STABILITY ENHANCEMENT OF A FOUR-PORT BIDIRECTIONAL DC–DC CONVERTER USING PI-BASED VOLTAGE REGULATION

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ABSTRACT

In order to increase the application of renewable energy sources in the hybrid electrical vehicle application and for zero tailpipe emission, a typical DC power converter interface, in addition of effective control of power flow is very important. On that aim, a novel four port dc–dc power converter with bidirectional power flow is proposed to integrate the two input ports for photovoltaic (PV) and battery to two output ports for motor load and light load. The MPBC is customized for operating in buck and boost states with power flow control in both directional through changing the switching combinations. This system is implemented in hybrid e-vehicles (HEVs), where different level of dc voltages at the battery and motor needs to be connected with the capability of bidirectional flow of power in the regenerative action of the vehicle to charge the battery. The different states of operation, steady state analysis, and control scheme to regulate the power are presented. Power loss analysis is carried out to do proper design with more efficiency. The proposed converter simulation is done using MATLAB/Simulink to verify the validity of the design, its behavior, and response in different states of operation. The switch control of the proposed converter is updated with closed-loop control integrating PI regulator for output voltage control. The output voltage can be controlled as per the reference set in the voltage loop controller.

Keywords: hybrid electrical vehicle (HEVs), Multiport Bidirectional DC-DC converter, photovoltaic (PV), MATLAB/Simulink, Proportional Integral (PI) regulator.

1. INTRODUCTION

The rapid growth in global energy demand, environmental pollution, and depletion of fossil fuel resources has accelerated the transition toward renewable energy–based transportation

systems. Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are widely recognized as promising solutions for reducing greenhouse gas emissions, improving energy efficiency, and achieving sustainable mobility. However, the large-scale adoption of EVs and HEVs requires efficient energy management systems capable of integrating multiple energy sources while ensuring reliable and flexible power delivery to vehicle loads [3]. Among various renewable energy sources, solar photovoltaic (PV) technology has gained significant attention due to its abundance, cleanliness, and declining installation costs. Integrating PV systems with HEVs can reduce dependency on grid charging and fossil fuels, thereby enhancing energy sustainability. In addition, energy storage systems (ESS), particularly batteries, play a crucial role in HEVs by storing excess energy, supplying power during peak demand, and enabling regenerative braking. The coexistence of multiple sources and loads in HEVs necessitates advanced power electronic interfaces to manage bidirectional power flow efficiently [4].

Conventional single-input single-output DC–DC converters are inadequate for modern HEV applications, as they require multiple conversion stages, resulting in increased component count, higher losses, and reduced system reliability. To overcome these limitations, multiport bidirectional DC–DC converters (MPBCs) have emerged as an effective solution. These converters allow multiple energy sources and loads to be interfaced through a single power conversion stage, thereby reducing system complexity, improving power density, and enhancing overall efficiency [10-11]. A key requirement of HEV power converters is the capability to operate in both buck and boost modes with bidirectional power flow. This is essential for handling diverse operating conditions such as acceleration, cruising, regenerative braking, and auxiliary load operation. Moreover, maintaining a stable output voltage under varying source availability and load demand remains a major challenge. Effective closed-loop control strategies, such as proportional–integral (PI) controllers, are widely used to achieve accurate voltage regulation and dynamic stability in such systems. In this context, this paper presents a novel four-port multiport bidirectional DC–DC converter designed for hybrid electric vehicle applications. The proposed converter integrates two input ports—photovoltaic (PV) source and battery—and two output ports—motor load and light load—within a single topology. The converter supports bidirectional power transfer and operates in both buck and boost modes by appropriately modifying the switching combinations. Different operating modes and states are analyzed to ensure flexible power flow management under various HEV

operating conditions. Furthermore, a closed-loop PI control scheme is implemented to regulate the output voltage and improve system performance.

The effectiveness of the proposed converter is validated through detailed MATLAB/Simulink simulations. The results demonstrate stable voltage regulation, efficient power sharing among sources, and reliable operation in all modes, confirming the suitability of the proposed MPBC for renewable energy–based HEV applications.

2. PV SYSTEM OPERATION OF EACH MODE WITH DIFFERENT STATES

2.1 Photovoltaic (PV) system

An inverter and one or more solar panels are among the mechanical and "electrical parts of a photovoltaic (PV) system", which uses solar energy to generate electricity. From small rooftop or portable units to massive utility-scale power plants, PV systems are available in a variety of sizes. This page pertains to grid-tied photovoltaic (PV) systems, which are connected to the utility grid, despite the fact that "off-grid PV systems" may operate autonomously.

Figure .1: Photovoltaic (PV) system

2.2 Operation of Each Mode with Different States

The properties of the source, load power, and associated voltages establish the four different modes that make up the proposed multiport converter's operational spectrum. These modes, which include regenerative braking, acceleration, and constant speed, change according to dynamic load power situations associated with an EV driving cycle. All operational modes' power flow is shown in Figure 2.
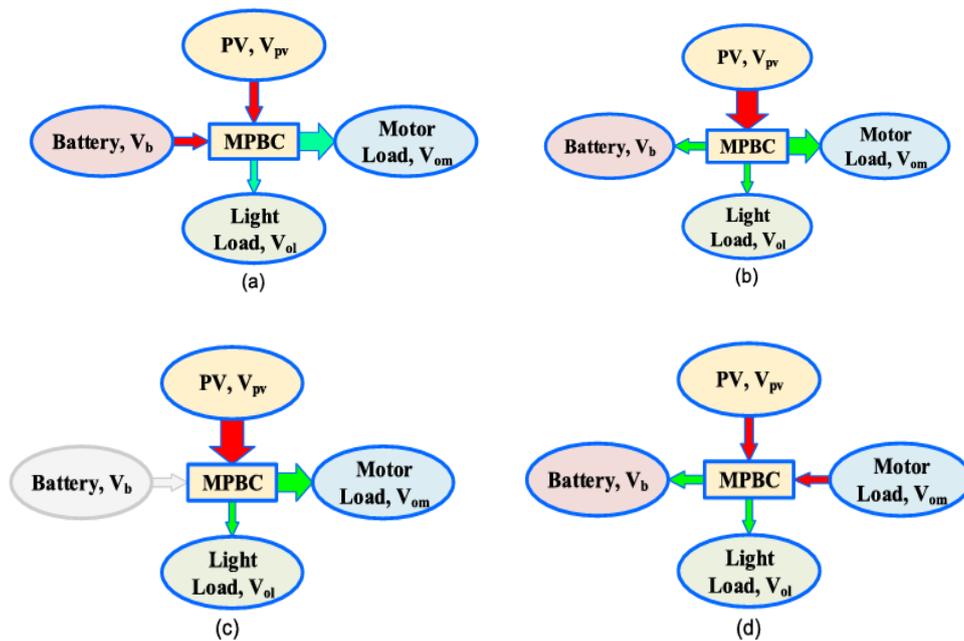
Figure 2: Power flow diagram in each State (a) Mode: 1 From PV & Battery to Loads (b) Mode: 2 From PV to Battery & Loads (c) Mode: 3 From PV to Loads (d) Mode: 4 From PV & Loads to Battery

