

DC Microgrid Architecture and Control for Integration of Photovoltaic System

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Abstract— Microgrid is one of the new conceptual systems for integrations of various distributed generations (DGs). Most of the microgrids adopt AC distribution systems, while DC microgrids are proposed and researched for better connection with DC output type sources such as photovoltaic (PV) system, fuel cell, and battery storage system. Moreover, if loads in the system are supplied with DC power, then conversion losses from sources to loads are eliminated compared with AC microgrid. DC microgrid is a novel power system using DC distribution that provides high quality power. The proposed DC microgrid architecture consists of a photovoltaic generation unit, electric vehicle battery charging, and DC load. Corresponding control strategy of each unit is presented. Maximum power point tracking (MPPT) technique is applied to photovoltaic (PV) system to extract maximum available power from it. Simulation results verify the effectiveness of the proposed DC microgrid.

Keywords— microgrid, DC microgrid, distributed generator (DG), photovoltaic (PV) system, maximum power point tracking (MPPT).

I. INTRODUCTION

As electric distribution technology steps into the next century, many trends are becoming noticeable that will change the requirements of energy delivery. These modifications are being driven from both the demand side where higher energy availability and efficiency are desired and from the supply side where the integration of distributed generation and peak shaving technologies must be accommodated [1].

The transmission and generation system capabilities have been stressed by increase in power demand [2]. An overall power system with central plants is less efficient due to transmission and generation losses along with frequent power outages. These perplexities allow research to focus on fields that can respond to the increasing energy demands without adding new transmission lines. At first glance, integration of the distributed generation to the main grid can be a feasible solution [1]. The distributed energy generation field has its own problems that need to be solved. Therefore, scientists and researchers proposed network architecture for distribution system called “microgrid” [3].

A microgrid is a localized grouping of distributed energy resources, loads and energy storage devices that have the capability to operate in islanding and in grid connected mode [3]. Microgrid is growing rapidly because of its ability to integrate Distributed Generators (DG). There are various advantages offered by microgrids to end-consumers, utilities

and society, such as: improved energy efficiency, minimized overall energy consumption, reduced greenhouse gases and pollutant emissions, improved service quality and reliability, cost efficient electricity infrastructure replacement [3].

Microgrids have low transmission losses in both combined heat and energy applications. Microgrid can help environment and the existing grids in many different aspects by:

- Enabling easy penetration of renewable energy sources.
- Reducing greenhouse gas emission.
- Reducing stress on the grid.
- Lowering energy bills.
- Improving the critical reliability and security of the electric grid.

II. DC MICROGRID

At present researchers focus on development of DC microgrid, because of development in DC power generating distributed generators, fluorescent lighting, battery energy storage devices and their inherent advantage for DC loads in commercial, industrial and residential applications [5].

A. DC microgrid Architecture

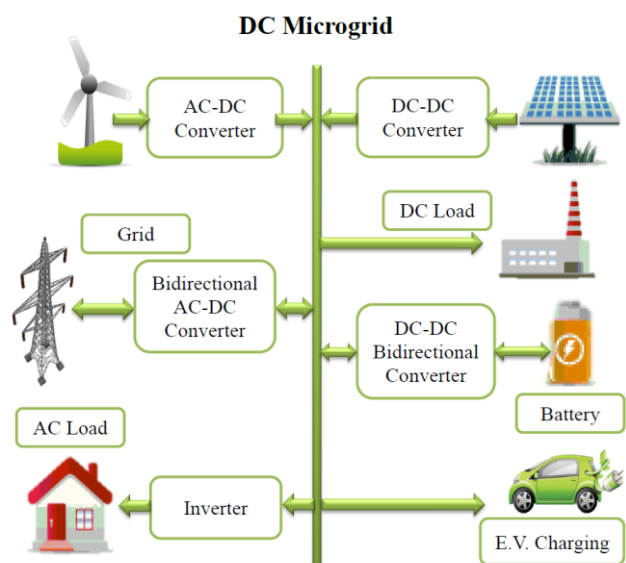


Fig.1 DC microgrid architecture

The DC microgrid architecture [4] is presented in figure 1. Two distributed generators are connected with DC bus. For integration of wind turbine generation system with DC microgrid there is a requirement of AC-DC converter. PV system is connected using DC-DC boost converter [7]. Battery energy storage system provides backup power [7]. All DC load can be directly connected with the DC bus. So, there is no requirement of AC-DC conversion, which increases overall efficiency and reduces cost of the power electronics converters [6]. However, DC-AC inverters are required for conventional AC loads connection.

