A Study and Implementation of Three-level Boost Converter with MPPT for PV Application

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***Abstract*—This paper presents present a study and implementation of a three-level boost converter. This converter feature includes low devices voltages stress requirement for high voltage application, small inductor size that leads to the reduction of cost and size and can be operated with a wide range input voltage. Unlike conventional method, output capacitor voltage balancing was done by a slight phase shift adjustment. Perturbation and Observation Maximum Power Point Tracking (MPPT) method is applied to the converter to track the maximum voltage in the different irradiation condition. A 5kW three-level boost converter with a wide range input voltage from 480V to 700V and high output voltage up to 750V was implemented. The MPPT control is realized by a digital signal processor (DSP) TMS320F28035. The efficiency of the prototype system can reach to 98% and the MPPT average accuracy reaches 98.5%.**

Keywords— Maximum power point tracking; perturbation and observation method; three-level boost DC/DC converter

I. INTRODUCTION

Based on the report of Renewable Energy Policy Network for 21st Century (REN21), renewable energy expansion has been increasing since recent decades. For instance, the Photovoltaic (PV) market was up 25% in 2015 from 2014 market. In 2015, the average rate of annual growth of solar power capacity was 28%, the largest growth in the renewable energy resources [1]. This report presented the importance of the solar energy. Supporting the expansion of the solar power means supporting the related technologies. As shown in Fig.1, a DC-DC converter is inserted between the PV array and the utilities or the DC grid to provide the constant output voltage to the grid or utilities. For this purpose, a boost type DC-DC converter is used widely. It is because the output of the PV array is a low voltage. Therefore, it needs to be boosted to a higher voltage. Comparing a grid system with a high voltage system to a low voltage system, a system with high voltage has a lower conduction loss than that with a low voltage system. Realization of high voltage grid system requires the devices with high voltage rating which is expensive.

In 1992, a multilevel converter was introduced to solve the high-stress component requirement [2]. The basic idea is by dividing the input voltage to some parts depend on the converter level. In this paper, three-level boost converter has

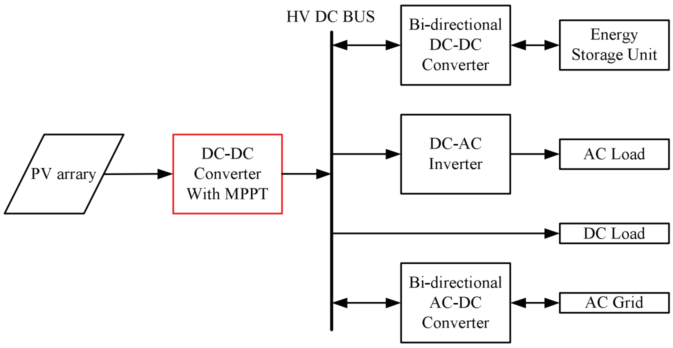


Fig. 1. Schematic diagram of a solar power grid system

been chosen as the power stage topology. The advantages of the three-level boost converter include the low voltage stress rating of the MOSFET, a smaller inductor, and smaller output capacitor requirements because of the doubling frequency, and the ripple cancellation [3, 4]. However, output capacitor may experience unbalance voltage that may damage the capacitors and the switching devices. Several methods have been published related this issue. Paper [3] introduced the balancing technique by only sensing the inductor current, determine and using the valley value of the inductor current to adjust the duty cycle of each switch. This method offers a fast transient response. Paper [5, 6] introduced the method that senses the output capacitor voltage and feeds it back to the control system to adjust the duty cycle. It provides a simple circuitry and more immune to the noise. But, by giving a fix reference of the input capacitor, soft-start may have the difficulty to be achieved. In addition, for wide range input voltage, the capacitor voltage balance may not be achieved. Although this two methods used a difference technique, it has a shared characteristic that adjusts the duty cycle of the switches to achieve the balance voltage on the output capacitor.

