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The Design and Simulation of a DC-DC Converter

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ABSTRACT : This paper presents the simulation of a DC-DC Boost converter using MATLAB-cum-PLECS software and in part two of this paper, the physical DC-DC Boost converter will be built and tested to validate the simulation result. This report also presents comprehensive results obtained in waveforms and the effects of varying some parameters such as input impedance, and input capacitance were explored. The results of the outcome of this variation are presented and discussed.
KEYWORDS: capacitance,converter, simulation, software, waveforms.
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I. INTRODUCTION

The importance of Power electronics, a technology associated with efficient conversion, control and conditioning of electric power from its available input into desired electrical output form, cannot be overemphasized. Power electronic circuits are employed in almost all the new electrical and electromechanical devices/equipment with the specific function of either power conversion or control [1]. Power electronics is a growing field due to the improvement in switching technologies and the need for more and more efficient switching circuits.Converters which forms the main circuits of power electronics can be divided into AC-DC converters, DC-AC converters, AC-AC converters and DC-DC converters [2].

The DC-DC converter is an electrical circuit that transfers energy from a DC voltage source to a load. The energy is first transferred via electronic switches to energy storage devices and then subsequently switched from storage into the load. The switches are transistors and diodes; the storage devices are inductors and capacitors. This process of energy transfer results in an output voltage that is related to the input voltage by the duty ratios of the switches.

Converters find application in different practical system such as in the development of maximum power point tracking for photovoltaic systems [3]–[6]. It is insightful and worthwhile to investigate why DC-DC converters are necessary before their detailed presentation and analysis. In addition to the constraints of size, weight, and cost, DC-DC converter technology also addresses the issues of efficiency and regulation [7].

II. THEORY

2.1DC-DC Converter Fundamentals

A DC-DC converter produces a regulated DC output voltage that has a magnitude or polarity different from an unregulated DC input voltage. There are different types of DC-DC converters, the required output guides the type of DC-DC converter selected. If an output voltage that is lower than the input voltage is needed, then a step-down or buck converter is used. A step-up or boost converter is employed when the output voltage is needed to be higher than the input voltage. For applications which requires an output voltage to be either higher or lower than the input voltage, a buck-boost converter may be used. This laboratory report presents the simulation of a boost converter using the MATLAB-cum-PLECS software and a laboratory designed model using component values similar to that used in the simulation to obtain desired outcomes and create good grounds for comparison. The implementation of a boost converter is shown in Fig. 1.
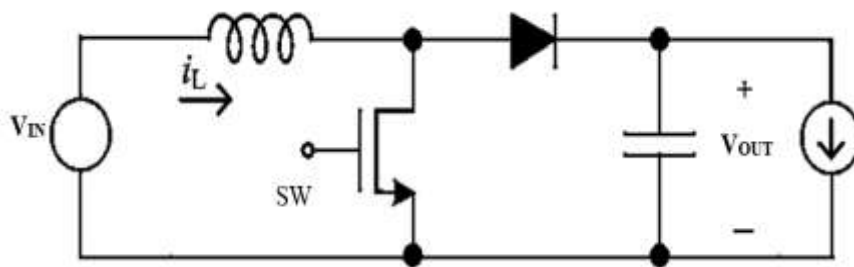
Fig. 1. Boost Converter

2.2 Principle of Operation of a BoostDC-DC Converters

The tendency of an inductor to resist changes in current is one important principle that drives the boost converters. MOSFET was used as switch as shown in Fig. 1.The property of MOSFET called duty ratio makes it a perfect switch for the present laboratory since this makes the switching ON or OFF at predetermined time interval possible. The principle of operation of a boost converter is made of two distinct states; the ON and OFF states.During the ON state, the MOSFET switch (SW) is closed, this results in an increase in inductor current IL owing to the fact that the voltage across the inductor is V_{IN}. The voltage across the diode is approximately equal to $-V_{OUT}$ and this makes the diode to become reverse-biased thereby isolating the output stage and consequently the input supplies energy to the inductor [2]. Fig.2 shows the red path through which current flows during the state.
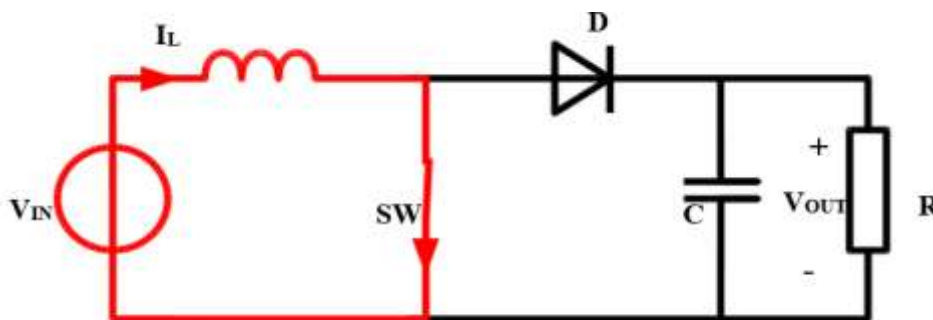

