Control Method for Parallel DC- DC Converters used in Standalone Photovoltaic Power System

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***Abstract*— The increasing trend in integrating renewable energy sources into microgrids presents challenges from the viewpoints of reliable operation and control. Paper gives outline of droop based current sharing issues of parallel DC-DC converters in standalone photovoltaic system. This paper also presents simulation of incremental conductance maximum power point tracking (MPPT) used in solar array power systems. The main drawbacks of parallel converters are poor current sharing and voltage drop. The paper describes about instantaneous droop calculation using droop index to improve the power sharing performance. The control technique is simulated using MATLAB/SIMULINK in PV system with MPPT and case study has been done with different condition.**

Keywords—Microgrid; droop method; incremental conductance (Income); maximum power point tracking (MPPT); photovoltaic (PV) system)

I. INTRODUCTION

Expensive technologies and global environmental damage retrieval techniques has led to a global scenario which is inclined towards generating clean and eco-friendly energy. Due to the rate of depletion of conventional energy sources, countries have begin to emphasize on generating power through renewable sources such as wind energy, solar energy, etc. For example a nation like India has set forth a mission to deploy 20,000 MW of grid connected solar power by year 2022. The growth of renewable energy has changed energy business in India. In many ways, it is having a leading role in the democratized energy production and consumption in the country. Of all the renewable energy sources available, solar cells have the least environmental impacts. Electricity produced from photovoltaic (PV) cells does not result in environmental pollution, deplete natural resources, or endanger living being [1].

Over many decades, the centralized power grid is one way electricity flow, generated by large, remote power plants and distributed over miles of transmission lines to homes and businesses. In recent years the system's shortcomings are increasingly evident. The conventional grid is highly dependent on planet-warming fossil fuels. Due to the upcoming of negative issues there is departing from the traditional system and introduced a new model called Microgrid. A microgrid is simply an independent system that supplies power for a specific physical entity, such as a shop, office building or factory. It can accept power from all kinds of energy sources. A microgrid is defined by the ability to generate power using renewable energy sources near or at the point of consumption independent of other generators. Microgrids usually make sense in areas having high energy prices, in remote areas (such as islands) or facilities, such as military or experimental installations that cannot risk losing power, etc. Microgrid, also named as minigrids, can be operated in islanded or grid connected mode. Compared to AC, DC microgrids are very reliable highly efficient, economic and easy to control.

The main problem faced by the DC Microgrid is that when converters are parallel connected the output voltage from converter won't be constant always. [2]- [8] Main reason for this variation is due to change in load and input power and also feedback voltage and current. Even a small mismatch of output voltage will initiate circulating current and difference in current sharing will cause an overload to the converters and also variation in power sharing. The converter with higher output voltage will give higher power. One of most popular control technique for proper sharing is droop control method. This paper mainly focus on the voltage control and power sharing of the converters using droop index and also maximum power point tracking for better performance.

The droop control method is a decentralized control technique in which each converter is controlled based on the output current [7]. This paper explains the importance of cable resistance in load sharing. In existing methods the droop used for voltage control is fixed which a major drawback [5]. An instantaneous droop is calculated to overcome this drawback which can improve the voltage control to larger extend.

The droop control method is local control method that relies on internally or externally added resistance of the parallel connected modules to maintain a relatively equal current sharing between the modules. Generally, the droop method is very simple and easy to implement, and it does not require any communication. However, fixed droop method achieves the current sharing accuracy but leads to poor output voltage regulation but instantaneously produced droop can adaptively controls the reference voltage of each module.[10]-[12] This greatly improves the output voltage regulation and the current sharing of the conventional method.

The solar cell efficiency depends on factors such as temperature, insolation, spectral characteristics of sunlight, dirt, shadow, and so on. Due to fast climatic changes such as cloudy weather there will be changes in irradiance on solar panels and increase in ambient temperature can reduce the PV array output power. PV cell produces energy depending to its operational and environmental conditions. Maximum power point tracking (MPPT) is a concept put forward to improve the efficiency of PV. All MPPT methods follow similar goal of maximizing the PV array output power by tracking the maximum on all operating condition. Analysis study and case study of the droop control method for voltage regulation and MPPT method is explained.

