9kW Isolated DC-DC Converter for Hybrid Bus.

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Abstract

This paper describes an OEM product – an isolated DC-DC converter - that is becoming popular on hybrid buses. This converter has 9kW output power and CAN-bus communication that allows complete integration in the electrical system of a bus. It is completely soft-switched and a cost-effective design: at least 10% lower than a comparable phase-shift topology converter. The converter replaces an alternator. This replacement provides significant cost reduction over the life of the bus. Also reliability of 24VDC system of the bus increases because the converter provides clean power unlike an alternator.

1. Introduction

At the present time most hybrid buses have an alternator which provides energy for 24VDC system of the bus. The requirement in this case is a minimum of 250A current, but the requirement tends to grow up to 500A. Alternators for this application have an efficiency of 65% and cost around $2000 (250-300A alternator); a more powerful alternator has a higher cost. We must also add accessories around, $700, furthermore they have a one to two year life time and the cost of other parts and labor to replace it is around $2000. Also an alternator produces stress on the 24V battery that significantly reduces the life time of the battery. The typical life time of the 24V battery is 6-12 months. With an alternator system, bus manufacturers use cable from alternator to battery with current density maximum of 1.5A/mm² because there has to be minimum voltage drop in the cable. In this case, an alternative would be an isolated DC-DC converter which provides energy for the 24V system of the bus directly from the main Hi-Voltage system of the bus.

2. Basic technical description

The DC-DC converter that we are going to discuss has 9kW output power and CAN-bus communication that allows complete integration in the electrical system of the bus. It is completely soft-switched and has a cost-effective design: at least 10% lower than a comparable phase-shift topology converter. The basic specification of the DC-DC converter is: high voltage side - 500VDC to 800VDC, low voltage side - 20VDC to 30VDC @300A, operational temperature - -40C to +70C, full power efficiency - 93 to 94% excluding reverse polarity protection and pre-charge, efficiency - 85% @ 5% load, life time, - minimum, 7 years, initial cost to the customer – 25% more than a conventional alternator. The converter replaces an alternator which has efficiency of 65% and a cost of around $2000. Fig.1 shows block diagram of how the converter is integrated into the bus electric system. With battery monitoring, this system has one more advantage: increased life time of 24VDC battery (with an alternator, it is around 6 months), because output voltage of converter is controlled by equalizer/battery monitor. At the present time we have data that Transit Authorities continue to use 24V battery after 3 years operation. Also manufacturing companies can use cable with current density 3.5A/mm² or more. This is one more way to save money and weight. This converter has an option that a customer may charge a HV battery from main grid when energy of the HV battery is not enough to start the engine.

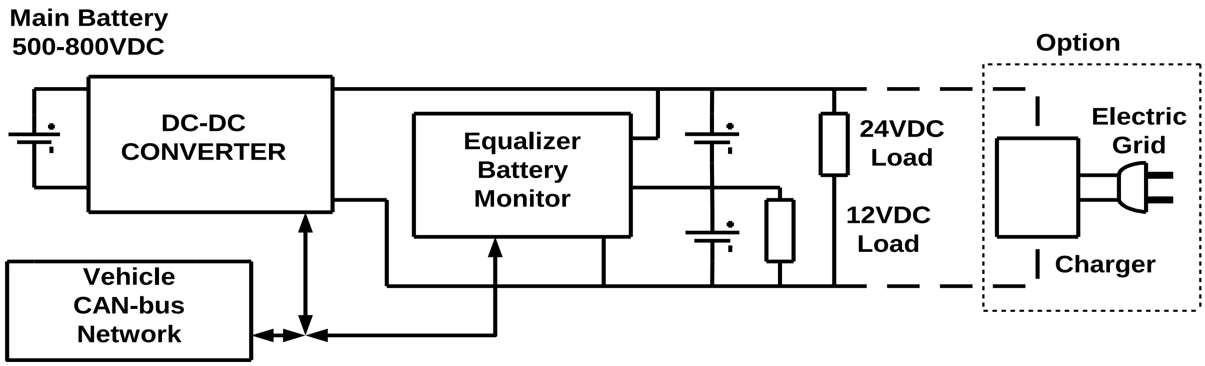


Fig.1 Block diagram of how the converter is integrated into the bus electric system

