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Characterization and Modeling of SiC based Positive Output Super Lift Luo Converter

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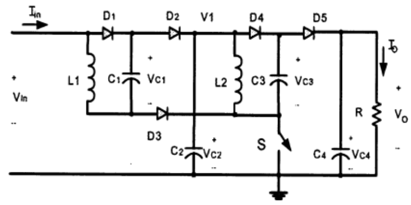
ABSTRACT
A behavioral model in PSpice for a silicon carbide (SiC) power MOSFET rated at 1200V / 33A for a wide temperature range is developed by extracting the device parameters from the data sheet. The static and dynamic behavior of the SiC power MOSFET is simulated and compared with the device characteristics to validate the accuracy of the PSpice model. The temperature dependent behavior of the MOSFET is simulated to show the effectiveness of the switch at the prolonged temperature. SiC based multistage super lift Luo converter is simulated for analyzing the performance of the converter in terms of energy factor, pumping factor, storage factor, ripple factor and efficiency.

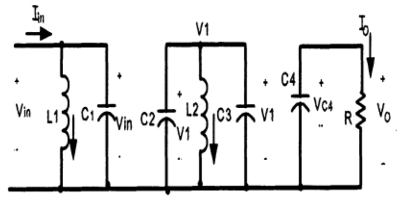
Key Words
Positive output super lift Luo converter, Silicon Carbide Switch, modeling in OrCad PSpice.

1. INTRODUCTION
Voltage Lift (VL) technique is a method used in electronic circuit design. The re lift circuit is formed from the self lift circuit and performs positive DC-DC step up voltage conversion with high efficiency and high power in a simple circuit. The re lift circuit is derived from elementary circuit by adding the parts inductor (L) and capacitor (C). Two capacitors are added to increase the output voltage by twice the input voltage [4]. The output voltage of the re lift circuit is doubled to that of the self lift converter. The output voltage increases in stage by stage ie, along the arithmetic progression. SiC based power MOSFETs has become more competitive because of its material properties. SiC power MOSFETs has higher blocking voltage, higher operational temperature and even higher switching frequency [1]. SiC having wide band gap results in small amount of leakage current. SiC-MOSFETs have lower on-resistance and are available for higher temperature operation than Si-MOSFET. The material properties of SiC in power devices are superior to those of Si MOSFETs and low-switching losses high efficiency and high power [8]. This paper presents the SiC MOSFET based positive output re lift type super lift Luo converter for analysing the effectiveness of switch at prolonged temperature.

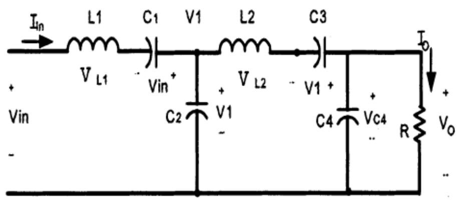
2. PRINCIPLE OF OPERATION OF SUPER LIFT LUO CONVERTER



(a) Positive output super lift Luo converter



(b) Mode 1 operation



(c) Mode 2 operation

Fig 1. Positive output re lift type super lift Luo converter

Super lift converters have very high voltage transfer gain and its output voltage increases in geometric progression stage by stage and used in industrial application requiring high output voltages. [3]
The working of the re-lift type positive output super lift converter is the output of the first stage is supplied as the input to the next stage is shown in fig 1 (a). When the switch is ON at mode 1 operation the current through inductor L_1 raises and capacitor C_1 is charged to the supply voltage V_{in}. At the same time, the current through inductor L_2 increases with the voltage V_1 and capacitor C_3 is charged to the node voltage V_1. Capacitor C_4 dissipates is energy through the load is shown in fig 1 (b).When switch is in OFF state at mode 2

operation the inductor current decreases. Capacitor C_2 is charged to the Voltage V_1 through the inductor current i_{L1} and capacitor C_4 is charged to the voltage V_o through the inductor current is shown in fig 1 (c). Voltage gain is given by, [3]
The ripple in the inductor current i_{L1} is

