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SIC Based on-Board Charger for Electric Vehicles

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ABSTRACT:

Electric Vehicle which we call it as a green machinery which offers a number of return over internal combustion engines, decreased need upon fuels and reducing greenhouse effects. But according to current situation electric vehicles are not successful because of its high cost, lower range, slow charging time, limited energy storage and not fit for heavy duty. Due to these problems, electric vehicles are not successful. So for the improvement in the existing topologies, SiC based devices can be used to make electric vehicle more efficient. It will help in increasing the efficiency, reducing switching losses, saving space and also reduces the number of power electronic switches with the use of simpler topologies.

Keywords — Electric vehicle, SiC, Charger, Silicon Carbide Power Devices, Li-ion Battery

INTRODUCTION

Recently, global warming has turned out to be a major problem for car producers due to the rise in greenhouse gas emissions from internal combustion vehicles [1]. Increasing percentage of carbon and extinction of fossil fuels has become a major problem. To overcome with this problem, we need to develop a new eco-friendly vehicle.Electric Vehicle (EV) was identified as replacement for an ICE vehicle. Due to various advantages of EV interest began to grow to develop it. There are various types and design has been made for the EV, like Fuel-cell type EV, hybrid EV in which battery and fuel both used and battery type EV in which battery is used as a fuel. As EVs evolution takes place, there is a cost factor and range anxiety still poses a major problem for the EV driver. To make it more efficient many research has been done like introduction of new topologies, new SiC based devices and variety of batteries etc.

According to the current situation electric vehicles are not much preferred because of its cost factor, slow charging of batteries and limitations of on-board charger. If electric vehicle charged once then it can run for limited distance and it can’t go beyond the limit. And with this we have to search for charging stations which are not much available. These problems restrict the growth of electric vehicle. Here it is desired to design an on-board charger which can charge the batteries at faster rate, along with reducing the size and reducing the complexity of the charger.

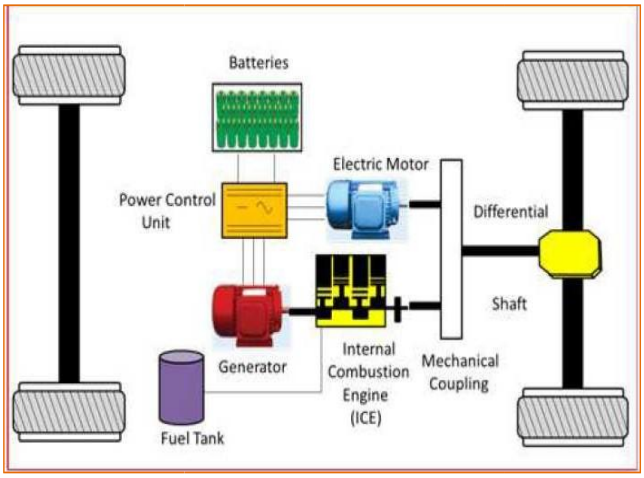


Fig. 1 Plug in hybrid electric vehicles

In this thesis work an onboard unified electric vehicle charger based on level 2 charging is designed which provides bidirectional flow of power. Conventional CCCV control algorithm is used to charge the battery at faster rate. Wideband technology is used to make the charger more efficient and simple. Fig. 1 shows Plug in hybrid electric vehicles.

II. LITERATURE REVIEW

An Many authors have conveyed their work in this field. In [1] author proposed a current controlled buck-boost converter by replacing Si diode with SiC diode. Transient current reduction has been observed through the MOSFETs when SiC diode is used. In [2] commercial SiC MOSFET QJD121007 (1200/100A) from POWEREX and Si IGBT CM100TF-24H (1200V/100A) from Mitsubishi were used to analyse the power loss of the devices. Push-pull converter is used to extent the voltage for high power application. Power loss comparison of the transistors, the SiC MOSFET circuit improves the efficiency, reduces the size of the technology and lowers the power loss. In [3] author proposes the comparison between two traction inverters in which SiC MOSFET and IGBT based switches were used for evaluating the efficiency and cost. At light load, SiC MOSFET based traction inverter gives higher efficiency than the IGBT. During three different driving cycles, mean efficiency of the SiC MOSFET Inverter is far better than IGBT based inverter. In [4] author basically focuses on replacing larger Si based converter with smaller SiC based converter. Current and voltage ratings of SiC power devices, desired for simpler topologies, are at least twice the ratings of Si IGBTs needed for 3 level NPC inverters and interleaved boost converter. In [5] author proposes an isolated power converter module of 50kW fast charger for plug-in electric vehicles which is of medium-voltage (2.4kV) with high-power-quality. For other rectifier application of medium voltage, module can be used as a structure block. A suitable unidirectional converter topology was selected according to system requirement. In [7] This paper proposes on-board charger of 20kW SIC based in which LLC topology is used. To achieve high performance Modified Discontinuous Pulse-Width Modulation (DPWM) is used in conjunction with a rotating Direct-quadrature (DQ) frame reference current control loop and an external DC bus voltage control loop and both are supplied by Phase-Lock Loop (PLL). In [9] author proposes an on-board battery charger in which motor winding traction converter of electric vehicle is used to make charger which leads to decrease the weight, space, cost and volume of the on-board charger. In addition, the proposed topology means that the converter with an inductive filter produces almost sinusoidal input current [9]. Traction motor winding also helps to decrease the THD of the system. In [10], to reduce circuit, operational complexity, improve the efficiency and for level-3 dc charging, a 60kW SiC-FET-based differential-mode rectifier (DMR) is proposed. The DMR comprises with three Cuk converter modules which are parallel connected at the dc side and differentially at the input side. For UPF and low THD for current, a nonlinear inverse transformation is applied to the original control scheme.

III. Problem Statement

All There are various types of DC-DC converters available for charging battery like buck converter, boost converter, buck-boost converter, CUK, Sepic and some bidirectional dc-dc converter like two-quadrant bidirectional dc-dc converter, bidirectional dual active-bridge dc-dc converter, Interleaved bidirectional dc-dc converter etc. Some converters are isolated type and some are non-isolated type. Due to the limitations of Silicon based devices, charger design becomes more complex as level of charging increase. And also charger becomes bulky and more heat sink device required and it also impacts on the cost of the charger.

By considering these problems, it might be possible that if wideband gap devices are used then these problems can be decreased by some percentage. Wideband devices like GaN, SiC etc, are the modern technologies and due to their advantageous features, it might be possible that these problems can be resolved.