For solar power system application, a DC-DC converter is also used to extract the maximum power of the PV array. It is important because of the characteristic of the PV array that depends on the environmental condition such as irradiation intensity, and solar array temperature [7, 8]. To deal with this challenge, Maximum Power Point Tracking (MPPT) is necessary. Many MPPT methods have been proposed in the previous years and were summarized in [8]. Perturbation and

Observation method (P&O) have been used in this paper because of its simplicity and ease.

As we can see, there are three things a circuit designer must consider about for using a three-level converter for PV system application. They are the balance of output capacitor, the regulation of output voltage and the MPP. If these three purposes solve only by using duty adjustment, the control-freedom will be very limited. To solve the problem, a phase-shift control has been used to maintain the output capacitor voltage, and duty cycle control has been used to achieve regulated output voltage and MPP.

This research extends the research of three-level boost converter in term of MPPT application, and capacitor voltage balancing method. This report includes the discussion about the three-level boost converter topology and its operation principle, the method were used to achieve the output voltage balance and the MPP method. At last, the experimental result of the proposed method will be presented.

II. System Architecture and Three Level Boost COnverter

A. System Architecture

Fig. 2 presents the system architecture of the PV system. The solar array is the combination of several PV modules. The output voltage (V) of each cell is connected serially to produce a higher voltage. Equation (1) and (2) describe the ideal characteristic of a solar cell. Here, I_{ph} and I_o are the photo-generated current and PV array saturation current respectively. Boltzmann constant and electron charge are represented by k_B, and q respectively, and T is the absolute temperature in Kelvin. These equations show that environment circumstances affect the output voltage and current of the solar array. A DC-DC converter with MPPT is employed to regulate the output voltage which is connected the grid or utilities. In order to control the converter and achieve the maximum power point, the output voltage, input voltage, and input current are sensed and fed to the Digital Signal Processing (DSP) to be processed to define the driving signal of MOSFET.

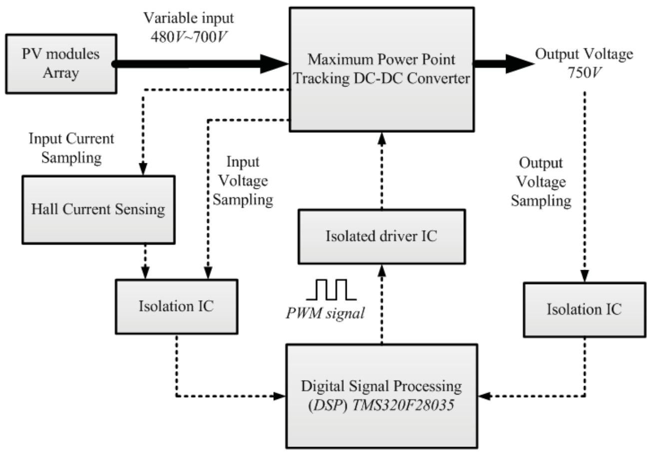


Fig. 2. System architecture of PV power system

$$V_{oc} = \frac{k_B T}{q} \ln\left(1 + \frac{I_{ph}}{I_o}\right) \tag{1}$$

$$I = I_{ph} - I_o\left(e^{\frac{qV}{k_B T}} - 1\right) \tag{2}$$

B. Three-Level Boost Converter

Figure 3 shows the topology of a three-level boost converter. The power stage consists of an inductor, two diodes, two MOSFETs, and two output capacitors. The operation is divided into two types. Firstly, the duty cycle is more than 50%. Secondly, the duty cycle is less than 50%.

The first type has switching states as shown in Fig.4. Because the duty cycle is larger than 50%, there will be a period when both MOSFETs are turned ON at the same time. Explanation of operation of each state presented as follow:

State 1 ($t_0 < t < t_1$), ($t_2 < t < t_3$): Schematic of this mode is drawn in Fig. 5.(a). During this time interval, MOSFET Q_1 and Q_2 are turned ON to enable the source to charge inductor. Therefore, the inductor current slope at this period is V_o/L. Diode D_1 and D_2 are reversed biased. Output capacitor C_{o1} and C_{o2} are discharged and supply the load.