3. Description of topology

DC-DC converters can generally be divided into two groups depending on what kind of regulation they use - fixed frequency with pulse width modulation (PWM) or converters with variable frequency. Converters with PWM provide good regulation from minimum power (5% of nominal power) to maximum power with good efficiency, but they have disadvantages. They are difficult to control at small pulse widths and have relatively high power consumption under idle or light load conditions (below 5% of nominal power), they are also strong EMI generators. Resonant topologies with variable frequency generate relatively little noise (EMI), can run at no load (depending upon topology), have low power consumption at idle (again, depending upon topology), and the cost is reasonable. However it is also more difficult with a resonant converter to achieve an input voltage range of more than: Vmax/Vmin = 1.3.
The topology described here uses the advantages of both PWM and variable frequency topologies to overcome these difficulties and is relatively cost effective. This topology uses PWM and fixed (maximum) frequency of commutation when the output power is between 25% and 100% of rated. When output power is less than 25% output regulation is done by reducing the commutation frequency and continuing to reduce the PWM duty cycle. The commutation frequency can reach as low as 2 to 3kHz and the PWM is at 0% duty cycle when at idle, hence achieving very low idle losses. This is very important for battery powered applications. Fig.2 shows a topology of DC-DC converter. This topology is a completely soft-switched, that helps to achieve a low level of EMI (class 4 of CISPR25), and also contributes to high reliability. [1,2,3,4]
The converter has a series resonant topology so the conversion process delivers energy packets of limited size, controlled by the resonant tank comprising Lres and capacitors C1-C4, and by the conversion pulse width. The maximum commutation frequency in this topology is:

$$f = \frac{1}{2\pi\sqrt{L_{res} \cdot \sum C_{res}}}$$

Fig.3 shows theoretical waveforms of the converter when the commutation frequency is at maximum and regulation is done by PWM. Figs. 4a to 4f show equivalent circuits of each operation mode. Starting with Fig. 4a, which shows the time segment t0-t2; at t0 the devices S2, D3, and S4 have just begun conduction, the current starts at zero and rises sinusoidally. The value and waveform of this current is determined by the resonant circuit (C1-C4 and Lres) and the value of the load. S2, C3 and C4 work during the time period t0-t1. C1, C2, D3 and S4 become active at t1. At t2 the switch S4 turns off and interrupts the current, at the same time S3 turns on, preparing for the next half cycle. This interruption happens under ZV conditions because S3 and S4 are located between the capacitors C1 and