2.2.1 Mode: 1 (PV and Battery to Loads, (state: 1a to 1d)

When a load (a rapid increase in load) exceeds the PV's available power (Ppv <(Pom+Pol)), "the converter operates in mode 1.
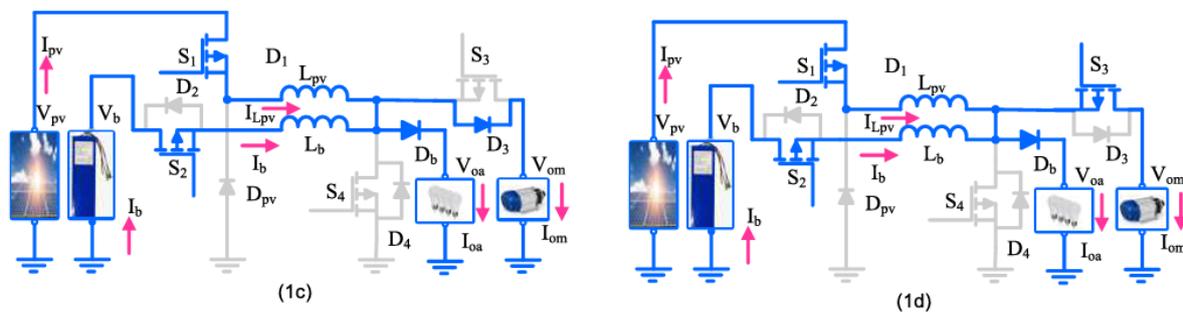

Figure 0: State operation of Mode: 1. State: 1a– Both inductors current rises; State: 1b- Lpv current is constant and Lb current rises; State: 1c &1d Lpv current falls and Lb current also falls.

2.2.2 Mode 2 (PV to Loads and Battery, (State: 2a 2d)):

The action of the inductor Lpv in this mode is identical to that of mode 1, except that the inductor Lb is conducting "the current in the opposite direction" of the last state current. since electricity is moved from PV to the battery (charging-buck operation).
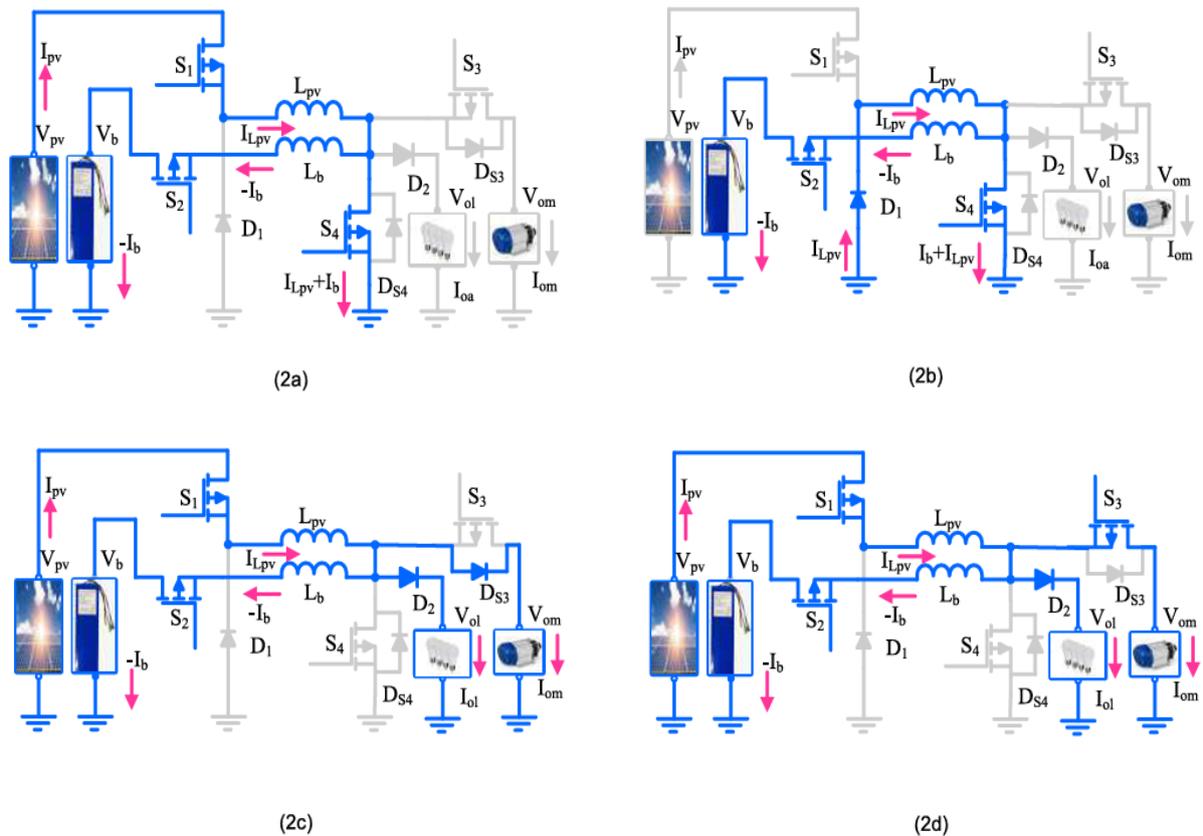
Figure 4: State operation of Mode 2. State: 2a– Both inductor currents rise; State:2b- Lpv current constant and Lb current falls; Mode: 1c & 1d Lpv current falls and Lb current rises.