State 2 ($t_1 < t < t_2$): Fig.5.(b) shows the schematic in this interval. During this interval, MOSFET Q_1 is remaining turn ON and Q_2 is turned OFF. In this condition, Diode D_1 is reversed biased and D_2 is forward biased. Capacitor C_{o1} is discharged to supply the load and C_{o2} is charged by the released energy from the inductor. Inductor current slope during the interval equals to $(V_{o1}-V_{Co2})/L$.

State 2 ($t_3 < t < t_4$): Fig.5(c) presents the schematic during the interval. MOSFET Q_1 is turned OFF and Q_2 is turned ON. Diode D_1 is in forward biased and D_2 is in reversed biased condition. Capacitor C_{o1} is charged and C_{o2} is discharged. Inductor current slope is equal to $(V_{o1}-V_{Co1})/L$.

Second type operation is identical to the first type. However, state 1 of first type operation does not exist here. It is replaced with a state when both switches are turned OFF at the same time as it is described in Fig.7. In this interval, MOSFET Q_1 and Q_2 are turned OFF. Diode D_1 and D_2 are forward biased to enable the source to charge inductor and output. Inductor current slope during the interval equals to $(V_{in}-V_{out})/L$.

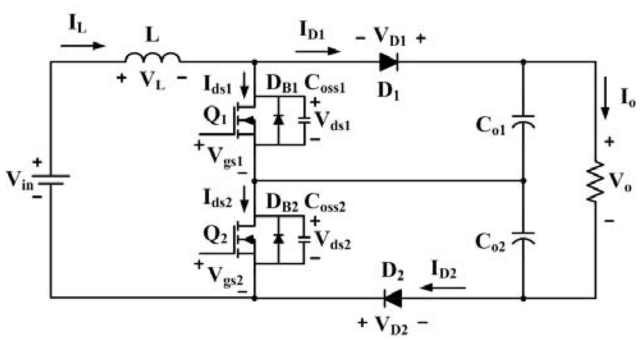


Fig. 3. Topology of three-level boost converter

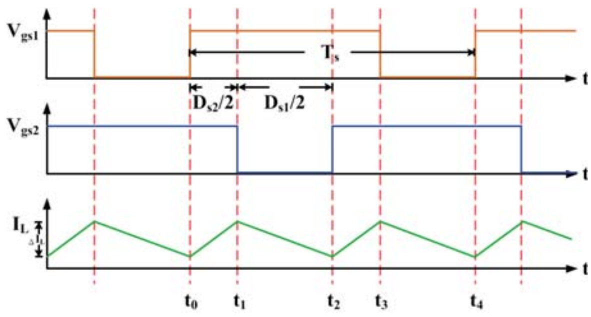
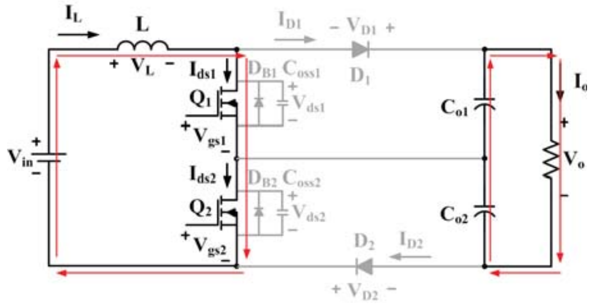
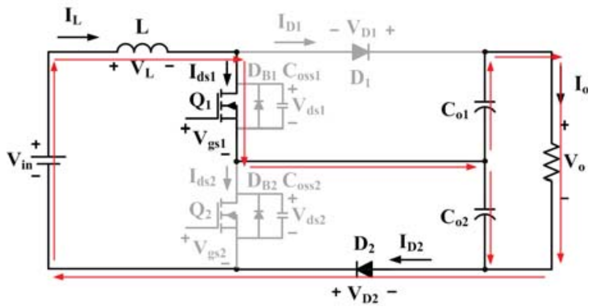


