Multi Bus DC-DC Converter in Electric Hybrid Vehicles

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Abstract: This paper is concerned with the design, simulation and fabrication of the prototype of a Multi bus DC- DC converter operating from 42V DC and delivering 14V DC and 260V DC. As a result, three DC buses are interconnected through a single power electronic circuitry. Such a requirement is energized in the development of a hybrid electric automobile which uses the technology of fuel cell. This is implemented by using a Bidirectional DC-DC converter configuration which is ideally suitable for multiple outputs with mutual electrical isolation. For the sake of reduced size and cost of step-up transformer, selection of a high frequency switching cycle at 10 KHz was done.

1. Introduction
The 42V power network has been proposed to cope with the ever increasing vehicle electrical loads in automobiles. Although the anticipated widespread deployment of the 42V systems has not materialized yet, as the automotive industry moves to drive-by-wire through the electrification of power steering, braking, suspension, and other engine control actuators, the 42V net will likely be needed to handle these heavy loads. This is because the existing 12V/14V system cannot efficiently power those loads and the need for higher voltage (>200V) (H.V.) bus for traction drive in full hybrid electric vehicles (HEVs) and fuel cell vehicles. In this situation it will be very difficult to meet the safety requirements and to suppress electromagnetic interferences (EMI) due to running of high voltage cables in the vehicle. While this is specially needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, the implementation of drive-by-wire technology in luxury vehicles also calls for such an intergration. For instance, the Toyota RX400h SUV uses dc-dc converters to transform the traction battery voltage to 14V for onboard electronics and to 42V for electric power steering. In addition, the 42V power system could be used for traction drives in mild hybrid vehicles and 42V based start/stop function along with limited power assist capability has been implement in pickup trucks and other vehicles on the market.

While full hybrids offer an option to eliminate the conventional starter/alternator, it may be kept as a backup for the motor/generator in the hybrid system. In HEVs with a 42V alternator, a dc-dc converter supplied from the 42V bus may be used to charge the high-voltage battery as shown in Fig.1.(a) On the other hand, for HEVs having a generator directly connected on the H.V. bus, a dc-dc converter is typically required to charge the 14V and/or 42V batteries.
Furthermore, when the H.V. bus is powered by a fuel cell, a bi-directional dc-dc converter is required to interconnect it to the low-voltage buses for vehicle auxiliary loads as shown in Fig.1.(b). An energy storage device is also required for startup of the fuel cell and for storage of the energy captured by regenerative braking because the fuel cells lack energy storage capability. One way to accomplish this is to utilize the vehicle 12V (on the 14V bus) or 36V (on the 42V bus) battery with the bi-directional dc-dc converter. During vehicle starting, the H.V. bus is raised up to around 300 V by the dc-dc converter and drawing power from the 14V or 42V battery. This H.V. bus then supplies power for the fuel cell compressor motor and brings up the fuel cell voltage, which in turn feeds back to the H.V. bus to release the loading from the battery. On the other hand, kinetic energy captured by regenerative braking can be stored in the battery by operating the converter in the buck mode.

In summary, a triple voltage bus (14V/42V/H.V.) system will likely be employed in future HEVs and fuel cell powered vehicles. Aside from bi-directional power control capability, the converter needs to provide galvanic isolation between the low- and high-voltage buses to meet safety requirements. Further, soft switching is preferred over hard switching because of the reduced level of EMI and switching losses.

A low cost, soft-switched, isolated bi-directional dc-dc converter using only four switches is proposed[1] for interconnecting the three bus nets. It is noted that the 12V battery may be eliminated in 42V dominant power systems. For such systems, the dc-dc converter does not need to transfer power out of the 14V bus.
2. Schematic of Multi Bus DC-DC Converter

The schematic of the reduced-part, triple voltage dc-dc converter is shown in Fig.3.3. It consists of dual half-bridges and a high-frequency transformer, which provide the required galvanic isolation and voltage level matching between the low voltage buses and the H.V. bus. The 14V and 42V buses share a common ground. The 14V bus is derived by tapping the capacitor leg at the midpoint; eliminating the buck/boost inductor, $L_f$ and the filter capacitor, $C_f$ on the 14V bus in the previous topology shown in Fig. 2.

Fig 2. Schematic of Multiple Bus DC-DC Converter

The use of dual half-bridges offers several advantages. It minimizes the number of switching devices and their associated gate driver components. This saving in part counts becomes more significant in multiphase configurations, which are preferred for high power applications due to reduced ripple current and easy packaging. The half-bridge converters are well suited for multiphase arrangements because all the phases can share the two capacitor-legs and the required capacitances do not necessarily increase with the number of phases. On the contrary, they can be reduced because the currents flowing into the midpoints of the capacitor legs decrease while their frequency multiplies. This leads to further reduction in component count and volume.