2.2.3   State 3 (PV to Loads, (Mode: 3a-3c):

When battery SOC exceeds SOCmax and load demand is less than Ppv, this mode of operation is used. Therefore, by instructing "S1 and S4 to transfer power to the load from PV" via the inductor Lpv, the MPBC is built as an increase (voltage) converter
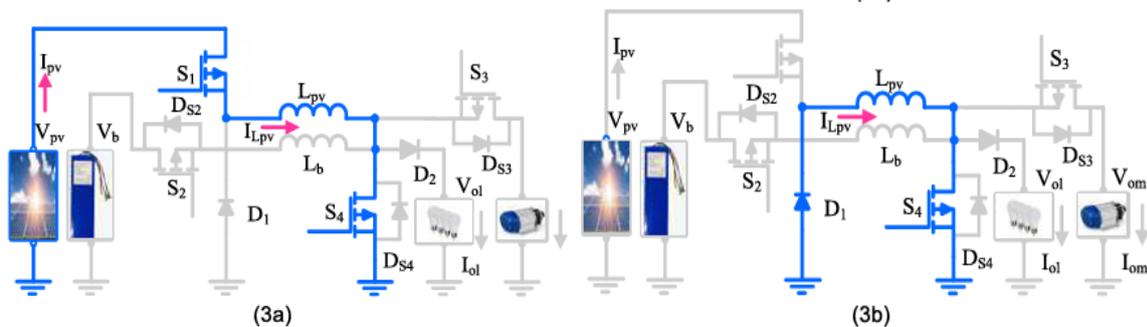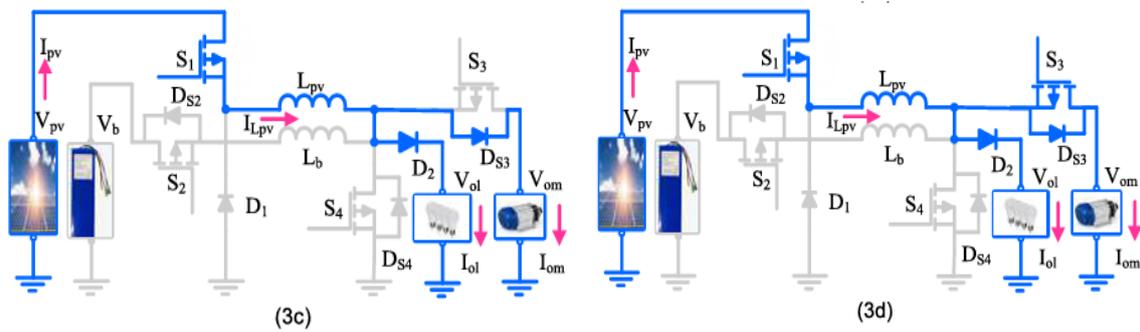
Figure 5: States operation of Mode 3. State: 3a– Inductor currents rise; state: 3b– Inductor current circulate through D1; State: 3c & 3d – Lpv current falls;

2.2.4   Mode 4 (PV & Loads to Battery, (State: 4a 4c)):

"When the battery's state of charge (SOC) is lower than SOCmax (during the day)" and the motor is operating in regenerative action, the converter transfers power in this mode.
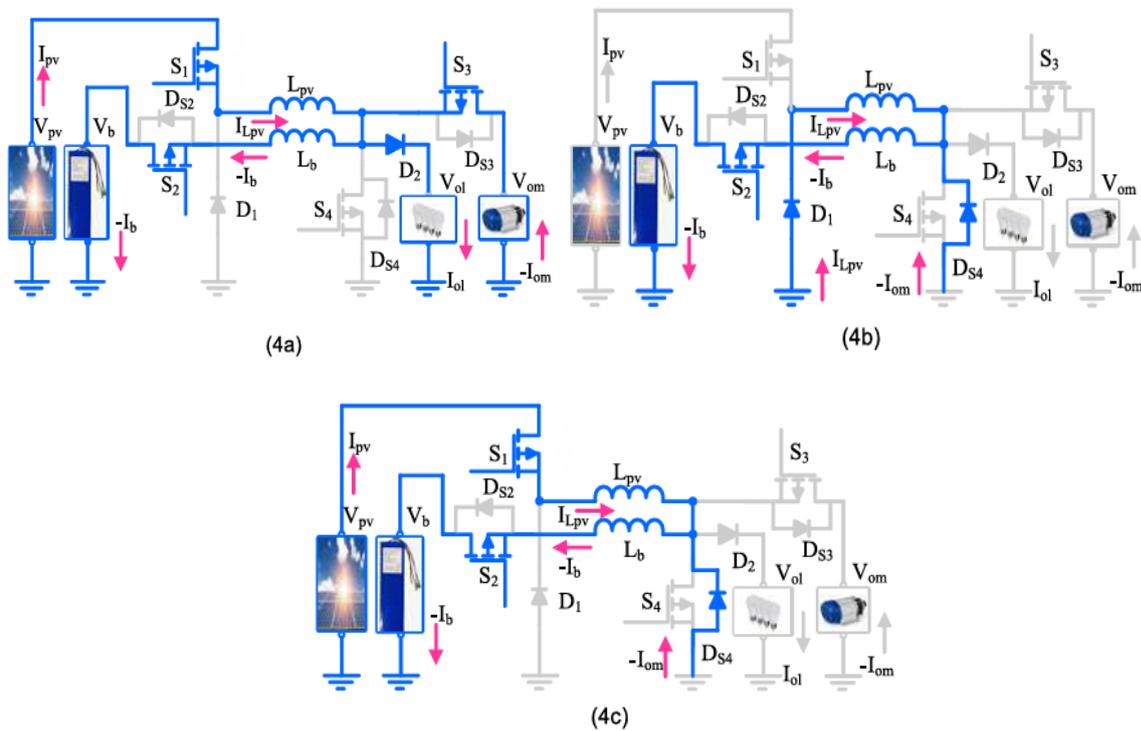

Figure 6: State operation of mode4. State: 4a – Both currents rise; State: 4b - ILpv rises and ILb falls; State: 4c– ILpv falls and ILb falls.

3. PROPOSED METHODOLOGY

3.1 Description of the system

A bidirectional DC–DC converter that is a multiport buck–boost based and is illustrated in Figure 7 is the proposed topology. It is intended "for hybrid electric vehicle (HEV) applications. Connecting two input sources—the battery and the photovoltaic (PV) system—with two distinct output ports—"the motor load and the auxiliary or light load"—is the primary goal of this converter. Because the voltage levels of both sources and loads vary, the converter is designed to function in both boost and buck modes. During charging and discharging, the topology uses two inductors: one for power transmission from the PV source to the loads, and another for power exchange between "the battery and the loads or between the battery and the PV source". These inductors work in coordination with four MOSFET switches. The converter may regulate the direction and mode of power flow by adjusting "the switching combinations of these devices. This enables not only unidirectional supply from sources to loads but also **bidirectional energy transfer**, which is essential in HEV systems. During regenerative braking, for instance, the motor functions as a generator, returning the recovered energy to the battery, while under normal driving circumstances, the PV system and battery work together to power the loads. This converter's efficiency and versatility are its most important features. In addition to direct PV-to-load transfer, the device is capable of operating in four distinct modes, including battery-to-load discharge, motor-to-battery regenerative charging, and PV-to-battery charging
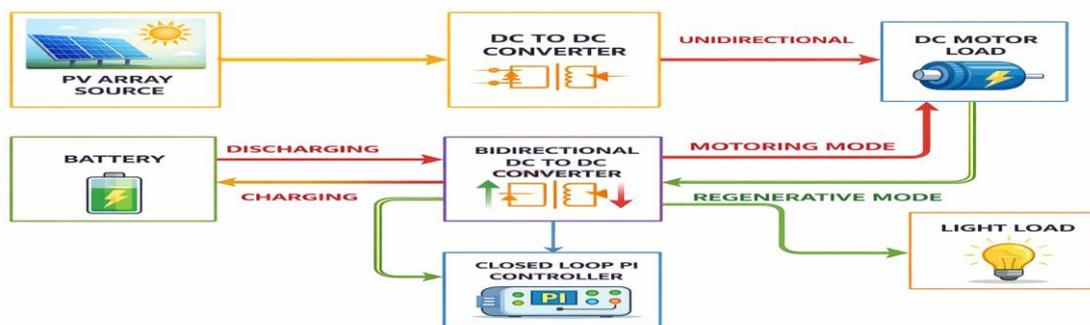
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Figure 7: Proposed Modular Buck-Boost Based Multiport Bidirectional DC–DC Converter

