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Evaluation and Operation of Various DC-DC Converter Topologies with Effective MPPT in a Photovoltaic System

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Abstract: - This article describes the reliable and efficient DC-DC converter for Renewable Energy Sources. The system will function more accurately when the solar panel's irradiance is low. The Maximum Power Point Tracking (MPPT) control algorithm is used to operate the similar system in order to achieve greater efficiency. The characteristics curves for solar panel current v/s voltage (I–V) and power v/s voltage (P–V) are produced by MATLAB simulation. The curves derived from the experiment results are also compared to the simulation curves. A thorough analysis of solar-fed DC–DC converters (Boost, Push-Pull, and Coupled Inductor based converter) is also carried out. The proposed converters are simulated in MATLAB. Simulation results are presented and discussed. Results demonstrate the validity of the models.

Keywords: MPPT, Boost, Push-Pull, Photovoltaic, Evaluation, DC-DC converter.

I. Introduction

When used optimally and effectively, renewable energy sources can produce clean energy when compared to conventional energy sources. The global use of renewable energy sources is being driven by rising consumer demand for electricity and environmental concerns[1]. The best options for generating energy are conventional energy sources plus renewable energy sources. Low output ratings are a characteristic of many renewable energy sources, including solar, wind, and tidal energy. Power Electronics circuits are therefore employed to maximize the use of these sources. Because renewable energy sources have lower voltage and power ratings, different DC-DC converters are crucial in this situation. Compared to other renewable energy resources, solar-based power generation is readily accessible[2]. It is frequently used for solar pumping, lighting, and battery charging, among other things. Utilizing emission-free, renewable energy sources and optimizing solar energy with smart grid technology to produce the most power possible reduces the energy problem[3].

Different MPPT techniques are employed with solar to obtain maximum power from PV modules. This DC-DC converter feed supply to load through Inverter circuit. Solar cell model is as shown in Fig. 1. Conventional Boost converter with Solar PV for step up the voltage level having several problems which are as below[4]

- Switching (ON/OFF) losses
- Voltage stress on power switches
- Reverse recovery Problem
- ZVS, ZCS problem due to Leakage Inductance
- Non-isolated converter

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Push-Pull converter are isolated converter which having a capability of ZVS and ZCS condition with low switching losses. Leakage inductance in primary of isolated transformer is used for obtaining ZCS of power switches and Leakage inductance in secondary of isolated transformer is used in Resonant circuit[5]. Isolated converter obtains high step up voltage through transformer turns ratio but having problem of high stress on power switches, weight problem, leakage inductance Problem etc.

All of the aforementioned problems with the step-up voltage level of the solar PV system can be resolved with coupled inductor-based converters. By employing the Active or Passive Clamp technique, ZVS can lessen the voltage stress on switches caused by leakage inductance. To represent the conversion ratio that lowers the coupled inductor's turn ratio, a voltage extension cell is utilized. With its high voltage gain and low stress on power switches, this converter allows us to use power switches with lower ON state resistance, improving efficiency and lowering conductional losses[6].

The energy of leakage inductor is used to achieve ZVS and ZCS in main and auxiliary switch which result in to reduce switching losses and high switching frequency. Presence of leakage inductance is mainly to avoid the problem of reverse recovery at Diode. The proposed circuit of Coupled Inductor based converter is as shown in Figure-8[7].

II. SOLAR PV MODULE

The equivalent circuit model of a PV cell can be represented in Fig. 1. The relation between voltage and current with respect to different solar irradiations and temperatures for a standard PV source can be expressed by equation (1).

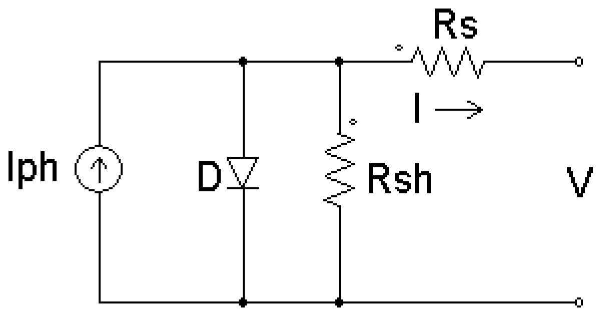


Fig. 1 Solar Cell Model

$$I = I_{PH} - I_S \left[exp^{\left(\frac{q(V+IR_S)}{kT_CA}\right)} - 1 \right] - \frac{(V+IR_S)}{R_{SH}} \quad (1)$$

$$\mathrm{I} = \mathrm{I_{PH}} - \mathrm{I_D} - \mathrm{I_{SH}} \quad (2)$$

Where

I = output current (amperes)

I_{PH} = photogenerated current (amperes)

I_D = diode current (amperes)

I_{SH} = shunt current (amperes).