Fig. 4. Driving signal and inductor current waveform of three level boost for duty cycle more than 50%



(a)



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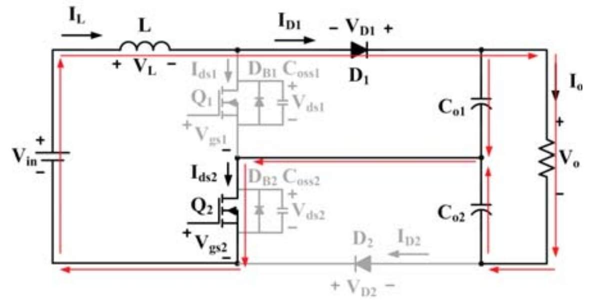


(c)

Fig. 5. Circuit schematic of three-level boost for duty cycle more than 50%. (a) State 1 ($t_0 < t < t_1$), ($t_2 < t < t_3$) (b) State 2 ($t_1 < t < t_2$) (c) State 3 ($t_3 < t < t_4$)

III. OUTPUT CAPACITOR BALANCING AND MPPT METHOD

A. Balancing of The Output Capacitor

A balanced condition of output capacitor voltage is very important in this application. It ensures the lower rating

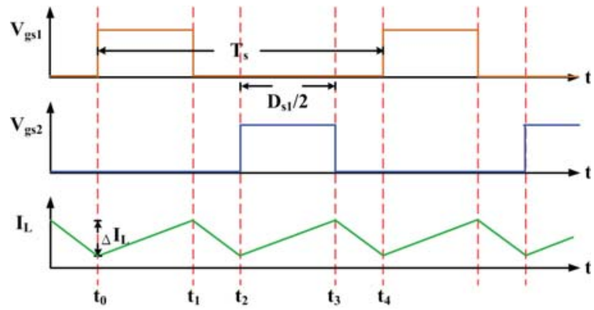


Fig. 6. Driving signal and inductor current waveform of three level boost for duty cycle less than 50%

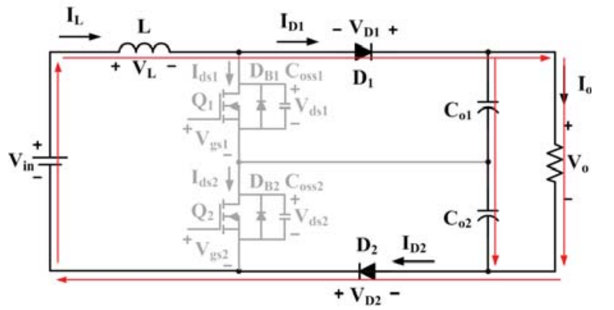


Fig. 7. Circuit schematic of three-level boost for duty cycle less than 50%

devices can be used for high voltage applications. Some balancing methods of multilevel converter capacitors have been proposed in [3, 5, 6]. Originally, these techniques are used to a multilevel buck by adjusting the duty cycle of the MOSFETs. In this paper, phase shift technique is used to balance the output capacitor voltage. In an ideal condition, the phase-shift of the driving signal of MOSFET Q1 and Q2 is 180°. With a slight phase-shift error, a serious imbalance condition will occur. Phase-shift implemented by sensing the output voltage and one of the output capacitor voltage.