Fig. 2. ON state of MOSFET Switch in a Boost DC-DC Converter

During the OFF state, the MOSFET switch (SW) is open, as can be seen in Fig.3, the only path available for current flow is through diode D as it is now forward-biased, capacitor C and the load R. In this state the energy accumulated in the inductor during the ON state combined with the input is transferred into the capacitor thereby charging it. It is worth noting that the input current is the same as the inductor current as shown in Fig.3. The voltage discharge across the capacitor follow the relationship
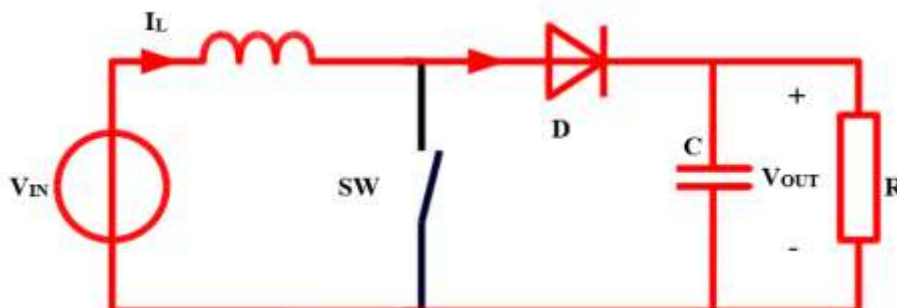
$$V = L\frac{di}{dt}$$

Fig.3. OFF state of MOSFET Switch

2.3Conversion Modes

The DC-DC boost converter has two conversion modes viz. the Continuous Conduction Mode, CCM for efficient power conversion and Discontinuous Conduction Mode, DCM for low power or stand-by operation [4]. In the CCM, the inductor current never falls to zero i.e $I_L>0$. If the switch is in the ON state for a time of t_{on}

as shown in Fig.4, inductor current is conducted as shown earlier in Fig. 2 and voltage across the inductor is equal to the input voltage, $V_L = V_{IN}$. When the switch is in the OFF state for a time t_{off}, i_L is then flowing due to the accumulated inductive energy with the discharging inductor voltage, $V_{L} = V_d-V_{o.}$ Since in steady state the time integral of the inductor voltage over one time period must be zero then we have

$T = t_{on} + t_{off} =$ zero.

The switching frequency, f_s , which defines the switching rate is used to calculate the period T as follows:

$T = \frac{1}{f_s}$,

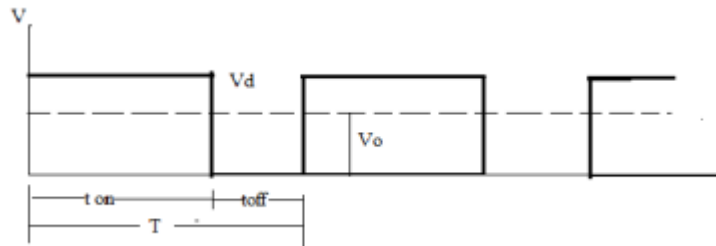where the period, T given the specified switching frequency of 25 kHz.

Fig.4. Switching cycles in the MOSFET (CCM)

2.4Converter Components Selection
In selecting components for this device care was taken to choose components which will give the required output. Calculations and simulations using different values for the components.

