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(Review)

Solar PV Fed Parallel SEPIC Converter for Highly Efficient Multilevel Inverter Integration

Shyam D[1,*], Sivamani D[2], Jaiganesh R[3] and Narendiran S[4]

[1] Department of EEE, Rajalakshmi Engineering College,Chennai, India; shyam.d@rajalakshmi.edu.in
[2] Department of EEE, Rajalakshmi Engineering College,Chennai, India; sivamani.d@rajalakshmi.edu.in
[3] Department of EEE, K. Ramakrishnan College of Technology, Trichy, India; jaiganesh.ram@gmail.com
[4] Department of ICE, Sri Krishna College of Technology, Coimbatore, India; narendiran.s@skct.edu.in
* Correspondence: shyam.d@rajalakshmi.edu.in; Tel.: +91-8428781270

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Abstract: In present occasions, sustainable sources of energy are increasingly valued worldwide because of energy shortage and environmental contamination. High step-up DC/DC converters are broadly utilized in sustainable power source applications, including photovoltaic frameworks. To satisfy the expanding power need, usage of the accessible vitality (Renewable vitality) is the promising answer for it. Solar Photovoltaic based Parallel Single Ended Primary Inductance Converter (SEPIC) fed resistive load and PMDC motor can be designed to obtain the desired voltage. SEPIC converter suitable for the PV applications, here the focus is made on a simple and cost-effective converter for the open-loop and closed-loop control design the SEPIC converter is capable of extracting PV power while extracting the available power from the PV source, which ensures the effective utilization of the renewable source. The circuit used Parallel based topology. To achieve high current ratings and reduce the ripple, the SEPIC converter is suggested. The simulation will be done with R load as well as with PMDC motor. The simulation work of the Parallel SEPIC converter fed R load and PMDC motor circuits with an open and closed loop with PI filter have been done using MATLAB software. Thus, voltage ripples are reduced and efficiency can be improved when compared with the conventional buck-boost converter. PI controller is used for the closed-loop system. A microcontroller used to generate pulses for controlling the SEPIC converter implemented in hardware.

Keywords: SEPIC converter; PV module; MPPT Algorithm; PMDC motor;

1. Introduction

Sustainable sources of energy are progressively dominant all over the world because of the shortage of supply-load demand and ecological pollution. Sustainable power source like solar and wind produce low output voltage. So high step- up DC/DC converters are generally utilized in numerous sustainable power source applications, including wind energy, fuel cells and Photovoltaic systems [1]. Among various sustainable power sources, photovoltaic system plays a significant role in future dominance which converts light energy into electrical energy by means of a step-up converter [2] (pp. 10403 – 10409). The Photovoltaic panel with maximum power point tracker is employed in most of the photovoltaic applications. As the name implied, it is a Photovoltaic system that uses the Photovoltaic array as a source of electrical power supply and since every Photovoltaic (PV) array has an optimum operating point, called the maximum power point, which varies depending on cell temperature, the insulation level and array voltage [3]. A Maximum Power Point Tracker (MPPT) is needed to operate the PV array at its Maximum PowerPoint. Aforementioned advantages of the Single-Ended Primary-Inductor Converter (SEPIC) makes its integral characteristics suitable for the solar photovoltaic (SPV) array. The SEPIC has been used for MPPT in various SPV based applications such as PV chargers and standalone PV systems. Because of cost and efficiency, the SEPIC is not used for high power applications. So, interfacing the SEPIC converter with the multilevel inverter would produce better output voltage by mitigating the harmonic level in the inverter side which allows the converter for medium and high- power applications [4] (pp.1-11).

The SEPIC converter has plenty of benefits rather than compared to other converters which produces non-modifying extremity output voltage with low input current pulsation. Other than these, the SEPIC converter drives as a DC-DC buck-boost converter with increase or decrease in the input voltage level at its output side [5](pp.1290 – 1297). The SEPIC is a DC-DC converter that possesses important characteristics such as reduced output ripple, high efficiency, and high-voltage transfer gain. It is mostly utilized in numerous different applications like cell phone battery charger, electronic stabilizer, media communications and DC power supplies [6][16](pp. 1053-1071). High-efficiency DC/DC boost converter must be used to increase the overall efficiency of the system. Perturb and observe (P and O) calculation has been utilized as the conventional method to decide MPPT. This calculation is straightforward and productive to decide the maximum power point (MPP). The soft switching strategy will be added to the execution of MPPT SEPIC Converter to reduce the switching losses in the system. The outcomes of the MPPT technique would increase the output voltage of PV [7] (pp. 673 – 681).

The power intensity of PV module is influenced by the measure of illumination of sun (amount of irradiation) and temperature of PV module. The difficulty that may arise during partial shading which may be caused due to environmental changes and uneven disturbances by objects such as heavy rains, shading of trees and buildings, mist formation, and so on. The uneven effect arises from different sources decreases the output power of PV system which reduces the effect of maximum power point (MPP) of PV characteristic curve will be more than one which requires GMPP (Global Maximum Power Point) and LMPP (Local Maximum Power Point). This case can't be explained based on the standard MPPT (Maximum Power Point Tracking) technique which only analyzes the ground work to attain maximum power caught on local points (LMPP). Modified P&O (Perturb and Observe) technique is used for MPPT strategy under partial shading condition to actualize on SEPIC converter to get genuine Global Maximum Power Point (GMPP) [8](pp.89857- 89868). Investigation results demonstrate the Modified P&O technique can create more noteworthy results of output power and provides quicker charging process to the battery [9] (pp. 129-133)-[10](pp. 1213 – 1222).

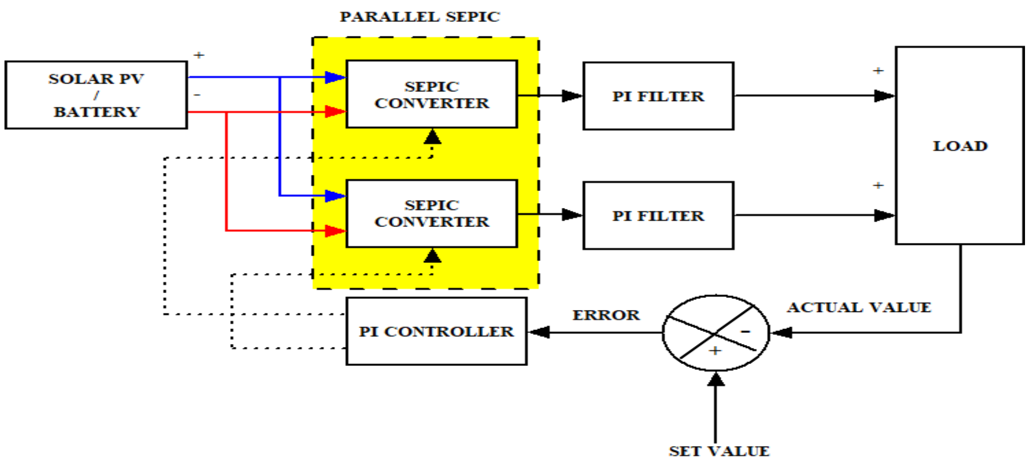


Figure 1. Block diagram of parallel SEPIC converter

Parallel connected SEPIC converter used to obtain regulated voltage and control the PMDC motor. Obtain Maximum Power by constant voltage method. Besides, current ratings are high and input current ripples and output voltage ripples of SEPIC converter are lower than those of the conventional topologies [11](pp. 3388 – 3394). closed-loop parallel SEPIC converter used to control the speed of PMDC motor with ripples free, which can be possible by connecting the PI filter and PI controller used as feedback. An analogue control circuit is designed to generate pulse width modulation (PWM) signals and to fulfil the closed-loop control function [12] (pp. 1-4).

2. SYSTEM MODEL OF PARALLEL SEPIC CONVERTER

The functional block diagram of the parallel SEPIC converter is shown in Figure.1. Solar power is given into a parallel SEPIC converter and it is connected into the PI filter then fed to Resistive load. The PI filter circuit comprises of two capacitors associated in equal followed by an inductor in series framing a Pi shape. PI filter produces high impedance at high frequency and low impedance at low frequency in the transmission line. The output voltage of a load can be compared with the reference voltage, Maximum Power Tracking and obtained control voltage given into a gate of two SEPIC converters.

The main aim of this work is an efficient design of solar panel for constant Current-Voltage (V-I) characteristics of a Photovoltaic array of various environmental conditions like different irradiance and temperature. A proposed model uses constant environmental condition in combination with actual solar radiation and ambient temperature.The new design is developed on MATLAB-Simulink platform for calculating and analyzing the power output from a PV panel by taking the values of current and voltage with constantly varying solar radiation at any geographical location and different day.