3.2 Role of Proportional Integral (PI) Control

In order to ensure stable and effective operation, PI controllers are used in "the motor and power converter speed and voltage control systems" of hybrid electric vehicles (HEVs) to reduce mistakes between the intended and actual values. They do this by responding with a proportional term to instantaneous mistakes and with an integral term to cumulative errors. This removes steady-state errors and offers a quick, precise, and stable response—all of which are essential for energy efficiency and performance optimisation.
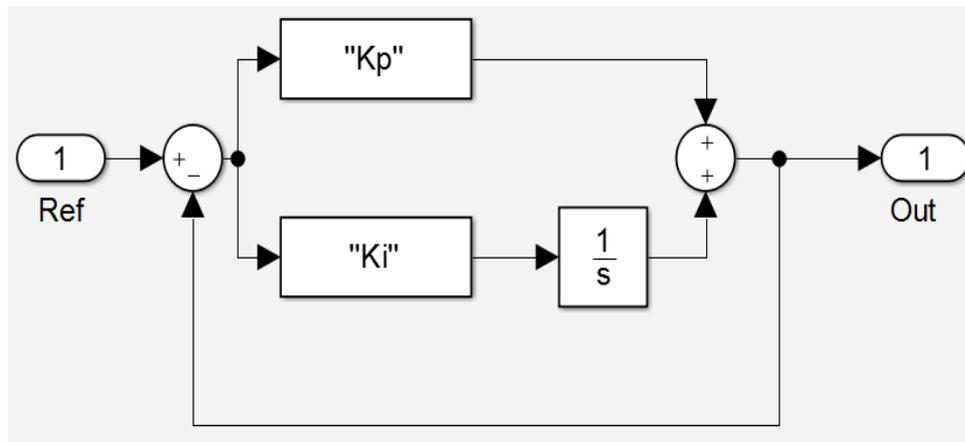

Figure 8: Structure of PI controller

Key Functions of PI Controllers in HEVs

- **Speed Control:** By adjusting the torque of the motor to get the required output and comparing the demanded and actual speeds, the PI controllers manage the vehicle's electric motor's speed.

- **Voltage Regulation:** The DC-link voltage is regulated by their function, which is crucial for "the efficient transmission of energy between the battery and the motor" and for the consistent power supply of the vehicle's components.

- **Power Factor Correction (PFC):** In the conversion of power "from sources such as solar photovoltaic (PV) systems", PI controllers are utilised in certain HEV charging devices to manage energy flow and reduce harmonics.

- **Component Performance Optimization:** "For electric motors and other power system components", PI controllers improve dynamic performance and energy efficiency by reducing rise time, steady-state inaccuracy, and fluctuations.

4. SIMULATION & RESULT ANALYSIS

4.1 Simulation Parameter

Table 1 Simulation Specification of the parameter

S. No.	Parameter	Specification
1.	PV Voltage $V_{pv} = V_{mp}, I_{pv} = I_{mp}$	250 W, $V_{mp} = 30.7\ V$, $I_{mp} = 8.15\ A$, $V_{oc} = 37.4\ V$, $I_{sc} = 8.63\ Amp$,
2.	Battery Voltage, V_b	24V, 20AH
3.	Inductor, L_{pv}	1.5mH
4.	Inductor, L_b	680µF
5.	Capacitor, C_{om}	470µF
6.	Capacitor, C_{ol}	68µF
7.	Load resistor, R_{om}	9.2Ω for 250W
8.	Load resistor, R_{ol}	46.1Ω for 50W

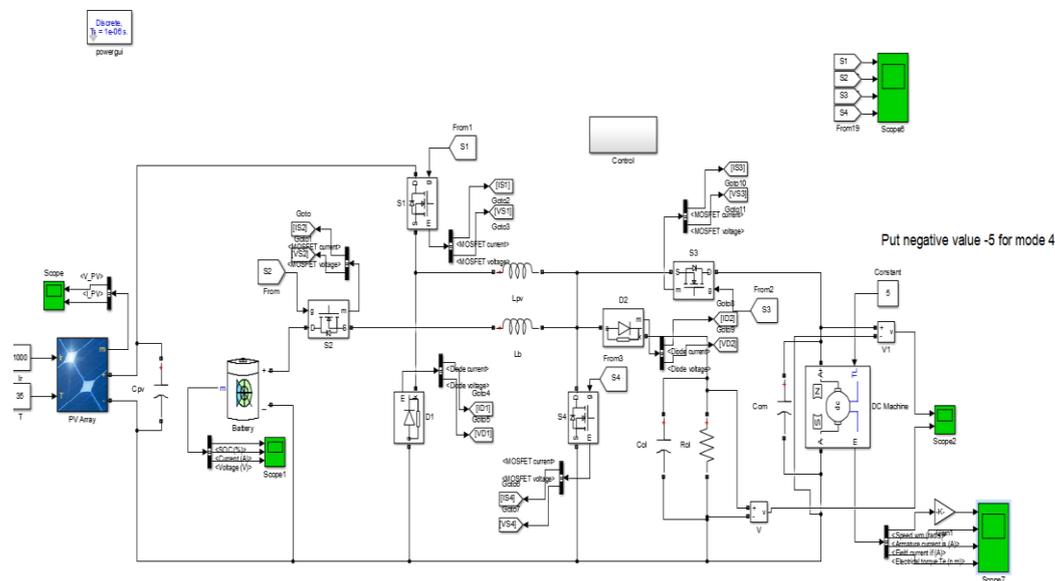### 4.1 Proposed MPBC Converter with PMDC Motor