Taking consideration of specification of SiC based device, it can be observed that due to rating, size and good thermal handling capability can reduce the complexity of charger and requirement of heat sink by giving efficient performance. So using SiC based device with bidirectional DC-DC converter can be beneficial.

A. System Configuration

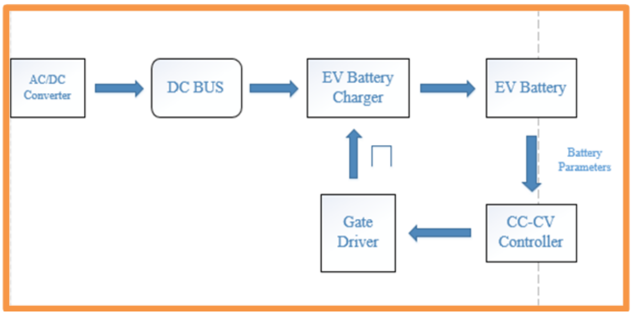


Fig. 2 Charger Design

The proposed charger configuration is mentioned above in figure 2.1.In this the charger is taking power from the DC bus. The AC/DC converter is used in the AC source side to convert AC into desired DC voltage level. On vehicle side, the charging and discharging of battery is accomplished using bidirectional DC/DC converter. The battery charging occurs in buck mode, while it discharges by operating converter in boost mode. As shown in fig. 2 Charger Design.

B. Silicon Carbide power device

Silicon Carbide devices are the next generation or next level technology. It leaves a huge impact on electric vehicle market. It is a compound semiconductor which is form by silicon and carbide. It gives number of advantages over silicon like low drain to source on-resistance, compact in size around 300-400 times smaller than silicon device, higher thermal conductivity, high breakdown voltage and high switching frequency etc. Fig. 3 shows Comparison of Silicon and Silicon Carbide based power devices.

Property	SiC advantage		
E_g (eV) - band gap	x3	Si	1.1
		SiC	3.3
v_{sn} (cm/s) – electron saturation velocity	x2	Si	1×10^7
		SiC	2×10^7
μ_n (cm²/Vs) – electron mobility	~	Si	1350
		SiC	950
e_r - dielectric constant	~	Si	11.8
		SiC	9.7
E_c (V/cm) - critical electric field	x15	Si	2×10^5
		SiC	3×10^6
k (W/cm K) - thermal conductivity	x3	Si	1.5
		SiC	5

Fig. 3 Comparison of Silicon and Silicon Carbide based power devices

c. Battery

Li-ion batteries are the most acceptable battery for electric vehicle as per its advantages. It can be recharged hundreds of times. It has higher energy density, voltage capacity and lower self-discharge rate than other batteries. It has better power efficiency with longer charge retention than other types of battery and light in weight. To make battery, A123 ANR26650M1BA 2500mAh 3.3V li-ion cell is used. To make 3.5kWh battery, 25 cells are used in series and 22 in parallel.

d. Charging method of battery

In this conventional Constant Current Constant Voltage (CCCV) method is used for charging the lithium ion battery. To charge the battery fast and safely, CCCV algorithm is used in which initially battery is charged at constant current with linearly increasing voltage up to certain percentage of State of Charge (SOC) as shown in below fig.4.

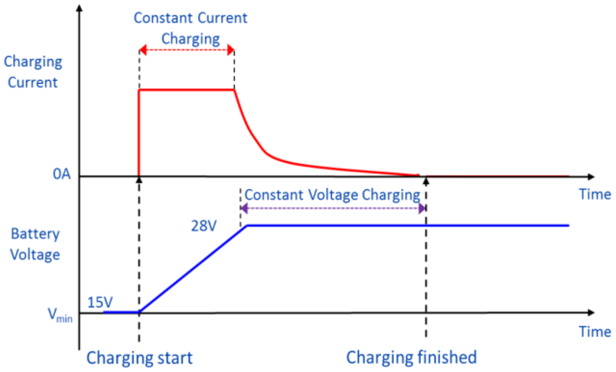


Fig.4. CCCV

After reaching that point voltage will become constant and current start decreasing and battery starts charging in constant voltage mode. At Constant-Current-mode battery charges at faster rate and at Constant-Voltage-mode battery charges at slow rate.

Formula used for reference voltage and current_Iref= 0.4*cellNominalDischargeI * n_parallel.
Vref = 0.95*cellFullChargeV * n_series.

IV. Results and Discussions

SiC Based DC-DC Converter

A.A SiC based buck-boost converter

A.A.1 Open loop control

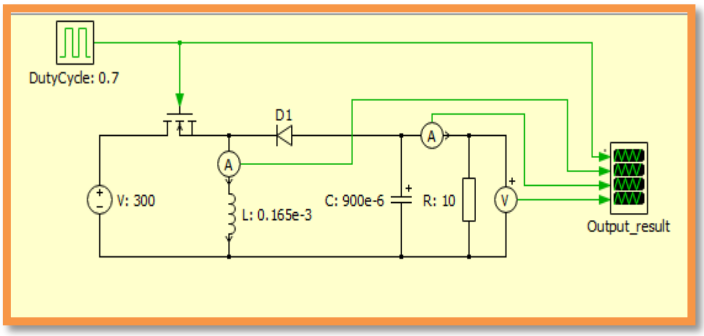


Fig. 5 Buck-boost open loop control

Components:

1. SiC Schottky Diode – C6D10065A (VRRM = 650V, IF(TC=155C) = 10A, QC=34 nC)
2. SiC Power MOSFET with Body Diode - C3M0060065K (VDS=650V, ID=37A, RDS(ON)=60m ohm)
3. Frequency = 50kHz
4. Software: PLECS