The execution of SEPIC converter and voltage source inverter for resistive and motor load utilizes photovoltaic vitality as a source. For the most part of the drives application which is utilized for commercial and industrial applications uses permanent magnet DC (PMDC) motor drives. To run such sort of motor application from the PV source, it is proposed to have a DC-DC converter and multilevel inverter circuit interfaced with each other [15] (pp. 5525-5532) which is shown in Figure 2. As the PV cell were grouped into modules which possess the nonlinear conduct behavior, a DC-DC converter with Maximum Power Point Tracker (MPPT) controller is expected to improve its proficiency level and helps in coordinating with the load to the Photovoltaic modules. The output power of solar panel is directly given to DC /DC controller to reduce circuit complexity. The estimation of MPP (maximum power point) of a Photovoltaic (PV) array is done by calculating the value of both ampere, voltage and power curves for changing environmental conditions. The PI filter is designed for Parallel SEPIC converter which is progressively dependable and effective approach to build the power rating of the SEPIC module by expelling the breaking point of the current ceiling of power semiconductors switches.

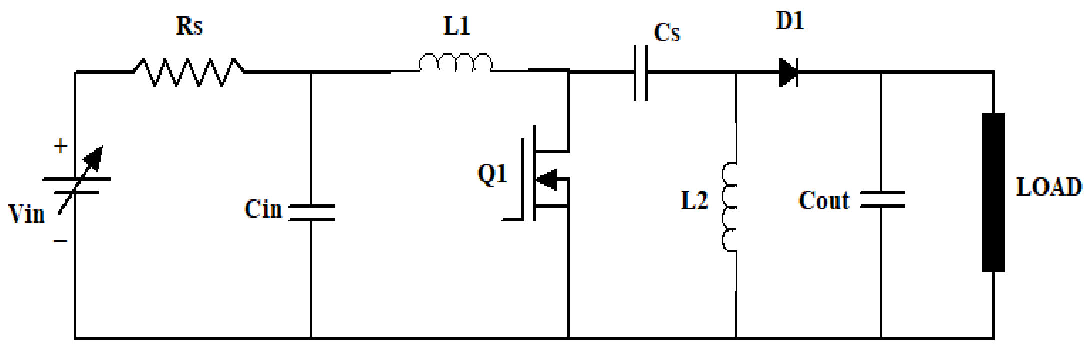


Figure 2 Single stage SEPIC converter with input DC source

3. DESIGN CALCULATION (SEPIC AND PARALLEL SEPIC CONVERTER)

The operation of the parallel SEPIC converter is very similar to SEPIC converter where parallel SEPIC is operated for multiple stages which is illustrated in Figure 3. The design of SEPIC converter is shown in Figure 2. Usually SEPIC converter is operated in two modes of conduction: One is continuous conduction mode (CCM) and discontinuous conduction mode (DCM).

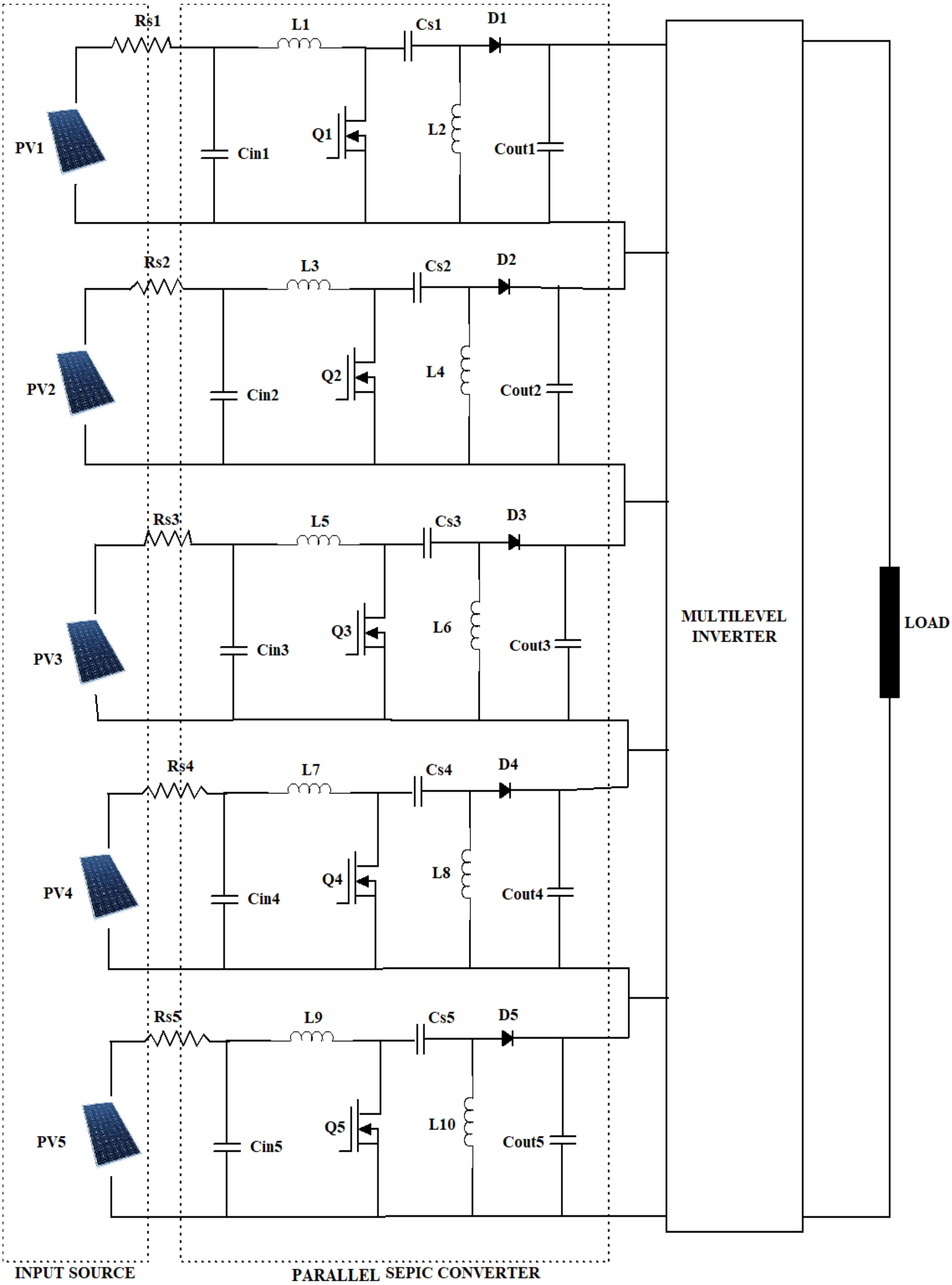


Figure 3. Block diagram ofParallel SEPIC converter interfaced with multilevel inverter with input PV

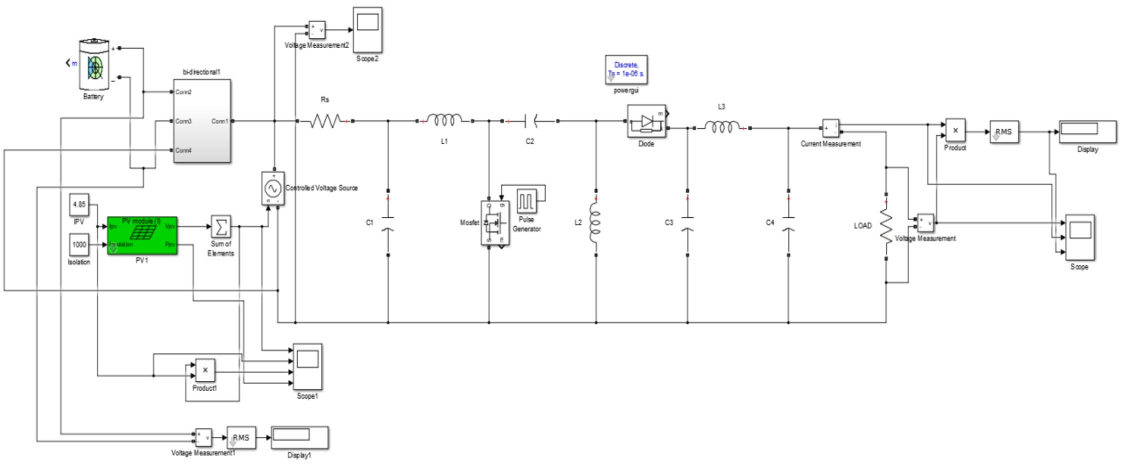
4.SIMULATION RESULTS OF SEPIC AND CASCDED SEPIC CONVERTER

