Design and Implemenatation of Non-Isolated Three Port DC/DC Converter for Stand-Alone Renewable System Applications

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***Abstract*—– An integrated non-isolated three-port DC-DC converters (NI-TPCs) interfacing a renewable source (Photovoltaic Array) , a storage battery and a load is proposed for stand-alone renewable power system application. The NI-TPCs proposed are generated by introducing a bidirectional cell to the basic DC-DC converters. With the NI-TPC proposed, single stage conversion between any two of the three ports can be achieved.**

A multi-carrier based PWM scheme is proposed and applied to the NI-TPC based upon analysis of the power relations among the three ports. Power management strategy with four regulators achieving maximum power point tracking (MPPT) control of input source, charging control of battery and voltage control of load is proposed for a stand-alone renewable power system.

The converters should operate in every operation mode and switch between different modes freely and seamlessly. The topology proposed in these has advantages of high efficiency and simple control. These advantages make the converter promising for medium and high power applications. This topology has high power density, low cost, lightweight and high reliability. Open loop and Closed loop of Three Port Converters (TPC) are designed in MATLAB/SIMULINK environment.

Keywords—Photovoltaic Array, DC-DC Boost converter, Bidirectional converter,MPPT controller.

I. INTRODUCTION

Renewable sources, such as solar, wind and tide, are intermittent in nature. Hence, a storage element, such as a battery or a super capacitor is required for the stand-alone renewable power system to improve the system dynamics and steady-state characteristics. Three-port converters (TPCs), as shown in Fig. 1, have been proposed with the advantages of less component count and fewer conversion stages instead of employing several independent two-port converters [1]-[3]. The TPC system has the advantages of lower cost, higher reliability and enhanced dynamic performance with centralized control. Due to the remarkable merits of the TPC ,a wide variety of topologies have been proposed for various applications, such as hybrid electric vehicles [4]-[7], fuel-cell and battery systems [8]-[9], aerospace power systems[10]-[11], micro-inverter with power decoupling [12] and PV systems with battery backup or hybrid energy storage systems
[13]-[18] etc..

The TPC topologies can be classified into two categories: non-isolated topologies and isolated topologies. A NI-TPC featuring compact design and high power density may be the better choice than an isolated one for applications where isolation is not required. Conventionally, for the non-isolated applications, the input source, battery and load are linked together via a common DC bus with a unidirectional DC converter (UDC) and a bidirectional DC converter (BDC) or two UDCs, as shown in Fig. 2. However, the major disadvantage is the low system efficiency due to multiple stage power conversion.

A family of integrated non-isolated three-port converter achieving single stage conversion between any two of the three ports is proposed in this paper. Based on the analysis of operation modes and system power control requirement, a PWM scheme is proposed. Experimental results are presented to validate the proposed PWM scheme and control strategy.

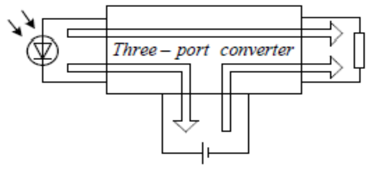


Figure 1. Three-port converter

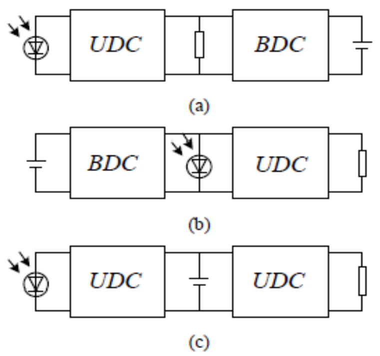


Figure 2. Conventional solutions for non-isolated stand-alone renewable power system

II. TOPOLOGY AND ANALYSIS

Fig. 3(a) shows the basic topology of the Boost converter, in which the power flow from the input source to the load is configured. To supply the load smoothly, a storage element like battery is required in a stand-alone renewable power system. When the input power is more than what the load needs, it will charge the battery. The charging is controlled by a power switch connected in series with the battery. And an extra diode is needed to prevent the reverse current from flowing, as shown in Fig. 3(b). On the other hand, the battery should discharge to the load when the input source can no longer support the load all alone. The discharging of battery is controlled by another switch connected with the battery in series. Since the input source can't be connected with the battery in parallel, another diode is needed, as shown in Fig.3(c).