Selection of Semi-conductor device
In selection of a switch, a semi-conductor (MOSFET) was selected owing to its property of timed controlled switching guided by duty ratio. It operates as a perfect switch- completely turned ON or completely turned OFF and controls the gate drive voltage. For the device to remain in the ON state, there is the need for a continuous application of gate-source voltage of the right magnitude. An N-channel MOSFET was chosen for this laboratory with signal strength never below amplitude of 5V.

Selection of Capacitor
The primary criterion for selecting the input and output filter capacitors the capacitance to enable the input capacitor to reduce the ripples that are present as a result of the input impedance and enable the output capacitor (energy storing device) to reduce the output ripples thereby smoothening the output waveform. The capacitance of the capacitor can be calculated from the equation for voltage ripple: The value chosen is picked to be large enough to effect this change but also not have a marked effect on the average steady state value of the inductance.

$$C = \frac{I\rho}{f_s \Delta V}$$

Diode
The important consideration in selecting a diode is its ability to block the required OFF state voltage. The boost diode reverse voltage rating is limited to the output voltage. The diode conducts when the power switch is in the "OFF" state and provides a current path for the inductor to the output.

Inductor
The purpose of the input inductor is to serve as an energy saving and discharging device for the circuit[4].Large inductance values tend to increase the start-up time slightly while small inductance values allow the coil current to ramp up to higher levels before the switch turns off i.e non-instantaneous rise to current owing to a voltage application across it [4]. This is characterized by its equation relating its inductance value, L to the voltage across it$v_L = L\frac{di}{dt}$, this shows clearly that time is involved.

III. METHOLOGY
The method adopted in this research involves simulation of a boost DC-DC converter using MATLAB/Simulink and PLECS software to test design calculations.
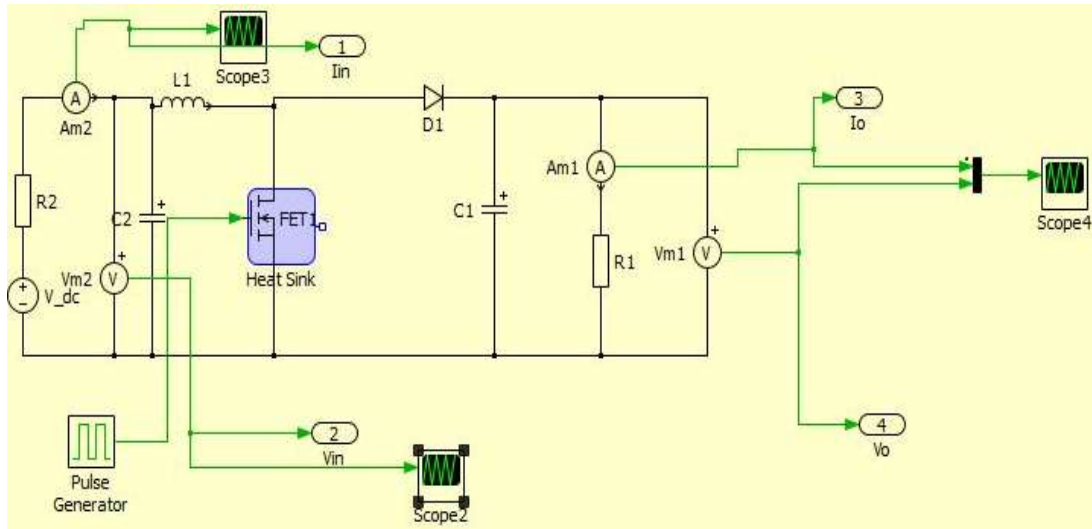
Fig.5. Boost Converter Model built in PLECS

3.1 Design Calculation
The designcalculations were based on the following design data.
Switching frequency = 25 kHz;
D.C. Input voltage, V_{DC} = 30 V
D.C. Output voltage, V_o = 48 V
Output power, P_{max}=80 W
Output voltage ripple, ΔV=100 mV = 0.1 V
The period, T can be calculated from equation (1)

$$T = \frac{1}{f_s} \quad --------\ (1)$$

Therefore $T = \frac{1}{25 \times 10^3} = 4 \times 10^{-5}$ s

$$T = 4 \times 10^{-5} \text{ s} = 40 \text{ μs}$$

Considering Fig.4, both areas under the **ON** and **OFF** states must be equal,

$$V_{DC} t_{on} + (V_{DC} - V_o)t_{off} = 0$$

Rearranging the terms with division by period, T will yield the following relationship