$$\Delta i_{L1} = \frac{V_{in}}{L_1} K = \frac{(V_1 - 2V_{in})}{L_1}$$

$$V_1 = \frac{(2-K)}{(1-K)} V_{in}$$

The ripple in the inductor current i_{L2} is

$$\Delta i_{L2} = \frac{V_1}{L_2} K$$

$$= \frac{(V_0 - 2V_1)}{L_2}(1-K)$$

$$V_0 = \frac{(2-K)}{1-K} V_1$$

$$V_0 = \frac{(2-K)^2}{(1-K)^2} V_{in}$$

3. SiC SWITCH MODELLING

Silicon Carbide MOSFET switch is modelled using in PSpice model editor by extracting the parameters from the data sheet for various temperatures like 25^0C, 125^0C, 225^0C.
Some important parameters computed in this model are channel length modulation parameter (λ), transconductance (K_p), gate source threshold voltage ($V_{GS\text{-}th}$), on state drain source resistance (R_{DS-ON}). These parameters are extracted by using the characteristics of transconductance curve, transfer curve, capacitance Vs drain source voltage curve and ON resistance curve from the data sheet. PSpice Model Editor has two options to model the MOSFET one by using the device characteristics and other by computing the parameters and using the .MODEL dot command in PSpice. Former method of modeling the device is adopted to realize the characteristics. Using characteristics curve model of PSpice model editor, the Silicon Carbide switch is modeled by extracting the parameters from the data sheet [2]. The following extraction parameters are used to model the device.

3.1 Transconductance Characteristics

Transconductance (g_{Fs}) is defined as the ratio of change in current to the change in voltage at constant drain source voltage (V_{ds}). This curve is plotted for drain current (I_d) and transconductance gain(gFs) shown in Table 1.

Table 1 Transconductance value of SiC MOSFET

I_d(A)	g_{Fs}
0.001	0.001
0.001	0.001
0.001	0.001
0.001	0.001
2	1
4	2
10	3
20	6.25
30	8.33
40	9
50	15
60	20

3.2 Transfer Curve

Transfer curve is a plot of gate source voltage (V_{gs}) versus drain current (I_d) at constant drain source voltage (Vds) shown in Table 2.

Table 2 Variation of I_d with gate source voltage V_{gs} of SiC MOSFET

Vgs(V)	Id(A)
0	0.001
2	0.001
4	0.001
6	1
8	4
10	10
11	15
12	21
13	30
14	41
15	50
16	60

3.3 ON- State Drain Source Resistance ($R_{DS\text{-}on}$)

When ON state resistance value decreases switching loss decreases, which in turn improve converter efficiency. For increasing the temperature, R_{DS} value increases with small amount since SiC having the higher operational temperature capability [10].

I_d = 20 A
R_{ds}(on) = 80 mΩ
Vgs = 20 V

3. 4 Zero Bias Leakage (I_{dss})

V_{ds} (drain source voltage) =1200 V
I_{dss}(zero gate voltage drain current) =1µA

3.5. Gate Charge (Q_g)

Qgd(gate to drain charge) = 43.1nC
Qgs(gate to source charge) = 23.8 nC
V_{ds} = 800 V
I_d = 20 A

3.6 Output Capacitance Characteristics

Shows the variation of output capacitance (C_{oss}) with drain source voltage (V_{ds}) shown in Table 3.

Table 3 Output Capacitance Characteristics of SiC MOSFET

V_{ds} (V)	C_{oss} (F)
0	3e-9
20	7e-10
40	4e-10
60	3e-10
80	2.8e-10
100	2.5e-10
120	2.2e-10
140	2e-10
160	1e-10
180	9e-11
200	8e-11

3.7 Switching characteristics

T_f (fall time) = 35.6 ns
I_d (drain current) = 20 A
V_{dd}(drain voltage) = 800 V
Z_o = 40

The following parameters are extracted from the PSpice model editor for the SiC MOSFET is shown in Table 4.

Table 4 Extracted parameters of SiC MOSFET

Parameter name	**Value**
L	0.000856
W	1800
K_P	1.0143e-6
R_S	0.01
VTO	4
R_{DS}	1200e-6
TOX	20E-6
CGSO	5.55e-18
CGDO	3.001e-14
CBD	2.95e-1
MJ	.79933
PB	3
FC	0.5
RG	0.01
IS	1e-14
N	1
RB	1
PHI	0.6

4. CHARACTERIZATION OF SIC MOSFET

Modelled SiC MOSFET static and dynamic characteristics are simulated using PSpice.

4.1. Transfer Characteristics

Transfer curve shows the variation of the drain current with respect to the gate source voltage as shown in fig 2 and its corresponding transconductance value is calculated in shown in Table 5.

