Design of a Variable Inductor Using MR Fluid Gap for Wide Load Range Efficiency Improvement of a Soft-Switching High-Power Density Bidirectional Dc-Dc Converter

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Abstract

In this paper, design of a variable inductor using MR Fluid Gap is proposed for wide load range efficiency improvement of a bidirectional DC-DC converter. As compared to conventional constant value inductor designed to have negative current for ZVS at heavy load but suffers high losses at light load due to its small inductance, the proposed variable inductor not only have small inductance at high current for ZVS but also it has large inductance at low current to decrease light load losses.

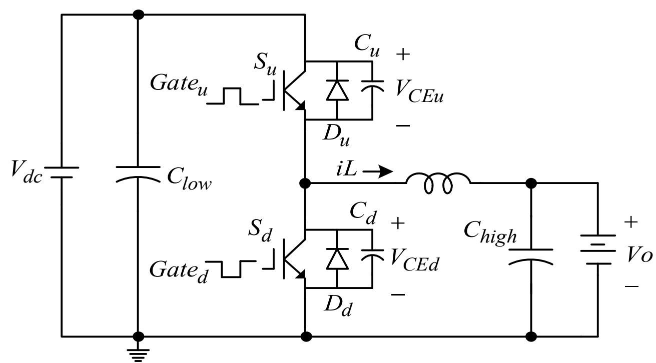
1. Introduction

A bidirectional dc-dc converter usually consists of a combination of buck and boost converters. To get high power density and soft switching, small value inductor is used with rather than operating in traditional DCM mode operation, the inductor current goes from positive to negative direction and then goes to positive direction again. In order to ensure realization of soft switching over wide load range, the value of inductor is kept so small that even at heavy load, there is some negative current for discharging of capacitor across the switch before its turn on. Light load efficiency of this converter reduces greatly due to high switching losses because peak to peak current swing is very large with the negative current ripple comparable to positive ripple, leading to high circulating energy [1]. The proposed variable inductor with MR Fluid Gap is designed to have large inductance at low current and its inductance decreases with increase in inductor current such that it not only improves efficiency over wide range from heavy load to light load but also ensures presence of negative current at heavy load for ZVS.

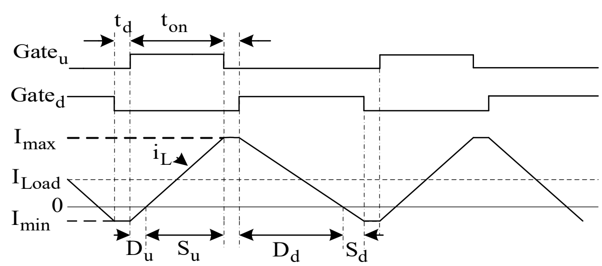
2. Circuit Topology and its Basic Operation

Fig.1 (a) and (b) show circuit configuration of bidirectional DC-DC converter, gate signals and inductor current waveform under buck mode operation. During the interval when gate signal $Gate_u$ is on, switch S_u conducts and current through inductor starts increasing. During dead time t_d when both switches are off, inductor current charges capacitor C_u and discharges C_d. After C_d is fully discharged, inductor current starts freewheeling through diode D_d, it keeps on decreasing until it becomes zero then switch S_d starts conducting and inductor current flows in negative direction. Since, switch S_d turns on under zero voltage across it as its anti-parallel diode D_d was carrying freewheeling current, so it has zero voltage switching ZVS. Now during dead time, inductor negative current charges C_d and discharges C_u. After C_u is discharged during dead time, diode D_u freewheels inductor negative current and when current goes positive direction upper switch S_u takes on inductor current under ZVS.

At heavy load, inductor negative current is small as compared to positive current and for soft switching of switch S_u, constant inductor value is selected so small that there is sufficient negative current for discharge of capacitor C_u during dead time for ZVS.



(a) Circuit diagram of bidirectional DC-DC converter.



(b) Gating signals and inductor current waveforms.

Fig.1. Circuit topology and buck mode operation.

3 Design of MR Fluid Gap Inductor

Magneto-Rheological Fluid has variable inductor behavior as its inductance is high at low current and becomes low at high current. Permeability of MR Fluid is very low as compared to ferromagnetic materials but higher than that of air. For comparison of MR Fluid Gap inductor with conventional constant inductor, two inductors are designed with two same EE7066 ferrite cores, same 9 number of turns , and same gap of 2.5 mm on each ferrite core, one filled with MR Fluid gap and other with air gap. The resulting experimental current vs inductances for two inductors are shown in Fig.2.

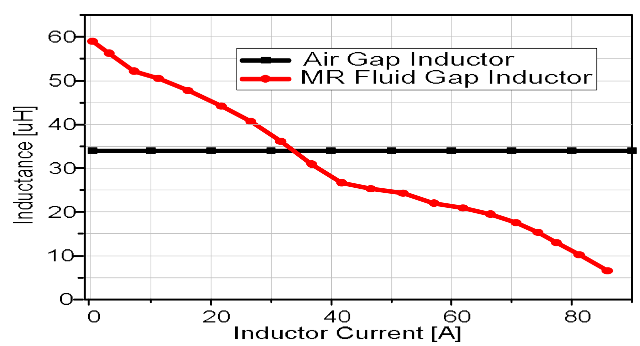
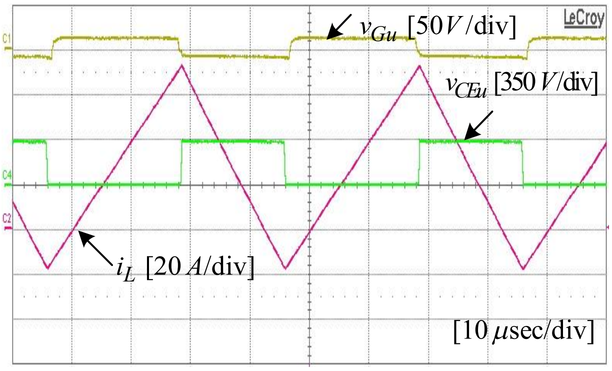