$$\frac{V_o}{V_{DC}} = \frac{T}{t_{off}} = \frac{1}{1 - \rho}$$

$$\rho = 1 - \frac{V_{DC}}{V_o}$$

For V_{INPUT}, V_{DC} = 30 V and V_{OUTPUT}, V_o = 48 V

$$\rho = 1 - \frac{30}{48} = 1 - 0.625 = 0.375$$

The duty ratio, ρ defines the length of time the devices remains in a particular state either ON or OFF state. The ratio is between 0 and 1 and output voltage always higher than the input for the present design (Boost converter).

Given that the main objectives of the converter are to be step-up from 30 V DC to 48 V DC and output capable of driving a load of 80 W, The load current I_L can be calculated from the equation for maximum power as shown below.

$$P_{max} = I_L \times V_o$$

$I_L = 1.667$ Aand is the same as the output current for clarity.

Inductor
Given the relationship of equation (2) below,

$$I_o = \frac{V_o}{2L}(1-\rho)^2\rho T \quad ------ \quad (2)$$

$$L = \frac{V_o(1-\rho)^2\rho T}{2I_o}$$

Re-writing this gives, $L = 84.3 \ \mu H$

Capacitor
Using the equation to solve the voltage ripple, ΔV given as 100 mV

$$\Delta V = \frac{I\rho}{f_s C}$$

$$C = \frac{I_L \rho}{f_s \Delta V} = \frac{1.667 \times 0.375}{0.1 \ \times 25 \times 10^3}$$

$$= 2.5 \times 10^{-4} \ F$$

$$= 250 \ \mu F$$

IV. RESULTS AND DISCUSSIONS

4.1. Results

The boost converter model of Fig.5 has component values as enumerated below:

Input DC voltage = 30 V, Input resistance = 0.18 Ω, Input Inductance = 470 µH, Input capacitance = 470 µF, MOSFET, Load resistor = 28.8

Simulated Results gives; Average input voltage=29.8V, Average input current =2.53A, Output current =1.67A, Average output voltage = 48.01 V, Average inductor current = 2.25A

From the simulated results, it can be observed that the values are a little different from the calculated values. Looking at the value of the duty ratio, ρ, the simulated value is 0.390 (39.0%)as against the calculated value of 0.375 (37.5%), this is because of a drop-in voltage across the internal resistor and it was observed that the output voltage increases with increase duty ratio.

Fig.6 shows the output voltage ripple from the simulation with the upper value being 48.0338 V and the lower value of the ripple as 47.9785 V. This results in a ripple voltage of 55.3 mV.
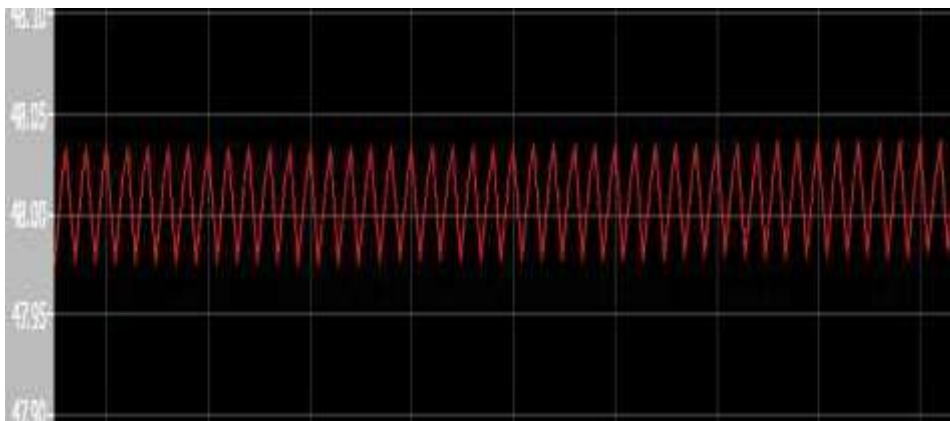

Fig.6. Output Voltage ripples from simulation

From the ripple voltage value obtained from the simulation as shown in Fig.6, the capacitance which would have been the correct one to use can be calculated from:

$$\Delta V = \frac{I_L \rho}{f_s C}$$

Knowing that the duty ratio, ρ is 0.375, the capacitance is given as

$$C = \frac{1.667 \times 0.390}{0.0553 \times 25 \times 10^3}$$

$$C = 4.702 \times 10^{-4} \approx 470 \times 10^{-6} = 470 \ \mu F$$

The use of this capacitance led to a lower ripple voltage compared to 100mV.