Where Is is the cell saturation of dark current, q (= 1.6 ×10−19C) is an electron charge, k (= 1.38 ×10−23J/K) is a Boltzmann's constant, Tc is the cell's working temperature, A is an ideal factor, Rsh is a shunt resistance, and Rs is a series resistance.

Electrical specifications which are considered for solar PV module simulation in MATLAB are shown in Table -1.

Table 1 Solarex MSX 60 Specifications (1kW/m^2, 25°C)

Characteristics	Specifications
Typical Peak Power	60W
Voltage at Peak Power	17.1V
Current at Peak Power	3.5A
Short-Circuit Current	3.8A
Open-Circuit Voltage	21.1V
Temperature coefficients of Open-Circuit Voltage	-73mV/°C
Temperature coefficients of Short-Circuit Current	3mA/°C
Approximate effect of Temperature on Power	-0.38W/°C
Nominal Operating Cell Temperature (NOCT)	49°C

The mathematical Equation (1) of solar PV module are simulated in MATLAB simulator. The V-I and P-V characteristics of PV module at constant cell Temperature 25°c with variable irradiation are as shown in Figure-2 and 3. The peak value of product of V and I gives the maximum power point of solar PV module which can be achieved by various MPPT Techniques at various atmospheric conditions.

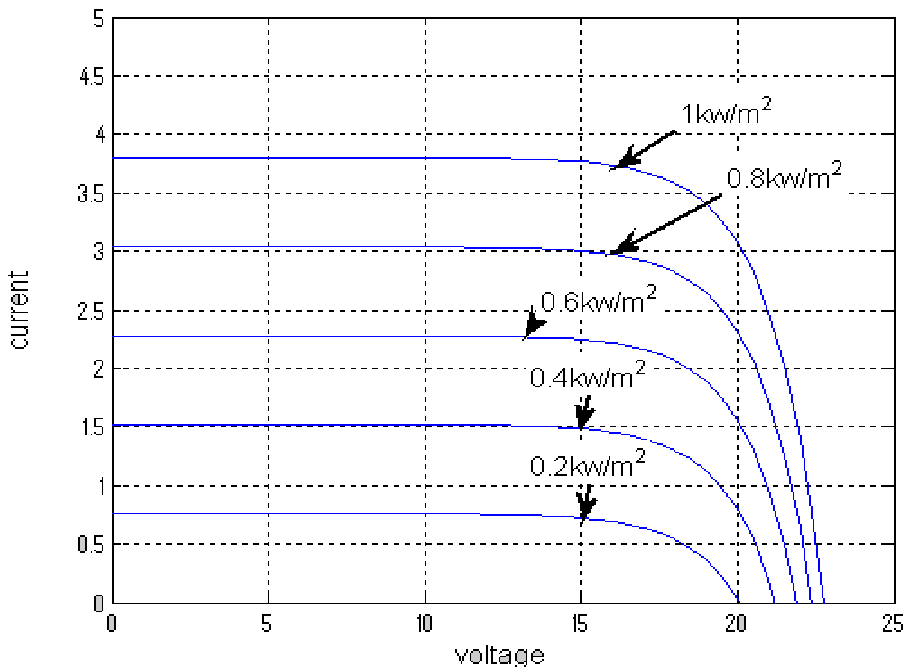


Fig. 2 I-V output characteristics at different Solar Irradiation.

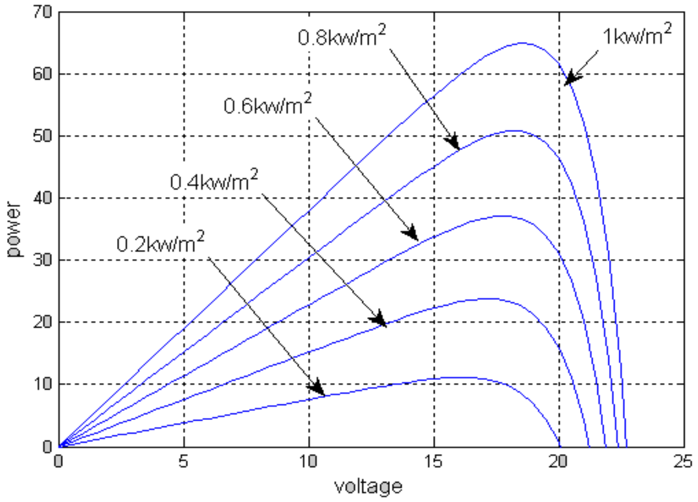


Fig. 3 P-V output characteristics with different solar Irradiation.