Based on the above analysis, a Boost TPC is derived by introducing two additional power flow paths into the Boost converter. The additional circuit in the Boost TPC can be regarded as a bidirectional cell as shown in Fig. 4. In the Boost converter, the inductor L and the power switch S_1 is connected to the input source in series. Thus, the power switch S_3 can be introduced into the converter and a power flow path is configured to bridge the battery and the load. The equivalent circuit is a Boost converter. On the other hand, another power switch S_2 is introduced into the converter and a power flow path can be configured to bridge the input source and the battery. The equivalent circuit is also a Boost converter.

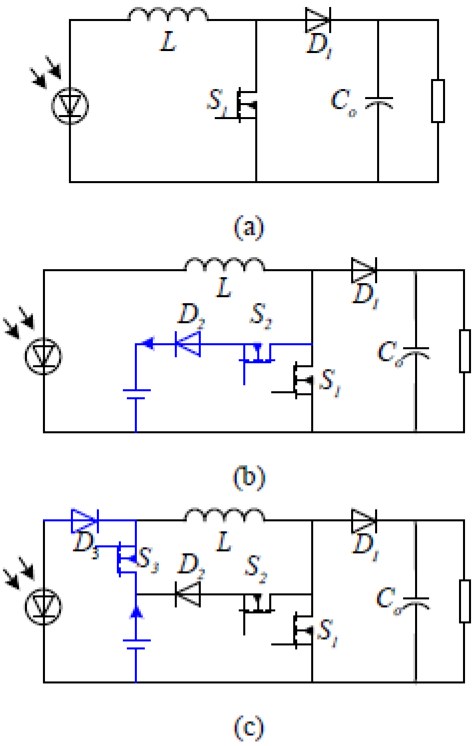


Figure 3. Generation procedure of Boost TPC: (a) the Boost converter, (b) charge circuit of battery, (c) discharging circuit of the battery.

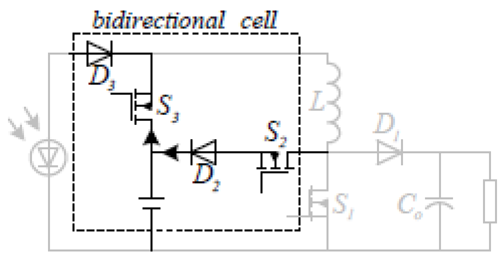


Figure 4. The Boost TPC with a bidirectional cell.

III. OPERATION MODE AND PULSE WIDTH MODULATION SCHEME

A. Operation Mode Analysis

In the Boost TPC, the power flows through the input source, battery and load are denoted with P_{in}, P_b and P_o, respectively. Assuming P_b is positive when the battery discharges and ignoring the power loss in the conversion, we have

$$P_{in} + P_b = P_o \quad (1)$$

There are three possible operation modes in the Boost TPC.

1) Dual-output mode: The Boost TPC works in dual-output (DO) mode when $p_{in} > p_o$, as shown in Fig. 5(a). The input source feeds the load and charges the battery with excess power at the same time. The power switch S_3 is kept off. p_{in} is regulated with the duty cycle of S_1, d_1, and p_o is regulated with the duty cycle of S_2, d_2.

In steady state, applying the volt-second balance principle to L, we obtain that:

$$u_o = \frac{u_{in} - d_2 u_b}{1 - d_1 - d_2} \quad (2)$$

2) Dual-input mode: The Boost TPC works in dual-input (DI) mode when $p_{in} < p_o$, as shown in Fig. 5(b). The input source doesn't have enough power and the battery discharges to supply the power gap of (p_o - p_{in}). In this mode, the power switch S_2 is kept off. p_{in} is regulated with d_1, same as that in DO mode. p_o is regulated with the duty cycle of S_3, d_3, instead of d_2.

In steady state, applying the volt-second balance principle to L, we obtain that:

$$u_o = \frac{(1 - d_3) u_{in} + d_3 u_b}{1 - d_1} \quad (3)$$

3) Single-Input Single-Output mode: The Boost TPC works in single-input single-output (SISO) mode when $p_{in} = 0$, as shown in Fig. 5(c). In this mode, the battery powers the load alone. S_3 is kept on and S_2 is kept off, thus the Boost TPC is simplified to a Boost converter.