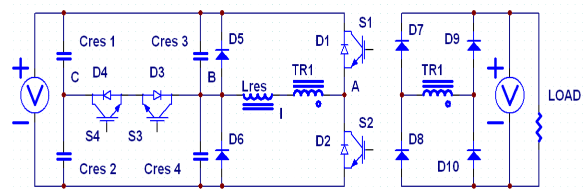


Fig.2 Converter topology

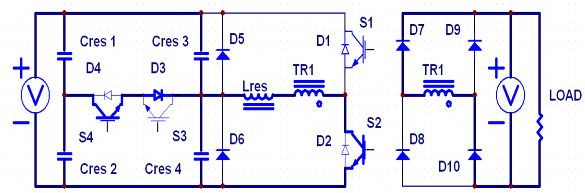


Fig.4a t0 to t2

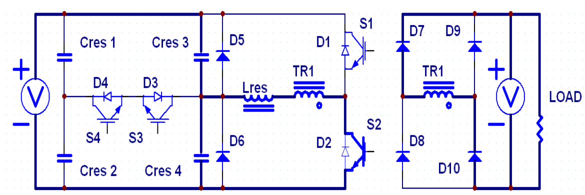


Fig.4b t2 to t3

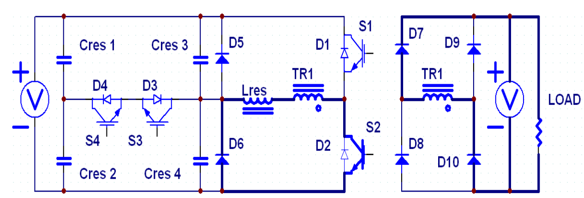


Fig.4c t3 to t4

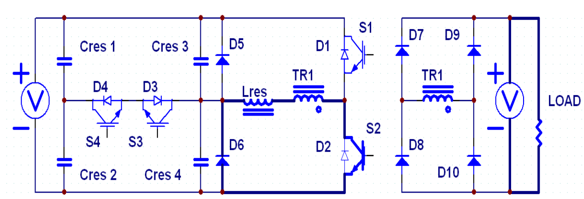


Fig.4d t4 to t5

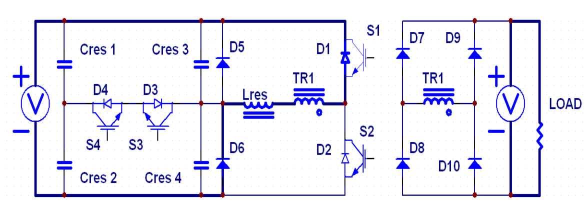


Fig.4e t5 to t6

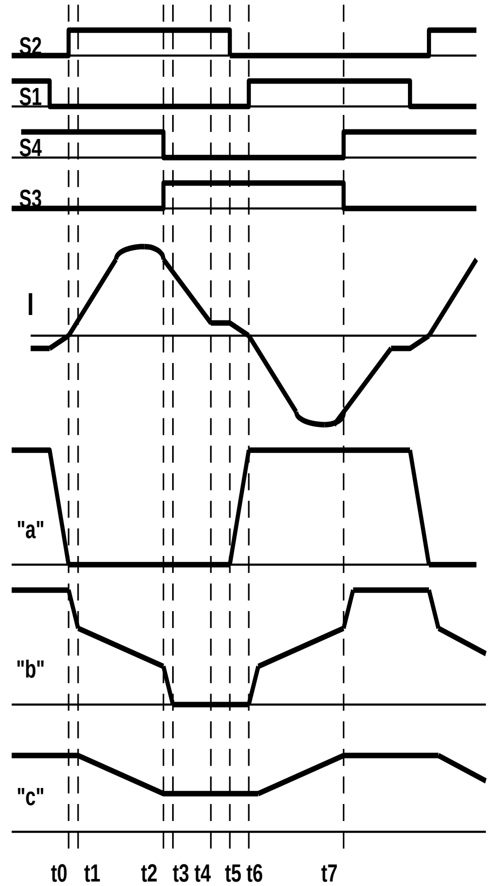


Fig.3 Theoretecal waveforms of the converter

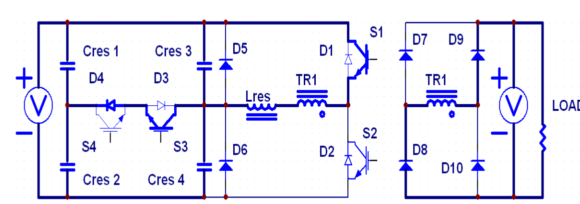


Fig.4f t6 tot7

C2 on one side and C3 and C4 on the other side. C3 and C4 have a significantly smaller value than C1 and C2, their purpose being to provide soft-switch commutation for S3 and S4 between t2 and t3 (Fig.4b). At t3 the energy discharge process of the inductor Lres begins. Between t3 and t4 current flows in the circuit D6, Lres, Tr and S2 (Fig.4c), reducing linearly to zero. At t4 the current flow in the low-voltage side in D7 and D10 has decayed to zero. Between t4 and t5 on the hi-voltage side, the magnetizing current is flowing via the circuit S2, Tr, Lres and D6 (Fig.4d).At t5 switch S2 turns-off, interrupting the magnetizing current, which has a relatively small value, therefore the body capacitance of S2 is sufficient to provide ZV turn-off.
Between t5 and t6 (Fig. 4e) the magnetizing current charges the body capacitance of S1 and S2 preparing S1 for ZV turn-on. At t6, S1 turns-on and a new half cycle of power conversion begins. The new half cycle is a mirror image to the half cycle between t0 and t5. Between t6 and t7 current flows via S1, Tr, Lr, S3, D4 and C1-C4 (Fig.4f).
Fig.5 shows actual waveforms of the current and voltage for the 9kW production unit at 700VDC input and 30VDC output with a 300ADC load. It is clear that the theoretical predictions of the waveforms are very close to the practical results. While developing this converter the decision was made to reduce efficiency by 2%. The prototype of the converter had efficiency 95-96% with full load. This reduction helped us to reduce cost by 15% by changing components and packaging.

