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PV Based High Gain DC-DC Step-Up Converter With Coupled Inductors Feeding DC Microgrid

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Abstract: *A PV based high gain DC-DC step-up converter with coupled inductors feeding DC microgrid is presented in this paper. The low input voltage of PV panel is stepped up to a higher level by using DC-DC boost converter with coupled inductor. In order to achieve maximum power in its entire operation, an MPPT converter is interfaced between the input and load stages. The topology does not use electrolytic capacitors and can be used for low power applications. Low cost and simple MPPT control algorithm are the distinctive advantages of the system which are essential for renewable applications.*
Keywords: *Coupled inductor, DC microgrid, Maximum power point tracking (MPPT), PV system, Voltage gain*

I. Introduction

The integration of distributed energy systems with renewable energy sources is indispensable as it can be an alternative to the energy crisis and environment pollution. Due to their beneficial features, higher demands on power electronics technology is also present in this scenario. Although, the unpredictable and intermittent nature of renewable energy sources is a major challenge, renewable energy sources have a defined place in power electronics. The energy storage elements are usually required to provide an uninterruptible, smooth and reliable power supply to the local loads. The power electronic converters act as an interface between the renewable energy source and load. The demand for renewable energy sources increases day-by day, ultimately triggering the development of new converter topologies. Most of the non-isolated converters offer low output voltage which are needed to be stepped up in sub-sequent stages. This can be done with the help of voltage multiplier cells or by cascading the blocks. This leads to the development of high voltage gain, high efficient converter topologies. These converters find their applications in several areas like UPS, storage batteries, high efficient lamp ballasts, locomotives that utilizes electric traction and in the equipment in medical field. Some other machines like variable speed AC induction motors and hybrid electric vehicles also need DC power for their operation. In earlier days, high-frequency isolated converters were used to boost voltage by adjusting the turn's ratio of transformer properly. Although the total rated power is processed by transformer, it makes the system bulkier with reduced efficiency. In the conventional volt-age step-up applications by the boost converter and fly-back converter, the high step-up cannot be achieved with high efficiency. This is because of extreme duty cycle or high turn's ratio and of the leakage inductance. The extreme duty cycle may cause large conduction losses and serious diode reverse-recovery problem. Meanwhile, the high turns ratio offers the large leakage inductance and creates the copper losses of windings. The fly-back converter provides a higher voltage gain but at the expense of large leakage inductance and a complex structure. Thus, non- isolated converter were used in practice as an alternative solution to step up the voltage. But, high rated switches are selected to meet the voltage stress which is equal to the output voltage. This in turn results in high conduction loss. Selection of large duty ratios to achieve high voltage gain leads the main switch to remain turned on for long time intervals. This not only increases the conduction losses and high voltage spikes, but also induces serious diode reverse recovery problem since the current through the diode is high. The interleaved converters, cascaded converters, quadratic converters, boost converters based on the three-state switching cell (3SSC) and boost converters with coupled inductors are the other topologies used for stepping up the voltage.

1.1 Background

Various non-isolated converters are proposed in the literature to achieve high voltage gain. In the view of the fact that most renewable energy sources, such as photovoltaic (PV), fuel cell(FC) and variable speed wind power systems, generate either DC or variable frequency/voltage AC power, a power electronics interface is an indispensable element for the grid integration. A converter topology based on the three-state commutation cell using solar panels is proposed [1]. It provides high voltage gain by single stage conversion in a single conversion stage. The circuit comprises of a soft switching converter which interconnects solar panels, battery and high gain boost converter. The resonant capacitor makes zero volt-age switching mode. Reduction in voltage conversion stages and improvement in efficiency with much simpler control circuit are the merits of this topology. The voltage stress across the active switches is reduced with less input current ripple. A review of different types of non-isolated DC-DC converters in photovoltaic grid-connected applications [2] to achieve high-step-up, low-cost, and high-efficiency. DC-DC conversion is presented. There are mainly four different classifications such as:

1. High-step-up converter with coupled inductor: The coupled inductor has dual functions in this topology. It stores the energy and acts as a transformer to increase voltage gain of DC-DC converter. The secondary winding of the coupled inductor operates as a voltage source. The voltage gain can be further increased by changing turns ratio of coupled inductor. Energy leakage and voltage stress during the turn off process are reduced considerably by the use of clamp capacitor and clamp diode.