4.1. OPEN LOOP SEPIC CONVERTER FOR RESISTIVE AND MOTOR LOAD

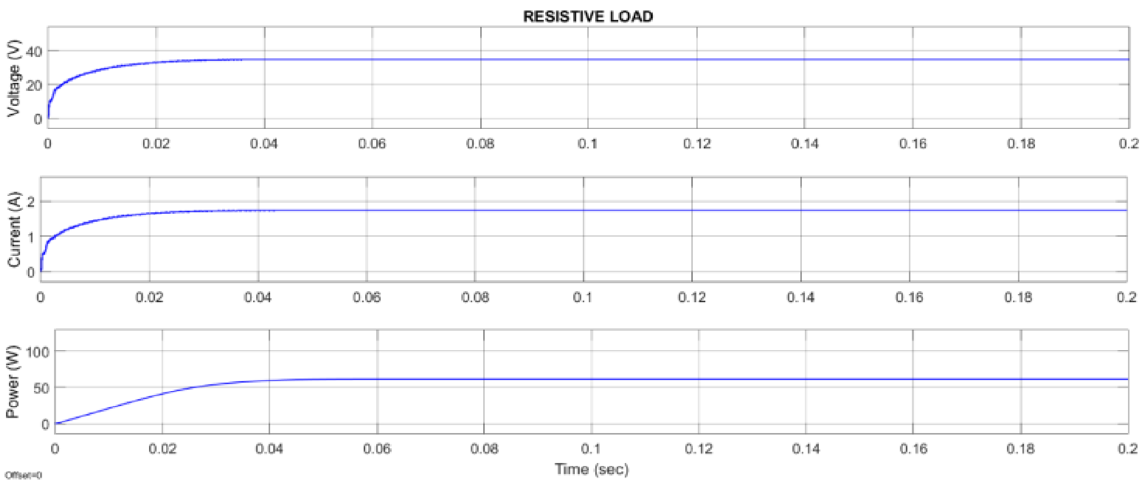
The proposed system works on Continuous conduction mode (CCM) as the current through the inductor (L1) does not reach zero. Before going into these modes, one has to know the importance of the duty cycle because duty cycle of the controlled switch (Q) determines the output of the SEPIC converter [13] (pp. 3562 – 3570).

$$Duty\ Cycle\ (D) = \frac{V_{out} + V_D}{V_{in} + V_{out} + V_D} \quad (1)$$

For example, if one has a requirement of output voltage (Vout) of 36V from a 12V input DC source (Vin) from a SEPIC converter where VD is the voltage drop of diode (D1) under forward condition. So, the output gain of three is required for conversion. The duty cycle for the above-mentioned problem is taken as 0.75 which is derived from Eqs.(1). The simulation results were discussed for resistive load for SEPIC converter with PV module interfaced with battery in Figure 4 in order to illustrate the design consideration.



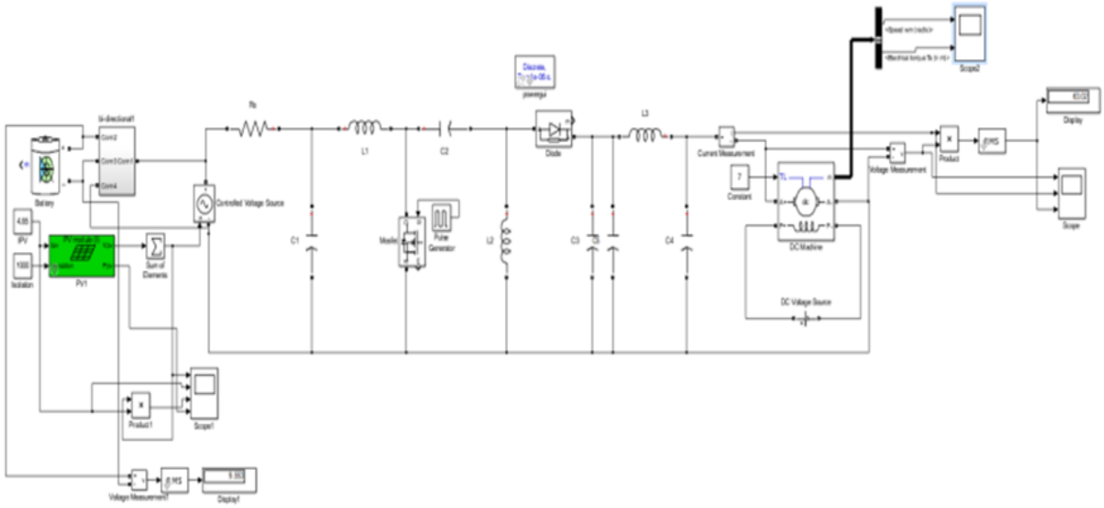
(a) Open loop simulation model of SEPIC converter with Resistive load



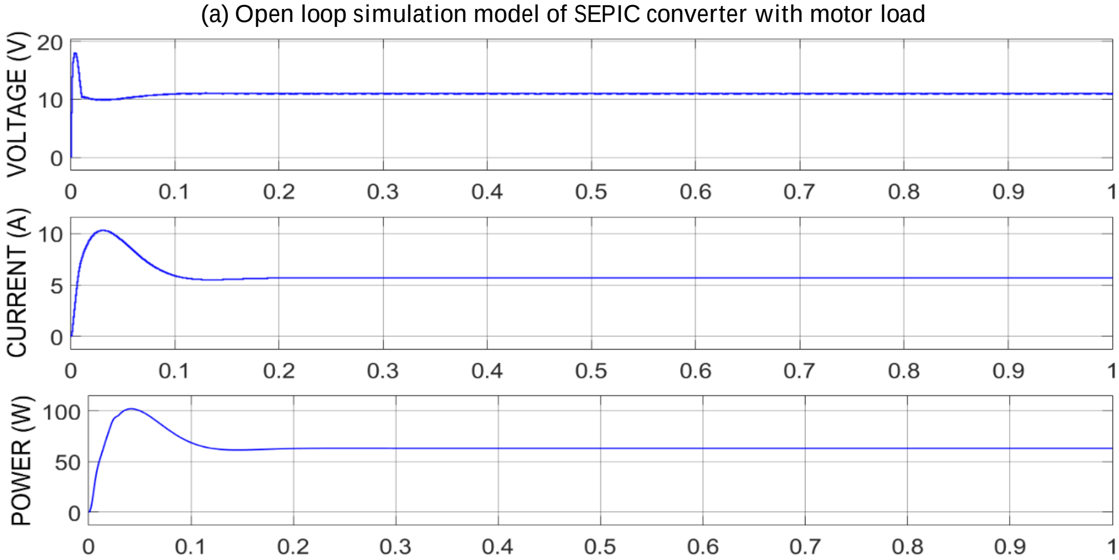
(b) Output results of SEPIC converter with Resistive load

Figure 4. Open loop simulation results of SEPIC converter with PV module for resistive load

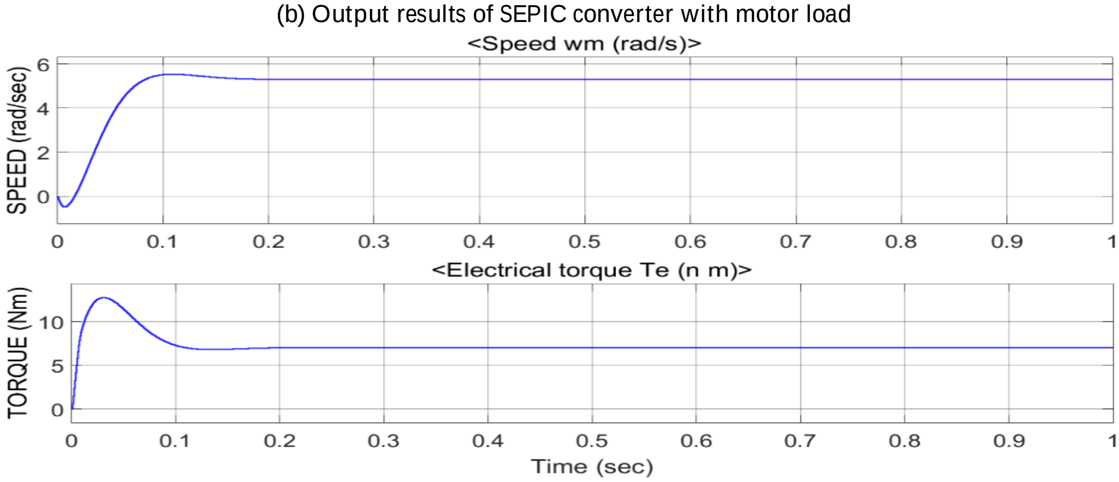
The simulation results were carried on open loop analysis of SEPIC converter with motor load. The motor load taken for analysis from MATLAB/Simulink is Separately excited DC motor which is shown in Figure 5. The input source of the SEPIC converter is taken as variable DC source which is fed from PV module interfaced with battery source for providing constant supply during cut-off. The output of the PV module needs to be operated at 12V DC supply even during shading condition with the help of battery.