In steady state, applying the volt-second balance principle to L, we obtain that:

$$u_o = \frac{u_b}{1 - d_1} \quad (4)$$

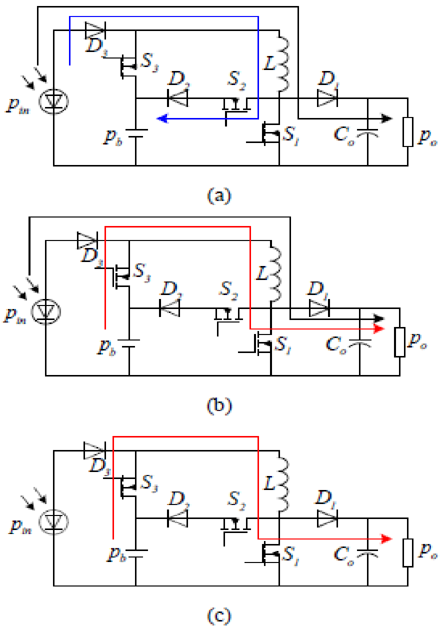


Figure 5. Power flows in different operation modes: (a) DO mode, (b) DI mode, (c) SISO mode.

B. Pulse width modulation Analysis

Because there are two ports under control in both DO mode and DI mode, two independent control variables are needed. Thus, two control voltages v_{c1} and v_{c2} should be utilized in the PWM scheme. The control voltage v_{c1} is used to control the input source port and the battery port. And v_{c2} is used to control the load port. Corresponding to three power switches in the Boost TPC topology, three independent saw tooth carrier waveforms, v_{t1}, v_{t2} and v_{t3}, are used for modulation. Fig. 7 shows the proposed PWM scheme for the Boost TPC. The voltage ranges of v_{c1}, v_{c2}, v_{t1}, v_{t2} and v_{t3} are $2V_T$~$3V_T$, 0 ~$2V_T$, 0~V_T, V_T ~$2V_T$ and $2V_T$~$3V_T$, respectively. The three carrier waveforms are compared with v_{c1} and v_{c2} to generate the drive signal v_{GS1}, v_{GS2} and v_{GS3}, respectively. The proposed. PWM scheme is analyzed in detail in the following.

1) DO mode: In this mode, v_{t1} is compared with v_{c1} to generate the drive signal v_{GS1}. While v_{t3} is compared with v_{c2} to generate the drive signal v_{GS2}, as shown in Fig. 7. The falling edge of v_{GS1} and the rising edge of v_{GS2} are regulated with v_{c1} and v_{c2}, and the rising edge of v_{GS1} and the falling edge of v_{GS2} are fixed. We can obtain that:

$$d_1 = \frac{v_{c1} - 2V_T}{V_T} \qquad (5)$$

$$d_2 = \frac{V_T - v_{c2}}{V_T} \qquad (6)$$

When the input power p_{in} decreases, the duty cycle d_1 will be regulated by the control voltage v_{c1} as (5), to achieve MPPT control of input source. The control voltage v_{c2} should increase, and d_2 decreases as (6), to reduce the charging power, p_b, of the battery, so that the output power p_o is maintained.

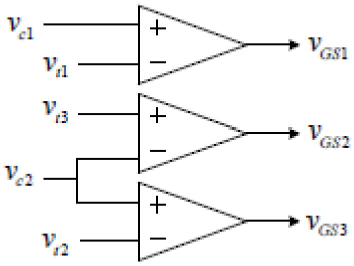


Figure 6. Generation circuit of proposed PWM scheme.

When p_{in} = p_o, p_b is equal to zero. The control voltage v_{c2} and the duty cycle d_2 are regulated to be V_T and 0, respectively. Then, v_{c2} increases higher than V_T and d_3 increases from 0. The Boost TPC turns into DI mode.

2) DI mode: In this mode, v_{GS1} is regulated by v_{c1} as in DO mode. v_{t2} is compared with v_{c2} to generate the drive signal v_{GS3}, as shown in Fig. 7. The falling edges of v_{GS1} and v_{GS3} are regulated with v_{c1} and v_{c2}, respectively. We can obtain that:

$$d_3 = \frac{v_{c2} - V_T}{V_T} \qquad (7)$$

As p_{in} continues decreasing, d_1 is regulated by v_{c1} as (5), too. v_{c2} should increase, and d_3 increases as (7), to increase the discharging power, p_b, of the battery, so that the output power p_o is maintained.

When p_{in} = 0, p_b is equal to p_o. v_{c2} and d_3 are regulated to be $2V_T$ and 1, respectively. Then, the Boost TPC turns into SISO mode.