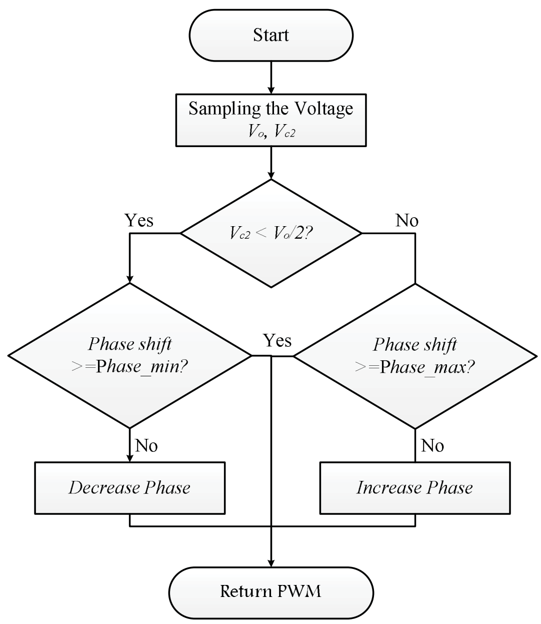


Fig. 8. Flowchart algorithm of the output capacitor voltage balancing

The voltage of the output capacitor should be a half of the output voltage. To achieve this condition a variable phase-shift control used in the DSP. Fig. 8 shows the flowchart of the algorithm. The used phase-shift range was very small. The goal is to avoid the excessive effect of the balancing method. In addition, the frequency of the balance controller should be set slower than the DSP interrupt subroutine frequency.

B. Perturbation and Observation MPPT Method

P&O method is the most widely used MPPT method because of easy implementation, and simple feedback measurement circuit [8-10]. Using this method will need to sense the output voltage and current of the solar array to get the instantaneous power. Then the solar array voltage is increased or decreased in the next cycle depend on the output power condition. Again, the output power of the solar array is measured, to be compared with the previous output power value. This repetitive process continuously searches the MPP value of the solar array by perturbing the output voltage of the solar array. It makes the solar array output voltage oscillate even in the steady state.

Controller implementation in DSP should consider the value of increment or decrement carefully to avoid the excessive effect and large oscillation amplitude. Care also must be taken to the value of updated period in order to get a robust response of control, but also fast enough to response the environment changing. The flowchart of implemented P&O method is shown in Fig.9.

IV. Implementation and Results

A prototype of a three-level boost converter with MPPT has been built with specifications: Output Power (P_o) 5000W, Input Voltage (V_{in}) 480V-700V, Output Voltage (V_o) 700V, and Switching Frequency 100kHz. The power stage devices are: Power MOSFET STW45NM60, Inductor (L) 94 µH, Output Capacitor 940 µF, and DSP controller TMS320-F28035.

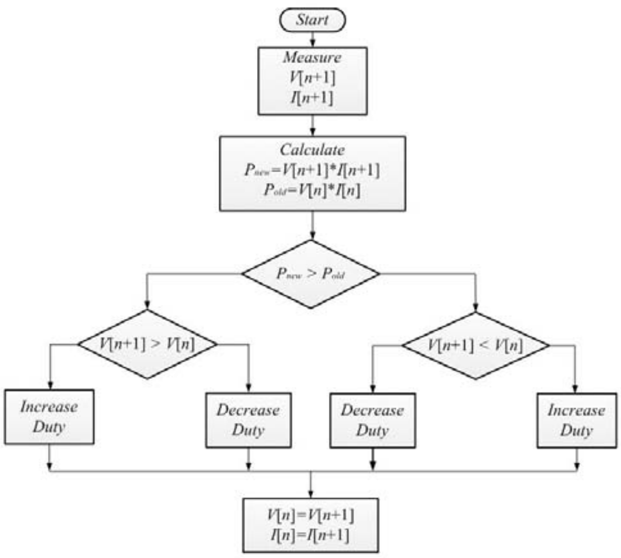
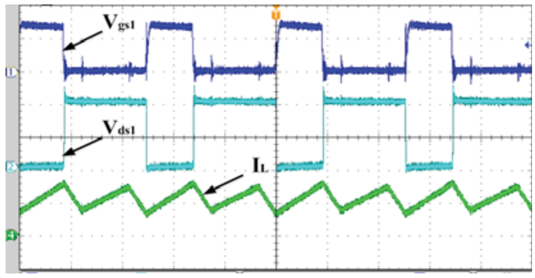


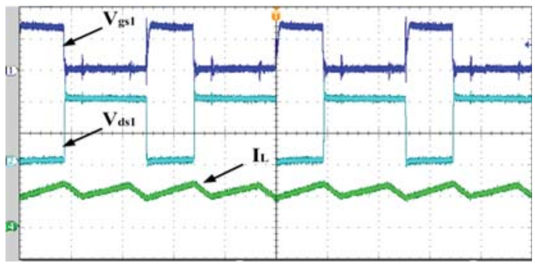
Fig. 9. Flowchart of P&O method with DSP

A. Evaluation of Converter Performance

The testing has been done with Programmable Source Chroma 62150H-1000S. Experimental results are presented in Fig.10 to Fig.12.