2. High-step-up converter with switched capacitor: Here, the voltage source is capacitor. The requirements of magnetic components are eliminated in this topology. Power density can be improved by increasing the switching frequency. However, this may make circuit more complex along with high cost. Poor output voltage regulation capability is another disadvantage.

3. High-step-up converter with inductor and switched capacitor: The switched-capacitor and boost converters can be interconnected together to obtain a step less voltage gain. The hard-switching operation causes switching losses. Also, the numbers of the magnetic components such as inductor are more, which limits the power. Hence, these are suitable for low-power applications.

4. High-step-up converter with coupled inductor and switched capacitor: The use of coupled inductor and the switched capacitor can provide a wide-range of voltage conversion. The reverse recovery problems associated with the output-diode is alleviated by the leakage inductance of the coupled inductor. The zero current switching scheme minimizes the switching losses of active switches. The leakage energy is absorbed, and the voltage stress on the active switch is suppressed by diode and capacitor. The energy stored in the clamp capacitor is transferred to the load by the resonant tank circuit consisting of inductor and the capacitor. The voltage gain is higher, and the switch voltage stress is lower than other high-step-up boost converter topologies.

A high voltage gain DCDC converter integrating coupled-inductor and diode capacitor [3] employs a clamped-capacitor circuit which is connected to the primary side of the coupled inductor. It has a diode-capacitor circuit integrated with the secondary winding. The former reduces voltage stress of the active switch and the transfers the primary leakage energy to the load whereas the latter is used for extending the voltage gain. The energy of secondary leakage inductor can be recycled. The voltage spikes on the main switch are suppressed and maintains continuous input current.

The high step-up converter with a coupled-inductor [4] has a coupled inductor with a lower-voltage-rated switch. Moreover, a passive regenerative snubber is used for absorbing the energy of stray inductance. This makes wider range of duty ratio for the switches and the voltage gain is improved than other coupled-inductor-based converters. The closed-loop control methodology is utilized in the proposed scheme to overcome the voltage drift problem of the power source under the load variations. The converters without extreme duty ratios [5] are introduced as in fig.1. The additional diode, capacitor and coupled windings are used to realize functions instead of active switches.

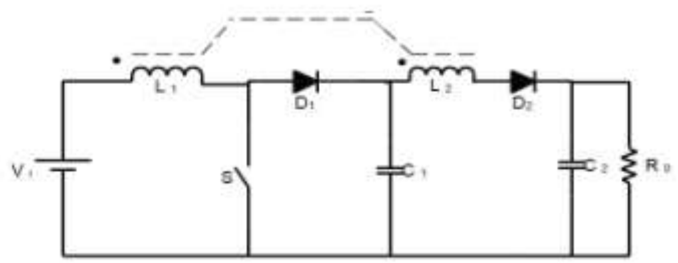

Fig.1 converter without extreme duty ratio

This provides better performance than their active-clamp counterparts. The additional diode serves as the body diode of the active-clamp switch. The coupled winding and output rectifier together act as a switch similar to a magnetic switch and serves the same function as the active-clamp switch. The converter steps up voltage across a single PV module 17.4 V to 311 V. The maximum voltage across diode is very high in this topology which leads to the use of high-cost diodes. High forward voltage drop and also low switching speed are the disadvantages. Since the analysis is based in continuous conduction mode (CCM), resonance may occur between the leakage inductances and capacitance when the inductor is not fully discharged.