III. MPPT TECHINIQUE

Solar PV module generate small power so task of MPPT to extract maximum power from solar PV module at particular voltage condition. According to maximum power theorem maximum power are transfer from source to load when load impedance is equal to source impedance. So here MPPT work as impedance matching. Different DC-DC converter are use as impedance matching devices between input and output by changing the Duty cycle of converter using MPPT. Output voltage depends on duty cycle. So MPPT use to calculate the Duty cycle for obtaining maximum output voltage. Now due to increase in output voltage Power is also increase.

Here we are using P & O MPPT Technique due to its low-cost implementation and low hardware complexity. MPPT Algorithm are the simplest one as shown in Figure-5. In which voltage only sensed and according to change in voltage, change in Power are observe and according to that Duty ratio are changed as shown in Figure- 4 and Table-2.

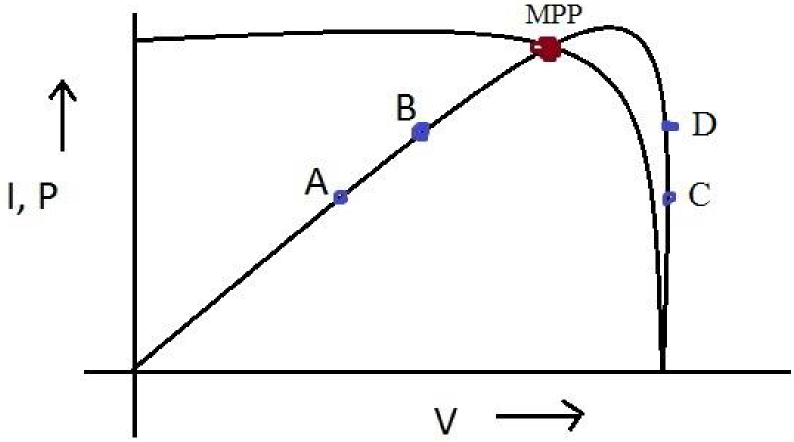


Fig. 4 Characteristic to find MPP

Table-2 Duty cycle from Observation of voltage and power[8]

Pnew – Pold	**Vnew - Vold**	**Duty Cycle**
+	+	+
+	-	-
-	+	-
-	-	+

Voltage corresponding to MPP point are known as Reference voltage point.

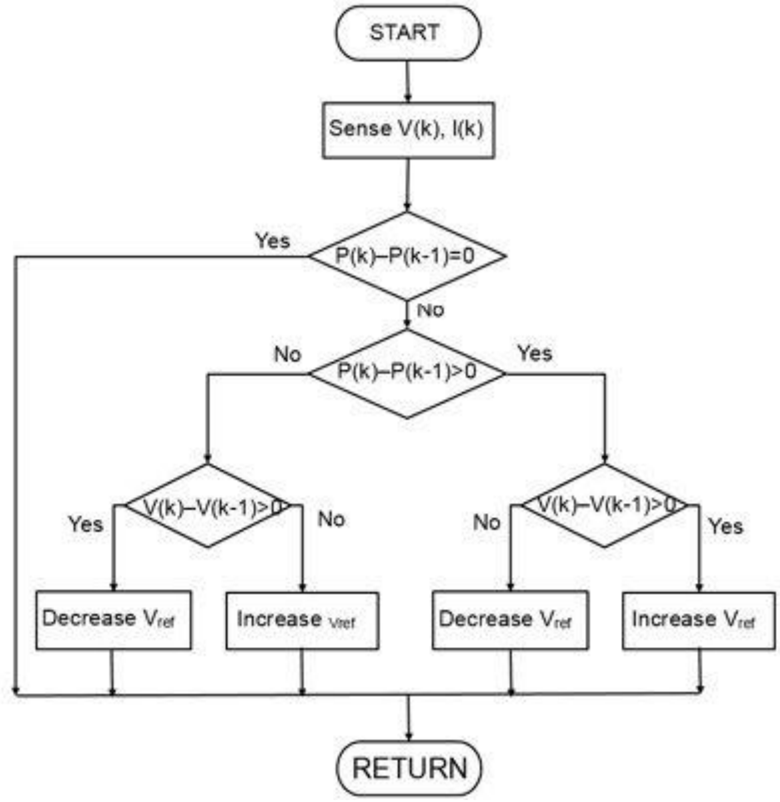


Fig. 5 Algorithm of P&O MPPT Technique

IV. DC-DC CONVERTER DESIGN

Design specification for the DC-DC Converter are taken as given below.