Figure 9: Circuit model with a DC motor at the load

In the above model (see figure 9), the resistance at the 'om' terminals is replaced by a permanent magnet DC motor. The graphs of the modules connected in the circuit for the modes is presented below.
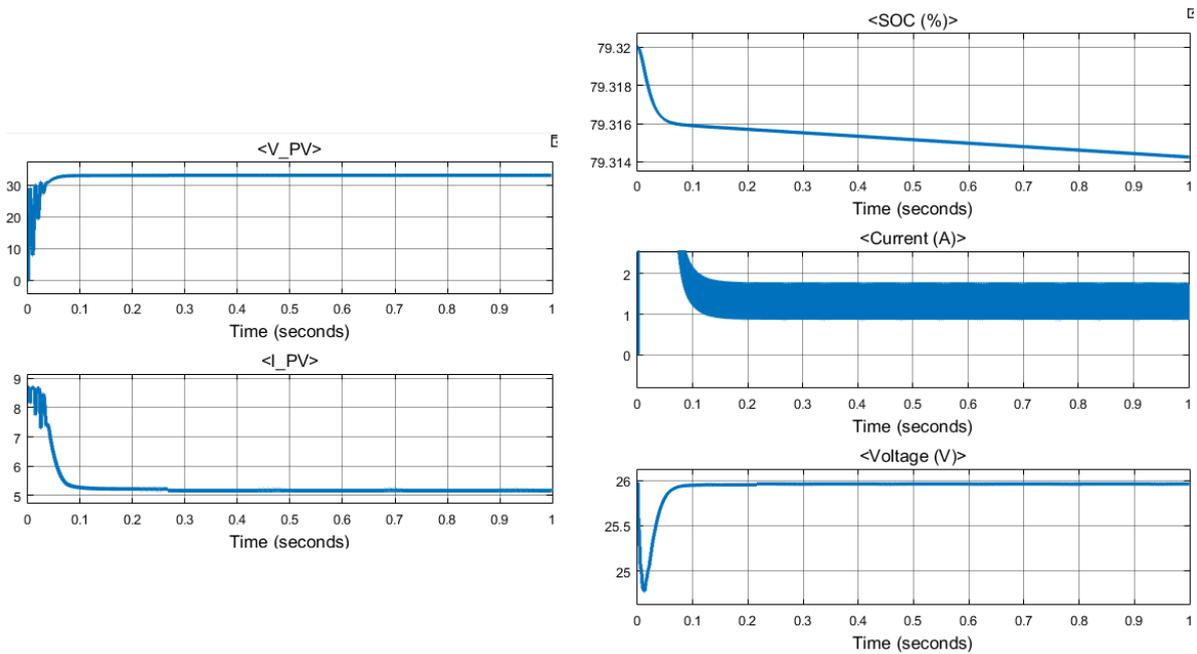
A. Mode 1 with motor

Figure 10: PV and Battery characteristics for mode 1

Figure 11 are the graphs of the PV and battery characteristics when operated in mode 1. The PV and battery both conduct to the machine operating in motoring mode.
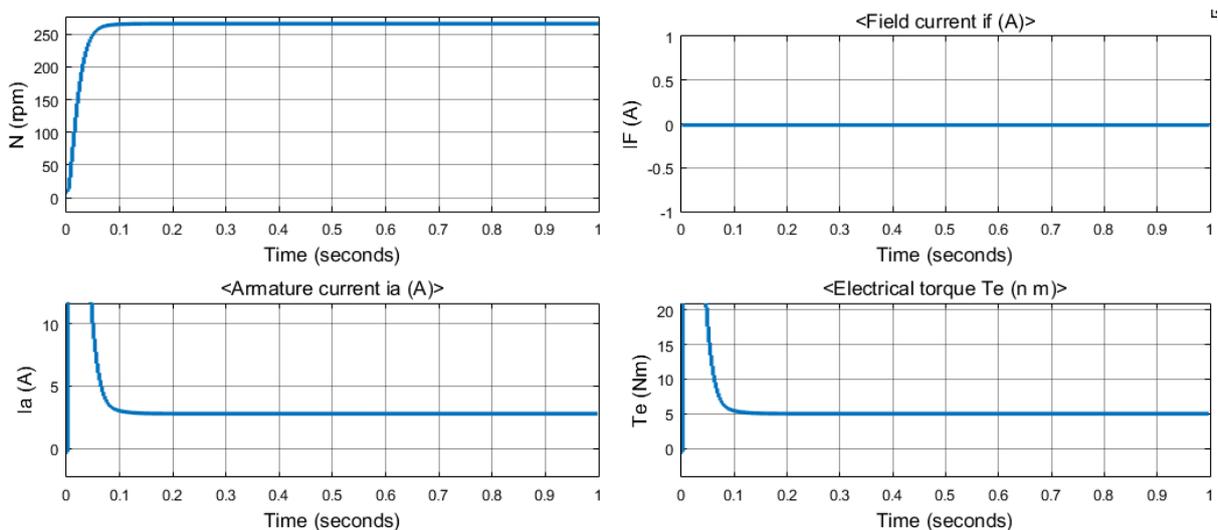

Figure 11: DC motor characteristics for mode 1

The motor characteristics is presented in the graphs (see figure 11) which shows 280rpm and 3A armature current. The field current shown is 0A as it is permanent magnet DC motor. The load torque given is 5Nm which need 5Nm electromagnetic torque.
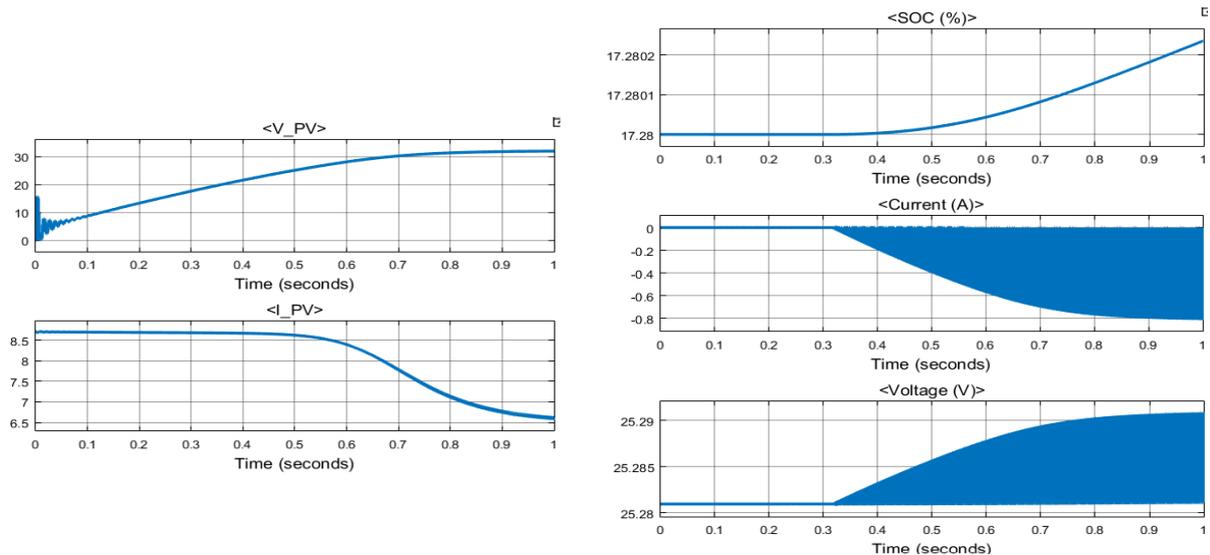
B. Mode 2 with motor

