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Three-level DC-DC Converter with GSS based MPPT for PV Applications

Hrishikesh Krishnakumar[1],Sruthy Sajith[2], Subha Jacob[3], Remya K P[4]
(1,2,3 - Department Electrical and Electronics Engineering, ASIET, Kalady, INDIA)
(4- Asst. Professor, Department Electrical and Electronics Engineering, ASIET, Kalady, INDIA)

Abstract: *The DC-DC converters are widely used in photovoltaic generating systems as an interface between PV module and the load. These converters must be chosen to be able to match the maximum power point (MPP) of PV module when climatic conditions change with different resistive load values. So DC-DC converters must be used with MPPT controller in order to reduce losses in the global PV system.The nonlinear power characteristic of PV greatly depends on the environmental conditions. Hence in order to draw maximum available power, various algorithms are used with PV voltage/current or both as an input for the maximum power point tracking (MPPT) controller. Non-isolated DC-DC converters with high voltage gain are desired in all photovoltaic (PV) energy conversion systems. The three-level boost converter provides the high voltage transfer which enables the high power PV system to work with low size inductors with high efficiency. The balancing of the voltage across the two capacitors of the converter and MPPT is achieved using a simple duty cycle based voltage controller. Detailed simulation of three-level DC-DC converter topology with GSS algorithm is carried out in MATLAB/SIMULINK platform. The validation of the proposed system is done by the experiments carried out on hardware prototype of 100 W converter with low cost AT'mega328 controller as a core controller. The proposed system will suit as one of the solutions for PV based generation system and will show high performance, such as a conversion efficiency of up to 94%.*
Keywords: *Golden section search, Incremental Conductance, Maximum power point tracking (MPPT), Perturb & Observe, Three-level boost converter*

I. Introduction

The world's energy consumption is increasing by about 3.5% annually and is expected to rise further because of population growth and demanding modern lifestyles. The increased energy demand results in rapid depletion of conventional fossil fuels and adds to the existing consequences of the environmental pollution. Solar energy—for all practical purposes as a source of energy, is inexhaustible, absolutely free (in terms of its availability), quiet, and environmentally friendly. In order to reduce the overall cost of PV systems, therefore, these are utilized effectively with interface to the existing systems through DC-DC converters. The major challenge is to extract the power under varying operating conditions which influence the output voltage extraction of the maximum power from a solar cell turns out to be a vital consideration for optimal system design.

Under fluctuation of climatic conditions, MPP changes and MPPT must adjust the converter duty cycle to track the new MPP. Therefore, the DC-DC converter must be chosen to be able to match the MPP under different atmospheric conditions. When the duty cycle changes as a result of changed climatic conditions, the boundary of the converter design parameters will change.

Isolated converter structures with cascaded configuration enables to achieve high voltage gain. Three level boost converters have significant advantage as compared to conventional boost converter. The size of the inductor is reduced and switch voltage rating is half of the output voltage. This reduces the overall size and improves the efficiency in three-level DC-DC converters.

The fundamental problem addressed by MPPT is to produce maximum output power under a given temperature and irradiance. Various algorithms for MPPT are reported in the literature and used for the efficient energy conversion process. These methods are derivative based and noise sensitive. Golden section search (GSS) based algorithm is having noise and signal fluctuation immunity with fast convergence as compared to many reported MPPT method is proved in this paper. The proposed system is easy to implement on low cost hardware with single current sensor. The PV connected system with three-level converter using GSS based MPPT is presented in Figure1.

