SIMULATION OF SOFT SWITCHING BI-DIRECTIONAL DC/DC CONVERTER

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ABSTRACT- This paper present the work carried out in developing computer simulation models of soft switching bi-directional DC/DC converter. This converter is composed from a few topologies and is assembled into two symmetrical parts. With the help of inductor and the transformer leakage inductance, ZVS is realized for all switches in the whole load range.

Moreover, the diode reverse recovery is also reduced with ZCS and the corporation of a designed pulse-width modulation control. These measures reduce switching losses, voltage and current stresses and electromagnetic interference (EMI). In the theoretical analysis, the switching cycle as well as the operation principle of soft switching is described in detail. Simulation results of 500W model is described to show all the switches of converter can operate in the ZVS condition without requiring any additional circuit components. The simulation models was developed using the MATLAB/Simulink.

Keywords: MATLAB/Simulink, bi-directional DC/DC converter, pulse width modulation (PWM), zero voltage switching (ZVS), zero current switching (ZCS), insulated gate bipolar transistor (IGBT), pulse generator.

1. INTRODUCTION

In the current years, the wide application of uninterruptible power supplies (UPS), distributed power systems (DPS), motor drives and fuel-cell vehicles make the bi-directional DC/DC converter become an important matter of the power conversion. In these applications, bi-directional DC/DC converters give out the solutions by considering the two different electrical behaviors which are; they regulate in direction and quantity of energy flow. Moreover, high power, high efficiency, high voltage, high reliability and soft switching become the demands not only for unidirectional DC/DC converters but also for the bi-directional DC/DC converters. Therefore, the soft-switching bi-directional DC/DC converter is the solution for these entire problems.

Currently, most of the existing DC/DC converter topologies are of low power or one direction power flow and also involving with switching losses, voltage and current stresses and electromagnetic interference (EMI) with regard to the wastage of energy. Meanwhile, there are also high-power, two way of direction with soft-switching operation and galvanic isolation have been introduced. These converters are using soft-switching circuit on a dual full-bridge topology. This technique could significantly improve efficiency and power density over the existing high-power DC/DC converters, but the large number of active switches and related components and complexity of control are arise. Thus, in order to reduce component count and achieve soft switching at once, a DC/DC converter with soft switching operation has been developed employs dual half-bridges interconnected with an isolation transformer to minimize the number of switching devices and their associated gate drive requirements which is the discussed in this paper.

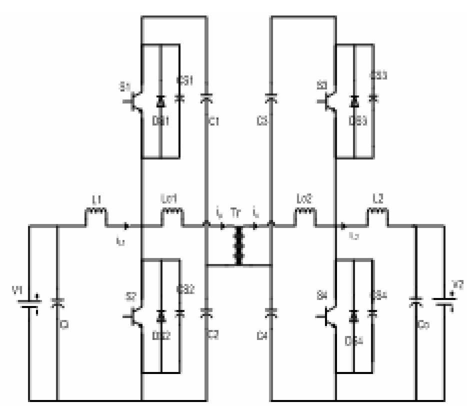


Fig. 1 Bi-directional DC/DC Converter

2. CONVERTER ELEMENTS AND DESCRIPTIONS

Fig. 1 shows the bidirectional DC/DC converter, which consists of half-bridge DC/DC converter combined with two other basic topology, a high-frequency transformer, IGBT switches and other fundamental elements such as inductors, capacitors and diodes.

The circuit is divided into two parts which are actually symmetrical, thus the converter can provide bidirectional power flow. In forward mode, the power flow is transfer from V_1 to V_2.In this mode, switches S_1 and S_2 are conducting, but the gate drive signal of S_2 is leading to S_3. The output voltage V_2 is mainly controlled by the duty cycle of switch S_2. In the reverse mode, which power is flowing from V_2 to V_1, the gate drive signal of S_3 is leading to S_1 and the duty cycle of S_4 determines the output voltage V_1. Inductances L_1 and L_2 act as the important component in the energy transfer. Besides, the designed converter is also to achieve ZVS with calibration of the leakage inductance of transformer.