(a) Open loop simulation model of SEPIC converter with motor load



(b) Output results of SEPIC converter with motor load



(c) Speed and Torque waveform of SEPIC converter with motor load

Figure 5. Open loop simulation results of SEPIC converter with PV module for motor load

The design specifications for open loop SEPIC converter for both resistive and motor load is discussed in Table 1. The basic rule for finding the inductance value (L1 and L2) of the SEPIC converter is to determine the ripple current (peak-peak) by approximating 40% of output voltage and output current at minimum input voltage.

$$\Delta I_L = \frac{0.40 \,.\, V_{out} \cdot I_{out}}{V_{in\,(min)}} \tag{2}$$

$$L1 = L2 = \frac{V_{in(min)} \,.\, D}{\Delta I_L \,.\, F_{sw}} \tag{3}$$

From the above equations Eqs.(2- 3), determination the inductance value L1 and L2 can be found out and replicated in the simulation model in order to produce the required results. The results of open loop system from SEPIC converter for both resistive and motor load is shown in Figure 4 and Figure 5. During the switching of MOSFET, switching operation were carried based on the modes of operation. When the MOSFET switch (Q1) is turned ON, the inductor starts to charge and the output load current (IL) is fed from the output capacitance (C_{out}) which is indicated in equations Eqs. (4-5).

$$I_{cs(rms)} = I_{out} \cdot \sqrt{\frac{V_{out} + V_D}{V_{in(min)}}} \tag{4}$$

$$C_{out} \geq \frac{I_{out} \,.\, D}{V_{ripple} \,.\, 0.5 \,.\, F_{sw}} \tag{5}$$

Due to this process, the output capacitance produces large ripples across the load which can be minimized on proper selection of output capacitor. The input capacitor will handle the RMS current which is present near the supply voltage reducing the effects of impedance effect with the supply system.

4.2. OPEN LOOP PARALLEL SEPIC CONVERTER FOR RESISTIVE AND MOTOR LOAD

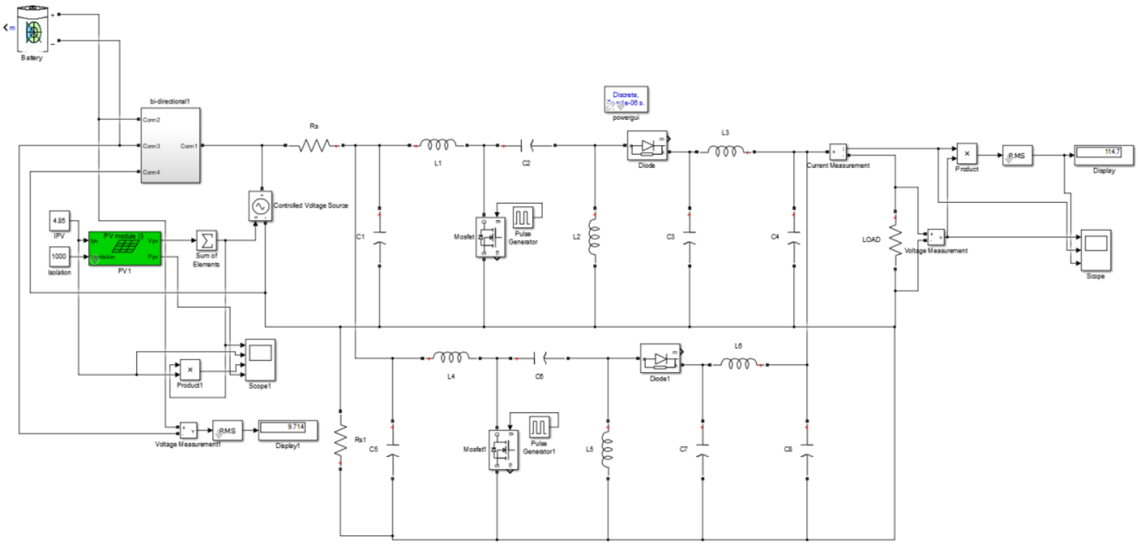
The parallel SEPIC converter is done for two stages in the proposed paper. For multilevel level outputs, the exact design would go for multiple stages. For nine level parallel multilevel output requires four supply sources which can be replaced by this parallel SEPIC converter interfaced with solar PV modules. For eleven level parallel multilevel output which requires five supply sources which is shown in Figure 3. Equations which are applicable for SEPIC converter is very much similar to parallel SEPIC converter too. The modes of operation of two stage parallel SEPIC converter for resistive load is shown in Table 1.

Table 1. Modes of operation for open loop analysis of two stage Parallel SEPIC converter

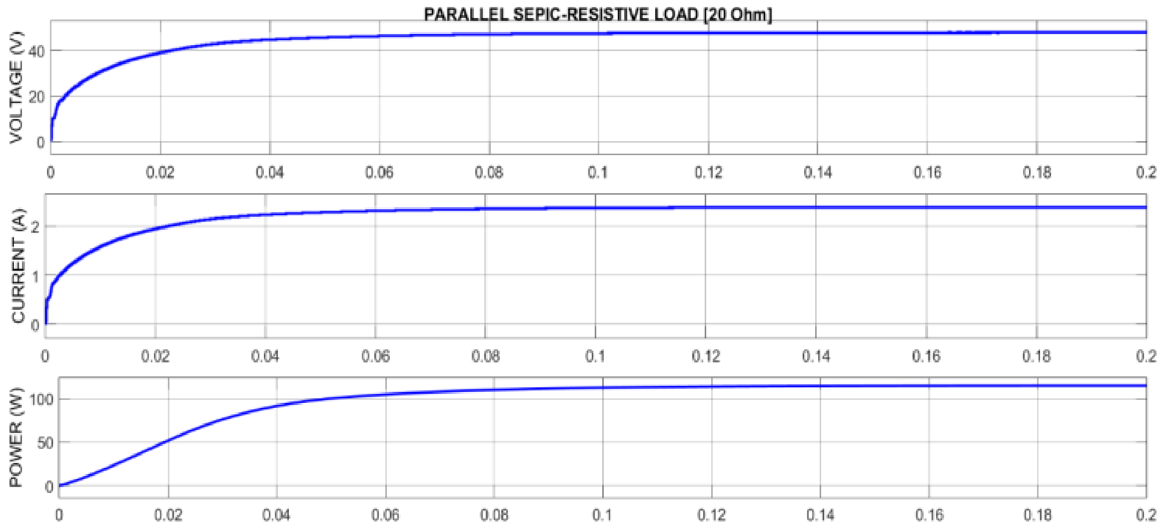
Modes of Operation	Switch I (Q1)	Switch II (Q2)	Remarks
Mode I	ON	OFF	Inductor is charged
Mode II	OFF	OFF	Energy transferred to output capacitor
Mode III	OFF	ON	Inductor gets charged
Mode IV	ON	ON	Inductor provide supply to load

The open loop control of the Parallel SEPIC converter for resistive and motor load is discussed in next chapter which is illustrated in Figure 5 and Figure 6.By varying the load resistance, the output voltage across the load increases with decrease in output current. This has been illustrated by taking two values of load resistances of 20 Ω and 10 Ω of Parallel SEPIC converter which is shown in

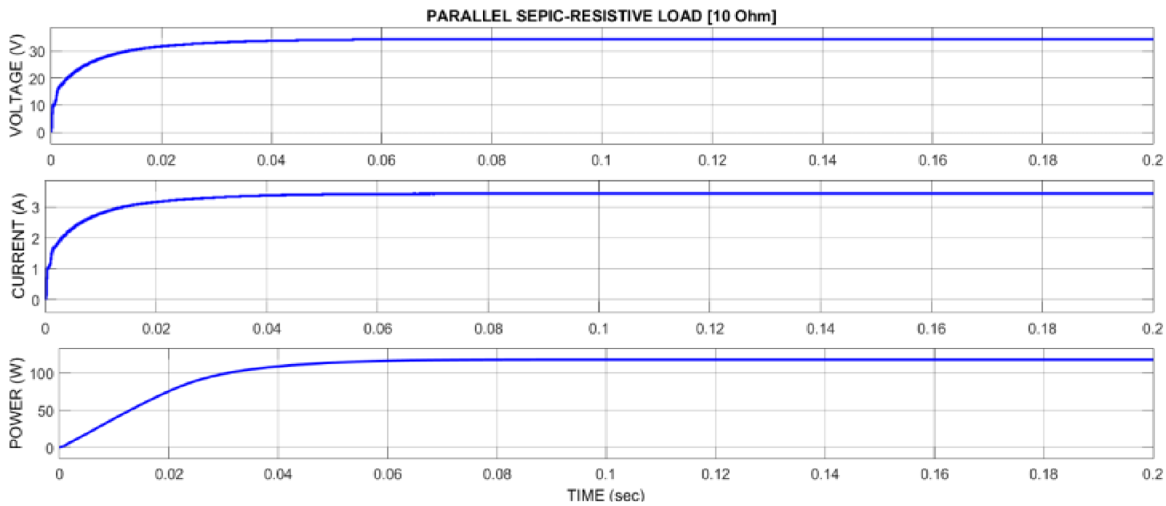
Figure 6(b) and 6(c). Load variation need to observed before integrating with the multilevel inverter which requires constant voltage.