2) SISO mode: The key waveforms are shown in Fig. 7. In this mode, v_{c2} is equal to $2V_T$. v_{GS1} is regulated by v_{c1} as in DO mode. And the output voltage is controlled by d_1 instead of d_3.

It can be seen that the drive signals in the proposed PWM scheme meet the needs of control in all of the three operation modes. When power of input source fluctuates, power flows are regulated by variations of duty cycles of the three power switches. The Boost TPC can operate in every mode and switch between different modes freely and seamlessly.

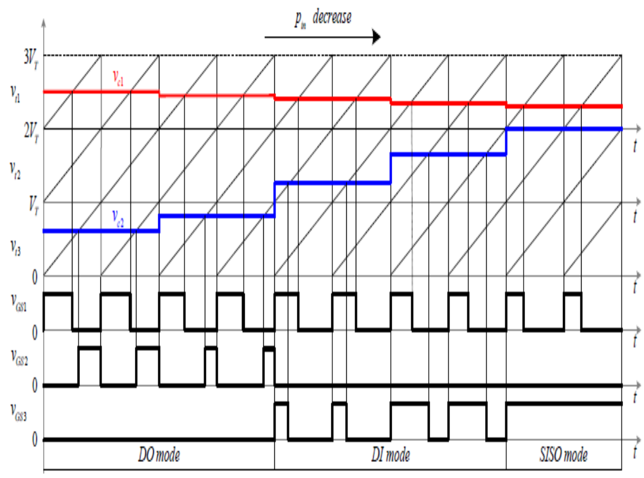


Figure7. Key waveform of PWM modulator in three operation mode.

IV. ANALYSIS OF CONTROL STRATEGY

To make the PWM active, two control variables, v_{c1} and v_{c2}, should be employed as analyzed above. And four PI regulators are needed to ensure MPPT at input source, maximum voltage/current charging at the battery side and the voltage control for the load, respectively. The control strategy proposed is illustrated in Fig. 8.

1) DO mode: When both the charging current and voltage doesn't reach the limitations, the control variable v_{c1} is regulated by the input voltage regulator (IVR), v_{c_IVR}, to achieve MPPT. And v_{c2} is regulated by the output voltage regulator (OVR), v_{c_OVR}, to realize the voltage control of the load. On the other hand, when i_b (or u_b) reaches the limitation, v_{c1} will be regulated by the battery current regulator (BCR) or the battery voltage regulator (BVR), v_{c_BCR} or v_{c_BVR}, to achieve maximum current charging control or maximum voltage charging control, instead of MPPT. And v_{c2} is still regulated by v_{c_OVR} to control the output voltage.

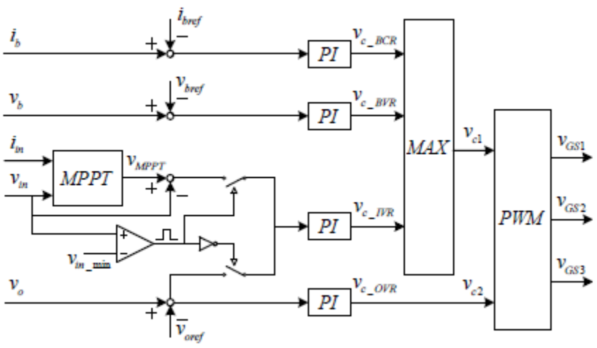


Figure 8. Power control strategy of the Boost TPC.

2) DI mode: The battery is discharged in this mode. The BCR and BVR outputs are saturated at the lower limit. Thus v_{c1} is controlled by v_{c_IVR}, to achieve MPPT. v_{c2} is controlled by v_{c_OVR}, to control the voltage of the load.

3) SISO mode: When the input source voltage is lower than the minimum voltage v_{in_min}, the input source should be cut off. The IVR is used to control the load port. v_{c1} is controlled by v_{c_IVR}, to control the voltage of the load.

It can be concluded that there are at most two regulators working at any time. v_{c1} is controlled by one of v_{c_IVR}, v_{c_BCR} and v_{c_BVR}. v_{c2} is controlled by v_{c_OVR} in DO mode and DI mode.

V. SIMULATION

Simulation is employed using MATLAB/SIMULINK in this project.

Design The Boost converter design as follow.