A.A.1.1 Duty cycle 0.5

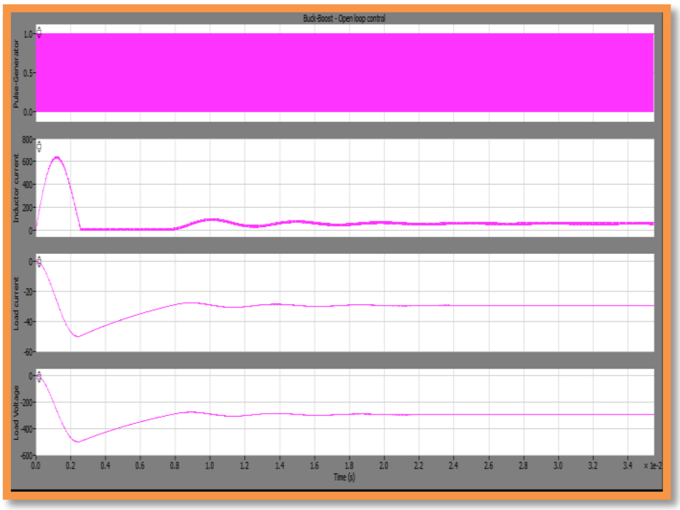
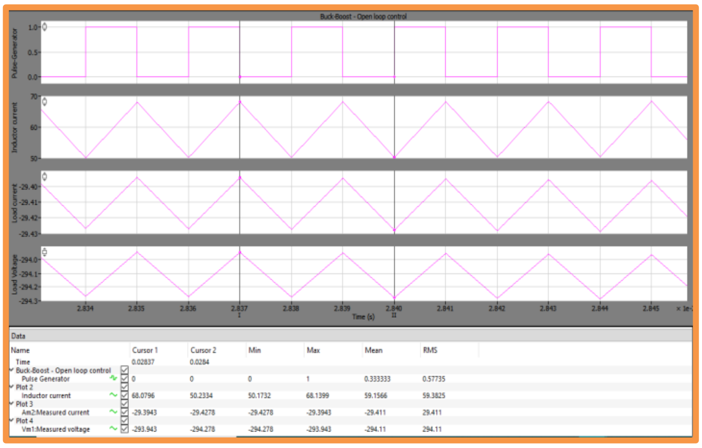


Fig. 6 Transient and steady state waveform at 0.5 Duty Cycle

Above waveform gives the combine image of transient and steady state. Below zoomed waveform of steady state is shown.



Name		Cursor 1	Cursor 2	Min	Max	Mean	RMS
Time		0.02837	0.0284				
Buck-Boost - Open loop control	☑						
Pulse Generator	☑	0	0	0	1	0.333333	0.57735
Plot 2	☑						
Inductor current	☑	68.0796	50.2334	50.1732	68.1399	59.1566	59.3825
Plot 3	☑						
Am2:Measured current	☑	-29.3943	-29.4278	-29.4278	-29.3943	-29.411	29.411
Plot 4	☑						
Vm1:Measured voltage	☑	-293.943	-294.278	-294.278	-293.943	-294.11	294.11

Fig. 7 Zoomed waveform of 0.5 Duty Cycle

From the above zoomed waveform we can conclude that the ripple percentage at 0.5 duty cycle in load current and voltage is 0.1%. And its efficiency is around 98.03%.

A.A.1.2 Duty cycle 0.7

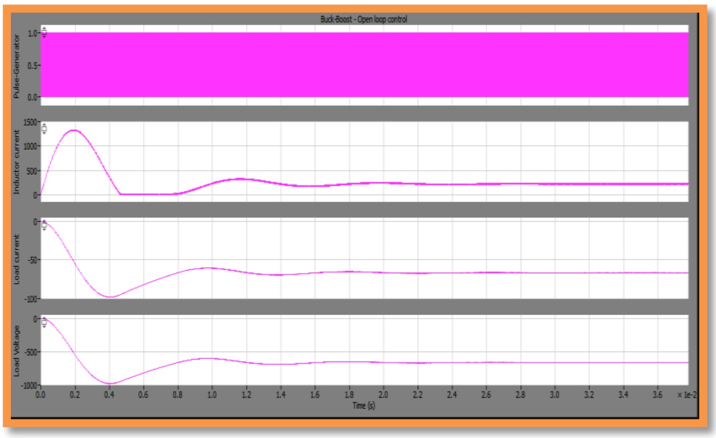
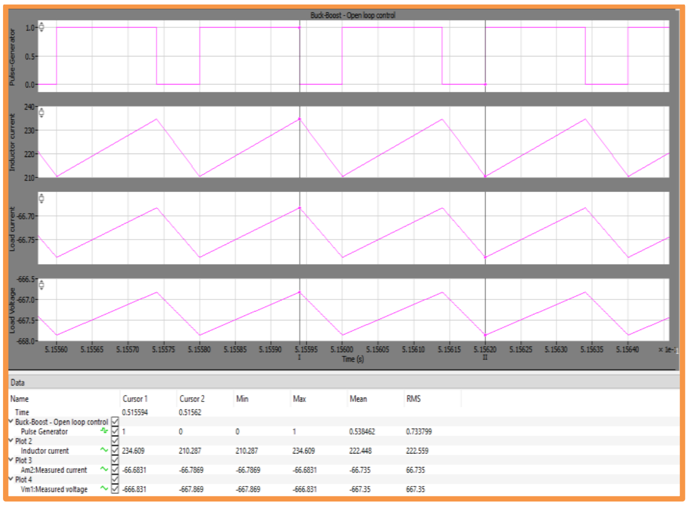


Fig.8 Transient and steady state waveform at 0.7 Duty Cycle



Name		Cursor 1	Cursor 2	Min	Max	Mean	RMS
Time		0.515594	0.51562				
Buck-Boost - Open loop control	☑						
Pulse Generator	☑	1	0	0	1	0.538462	0.733799
Plot 2	☑						
Inductor current	☑	234.609	210.287	210.287	234.609	222.448	222.559
Plot 3	☑						
Am2:Measured current	☑	-66.6831	-66.7869	-66.7869	-66.6831	-66.735	66.735
Plot 4	☑						
Vm1:Measured voltage	☑	-666.831	-667.869	-667.869	-666.831	-667.35	667.35

Fig.9 Zoomed Waveform at 0.7 Duty Cycle

From the above zoomed waveform we can conclude that the ripple percentage at 0.7 duty cycle in load current and load voltage is 0.15%. And its efficiency is around 95.33%.