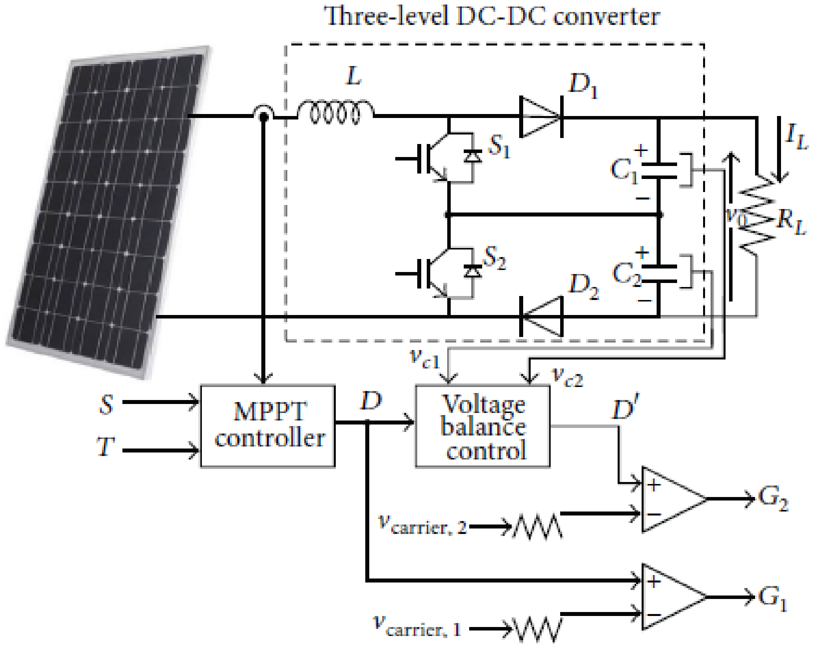

Figure.1 Proposed scheme with PV-fed three-level boost converter

A GSSMPPT based three-level DC-DC boostconverter for PV energy conversion system is presented in this paper with a simple duty cycle based pulse width modulation (PWM) andcapacitor voltage controller. In the three-level boost converterthe switching andreverse recovery losses are less. A hardware prototype of 20W converter is built andthe control is made cost effective using AT'mega based lowcost controller. Both the simulation and hardwareresults are seen to have clear agreement with inherent robustness built using GSS MPPT algorithm when compared to the existing P&O and Incond.

II. Three-Level Nonisolated Dc-Dc Converter

To maintain DC bus voltage constant, in high power rating PV systems with high voltage gain requires boost converter with controller.Interfacing PV with boost converter having three-level with wider range of voltage level is preferred due to reduce input filter size and current ripple cancellation. Three-level boost converter have increased power density, efficiency, and reduction in cost as the switching device's voltage rating is half of the output voltage. As the capacitors C_1 and C_2 are equal, voltage of the center point is $V_o/2$. This alsoreduces the voltage stress across the switching devices in these converters.

2.1Operating Principle

In three-level boost converter V_{c1}, $V_{c2}$are the voltage across the capacitorsC_1, C_2, respectively.The switch S_1 is upper switch and S_2 islower switch and switching frequency is f_s. In this converter,carrier signals $V_{carrier,1}$ and $V_{carrier,2}$ for PWM generation are triangular for both switches but those are in 180° phase shiftto each other.With these carrier signals both switches can beturning ON and OFF at the same time. Therefore, the converter operates in four distinct modes as shown in Figure 2.

