A Reduced-Part, Triple-Voltage DC-DC Converter for Electric Vehicle Power Management

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*Abstract**

Electrical power systems in future hybrid and fuel cell vehicles may consist of three voltage nets; 14V, 42V and high voltage (200~500V) buses. A low cost, soft-switched, bidirectional dc-dc converter using only four switches has been proposed for interconnecting the three nets. This paper presents a reduced part count dc-dc converter, which further reduces the converter cost while retaining all the favorable features of the original topology. Simulation and experimental data on a 2 kW prototype is included to verify a novel scheme to control power flow among the three busses.

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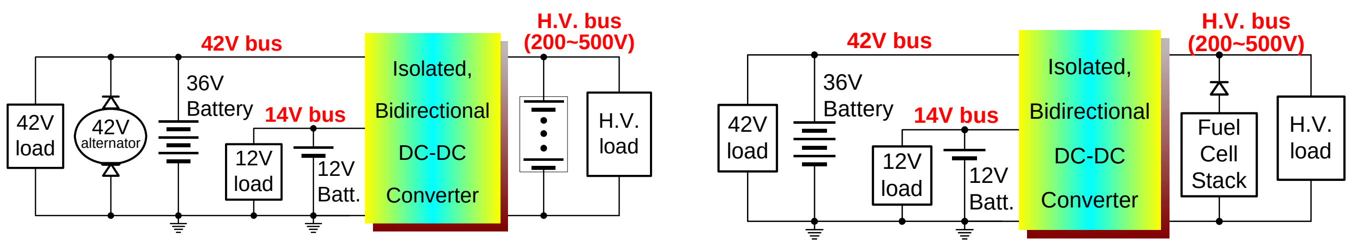
Digest

I. Introduction

A 42V power net has been proposed to cope with the ever increasing vehicle electrical loads in automobiles. Although the anticipated widespread deployment of 42V systems have not materialized yet, as the automotive industry moves to drive-by-wire through the electrification of power steering, braking and suspension, the 42V net will likely be needed to handle these heavy loads. This is because the existing 14V system cannot efficiently power those loads and using the higher voltage (200~500V) (H.V.) bus required for the traction drive in hybrid electric vehicles (HEVs) would create safety and electromagnetic interference (EMI) issues by running H.V. wires throughout the vehicle. Drive-by-wire technology will be needed for fuel cell vehicles, which have no IC engines to assist those mechanisms, and is already being employed in luxury vehicles. For instance, Toyota RX400h SUV uses dc-dc converters to transform the traction battery voltage to 14 V for onboard electronics and to 42 V for electric power steering. 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 [1, 2].



(a) HEVs. (b) Fuel cell powered vehicles.

Figure 1. A dc-dc converter interconnecting 14V/42V/H.V. bus nets in HEVs and fuel cell–powered vehicles.

Furthermore, when the H.V. bus is powered by a fuel cell, a bidirectional dc-dc converter is required to interconnect it to the low voltage buses for vehicle auxiliary loads as shown in Fig. 1(b) [3]. 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 14V or 42V battery with the bidirectional dc-dc converter. During vehicle starting, the H.V. bus is raised up to around 300V by the dc-dc converter operating in the boost mode and drawing power from the 14V or 42V battery. This H.V. bus then supplies power for the fuel cell compressor motor expanding unit controller and brings up the fuel cell voltage, which in turn feeds back to the H.V. bus to release the loading from the battery [4, 5]. One 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. Dc-dc converters are already available to interconnect any two of the buses; however, to reduce component count, size, cost, and volume, it is desirable to employ an integrated dc-dc converter to interconnect the three voltage buses instead of using two separate converters. 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 [6–9].

A low cost, soft switched, isolated bidirectional dc-dc converter using only four switches was proposed in [10] for interconnecting the three bus nets and is shown in Fig. 2. It utilizes snubber capacitors and the transformer leakage inductance to achieve zero voltage switching (ZVS). No extra resonant components are required for ZVS, further reducing component count. The inherent soft switching capability and the low component count of the converter allow high power density, efficient power conversion, and compact packaging.