A.A.2 Close-loop voltage controlled

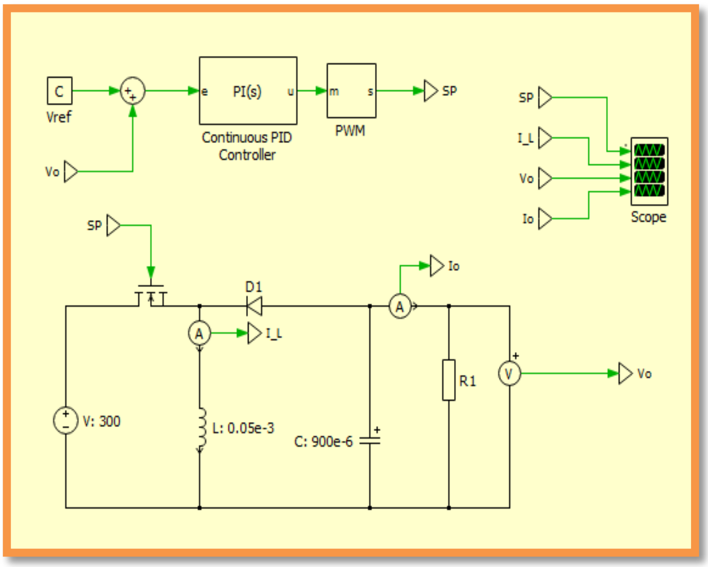


Fig.10 Buck-boost Close Loop Voltage control

In this close-loop Voltage control is used in which output voltage is compared with reference voltage then error signal is generated which is then fed to the PI controller. The output of PI controller is fed to the PWM in which output is compared with triangular wave of 50kHz and generates suitable switching pulses for the device.

A.A.2.1 Voltage reference = 90V

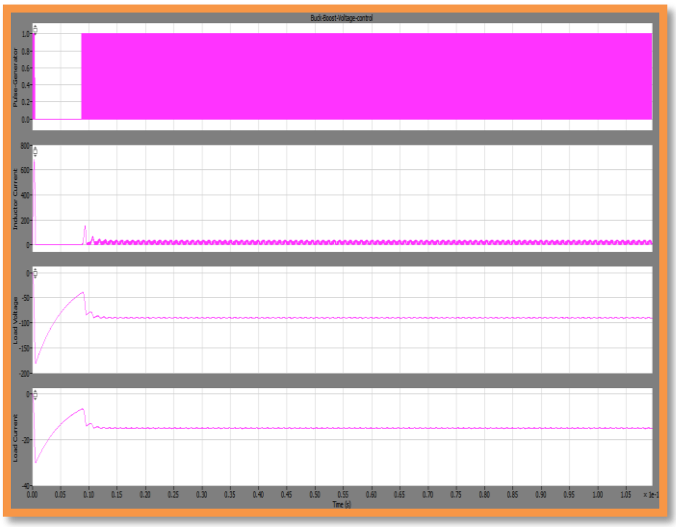
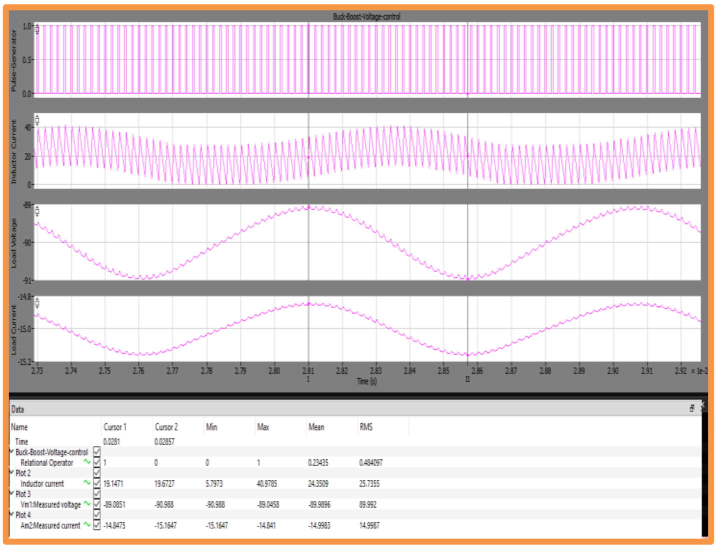


Fig.11 Transient and steady state waveform at 90Vref.



Name		Cursor 1	Cursor 2	Min	Max	Mean	RMS
Time		0.0281	0.02857				
Buck-Boost-Voltage-control	☑						
Relational Operator	☑	1	0	0	1	0.23435	0.484097
Plot 2	☑						
Inductor current	☑	19.1471	19.6727	5.7973	40.9785	24.3509	25.7355
Plot 3	☑						
Vm1:Measured voltage	☑	-89.0851	-90.988	-90.988	-89.0458	-89.9896	89.992
Plot 4	☑						
Am2:Measured current	☑	-14.8475	-15.1647	-15.1647	-14.841	-14.9983	14.9987

Fig.12 Zoomed Waveform of 90V ref.

From the above zoomed waveform we can conclude that the ripple percentage in load current and load voltage is 2.15%. And its efficiency is around 99.98%.

A.A.2.2 Voltage reference = 200V

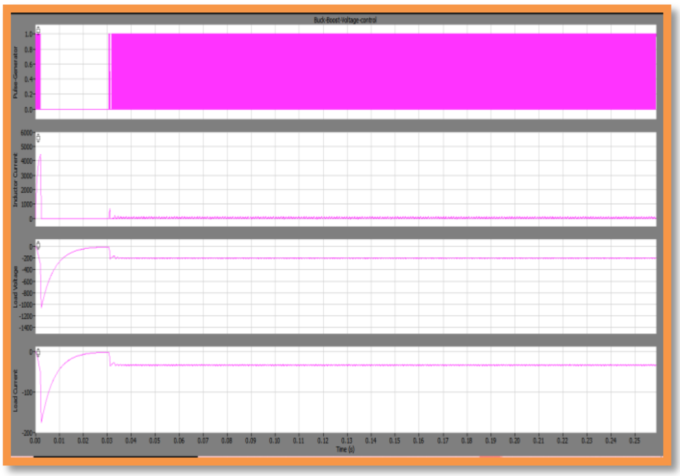
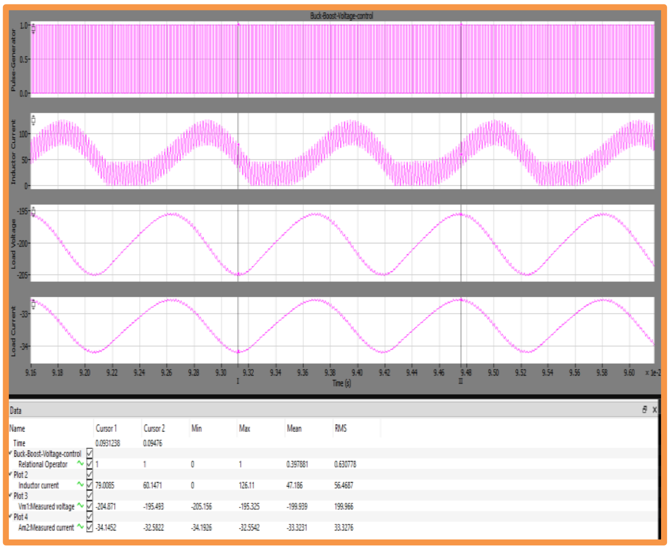


Fig.13 Transient and steady state waveform at 200V ref.