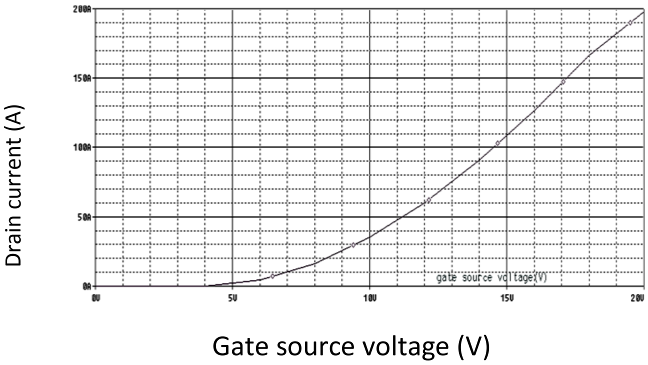


Fig 2. Transfer characteristics

Table 5 Transconductance value of modelled SiC MOSFET

Z	**g_{FS}**
0	0.0001
0	0.0001
0	0.0001
3	3.75
18	8
35	10
75	13.888
110	20
165	22.5
200	17.85

4.2 .Switching characteristics curve

Switching characteristics curve for SiC MOSFET is shown in fig 3 and it provides the information of the MOSFET under transient and saturation region [9] and its corresponding dynamic parameters are shown in Table 6

Table 6 Dynamic Parameters

Parameter	Value
Turn on time (t_{on})	40 ns
Turn off time (t_{off})	30 ns
Delay time (t_{d-on})	15 ns
Fall time (t_f)	30ns
Rise time (t_r)	8 ns

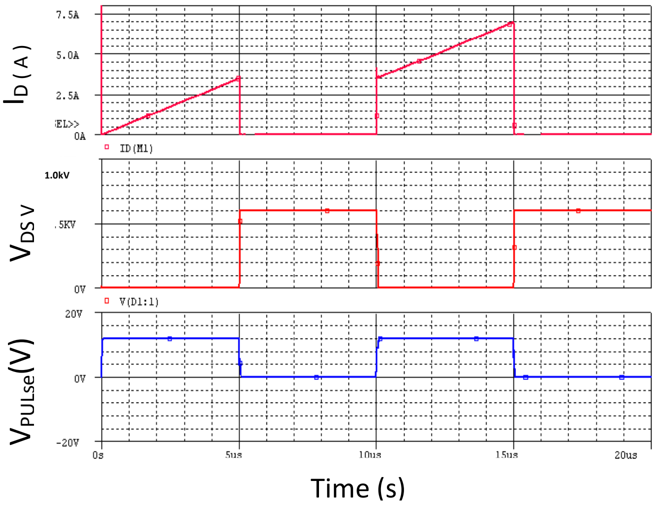


Fig 3. Switching characteristics

4.3 Temperature dependent behaviour comparison between IRF830 and SiC MOSFET

The R_{DS} characteristic of Si [6] and SiC MOSFET is shown in fig 4 and 5 respectively and the values for various temperatures between 0˚C to 125˚C.