Figure 12: PV and Battery characteristics for mode 2

Figure 12 shows the graphs of the PV and battery characteristics when operated in mode 2. The PV power is delivered to the machine operating in motoring mode.
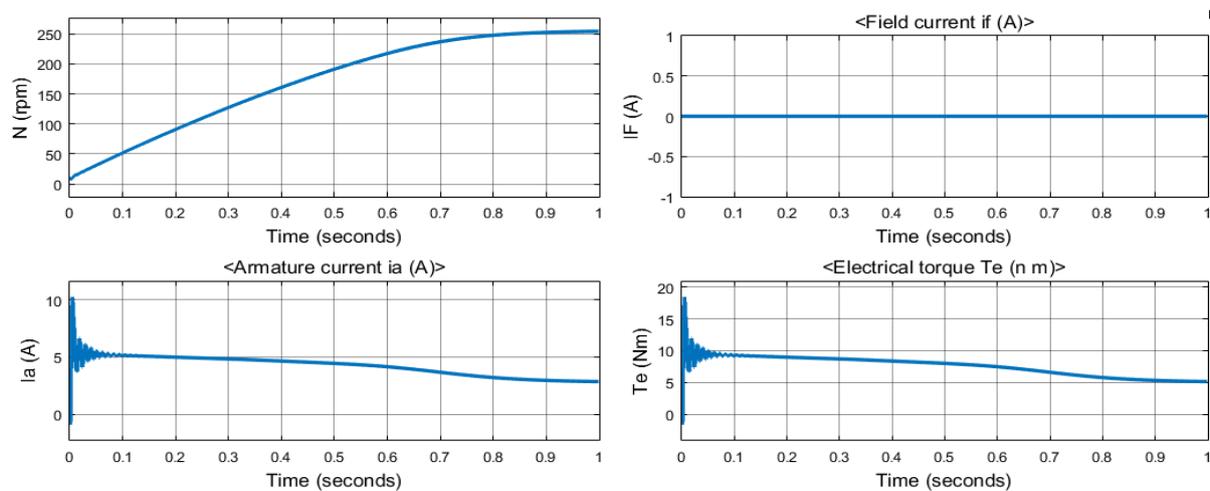

Figure 13: DC motor characteristics for mode 2

Figure 14 shows the motor characteristics operating in mode 2 which is absorbing power from PV only. The speed recorded is 250rpm, armature current is 3A and Te is 5Nm settling at 0.9sec.
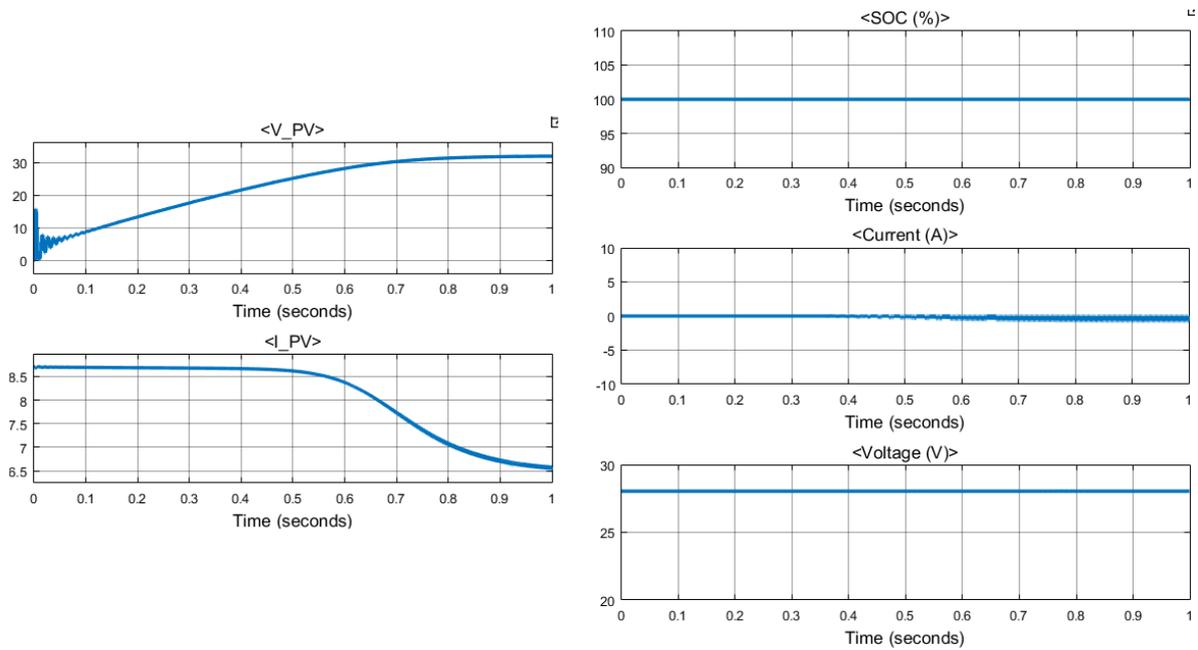
C.Mode 3 with motor

Figure 14: PV and Battery characteristics for mode 3

Figure 14 are the graphs of the PV and battery characteristics when operated in mode 3.The PV power is delivered to the machine operating in motoring mode and the battery is not charging as SOC reached 100% from PV with increasing SOC.
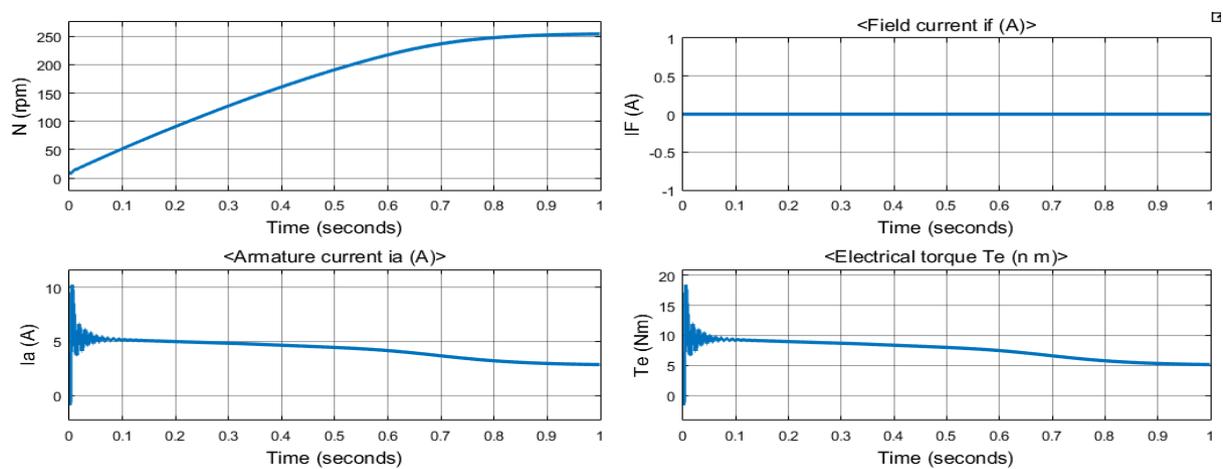
Figure 15: DC motor characteristics for mode 3