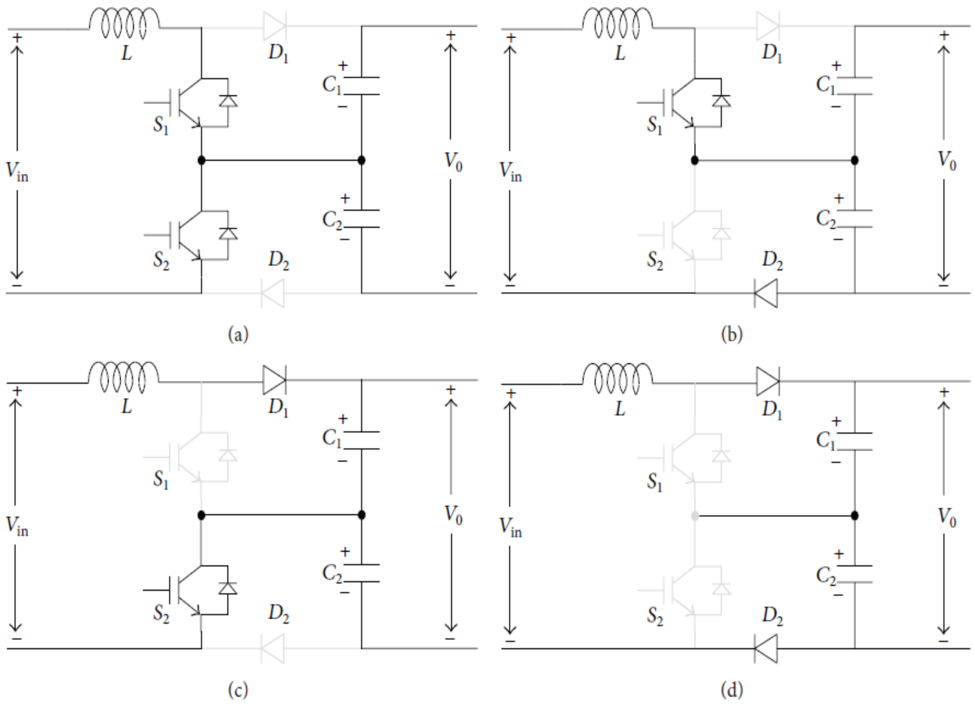

Figure.2 Operating modes of three-level DC-DC converter

(1) Mode 1: both switches are turn ON as shown inFigure 2(a) and the voltage across inductor is (V_L) =input voltage (Vin > 0). In this mode the inductoris always in charging mode and charged capacitorssupply the current to the load.
(2) Mode 2: in thismode S_1 isONand S_2 isOFF as shownin Figure 2(b) and voltage across the inductor is V_L=Vin − Vc_2. In this mode inductor may be in chargingmode or discharging mode and charged capacitor C_1 supplies the current to the loadwhile C_2 is in chargingmode.
(3) Mode 3: in this mode, S_1 is OFF and switch S_2 isON as shown in Figure 2(c) and voltage across the inductor is V_L= Vin−Vc_1. In thismode inductormaybein charging mode or discharging mode and chargedcapacitor C_2 supplies the current to the load while $C_1$is in charging mode.
(4) Mode 4: both switches are turned OFF as shown inFigure 2(d) and inductor voltage is V_L= Vin − Vc_2< 0.Due to boosting operation Vc_1+ Vc_2> Vin, so inthis mode inductor always is in discharging modeand both capacitors are in charging mode and inputsupplies the current to the load.
In modes 1 and 4 inductor is in charging mode anddischargingmode, respectively, but inmodes 2 and 3 inductorcurrents raising polarity depend on the voltages Vc_1 and Vc_2,depending upon the relation between Vin and half of the output voltage ($V_0/2$); there exist two operating regions.
(1) Region 1: Vin > $V_0/2$
(2) Region 2: Vin < $V_0/2$
In region 1, Vin > $V_0/2$; hence V_L= Vin − $V_0/2$ > 0 soinductor current raising polarity is positive in modes 3 and 2as shown in Figure 3(a).Thiswill occur onlywhen duty ratiosof upper switch (D_1) and of lower switch (D_2) are less than0.5; in this region both switches must not be ON at the sametime. In region 2, D_1= D_2> 0.5; input voltage is Vin < $V_0/2$;then, inductor current raising polarity is negative V_L= Vin −$V_0/2$ < 0 in modes 2 and 3 as shown in Figure 3(b). In thisregion both switches must not be OFF at the same time.

III. MPPT Techniques

PV array has non-linear I-V characteristic and output power depends on environmental conditions such as solar irradiation and temperature. The point on the I-V, P-V characteristic curve of PV array where the PV system produces its maximum output power is called as Maximum Power Point (MPP). The purpose of MPPT is to adjust the solar operating voltage close to MPP under changing environmental conditions. In order to continuously gather the maximum power from the PV array, they have to operate at their MPPT despite of the inhomogeneous change in environmental conditions.

There are different types of MPPTs. The conventional MPPTs are generally based on the “hill climbing” method and give an accurate MPP but the time taken to obtain the MPP is larger, thereby resulting in a lesser efficiency. They are also economically favorable.

Modern MPPT techniques are faster and find the MPP with lesser time and by executing a smaller number of cycles as they have the ability to deal with non-linearity and models which are not mathematically defined.

3.1 Perturb & Observe Method

In this method, the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. This is called the perturb and observe method and is most common, but this method can result in oscillations of power output. It is referred to as a hill climbing method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. Perturb and observe is the most commonly used MPPT method due to its ease of implementation. Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted.

