Design of a Two-Level Boost Converter

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ABSTRACT

The objective of this paper is to demonstrate the design of a two-level boost converter and its controller. First, the context of the importance of such a converter is stablished. Then, the operation of an ideal converter is studied to determine some fundamental relationships necessary for design. Also, the non-idealities of the converter are introduced and a set of equations are developed which are later used to design a converter for a hybrid vehicle application. Finally, various control strategies are studied for the designed converter and implemented in MATLAB/Simulink.

Keywords: Multilevel converters, DC-DC converters, hybrid-electric vehicles, power electronic converters, boost converter

1. INTRODUCTION

Lately, there has been a significant increase in demand of high power high efficiency DC-DC converters. This growth is mostly related to a more widespread use of renewable energies operating under the distributed generation scheme. Also, most of these sources have low output levels, which impose even more constraints to the power conditioner design (Palma et al., 2005).

The same problem is present on DC-DC converters used on low power switched power supplies. In this case, efficiency is important in order to achieve portability, and the required voltage gains are constantly increasing with the integrated circuit design standards.

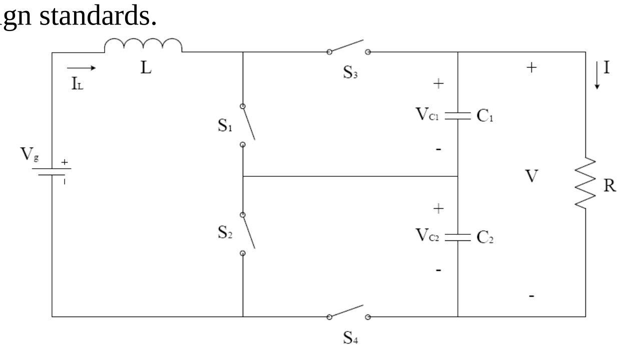

Figure 1: Two-level boost converter

When a DC voltage has to be stepped up, the boost converter has long been the preferred scheme. This is because of its adjustable step-up voltage conversion ratio, continuous input current, simple topology and high efficiency (Zhang et al., 1995). Nevertheless, when the power level increases, the inductor becomes large, bulky, costly and heavy. Also, as the required output voltage rises, conduction and switching losses increases as they are proportional to voltage. Sometimes, there aren't devices capable to withstand such stresses.

An extensive amount of research has been carried out on these issues. Many different topological modifications have developed from this, for example: serializing switching components (Brooks, 1979), cascading converters (Walker and Sernia, 2004), high frequency transformer based converters (Kang et al., 1999) and even multilevel converters, either diode clamped or of the flying capacitor type (Zhang et al., 2004).

Multilevel converters have had a lot of success, especially on DC-AC applications (Kouro et al., 2010). Some research has been made on their application on DC-DC circuits (Zhang et al., 2004) mostly of the diode clamped and the flying capacitor types. Nevertheless, a two level version of the boost converter will be very simple efficient and will have a low part count.

On a two level boost converter (Figure 1), the inductor loading stage is divided in half, which allows the input inductor to be one fourth of that on the single level version (Zhang et al., 1995). Also, as the output stage is divided, the switching devices (even though double in number) have half the voltage rating of the single level version, which greatly reduces the losses.

2. OPERATION AND IDEAL STEADY STATE ANALYSIS OF A TWO-LEVEL BOOST CONVERTER

The operation states of a single phase two-level boost converter takes place along the switching period and each state is determined by the duty cycle. The operating states of the converter are shown in figure 2.

- Inductor charging (States 1 and 3): corresponds to the instants when switches S_1 and S_2 are closed (Figure 2a). During these states the inductor is being charged from the source and the load is powered from the energy stored in the capacitors over the previous cycle. The equations corresponding to these states are:

$$\upsilon_L = V_g \qquad i_{C1} = i_{C2} = -\frac{V}{R} \tag{1}$$

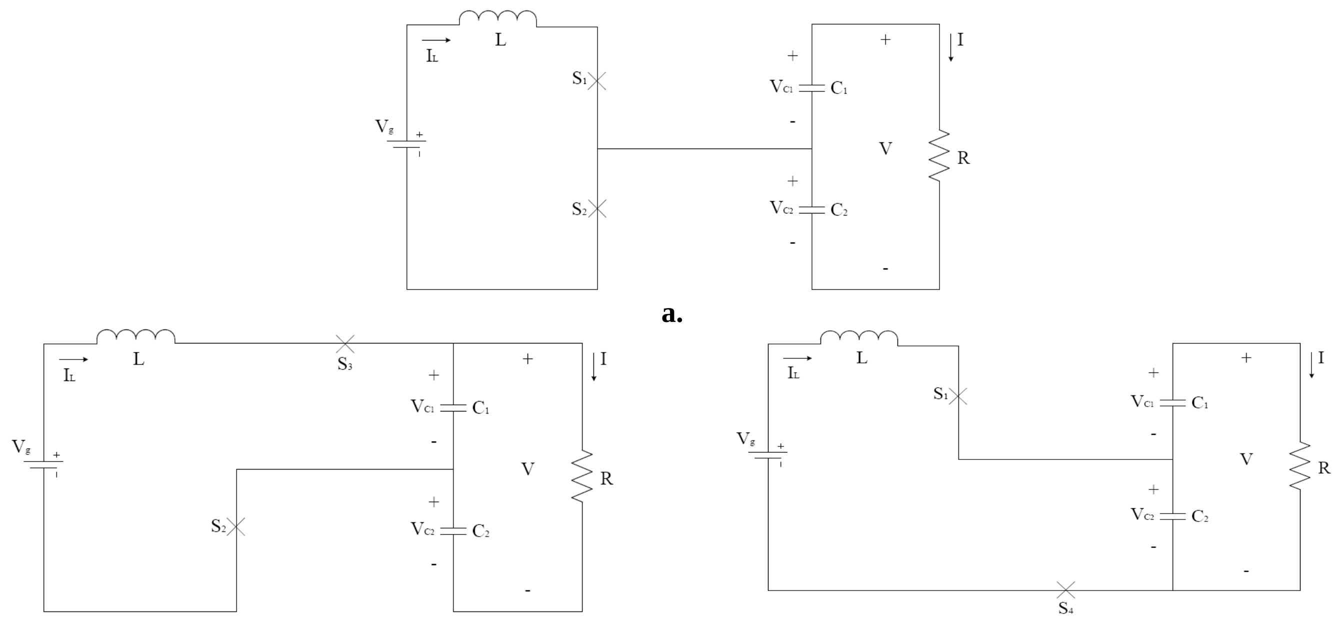

Figure 2: Operation states of the two-level boost converter: a. inductor charging, b. capacitor 1 charging and c. capacitor 2 charging

- Capacitor 1 charging (State 2): corresponds to the instant when switches S_2 and S_3 are closed (Figure 2b). During this state, energy is being transferred from the inductor to capacitor 1 and the load is powered from the source and the inductor. The equations corresponding to this state are:

$$\upsilon_L = V_g - \upsilon_{C1} \qquad i_{C1} = I_L - \frac{V}{R} \qquad i_{C2} = -\frac{V}{R} \tag{2}$$

- Capacitor 2 charging (State 4): corresponds to the instant when switches S_1 and S_4 are closed (Figure 2c). During this state, energy is being transferred from the inductor to capacitor 2 and the load is powered from the source and the inductor. The equations corresponding to this state are:

$$\upsilon_L = V_g - \upsilon_{C2} \qquad i_{C1} = -\frac{V}{R} \qquad i_{C2} = I_L - \frac{V}{R} \tag{3}$$

In steady state the switching pattern (Figure 3) used for the converter operation is as follows

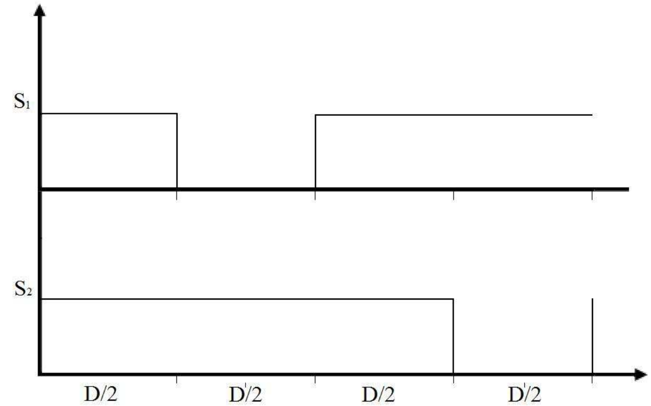

Figure 3: Switching pattern

Following the above switching pattern we proceed to derivate the voltage relationship, the inductor and capacitor size equations.