4.2 Effect of varying capacitance on input/output voltage and current waveforms

The main functions of a capacitor in DC-DC converter are to stored charge and smoothen out the ripples. These are shown in Fig. 7 and 8. The higher the input capacitance the higher the smoothening effect.

Comparing Fig. 7 and 8, the major dip can be seen to reduce considerably with increase in the value of input capacitance. The dip in Fig.7 and 8 were measured and for 470 µF the dip measures 4.8 V and for 1000 µF the dip measures 3.1 V. This invariably confirms the smothening effect of increase in input capacitance. This was further demonstrated when a very high capacitance of 4.5×10^{-2}F was used, a completely smothened out waveform was obtained as shown in Fig.9. The transient time is seen to increase with the ripples taking a sinusoidal form.

Fig.7. Input Voltage waveform with input capacitance (470 µF)

Fig.8. Input Voltage waveform with input capacitance (1000 µF)
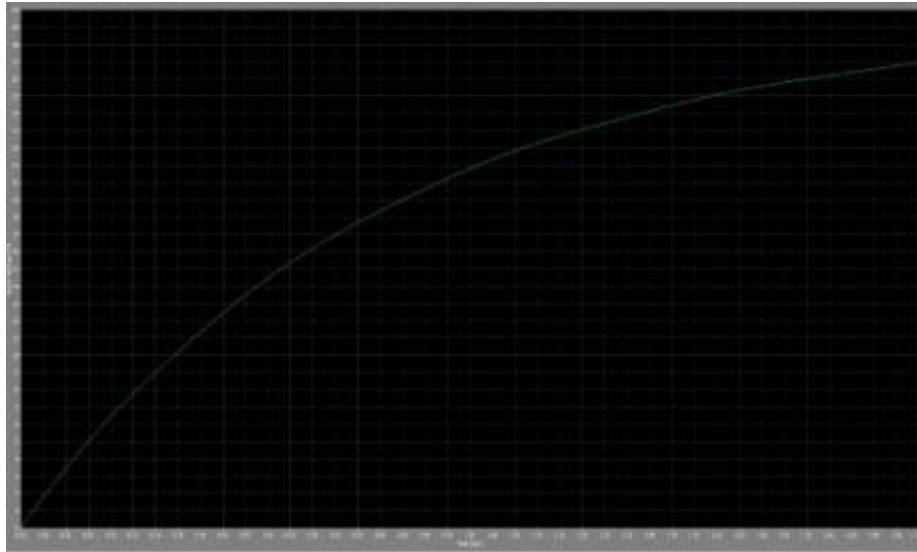
Fig.9. Output voltage waveform using very high input capacitance(4.5 x10⁻² F)

4.3 Effect of varying input impedance on Input/output current and voltage

The effect of the power supply impedance can be seen on the input current waveform. For an input impedance of 0.1Ω the dip of the input current waveform was measured to be 24A and for an input impedance of 0.4Ω, the dip of the input current waveform was measured to be 8 A as shown in Fig. 10 and Fig.11. The input impedance also affects the transient time. The transient time reduces with increase impedance.

The power supply impedance affects the steady state value of the dc voltage that is finally delivered. An increase in the input impedance results a decrease in the steady state dc output voltage that is finally delivere and a reduction in the overshot and also reduction in transient time. From Fig.12 the dc voltage that is delivered for input impedance of 0.1 Ω is 48 V with an overshot of 78.9 V and transient time of 0.125 second. Fig.13 shows the output current waveform for input impedance of 0.1 Ω having steady state current of 2.55 A and an overshot of 4.2 A.

