Cost effective resonant DC-DC converter for hi-power and wide load range operation.

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Abstract- **This paper describes an original topology for a step-down DC-DC converter. This converter is a resonant converter with zero voltage switching and zero current switching. Regulation of the converter is done by PWM and variable frequency; this provides good regulation, from no load to full load. A prototype was built for an output power of 4kW, an input voltage range of 280VDC to 440VDC, and an output voltage of 14VDC. The prototype converter has an efficiency of 92-94%, is cost effective, and a good fit for high power and high current applications. The authors suggest that the presented topology is a better alternative to a typical phase-shift topology, with an additional advantage of being bi-directional.**

I. BACKGROUND

While there are many applications for step-down DC-DC converters, there are also a large number of topologies for these converters. All these 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. When these technical problems are solved the cost increases.

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.

At the present time topologies using PWM by phase-shift control are popular, for basic high-power applications of 4kW or more. These topologies reduce the amount of EMI, because they use soft-switch technology. Small pulse widths can also be generated, but hard switching occurs at light load (unless complexity is added), increasing losses and EMI. More problems occur when low output voltages (14VDC) and high currents (200ADC and more) are required.

In this case, using the power inductor in the rectifier circuit [1,2,3,4,5] will be a problem for three reasons:

1. The power losses in the inductor are large.
2. It will be difficult to provide soft-switch for the rectifier diodes.
3. The cost of the inductor significantly impacts the total converter cost.

Several designs [6,7,8,9,10,11] have gone a long way toward solving these issues, but not completely. Some have a greater number of active switches, in some commutation is not purely ZVS. In addition, it is not clear how they would behave under idle or light load conditions. Finally there is a question as to whether they would still achieve good efficiency with power levels of two or more kW.

II. TECHNICAL DECRIPTION

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 (up to approximately 200kHz) when the output power is between 25% and 100% of rated. When output power is less than 25% control in the converter is done by reducing the commutation frequency and continuing to reduce the PWM duty cycle. The commutation frequency can reach 2-3kHz and the PWM is 0% duty cycle when at idle, hence achieving very low idle losses (maximum 8W).This is very important for battery powered applications. Fig.1 shows the topology (the implementation characterized here is bi-directional, but only step down operation will be discussed).

How this topology works in step-up mode is described in [12,13]).

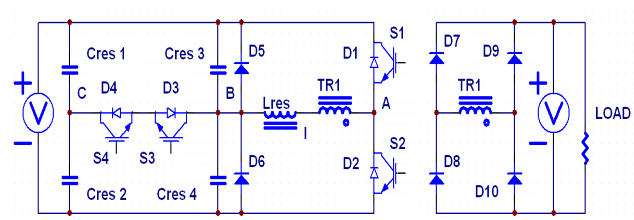

Fig. 1 Converter topology

The converter has a series resonant topology so the conversion process delivers energy packets of limited size. The energy packet size is controlled by the resonant tank, comprising Lres and capacitorsC1-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.2 shows theoretical waveforms of the converter when the commutation frequency is at maximum and regulation is done by PWM. Figs. 3a to 3f show equivalent circuits of each operation mode.