I. Table

Design parameters	Boost DC/DC converter	
	Parameters	***Values***
	Input voltage Vin	40V
	Output voltage Vo	100V
	Switching frequency Fs	100kHz
	Inductance L	50uH
	Output Power	500W

Simulation Circuit:

MATLAB simulation diagram of DC/DC converter with bidirectional cell is employed. Design parameter values are shown in table 1.

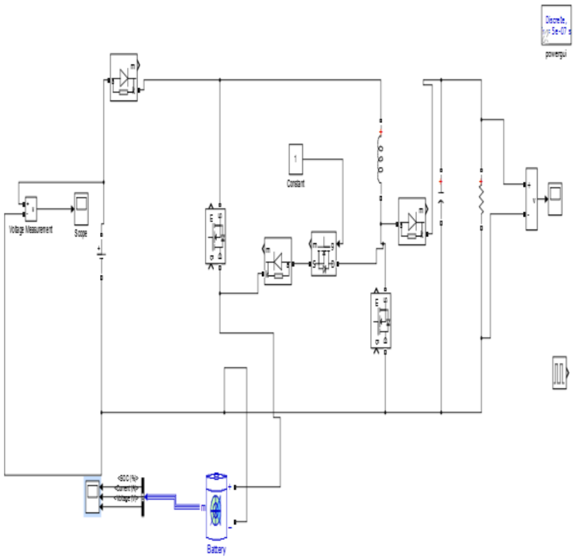
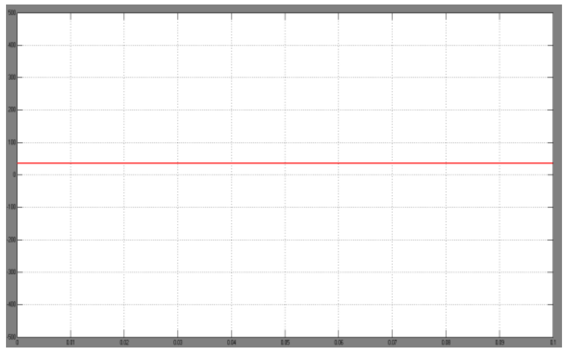


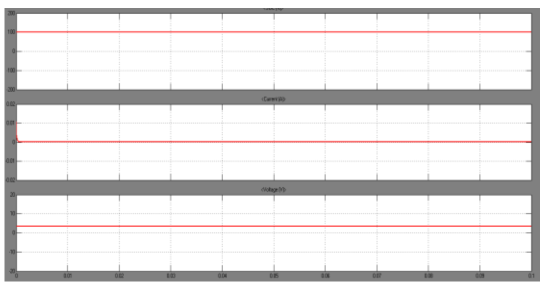
Figure 9. Conventional circuit of Boost DC/DC converter with bidirectional cell.

Input voltage=40v



Time in second

Output DC voltage=100v



Time in second

Open loop block diagram of Three Port DC/DC Converter (TPC) without MPPT controller.

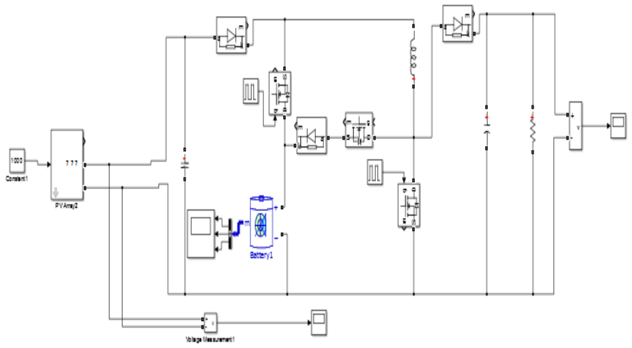
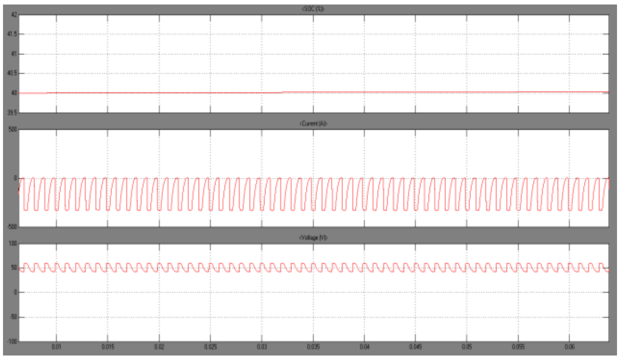