II. Objectives

Several types of applications such as uninterruptible power systems and adjustable-speed drives often demand the low dc voltage from renewable sources such as batteries, photovoltaic (PV) panels, fuel cells and small wind turbines to be stepped up. The proposed converter is adequate for low input voltages and low-power applications, where a high-voltage dc bus is necessary to supply an inverter. The main objectives of the proposed system are as follows:

1) To design, simulate and develop a low cost high voltage gain dc-dc boost converter with coupled inductor for PV systems.
2) To implement Perturb and Observation MPPT algorithm
3) To reduce the maximum voltage across diode in [5].
4) To operate DC bus in maximum power with changes in solar radiation.

III. Overview

A high-voltage gain DC-DC converter with coupled inductor operating in discontinuous conduction mode (DCM) is shown in fig.2.

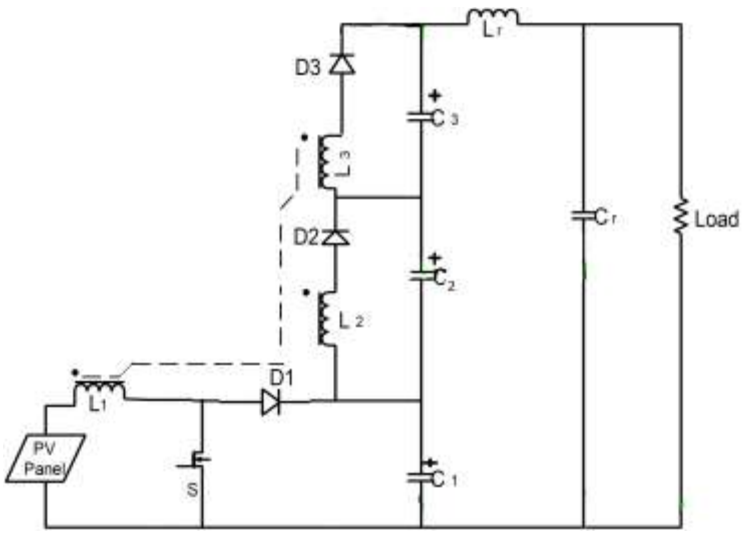

Fig.2. Basic circuit diagram of the high gain DC-DC converter

The high reverse voltage across the output diode in the previous topology [5] because of the resonance between the leakage inductance and the switch intrinsic capacitance can be alleviated by adding another cell Diode D_3, inductor L_3 (which is coupled to L_1 and L_2) and one capacitor C_3. Hence, the voltage across the boost diode is divided by two, thus allowing the use of ultra-fast diodes. The assumptions for the analysis are as follows:

1) The components used are ideal.
2) Parasitic elements such as leakage inductances and series resistances are neglected.
3) Large capacitors are selected to maintain constant volt-age operation.
4) The current ripples are neglected.
5) The magnetic coupling coefficient is unity

Aiming to overcome this limitation, the converter in Fig.2 must operate in discontinuous conduction mode (DCM), so that inductor L_1 can be fully discharged.

3.1 Modes of Operation

Mode I: Mode I starts from t_o to t_1 by turning ON switch S. This is shown in fig 3. The energy is stored in inductor L_1. The capacitors C_1, C_2 and C_3 are discharged and delivers power to the output load inductors L_2 and L_3 are charged as shown.

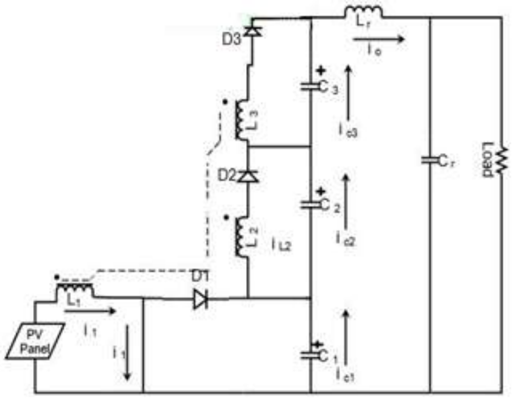

Fig.3. Equivalent circuit of Mode I

L_1 is delivering charge to capacitor C_1 from input panel even though it was fully discharged because of the inherent leakage inductance.