Figure 15 present the motor characteristics operating in mode 3 which is absorbing power from PV only. The speed recorded is 250rpm, armature current is 3A, and Te is 5Nm settling at 0.9sec.
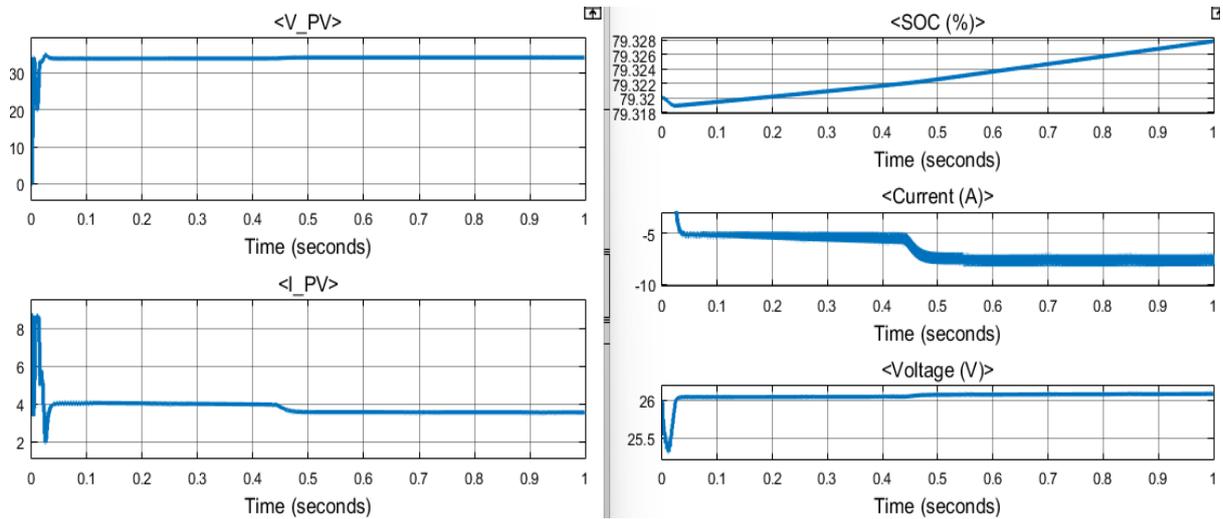
D.Mode 4 with motor

Figure 16: PV and Battery characteristics for mode 4

Figure 16 shows the graphs of the PV and battery characteristics when operated in mode 4. The PV and DC machine charges the battery with raising SOC. The battery current is observed to be -8A representing charging of the battery.
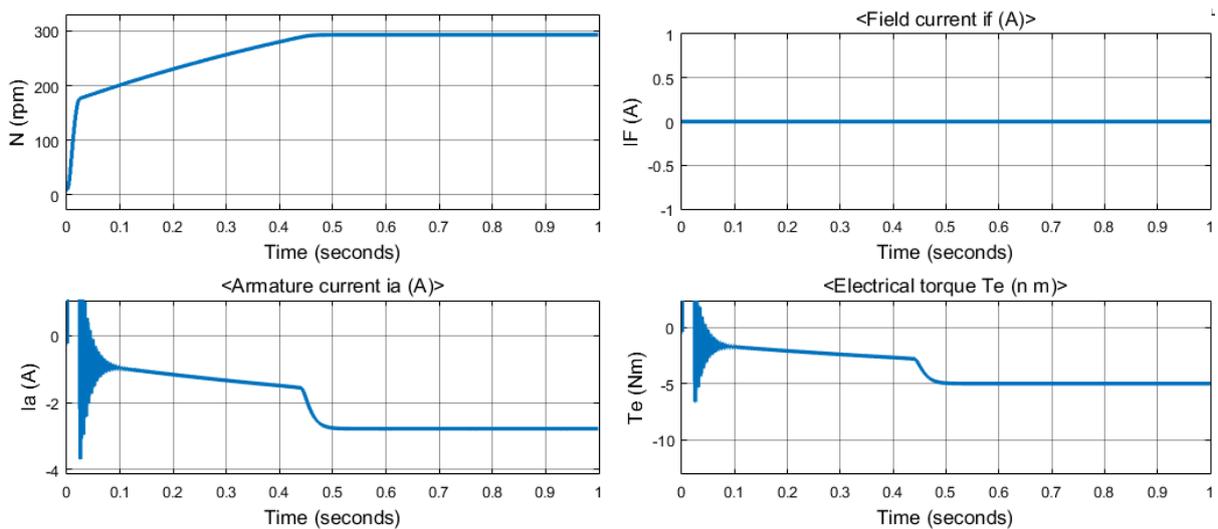

Figure 17: DC motor characteristics for mode 4

Figure 18 present the motor characteristics in mode 4 which is operating in regenerative braking mode. The torque and armature current is in negative direction recorded at -5Nm and -3A.

4.2 Closed-loop Control Technique:

The switching of the switch S4 is updated with closed loop control with PI regulator connected to output voltage error signal. By comparing "the measured signal of the converter's output terminals" with the reference signal, the error is produced. However, all the remaining signals are maintained same.
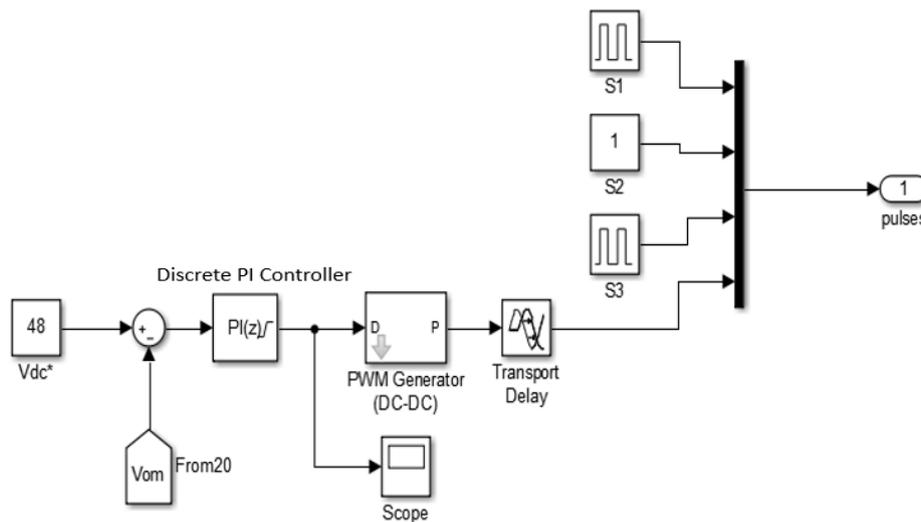