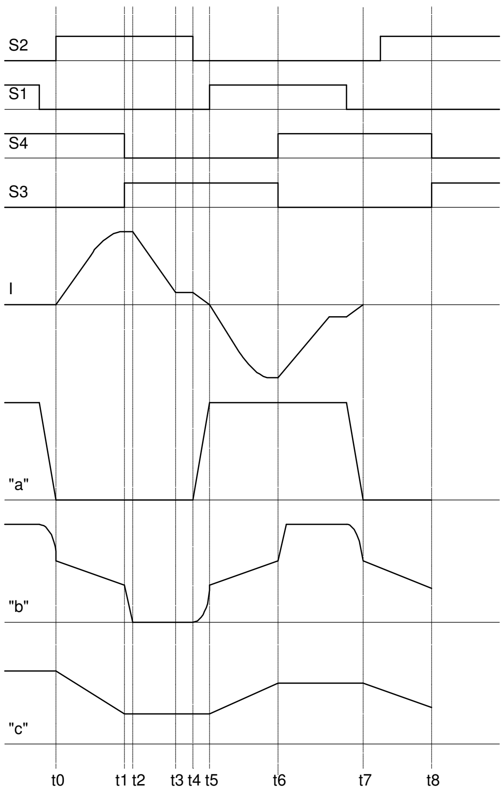

Fig. 2 Theoretical waveforms of the converter

Starting with Fig. 3a, which shows the time segment t0-t1; at t0 the devices S2, D3, and S4 have just begun conduction, they started conduction with zero current and the current in the circuit rises sinusoidally. The value and waveform of this current is determined by the resonant circuit (C1-C4 and Lres) and the value of load.

At t1 the switch S4 turns off and interrupts the current, at the same time S3 turns on and prepares for the next half cycle. This interruption happens under ZVS conditions because S3 and S4 are located between the capacitors C1 and C2 on one side and C3 and C4 on the other side. C3 and C4 have a significantly smaller value than C1 and C2. The purpose of C3