Mode II: Mode II starts by turning OFF Switch S from t_1 to t_2 .The previously charged inductorL_1 is now discharged. The inductors L2 and L3 are charged as shown in fig.4. L1 is delivering charge to capacitor C1 from input panel even though it was fully discharged because of the inherent leakage inductance.

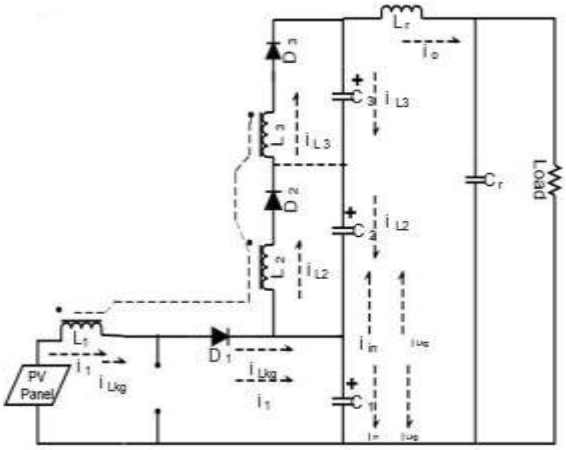

Fig.4. Equivalent circuit of Mode II

Mode III: In mode III that starts from t_2 to t_3, the active switch S remains OFF. The voltages across the inductors L1 and L2 are zero since they are fully discharged. This is shown in fig. 5. The load gets energy only from capacitor C1.

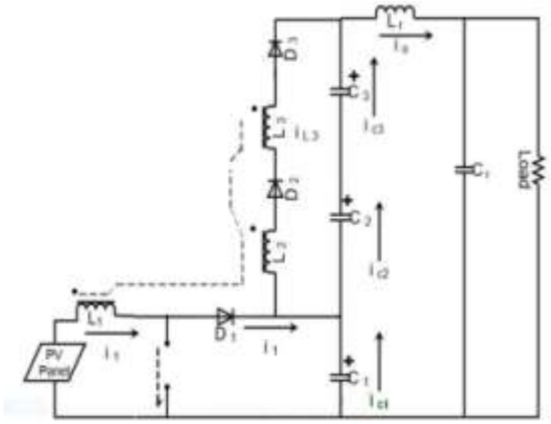

Fig.5. Equivalent circuit of Mode III

The diodes in the circuit are reverse biased and there exists no energy transfer between input solar panel to the output capacitors. The output voltage maintained nearly constant in this mode. The steady state analysis in DCM is depicted in fig.6. The DCM allows the inductor to be fully discharged.

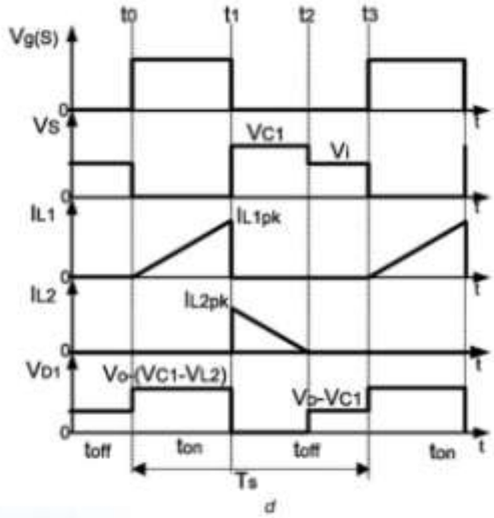

Fig.6. Steady State Analysis of the proposed topology in DCM

IV. Design

The steady state analysis in discontinuous conduction mode (DCM) is depicted in fig.6. The DCM allows the inductor to be fully discharged.

$$\frac{Vo}{Vimin} == \frac{1}{1-Dmax} + \frac{N2}{N1}\left(\frac{1}{1-Dmax} - 1\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where, N_1 and N_2 are the number of turns of inductors L_1 and L_2, respectively.

$$\frac{N2}{N1} = 29 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

It is also worth to mention that the same number of turns is ad opted for inductors L_2 and L_3, that is, $N_2 = N_3$.