(a) Open loop simulation model of Parallel SEPIC converter with Resistive load



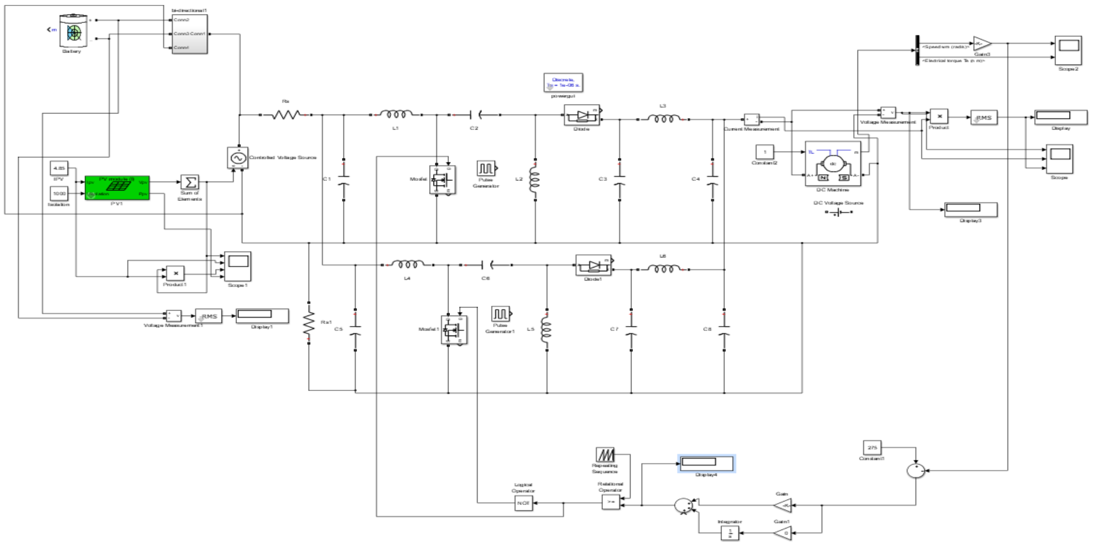
(b) Output results of SEPIC converter with Resistive load (20 ohm)



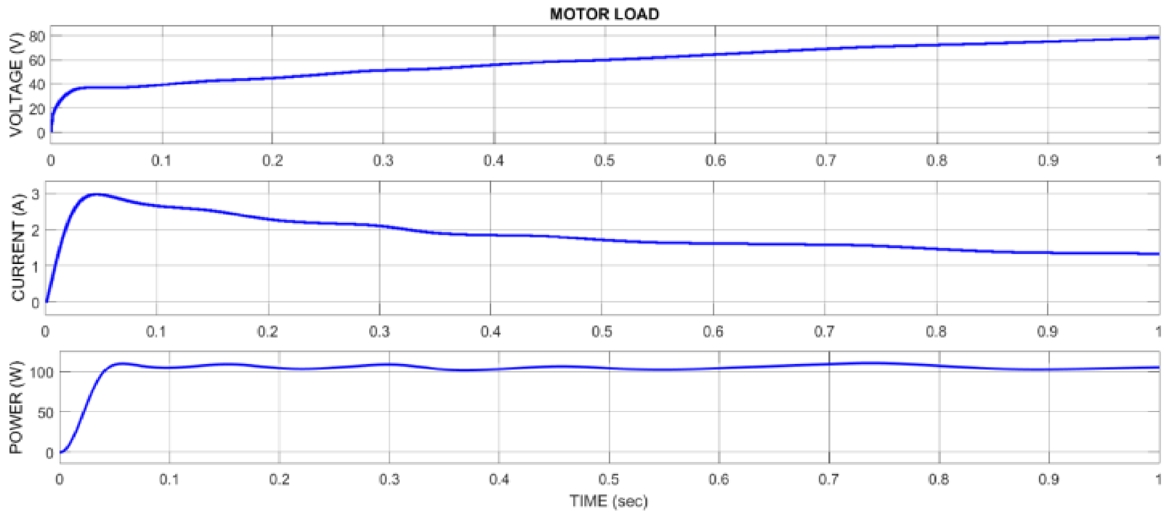
(c) Output results of SEPIC converter with Resistive load (10 ohm)

Figure 6. Open loop simulation results of Parallel SEPIC converter with PV module for resistive load

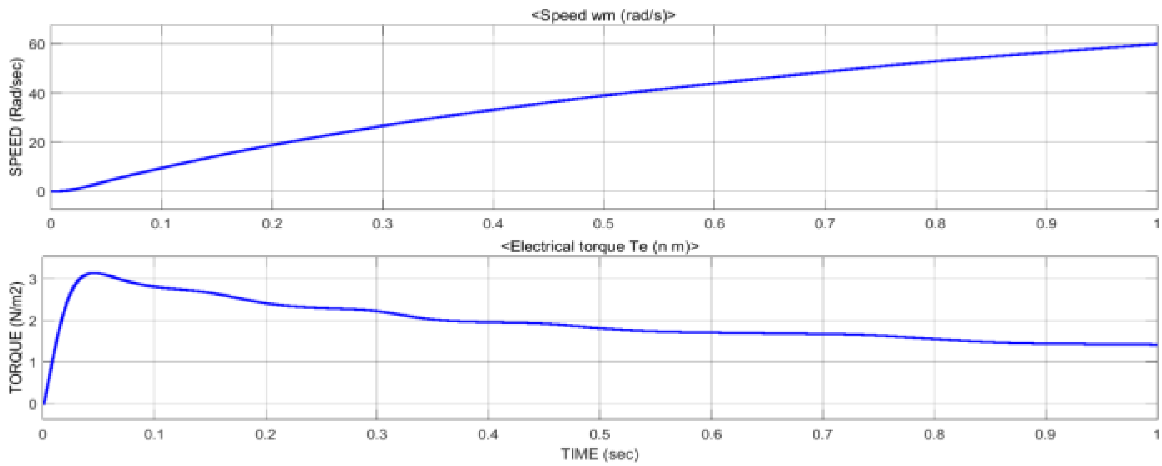
Open loop analysis was performed on Parallel SEPIC converter for two stages with motor load. The motor load uses separately excited field motor which is shown in Figure 7(a) and its simulation results were shown in Figure 7(b) and Figure 7(c).



(a) Open loop simulation model of Parallel SEPIC converter with motor load



(b) Output results of Parallel SEPIC converter with motor load



(c) Speed and Torque waveform of Parallel SEPIC converter with motor load

Figure 7. Open loop simulation results of Parallel SEPIC converter with PV module for motor load

Open loop design specifications details were provided in Table 2 for both SEPIC and Parallel SEPIC converter which is used in MATLAB/Simulink 2015b. The battery source which is used for storing from the PV module for both SEPIC and Parallel SEPIC is Nickel metal hydride which uses nominal voltage of 10 V.

Table 2. Design specification on open loop analysis for SEPIC and Parallel SEPIC converter

Specifications	Parameters Used
Battery	NICKEL METAL HYDRIDE
Battery Nominal Voltage	10 V
Battery Rated Capacity	1.5 Ah
Battery Response Time	30 sec
Internal Resistance of The Battery During Discharge	0.066 ohm
Battery Nominal Discharge Current	0.3 A
Switches Used	MOSFET
PV Module Open Circuit Voltage	12 V
PV Module Short Circuit Current	5.15 A
Irradiance	1000 W/m^2
Internal Resistance of SEPIC/Parallel SEPIC	0.001ohm
Capacitance	470 µF
Switching frequency	1 KHz
Resistive Load	10 Ω, 20 Ω
Field excitation voltage (Open loop)	150 V
Motor specification- wound field (Open loop)	5HP, 500V, 1750 RPM
Motor Load	DC Machine

Closed loop specifications details were provided in Table 3 for both SEPIC and Parallel SEPIC converter with resistive and motor load. Almost all the parameters taken from Table 2 for resistive load is very similar to that of open loop. Therefore, the specifications taken for closed loop control using motor load is specified in Table 3 for both SEPIC and Parallel SEPIC converter.

Table 3. Design specification on closed loop analysis for SEPIC and Parallel SEPIC converter

Motor Specifications	Parameter used
Motor specification- Permanent magnet	
Armature resistance (Ra)	11.2 ohm
Armature inductance (La)	0.1215 H
Torque constant	1.8 N.m/A
Total inertia J	0.02215 kg.m^2
Initial field current	0.533 A
Viscous friction coefficient (Bm)	0.002953 N.m.s

The simulation output results obtain from MATLAB/Simulink is mapped in the Table 4 from open loop analysis done for SEPIC and Two sage Parallel SEPIC converter to better understand its feasibility in implementation on hardware platform. The results were comparatively better for parallel SEPIC converter when compared with SEPIC converter for both resistive and motor load under open loop condition. It is necessary to check closed loop analysis in order to determine its feasibility.