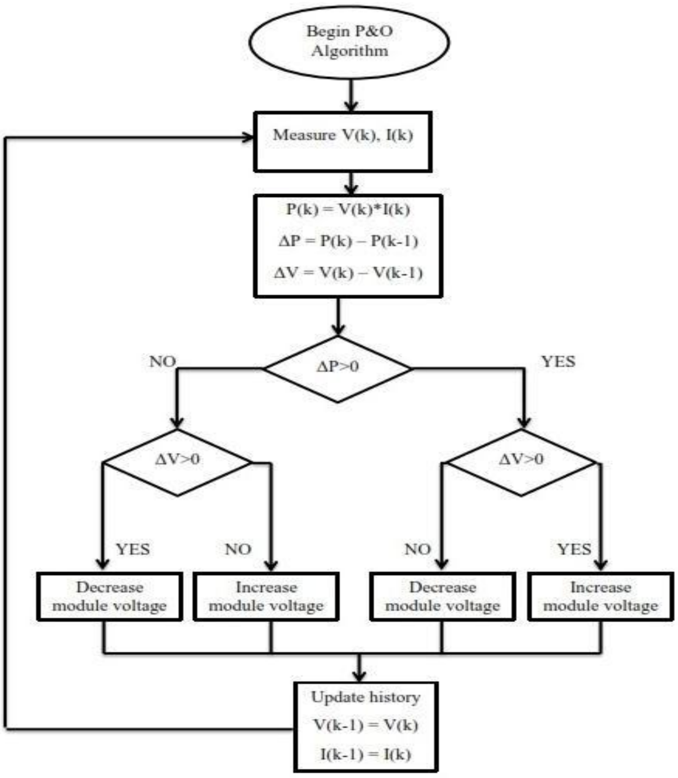

Figure.3 Flowchart of P&O Algorithm

In the P&O algorithm, the inputs of the MPPT system are the power output in watts and the working voltage of the PV module. A perturbation is given to the system and the change in power is observed. If the value of change in power is positive, a similar perturbation is applied in order to check for a higher power. If the change in the power output is negative, then the sign of the perturbation is reversed.

3.2 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 output. This 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.

The incremental conductance method is derived from the P&O method. In P&O method the ratio of change in power by change in voltage (dP/dV) is monitored to track the MPP.
Since,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \quad ;$$

So, The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (Δ I/ΔV).

In In Cond method, the working voltage and current of the PV module is monitored using different sensors. Using these values, the instantaneous conductance (I/V) and the incremental conductance (Δ I/ΔV) are computed and their ratio is compared in order to trace the MPP of the system. In comparison to the P&O method the value of power output is not considered.

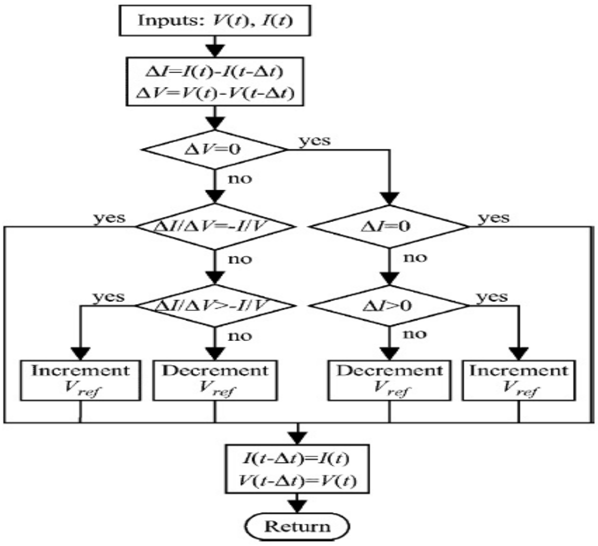

Figure.4 Flowchart of Incremental Conductance

3.3 Golden Section Search Algorithm

The golden section search is a technique for finding the extremum (minimum or maximum) by successively narrowing the range of values inside which the extremum exists is known to exist. The technique derives its name from the fact that the algorithm maintains the function values for triples of points whose distances form a golden ratio. The algorithm is the limit of Fibonacci search for a large number of function evaluations. Fibonacci search and Golden section search were discovered by Kiefer in 1953.