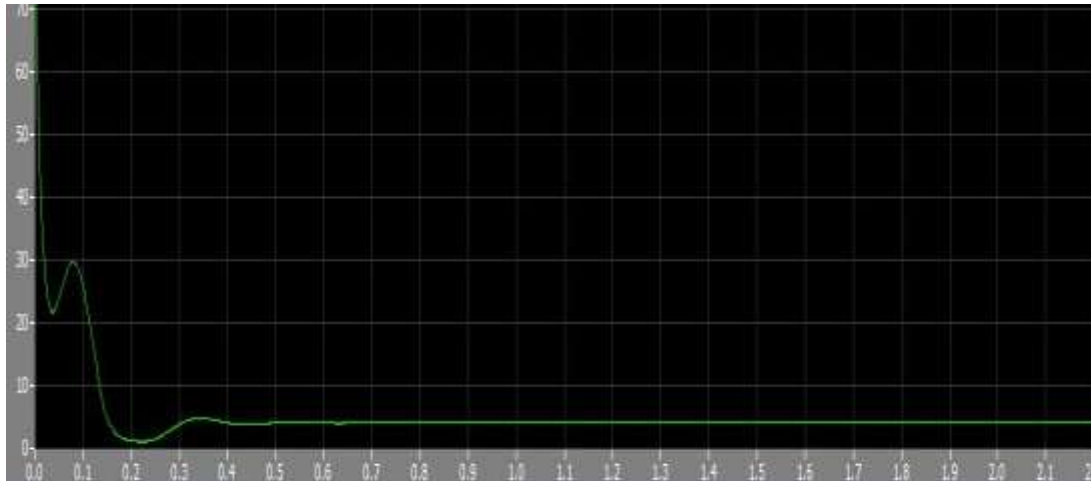**Fig.10. Input current waveform for 470 μF and input impedance of 0.1 Ω**

Fig.11. Input current waveform for (470 µF and input impedance of 0.4 Ω)

Fig.12. Output voltage waveform for 470 µF and input impedance of 0.1 Ω

Fig. 13. Output current waveform for 470 µF and input impedance of 0.1 Ω

As the impedance increases, the value of steady state voltage delivered falls and the overshot for both output voltage and current also reduces. Fig.14 and 15 shows the output voltage and current waveforms for 470 µF and input impedance of 0.4 Ω. This gives a steady state output voltage of 46 V and a reduced overshot of about 3 A. the steady state current is not visibly affected.

A trade off is in choosing values that reduces the output voltage transient time and also the overshoot within that time so that it can be applicable in viable working conditions without damaging the devices.
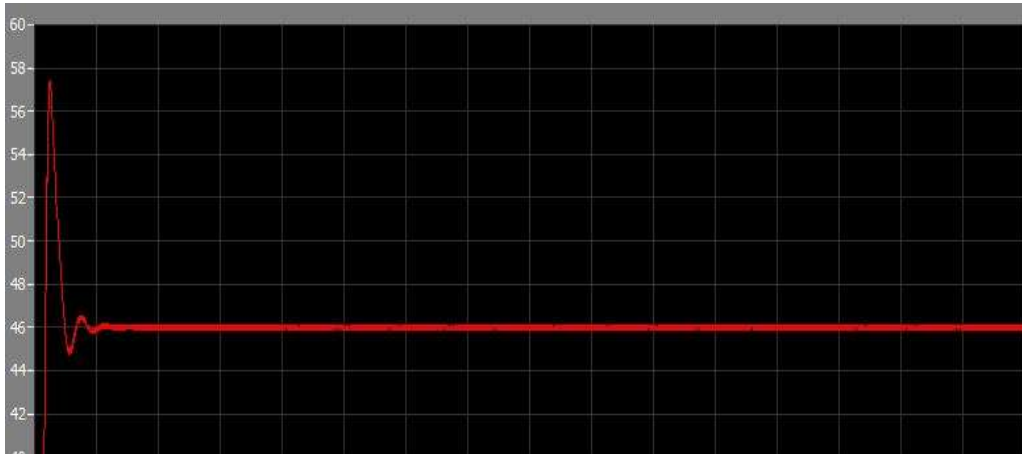
Fig.14. Output voltage waveform for 470 μF and input impedance of 0.4 Ω

Fig.15. Output current waveform for 470 μF and input impedance of 0.4 Ω

Completed look-up tables: Conduction losses

This was completed using the forward characteristics provided for both the Diode and MOSFET switching devices provided in the data sheets. These values are added to the design specification parameters within the simulation which account for the losses in the system.

