

DESIGN AND DEVELOPMENT OF DC/DC FLYBACK CONVERTERS FOR ELECTRIC VEHICLES

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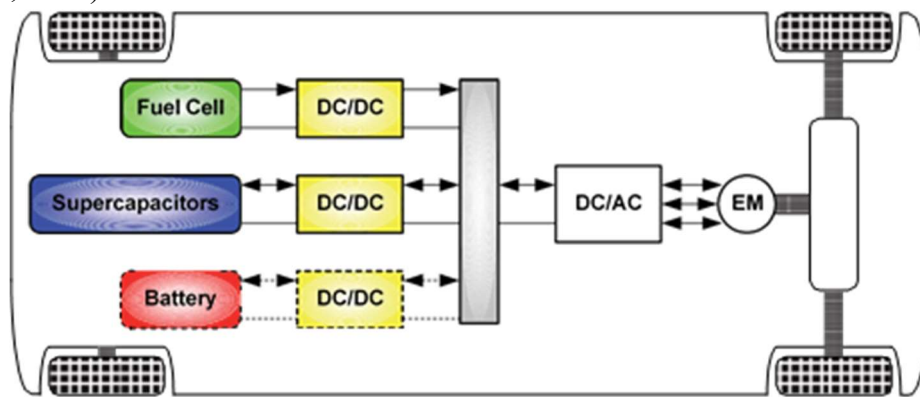
Introduction

The large number of automobiles in use around the world has caused and continues to cause serious problems of environment and human life. Air pollution, global warming, and the rapid depletion of the earth's petroleum resources are now serious problems. Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs) have been typically proposed to replace conventional vehicles in the near future. Most electric and hybrid electric configurations use two energy storage devices, one with high energy storage capability, called the "main energy system" (MES), and the other with high power capability and reversibility, called the "rechargeable energy storage system" (RESS). MES provides extended driving range, and RESS provides good acceleration and regenerative braking. Energy storage or supply devices vary their output voltage with load or state of charge and the high voltage of the DC-link create major challenges for vehicle designers when integrating energy storage / supply devices with a traction drive. DC-DC converters can be used to interface the elements in the electric power train by boosting or chopping the voltage levels. Due to the automotive constraints, the power converter structure has to be reliable, lightweight, small volume, with high efficiency, low electromagnetic interference and low current/voltage ripple. Thus, in this chapter, a comparative study on three DC/DC converters topologies (Conventional step-up dc-dc converter, interleaved 4-channels step-up dc-dc converter with independent inductors and Full-Bridge step-up dc-dc converter) is carried out. The modeling and the control of each topology are presented. Simulations of 30KW DC/DC converter are carried out for each topology. This study takes into account the weight, volume, current and voltage ripples, Electromagnetic Interference (EMI) and the efficiency of each converter topology.

1. Electric vehicles powertrain

An Electric Vehicle is a vehicle that uses a combination of different energy sources, Fuel Cells (FCs), Batteries and Supercapacitors (SCs) to power an electric drive system as shown in Fig. 1. In EV the main energy source is assisted by one or more energy storage devices. Thereby the system cost, mass, and volume can be decreased, and a significant better performance can be obtained. Two often used energy storage devices are batteries and SCS. They can be connected to the fuel cell stack in many ways. A simple configuration is to directly connect two devices in parallel, (FC/battery, FC/SC, or battery/SC). However, in this way

the power drawn from each device cannot be controlled, but is passively determined by the impedance of the devices. The impedance depends on many parameters, e.g. temperature, state-of-charge, health, and point of operation. Each device might therefore be operated at an inappropriate condition, e.g. health and efficiency. The voltage characteristics also have to match perfectly of the two devices, and only a fraction of the range of operation of the devices can be utilized, e.g. in a fuel cell battery configuration the fuel cell must provide almost the same power all the time due to the fixed voltage of the battery, and in a battery/supercapacitor configuration only a fraction of the energy exchange capability of the supercapacitor can be used. This is again due to the nearly constant voltage of the battery. By introducing DC/DC converters one can chose the voltage variation of the devices and the power of each device can be controlled (Schaltz & Rasmussen, 2008).



Electric vehicle drive system.

In reference (Schaltz & Rasmussen, 2008), 10 cases of combining the fuel cell with the battery, SCs, or both are investigated. The system volume, mass, efficiency, and battery lifetime were compared. It is concluded that when SCs are the only energy storage device the system becomes too big and heavy. A fuel cell/battery/supercapacitors hybrid provides the longest life time of the batteries. It can be noticed that the use of high power DC/DC converters is necessary for EV power supply system. The power of the DC/DC converter depends on the characteristics of the vehicle such as top speed, acceleration time from 0 to 100 Km/h, weight, maximum torque, and power profile (peak power, continuous power) (Büchi et al., 2006). Generally, for passenger cars, the power of the converter is more than 20 KW and it can go up to 100 KW.