In many countries people are using electric battery operated vehicles. Charging of Electrical Vehicle (E.V.) battery requires DC voltage [11], so in DC microgrid electrical vehicle can be charged easily. The main advantage of the DC system is that we can directly connect battery storage devices for backup power supply [6]. This energy storage will provide power in the absence of any DG or in peak load period. It is also used to avoid supply interruptions in hospitals for critical equipment's, in big offices buildings for computers or in industries that required high quality power supply. Presently it is implemented with Uninterruptible Power Supply (UPS) with back to back conversion. A direct connection with DC microgrid saves conversions and increasing system efficiency.

B. Benefits of DC microgrid

- 1) The operating cost and power converter losses of DC system can be reduced because there is only a single AC main grid connected inverter unit is required.
- 2) DC renewable energy resources like PV cells, fuel cell can easily incorporate with DC bus, because only DC bus voltage is to be controlled. Therefore, the phase detection like AC grid is not needed.
- 3) In DC microgrid battery storage will continuously supply the power to load during any power outages in the AC main grid. So, it is more reliable and consumers get uninterrupted power supply.
- 4) Our Movement towards lighting technologies like compact fluorescent lamps could accompany DC distribution.
- 5) In grid connected mode when main grid experiences an abnormal or fault condition, the DC microgrid is disconnected from the main grid and operates in the isolated mode. In this mode all the generated power is supplied to the loads connected to the DC grid. So, DC load in DC microgrid will not be affected from main grid disturbance.
- 6) Although in the DC microgrid separate DC distribution line is required, the cost performance of DC houses, information centres and hospitals are satisfactory.

C. Drawback of DC microgrid

- 1) The DC power distribution is limited up to a small short line length (km).
- 2) Compared to AC system voltage transformation in DC system is less efficient.

- 3) For integrating of AC distributed generators rectifier is required to convert AC power into DC.
- 4) For AC load DC to AC conversion is required.

III. PHOTOVOLTAIC (PV) SYSTEM

Photovoltaic technology is the fastest growing technology used in current distribution systems [8]. PV utilizes sunlight to generate energy and it is an attractive alternate energy source because it is renewable, and harmless. PV system basic component is the PV cell which produces around 0.5V to 0.7V voltage on average [8]. Because of the low voltage generation in a PV cell, several PV cells are connected in series (for high voltage) and in parallel (for high current) to form a PV module for desired output [8]. The power produced by single module is not enough to meet the requirements of commercial applications, so modules are connected to form an array to supply the load. The modules in a PV array are usually first connected in series to obtain the desired voltages known as string. Then these strings are connected in parallel as shown in figure 2 to allow the system to produce more current.

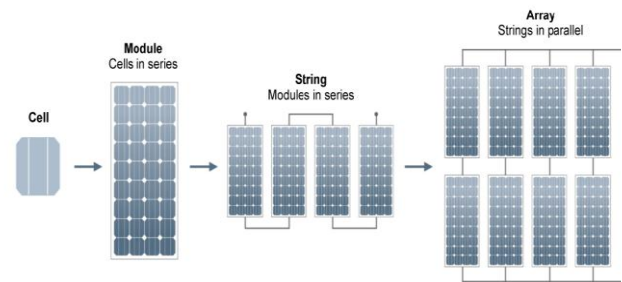


Fig.2 PV array formation

A PV cell delivers different amount of current depending on the irradiation (or insolation), the PV cell temperature and where on the current-voltage curve the PV cell is operated. A PV cell behaves differently depending on the size/type of load connected to it. This behaviour is called the PV cell characteristics. The characteristic of a PV cell is described by the current and voltage levels when different loads are connected. When the cell is not connected to any load there is no current flowing and the voltage across the PV cell reaches its maximum. This is called open circuit voltage (V_{oc}). When a load is connected to the PV cell, current flows through the circuit and the voltage goes down. When the two terminals are directly connected with each other maximum current will flow and the voltage is zero. The current in this case is called short circuit current (I_{sc}). I-V and P-V characteristics are shown in figure 3.

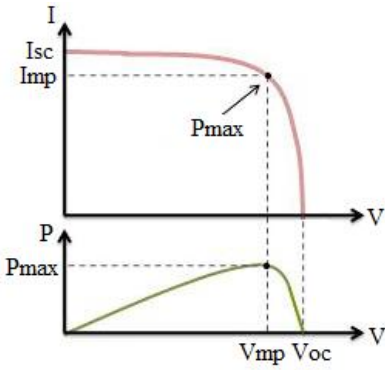


Fig. 3 I-V & P-V characteristics

The basic building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts light energy into electricity. PV array is designed based on equivalent circuit of PV cell [10] presented in figure 4. For modeling Mitsubishi PV-UD190MF5 Module data are used and it is taken from the NREL System Advisor Model (SAM 2014). The System Advisor Model (SAM) is developed by the National Renewable Energy Laboratory (NREL), which is operated by the Alliance for Sustainable Energy, LLC for the U.S. Department of Energy (DOE) and may be used for any purpose whatsoever [14].