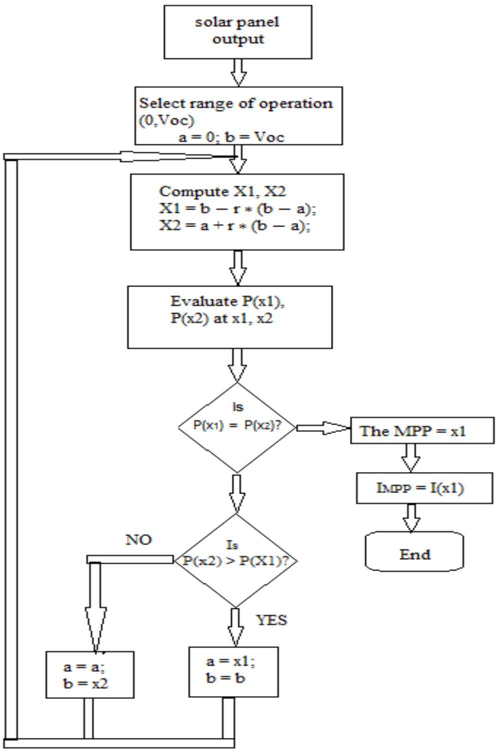

Figure.5 Flowchart of GSS Method

IV. Proposed MPPT Scheme

5.1 Golden Section Search Principle

For a GSS based MPPT for photovoltaic system, the P-V characteristics are the operating characteristics wherein $f(x)$ corresponds to power, whose maximum value has to be tracked. The range of operation is from zero to open circuit voltage (Voc); that is, a = 0 and b = Voc as shown in Figure.6(b). The way of tracking maximum point is shown in Figure.7. The voltage corresponding to the maximum power is obtained and mapped into the V-I characteristics to obtain the current reference.

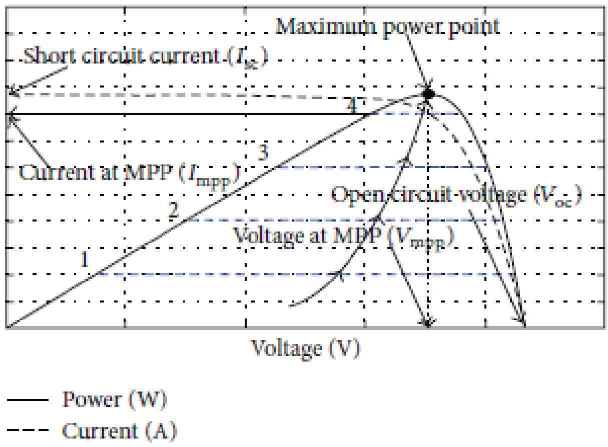

Figure.6 (a) MPPT tracking with GSS algorithm

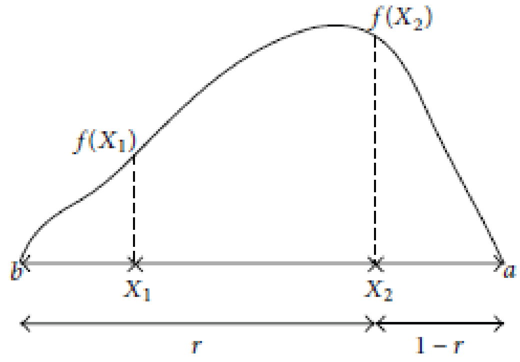

Figure.6 (b)Division of interval on the characteristics

The main aim is to find maximum functional value of (x) within the input interval $[ab]$. Two points $x1$ and $x2$ are selected in the interval $[ab]$ and function (x) is evaluated at these points. Points $x1$ and $x2$ are selected such that each point subdivides interval intotwo parts and length of whole line/length of larger fraction = length of larger fraction/length of smaller fraction. Assume a line segment [0, 1] as shown inFigure 6(b).

Then,
$1/r = r/1-r$;
that is,
$r^2 + r - 1 = 0$; hence $r = 0.618$.
Consider $x1= b-(b-a)$; that is, $x1$ is 0.618 of interval away from b.
Consider $x2= a+(b-a)$; that is, $x2$ is 0.618 of interval away from a.
For a GSS basedMPPT for photovoltaic system, the P-Vcharacteristics are the operating characteristics wherein (x) corresponds to power, whose maximum value has to betracked. The range of operation is from zero to open circuitvoltage (Voc); that is, a = 0 and b = Voc as shown inFigure 6(b). The way of tracking maximum point is shown in Figure 6. The voltage corresponding to the maximumpower is obtained and mapped into the V-I characteristics toobtain the current reference.
The inductor current feedback is used to generate the error by comparing it with the reference current I_{MPP} generatedby the GSS algorithm and it is processed throughproportional (P) controller.
This P controller changes the dutyratio (D) according to error and governs the PV to track themaximum power point on its characteristics. Figure 7 showsthe block diagram of GSS MPPT based reference generator.