$$\upsilon_{c1} = \upsilon_{C2} = \frac{1}{2}V \tag{4}$$

From the inductor volt-second balance equation we obtain the relationship of the voltages as a function of the duty cycle D:

$$\frac{V}{V_g} = \frac{2}{(1-D)} \tag{5}$$

And from the capacitor charge balance equation

$$I_L = \frac{2V}{(1-D)R} \tag{6}$$

We can also then derivate the inductance formula for a constant load and duty cycle. This yields:

$$L = \frac{R(1-D)D}{8f} \tag{7}$$

And then the capacitance formula for a constant load is as follows,

$$C = \frac{VD}{4Rf\Delta v} \tag{8}$$

For a variable input voltage, output voltage and load that follows the relationships

$$V_{g\min} < V_g < V_{g\max} \qquad V_{\min} < V < V_{\max} \qquad P_{\min} < P < P_{\max} \tag{6}$$

The duty cycle is,

$$D = 1 - 2 \cdot \frac{V_g}{V} \tag{9}$$

From (9) we can see that to have a positive and non-zero duty cycle $V > 2V_g$ therefore, $V_{\min} > 2V_{g\max}$. Then the inductance is,

$$L = \frac{VD(1-D)^2}{16f \cdot I_{Load}} \tag{10}$$

And the capacitance is the same as in equation (8).

3. Operation and Steady State Analysis including Losses of a Two-Level Boost Converter

From an analysis of the operating conditions of the ideal two-level boost converter and a switch realization study, it can be concluded that switches 1 and 2 are voltage-blocking fully-controllable switches (either BJT's or IGBT's) and that switches 3 and 4 are current-blocking circuit-controlled switches (diodes). Therefore, a more detailed analysis of the converter can be developed by integrating the non-idealities associated with these devices.

A satisfactory way to model those non-idealities is representing the on state of the power electronic devices by their characteristic voltage drop and grouping conducting, leakage, stray and terminal losses as a single resistor in series with the input inductor. Such a representation is shown in Figure 4.