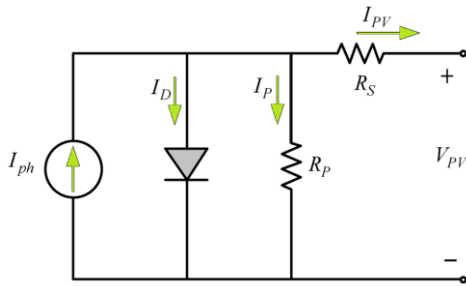


Fig. 4 Equivalent circuit of PV cell

Applying Kirchhoff's Current Law (KCL) to the node where I_{PH} , Diode, R_p and R_s meet, we get the following equation:

$$I_{PV} = I_{PH} - I_D - I_P \quad (1)$$

Where,

- I_{PV} = PV module current (A)
- I_{PH} = Photo-current (A)
- I_D = Current through the diode of PV module (A)
- I_P = Current through the parallel resistance of PV module (A)

Here, I_{PH} represent photo current generated by the solar irradiation and calculated using following equation:

$$I_{PH} = I_{SC} + k_i(T - T_r) \frac{\lambda_s}{1000} \quad (2)$$

Where,

- I_{PH} = Photo current (A)
- I_{SC} = Short circuit current (A)
- k_i = Short circuit current temperature coefficient
- T = Surface temperature of PV module ($^{\circ}\text{C}$)

- T_r = Reference temperature ($^{\circ}\text{C}$)
- λ_s = Solar radiation level (W/m^2)

The current I_D in equation 1 represent diode current and can be given by the Shockley's diode equation:

$$I_D = I_{SAT} \times [e^{(V_D/V_T)} - 1] \quad (3)$$

Where,

- I_D = Current through the diode of PV module (A)
- I_{SAT} = Diode saturation current of PV module (A)
- V_D = Voltage across diode of PV module (V)
- V_T = Thermal voltage (V)

Where, voltage across diode is calculated using following equation:

$$V_D = V_{PV} + I_{PV} \times R_s \quad (4)$$

Where,

- V_D = Voltage across diode of PV module (V)
- V_{PV} = PV module voltage (V)
- I_{PV} = PV module current (A)
- R_s = PV module series resistance (Ω)

And thermal voltage is calculated using following equation:

$$V_T = \frac{K \times T}{q \times N_{CELL} \times Q_D} \quad (5)$$

Where,

- V_T = Thermal voltage (V)
- K = Boltzmann constant = $1.3806 \times 10^{-23} \text{ J K}^{-1}$
- T = Cell temperature = 298 K
- q = Electron charge = $1.6022 \times 10^{-19} \text{ C}$
- Q_D = Diode quality factor of PV module = 1.25
- N_{CELL} = No. of series connected cells per module = 50

Current passing through the parallel resistance I_P is calculated by applying KVL in equivalent circuit of PV cell.

$$I_P = \frac{V_{PV} + I_{PV} \times R_s}{R_p} = \frac{V_D}{R_p} \quad (6)$$

Where,

- I_P = Current through the parallel resistance of PV module (A)
- V_{PV} = PV module voltage (V)
- I_{PV} = PV module current (A)
- R_s = PV module series resistance (Ω)
- R_p = PV module parallel resistance (Ω)
- V_D = Voltage across diode of PV module (V)

PV system is designed for 100 KW using Mitsubishi PV-UD190MF5 Module and parameters of module are listed in Table I.

TABLE I
MITSUBISHI PV-UD190MF5 MODULE PARAMETERS

No.	Parameter	Temperature (°C)			
		0°C	25°C	75°C	100°C
1	I _{PH}	8.17	8.25	8.49	8.67
2	I _{SAT}	1.08×10^{-9}	3.80×10^{-8}	1.01×10^{-5}	9.56×10^{-5}
3	V _T	1.4703	1.6049	1.8742	2.0088
4	R _S	0.22154	0.2231	0.25351	0.28829
5	R _P	760.17	1011.15	953.25	1044.70

PV array design configuration parameter is listed in TableII.