II. PV MODULE WITH MPPT

A. Solar cell

The basic structural unit of solar module is PV cells. A solar cell converts energy in photons of sunlight into electricity by means of photoelectric phenomenon found in certain types of semiconductor materials such as silicon and selenium. A single solar cell can only produce a small amount of power. To increase the output power of a system, solar cells are generally connected in series or parallel to form PV. The main equation for the output current of a module is

$$I_0 = n_p I_{ph} - n_p I_{rs}\left[\exp\left(k_0 \frac{v}{n_s}\right) - 1\right] \quad (1)$$

where I_o is the PV array output current, v is the PV output voltage, Iph is the cell photocurrent that is proportional to solar irradiation, Irs is the cell reverse saturation current that mainly depends on temperature, k_o is a constant, *ns* represents the number of PV cells connected in series, and *np* represents the number of such strings connected in parallel.

$$I_{ph} = [I_{scr} + k_i(T - T_r)]\frac{S}{100} \quad (2)$$

Where I_{scr} cell short-circuit current at reference temperature and radiation; k_i short-circuit current temperature coefficient; T_r cell reference temperature; *S* solar irradiation in mill watts per square centimeter. Moreover, the cell reverse saturation current is computed from

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{KA}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \quad (3)$$

Where T_r cell reference temperature; I_{rr} reverse saturation at T_r; E_G band-gap energy of the semiconductor used in cell. A maximum power point tracker has high-efficiency DC-DC converter, which functions as an optimal electrical load for photovoltaic cell, most commonly used for solar panel and converts the power to a voltage or current level which is more suitable to whatever load the system is design to drive. PV cells have a single operating point where the values of current and voltage result in a maximum power output for the cell. Maximum power point tracker is basically an electronic system that controls the duty circuit of the converter to enable the photovoltaic module operate at maximum operating power at all condition. The advantages of MPPT regulators are greatest during cloudy or hazy days or even cold weather.

There are different types of maximum power point tracking methods developed over the years and they are (1) Perturb and observe method, (2)Incremental conductance method, and (3) Artificial neutral network method.

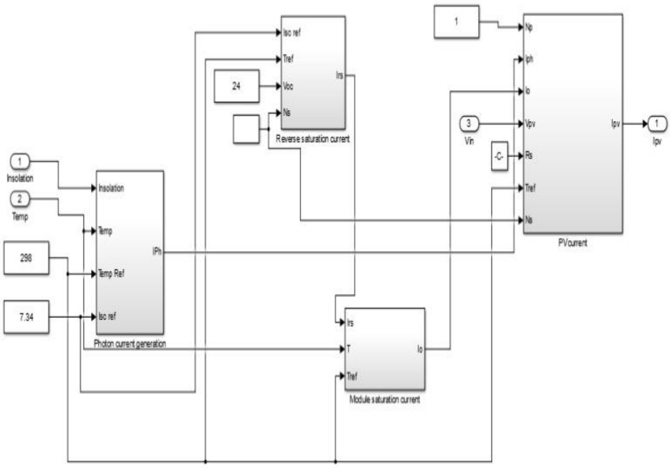

Fig 1. Simulink model of solar panel

B. Incremental conductance method

In incremental conductance method is always adjusted according to the MPP voltage, it is based on the incremental and instantaneous conductance of the PV module. The IC can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dl/dV and –I/V This relationship is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP. This algorithm has advantages over P&O in that it can determine when the MPPT has reached the MPP, where P&O oscillates around the MPP. Also, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than P and O.

The maximum output power,

$$P_{MPP} = V_{MPP} I_{MPP} \quad (4)$$

is obtained by differentiating the PV output power with respect to voltage and setting the result to zero.

Applying the chain rule for the derivative of products yields to $\partial P/\partial V = [\partial(VI)]/\partial V$ At MPP, as $\partial P/\partial V=0$ The above equation could be written in terms of array voltage V and array current I as $\partial I/\partial V = - I/V$ The MPPT regulates the PWM control signal of DC-DC boost converter until the condition: $(\partial I/\partial V) + (I/V) = 0$ is satisfied. In this method the peak power of the module lies at above 98% of its incremental conductance.