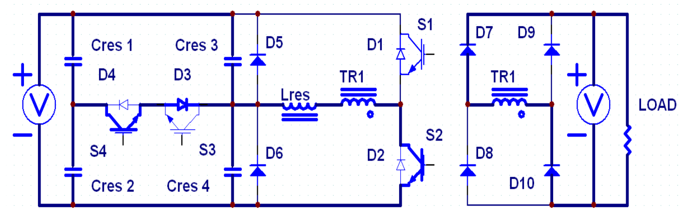

Fig. 3a t0 to t1

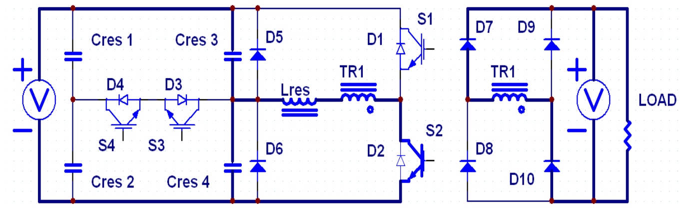

Fig. 3b t1 to t2

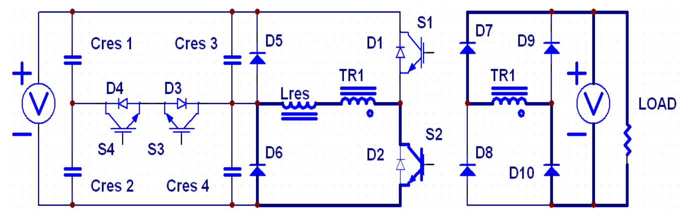

Fig. 3c t2 to t3

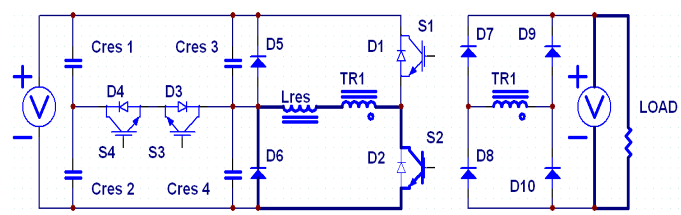

Fig. 3d t3 to t4

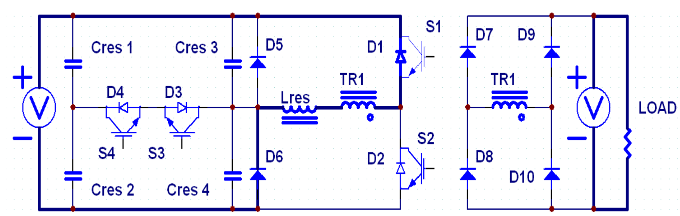

Fig. 3e t4 to t5

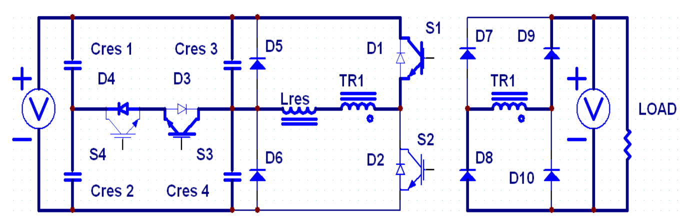

Fig. 3 t5 to t6

and C4 is to provide soft-switch commutation for S3 and S4 between t1 and t2 (Fig.3b).

At t2 the discharge energy process of the inductor Lres begins. Between t2 and t3 current flows in the circuit D6, Lres, Tr and and S2 (Fig.3c). This current reduces linearly to zero in time:

$$T_{redu} = \frac{I \cdot L_{res}}{n \cdot V_{out}}$$

Where:

n is the turns ratio of the transformer.
I is the peak current, at t2

At t3 the current flow in the low-voltage side in D7 and D10 has decayed to zero. Between t3 and t4 on the hi-voltage side, the magnetizing current flows via circuit S2, Tr, Lres and D6 (Fig.3d). At t4 switch S2 turns-off, interrupting the magnetizing current, which has a relatively small value, therefore the body capacitance of S2 provides ZVS turn-off.

Between t4 and t5 (Fig. 3e) magnetizing current charges the body capacitance of S1 and S2 and prepares S1 for ZVS turn-on.

At t5, S1 turns-on and a new half cycle of power conversion begins, which is identical to the half cycle between t0 and t5. Between t5 and t6 current flows via S1, Tr, Lr, S3, D4 and C1-C4 (Fig.3f).

How to calculate the values of the resonant components can be found in [12] where the authors of this paper described the step-up operational mode of this topology. Here we would like to emphasize that the quality factor of resonant inductor should be greater than 7 in order to achieve good performance.

A prototype was built for an output power of 4kW, an input voltage range of 280VDC to 440VDC and an output voltage of 14VDC. Fig.4 shows the basic schematic.

Where:

Q1, Q2 are IXSN80N60BD1
Q3, Q4 are IXKN75N60C
Q5, Q6, Q7, Q8 are IRF2804, 7 in parallel
D1, D2 are DSEI2x101-06A

MOSFETs were used in the rectifier (Q5-Q8) in synchronous rectification mode.

Fig.5 and Fig.6 show actual waveforms of the current and voltage for the 4kW prototype at 400VDC input and 14.2VDC output with 280ADC load. It is clear that the theoretical predictions of the waveforms are very close to the practical results.