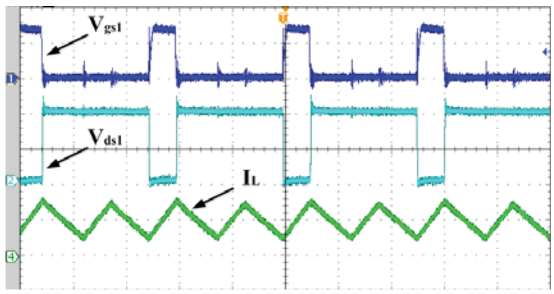


(a)



(b)

Fig. 10. Key-waveforms of three-level converter with 480V input voltage (a) At 50% load (b) at 100% load [scale: CH 1:10V/unit, CH 2:200V/unit, CH 3: (a) 5A/unit,(b) 10A/unit, times:160nS/unit]



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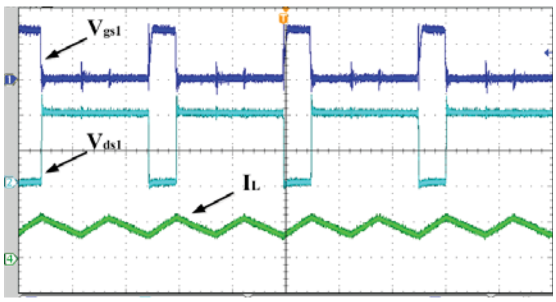
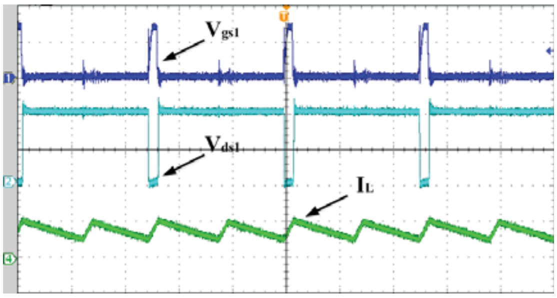
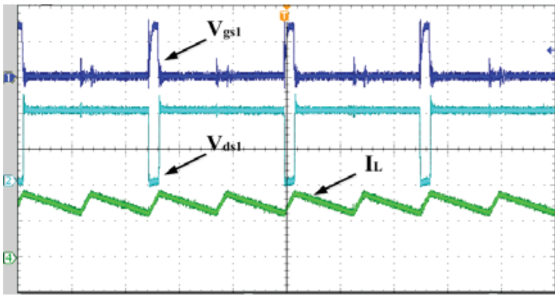


(b)

Fig. 11. Key-waveforms of three-level converter with 600V input voltage (a) At 50% load (b) at 100% load [scale: CH 1:10V/unit, CH 2:200V/unit, CH 3: (a) 5A/unit,(b) 10A/unit, times:160nS/unit]



(a)



(b)

Fig. 12. Key-waveforms of three-level converter with 700V input voltage (a) At 50% load (b) at 100% load [scale: CH 1:10V/unit, CH 2:200V/unit, CH 3: (a) 5A/unit,(b) 10A/unit, times:160nS/unit]

In this experiment, a various input voltage were supplied to see the performance of the converter for wide range input voltage. Three selected voltage values were 480V, 600 V, and 700V. Each input voltage was tested with 50% load and full load. All figures show that the converter work properly as expected. The maximum peak-to-peak current is 6A at full load, and about 5A at 50% load.

Efficiency curve of the three-level converter is presented in Fig.13. This result shows the efficiency at full load test of correspondent voltage. It shows that the minimum efficiency is 98.07% at 480V input and maximum efficiency is 98.87% at 700V input voltage.