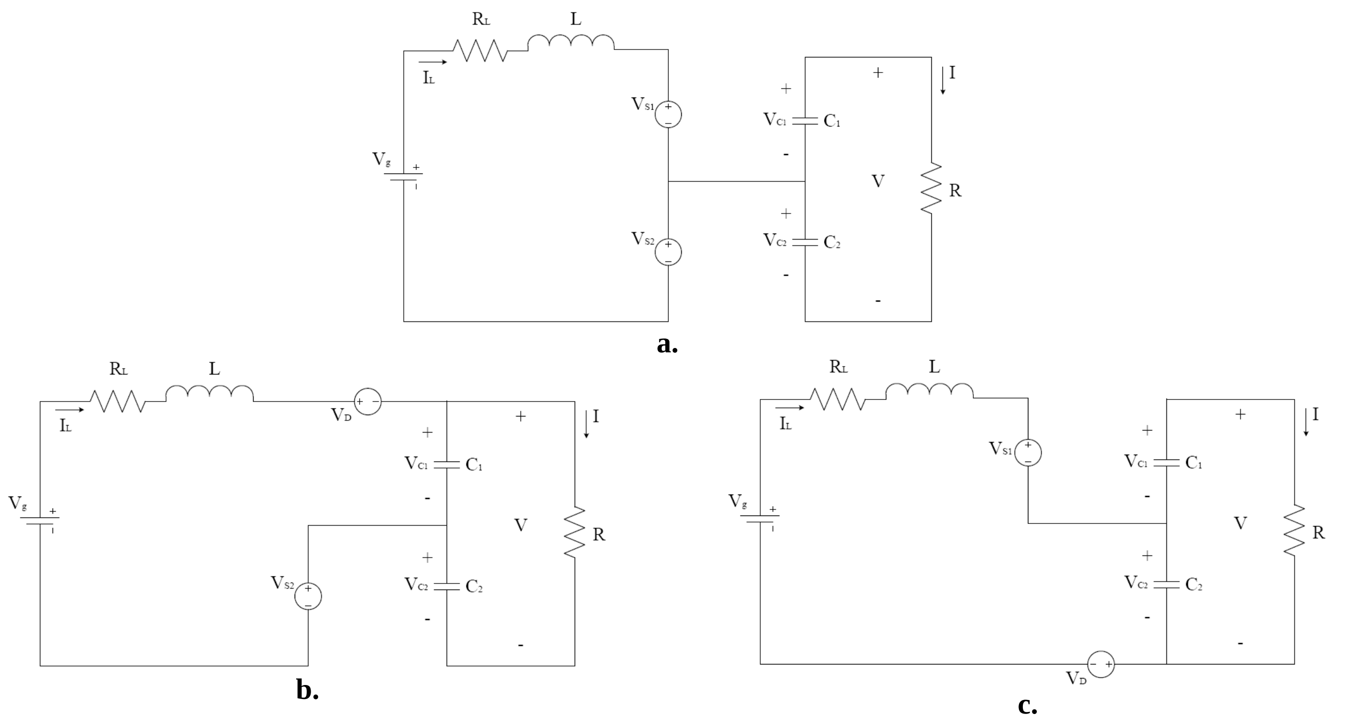

Figure 4: Loss model for each operation state of the two-level boost converter: a. inductor charging, b. capacitor 1 charging and c. capacitor 2 charging

With these additions, equations 1, 2 and 3 are modified as follows:

- Inductor charging (States 1 and 3, Figure 1a)

$$\upsilon_L = V_g - I_L R_L - V_{S1} - V_{S2} \qquad i_{C1} = i_{C2} = -\frac{V}{R} \tag{11}$$

- Capacitor 1 charging (State 2, Figure 1b)

$$\upsilon_L = V_g - I_L R_L - \upsilon_{C1} - V_{S2} - V_D \qquad i_{C1} = I_L - \frac{V}{R} \qquad i_{C2} = -\frac{V}{R} \tag{12}$$

- Capacitor 2 charging (State 4, Figure 1c)

$$\upsilon_L = V_g - I_L R_L - V_{S1} - \upsilon_{C2} - V_D \qquad i_{C1} = -\frac{V}{R} \qquad i_{C2} = I_L - \frac{V}{R} \tag{13}$$

Then, following the switching pattern presented in Fig.2, for $\upsilon_{c1} = \upsilon_{C2} = \frac{1}{2}V$ and $V_S = V_{S1} = V_{S2}$, the inductor volt-second balance equation yields

$$V_g - I_L R_L - (1+D)V_S - 1/2\, D'V - D'V_D = 0 \tag{14}$$

The inductor current remains equal to equation (6) and is rewritten here for completeness

$$I_L = \frac{2V}{(1-D)R} \tag{6}$$

From equation (14) and replacing I_L as in equation (6), we obtain

$$\frac{V}{V_g} = \frac{2}{D'}\left[1 - (1+D)\frac{V_S}{V_g} - D'\frac{V_D}{V_g}\right] \cdot \left[\frac{1}{1 + \frac{4R_L}{(D')^2 R}}\right] \tag{15}$$

The efficiency of the converter is obtained calculating $\eta = \frac{P_{out}}{P_{in}}$ where,

$$P_{in} = V_g \cdot I_L \qquad P_{out} = V \cdot I = V(1/2\, D' I_L) \tag{16}$$

Therefore,

$$\eta = \left[1 - (1+D)\frac{V_S}{V_g} - D'\frac{V_D}{V_g}\right] \cdot \left[\frac{1}{1 + \frac{4R_L}{(D')^2 R}}\right] \tag{17}$$

4. Design Example

In order to prove the two level boost converter concept, a converter of this type will be designed for a parallel hybrid-electric vehicle application. An input voltage will be provided, that could change its value from 40 to 30 volts. The load is rated to 45 kW and the converter should be able to operate on the continuous conduction mode all the way from 100% to 10% of the load. The output voltage is rated at 300V and a 2% voltage ripple is allowed. Also, operation from 90 to 300 volts is required and the converter frequency is 5 kHz.

