltaic output current changes mainly with insolation. When the temperature rises, the photovoltaic output power decreases with a constant irradiation. With constant temperature specified, the photovoltaic output power increases when the insolation increases. Thus the main function of the interfacing the Z-source inverter is to extract the maximum power out of the photovoltaic at any given temperature and irradiation. In the Z-source inverter, the output voltage can be controlled to the desired level by controlling the shoot-through time period. Thus the shoot-through state is used to control the MPPT.

The Z-source inverter interfacing the photovoltaic is developed in Matlab/Simulink. Here four numbers of Solkar PV modules are connected in series to make a photovoltaic array, which acts as the DC source to the Z-source inverter. Thus a maximum power of 148W can be obtained from this array under standard conditions. The inductors in the impedance network limit the current ripple through the devices during boost mode with shoot-through. The capacitors in the impedance network absorb the voltage ripple and maintain a reasonably constant voltage across the bridge. For both simulation and experiments, the impedance network elements are designed with the following values: $L_1=L_2=3mH$ and $C_1=C_2=1000\mu F$ [14]. The switching frequency is 5 kHz and the fundamental frequency is 50Hz. The semiconductor devices in the inverter bridge are selected based on the current through them and the maximum voltage across them. Here IGBTs are taken as the switching devices. The complete system is simulated and the output voltage waveform and its harmonic profile are shown in Fig.7. Harmonic analysis on the output voltage is performed and the total harmonic distortion is calculated as 6.28%.



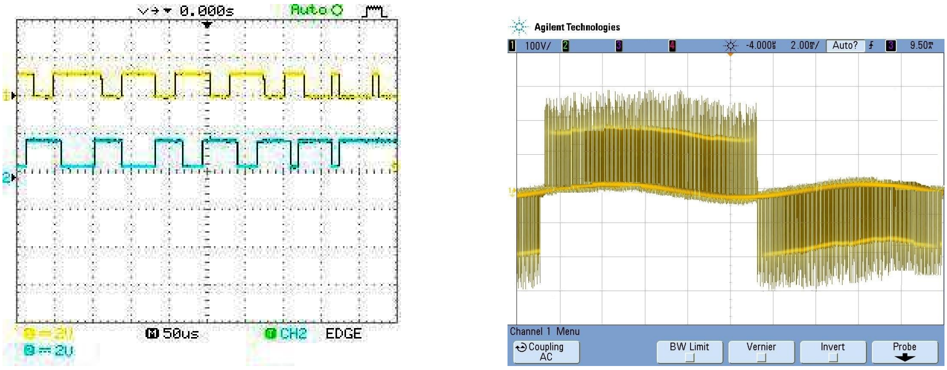




(a) (b)

Fig.7. Simulation results (a) Output line voltage (b) Harmonic spectrum of output line voltage

## 4.2 Experimental Results

The hardware model of Z-source inverter is constructed. The same parameters used in simulation are used for hardware implementation. The DSP TMS320F2812 is used to implement the pulse width modulation control along with maximum power point tracking algorithm. Experimental readings are taken on a brighten day with irradiation of 868 W/m$^2$ and temperature of 38$^o$C. The firing pulses for the two switches in one phase leg of the Z-source inverter and the output line-to-line voltage is shown in Fig.8. Table 2 shows the voltage, current and power taken at the photovoltaic array and the output side voltage, current and power taken from the inverter output terminals for various values of irradiation but at a constant temperature of 38$^o$C. Input and output powers are directly measured using power quality analyzer and these values are displayed in fig.9. The values in watts and VA are rounded-off values by the meter. From the results, the output line voltage obtained from the Z-source inverter is 107.2V rms and the load current is 0.62A. The total output power can be calculated based on the output voltage and load current. The total output power is 115W. Thus the maximum power output from the photovoltaic is obtained. The tracking of PV array voltage, current and power is shown in fig.10.