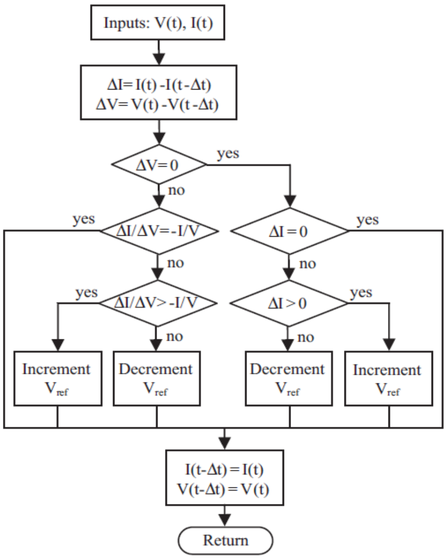

Fig 2. Incremental conductance Algorithm

III. PARALLEL DC- DC BOOST CONVERTER

The boost type DC-DC converters are used in applications where the required output voltage needed to be higher than the source voltage. The control of this type DC-DC converters are more difficult than the buck type where the output voltage is smaller than the source voltage. The difficulties in the control of boost converters are due to the non-minimum phase structure since, the control input appears both in voltage and current equations, from the control point of view the control of boost type converters are more difficult than buck. Here we are using PI controlled boost converter.

The integral term in a PI controller causes the steady-state error to reduce to zero, which is not the case for proportional-only control in general. The lack of derivative action may make the system steadier in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs. Without derivative action, a PI-controlled system is less responsive to real (non-noise) and relatively fast alterations in state and so the system will be slower to reach set-point and slower to respond to perturbations than a well-tuned PID system.

TABLE I. DC-DC BOOST CONVERTER PARAMETERS

Parameters	*Values*
Output power	96
Output voltage	48
Filter inductor	710 μH
ESR of filter inductor	0.03Ω
Filter capacitor	2220μF
ESR of filter capacitor	0.05Ω
Nominal switching frequency	10 kHz

A. *Mathematical Analysis Of Circulating Current For Two Parallel Connected Converters*

When converters are connected in parallel and if there is change in power output or load, then this will cause mismatch in converter output voltage which will cause circulating current. Circulating current will increase the flow current through the switches which will increase the power electronic switch ratings and loses and cause overload to converters. This section explains load current sharing and circulating current issues for parallel dc–dc converters connected to a low-voltage dc microgrid. Fig.2 shows simplified diagram of two parallel connected DC – DC converters. Output voltages, cable resistance and output currents of converter- 1 and converter-2 are represented using V_{DC1}, V_{DC2} , R_1 and R_2, I_1 and I_2 respectively. I_{C12} is the circulating current component from converter-1 to converter-2 and load current component from converter-1 is $I_1{}'$.

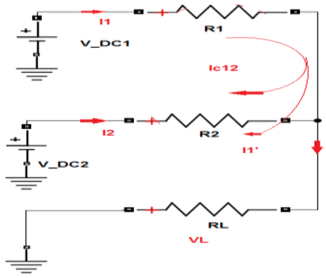

Fig 3. Parallel boost converter equivalent circuit

By applying Kirchhoff's voltage law, the expression for output converter currents can be derived from equation and circulating current can be calculated.

$$V_{DC1} - I_1 R_1 - I_L R_L = 0 \quad (5)$$

$$V_{DC2} - I_2 R_2 - I_L R_L = 0. \quad (6)$$

The expression for output converter currents I_1 and I_2 can be derived from equation (5) and (6) and circulating current is given as:

$$I_1 = \frac{(R_2+R_L)V_{DC1}-(R_L)V_{DC2}}{R_1R_2+R_1R_L+R_2R_L} \quad (7)$$

$$I_2 = \frac{(R_1+R_L)V_{DC2}-(R_L)V_{DC1}}{R_1R_2+R_1R_L+R_2R_L} \quad (8)$$

$$I_{C12} = \frac{V_{DC1}-V_{DC2}}{R_1+R_2} = \frac{I_1 R_1 - I_2 R_2}{R_1+R_2} = \frac{I_1-I_2}{2} \quad (R_1 = R_2) \quad (9)$$

B. *Voltage Regulation and circulating current control By Fixed Droop Method*

This section explains converter voltage regulation and minimization of circulating current by adding a series resistor, R_{droop} to each converter output as shown in Fig.2. R_{droop} is implemented using virtual impedance method. Fig4. By adding R_{droop1} and R_{droop2} the current sharing can be controlled and thus circulating currents can be minimized to some extent. This can be done by taking output current from converters and multiplied with corresponding

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R_{droop}. Then the resultant signal is subtracted from the reference voltage of each corresponding converter give new voltage reference signal .

$$V_{DCnew} = V_{DC} - I\, R_{droop} \quad (10)$$

But this method has still got drawbacks as it's a fixed value and therefore the voltage regulation will be poor.