- Inductors

The inductance values that represent the boundary condition between CCM and DCM are:

$$L1 = \frac{Vimin\cdot Ts}{2\cdot Po}\cdot\left[Vimin.D2\max + \frac{N12.(1-Dmax)2}{(N1+N2)2}\cdot(V_o - V_{i\,min})\right] = 2.584\mu H\ldots\ldots \text{(3)}$$

$$L_2 = L_3 = \left[\frac{N2+N1}{N1}\right]^2\cdot L1 = 2.384 \text{ mH}\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

- Capacitors

From the theoretical analysis, capacitor C1 can be calculated according to the following expression:

$$C_1 = \frac{IL2pk.Dnom}{2.fs.\Delta Vc1} \cong 2.2\mu F\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$C2=C3=\frac{10.Po}{Vo2.2.\pi.fs.} \cong 220nF \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

V. Maximum Power Point Tracking (MPPT)

The photovoltaic system should operate at the voltage where the global maximum of the P-V characteristic is present. The point at which product V and I is maximum in VI characteristics of a solar cell is defined as maximum power point (MPP). This point in the P-V characteristic is called the Maximum Power Point (MPP). The MPP changes when the irradiation and temperature changes or when the solar panel is partially shaded. MPP is unique and it is located at the knee of PV characteristics. MPPT system is actually an electronic device interface between the PV array and the load. They are used to track peak power by operating PV panel at peak voltage. The MPPT consists of two main parts, a micro-controller part to track the MPP and a converter to convert the generated voltage to a desired level suitable for the load. An algorithm runs on the microcontroller to track the MPP. There are a lot of different algorithms to track the MPP such as

- Hill Climbing Method
- Incremental Conductance Method
- P & O Method

Here we are employing P&O MPPT method for maximum power extraction. In this P & O method is commonly used in all sort of applications due to several advantages. Simple structure, easy implementation and less required parameters for tracking down MPP are some of the advantages of P & O method. Even though, it has some drawbacks such as power tracked by the P and O method will oscillate and perturb up and down near the maximum power point and the changes in weather conditions are not specified. The algorithm followed to track MPP using P and O is shown in fig.7. The Perturb & Observe (P & O) algorithm perturbs the duty cycle which controls the power converter, in this way it takes steps over the P-V characteristic to track the MPP. This perturbation causes a new operating point with a different output power. To achieve maximum power point of PV modules, the condition (dP/dV = 0) is to be attained in P-V characteristics. The load of the PV system is adjusted in order to change the terminal voltage and output power of the PV modules. In P & O, the variations of the output voltage and power before and after the sampling instant are observed. The present power is compared to be the reference for increasing or decreasing the load in the next perturbation. If the perturbation causes an increased output power of PV modules than that before the variation, the perturbation direction is positive. Otherwise, if the output power of PV modules is less than that before variation, it indicates that the varying direction should be reversed.

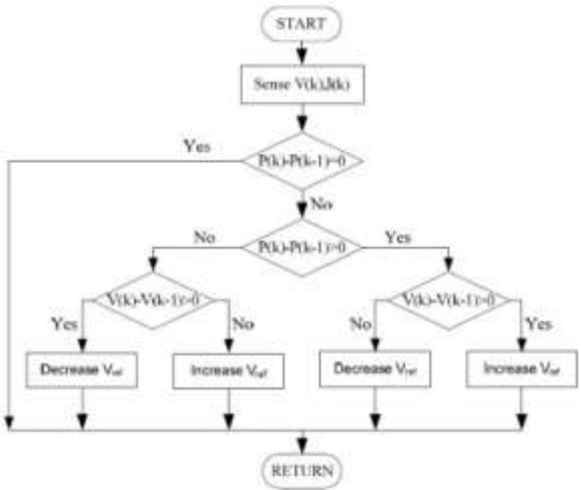

Fig.7. P&O Algorithm

VI. Simulation

The MATLAB simulation of PV based high gain DC-DC step-up converter with coupled inductors applied for a resistive load is done as per the parameters used are tabulated in designed table 1.The simulation of DC-DC boost converter with resistive load is done.