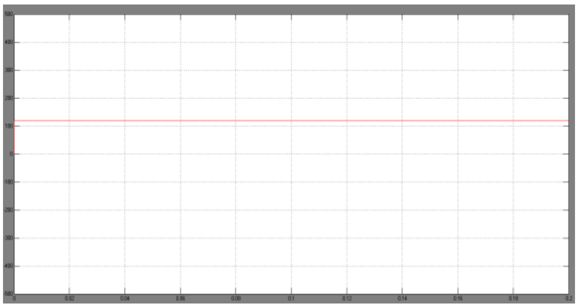
Figure 10. Conventional circuit of TPC without MPPT controller

Photovoltaic Array

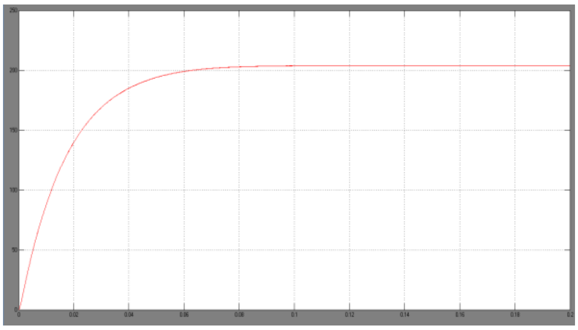
The power that one module can produce is not sufficient to meet the requirements of home or business. Most PV arrays use an inverter to convert the DC power into alternating current that can power the motors, loads, lights etc. The modules in a PV array are usually first connected in series to obtain the desired voltages; the individual modules are then connected in parallel to allow the system to produce more current.



State Of Charge (SOC) voltage (40v) versus Time in second



Input voltage (120v) versus Time in second



Output voltage (230v) versus Time in second

Closed loop block diagram of Three Port DC/DC converter with MPPT controller

In this Project Incremental Conductance MPPT controller is used.

Maximum Power Point Tracking, referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in manner that allows the modules to produce all the power they are capable of. MPPT is not a mechanical tracking system that “physically moves” the modules to make them point more directly at the sun. MPPT is a fully electronic system that varies the electrical operating point of the modules are able to deliver maximum available power. Additional power harvested from the modules is then made available as increased battery charge current. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different.

Incremental conductance

- In the incremental conductance method, the controller measures incremental changes in PV array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O).
- Like the P&O algorithm, it can produce oscillations in power outputThis method utilizes the incremental conductance (dI/dV) of the photovoltaic array to compute the sign of the change in power with respect to voltage (dP/dV)
- The incremental conductance method computes the maximum power point by comparison of the incremental conductance (I_Δ / V_Δ) to the array conductance (I / V). When these two are the same (I / V = I_Δ / V_Δ), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated

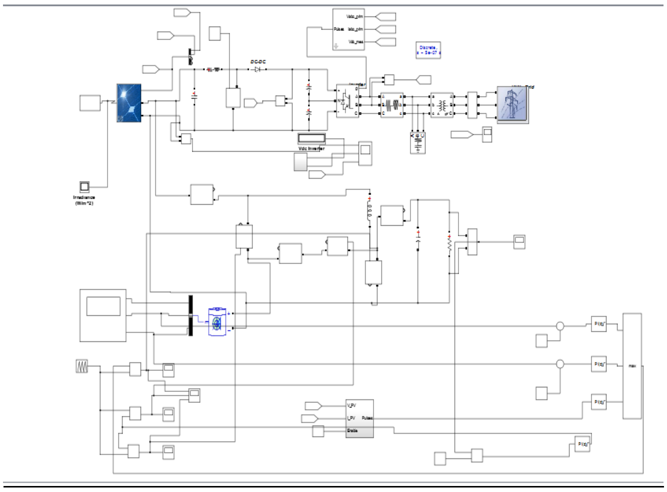
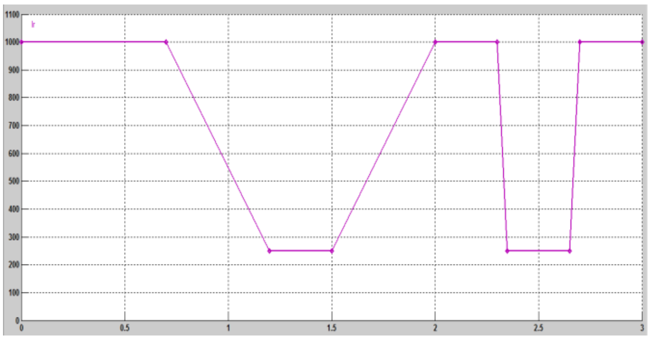
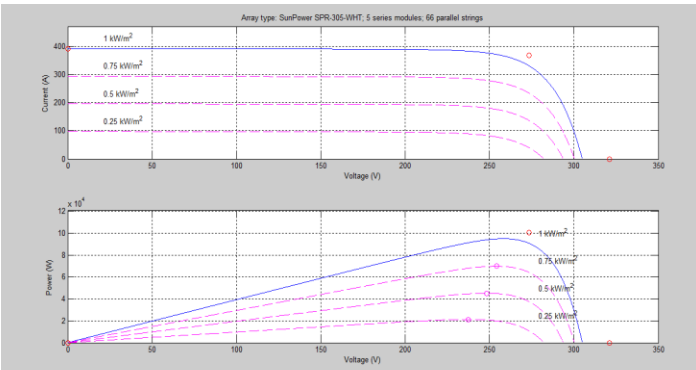