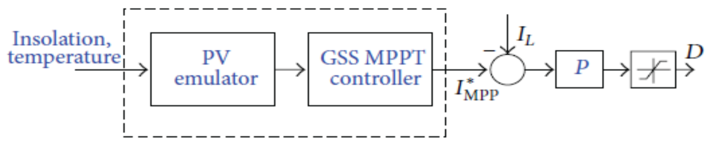

Figure.7 GSS MPPT

5.2Voltage Balancing Control

Eventhough both capacitor values C_1 and C_2 are equal, there is a voltageunbalance between output capacitors (Vc_1 and Vc_2) due tomismatch of tworeal capacitors and equivalent series resistance. The voltagebalancing controller is required tomaintain the equal voltagesacross these capacitors through duty cycle control and isimplemented as shown in Figure 8.G_1 and G_2 are the gatepulses for switches S_1 and S_2, respectively. In the three-levelboost operation of the DC-DC converters with duty ratio relates the fact that the input and output voltage are given as

V_0/Vin=1/(1 − 0.5d_1− 0.5d_2) ;
If d_1= d_2= D, then
V_0/Vin=1/(1 –D);
where the input DC voltage Vin is PV input voltage andvaries with respect to varying environmental conditions.The duty ratio of the boost switch S_1 is determined by theMPPT control (D) and duty ratio of the boost switch S_2 isdetermined by the additional controller. The PI generatesthe duty (D) from the voltage error obtained from (Vc_1− Vc_2).

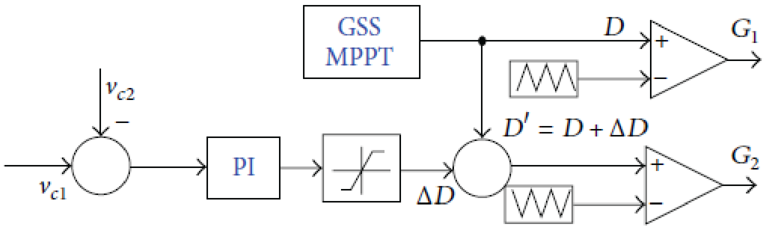

Figure.8 Block diagram of MPPT with voltage balance control

Consider
$\Delta D = Kp$+[Ki(Vc1− Vc2)]/s ;
where Kp+ Ki/s is the transfer function of the PI controller.The duty cycle $D' = D + \Delta D$ controls switch S_2 of theconverter to balance the voltage across the capacitors.

V. Simulation Results

The proposed MPPT method is compared with Perturb and Observe and Incremental Conductance based MPPT techniques.It is observed that the iterations required for the GSS are 4-5 nos. as other methods take 7-8 nos. The simulation circuit for incremental conductance and P&O algorithms are same and is shown in the figure.9. The output waveforms obtained for the both the Incond and P&O are alomost the same. The area between the panel output and converter output gives the gain of the system. The simulation circuit for GSS is shown in figure.13.The proposed scheme is implemented in AT'mega328 controller with GSS based MPPT and duty ratio control.