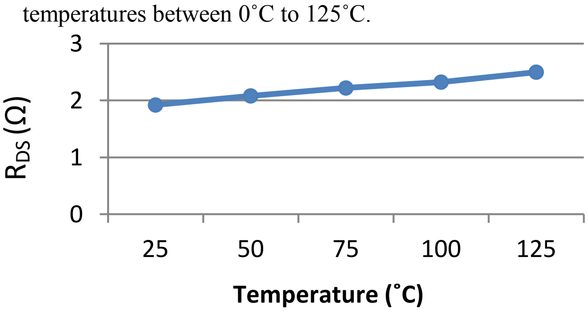


Fig 4. ON state drain source resistance (R_{DSON}) for Si MOSFET

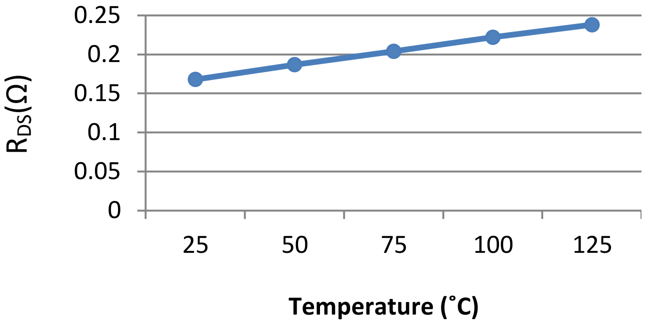


Fig 5. ON state drain source resistance (R_{DSON}) for SiC MOSFET

5. APPLICATION OF MODELED SICSWITCH TO SUPER LIFT LUO CONVERTER

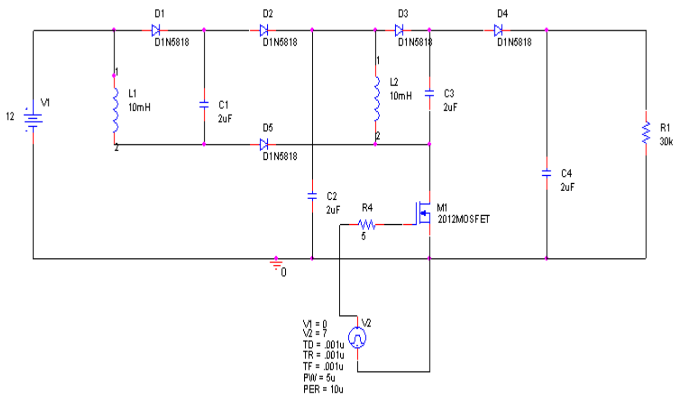


Fig 6. Simulation circuit for super lift Luo converter

Modelled SiC switch is applied to the super lift Luo converter for showing the effective features converter shown in fig 6. This circuit is simulated in OrCad PSpice and corresponding output voltage and inductor current waveforms are shown for the run time of 100 ms.

6. SIMULATION RESULTS

Output voltage wave form for positive output super lift Luo converter is shown in fig 7, and inductor current L1 and L2 for steady state region is shown in fig 8,9 correspondingly.

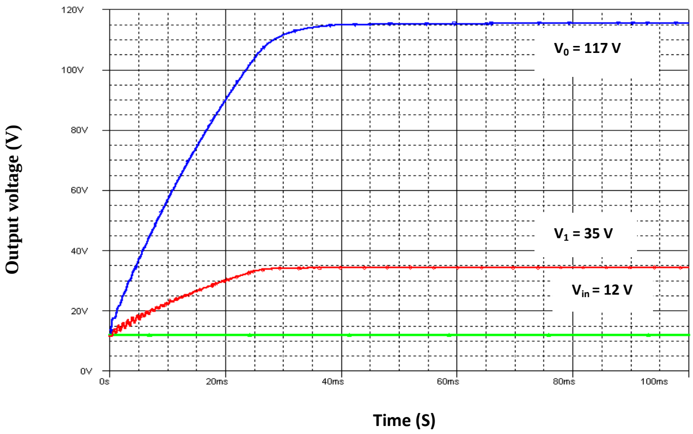


Fig 7. Output voltage waveform of super lift Luo converter

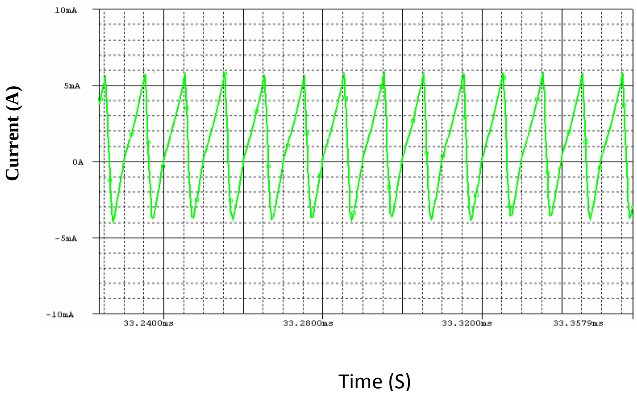


Fig 8. Inductor current i_{L1} in steady state region for SiC MOSFET based super lift converter

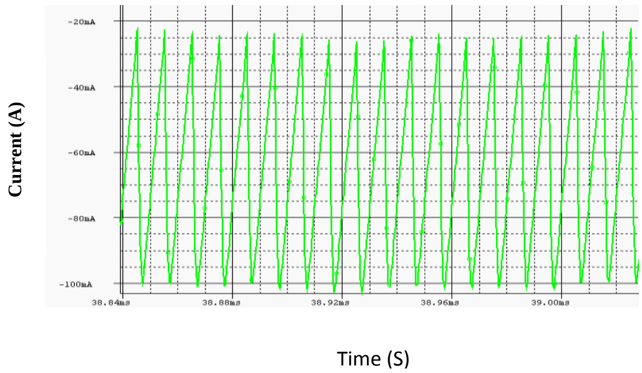


Fig 9. Inductor current i_{L2} in steady state region for SiC MOSFET based super lift converter