$$Vin = 50 \text{ V}$$

$$Vout = 230 \text{ V}$$

$$Iout = 1.74\ A$$

$$Pout = 400 \text{ Watt}$$

$$fs = 10\ \text{k}Hz$$

(A) Boost converter

The circuit Diagram of Boost converter are shown in Fig. 6. The design of boost converter for given specification are as shown below

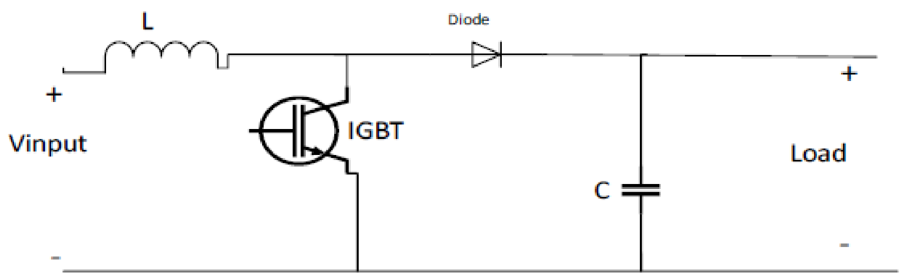


Fig. 6 Boost converter

(1) Duty ratio Calculation

$$D = 1 - \frac{V_{in} * Efficiency}{V_{out}} \tag{3}$$

(2) Inductor Calculation

Allowed some ripple in inductor value to minimize the size and cost of inductor (20-40) % ripple of total output current is allowed for better estimation. Value of “di” for allowable current ripple are given by following Equation (4),

$$di = I_{ripple} * I_{out} * \frac{V_{in}}{V_{out}} \tag{4}$$

So minimum value with allowable current ripple are obtain by following Equation (5),

$$L = \frac{V_{in} * (V_{out} - V_{in})}{di * f_s * V_{out}} \tag{5}$$

(3) Capacitor Calculation

Allowed some voltage ripple in the capacitor for economical design. Generally, 1% ripple in voltage are allowed. Capacitor value calculation are obtained by following Equation (7),

Value of “dv” for allowable voltage ripple is obtain as following Equation (6).

$$dV = V_{out} * \frac{dv_{present}}{100} \tag{6}$$

So, required value of capacitor with 1% allowable voltage ripple are as following Equation (7).

$$C = \frac{I_{out} * D}{f_s * dv} \tag{7}$$

Simulation of boost converter for the given specification is as shown in Fig. 9 in MATLAB. The simulation results for boost converter are given as following in Fig. 10.

(B) Push-Pull Converter Design

The circuit Diagram for the isolated Push-Pull converter are as shown in Fig. 7. The design of Push-Pull converter for the given specification are as given below

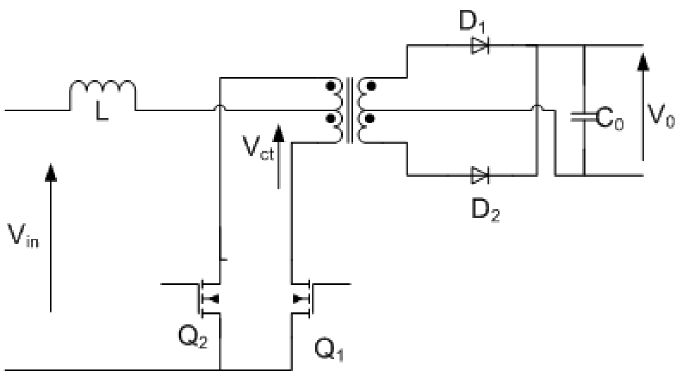


Fig. 7 Push-Pull Converter

(1). Duty cycle calculation

Transformer center tap voltage for given isolated transformer are given by following equation.

i. When both switch are on energy not transfer from primary to secondary but energy stored in inductor are increase linearly through two short circuit switches.