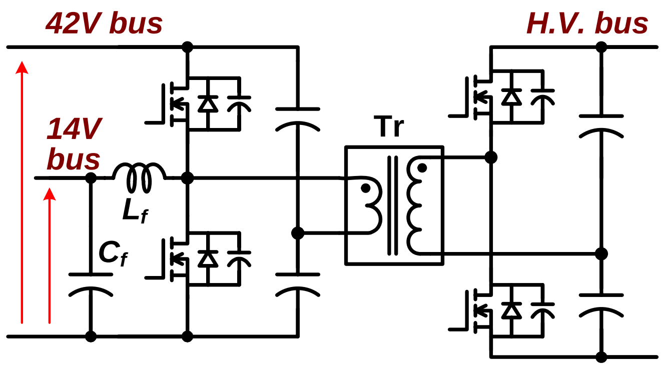


Figure 2. A triple-voltage dc-dc converter proposed in [10].

This paper presents a dc-dc converter for power management in triple voltage vehicle power systems with a further reduced part count. Simulation and experimental data are included to verify the power flow control scheme based on a combined duty ratio and phase shift angle control.

II. Description of The Reduced-Part DC-DC Converter

Fig. 3 shows the reduced part count, triple voltage dc-dc converter; the LC filter on the 14V bus in the original topology has been eliminated. The converter consists of dual half bridges and a high frequency transformer, which provides 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 leakage inductance of the transformer is utilized as the intermediate energy storing and transferring element between the two low voltage buses and the H.V. net. The snubber capacitors of the switches resonate with the transformer leakage inductance to provide ZVS switching conditions for the switches.

Duty ratio control is utilized for power flow control between the 14V and 42V buses, making the two bus voltages, V_{14V} and V_{42V} track each other by $V_{14V}=d\bullet V_{42V}$, where d is the duty ratio of the switches S_1 and S_3. For 14V/42V systems, the duty ratio is fixed at d=1/3 during normal operation and can be changed to adjust the state of charge of the low voltage batteries when necessary. In addition, a phase shift angle, ϕ, between the transformer primary and secondary voltages is employed for power-flow control between the 42V and H.V. buses as shown in Fig. 4. At d = 1/3, i.e. $\varphi = 2\pi/3$, the power transferred through the transformer can be expressed by

$$P = \frac{V_{42v}V_{HV}}{n} \cdot \frac{\phi}{2\pi f_{sw} L_s} \cdot [\frac{2}{9} - \frac{\phi}{4\pi}]$$

where

n = transformer turns ratio,

ϕ = phase shift angle,

L_s = transformer leakage inductance, and

f_{sw} = switching frequency.

For a given design, the maximum power is determined by

$$P_{\max} = \frac{V_{42v}V_{HV}}{n} \cdot \frac{2}{81 f_{sw} L_s} \text{ at } \phi_{P_{\max}} = \frac{4\pi}{9}.$$

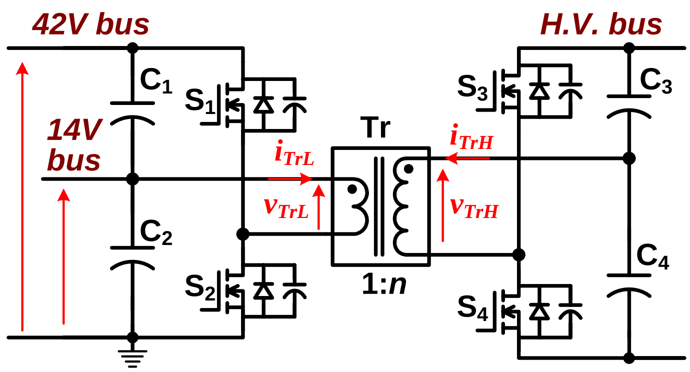


Figure 3. A reduced-part, triple-voltage dc-dc converter.