2. DC/DC converters for electric vehicles

The different configurations of EV power supply show that at least one DC/DC converter is necessary to interface the FC, the Battery or the Supercapacitors module to the DC-link.

In electric engineering, a DC to DC converter is a category of power converters and it is an electric circuit which converts a source of direct current (DC) from one voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors).

DC/DC converters can be designed to transfer power in only one direction, from the input to the output. However, almost all DC/DC converter topologies can be made bi-directional. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking.

The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of on/off time of the switch). Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power. Transformer- based converters may provide isolation between the input and the output. The main drawbacks of switching converters include complexity, electronic noise and high cost for some topologies. Many different types of DC/DC power converters are proposed in literature (Chiu & Lin, 2006), (Fengyan et al., 2006). The most common DC/DC converters can be grouped as follows:

2.1 Non-isolated converters

The non-isolated converters type is generally used where the voltage needs to be stepped up or down by a relatively small ratio (less than 4:1). And when there is no problem with the output and input having no dielectric isolation. There are five main types of converter in this non-isolated group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step- down or step-up. The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

Flyback Converter Converters

Usually, in this type of converters a high frequency transformer is used. In the applications where the output needs to be completely isolated from the input, an isolated converter is necessary. There are many types of converters in this group such as Half-Bridge, Full- Bridge, Fly-back, Forward and Push-Pull DC/DC converters (Garcia et al., 2005), (Cacciato et al., 2004). All of these converters can be used as bi-directional converters and the ratio of stepping down or stepping up the voltage is high.

Electric vehicle converters requirements

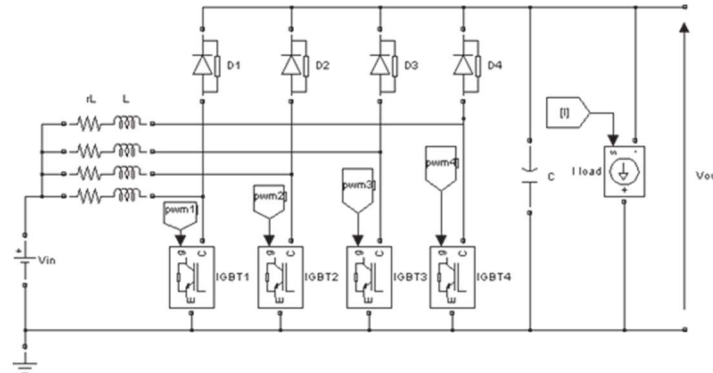
In case of interfacing the Fuel Cell, the DC/DC converter is used to boost the Fuel Cell voltage and to regulate the DC-link voltage. However, a reversible DC/DC converter is needed to interface the SCs module. A wide variety of DC-DC converters topologies, including structures with direct energy conversion, structures with intermediate storage components (with or without transformer coupling), have been published (Lachichi & Schofield, 2006), (Yu & Lai, 2008), (Bouhalli et al., 2008). However some design considerations are essential for automotive applications:

- Light weight,
- High efficiency,
- Small volume,
- Low electromagnetic interference,

- Low current ripple drawn from the Fuel Cell or the battery,
- The step up function of the converter,

Interleaved 4-channels step-up DC-DC converter.

Control of the DC/DC converter power flow subject to the wide voltage variation on the converter input. Fig. 10 shows a basic interleaved step-up converter of 4 identical levels where the inductances L1 to L4 are built by a separate magnetic core. The gate signals to the power switching devices are successively phase shifted by T/N where T is the switching period and N the number of channels. Thus, the current delivered by the electric source is shared equally between each basic step-up converter level and has a ripple content of period T/N (Destraz et al., 2006).



Interleaved 4-channels step-up DC-DC converter.

The design of the 4-channels converter is the same like the boost one. The output voltage is adjustable via the duty cycle α of the PWM signal switching the IGBTs as given in the following expression:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-\alpha} \tag{42}$$

Where:

- α : the duty cycle,
- V_{in} : the input voltage,
- V_{out} : the output voltage.

The inductor value of each channel is given by the following expression:

$$L_k = \frac{V_{out}}{4 \cdot F \cdot N \cdot \Delta I_{In} \max} = 100mH \tag{43}$$

Where:

- N : the number of channels,
- $\Delta I_{In} \max$: the input current ripple,
- F : the switching frequency.
- $I_{In} \max$: the maximum input current,
- $\Delta V_{out} \max$: the maximum output voltage ripple.