In forward mode, on the left part, the working concepts of the converter are the combination of a boost DC/DC converter and half bridge inverter. It not only boosts up the input but it also inverts the DC voltage to AC voltage with help of the high-frequency transformer. Meanwhile, on the right part, the converter act similarly as the combination of half bridge DC/DC converter with buck DC/DC converter. The AC voltage of the transformer is rectified to DC voltage by the antiparallel diodes in S_3 and S_4. Due to the capacitors C_3 and C_4, the voltage across them could be regard as constant and the output are regulated in the similar to buck DC/DC converter. Moreover, in the same time when the converter operate either in forward mode or reverse mode, the principle of soft switching could be achieved with the help of parallel junction capacitors.

3. OPERATIONAL PRINCIPLES

To simplify the analysis of the converter, some assumptions are made as follows:
1) The circuit operates in steady state.
2) All the switches are considered as ideal devices.
3) The parasitic capacitances of switches are equal.
4) All energy storage components are free of loss.
5) Inductance L_σ is composed of the leakage inductance of transformer and additional series inductances.

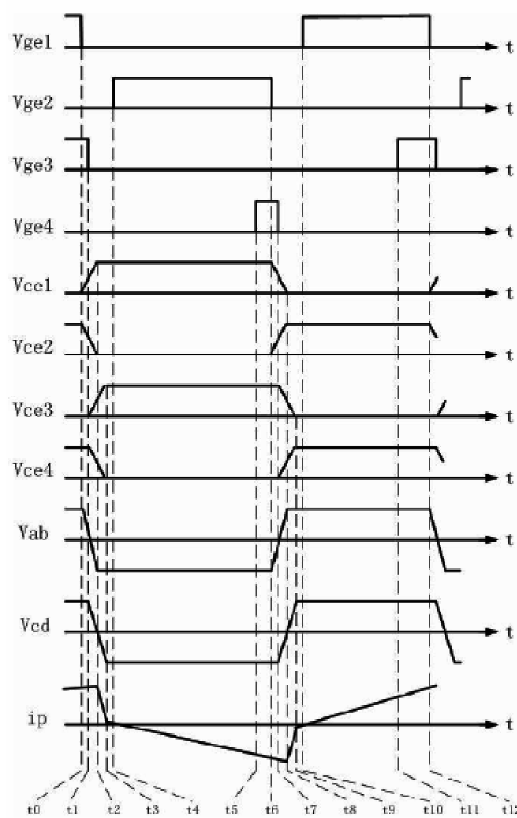


Figure 2. Theoretical voltage and current waveform

The switching cycle of the converter can be divided into twelve stage as shown in fig. 2 and the description have been done based on the forward mode of operation of the bidirectional DC/DC converter.

Before t_0, S1 and S3 are conducting.
Stage 1 (t_0-t_1):
At time t_0, S_1 is turned off with ZVS due to the junction capacitance C_{S1}, paralleled with S_1.
Owing to the leakage inductance $L_{\sigma 1}$, the transformer primary current i_P keeps on flowing in the previous direction. During this stage, C_{S1} is charged and C_{S2} is discharged while the voltage over C_{S2} begins to decrease.

Stage 2 (t_1-t_2): At time t_1, S_3 is turned off with ZVS due to C_{S3}. During this stage, C_{S3} is charged and C_{S4} is discharged while the voltage over C_{S4} begins to decrease.

<u>Stage 3</u> (t_2-t_3): At time t_2, the voltage over C_{S2} decreases to zero; therefore D_{S2} is forward biased and begins to conduct. At this time, S_2 can be turned on with ZVS. In this interval, inductance current i_{L1} begins to increase and i_P begins to decrease. The transformer secondary current i_S is also decreases following i_P. The voltage of the secondary side is not changed while the voltage over $L_{\sigma1}$, is equal to the sum of primary winding's voltage and the voltage over C_2.

<u>Stage 4</u> (t_3-t_4): At time t_3, the voltage over C_{S4} decreases to zero; therefore D_{S4} is forward biased and begins to conduct. At that time, S_4 can be turned on with ZVS. The secondary winding voltage changes its polarity and inductance current i_{L2} begins to decrease.

<u>Stage 5</u> (t_4-t_5): At time t_4, i_{L1} is lager than i_P, so S_2 is turned on with ZVS and D_{S2} is turned off with ZCS. When i_P decreases to zero, it changes the direction. Then, i_{L2} changes the direction at the end of this stage.