Name		Cursor 1	Cursor 2	Min	Max	Mean	RMS
Time		0.0931238	0.09476				
Buck-Boost-Voltage-control	☑						
Relational Operator	☑	1	1	0	1	0.397881	0.630778
Plot 2	☑						
Inductor current	☑	79.0085	60.1471	0	126.11	47.186	56.4687
Plot 3	☑						
Vm1:Measured voltage	☑	-204.871	-195.493	-205.156	-195.325	-199.939	199.966
Plot 4	☑						
Am2:Measured current	☑	-34.1452	-32.5822	-34.1926	-32.5542	-33.3231	33.3276

Fig.14 Zoomed waveform at 200V ref.

From the above zoomed waveform we can conclude that the ripple percentage in load current and load voltage is 4.91%. And its efficiency is around 99.96%.

A.A.3. Observations

Table IV.1 Buck-boost open loop control

Duty Cycle	Input voltage (V)	Desired Output Voltage(V)	Output Voltage (V)	Efficiency (%)	Ripple(%)
0.5	300	300	295.128	98.38	0.10
0.7	300	700	667.35	95.33	0.15

From the above observation table of open loop control Buck-Boost converter, we can conclude that output voltages are close enough to desired output voltage and efficiency is more than 90%. As the duty cycle increases, efficiency gets decreased. Ripple percentage is under the limit of 5%.

Table IV.2 Buck-boost close loop Voltage control

Voltage Reference	Input voltage (V)	Output Voltage (V)	Efficiency (%)	Ripple(%)
90	300	89.98	99.98	2.15
200	300	199.939	99.96	4.91

From the above observation table of close loop control Buck-Boost converter, we can conclude that output voltages are close enough to reference voltage and efficiency is around 99%. Ripple percentage is under the limit of 5%.

Overall we can conclude, Silicon carbide based buck-boost converter in close loop voltage control has better efficiency as compared to open loop voltage control. With fine tuning PI in close voltage control, the ripple percentage could be decreased.

B. BIDIRECTIONAL LITHIUM-ION BATTERY CHARGER

B.1 Li-ion Battery charging by Bidirectional DC-DC Converter

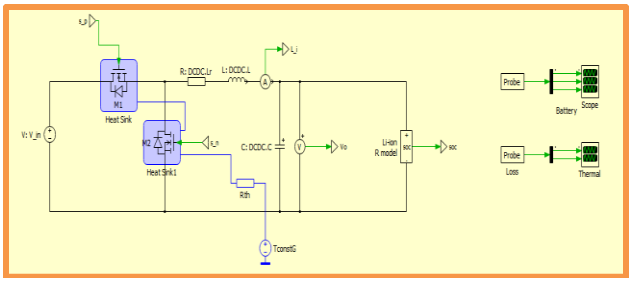


Fig.15 Li-ion Battery with Bidirectional DC-DC converter

Components Used:

1) 1. SiC Power MOSFET with Body Diode - C3M0060065K (VDS=650V, ID=37A, RDS(ON)=60m ohm)
2) 2. Li-ion Battery (3.8kWh) - A123 ANR26650M1BA 2500mAh 3.3V li-ion cell (n_s=25, n_p=22)
3) 3. R=0.08 ohm, L=1.5e-3 H, C=800e-6 F
4) 4. Frequency = 100kHz

CCCV Controller:

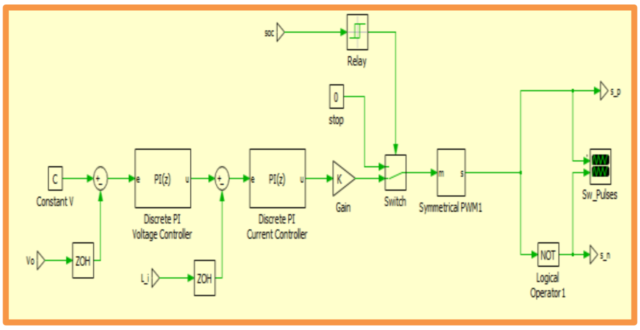
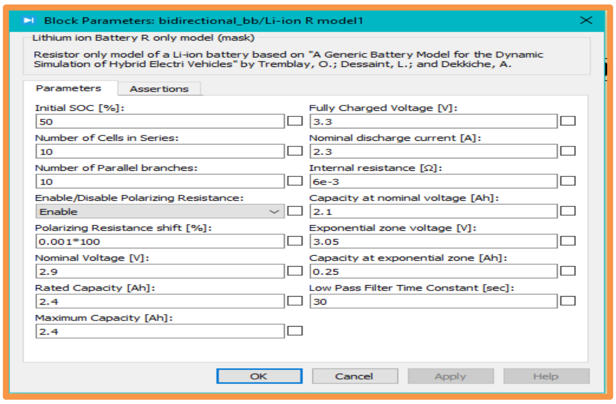


Fig.16 CCCV controller

In constant current constant voltage (CCCV) controller, initially reference voltage is compared with the battery output voltage, the error signal is fed to PI voltage controller which gives output in form of reference current. Then this reference current is compared with the inductor current, error signal is fed to the PI current controller. Then the output of PI current controller multiply with gain and then to the switch. The purpose switch is to switch off the controller as SOC reaches to maximum. Relay working as trigger which triggers the switch as SOC reaches maximum and switch shifts to zero position. The output of switch is connected with PWM and that PWM generates switching pulse for M1 and M2. During charging M1 will get positive switching pulse and M2 will get negative switching pulse.

Battery Parameters: lithium ion Battery R only model:



Lithium ion Battery R only model (mask)

Resistor only model of a Li-ion battery based on "A Generic Battery Model for the Dynamic Simulation of Hybrid Electri Vehicles" by Tremblay, O.; Dessaint, L.; and Dekkiche, A.