Table I: Simulation Parameters

Parameters	Values
Inductor L_1	2.584 μH
Inductor L_2, L_3	2.384 mH
Capacitor C_1	2.2 μF
Capacitor C_2	220 nF
Switching frequency	50 kHz

The variation of output voltage for changes in input voltage and variation of output voltage for changes in duty ratio are found out to design a feedback loop. The simulation employing Perturb and Observation (P&O) MPPT technique is given in fig.8.

6.1 Simulation Diagrams

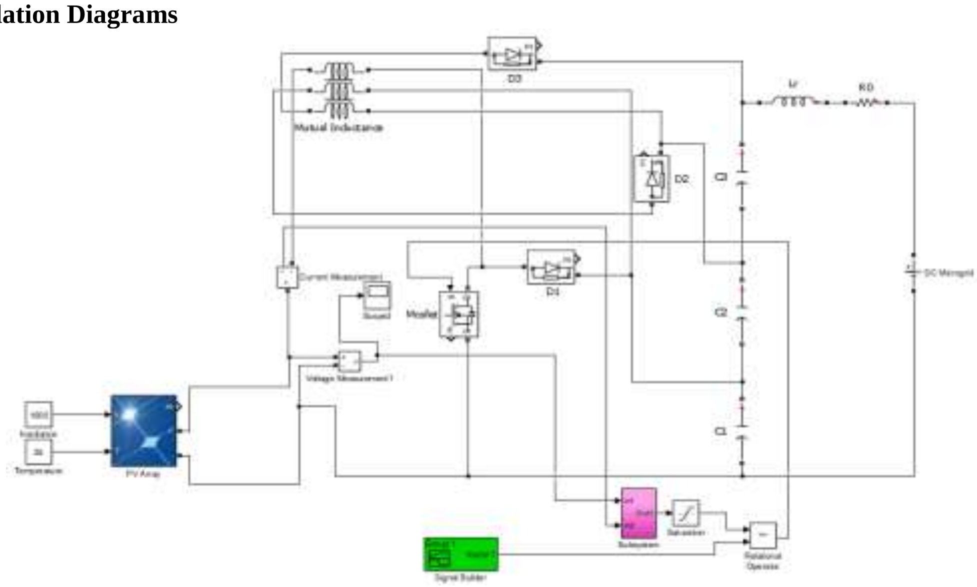

Fig.8. Simulation of proposed topology employing P&O MPPT Algorithm

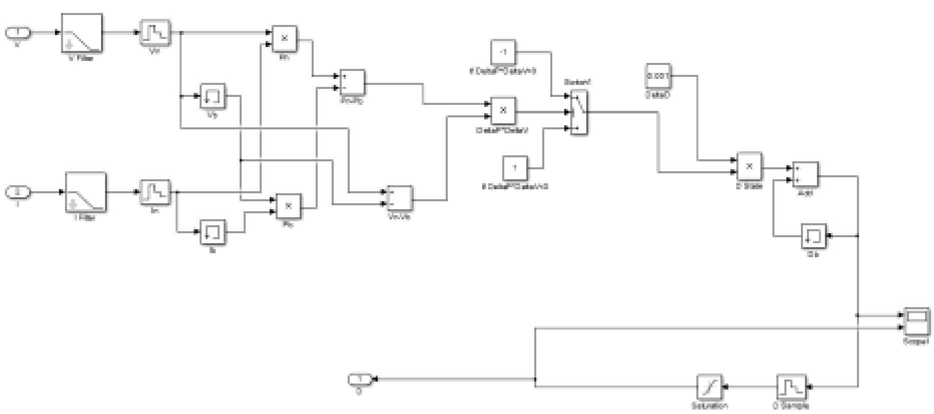

Fig.9. P&O MPPT Algorithm

6.2 Simulation Results

The output voltage and output power of proposed converter with P&O MPPT method is given in fig.10 and 11 resp.