<u>Stage 6</u> (t_5-t_6): At time t_5, i_{L2} is larger than i_S, so S_4 is turned on with ZVS and D_{S4} is turned off with ZCS.
Stage 7 (t_6-t_7): At time t_6, S_2 is turned off with ZVS due to C_{S2}. Then C_{S2} is charged and C_{S1} is discharged while the voltage over C_{S1} begins to decrease.

<u>Stage 8</u> (t_7-t_8): At time t_7, S_4 is turned off with ZVS due to C_{S4}. During this stage, C_{S4} is charged and C_{S3} is discharged while the voltage over C_{S3} begins to decrease.

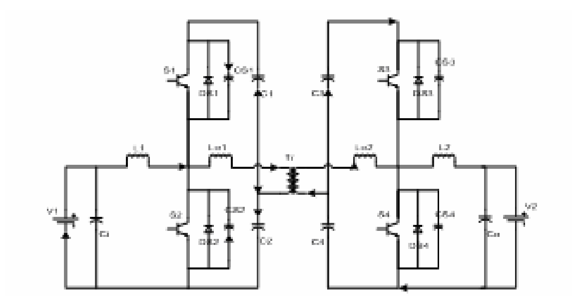
<u>Stage 9</u> (t_8-t_9): At time t_8, the voltage over C_{S1} decreases to zero; therefore D_{S1} is forward biased and begins to conduct. At that time, S_1 can be turned on with ZVS. In this interval, i_{L1} begins to decrease and i_P begins to increase, while i_S follows i_P.

<u>Stage 10</u> (t_9-t_{10}): At time t_9, voltage over C_{S3} decrease to zero, therefore D_{S3} begins to conduct. At that time, S_3 can be turned on with ZVS and the secondary winding voltage changes its polarity again. In this interval, i_{L2} begins to increase. When i_P (or i_{L2}) increases to zero, the direction is changed.

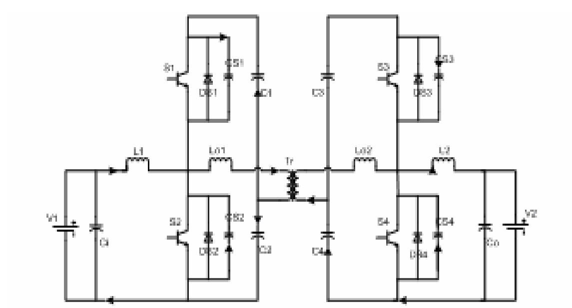
<u>Stage 11</u> (t_{10}-t_{11}): At time t_{10}, i_P is lager than i_{L1}, S_1 is turned on with ZVS, and D_{S1} is turned off with ZCS.

<u>Stage 12</u> (t_{11}-1_{12}): At time t_{11}, i_S is lower than i_{L2}, so S_3 is turned on with ZVS and D_{S3} is turned off with ZCS. A complete period is ended.

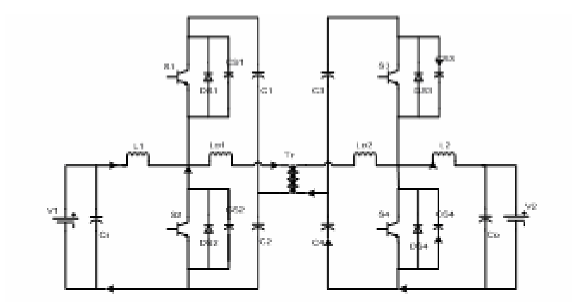
The interval of stage 6 is very short. When the ripple of inductor current i_1 is small, there is no current flowing through S_1.Therefore the gate drive signal of S_1 is not needed. With the suitable value of L_1, D_1 could also be turned off in ZCS.
The operation principle of the reverse mode is similar to that of the forward mode, so it will not be explained again.