Initial SOC [%]: 50 ☐
Number of Cells in Series: 10 ☐
Number of Parallel branches: 10 ☐
Enable/Disable Polarizing Resistance: Enable ☐
Polarizing Resistance shift [%]: 0.001*100 ☐
Nominal Voltage [V]: 2.9 ☐
Rated Capacity [Ah]: 2.4 ☐
Maximum Capacity [Ah]: 2.4 ☐
Fully Charged Voltage [V]: 3.3 ☐
Nominal discharge current [A]: 2.3 ☐
Internal resistance [Ω]: 6e-3 ☐
Capacity at nominal voltage [Ah]: 2.1 ☐
Exponential zone voltage [V]: 3.05 ☐
Capacity at exponential zone [Ah]: 0.25 ☐
Low Pass Filter Time Constant [sec]: 30 ☐

Fig.17 Li-ion Battery parameters

Component:

1. Li-ion Cell– ANR26650M1BANR26650M1B
2. Battery: n_series = 25 and n_parallel = 22, 3.5kWh.

1) Switching Pulse:

Fig.18 Switching Pulses

2) Battery Charging in CCCV mode at 95% SOC:

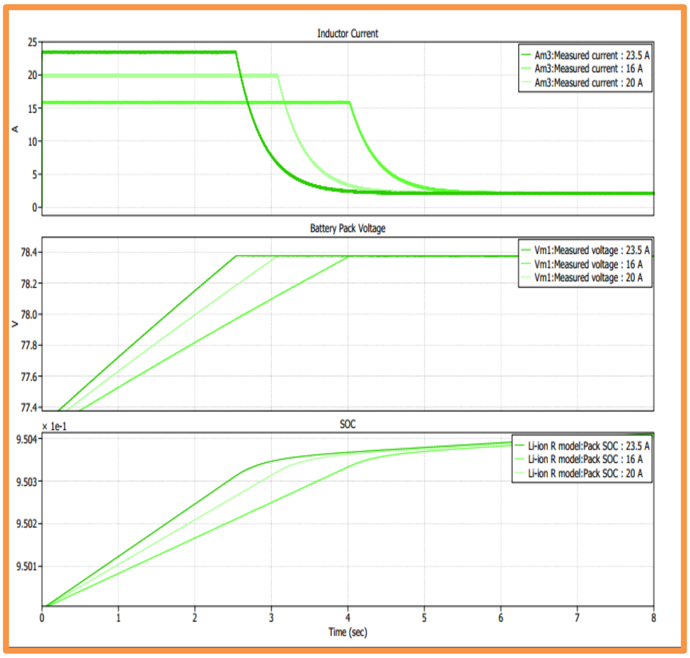


Fig.19 Charging in CCCV mode at 95% SOC

In the above graph, Lithium-ion battery charging is shown for three different currents 16A, 20A and 23.5A. As battery reaches to 95% of state of charge (SOC) then constant current mode stops and constant voltage mode begins as we can see that in the above fig.4.5. As we can see, as constant current value increase battery takes less time to jump into the constant voltage mode. We can conclude that battery will take less time if the amplitude of constant current is high but it should be under the safe limit.

Constant I =16 A

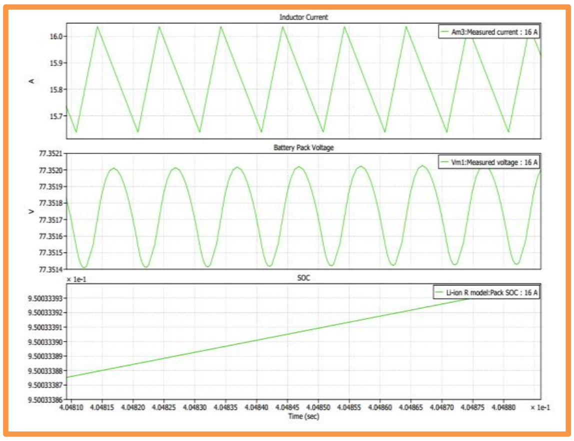


Fig.20 Zoomed waveform at CC 16 A

For constant current 16 A, the ripple percentage is around 2.15% and ripple in voltage is 0.001%.

Constant I =20 A

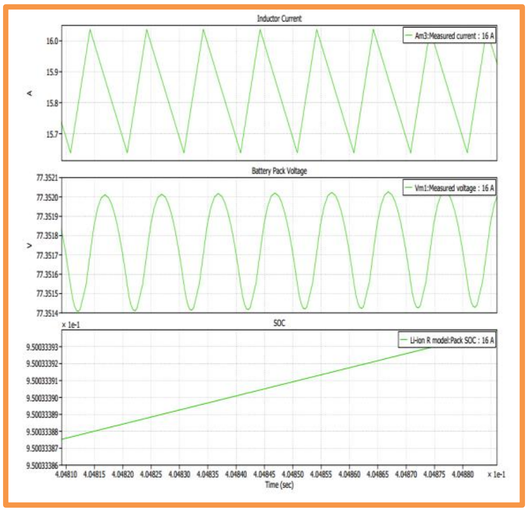


Fig.21 Zoomed waveform at CC 20 A

For constant current 16 A, the ripple percentage is around 2.04% and ripple in voltage is 0.001%.

Constant I =23.5 A

Current Amplitude	**Time (sec)**	**Initial SOC % In CC**	**Final SOC % End of CC mode**	**Time to reach at end of CC mode**	**Time taken to Charge up to 95% SOC**
I = 16 A	8	95.00	95.034	4.0 sec	3.2 hr
I = 20 A	8	95.00	95.032	3.1 sec	2.69 hr

I = 23.5 A	8	95.00	95.035	2.6 sec	2.06 hr

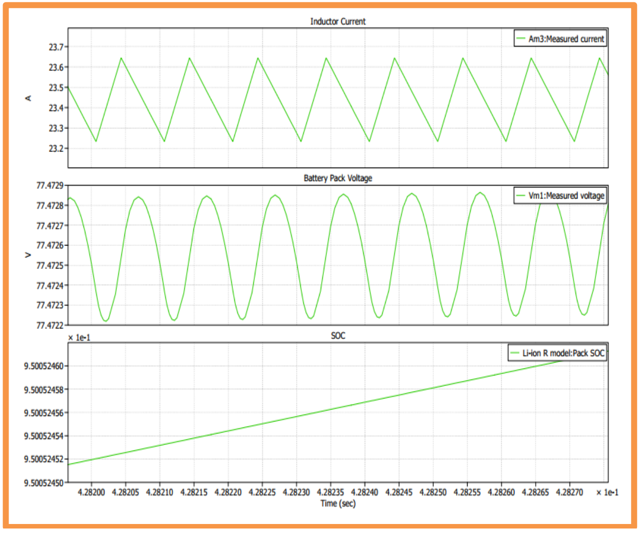


Fig.22 Zoomed waveform at CC 23.5 A

For constant current 16 A, the ripple percentage is around 1.75% and ripple in voltage is 0.009%.