Table 4. Comparative results obtained from open loop analysis for SEPIC and Parallel SEPIC converter

Topology	Load used	Vin(V)	Vout(V)	Io(A)	Po(W)
SEPIC	Resistive (20 Ω)	12	38	1.8	68
	Motor load	12	55	1.1	60
Parallel SEPIC	Resistive (20 Ω)	12	45	2.5	112
	Resistive (10 Ω)	12	35	3.5	122
	Motor load	12	80	1.4	112

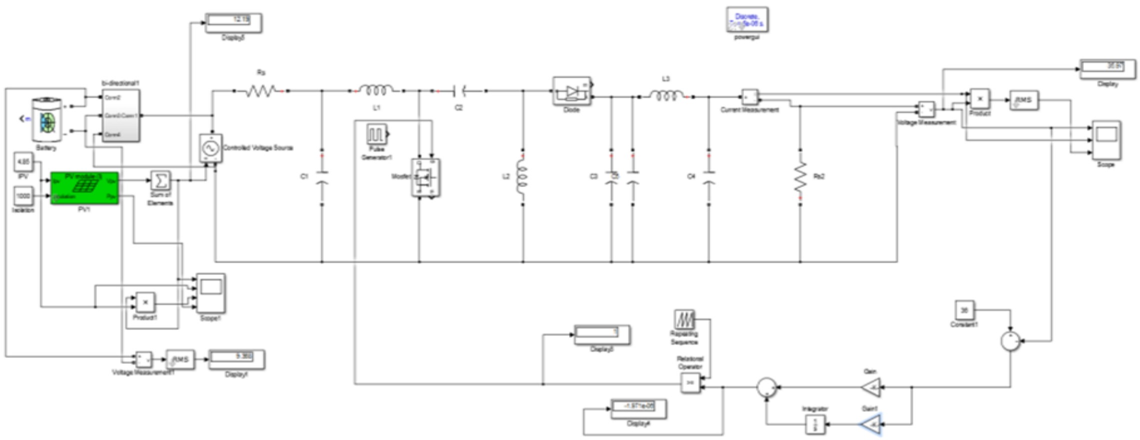
4.3. CLOSED LOOP OF SEPIC CONVERTER FOR RESISTIVE AND MOTOR LOAD

The closed loop parallel SEPIC converter is designed for MPPT controller which provides the relationship between P-V and V-I characteristic curve obtained from the solar module with constant Io and Isc.

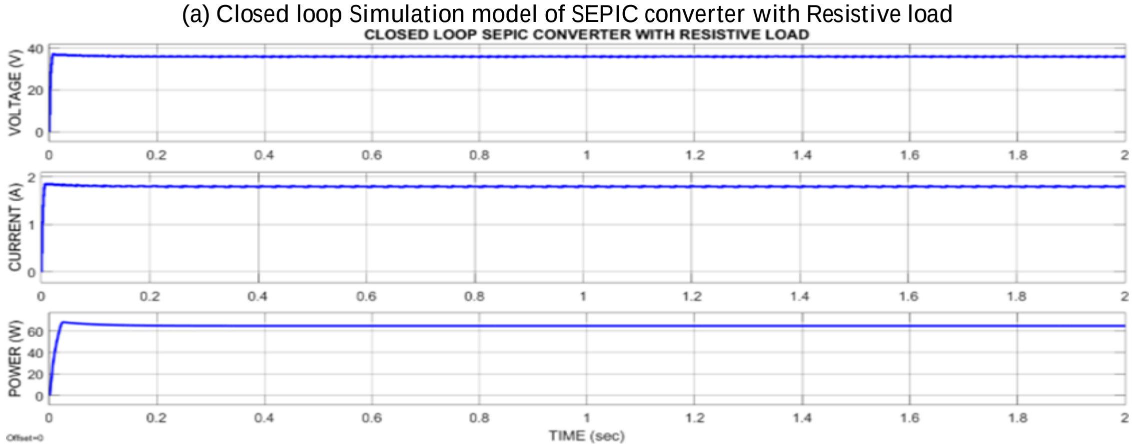
$$I_{pv} = I_{ph} - I_D - I_{shunt} \tag{6}$$

$$I_{pv} = I_{ph} - I_o * \left[exp\left(\frac{V_{pv} + I_{pv} * R_s}{N_s * \left(\frac{\eta K_b T}{q} \right)} \right) - 1 \right] - \frac{V_{pv} + I_{pv} * R_s}{R_{sh}} \tag{7}$$

$$Impedance\ of\ PI\ filter\ (Z_0) = \sqrt{\frac{L}{C}} \tag{8}$$



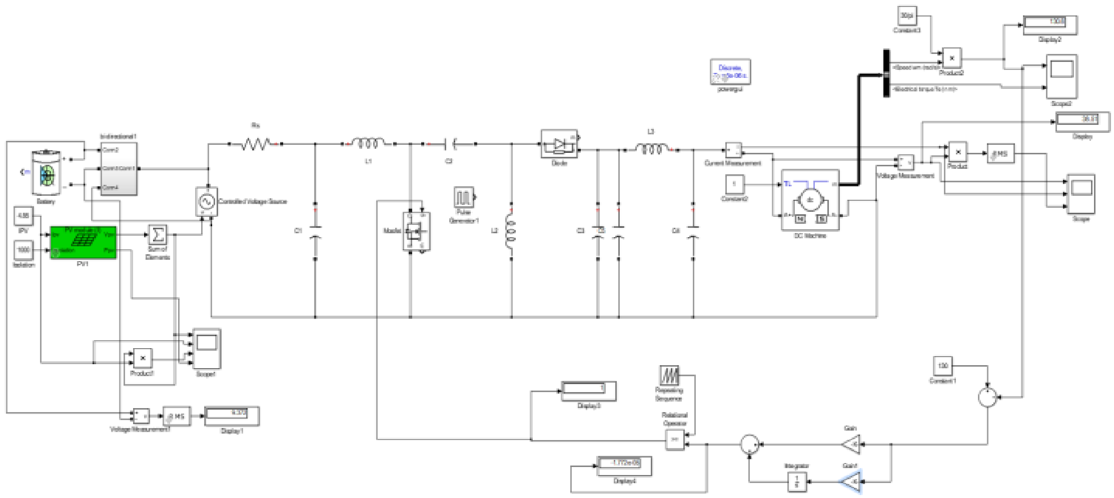
(a) Closed loop Simulation model of SEPIC converter with Resistive load



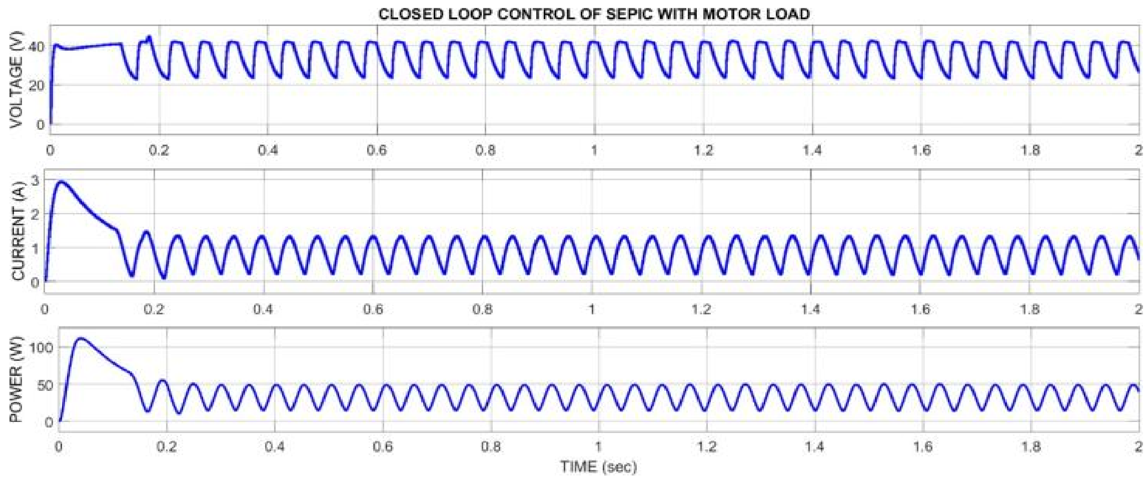
(b) Output results of SEPIC converter with Resistive load

Figure 8. Closed loop simulation results of SEPIC converter with PV module for resistive load

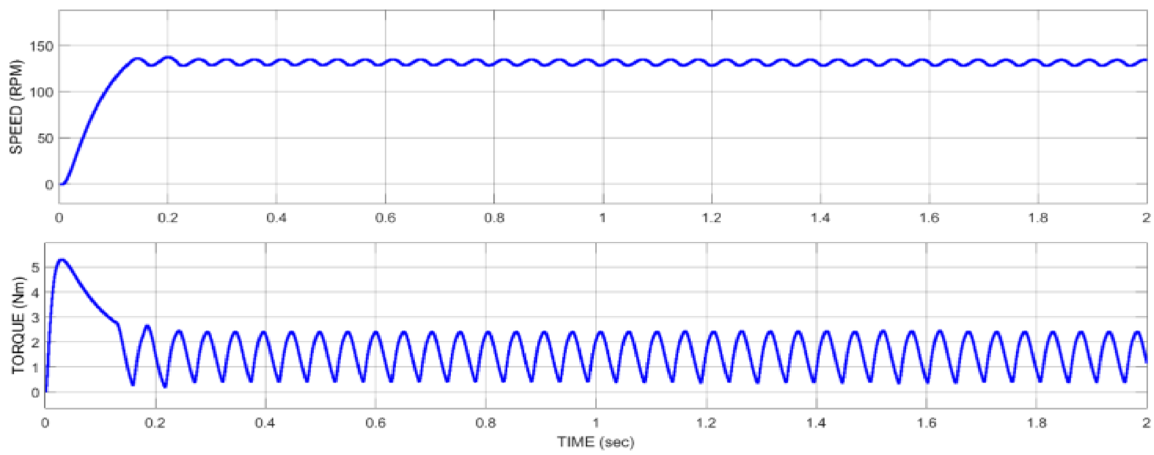
The conductance value of the solar module is taken to find the ratio of both short circuit current (Isc) and open circuit voltage (Voc) where Isc denotes the maximum current which flows in the circuit panel when it is shorted, Rsh and Rs denotes shunt and series resistance which is shown in equations Eqs. (6-7). The closed loop control of the SEPIC converter is discussed and illustrated in Figure 8 and Figure 9.