TABLE II
PV ARRAY DESIGN CONFIGURATION PARAMETERS

No.	Parameters	Values
1	P _{MPP_ARRAY}	100.5 KW
2	N _{SER}	16
3	N _{PAR}	33
4	V _{MPP_ARRAY}	395.1984 V
5	I _{MPP_ARRAY}	254.5198 A

TABLE III
PV ARRAY CALCULATED PARAMETERS

No	Parameter	Calculation	Temperature (°C)				
			0°C	25°C	50°C	75°C	100°C
1	I_{PH_ARRAY}	$I_{PH_ARRAY} = I_{PH} \times N_{PAR}$	269.80	272.53	276.02	280.38	286.12
2	I_{SAT_ARRAY}	$I_{SAT_ARRAY} = I_{SAT} \times N_{PAR}$	3.59×10^{-8}	1.25×10^{-6}	2.54×10^{-5}	3.35×10^{-4}	3.15×10^{-3}
3	V_{T_ARRAY}	$V_{T_ARRAY} = V_T \times N_{SER}$	23.52	25.67	27.83	29.98	32.14
4	R_{S_ARRAY}	$R_{S_ARRAY} = R_S \times \frac{N_{SER}}{N_{PAR}}$	0.107	0.108	0.112	0.122	0.139
5	R_{P_ARRAY}	$R_{P_ARRAY} = R_P \times \frac{N_{SER}}{N_{PAR}}$	368.56	490.25	446.14	462.18	506.52

If PV array is controlled to operate at maximum power point (MPP), and if all modules in the array are identical in all aspects and assumed to operate under identical environmental conditions, then each module in the array will also operate at MPP. At MPP under STC, the array voltage is 395.1984 V and the power produced by one module is 190.437W, and hence by one string is 3.0470 KW. Therefore, 33 strings in parallel will be able to produce approximately 100.5 KW of power.

Array parameters can be estimated from datasheet values of the module and from the number of modules in series-parallel combination in the array. If the number of modules connected in series in a string is N_{SER} and the number of strings connected in parallel to form an array is N_{PAR} , then the specifications of the array will be as shown in Table III, assuming identical characteristics of each module and identical operating conditions.

A. Maximum Power Point Tracking (MPPT)

As an electronic system maximum power point tracker (MPPT) functions the photovoltaic (PV) modules in a way that allows the PV modules to produce maximum power[9]. It is not a mechanical tracking system which moves physically the modules to make them point more directly at the sun. Since MPPT is a fully electronic system, it varies the module's operating point so that the modules will be able to deliver maximum available power. As the outputs of PV system are dependent on the temperature, irradiation, and the load characteristic MPPT cannot deliver the output voltage perfectly. For this reason MPPT is required to be implementing in the PV system to maximize the PV array output voltage.

B. Perturb and observe algorithms for MPPT

In this algorithm a slight perturbation is introduced in the system. The power of the module changes due to this perturbation. If the power increases due to perturbation then the perturbation is continued in that direction. When power attains its peak point, the next instant power decreases and so also the perturbation reverses. During the steady state condition the algorithm oscillates around the peak point as shown in figure 5. The perturbation size is kept very small to keep the power variation small. It is examined that there is some power loss because of this perturbation and also it fails

to track the power under fast varying atmospheric conditions. But still this algorithm is very popular and simple [9].