2.1. Control of 14V bus

It is important to note that, at steady state, the voltages across the capacitors, $C_1$ and $C_2$, $C_3$ and $C_4$, are determined by the duty ratio, $d$, as follows,

$$V_{C1} = d_3 \times V_{42V}$$
$$V_{C2} = d_1 \times V_{42V}$$
$$V_{C3} = d_2 \times V_{HV}$$
$$V_{C4} = d_4 \times V_{HV}$$

where $V_{C1}, V_{C2}, V_{C3}, V_{C4}$ represent the voltage across the capacitors, $C_1, C_2, C_3$ and $C_4$, and $V_{42V}$ and $V_{HV}$ the voltage of the 42V and H.V. buses, respectively and $d_1, d_2, d_3$ and $d_4$ are pulse widths of the four switches according to which it is ON or OFF. The pulse widths are calculated as follows;

$$d_1 = R_{1a} \times P_1$$
$$d_2 = R_{1a} - d_1$$
$$d_3 = R_{1b} \times P_1$$
$$d_4 = 0.1 - d_3$$

where, $R_{1a}$ and $R_{1b}$ are different pulse widths for a particular duty ratio.

The equations of voltage across capacitors is due to the fact that the products of Volt × second of the transformer primary and secondary voltages over the positive half cycles must be equal.
to those over the negative half cycles. Therefore, duty ratio adjustment can be utilized for making the 14V bus voltage, $V_{14V}$, track the 14V bus voltage by

$$V_{C2} = d_1 \times V_{42V}$$

For 14V/42V systems, the duty ratio is fixed at $d = \frac{1}{3}$ for normal operation and can be changed to regulate the bus voltage during load transients.

Since the 14V bus is derived by tapping the capacitor leg at the midpoint, the 14V load must be supplied from the 42V bus. Fig. 3 shows the four states of the low-voltage side converter.

1. State-a is formed with SW1 closed and SW2, SW3 and SW4 open and lasts for a period of $t_{p1}$.
2. While state-b is created by making SW4 closed and all the other three switches (SW1, SW2 and SW3) open and staying over an interval of $t_{p2}$.
3. State-c is formed with SW2 closed and SW1, SW3 and SW4 open and lasts for a period of $t_{p3}$.
4. State-d is formed by making SW3 closed and other switches SW1, SW2 and SW4 open and staying over an interval of $t_{p4}$.

2.2. State-a: $SW1$ closed and $SW2$, $SW3$ and $SW4$ open.

2.3. State-b: $SW4$ closed and $SW1$, $SW2$ and $SW3$ open.
2.4. State-c: SW2 closed and SW1, SW3 and SW4 open.

2.5. State-d: SW3 closed and SW1, SW2 and SW4 open.

Fig.3 Operating states of the low-voltage side and high-voltage side converter.

This is achieved by varying the duty ratios along with the percentage of reduction in conduction periods. For example, if duty ratio is assumed to be 1/3rd and 2/3rd i.e.; 33.33% and 66.67%, then for tp2 is created by % reduction in conduction of 33.33% like 5%, or 10%, or 15% etc. Similarly tp4 is created by % reduction in conduction of 66.67%.

3. Equivalent Circuit

Control of the power flow between the low-voltage and H.V. sides can be achieved by adjusting the switching frequency and the phase shift angle between the transformer terminal voltages. Here, a percentage of reduction in conduction for various duty ratios is employed for the power flow control as shown in Fig.4. For the discussion of the percentage of reduction in conduction for various duty ratios based power flow control, a simplified, primary-referred equivalent circuit is drawn in Fig.4 (a), where the half-bridges are reduced to ideal voltage sources and the transformer its leakage inductance, Ls. For d = 1/3, the voltage sources have positive and negative amplitudes of 2/3 and 1/3 of the dc bus voltage, respectively. Idealized voltage and current waveforms of the transformer can then be illustrated in Fig.4 (b). Power flows from the 42V bus to the H.V. bus by the transformer primary voltages, vTrL, supplied by the 42V half-bridges to the, vTrH, supplied by the H.V. half-bridges. The converter thus works in the boost mode to power the H.V. bus. During regeneration, power flow is reversed.
Fig 4(a) Equivalent circuit for 42V and H.V. buses

For a given low-side bus voltage, $V_{42V}$, and switching frequency, $f_{sw}$, varying the duty ratio, $d$, and corresponding percentage of reduction will change the voltage distribution between the two capacitors, $C_1$, $C_2$, $C_3$ and $C_4$. Assuming the voltage drops across the switches can be ignored, the positive transformer primary voltage is equal to the capacitor voltage, $V_{C1}$, and this voltage is applied for an interval of $t_{p1} = \frac{d_1}{f_{sw}}$. Similarly, the negative primary voltage, $V_{C2}$, is imposed over an interval of $t_{p2} = \frac{d_2}{f_{sw}}$. At steady state, the products of voltage and time over the positive and negative cycles must be equal, i.e.

$$V_{C1} \times t_{p1} = V_{C2} \times t_{p2}$$

Likewise the transformer secondary voltage is equal to the capacitor voltage, $V_{C3}$, and this voltage is applied for an interval of $t_{p4} = \frac{d_4}{f_{sw}}$. Similarly, the negative secondary voltage, $V_{C4}$, is imposed over an interval of $t_{p4} = \frac{d_4}{f_{sw}}$. At steady state, the products of voltage and time over the positive and negative cycles must be equal, i.e.