As control signals are interleaved and the phase angle is $360^\circ/N$, the frequency of the total current is

N times higher than the switching frequency F. The filter capacitor of the interleaved N-channel dc-dc converter is given by the following expression:

$$C_{f\min} = \frac{I_{In_max}}{4 \cdot F \cdot N \cdot D \cdot V_{out_max}} = 195mF \tag{44}$$

Table 2 shows the specifications of the converter.

ΔV_{out_max}	Output voltage ripple (1% of $V_{out} = 4\text{ V}$)
V_{out}	Output voltage (400 V)
F	Switching frequency (20 KHz)
I_{in_max}	Inductor current (250 A)
ΔI_{in_max}	Input current ripple (5% of $I_{in_max} = 12.5$)

A)Table 2. Interleaved 4-channels DC-DC converter parameters

F Switching frequency (20 KHz)

ΔI_{in_max} Input current ripple (5% of $I_{in_max} = 12.5\text{ A}$) Table 2. Interleaved 4-channels DC-DC converter parameters

Modeling and control

The 4-channel converter is modeled in the same way of the boost converter. The current and voltage loop are designed also using the same methodology used for boost converter. The calculated current reference is divided by 4 (number of channels). The output voltage control loop is shown is Fig. 11.

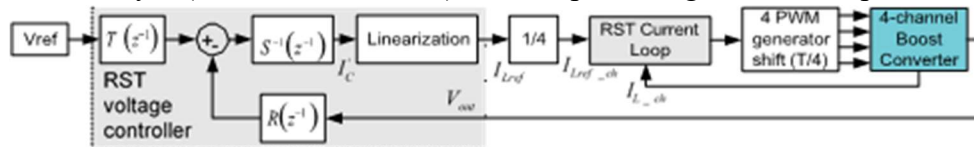


Fig. 11. 4-channels converter output voltage control loop.

In the proposed control, the duty cycle is calculated from one reference channel. The same duty cycle is applied to the other channels. The PWM signals are shifted by $360/4^\circ$.

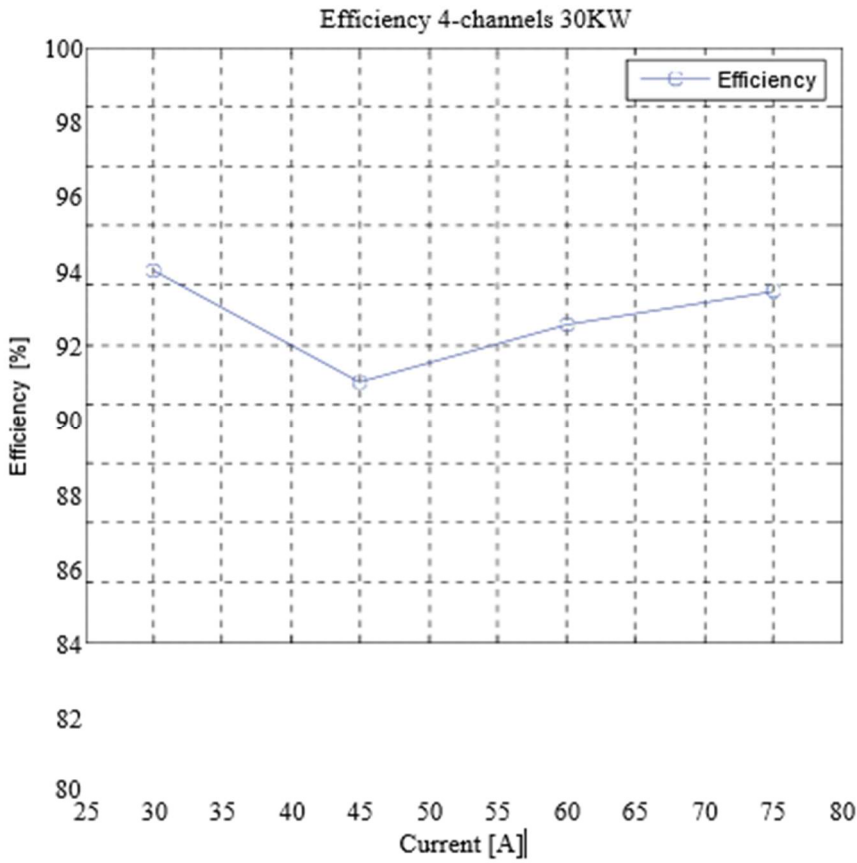
Simulation results

Thanks to the interleaving technique, the total current ripples are reduced and can be neglected; the voltage ripples are about 0.5V. The results show that the converter follows the demand on power.