Voltage across switches in off condition are twice the primary voltage of transformer which result high stress produced on switch. So center tap voltage of transform sat by following Equation (8) to reduce the stress on switch.

$$V_{ct} \cong 1.05 * V_{in\,max}, Where\ V_{in} = \frac{2 * L * \Delta I}{t_{off}} \tag{8}$$

ii. When only one switch is on energy are transfer from primary to secondary. The voltage feed from primary to secondary are given by following Equation (9 & 10).

$$V_{ct} = V_{in} + \frac{2 * L * \Delta I}{t_{off}} \tag{9}$$

$$V_{ct} = V_{in} + \frac{1}{2(1 - D)} \tag{10}$$

(2) Transformer turns ratio calculation is as given below Equation (11),

$$n = \frac{Vct}{V_o} \tag{11}$$

(3) Inductor design

Consider the 90% efficiency and allowed 20%ripple current in inductor design for economic size and weight of inductor. The minimum value for the continuous conduction mode are given as below Equation (12). X=0.1 for 20% ripple in current.

$$I_{i\,max} = \frac{P_i}{\eta * V_{in\,min}} \tag{12}$$

Minimum Inductor value Calculations are obtain from following Equation (13).

$$L_{min} = \frac{V_{ct}}{16 * f_s * \Delta I_{max}} \tag{13}$$

(4). Value for Output Capacitor

With 3% voltage ripple. The capacitor value is obtained from following Equation (14),

$$C = \frac{P_o(2D - 1)}{4 * y * V_0^2 * f_s} \tag{14}$$

The simulation for Push pull converter for Solar PV Application with MPPT technique is shown in Fig. 11. The simulation result for Push-Pull converter are as shown in Fig. 12.

(C) Coupled inductor based DC-DC converter

The proposed converter is as shown in Fig. 8. The design of coupled inductor based converter for given specification are as below

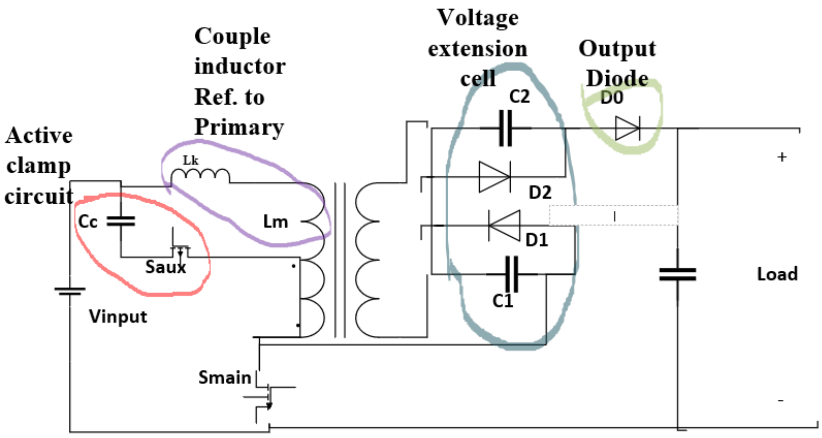


Fig. 8 Coupled Inductor Based Converter

(1) Design of coupled inductor

The minimum value of the coupled Inductor for continuous conduction mode and economical design are given by Equation (15).

$$L_m = \frac{R_{0B} * D * (1-D)^2}{2 * (1+N) * (1+2N-ND) * f_s} \tag{15}$$

(2) Design of output Capacitance

Output capacitance design is based on voltage ripple. Allowable voltage ripple is 0.1% of output voltage for the economic and minimum value of capacitor. To obtain minimum value of output capacitor is calculated as following Equation (16).

$$C_0 \geq \frac{10 * D}{f_s * \Delta V} \tag{16}$$

(3) Design of switched capacitor

Switched capacitor value is depending on output power level as well as voltage ripple. Allowable voltage ripple in switched capacitor is 1.2%. The value of switched capacitor is given as below Equation (17)

$$C_1 = C_2 = \frac{10 * (1-D)}{f_s * \Delta V_{c1}} \tag{17}$$

(4) Design of Clamp capacitor

Clamp capacitor is carry very high ripple current. Value of clamp capacitor is chosen such a way that the resonant period is formed in clamp capacitor are greater than the turn off period of main switch. The value of clamp capacitor is given as below Equation (18).

$$C_c = \frac{(1-D_{min})^2}{\pi^2 * L_k * f_s^2} \tag{18}$$

Simulation of coupled inductor based converter is as shown in Fig. 13. The simulation result of coupled inductor based converter are given as in Fig. 14.

From above three converters coupled inductor based converter is most suitable for renewable energy sources. Due to high voltage gain with reduced voltage stress. Comparison of this converters are given in below table 3.