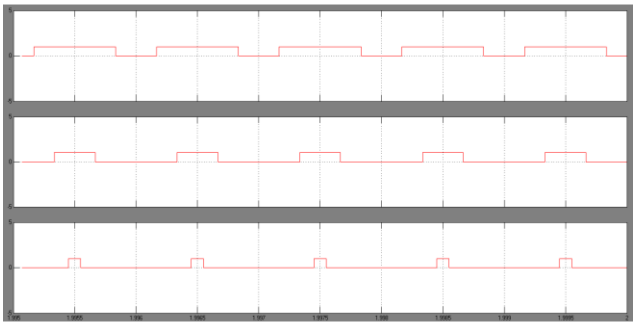
Figure 11. Conventional circuit of TPC with MPPT controller



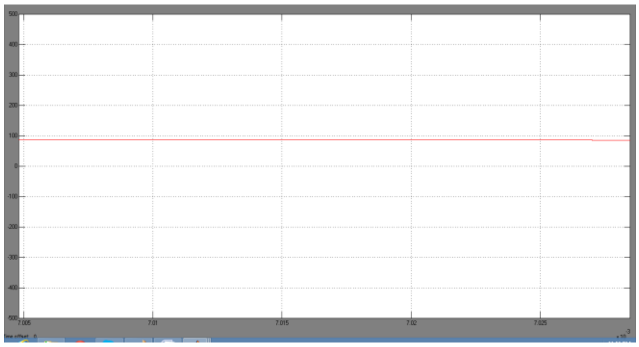
Solar irradiance (1000w/m^2) Photovoltaic array



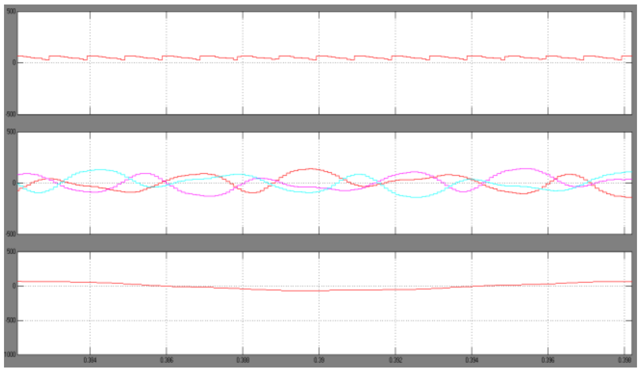
The IV and PV curves for various irradiance but a fixed temperature (25^{0}c) is shown below in Figure.



PWM pulses given to the switches



DC Output voltage



AC Output voltage (230v)

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VI. CONCLUSION

With a bidirectional cell introduced into the basic converters, a family of NI-TPCs is proposed in this project. The proposed NI-TPCs share the same PWM scheme and control strategy. A PWM scheme and a control strategy are also proposed for the NI-TPCs. The PWM scheme and control strategy achieve MPPT at input source, the charging control at the battery and the voltage control for the load. The analysis on the topologies and the PWM scheme is verified with a prototype of the Boost TPC, which has good dynamic performance in each operation mode and during mode transitions. The power efficiencies of all the three power flows paths in the Boost TPC are higher than 96%.

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