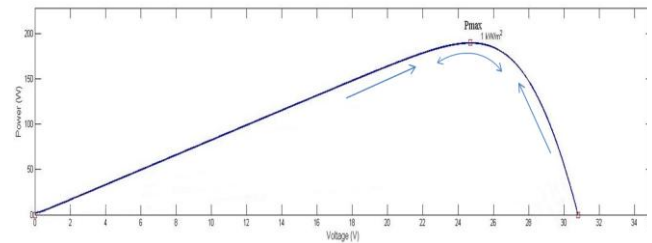


Fig. 5 Perturb and Observe (P&O) algorithm

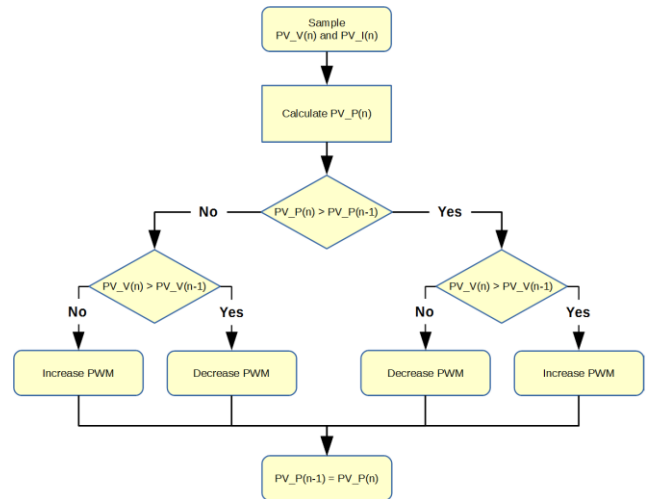


Fig. 6 Perturb and Observe (P&O) algorithm flowchart

Figure 6 represent flowchart of P&O algorithm. Here a reference duty cycle is set 0.5 corresponding to the peak power point of the module. The value of current and voltage can be obtained from the solar PV module. From the measured voltage and current power is calculated. The value of voltage and power at n instant are stored. Then values at n+1 instant are measured again and power is calculated from the measured values. The power and voltage at n+1 instant are subtracted with the values from n instant. If change in power is positive then next perturbation is positive and if change in power is negative then next perturbation is reversed. This

algorithm is used for maximum power point tracking in simulation. By changing duty ratio of the boost converter system is operate at maximum power point.

IV. MODELING AND SIMULATION RESULTS

A DC microgrid whose parameters and design are given in section III is simulated using MATLAB/SIMULINK environment. The operation is carried out for isolated mode. Along with the DC microgrid, the performance of the photovoltaic system is also analyzed. The solar irradiation and cell temperature are also taken into consideration for PV system design. The performance analysis is done using simulated results which are found using MATLAB.

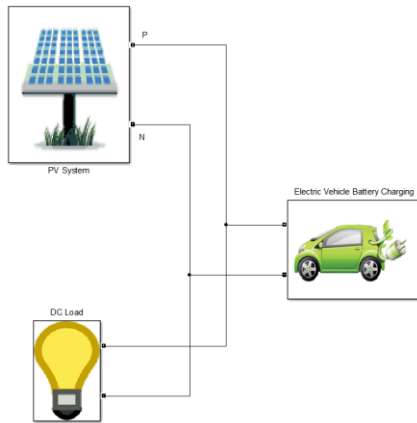


Fig. 7 DC microgrid system

PV system block consist PV Array and Boost converter. PV system is presented in figure 8.

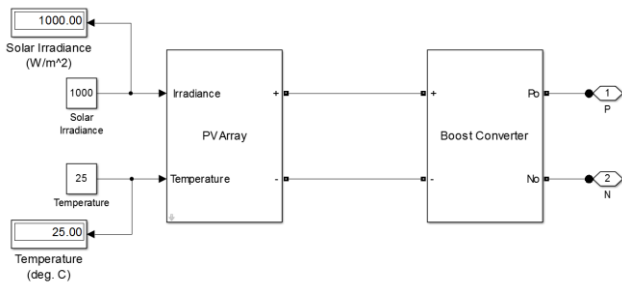


Fig. 8 PV system

PV array is designed using equivalent circuit of PV cell presented in figure 4. It includes 3 subsystems, which are presented in figure 9.

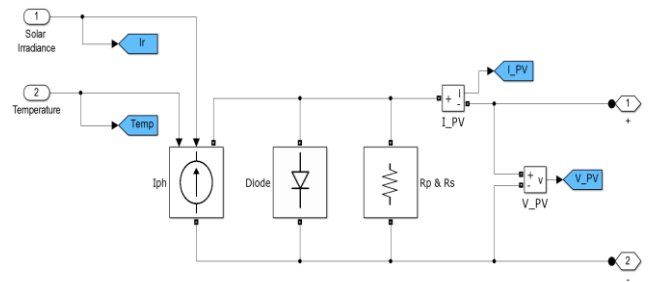


Fig. 9 PV array subsystem

I_{PH} block represents photo current produced by solar irradiation. It is modelled using equation 2.

I_{PH_ARRAY} represents lookup table and contain data of photo current calculated in Table III.

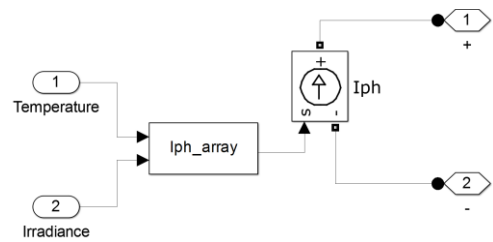


Fig. 10 I_{PH} subsystem

Diode block in figure9 represents PV cell diode characteristic and modelled using Shockley's diode eq. 3.