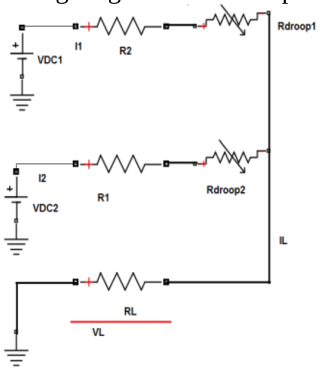


Fig 4. Parallel boost converter with Rdroop

C. Adaptive Droop Control Method

Instantaneous method for droop calculation for voltage regulation and circulating current minimization is explained in this section.

As we have seen in above equation (9) in two parallel converters, circulating current directly proportional to the current sharing difference. If the current sharing is equal then the resultant circulating current becomes zero. There will constant output voltage from converters. But simultaneous insertion of the series resistor will cause additional power loss in the system and it will leads to reduction in the load voltage. R_{droop1} and R_{droop2} are corresponding droop value of each converter. The output power loss can be expressed as,

$$P_{loss} = {I_1}^2 (R_1 + R_{droop}) + {I_2}^2 (R_2 + R_{droop}) \quad (11)$$

Calculation of droop values based on the proposed figure-of-merit called droop index. The droop index is considered function of normalized current sharing difference and output power losses based on the need of voltage regulation issues and are given as

$$\text{Droop Index} = min \quad [\tfrac{1}{2} |I_1 - I_2|_N + (P_{loss})_N] \quad (12)$$

The current sharing and power loss equation can be modified in terms of parameters of second converter by introducing new variables *x*, *y* and *m* and given as

$$x = \frac{V_{DC1}}{V_{DC2}},$$

$$y = \frac{R_1}{R_2},$$

$$m = R_2 + R_{droop2}$$

$$|I_1 - I_2| = \left| \frac{y(R_2 + R_{droop2} + R_L)V_{DC2} - 2(x-1)V_{DC2}R_L}{m^2 y + m R_L (y+1)} \right| \quad (13)$$

Using the modified equation of circulating current and power loss the minimum droop index is calculated. R_{droop} value for corressponding converter is selected in such way that R_{droop} varied from zero and corresponding droop inex value is noted and R_{droop} value for minmum droop index is selected for further procedure. For the calculation of minimum droop index by varying R_{droop}, the product of converter output current and R_{droop} should not increase the maximum allowable voltage deviation (± 5% nominal voltage).

R_{droop2} value for minimum droop index value of converter2 is droop value . Now the droop value for converter 1 can be calculated using

$$R_{droop1} = \left[\frac{R_1}{R_2}\right] R_{droop2} \quad (14)$$

The calculated droop value is may not be enough for voltage regulation. Therefore fine tuning of value is required to make the output voltage same but since the value is positive further increase will cause poor load voltage. To avoid this problem R_{droop} shifting is done. R_{droop} Shifting is done bases of the converter output value.

If the difference between converter output voltage is positive then ie;

$V_{DC1} > V_{DC2}$ then,

$$R_{droop1new} = R_{droop1} + (k_1 * I_L)$$
$$R_{droop2new} = R_{droop2} - (k_2 * I_L) \quad (15)$$

If the difference between converter output voltage is negative then ie;

$V_{DC1} < V_{DC2}$ then ,

$$R_{droop1new} = R_{droop1} - (k_2 * I_L)$$
$$R_{droop2new} = R_{droop2} + (k_1 * I_L) \quad (16)$$

And if the converter output voltage values are equal then the corresponding droop values same as before. The droop correction factor $k_1$and k_2 (0.001 and 0.02 respectively) should be selected such that $k_1 < k_2$ to maintain load voltage within the limit.