(a) Closed loop simulation model of SEPIC converter with motor load



(b) Output results of SEPIC converter with motor load



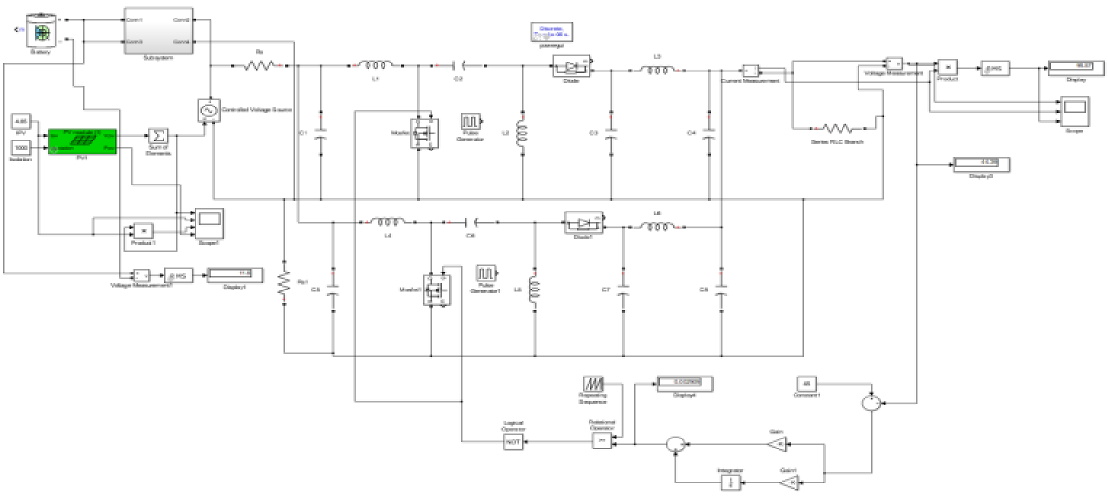
(c) Speed and Torque waveform of SEPIC converter with motor load

Figure 9. Closed loop simulation results of SEPIC converter with PV module for motor load

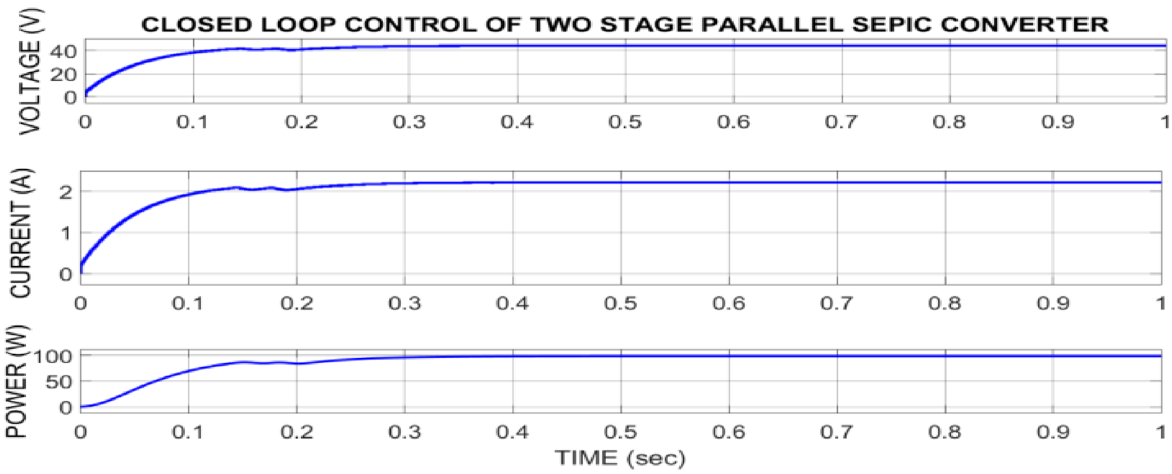
To remove the larger ripple current from the system, PI filter is introduced after the SEPIC converter which reduces the ripple content. PI filter consist of two capacitors connected in parallel with series inductor. The filter calculation was made to suppress the ripples in the output side. There are different of filters that can be used but for integration with multilevel inverter, PI filter would be best suited which is shown in equation Eqs.(8). The motor load used for closed loop control of SEPIC converter uses Permanent Magnet DC motor which is shown in Figure 8. The closed loop controller used for both resistive load and motor load is Proportional-Integral controller. For resistive load, output voltage is controlled and for motor load, rotor speed of PMDC motor is controlled.

4.4. CLOSED LOOP OF PARALLEL SEPIC CONVERTER FOR RESISTIVE AND MOTOR LOAD

Simulation analysis for closed loop parallel SEPIC converter is used to control the output voltage for resistive load and speed of PMDC motor for motor load with reduced ripples, which can be achieved by connecting PI filter in between the system module and load. Parallel connection of the SEPIC converter is the effective way of expanding the power rating of the proposed system. Different switching strategies can be used to effective utilization of the switches. This reduces the conduction and switching losses from the proposed model.



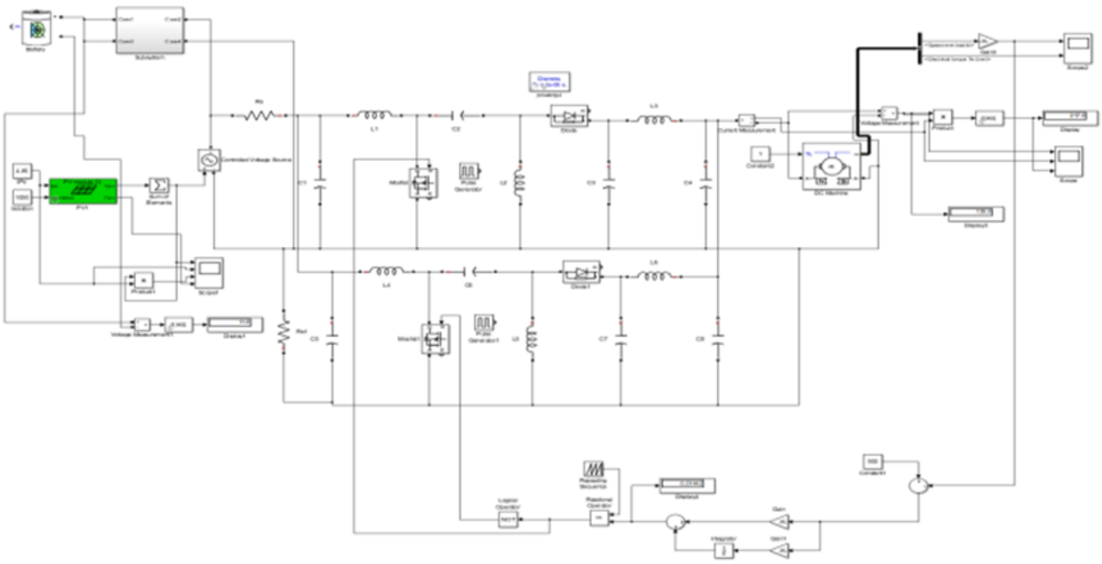
(a) Closed loop Simulation model of Parallel SEPIC converter with Resistive load