Table- 3 Comparison of converters

Converter Topology	**Boost converter**	**Push Pull Converter**	**Proposed converter**
MOSFET	1	2	2
Diode	1	4	3
Voltage Gain	$\frac{1}{1-D}$	$\frac{N}{1-D}$	$\frac{1+2N-ND}{1-D}$
Voltage stress on MOSFET	V_0	$\frac{V_0}{N}$	$\frac{V_0-N*V_{in}}{1+N}$
Voltage stress on output Diode	V_0	V_0	$\frac{(1+N)V_0}{1+2N-ND}$
Reverse recovery losses	High	Medium	Small
Conduction losses	High	Medium	Small
Waveform Settling Time	High	Medium	Small

V. SIMULATION AND RESULT ANALYSIS

Simulation of Boost Converter fed by Solar PV source is shown as in fig. 9. To extract maximum Power from Solar PV using P&O MPPT method is used for simulation. Simulation results of Boost converter with and without MPPT are as shown in Fig. 10.

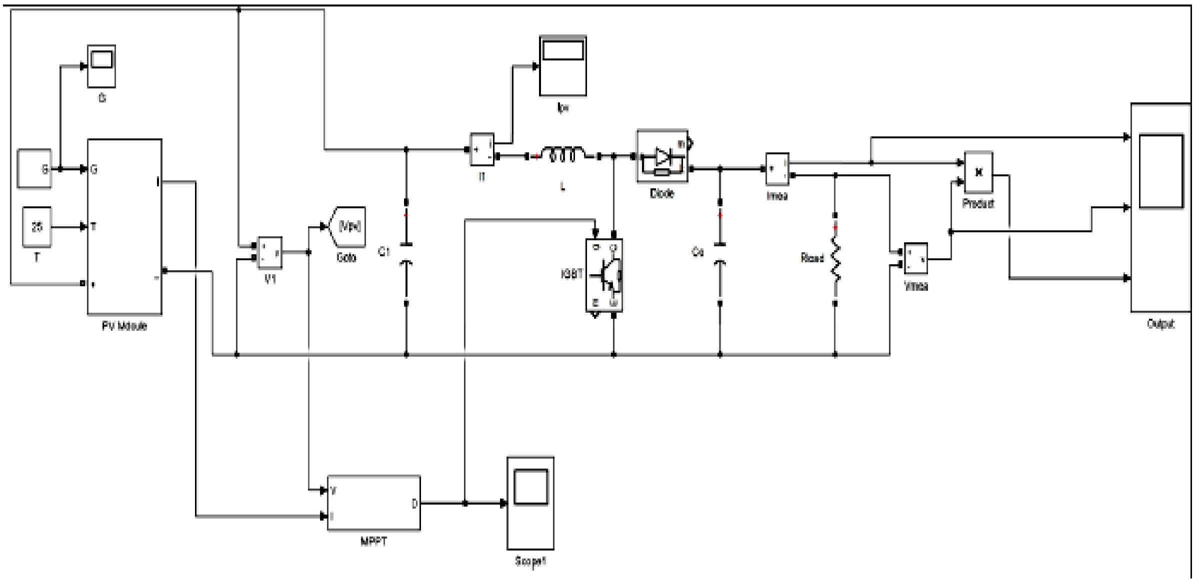
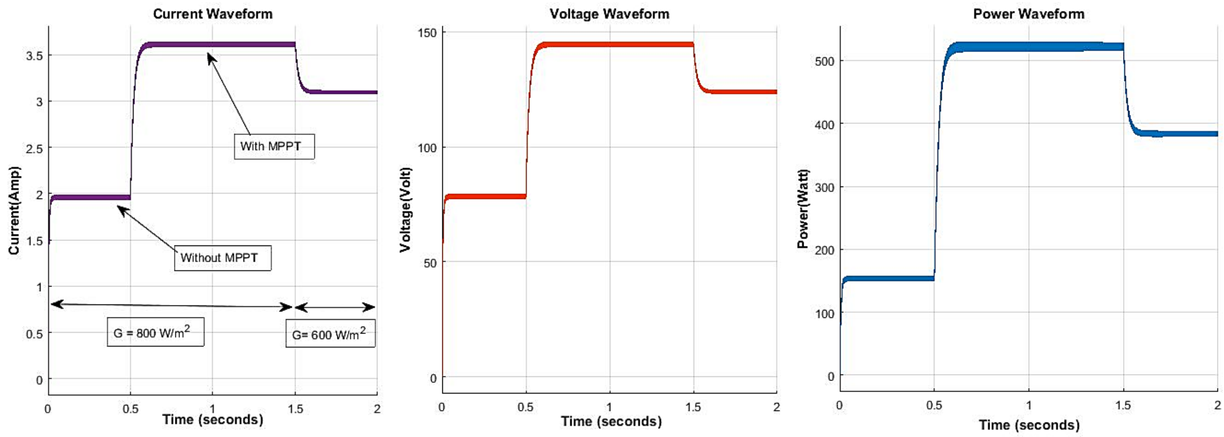