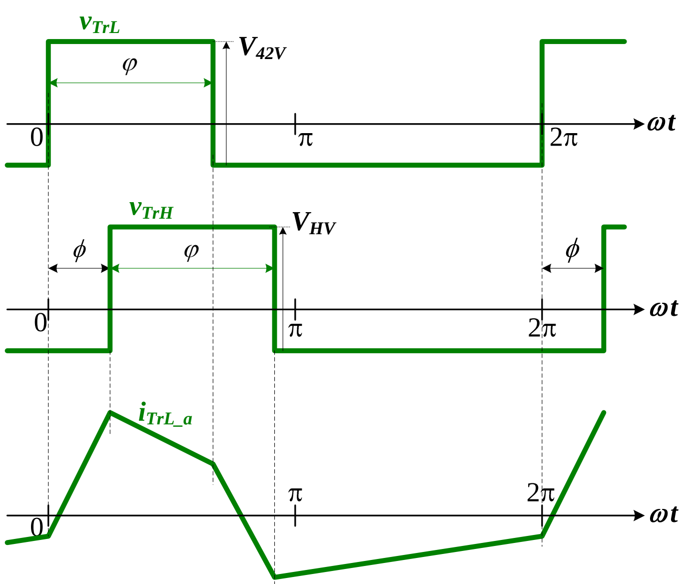
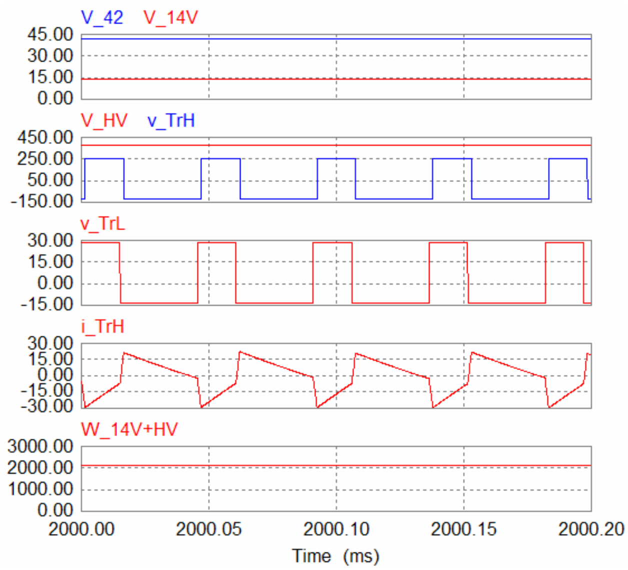


Figure 4. Ideal transformer voltage and current waveforms illustrating power-flow control between the 42V and H.V. buses.

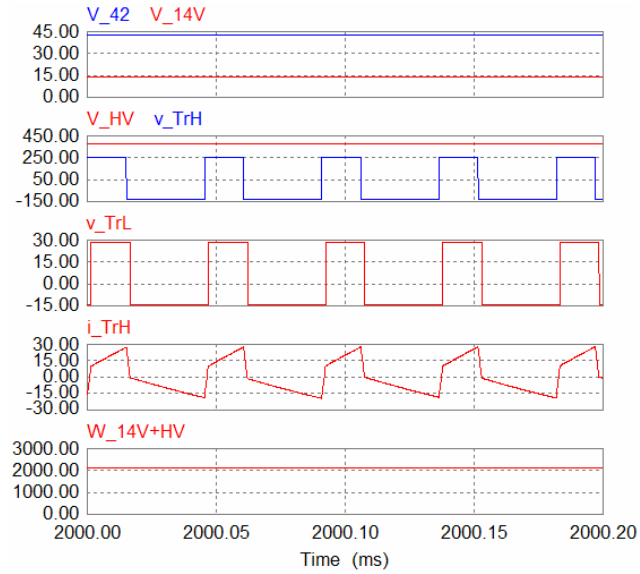
III. Simulation and Experimental Results

A detailed circuit simulation was performed to verify the design goal; at least 2 kW power transfer through the transformer at a voltage range of 250~400V on the H.V. bus. Fig. 5 gives simulation results showing bidirectional power flows.

Fig 5(a) shows 2.1 kW transferred from the 42V bus to the 14V and H.V. busses, while 5(b) shows power transferred from the H.V. bus to the 42V and 14V nets. The simulation results confirm the design goal.



(a) Power transfer from 42V to the 14V and H.V. bus.



(b) Power transfer from the H.V. bus to the 14V and 42V busses.

Figure 5. Simulation results showing bi-directional power transfer.

A 2 kW reduced-part-count converter prototype was designed and fabricated. Fig. 6 shows a photo of the prototype, which is laid on a liquid cooled heat sink with a footprint of 11” in width by 12” in length. To verify the combined duty ratio and phase shift angle control scheme for power flow management among the three buses, testing was conducted by connecting a dc power source at one of the 42V and H.V. busses for powering resistive loads on the other two busses. Figs. 7 and 8 show typical oscillograms of the initial test results which confirmed the performance of the power flow control scheme. More extensive testing data and a performance analysis will be given in the full paper.