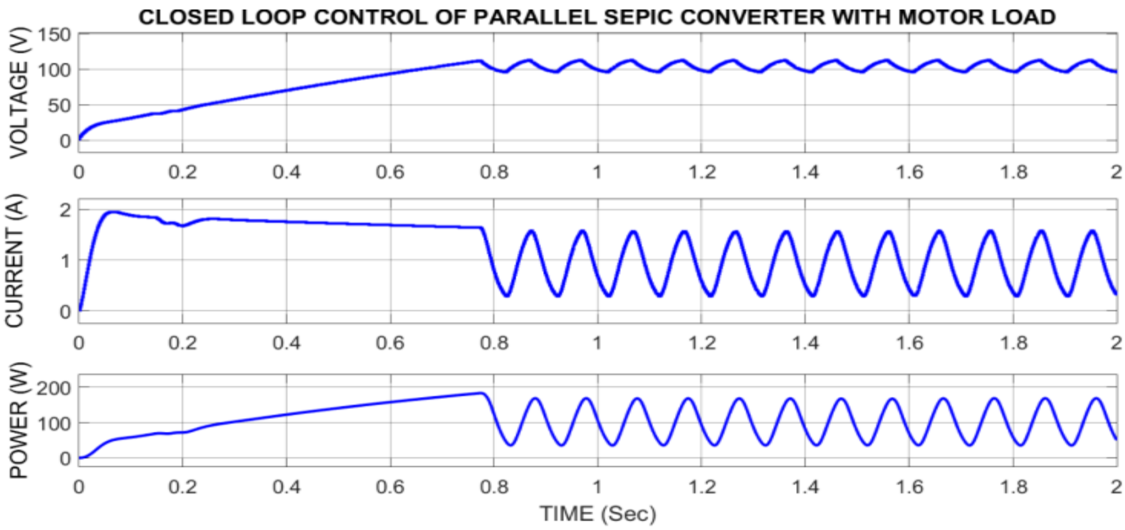
(b) Output results of Parallel SEPIC converter with Resistive load

Figure 10. Closed loop simulation results of Parallel SEPIC converter with PV module for resistive load

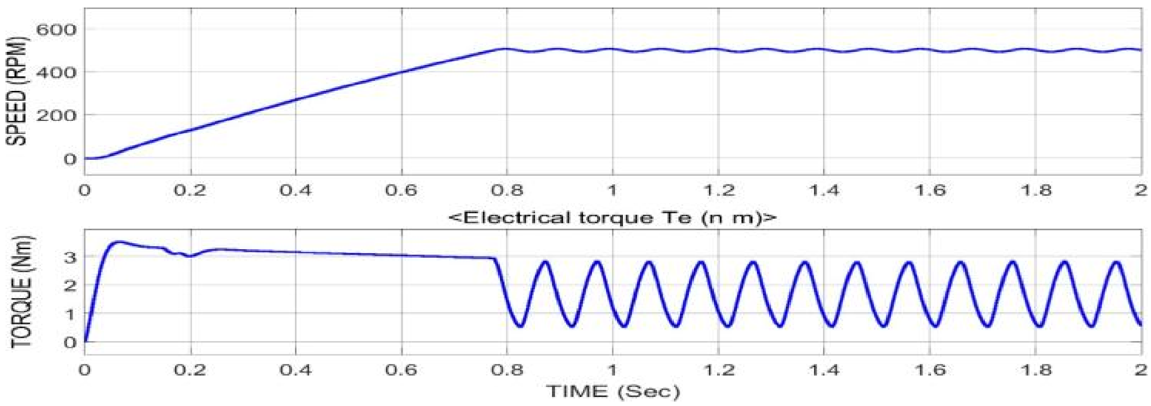
The inductance value of L1 is similar and equal to L3 and L2 is similar and equal to L4 for the proposed two stage parallel SEPIC converter. The results of the open loop is taken as the reference value of the closed loop control.



(a) Closed loop simulation model of Parallel SEPIC converter with motor load



(b) Output results of Parallel SEPIC converter with motor load



(c) Speed and Torque waveform of Parallel SEPIC converter with motor load

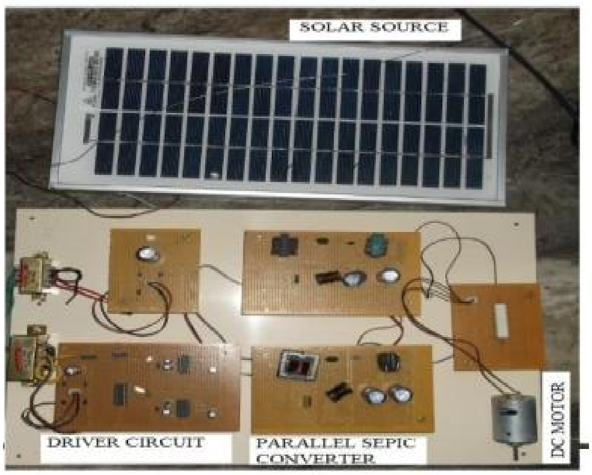
Figure 11. Closed loop simulation results of Parallel SEPIC converter with PV module for motor load

The reference value of the output voltage for resistive load can be kept till 45V. If the voltage value kept beyond 45V, there would be lot of oscillations in the system with increased ripples and it will take lot of time to settle down. The reference value of the motor load is taken from the rotor speed of PMDC motor which is kept as 500 RPM. Proportional Integral controller is used as the feedback circuit for the controller. The closed loop simulation of the two-stage parallel SEPIC converter for resistive load is shown in Figure 10 and for motor load is shown in Figure 11. The structured SEPIC and Parallel SEPIC converter works well with closed loop control with reduced EMI effects. In Closed loop control of Parallel SEPIC converter only one stage works at a time. During the load operation when the load current operates over half of its period, then the other stage starts to operate which provides the load current. Even under different load conditions, there would be certain load voltage that will be always maintained. The problem which one would face during low voltage condition is low voltage ride through capability (LVRT). There should be minimum amount of voltage that should run the system in order to safe guard from blackout. So, this can be overcome by moving into Parallel SEPIC. Due to mutual operation of the switches, there will be less operational losses which affects the system.

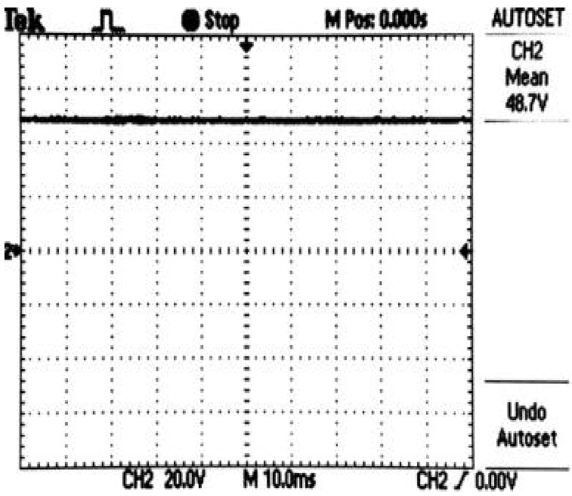
The Proportional Integral value for the closed loop system is given as 0.000012 and 0.015. The torque of the parallel system under motor load produces oscillations after it reaches the base value of 500 RPM whereas the time taken to reach the reference speed is also more and it maintains the base speed. When resistive load is used, Parallel SEPIC converter does not face any issue in order to maintain constant output voltage whereas for SEPIC converter faces oscillations issues after reaching the base voltage. Also, the output current oscillates near to the origin. It is proven from the simulation results that the Parallel system would be better compared to normal SEPIC converter. Parallel SEPIC is carried under different variations such as line regulation, load regulation, steady state condition to produce constant voltage. PWM signals are generated by designing an analog control circuitry under closed loop system. This would really provide a boost in interfacing the multilevel inverter to it.

5. HARDWARE IMPLEMENTATION OF PARALLEL SEPIC CONVERTER

The hardware implementation is done based on the simulation results carried on Parallel SEPIC converter which provides better results compared to SEPIC converter. The experimental analysis is done for the two stage Parallel SEPIC converter with resistive load and PMDC motor. The gate driver circuits which is connected to the power MOSFETs IRF840 drives the gating pulse for the proposed system through C2000 microcontroller board. The hardware model of two stage Parallel SEPIC converter and its measured output voltage was shown in Figure 12. The input of the converter is fed from solar panel as well as from 230V transformer which is step down to 12V.



(a) Hardware model



(b) Output result obtained from DSO

Figure 12. Hardware implementation of the proposed parallel SEPIC converter

During daytime the solar panel would produce the supply needed to drive the system. During night- time the normal AC supply through transformers were applied to drive the system. The Parallel SEPIC converter is designed to boost the input voltage 12V to around 46 V which is practically tested using the design specifications which is indicated in Table 5.

Table 5. Hardware specifications of Parallel SEPIC Converter

Parameters	**Hardware specifications**
Input voltage (Vin)	230~12V RMS at 50 Hz
Output Voltage (Vo)	46 V
Output Power (W)	150 W
Switching frequency (F_{SW})	1 KHz
Load resistance	100 KΩ
Output capacitance (C_{out})	100 µF
Input inductors (L1 , L2)	0.6 mH

6. Conclusions

The simulation analysis of single stage SEPIC converter and two stage (Parallel) SEPIC converter is analyzed to prove its feasibility in both open loop and closed loop system. The two stage (parallel) system can be allowed to attain higher voltages when compared to single stage SEPIC converter. The experimental setup of two stage parallel SEPIC converter has been performed to meet its performance. The output voltage waveforms of both the simulation and experimental setup for resistive and motor load were analyzed for two stage parallel SEPIC converter. During simulation, the output voltage attained is 45V whereas in experimental setup, the output voltage attained is 46.7V. This output voltage can be fed to fifteen level multilevel inverter with 46V as input for each bridge circuit. Thus, integrating the Parallel SEPIC converter with multilevel inverter is the need of the hour.

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