Fig. 9 Simulation of Solar PV Fed Boost Converter with MPPT



(a) Current (b) Voltage (c) Power

Fig. 10 Output Waveform of Solar PV Fed Boost converter with and Without MPPT

Push-Pull converter is simulated to avoid problem appeared in boost converter as shown in Fig 11. Push-pull converter can be used for alternative of Boost converter but as economical point of its having issues related to size, weight etc. Coupled inductor based DC-DC Converter are used as alternative of above converter which can simulate as shown in Fig. 13. Simulation results of coupled inductor based converter are as shown in Fig. 14.

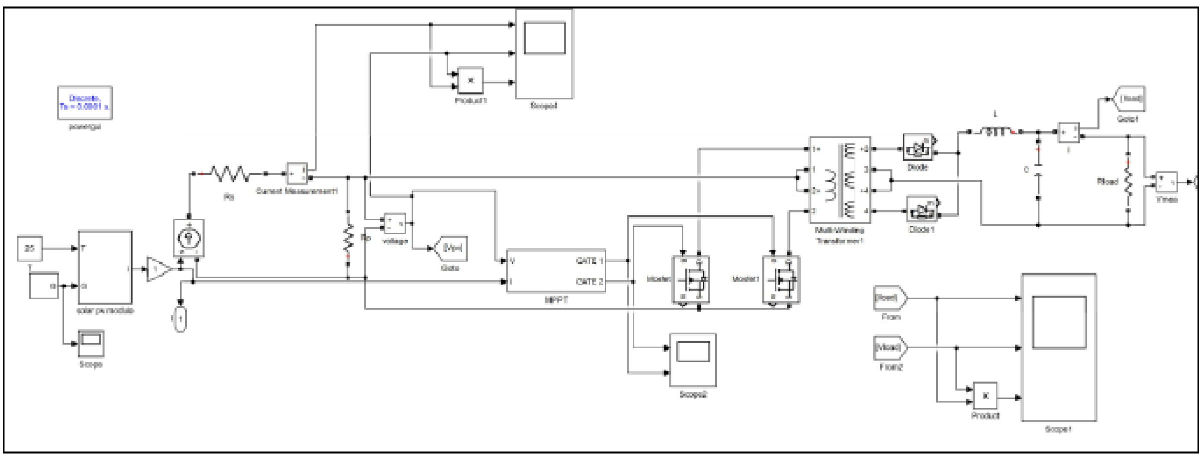
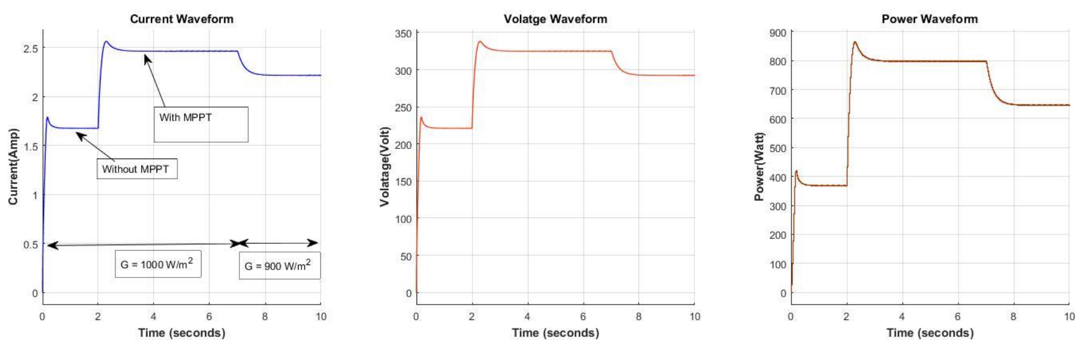


Fig. 11 Simulation of Solar PV Fed Push-Pull Converter with MPPT



(a) Current (b) Voltage (c) Power

Fig. 12 Output Waveform of Solar PV Fed Push-Pull converter with and Without MPPT