7. PERFORMANCE ANALYSIS

7.1. Stored Energy(SE)

DC to DC converter is also known as energy container since it has some energy storing components ie, capacitor and inductor. This energy stored in L and C are called storage factor. [5]

$$SE=\sum_{j=1}^{n} WLj + \sum_{j=1}^{n} WCj \quad (1)$$

$$WCj = \frac{1}{2} CjVj^2 \quad (2)$$

$$= \frac{1}{2} 2u(12^2 + 33.5^2 + 33.5^2 + 110^2)$$

$$WCj = 14.488 \text{ mJ}$$

$$WLj = \frac{1}{2} LjIj^2 \quad (3)$$

$$= \frac{1}{2} \times 10 \times 10e^{-3}(50.66^2 + 2.25^2)$$

$$WLj = 12.86 \text{ uJ}$$

7.2. Pumping Energy (PE)

The convertors having circuit, to transfer energy from source to the storing elements, that is L and C. Pumping energy is used to count the input energy in a switching period (T)

$$PE = V_1 I_1 T \quad (4)$$

$$= 12 \times 76m \times 10u$$

$$PE = 9.12 \text{ uJ}$$

7.3. Energy Factor (EF)

When the converter performs one steady state to another steady state the stored energy in the inductor and capacitor gets changed. There must be a transient process from one state to the other is called energy factor.

$$EF = \frac{SE}{PE} \quad (5)$$

$$= \frac{14.50m}{9.12u}$$

$$EF = 1589.912\, J$$

7.4. Ripple in the inductor current L_1 (Δi_{L1})

Variation ratio of the inductor current (Δi_{L1})

$$\Delta i_{L1} = \frac{V_{in} KT}{L_1} \quad (6)$$

$$= \frac{12 \times 0.5 \times 10u}{10m}$$

$$\Delta i_{L1} = 0.006 = 0.6\%$$

7.5. Ripple in the inductor current L_2 (Δi_{L2})

$$\Delta i_{L2} = \frac{V_{in} KT}{L_2} \quad (7)$$

$$\Delta i_{L2} = 0.01675$$

=1.675 %

7.6 Average value of the inductor current (i_{L1})

$$I_{L1} = \frac{I_{in}}{2-K} \quad (8)$$

$$= \frac{54.44\ m}{2-K}$$

$$= 36.296\ mA$$

7. 7 Average value of the inductor current (i_{L2})

$$I_{L2} = \frac{I_o}{2-K} \quad (9)$$

$$= \frac{3.6\ m}{2-0.5}$$

$$I_{L2} = 2.25\ mA$$

7.8. Switching losses of converter (P_{SW})

Switching losses for Mosfet is calculated by [7],

$$P_{SW} = \frac{I_D V_D (t_{ON} + t_{off}) f}{2} + 0.5 C_{oss} V_D^2 f \quad (10)$$

$$= \frac{70.94e^{-3} \times 33.5\left(40n + 30n\right) \times 100K}{2} + 33.5^2 \times 120e^{-12} \times 100K \times 0.5$$

P_{SW} =15.05 mW

7.9. Determination of efficiency

$$\text{Input power} = V_1 I_1 \quad (11)$$

$$\text{Pin} = 12 \times 0.4355$$

$$= 0.6533\ W$$

$$\text{Output power} = V_o I_o \quad (12)$$

$$= 110 \times 3.38e\text{-}3$$

$$P_o = 0.3718\ W$$

$$\text{Efficiency} = \frac{Outputpower}{Inputpower} \quad (13)$$

$$= \frac{0.378}{0.6533}$$

Efficiency = 57.85 %

The super lift converter enhanced the voltage transfer gain successfully, but the efficiencies of the tested circuits are 41–78%, which is good for high voltage output equipment [3]. The analysed parameters of SiC MOSFET are compared with the Si MOSFET shown in Table 8.

Table 8 Comparison of IRF830 and CMF2012D

Parameters	IRF830	CMF20120D
ΔI_{L1}	6 mA	6 mA
ΔI_{L2}	18 mA	17 mA
I_{L1}	49.86 mA	36.296 mA
I_{L2}	2.466 mA	2.25 mA
Storage Factor	15.150 mJ	14.50 mJ
Energy factor	1688.96 W	1589.92
Pumping factor	8.976 uJ	9.12 uJ
Input power	0.8976 W	0.6533 W
Output power	0.414 W	0.3718 W
Efficiency	46.12 %	57.85 %

8. CONCLUSION

Modelling of SiC switch is performed in PSpice and SiC based multistage positive output super lift Luo converter is simulated for analyzing the performance of the converter in terms of new parameters such as energy factor, pumping factor, storage factor, ripple factor and efficiency are computed and compared with Si based power MOSFET. From the analysis it is clear that the wide band gap device has much better performance and ideal for prolonged temperature applications.

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