$$V_{C3} \times t_{p4} = V_{C4} \times t_{p3}$$

4. **Regeneration**

Implementation of power electronics based electrical system in a Hybrid Automobile, calls for the generation of motive power at the high voltage bus initially drawn from the 42V DC bus and subsequently meeting the same from the fuel cell unit directly at the high voltage level. The above covers the starting and steady running of the HEV till possibility of regeneration appears due to road conditions. It is advantageous to provide for regeneration of power during negotiating steep descend in hilly terrain. While the dc motor is readily capable of regenerating power, it is necessary to design and operate the power electronic circuits in a new functioning mode so as to absorb the above problem to charge the 42V system. From the control point of view, this process is characterized by two variables viz., the duty ratio and the percentage of reduction.
Design of High frequency transformer Design data

\[ V_{in} = 30 \text{ V} \]
\[ f_s = 10 \text{ kHz} \]
\[ V_o = 90 \text{ V} \]

**Assumptions**

Flux density (\(B_m\)) = 0.5 \(wb / mm^2\)

\[ A_c = 3.89 \times 100 \text{ mm}^2 \]

**Calculations of Parameters**

1. **Primary no of turns (\(N_1\))**

\[ V_{in} = 4 B_m A_c f_s N_1 \]

\[ N_1 = \frac{30}{4 \times 0.5 \times 3.89 \times 100 \times 10^{-6} \times 10^{-7}} \]

\[ N_1 = 3.856 \]

\[ N_1 \approx 4 \text{ turns} \]

2. **Secondary no of turns (\(N_2\))**

\[ \frac{V_2}{V_1} = \frac{N_2}{N_1} \]

\[ N_2 = \frac{90}{30} \times 4 \]

\[ = 24 \text{ turns} \]

In simulation the transformer turns ratio is assumed to be 1:6, whereas in hardware circuit high frequency transformer with 1:3 turns ratio is being used.

**Design of Capacitors**

5% ripple on 14 V system = \(\frac{5}{100} \times 14\)

\[ = 0.7 \text{ V} \]

Mean value = 14 V

Average value of ripple = 0.35

Variation of voltage across \(C_2\) varies between 14.35 to 13.65.

The corresponding voltage variation across \(C_1\) = 28.35 to 27.65

One- third cycle time = 33.3 \(\mu\)sec

Nominal load power = 200 W

Current drain from 42 V battery = 4.76

Ripple in this current is calculated as = \(\frac{4.76}{0.85}\)

\[ = 5.6 \text{ A} \]

where 0.85 is the assumed efficiency.

\[ 5.6 \times 33.3 \times 10^{-6} = C_d \Delta V \]

\[ C_d = \frac{5.6 \times 33.3 \times 10^{-6}}{0.7} \]
Similarly for capacitor $C_2$:

5% ripple on 14 V system = $\frac{5}{100} \times 28$

= 1.4 V

Mean value = 28 V

Two-third cycle time = 66.7 µsec

Nominal load power = 200 W

Current drain from 42 V battery = 4.76 A

Ripple in this current is calculated as = $\frac{4.76}{0.85}$

= 5.6 A

where 0.85 is the assumed efficiency.

$5.6 \times 66.7 \times 10^{-6} = C_2 \Delta V$

$C_2 = \frac{5.6 \times 66.7 \times 10^{-6}}{1.4}$

= 266.4 µF

Since only 330 µF is available in practice, which is near to the values of capacitor $C_1$ and $C_2$, it is used.

5. Simulations

![Simulation circuit for Forward power flow](image)
Fig 6. Capacitor Voltage (14V bus)

Fig 7. Transformer Voltages

Fig 8. Output Voltage (H.V. bus)
Fig 9. Simulation circuit for Regeneration

Fig 10. Capacitor Voltages (14V bus)

Fig 11. Transformer voltages
6. CONCLUSIONS

On the whole this paper is concerned with the in depth study of a Multi-bus DC-DC Converter has two major blocks of work. The first one closely follows the basic theory and principle of operation of the dual half bridge converter, where the entire circuit simulation was carried out using Simulink. This covers four stages of the power circuit development along with logic driver circuits applied to the set of gate circuit. The essence of the whole development centers on the feasibility of voltage and power control by manipulating low power gate trigger pulse waveforms, which can be readily be programmed in a Microprocessor/ Microcontroller board are even in a PC provided with a digital I/O Add- on card.

The later part of the paper covers the design and fabrication of the Multi Bus DC-DC converter. Here the exercise is concerned with actual power semiconductor devices, designed values of electrolytic capacitors and a ferrite core based high frequency transformer. The circuit configuration is identical to that used in simulation and the work involved painstaking hooking up of the various power and control modules. The above work can be extended to handle a larger power and also in meeting the practical requirements of regeneration, in the context of driving a DC traction motor.

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