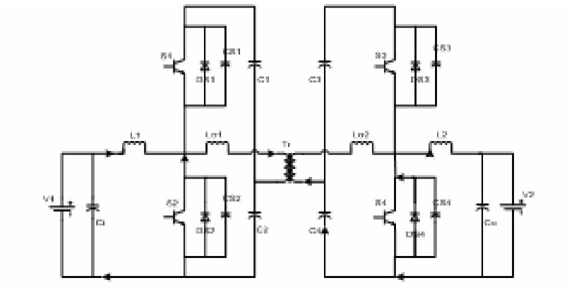
Stage 1



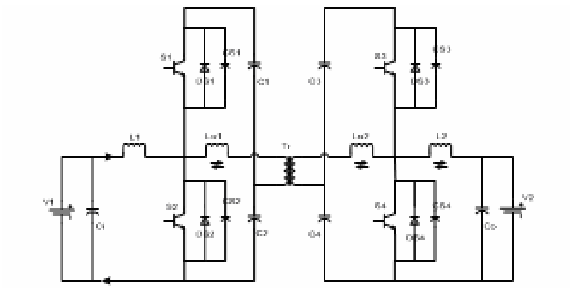
Stage 2



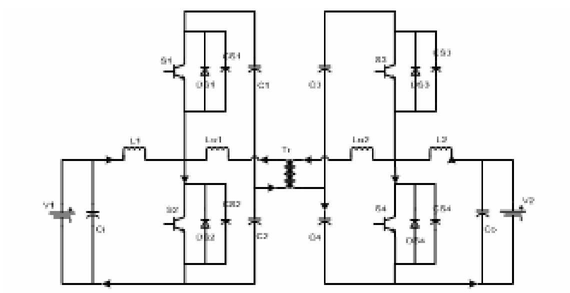
Stage 3



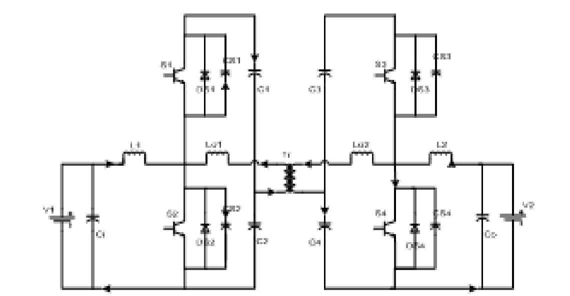
Stage 4



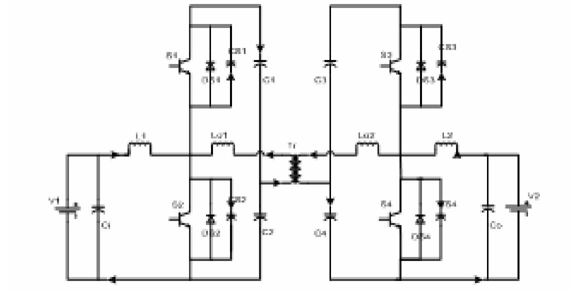
Stage 5



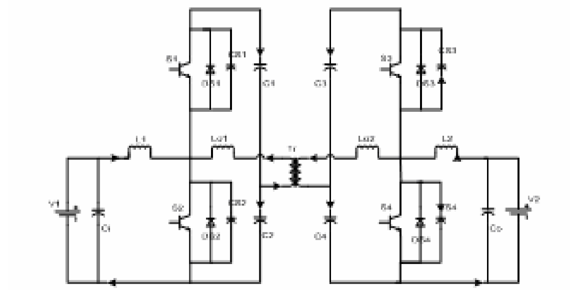
Stage 6



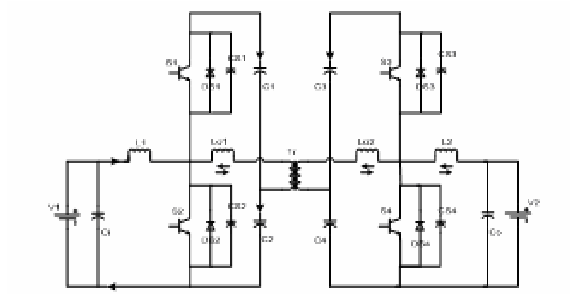
Stage 7



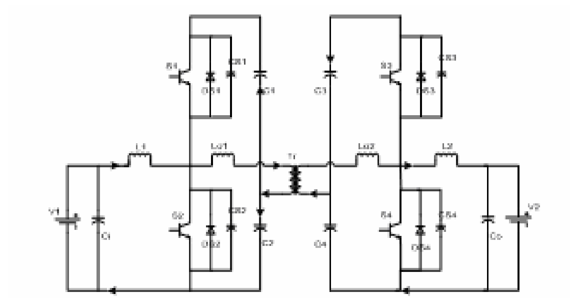
Stage 8



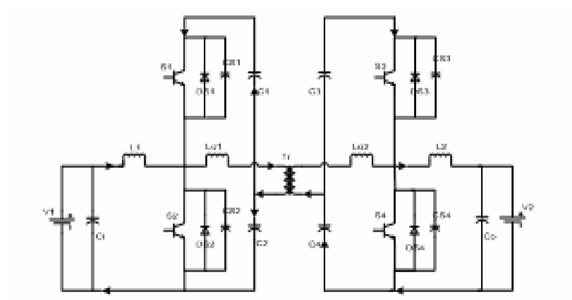
Stage 9



Stage 10



Stage 11



Stage 12

4. PULSE WIDTH MODULATION

PWM is digital technique that used in this study to synthesize the output waveform given by the source of voltage either AC or DC voltage source. Generally, the switching pulse is generated by comparing the DC signal with the triangular waveform (shown in fig. 3). The advantage of the PWM technique is that the modulation may be performed in such a way that certain harmonic may be eliminated (selective reduction of harmonic). The waveform generated from PWM is to be feed into the IGBT switch as the drive signal waveform. In the research, the pulse generators are used instead of PWM because the research only converges to the operation of the converter.