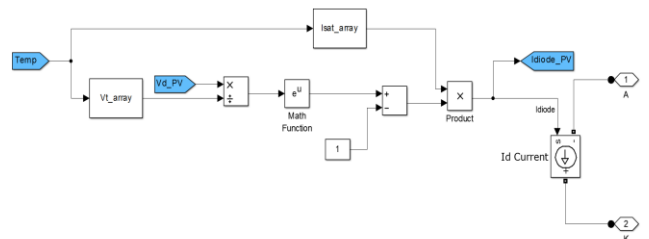


Fig. 11 Diode subsystem

In figure 11 I_{SAT_ARRAY} and V_{T_ARRAY} are saturated current and thermal voltage of PV array that contains lookup table's data calculated in Table III. From eq. 6 R_p and R_s effect is modelled and presented in figure 12.

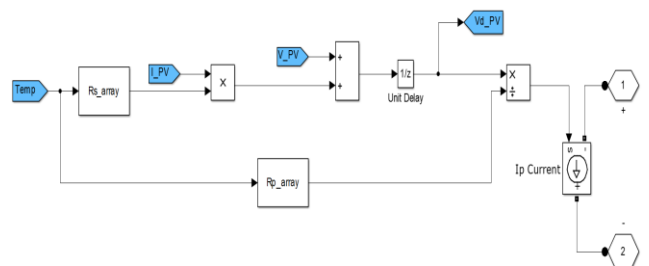


Fig. 12 R_p & R_s subsystem

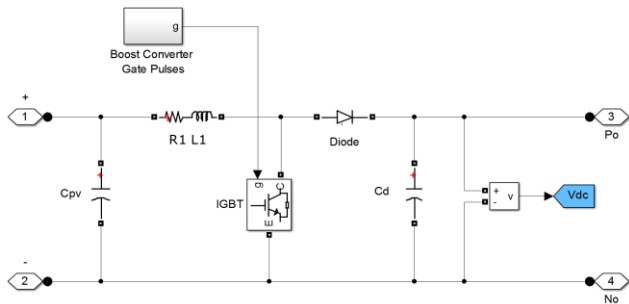


Fig. 13 PV boost converter

PV Boost converter is presented in figure 13. MPPT algorithm is implemented in MATLAB function block that allows program execution in Simulink model. By measuring V_{PV} and I_{PV} output of PV array maximum power point is obtained using P&O algorithm as presented in figure 6.

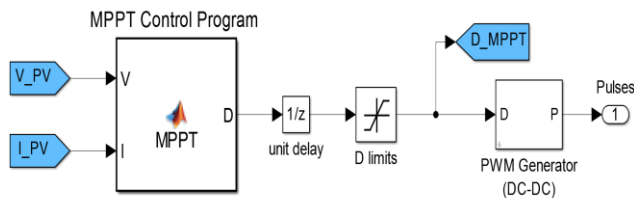


Fig. 14 MPPT based boost converter gate pulses subsystem

Figure 15 shows waveforms of change in duty ratios as per MPPT, PV system voltage and power deliver by the PV system. It is clear from the waveforms that MPPT will operate PV system at its maximum power point and delivers maximum power that is 100KW.

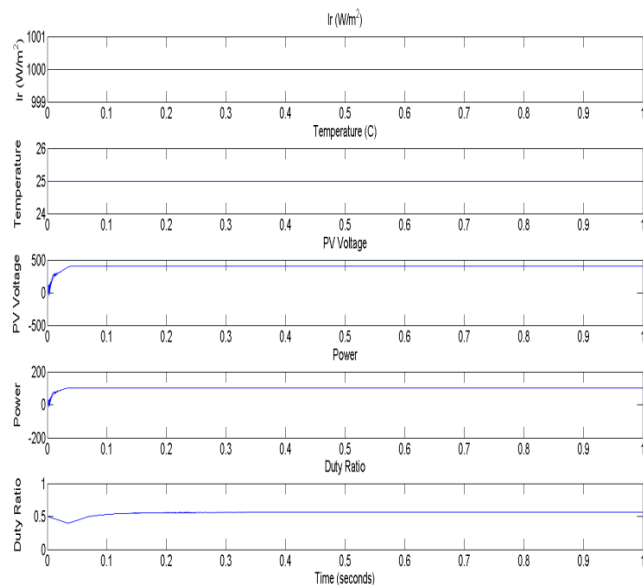


Fig. 15 Waveforms of (1) Irradiation, (2) Temperature, (3) PV voltage, (4) PV output power and (5) Duty ratio of boost converter

Figure 16 and 17 represents I-V, P-V, characteristics with variation in solar irradiation. The nonlinear nature of PV cell is noticeable as shown in the figures, i.e. the output current

and power of PV cell depend on the solar irradiation. As the solar irradiation increase output current and power is increases.