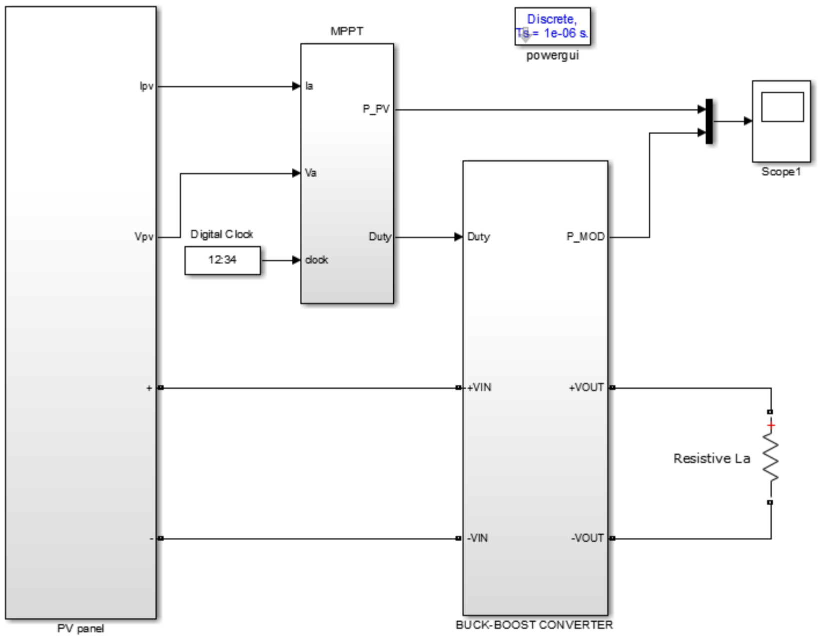

Figure.9. Simulation Circuit for Incond and P&O

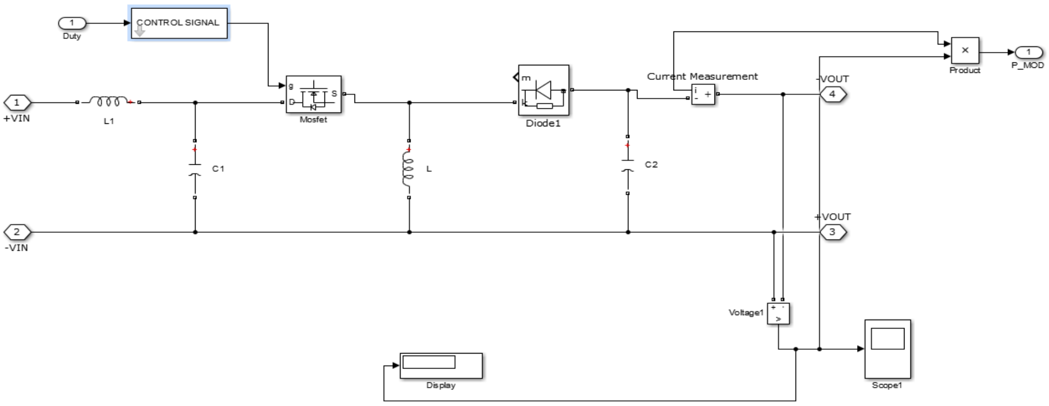

Figure.10. Buck-Boost converter

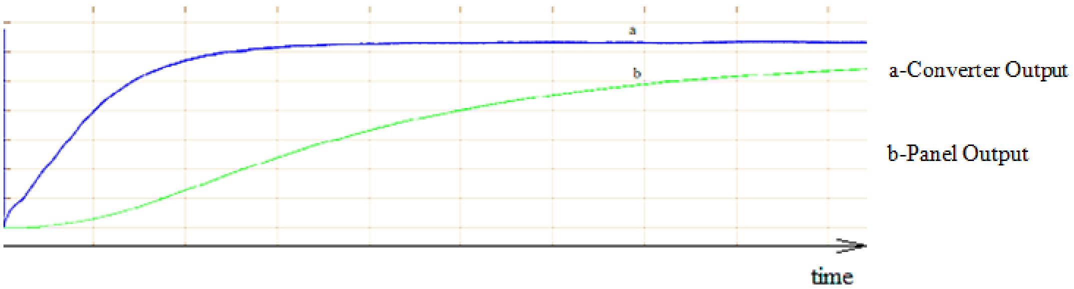

Figure.11.Output Waveform of Incond

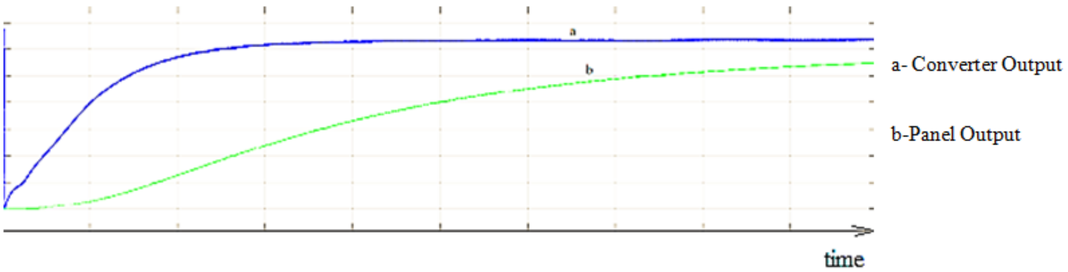

Figure.12. Output Waveform of P&O

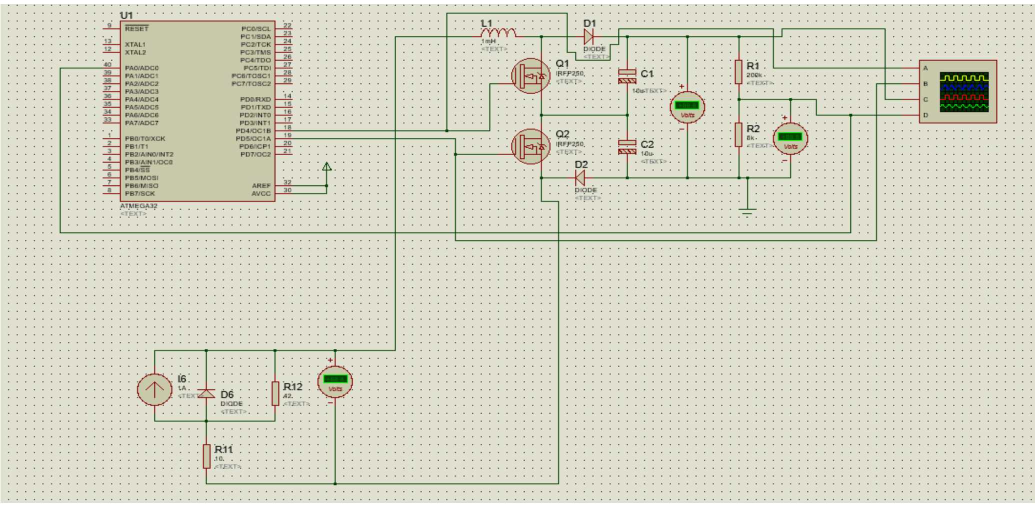

Figure.13. Circuit diagram for implementation of GSS

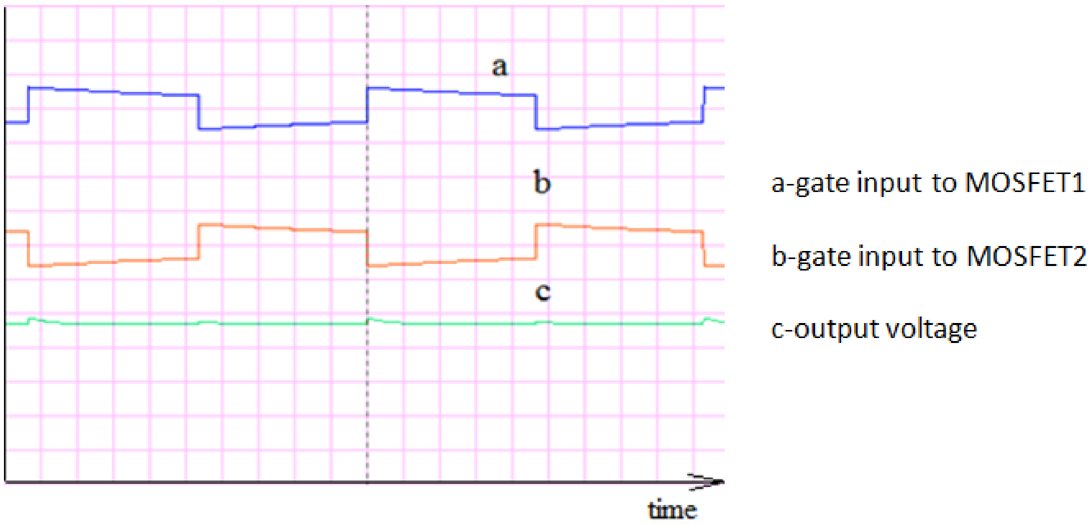

Figure.14.Output waveforms of GSS

VI. Conclusion

The three-level boost converter is used to interface the PV system for maximization of the power extraction. Various maximum power point tracking algorithms- P&O, InCond and Golden Section Search were compared in the simulation and found that GSS algorithm shows the better dynamic response with the faster convergence without any oscillations while tracking. So the hardware was implemented using GSS algorithm. The voltagebalancing of the DC bus is executed through the PI controller and performance is observed to be satisfactory.

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