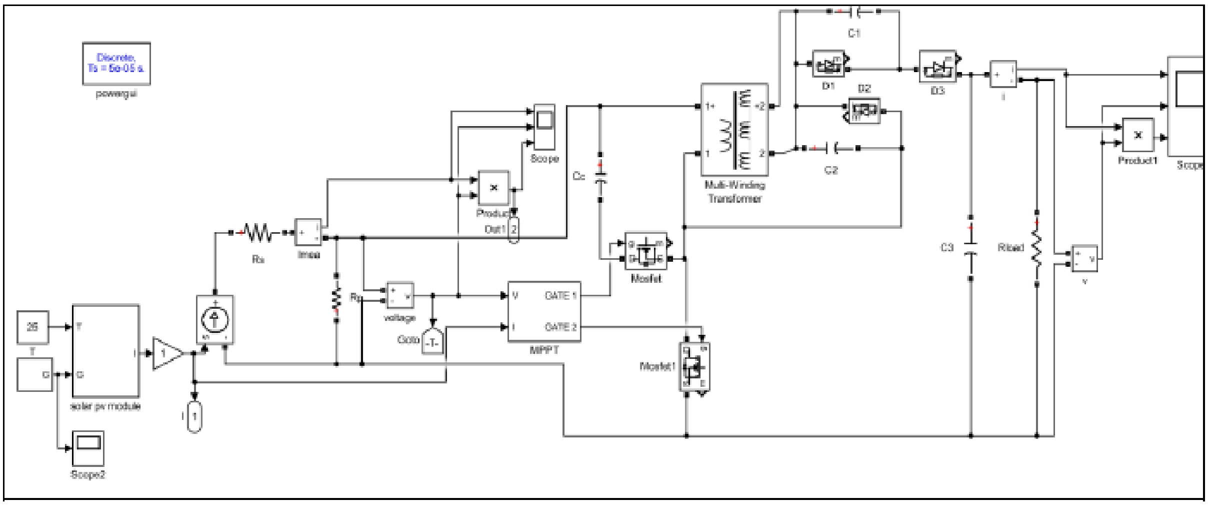


Fig. 13 Simulation of Solar PV Fed Coupled Inductor based converter with MPPT

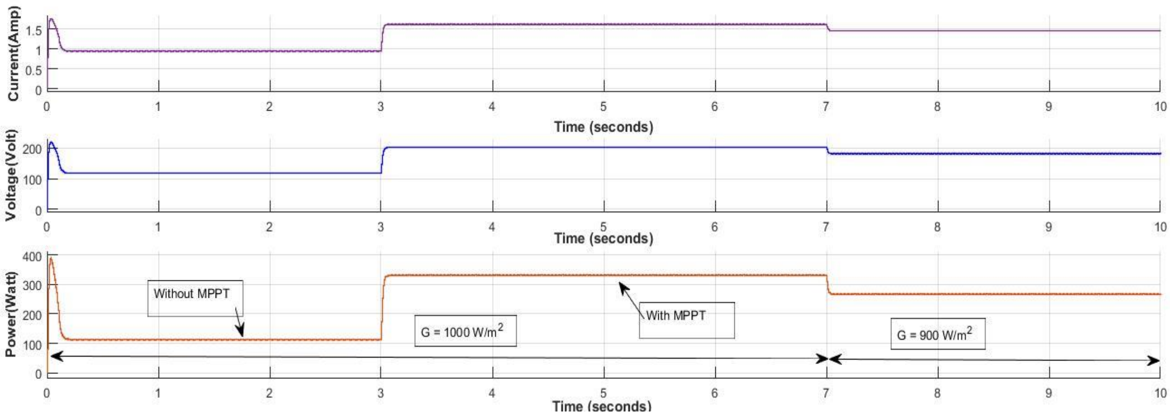


Fig. 14 Output Waveform of Solar PV Fed Coupled Inductor Based converter with and Without MPPT

Output waveform of Boost Converter required 0.39 Sec to obtain the steady state condition as per fig. 10. Push Pull Converter required 0.31 Sec to reach up to steady state value as shown per fig. 12. As compare to above to converter Coupled inductor based converter required least time to reach up to its steady state value are 0.29 Sec as per fig. 14.

VI. CONCLUSION

In this article various converters are presented for application of Distribution Generation. Among all present converters, coupled inductor based converter is the economical and efficient converter for low voltage Renewable energy sources (Solar PV, wind, Tidal etc.). Proposed converter is having high voltage step up capability which can improved by selecting appropriate turns of coupled inductor. This converter is able to reduce stress on a power switches and output diode as compare to conventional Boost converter and Push-Pull converter which result in lower switching losses. Active clamp circuit is used for ZVS of power switches with reduced effect of leakage inductance on switches. The energy stored in leakage inductance is used to neglect the reverse recovery problem of output diode. Hence Coupled inductor converter is economical and efficient converter for DC-DC converter for Solar PV system.

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