Table 1: Design Parameter

Parameters	Values
Input Voltage (V_g)	30 V – 40 V
Output Voltage (V)	90 V – 300 V
Frequency (f)	5kHz
Power	45 kW

The critical capacitance is obtained using $V = 90V$, $V_g = 30V$, $P = 45kW$

$$D = 1 - 2 \cdot \frac{30}{90} = \frac{1}{3} \qquad R = \frac{V^2}{P} = \frac{90^2}{45\times 10^3} = 0.18\Omega \qquad I_{Load} = \frac{45\times 10^3}{90} = 500A$$

$$C_{critical} = \frac{(90)(1/3)}{4(0.18)(5\times 10^3)(90/100)} = 9259.26\mu F$$

$$C_{critical} \approx 9300\mu F$$

The critical inductance is obtained using $V = 300V$, $V_g = 40V$, $P = 4.5kW$

$$D = 1 - 2 \cdot \frac{40}{300} = \frac{11}{15} \qquad R = \frac{V^2}{P} = \frac{300^2}{4.5\times 10^3} = 20\Omega \qquad I_{Load} = \frac{4.5\times 10^3}{300} = 15A$$

$$L_{critical} = \frac{(300)(11/15)(1-11/15)^2}{16(5\times 10^3)(15)} = 13.04\mu H$$

$$L_{critical} \approx 13\mu H$$

The current rating of the switches is

$$I_{rated} = \frac{2}{(1-1/3)} \cdot \frac{45\times 10^3}{90} = 1500A$$

The voltage rating of the switches is

$$V_{rated} = \frac{1}{2}(300) = 150V$$

Using these values we select the IGBT's and diodes that hold these values and from their datasheets we can obtain their voltage drop:

IGBT $V_{S,on} = 1.7V$ Diode $V_{D,on} = 0.7V$

To calculate the inductor resistance, we use the Q factor which we know is in range of $50 < Q < 500$, we choose Q=500

$$R_L = \frac{\omega \cdot L}{Q}$$

$$R_L = \frac{2\pi(5\times 10^3)(13.04\times 10^{-3})}{500} = 0.82m\Omega$$

The efficiency of this converter for an operating point of P=45kW, V=300V and V_g=30V is calculated as follows,

$$\eta = \left[1-(1+0.8)\frac{1.7}{30}-0.2\left(\frac{0.7}{30}\right)\right]\cdot\left[\frac{1}{1+\frac{4(0.82e-3)}{2(0.2)^2}}\right]$$

$$\eta = 85.81\%$$

Figure 5 shows the range of efficiencies of this converter which is delimited by the minimum and maximum loads.