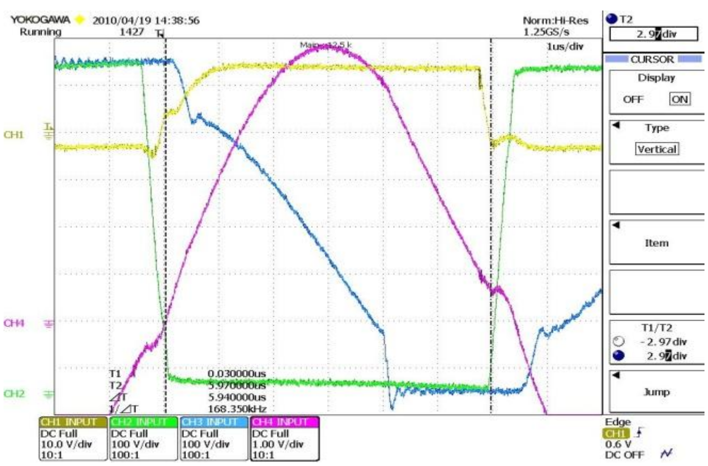
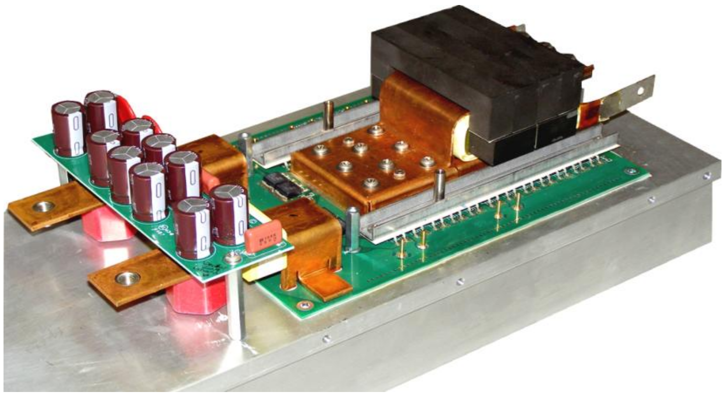


Fig.5 Ch.1-gate signal
Ch-2 cross S2
Ch-3 cross D6
Ch.4 current via
TR1(10A/div)

4. Comparison and description of design

For this converter a power transformer was developed which is a physical part of the power stage. It also uses surface mount assemble (SMA) with a maximum constant current of 300ADC. [5] Full integration of a power transformer into the power stage has very strong benefits when we have a current of 100A and more. Fig.6 shows this power transformer with SMA power stage for prototype. We made a comparison of our transformer with a planar transformer with the same conditions (110kHz 280A output). Fig.7 The planar transformer has a price which is 20% higher than our transformer and 2% lower efficiency. Efficiency is reduced because the planar transformer has not enough contact area for 280A. If the contact of the area increases, the cost will increase too. The converter works fine under current mode when it has over load conditions. It provides 300A current continuously and when over load is disconnected overshoot is minimal compared with an alternator. That allows many customers use this mode for running heavy load for 2-3 min. The converter will provide energy along with a 24V battery. When the heavy load is disconnected the battery gets charged without damage and without stress to the electrical system, which would not be the case if an alternator was used. With an alternator system the customer would need to use a more powerful alternator or two alternators, which of course significantly increases the cost.