IV. SIMULATION

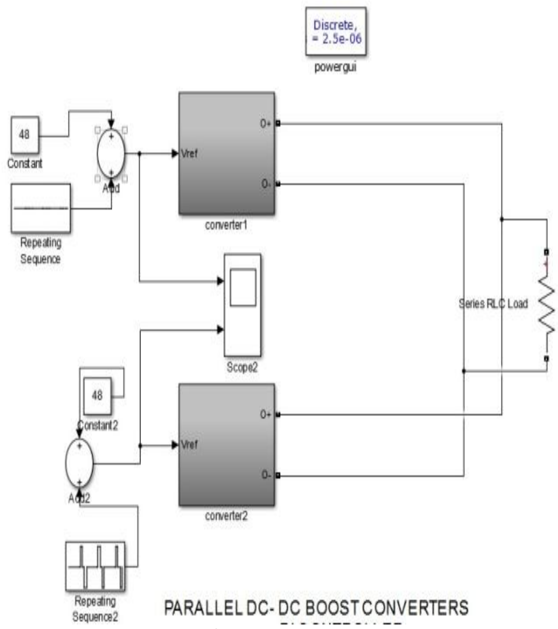


Fig 5. Simulink of parallel converters without droop

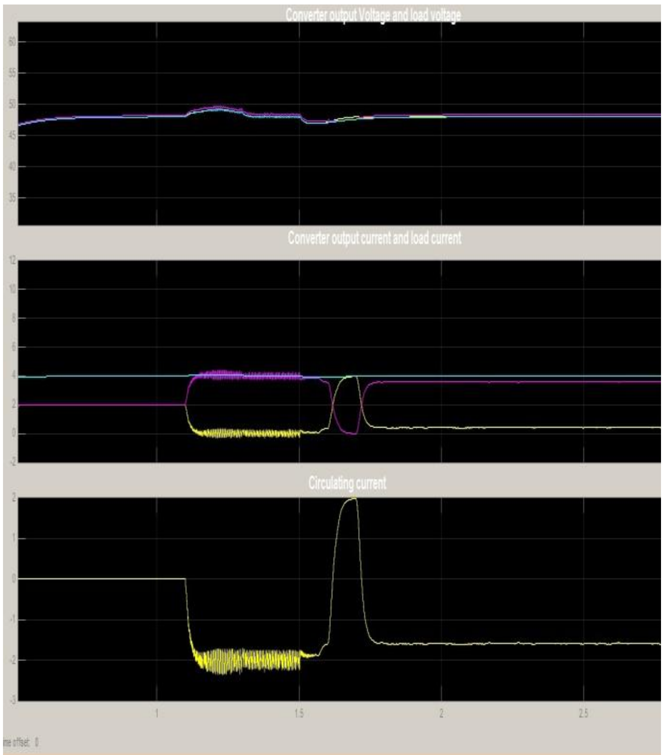


Fig 6.Simulation Result without Rdroop (a) Converter output Voltage and load voltage (b) converter output current and load current (c) Circulating Current.

To check the performance of the droop method in different cases, two parallel DC –DC boost converters (24V-48V) with solar energy as source has been simulated using MATLAB/SIMULINK. The output cable resistance is 100mΩ for each converter. The control algorithm is verified for the following cases, (i) Step change in output voltage of any one converter with both converters with same cable resistance (a) without droop control Fig.5. (b) with R_{droop} control method.Fig.7

TABLE II. SIMULATION RESULTS WITHOUT DROOP

Time	Output values		
	Vdc1,Vdc2,Vl (V)	I1,I2,Il (A)	|Ic12| (A)
0 -1.101	48,48,47.7	2,2,4	0
1.101-1.3	48,48.48,47.65	0.1,3.9,4	1.9
1.3 – 1.501	48,48,47.7	2,2,4	0
1.501 -1.7	48,47.52,47.6	3.9,0.1,4	1.9

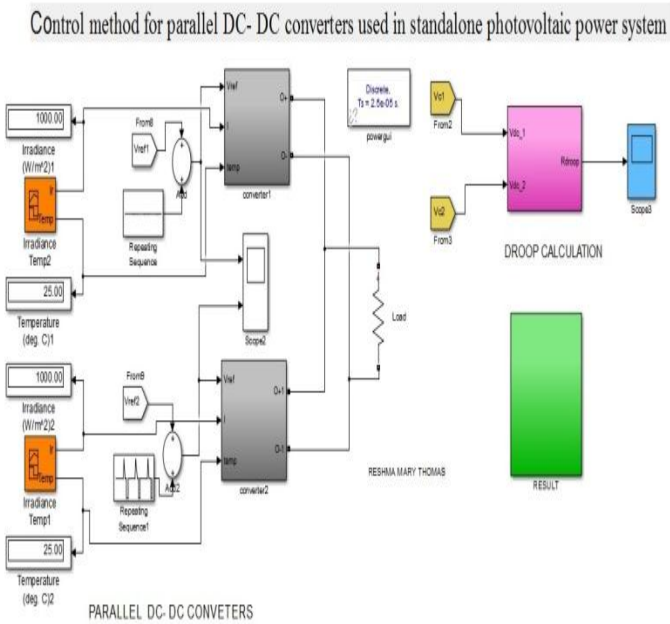
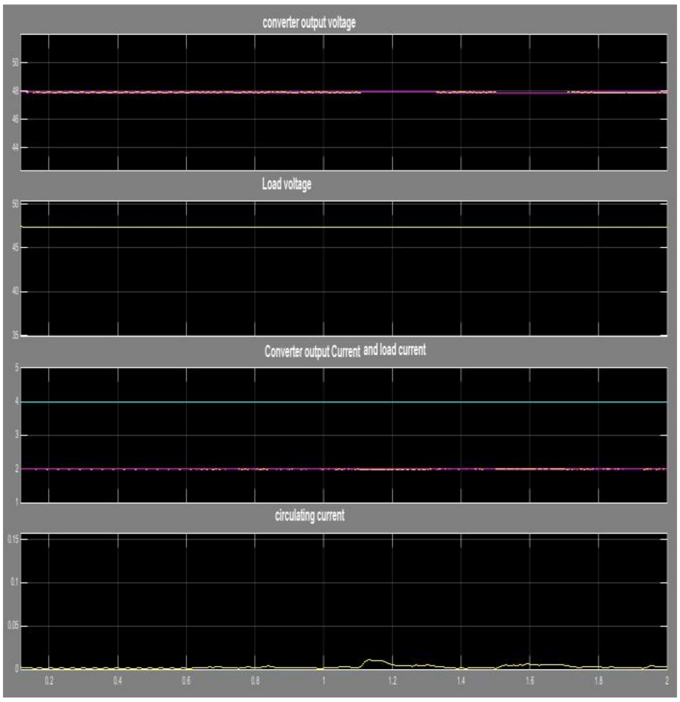