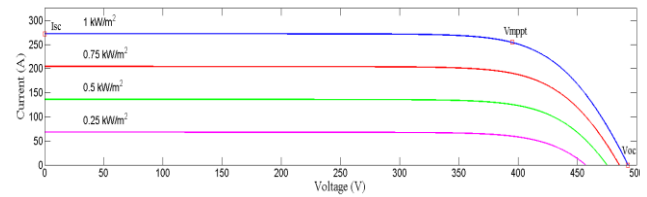


Fig. 16I-V output characteristics of PV array for different irradiation

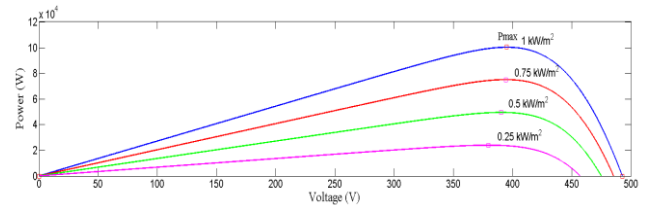


Fig. 17P-V output characteristics of PV array for different irradiation

Figures 18 and 19 verify that with increase of cell's working temperature, the current output of PV module increases, whereas the maximum power output reduces. Since the increase in the output current is much less than the decrease in the voltage, the total power decreases at high temperatures.

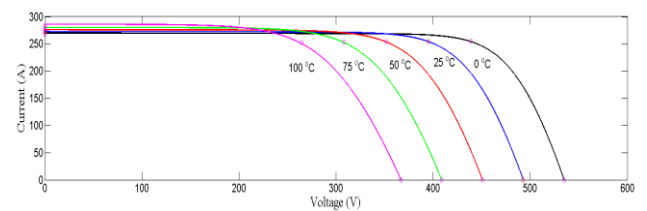


Fig. 18I-V output characteristics of PV array for different temperatures

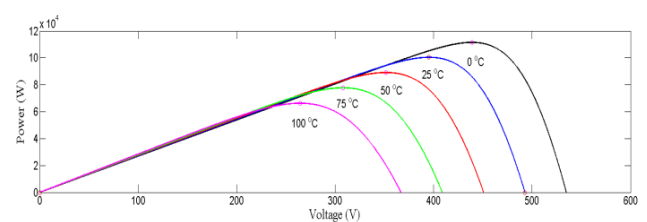


Fig. 19P-V output characteristics of PV array for different temperatures

Electric vehicle charging configuration is presented in figure 20. The constant current and constant voltage charging strategy is used to charge EVBC [12].

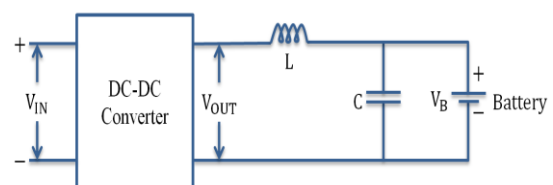


Fig. 20 Electric Vehicle Battery Charging(EVBC) configuration

Electric vehicle battery charging is implemented and presented in figure 21. State of Charge (SOC) is used to protect battery from over charging. If SOC goes above 98 gate pulses to buck converter is become zero.

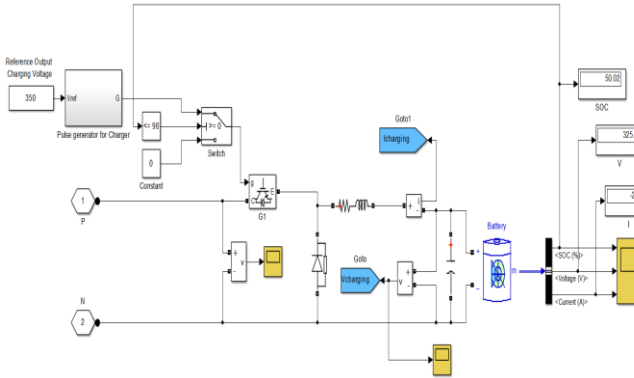


Fig. 21 Electric Vehicle Battery Charging (EVBC) Subsystem

Lithium-Ion battery of 300 V and 40 Ah of capacity is used in simulation. Initial SOC is taken as 50%. In constant current control, when battery voltage is reached to a design charging voltage, the control method changed to constant voltage control method to make the charging voltage stable, and the charging current amount of flowing current is getting decreased simultaneously [13].