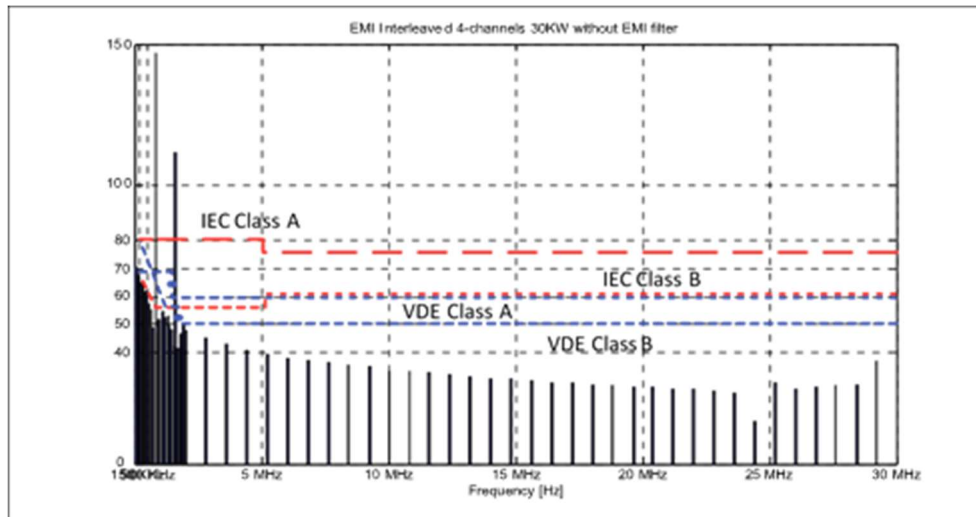
The efficiency of the 4-channels dc/dc converter is about 92% at full load as shown in Fig.

12. The drop in efficiency is due to the changing from discontinuous mode (DCM) to continuous mode (CM). In DCM, the technique of zero voltage switching (ZVS) is operating which permits to reduce the switching losses in the switch, thus the efficiency is increased. Fig. 13 shows the EMI of the interleaved 4-channels DC/DC converter. It is seen that the level of conducted interference due to converter is not tolerable by the regulations. As a consequence this converter without EMI filter

suppression does not meet the terms of the regulations. Thus, EMI filter suppression is required.



4-channels converter efficiency versus current load.



EMI simulation results of interleaved 4-channels DC/DC converter.

Modeling and control

The Full-Bridge DC/DC converter will have to maintain a constant 400V DC output. By increasing and decreasing the duty cycle $\alpha=t/T$ of the PWM signals, the output voltage can be held constant with a varying input voltage. The output voltage can be calculated as follows:

$$V_{out} = \frac{2 \cdot t}{T} \frac{V_{in}}{n} \Rightarrow V_{out} = 2 \cdot n \cdot \alpha \cdot V \quad (48)$$

Where, T is the switching period ($T=1/F$), n is the transformer turns ration ($n=N_s/N_p$), and t is the pulse width time.

The inductor current and voltage models are obtained by expressions 49 and 50, respectively.

$$I_L(s) = \frac{1}{Ls} \frac{4n\sqrt{2}}{p} \alpha(s) V_{in}(s) - V_{out}(s) \quad (49)$$

$$V_L(s) = \frac{4n\sqrt{2}}{p} \alpha(s) V_{in}(s) - V_{out}(s) \quad (50)$$

The linearization of the system is done by using an inverse model. Thus an expression between the output of corrector and the voltage of the inductor should be found. Thus, the following expression is proposed:

$$V_L'(s) = \frac{V_L(s) + V_{out}(s)}{\frac{4n\sqrt{2}}{p} \alpha(s) V_{in}(s)} \quad (51)$$

$V_L'(s) = \frac{V_L(s) + V_{out}(s)}{\frac{4n\sqrt{2}}{p} \alpha(s) V_{in}(s)}$

Where, VL' is a new control variable represents the voltage reference of the inductor. Thus, a linear transfer between VL'(s) and IL(s) is obtained by:

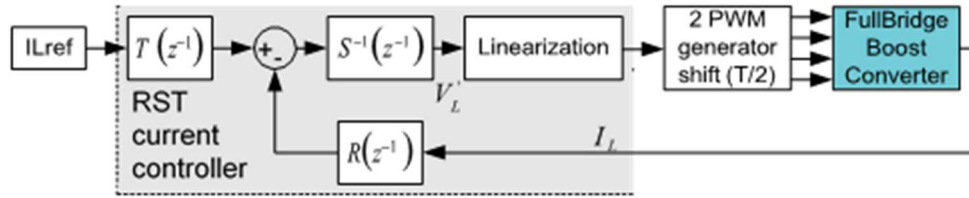
$$I_L(s) = \frac{1}{Ls} V_L'(s) \quad (52)$$

$$\omega_i \ll \frac{f}{10} \ll \frac{2pf}{10} \quad (53)$$

The bandwidth of the current loop ω_i should be ten times lower than the switching frequency.

$$\omega_i \ll \frac{f}{10} \ll \frac{2pf}{10} \quad (53)$$

The inductor current lo



Full-bridge converter inductor current control loop.

The output voltage loop was designed following a similar strategy to the current loop. To define the voltage controller, it is assumed that the current control loop is perfect. The capacitor current and voltage models are obtained by expressions 54 and 55:

$$I_C(s) = I_L(s) - I_{out}(s) \tag{54}$$

$$V_C(s) = \frac{1}{Cs} (I_L(s) - I_{out}(s)) \tag{55}$$

The linearization of the system is done by the following expression:

$$I_L(s) = I_c(s) + I_{out}(s) \quad I_{ref}(s) = I_c(s) + I_{out}(s)$$

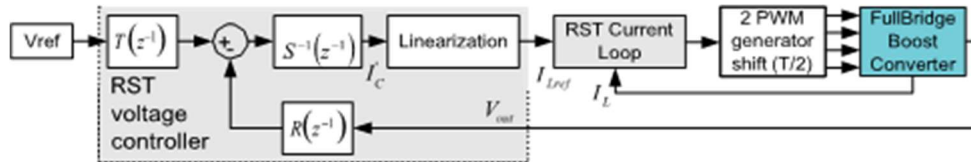
Where I_c is a new control variable represents the current reference of the capacitor. Thus, a linear transfer between $V_{out}(s)$ and $I_c(s)$ is obtained by:

$$\frac{V_{out}(s)}{I_c(s)} = \frac{1}{Cs}$$

The bandwidth of the voltage loop ω_v should be ten times lower than the current loop bandwidth ω_i which means hundred times lower than the switching frequency.

$$f_v \approx \frac{f_{sw}}{100} \approx \frac{2pf}{100} \tag{58}$$

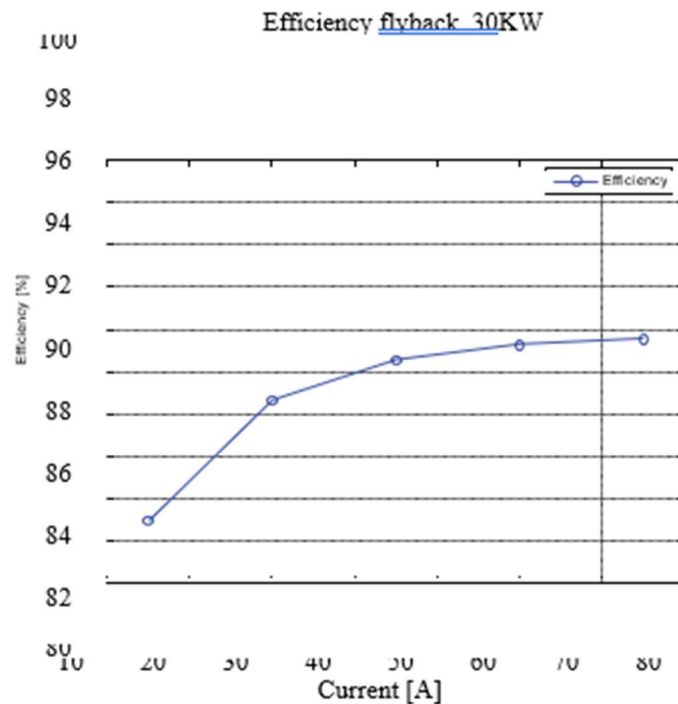
The output voltage control loop is shown in Fig. 16.



Full-bridge converter output voltage control loop.

Simulation results

The efficiency of the Full-bridge dc/dc converter is about 91.5% at full load as shown in Fig. 17. The efficiency of this converter can be increased by using phase shifted PWM control and zero voltage switching ZVS technique.



. FLYBACK converter efficiency versus current load.

. The level of conducted interference is not tolerable by the regulations. As a consequence EMI filter suppression is necessary to meet the terms the regulations.

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