Fig 7. Simulink model with droop

Initially up to 1.101s the simulation is done with nominal value, 48V. During time 1.101-1.3s the converter2 voltage value is increase by 1% of nominal value, 48.48V and at time 1.301s the voltage is brought back to 48V. Then again during time 1.501-1.7s the value is decreased by 1 % of the nominal value, 47.52 V. Then for the rest of the simulation time the voltage of converter is again brought back to nominal voltage. From simulation result of without droop, it can observe that the sharing is not proper and has a current sharing error of 25%.

For simulation with novel droop control method, the R_{droop1} and R_{droop2} values are calculated as 0.2Ω and still there is mismatch output converter voltage.After fine tuning of R_{droop} voltage is not regulated completely. Then

Fig 8.Simulation Result with adaptive droop control (a) Converter output Voltage (b) load voltage ,(c) converter output current and load current and (d) Circulating Current.



instantaneous value of $R_{droopnew}$ is introduced with droop shifting which will improve the current sharing and the output
converter voltage constant. From the above simulation studies, it can be seen that droop control method gives proper load sharing with minimum circulating current and improves load voltage.

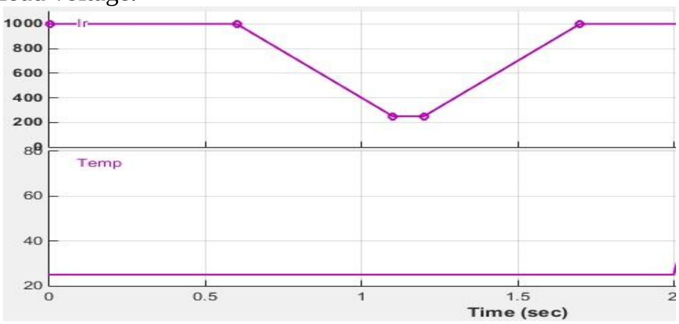


Fig 9. Solar irradiance and temperature

TABLE III. SIMULATION RESULTS WITH DROOP

Time	Output values		
	Vdc1,Vdc2,Vl (V)	I1,I2,Il (A)	|Ic12| (A)
0 -1.101	48,48,47.9	2,2,4	0
1.101-1.3	48,48.48,48.1	1.9,2.01,4	0.1
1.3 – 1.501	48,48,47.9	2,2,4	0
1.501 -1.7	48,47.52,48.1	2.01,1.9,4	0.1

V. CONCLUSION

The performance of droop control method for parallel DC-DC converter used in standalone photovoltaic system is studied in different cases. The entire energy conversion system has been designed in MATLAB/SIMULINK environment. Incremental conductance method of MPPT is used to track maximum output. The R_{droop} values are calculated considering the effect cable resistance and implemented using virtual impedance method. For different irradiation of PV array the droop control is tested and verified. Based on the instantaneous condition the new R_{droop} value is introduced into the system, which will minimize the circulating current and gives proper sharing. This droop control technique can be used in any number of parallel connected converters.

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