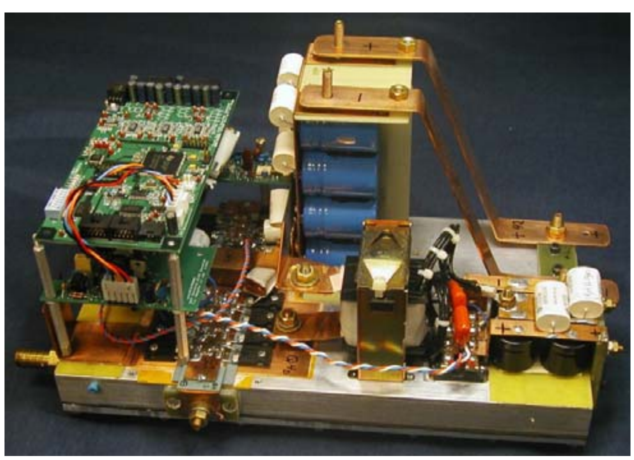


Figure 6. Photo of the 2 kW reduced-part converter prototype.

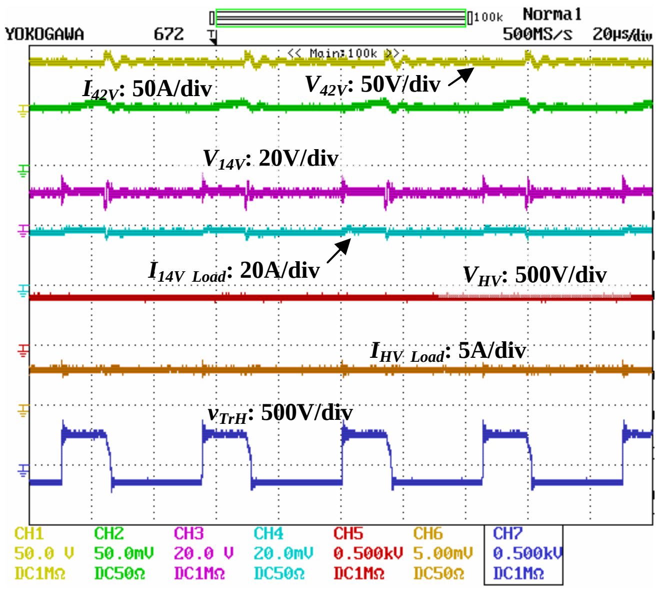


Figure 7. Experimental waveforms for a power transfer of 1.4 kW from 42V bus to 14V and HV busses.

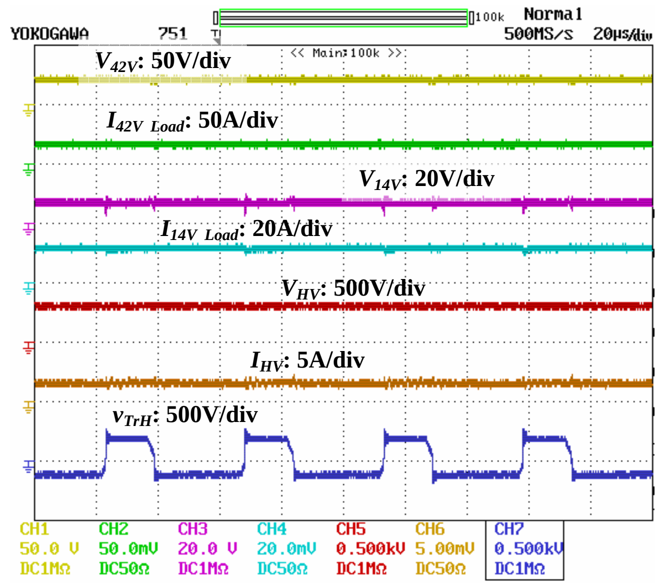


Figure 8. Experimental waveforms for a power transfer of 0.6 kW from HV bus to 14V and 42V busses.

IV. SUMMARY

A reduced part count dc-dc converter for triple voltage bus (14V/42V/H.V.) systems in electric vehicles which eliminates the LC filter present in the original topology is presented with the following beneficial features:

- Uses only four switching devices, leading to significant cost savings and higher power density.
- Requires no auxiliary circuit or complex control dedicated for soft switching.
- Achieves flexible power flow management from bidirectional power transfer between the low voltage buses and the H.V. bus by employing the combined duty ratio and phase shift angle control schemes.

Simulation and initial test results on a lab prototype confirmed the operating principles of the converter. Detailed design considerations with extensive test results will be given in the full paper.

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