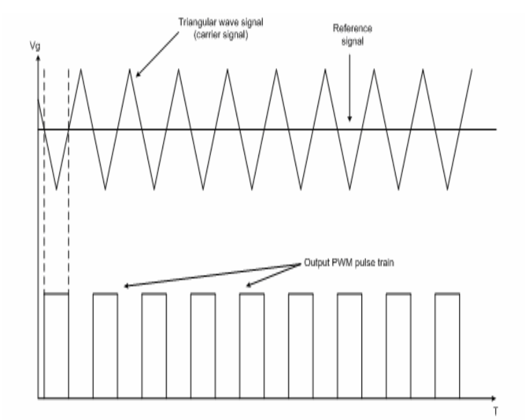


Figure 3: PWM waveform

5. METHODOLOGY

- Literature Review/ Background Studies
- Modeling and Simulation of Basic Topology DC/DC converter such as Boost DC/DC converter, Buck DC/DC converter using IGBT
- Modeling and Simulating the topology of Half Bridge DC/DC converter
- Modeling and simulating the Bi-directional DC/DC Converter
- Analysis and Synthesis of results
- Final Report

In order to complete the simulation, several parameters are chosen to be put in the model and analysis is made to verify whether it is compatible to the model. Examples of parameter that have been adjusted are the capacitors, inductors, and the duty cycle of the switches. The reasons are to obtain the results and to make comparison between the results obtained from each of parameter. All of these procedures are done by using the MATLAB/Simulink Program.

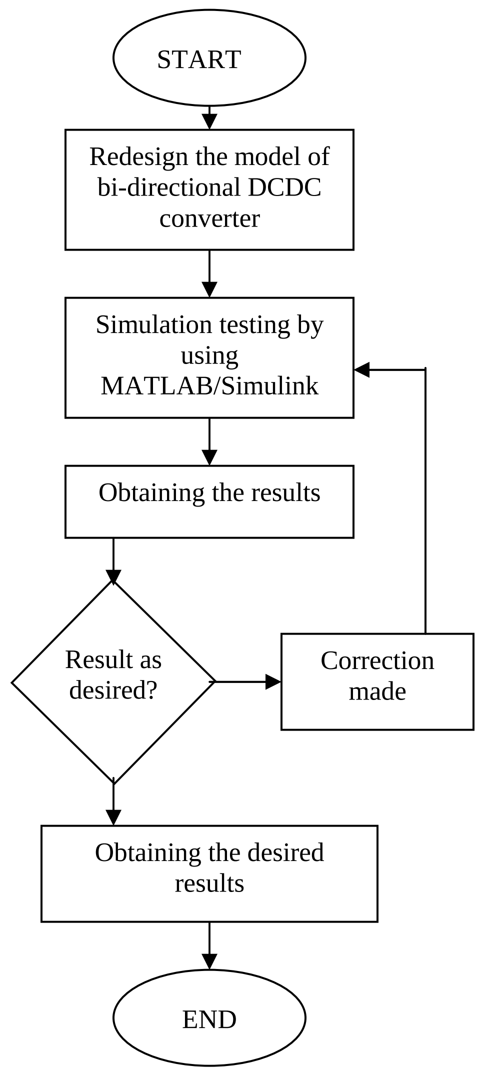


Figure 4: Simulations procedures

6. RESULTS AND DISCUSSIONS

A model of soft switching bi-directional DCDC converter has been rebuilt to verify the analysis operation described. Specifications of the model are as follows:

- Input voltage: 48 Vdc
- Output voltage: 120 Vdc
- Rated power: 500 W
- $L_{\sigma 1}$: 4 μH
- $L_{\sigma 2}$: 25 μH
- Inductor L_1: 138 μH
- Inductor L_2: 98 μH
- Transformer ratio: 2:5
- Switching frequency: 1000Hz

Figure 4-7 show the waveform of the bi-directional DC/DC converter gained by simulation of MATLAB/Simulink. The waveform show gate drive signal, Vge and Vce of S_1, S_2, S_3 and S_4 respectively. They demonstrate that the voltage across those switches decrease to zero before the gate drive signal is given except switch S_4.

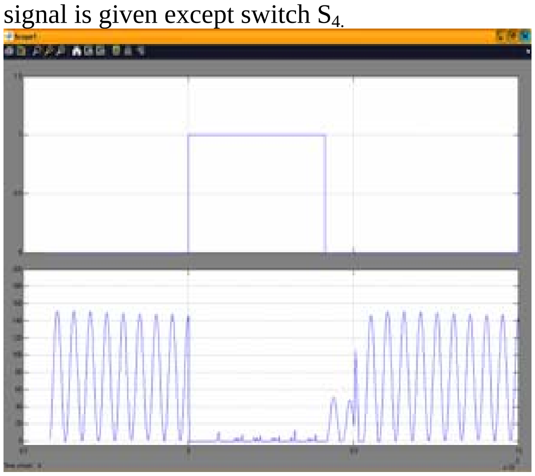


Figure 5: Waveform Vge1 and Vce1

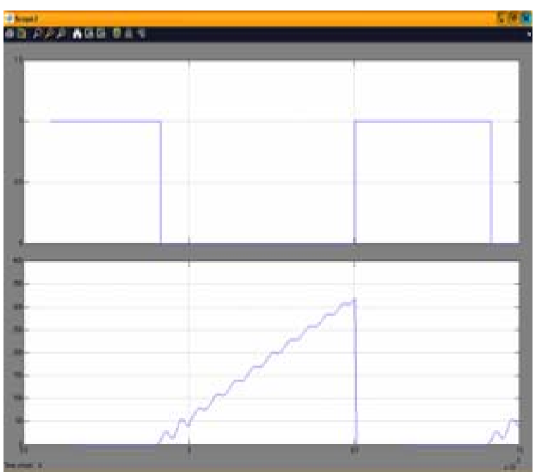


Figure 6: Waveform Vge2 and Vce2

Figure 7: Waveform Vge3 and Vce3

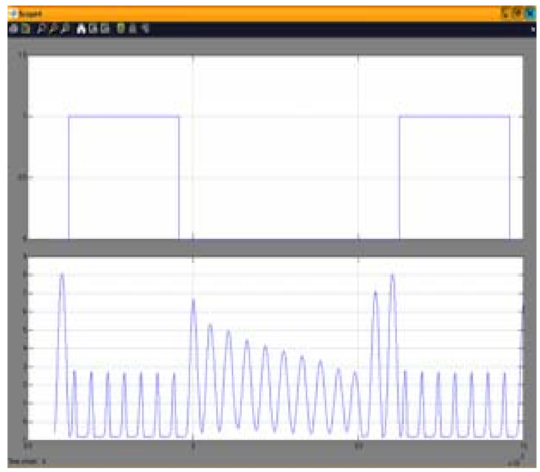


Figure 8: Waveform Vge4 and Vce4

7. CONCLUSION

This technical paper has outlined and illustrated all the operations principles and switching concept in the soft switching bi-directional DC/DC converter. By soft switching for all power switches and diode, it dramatically reduces switching loss, current stress, voltage stress and EMI emission. Moreover, by comparing with the first-generation and other soft-switched bi-directional dc/dc converters, this topology has the fewer switching devices. Compared with the full-bridge topologies, this converter has half the number of switching devices. This reduction also leads to significant savings on the gate drive and accessory power requirements. No auxiliary circuit or complex control dedicated for soft switching.

8. REFERENCES

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