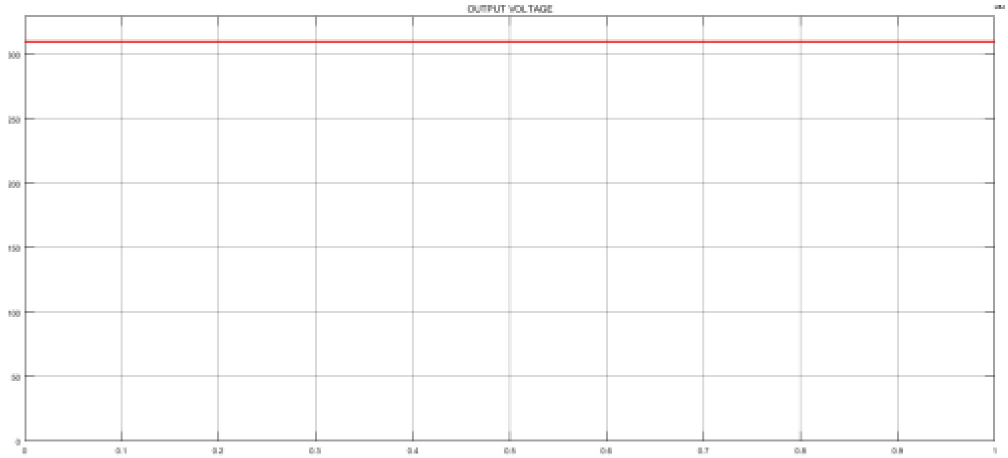

Fig.10. Output voltage of converter with MPPT

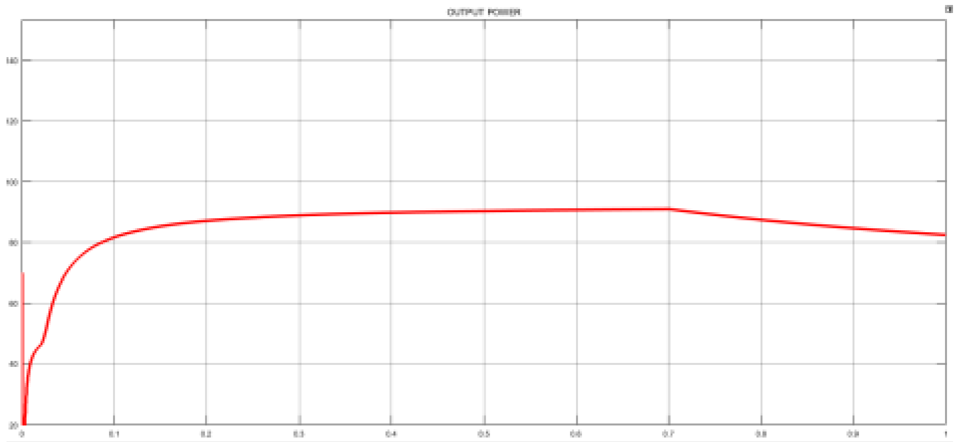

Fig.11. Output power of converter with MPPT when solar irradiation varying from 1000 w/m^2 to 700 w/m^2 and 25 ^{0} C

VII. Conclusion

The design and simulation of High gain DC-DC boost converter with coupled inductor for photovoltaic system with resistive load with and without closed loop operation done. Satisfactory results are obtained. To operate the converter in maximum power point P&O algorithm is employed. The MPPT tracks maximum power with changes in solar irradiation at standard temperature 25 ^{c} C.

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