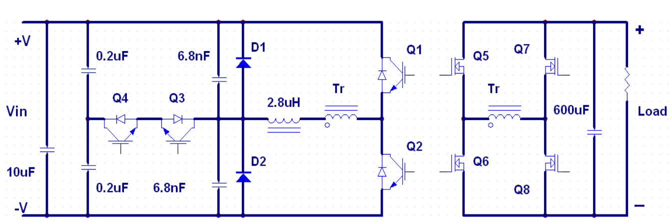

Fig. 4 Prototype schematic

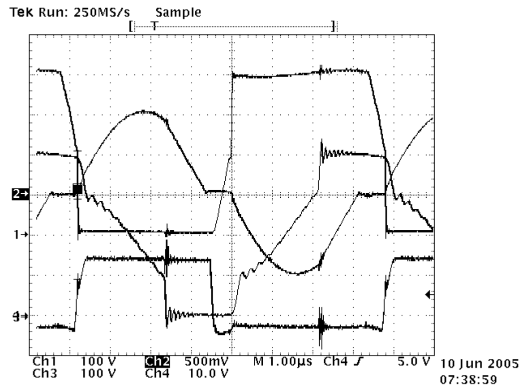

Fig. 5 Measured waveforms 25A/div

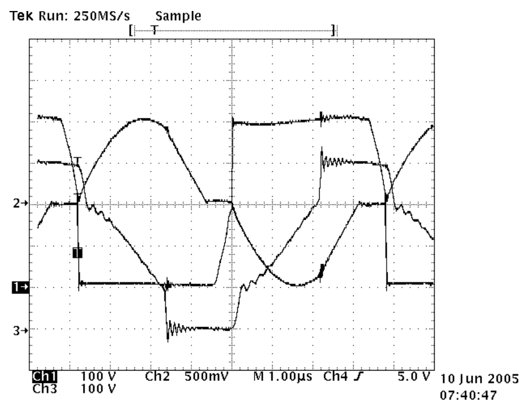

Fig. 6 Measured waveforms 25A/div

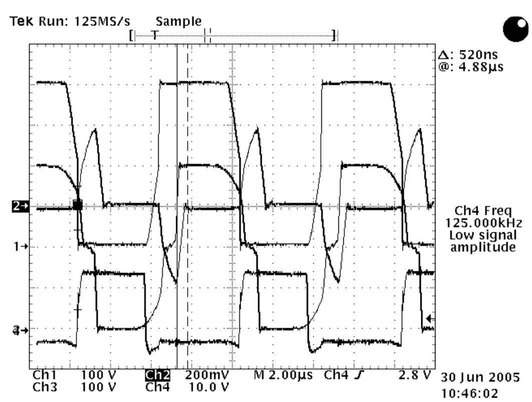

Fig. 7 Measured waveforms 10A/div

Fig.7 shows the waveforms when the converter is producing 540W of output power, we can see how the commutation frequency has started to change, the current scale is 10A/div.
Fig.8 shows measured data taken from the 4kW prototype under different operating conditions. Note: converter has an efficiency under light load (200W output power, 5% of nominal power) of above 80%.

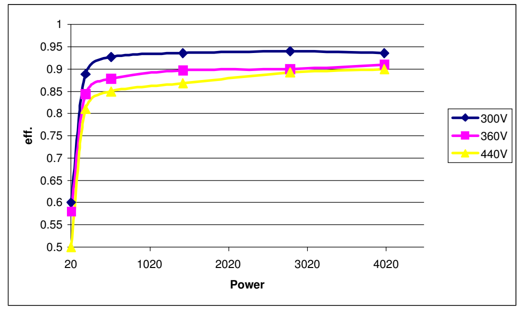

Fig. 8 Efficiency vs load

III. Comparison and analysis

Fig. 9 Table - Topology comparison: Phase-shift and New Topology at 4kW

Parameters	Standard	Improved	New Topology
Primary current	1	1	2
Isolated Gate drivers	4	4	3
Maximum commutation frequency	1	1.2	2
Input voltage range	Approximately the same for all three		
Load range	Limited		Unlimited
EMI	Acceptable	Better	Good
Commutation	ZVS	ZVS ZCS	ZVS ZCS
Rectifier recovery	Recovery losses	More complex	Simple and soft
Paralleling of power stages	Requires additional control		Simple
Operation of power transformer	Not optimal		Optimal
Control	Standard		Special
DC bias	Possible		Not possible
Reliability	Acceptable	Better	Good
Efficiency	Approximately the same for all three		
Idle losses (% of rating)	1.5%		0.15%
Bi-directional	Additional constraints		Readily achieved
Cost	Standard	Standard plus	Less than standard

The table in Fig.9 summarizes a comparison between the new topology and two topologies using phase-shift control. Fig.10 shows the standard phase shift controlled topology, and Fig.11 shows an improved variant of that topology [1]. We did this comparison with one assumption-all topologies have the same efficiency, output power and input and output voltage.