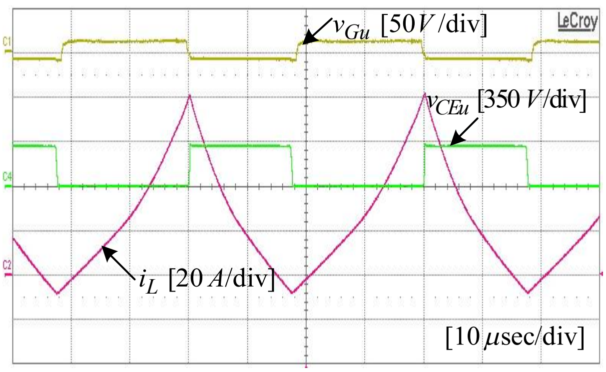
Fig. 2. Measured inductances for two inductors.

4. Experimental Results

A bidirectional DC-DC converter is implemented and performance of both inductors is tested with same power stage and same test conditions having switching frequency of 25 KHz, input voltage of 340 V and regulated output voltage 195 V, output power is varied from heavy load to light load by decreasing output current. From experimental waveforms for two inductors at heavy load, it can be seen that both inductors have some negative current for ZVS and peak to peak current ripple for both inductors is 90 A. But as output load is decreased, the peak to peak current ripple of constant inductor remain constant but that of MR Fluid gap inductor decreases with decrease in current because of its large inductance at low current. From Fig. 4 it can be seen that at light load,

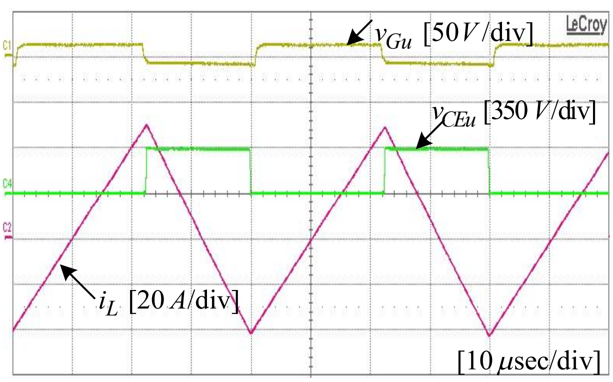


(a) Experimental waveforms for air gap inductor.



(b) Experimental waveforms for MR Fluid gap inductor.

Fig. 3. Experimental waveforms of gating signals, inductor currents and main switch voltages at heavy load, Po= 5.5 kW.



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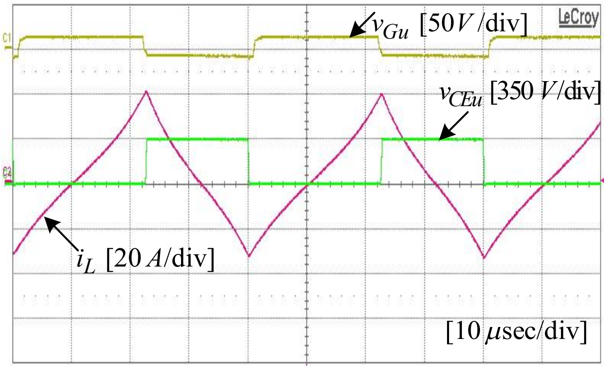

(b) Experimental waveforms for MR Fluid gap inductor.

Fig. 4. Experimental waveforms of gating signals, inductor currents and main switch voltages at light load, Po=400 W.

peak to peak current swing for MR Fluid gap inductor has decreased from 90A to 70A while that for air gap inductor stay constant. With this decreased current swing, circulating energy and conduction losses for MR Fluid gap inductor are smaller as compared to air gap inductor, hence improving efficiency of MR Fluid gap inductor over wide load range which can be seen from efficiency graphs for two inductors in Fig. 5.

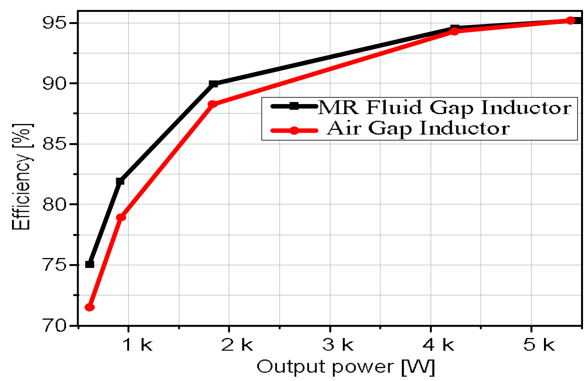

Fig. 5. Output power vs efficiency curves for two inductors.

5. Conclusion

This paper proposed design of a variable inductor using MR Fluid gap which compared to constant inductor, due to its large inductance at low current at small inductance at high current, has capability to improve efficiency of soft switching bidirectional DC-DC converter at wide load range. Experimental results were presented to validate the advantages of proposed inductor over traditional one.

Acknowledgement

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Reference

[1] J. Zhang, J.S. Lai, R.Y. Kim and W. Yu, " High-Power Density Design of a Soft-Switching High-Power Bidirectional DC-DC Converter," IEEE Transactions on Power Electronics, Vol. 22, No. 4, July 2007.