3) Junction temperature (JT) and conduction loss (CL) across the SiC power MOSFET

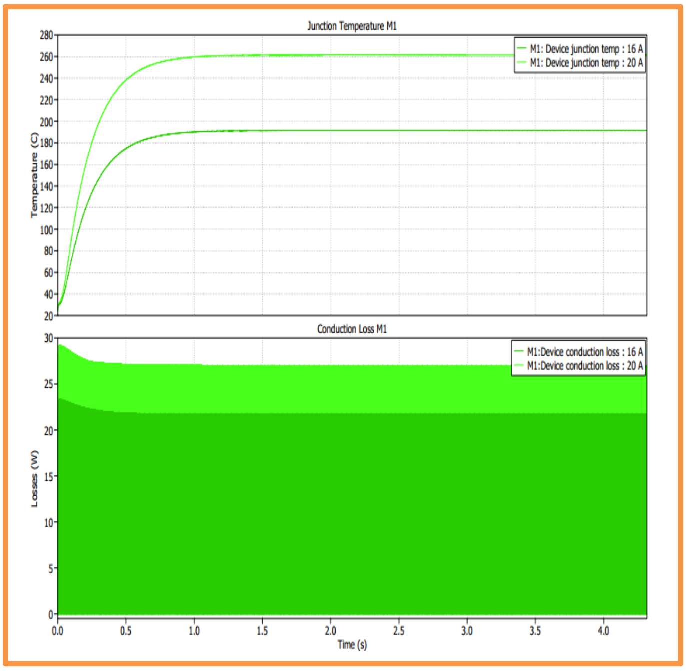
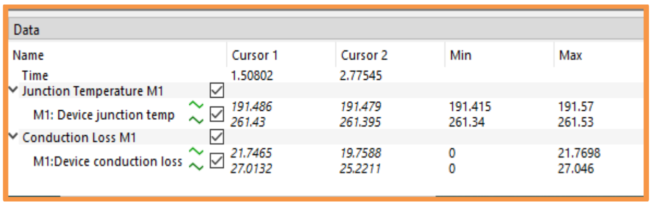


Fig. 23 Junction Temperature and Conduction Loss at 16A & 20A, 95% SOC

From the above fig. 4.9 we can see that as amplitude of current increases, the junction temperature crosses the device temperature limit and conduction losses also gets increased.


Data

Name		Cursor 1	Cursor 2	Min	Max
Time		1.50802	2.77545		
Junction Temperature M1	☑				
M1: Device junction temp	☑	191.486 261.43	191.479 261.395	191.415 261.34	191.57 261.53
Conduction Loss M1	☑				
M1:Device conduction loss	☑	21.7465 27.0132	19.7588 25.2211	0 0	21.7698 27.046

Fig.24 Junction Temperature and Conduction loss data at 16A & 20A, 95%SOC

From the above fig.4.9 and fig.4.10, we can see that as we increase the amplitude of charging current at constant sampling frequency 100kHz, the conduction loss and junction temperature reaches to the critical point or beyond it. The maximum operating temperature of SiC based Power device is 175 oC but at 20 A junction temperature reaches to 261oC which is totally inappropriate operating condition. So according to that increasing the amplitude of current with simple topology is not feasible. Charger is valid for fast charging when the battery is of small capacity.

4) Junction temperature (JT) and conduction loss (CL) across the SiC power MOSFET at three different Switching Frequency

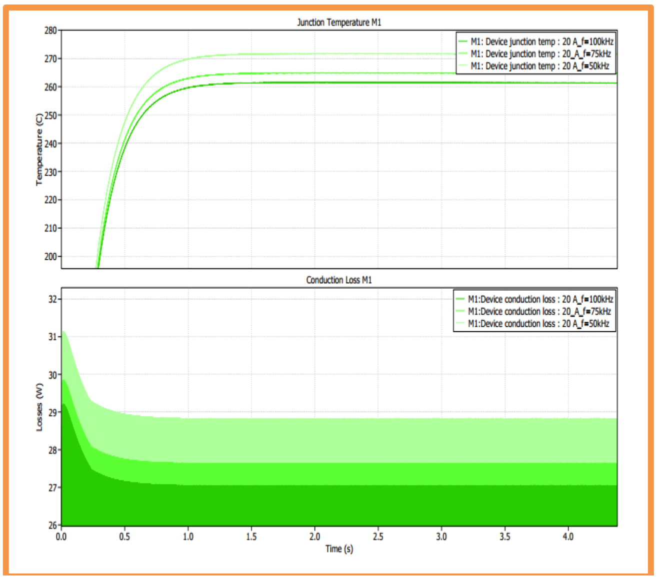
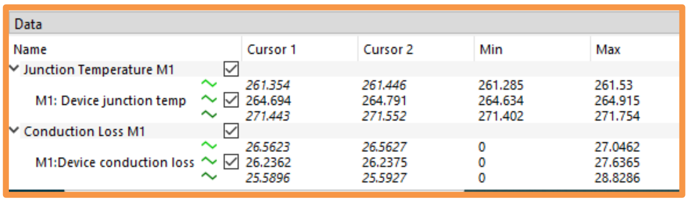


Fig. 25 JT and CL, 95% SOC, at 50kHz, 75kHz & 100kHz


Data

Name	Cursor 1	Cursor 2	Min	Max
Junction Temperature M1 ☑				
	261.354	261.446	261.285	261.53
M1: Device junction temp ☑	264.694	264.791	264.634	264.915
	271.443	271.552	271.402	271.754
Conduction Loss M1 ☑				
	26.5623	26.5627	0	27.0462
M1:Device conduction loss ☑	26.2362	26.2375	0	27.6365
	25.5896	25.5927	0	28.8286

Fig. 26 JT and CL data, 95% SOC, at 50kHz, 75kHz & 100kHz

Here we kept the heat sink at constant temperature 25oC and current at 20 A and performed the test at three different switching frequencies of 50kHz, 75kHz and 100kHz. From the above fig.4.11 and fig.4.12, we can see that as we increase the switching frequency the junction temperature and conduction loss decreases. This is the advantage of higher switching frequency.