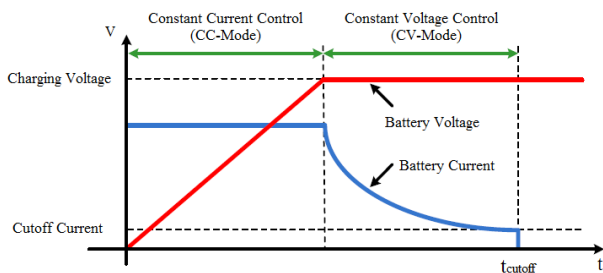


Fig. 22 Constant Current (CC) and Constant Voltage (CV) control of the battery charging

Gate pulses for buck converter are generated using 2 PI loops. The control block diagram is presented in figure 23.

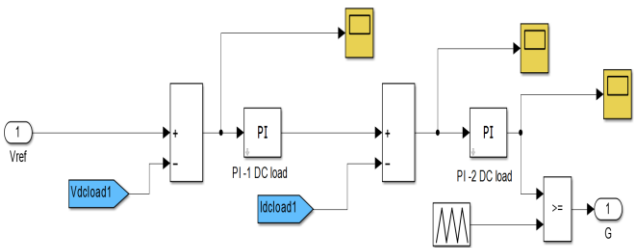


Fig. 23 Pulse generator for charging subsystem

Two PI controllers $K_p + \frac{K_i}{s}$ are used for to CC control and CV control. CV control is composed of battery voltage V_{Charging} , battery voltage reference V_{ref} , two PI-controller and limiter. A difference in values between battery

voltage and reference voltage is passed through PI controller which generates reference I_L . State of charge is increased from its initial value 50% as shown in figure 24.

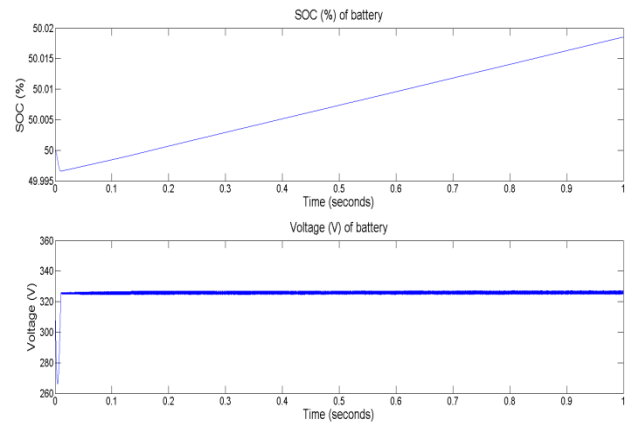


Fig. 24 Battery state of charge and Battery voltage

DC bus voltage is maintained constant at 1000 V. A 90 KW DC load is connected with the DC microgrid. So, 90 A current will flow to the load. Waveform of DC bus voltage and DC load current is presented in figure 25. Steady state is reached after 0.2 second.

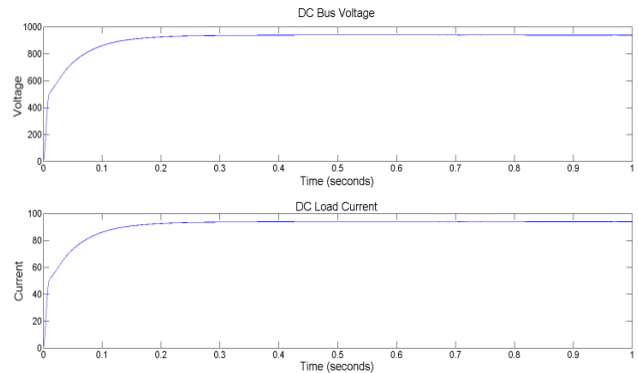


Fig. 25 Waveforms of (1) DC bus voltage and (2) DC load current

V. CONCLUSIONS

For smooth integration of DGs, we proposed “DC microgrid” to satisfy high efficiency and high quality power supply. The modeling of DC microgrid is carried out in MATLAB/SIMULINK environment. The present work mainly includes PV system, Electric Vehicle Battery Charging (EVBC) and DC load. The models are developed for all the converters to maintain stable system operation under various source conditions. Effect of solar irradiation and temperature on PV system is also presented in this paper. Maximum Power Point Tracking (MPPT) algorithm is used to harness maximum power from PV system. Simulation results of MPPT control verified that it is tracking maximum power point and accordingly it changes duty ratio of boost converter. The DC bus voltage is maintained stable at setting value. The developed DC microgrid provides a basic research foundation and it is easily extended to DC dispatch system.

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