B. *Evaluation of MPPT Performance*

Performance evaluation of the used MPPT method has been done by using a PV simulator.

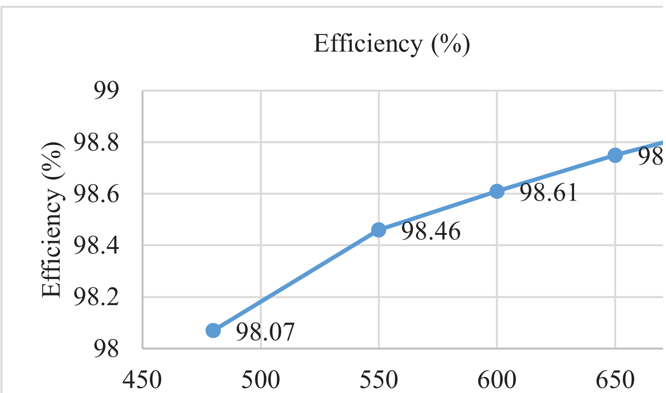


Fig. 13. Efficiency curve of three-level boost converter

The simulator was programmed by using the specification of the TSM-245 solar panel that has the characteristic parameters as follow: Peak Power 245W, Open Circuit Voltage 37.5V, Short Circuit Current 8.68A, Maximum Power Voltage 30.2V, and Maximum Power Current 8.13A. Because the nominal power is 5kW, for the purpose of testing, 20 TSM-245 solar panels connected in series are assumed to be used as the power supply in the real situation. For this condition the characteristic of PV array has been calculated based on the single panel. Table I shows the parameter that has been used for testing.

A various irradiation values that are correspondent to the I-V curves were programmed into the source. Tested irradiation values were 400W/m^2, 600400W/m^2, 800400W/m^2, and 1000W/m^2. The result are presented in Fig.14-17. Accuracy results is provided in Table II. Accuracy performance of the prototype in dynamic irradiation has been investigated as well. It has been done by changing the characteristic of I-V curve for every 10 seconds. The result is presented in Fig.18. It has average accuracy is about 98.5%.

TABLE I. CHARACTERISTIC OF 20-SERIES-CONNECTED TSM-245 SOLAR PANEL

Parameters	Value
Open Circuit Voltage (V_{oc})	750V
Short Circuit Current (I_{sc})	8.68A
Maximum Power Point Voltage (V_{MPP})	604V
Maximum Power Point Current (I_{MPP})	8.13A
Maximum Power Point (P_{MPP})	4910W