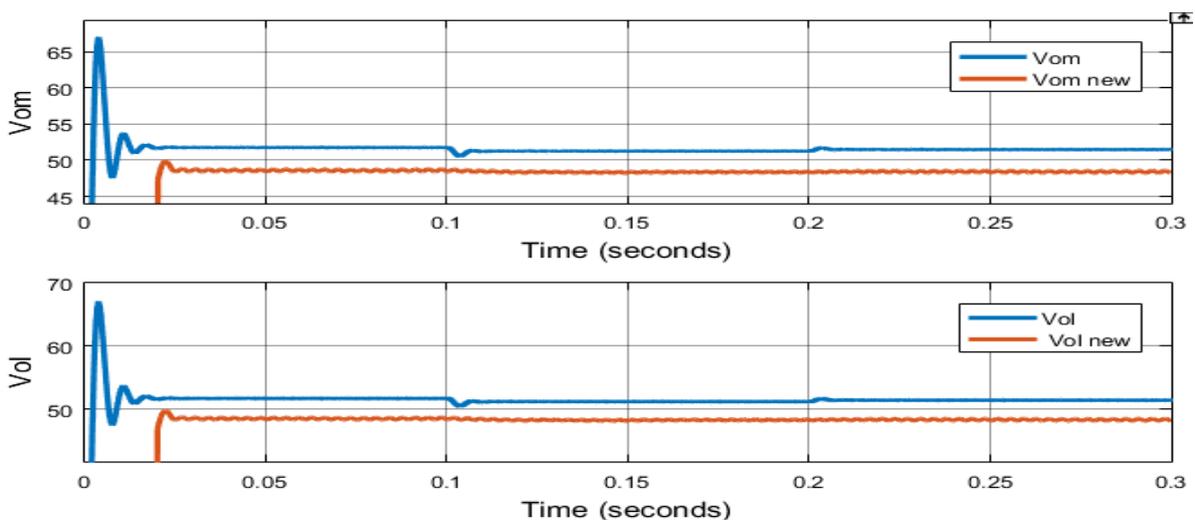Figure 18: Closed-loop control modeling of the proposed circuit

Figure 19: Voltages at both terminals with 48 reference value using closed loop control

Figure 19 The above graph depicts that the output voltage is set at 48.5V as per the given desired value of 48V in the constant block. This is achieved by the closed loop control with voltage PI regulator integrated to switch S4 for controlling the ON time of the switch. The peak overshoot is also mitigated when compared to open loop system voltage measurement. The output voltage is more stable for the irradiation changes in the PV module. The closed loop control is also implemented with DC motor connected at the resistance and the comparison graph is generated as below.
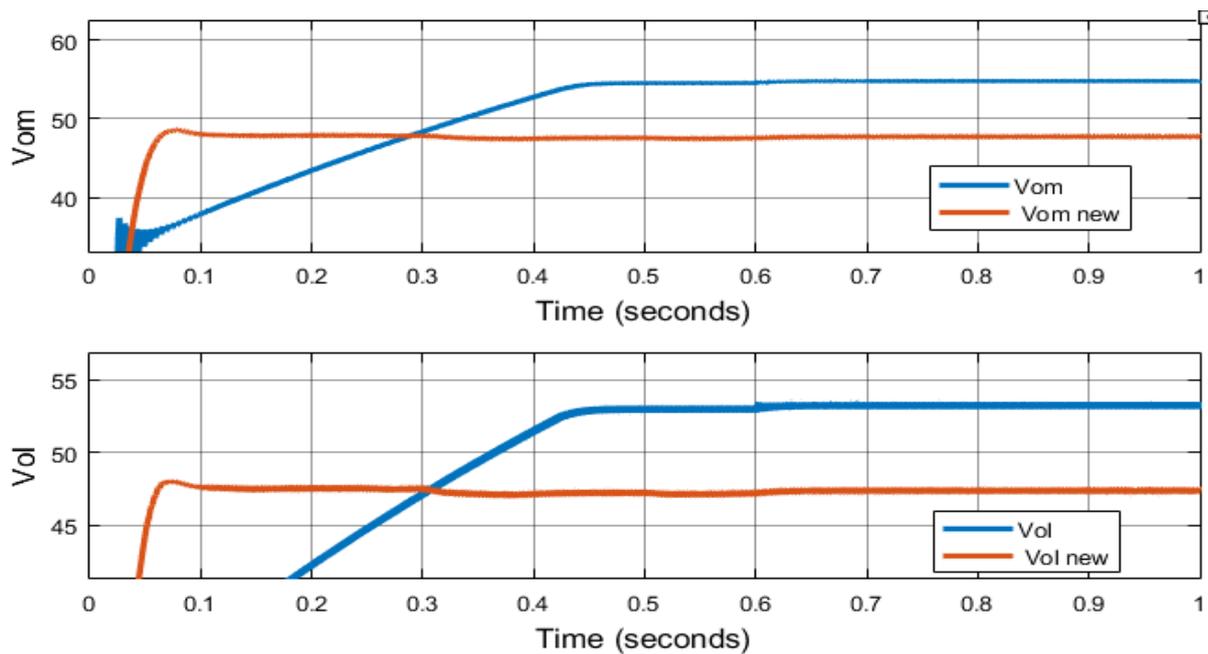

Figure 20: Voltages at both terminals with 48 reference value using closed loop control with a DC motor

As it can be observed in the graph the voltage settles faster for the system with closed loop control. The settling time is 0.1sec for closed loop whereas the settling time is at 0.45sec for the open loop system. The voltage magnitude is also maintained at 48V in closed loop whereas the voltage for the open loop is at 55V.

4. CONCLUSION

This research work has presented a multiport DC–DC converter with bidirectional flow of power to link the two inputs at different voltage levels and two outputs with different power but same voltage. The switches control the operations of the converter either in buck or in boost and flow of power flow. It is possible to control the power flow between the battery and loads in battery mode as well as in regenerative mode of operation. This research work stretches detailed analysis of all possible states with different modes of operation of the converter. In each state, the relationship between the sources, source and loads are derived,

which assists in the calculation of duty ratio to implement the controller for switching the switches. The converter is designed for a typical hybrid PV powered vehicle has been described. The interfacing of the outputs, Battery bank and PV Panels has been explained with all possible power flow. The performance of the designed MPBC is verified using MATLAB/Simulink. This converter finds application not only in PV power vehicle but also deployed in battery management system and distributed energy resources etc., where two dc sources interfaced with bidirectional ability for flowing the power. The modification with PI regulator for voltage control validates that the output voltage can be maintained at the desired value in variable conditions. The output voltage is maintained at 48.5V for the given reference of 48V.

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