Power Stage Incorporating:	Product Cost	System Efficiency
Integrated Transformer	1	94%
Planar Transformer	1+20%	92%

Fig.7 Table1- Comparisons integrated transformer and planar transformer

Fig.6 Power stage with integrated power transformer for prototype

Let us make a comparison of efficiency of alternator's system and DC-DC converter system. Alternator's system has an efficiency of about 65% from the engine shaft to DC-load. The DC-DC converter system has minimum efficiency of 82% from engine shaft to DC-load. We have a minimum difference 17%. That means that we have additional 1.5kW power available or we can save 1.5kW. For bus it means that the customer can save on average 0.1 mpg or 370 gallons per year per bus. If the customer needs more power than 9kW, of course fuel saving will be higher.We made a comparison between our topology and phase-shift topologies Fig.8 and Fig.9 which we call standard and improved. [6] We made this comparison with the assumption that all topologies have the same efficiency, an output power and input and output voltage with output current above 100A. Fig.10 The main advantages which help us achieve cost reduction are the following: the power transformer works in optimal conditions, approximately a trapezoidal waveform with roughly constant RMS voltage regardless of the input voltage. The current carried by the winding is almost sinusoidal with a duty cycle of 90-95% and does not change with the input voltage. This is an advantage when considering transformer losses, and along with the fact that the new topology can reach a higher commutation frequency, significantly helps to reduce the size of the transformer, decreases price, and increases the transformer's efficiency. When the topology operates under PWM control, it works like a current source, because during this time the resonant inductor is discharging energy into the load via the transformer (time period t3-t4, Fig.4c). This high impedance condition and strong control through energy packets help when we parallel two or more of these power stages, it leads to good sharing of current without any special current sharing control needed. This is convenient when we use two or more converters in parallel connected to one load.

5. Conclusion

The isolated DC-DC converter for Hybrid bus presented here has some notable advantages compared with an alternator:

1. It provides fuel economy improvement.
2. Significant increase of reliability of the 24VDC system of the bus, life time is minimum 3 times longer compared to an alternator
3. Higher performance- overshoot voltage, CAN-bus communication, ease of external control.

4. Cost of maintenance of 24VDC system significantly reduced (life time of battery)
5. Compared to phase-shift topology, this converter has cost reduction and is easy to be connected in parallel.

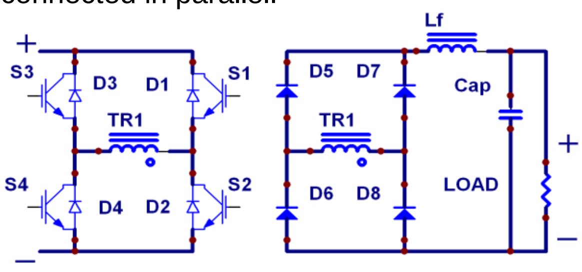


Fig.8 Standard phase shift control topology

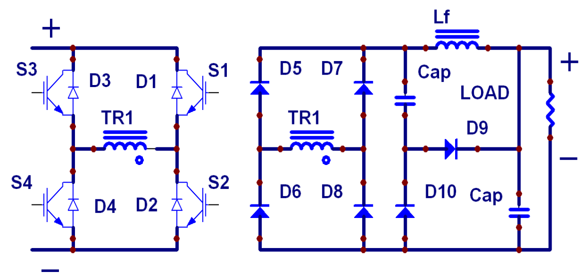


Fig.9 Improved phase shift control topology

Parameters	Standard	Improved	New topology
Max. com. freq.	1x	1.2x	2x
Load range	Limited	Limited	Unlimited
Commutation	ZVS	ZVS ZCS	ZVS ZCS
EMI	Acceptable	Better	Good
Rectifier recovery	Recovery Losses	More complex	Simple and soft
Paralleling of stages	Requires control	Requires control	Simple
Operation of power transformer	Not optimal	Not optimal	Optimal
Control	Standard	Standard	Special
Idle losses (% of rating)	1.5%	1.5%	0.15%
Bi-directional	Additional constraints	Additional constraints	Ready
Cost	**Basis**	**Basis plus**	**Basis minus >10%**

Fig.10 Table2 - Topology comparison: Phase-shift and New Topology

6. Acknowledge

We would like to acknowledge Kaschke Components of Germany and Olaf Niemann, in particular for their assistance with the design and manufacturing of the power transformer used in the present converter.

7. References

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