Let us examine these comparisons:

When the new topology produces nominal output power the voltage that appears across the winding of the transformer has approximately a trapezoidal waveform with roughly constant RMS voltage regardless of input voltage. The current carried by the winding is almost sinusoidal with a duty cycle of 90-95% and does not change with input voltage. This is an advantage when considering transformer losses, and along with the fact that the new topology can reach higher commutation frequency, significantly helps to reduce the size of the transformer, decrease price, and increase the transformer’s efficiency. The benefits in operating frequency are driven by the lack of rectifier recovery, since the new topology is resonant, rectifier recovery time does not contribute to loss in the circuit. The phase-shift topology runs into hard switching at light load unless additional circulating energy is provided to commutate the switches. The new topology has much less capacitance to commutate at light load. The benefits of continuous soft switching of all of the semiconductors and lower transformer losses will make this topology a more reliable configuration.

When the new 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 t1-t3, Fig.2). 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. The impedance is also helpful when using the new topology as a power factor corrector with an isolation transformer.

It is important to note that the simplicity of the rectifier in the new topology significantly contributes to cost reduction therefore leading to greater cost effectiveness. Although the control for this new topology is more complex it should be pointed out that if the control used in this topology is implemented in an integrated fashion, such as with an ASIC, the cost of the control will decrease and its use will be much less of a factor in overall cost than the benefits accrued in the power stage. The new topology has a minimum of 10% lower cost than the standard phase-shift control topology at the present time. When the cost of the control reduces, this number will increase. In other words the cost of the topology will go down even more. One further benefit of this new topology is that it can readily be adapted to bi-directional operation, as can most other topologies, however in this case both directions can be operated with soft switching [12,13]. This allows for the design of a bi-directional converter that is not hampered by the operating conditions in any particular conversion direction. In other words up-conversion will have a similar efficiency to down conversion.

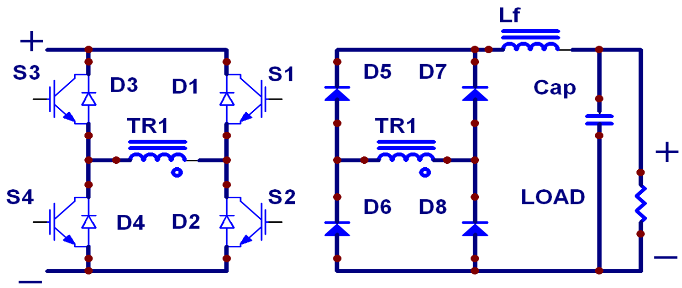

Fig. 10 Standard phase shift control topology

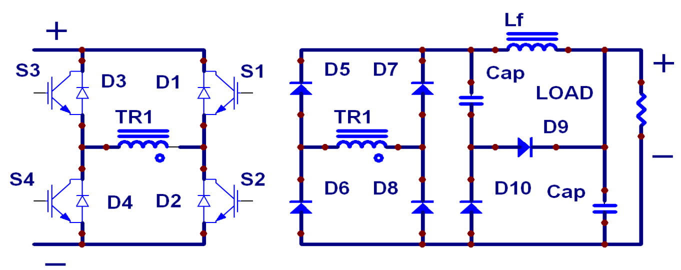

Fig. 11 Improved phase shift control topology

IV. Conclusion

The topology presented here has some notable advantages compared with a typical phase shift controlled topology, notably:

1. It uses of all of the power components efficiently, all of the switches having low switching losses, and can work with any rectifier topology without an inductor.
2. Very low consumption under idle or light load conditions which makes this topology very suitable for battery powered applications.
3. Bi-directional operation is readily achieved with high performance in both directions offering particular benefits in specialist applications.
4. It is Cost effective.
5. There is ease of paralleling.
6. Having a wide input voltage range also makes this topology a good candidate for applications such as power factor correction,

Authors think that it is very reasonable to use the new topology in a DC-DC converter when at input voltages greater than 200VDC and at power levels greater than 2kW.

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