**(a)** **(b)**

Fig.8. Experimental Waveforms (a) Switching pulses (b) Output line voltage waveform

Table 2: Results at different irradiation (At 38$^o$ Temperature)

| $\lambda$ (W/m$^2$) | $P_{in}$ (W) | $V_{in}$ (V) | $I_{in}$ (A) | $P_{out}$ (W) | $V_{out}$ (line) (V) | $I_o$ (line) (A) |
|---|---|---|---|---|---|---|
| 1000 | 143 | 15.8 | 9.05 | 135 | 116.19 | 0.6708 |
| 800 | 114 | 15.5 | 7.35 | 107.2 | 103.54 | 0.5978 |
| 600 | 84.6 | 15.0 | 5.64 | 79.4 | 89.11 | 0.5144 |
| 400 | 54.8 | 14.6 | 3.75 | 50.7 | 71.20 | 0.4111 |
| 200 | 25.4 | 14.2 | 1.79 | 23.2 | 48.17 | 0.2780 |

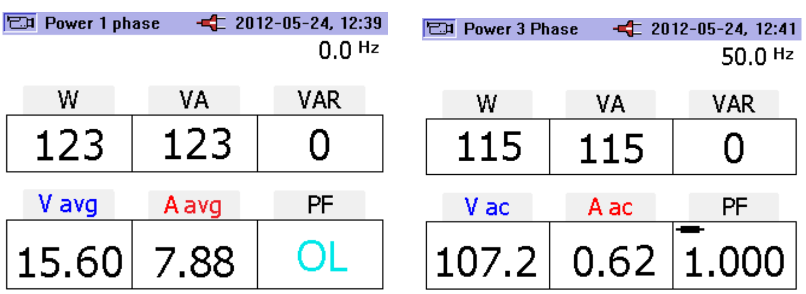
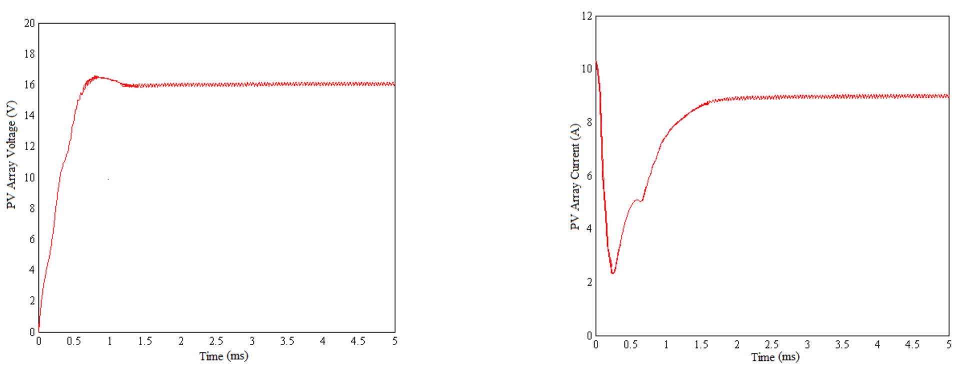
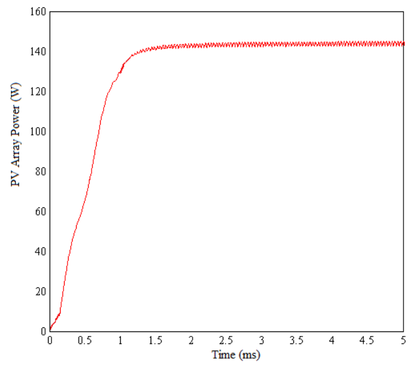



Fig.9. Experimental input and output readings




(a) (b)




(c)

Fig.10. The tracking waveforms of PV array (a) voltage, (b) current and (c) power

## 5. Conclusion

A new modified MPPT algorithm is derived by the well known method of incremental conductance. In this new technique, the power is measured in the middle of the sampling period, which can overcome the confusion of conventional algorithm during rapidly changing irradiance. Z-source inverter is taken as the power conditioning circuit for photovoltaic energy conversion system. This inverter is used for boosting the voltage level and for rapid tracking of the photovoltaic array's maximum power point in a single stage operation. The photovoltaic array is modelled and developed in the Simulink environment. The complete power conditioning system is simulated using Matlab/Simulink software to verify the algorithm. The frequency spectrum and the total harmonic distortion of the output voltage are obtained. Also the presented concepts are verified experimentally using a laboratory prototype. The results show that the maximum power is extracted from the photovoltaic array using the Z-source inverter. So the proposed control is very promising for photovoltaic applications.

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