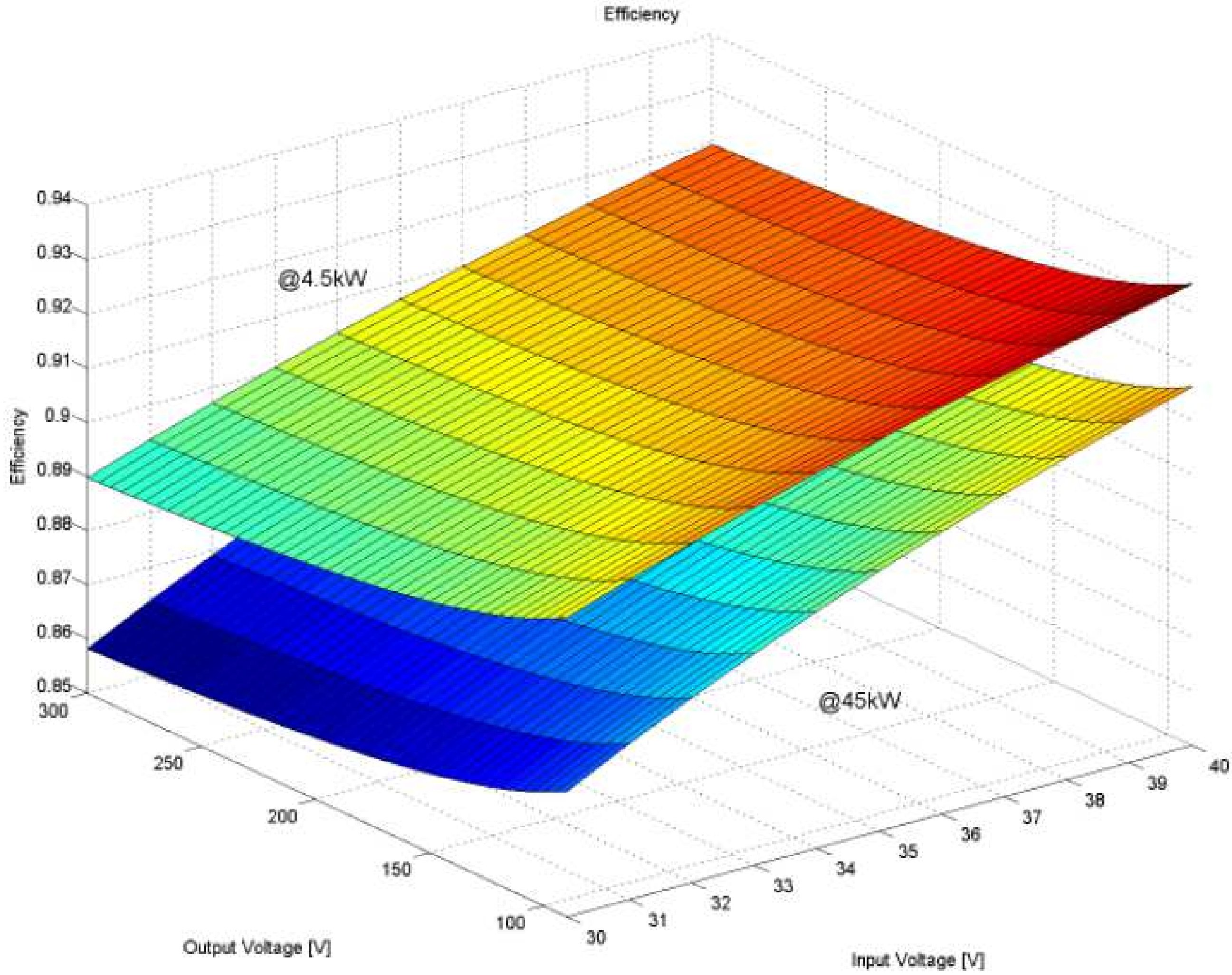

Figure 5: Efficiency of the two-level boost converter as a function of input voltage, output voltage and load.

5. SIMULINK MODEL AND RESULTS

In order to verify the performance of our design we have developed a model of the converter in MATLAB–Simulink, and the most important results are presented here. The controller is designed in such a manner that it could be easily implemented into a digital controller (either a DSP or a Microcontroller).

First, an open loop controlled model was developed, in which the control calculates the duty cycle based on the reference signal, and then generates the gating signals on a per-time basis (Figure 6).

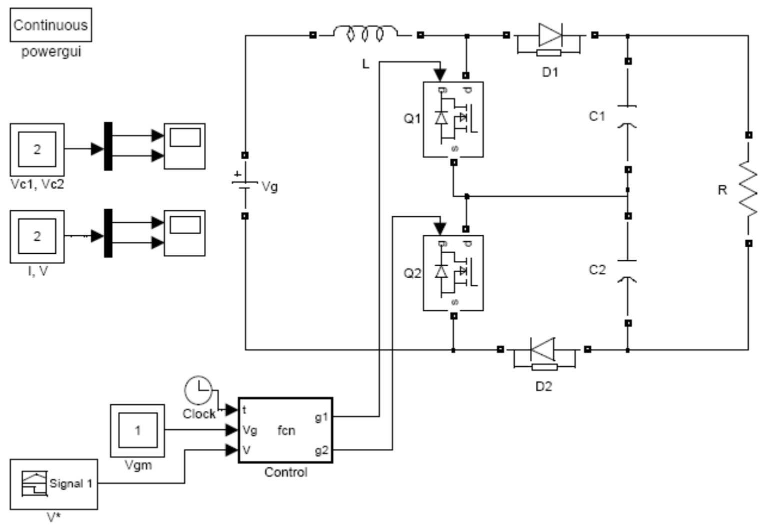

Figure 6: Open loop control

Figures 7 and 8 present the results obtained for this controller. In the test, the voltage was dynamically changed in steps from half to maximum of the output voltage and back to half.