Table 1: DIODE Look-up Table

	0.01 A	0.03 A	0.9 A	7 A	20 A
25ºC	0.5V	0.6 V	0.8 V	1.0 V	1.2 V

Conduction loses for diode as determined from forward characteristics

Table 2: MOSFETS Look-up Table

	2 A	4 A	6 A	8 A	10 A
25ºC	0.1 V	0.2 V	0.4 V	0.8 V	1.0 V
175ºC	0.2 V	0.3 V	0.4 V	0.7 V	1.0 V

Conduction losses for MOSFETS over the different working temperatures

Estimating power losses

Power losses are important element in the working of switching devices. This was estimated using heat flow meters in the simulation to measure the actual heat dissipated in the switching device. The resultant plot is shown in Fig. 16. This is achieved using heat flow meters in the simulation to measure the heat dissipated in the switching devices. The resultant plot is shown below:
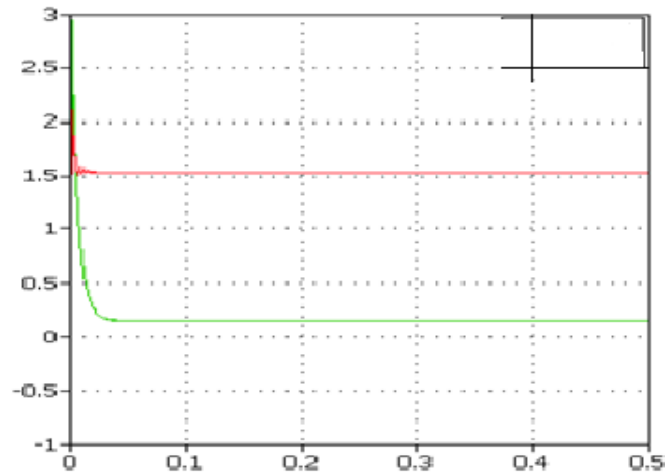
Fig.16. Diode Losses (red colour) and MOSFET Losses(green colour)

Diode losses = 1.53 W; MOSFET losses = 0.15 W; and this equates to a total of 1.68 W. Output power = Input power - losses

= 29.8 x 2.53 – 1.68

= 75.394 – 1.68 = 73.714 W.

Hence the efficiency would be $\eta = \frac{Output\ power}{input\ power} = \frac{73.714}{75.394} \times 100 = 97.8\%$

Temperature of the Device and Heatsink

The specified thermal resistance of (4.5^0C /W) was then simulated for the converter, considering the room temperature of 25℃ when adjusting for the increase in temperature of both diode and MOSFET below (Fig. 17)
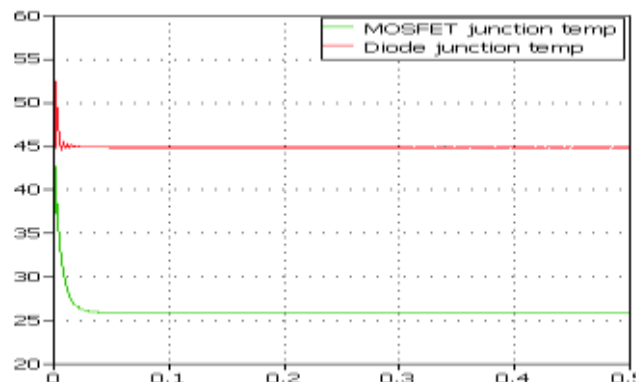

Fig.17. MOSFET (green) and Diode (red) junction temperature

V. CONCLUSIONS

DC-DC Boost converter has been designed and simulated in MATLAB-cum-PLECS software. The simulation results and the calculated results are in good agreement. The difference in duty ratio between the simulation and calculated results is 1.5% which is a result of drop in voltage across the internal resistor. The effect of increased input capacitance is higher smoothening of the signals. Increased input impedance reduces the transient time and also affects the steady-state value of the DC voltage that is finally delivered. Due to the rise in temperature of almost 45 ^{0}C in the diode and an increase of 26^0C in the MOSFET it can be concluded that the greater losses occur in the diode.

ACKNOWLEDGEMENT

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