5) Observations& Results

From the above table we can conclude that, by increasing the constant current amplitude, battery can take less time to charge up to 95%SOC.

B.2 Li-ion Battery discharging by Bidirectional DC-DC Converter

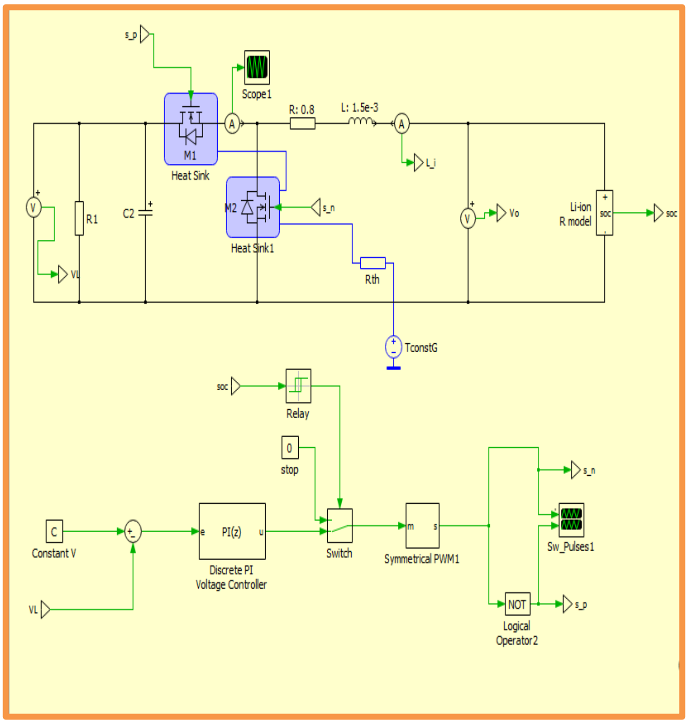


Fig. 27 Battery in discharging mode

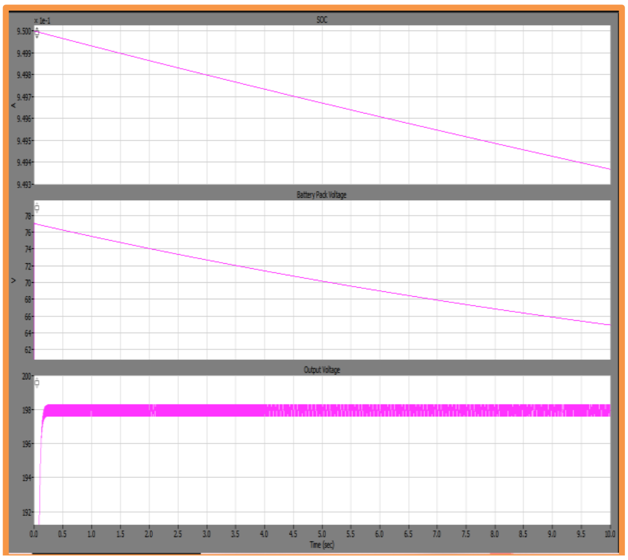
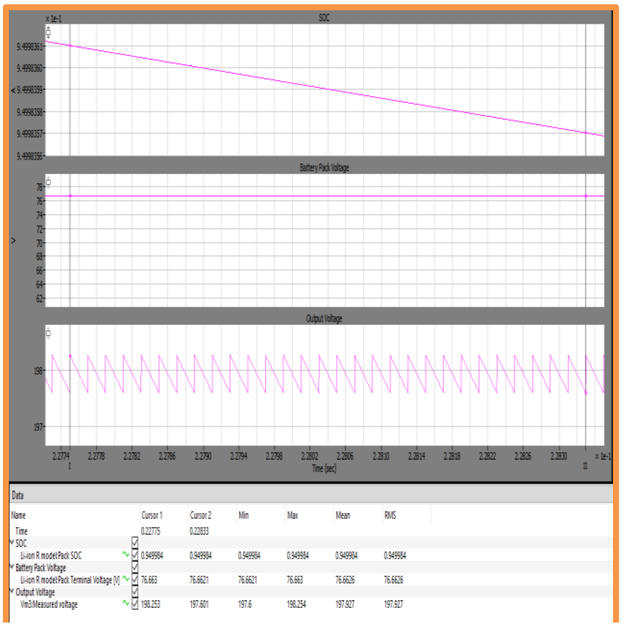


Fig. 28 Output Voltage Waveform during discharging

From the above fig. 4.14 we can see that battery is discharging in close loop voltage control mode by giving output voltage 198V. It will discharge up to 20% SOC and after that it will stop so that battery life can be maintain.



Name	Cursor 1	Cursor 2	Min	Max	Mean	RMS
Time	0.22775	0.22833				
SOC ☑						
Li-ion R model:Pack SOC ☑	0.949984	0.949984	0.949984	0.949984	0.949984	0.949984
Battery Pack Voltage ☑						
Li-ion R model:Pack Terminal Voltage [V] ☑	76.663	76.6621	76.6621	76.663	76.6626	76.6626
Output Voltage ☑						
Vm3:Measured voltage ☑	198.253	197.601	197.6	198.254	197.927	197.927

Fig.29 Zoomed waveform of Output Voltage

From the above fig 4.15, the ripple percentage in output voltage is 0.33% .”.

V. CONCLUSIONS

- By increasing the current amplitude in constant-current-mode, battery takes less time to charge up to 95% SOC.
- With the increase in current amplitude, junction temperature and conduction loss across the device gets increased and sometime go beyond the limit which is unacceptable condition and it may lead to damage the device.
- At higher switching frequency, losses and temperature across the device gets decreased and this is very beneficial to make the converter more efficient.
- High amplitude current can be used in constant-current mode to charge the battery at faster rate but it increases the cost of the charger with the requirement of high quality heat sink device.
- Use of silicon carbide based device can make the converter less bulky and also make the converter more efficient.
- Use of SiC based device, increases the efficiency of the converter when it is operated in close loop control mode.
- It is important to design high voltage resistant chargers otherwise it will affect the battery SOC.

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