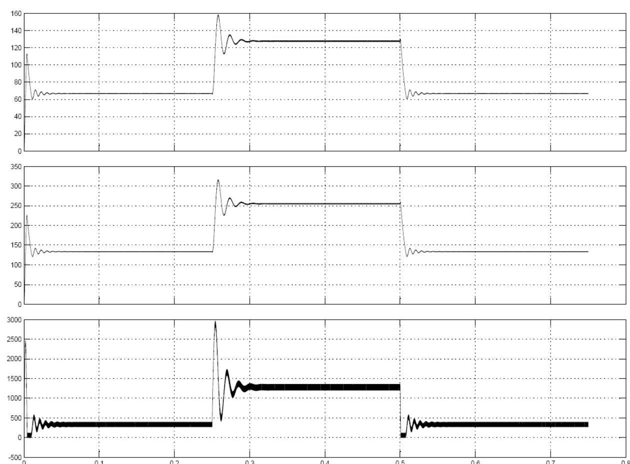

Figure 7: Output current, Voltage and Input Current

[V=150/300/150V, Vg=30, P=45kW]

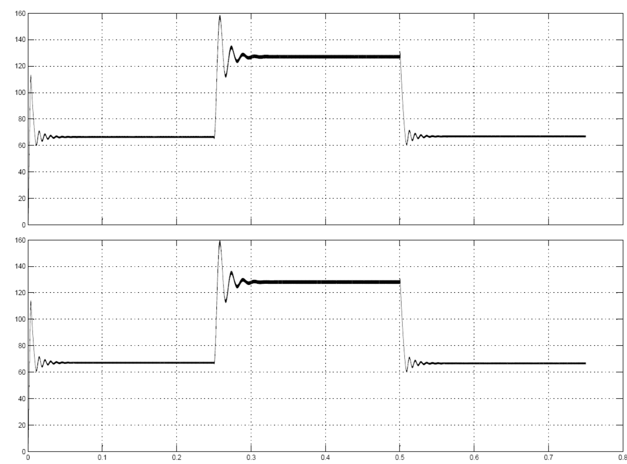

Figure 8: Capacitors' voltages (VC1, VC2)

[V=150/300/150V, Vg=30, P=9kW]

Three problems can be identified from the previous figures:

- The settling time is too long
- The overshoot almost doubles the rated values
- During the transient, the converter operates intermittently on discontinuous conduction mode.

In order to eliminate some of the problems present on the open loop control configuration, a closed loop controller was developed. This controller (Figure 10) is based on the hysteresis control technique, which allows us to ensure continuous conduction operation of the converter at all times, no overshoots and shorter settling times.