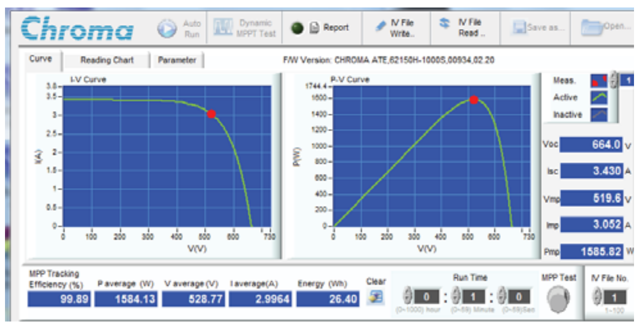


Fig. 14. Maximum power point tracking curve for 400W/m^2 irradiance

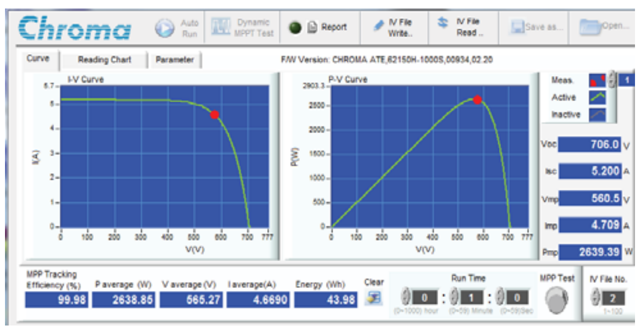


Fig. 15.Maximum power point tracking curve of 600 W / m^2 irradiance

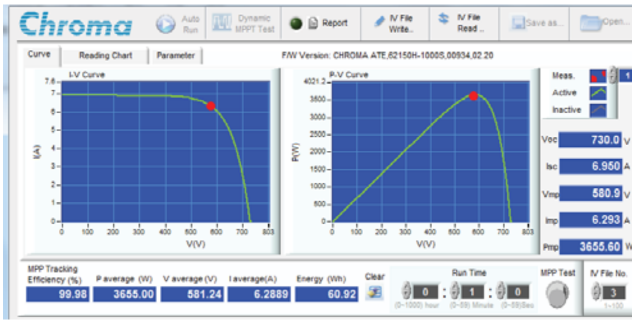


Fig. 16. Maximum power point tracking curve of 800 W / m^2 irradiance

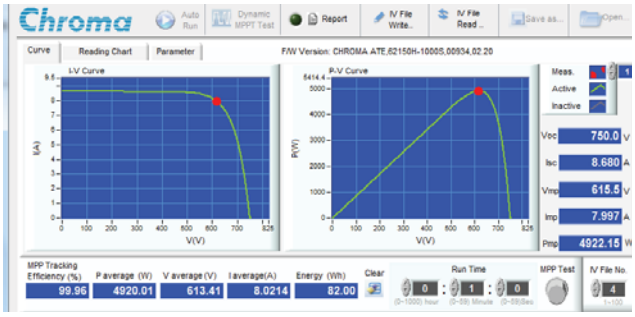


Fig. 17. Maximum power point tracking curve of 1000 W / m^2 irradiance

TABLE II. MPPT ACCURACY FOR VARIOUS IRRADIEANCE

Irradiance (W/m^2)	V_{OC} (V)	I_{SC} (A)	V_{MPP} (V)	I_{MPP} (V)	P_{MPP} (W)	MPPT Accuracy (%)
400	664	3.43	519.6	3.05	1585.8	99.89
600	706	5.2	560.5	4.71	2639.4	99.98
800	730	6.95	580.9	6.29	3655.6	99.98
1000	750	8.68	615.5	7.997	4922.2	99.96

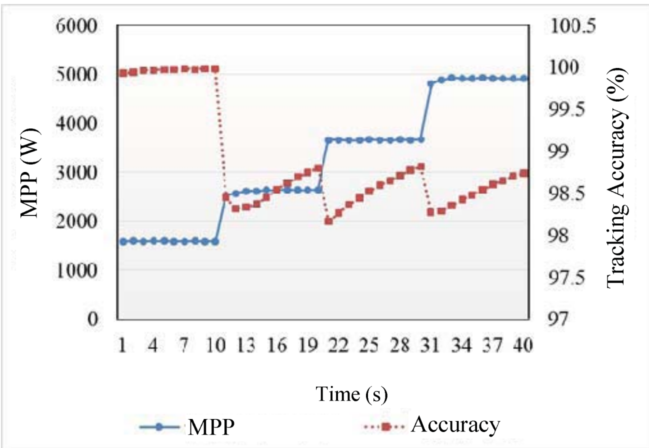


Fig. 18. Dynamic Accuracy Measurement in various irradiation condition

V. CONCLUSION

Three-level boost converter with MPP has been discussed in this paper. It is clear that the converter has some advantages such as low voltage rating devices requirement, and smaller inductor requirement in comparison to the conventional boost converter.

A 5kW prototype also has been built and the results have been presented. The conclusion can be made that the proposed circuit and method has been successfully implemented. The results show that the efficiency of the converter achieved 98% at full load at 700V input voltage. We can also observe that the efficiency only suffers a slight decrease in the lower input voltage, it shows that converter can be used for wide range input without a significant impact on the efficiency.

In term of Maximum Power Tracking, the P&O MPPT method has performed well and showed a very satisfy result by having the average accuracy 98.5% in dynamic irradiance condition.

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