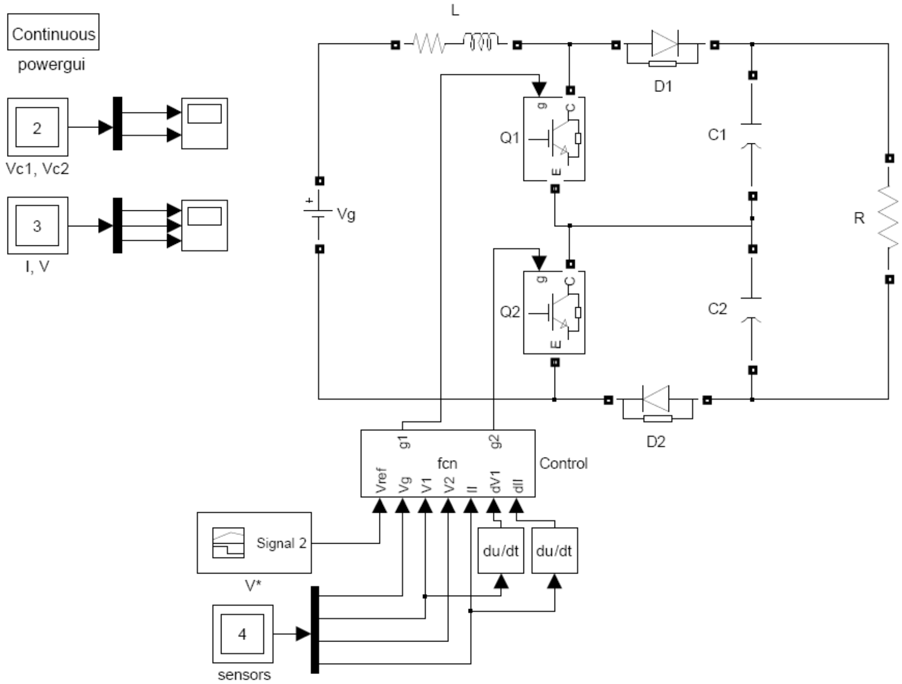

Figure 10: Closed Loop Model

The results obtained with this control while dynamically changing the voltage are shown in figures 11 and 12. The voltage transients have been eliminated, and the settling time is improved. Also the input current is strictly controlled as to maintain the circuit in continuous conduction mode operation. Even though there is an overshoot in the current during the firs two subcycles, this is caused by the fact that the switching is based on the natural charging constants of the circuit, and as the dc value of this current increases, these overshoots will be reduced so the switches will stay safe.

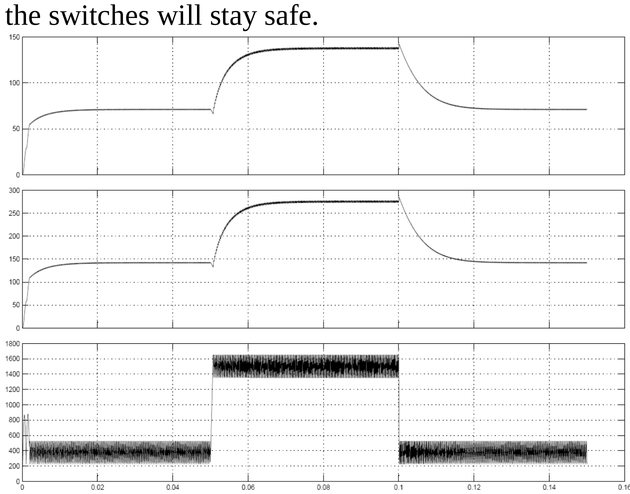

Fig. 11 Output current, Output Voltage and Input Current

[V=150/300/150V, Vg=30, P=45kW]

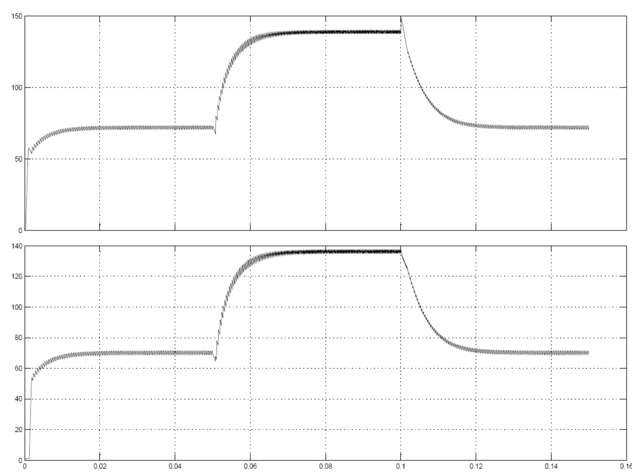

Fig. 12 Capacitors' voltages (VC1, VC2) [V=150/300/150V, Vg=30, P=45kW]

To compensate for the switching and conduction losses of the circuit, a PI controller is implemented to reduce the error of the output voltage with respect to the reference signal. However, the settling time has incremented greatly and the improvements of the results are not sufficient to justify that.

6. CONCLUSIONS

The two-level boost converter has been presented and its operation explained. The analysis of the circuit was done using the DC averaging technique and satisfactory results were obtained for the ideal case and also when the losses were accounted for. From these analyses, design equations have been developed for the converter.

Also, in order to demonstrate the two level boost converter principle, a design was developed for a Hybrid Electric Vehicle (HEV) application. Finally, the resulting design was simulated using the MATLAB-SIMULINK software and improved control techniques were developed for the converter.

Based on the simplicity of this converter, its robustness and its low part count, application on high power high reliability applications like HEV's seems really attractive. This is specially the case if fast and compact control techniques, like the one presented here, are used that allow for inexpensive and robust controllers use.

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