Comparison of an Isolated bidirectional Dc-Dc converter with and without a Flyback Snubber

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Abstract : *Renewable energy sources like solar and fuel cells are emerging as a promising supplementary power sources due to their merits of cleanness, high efficiency, and high reliability. But the output levels of these are low. An isolated bidirectional full-bridge dc–dc converter can be used for interfacing battery to the system. Because of the presence of leakage inductance of the isolation transformer voltage spikes are produced. An isolated bidirectional converter with a flyback snubber can reduce voltage spike caused by the current difference between the current-fed inductor and leakage inductance of the isolation transformer. In this work an isolated bidirectional full bridge dc-dc converter with and without flyback snubber is simulated using MATLAB SIMULINK Tool and compared the simulation results . Also implemented the hardware of boost mode operation of the same converter with input as 10V and compared it with the simulation results.*
Keywords: *Clamping capacitor, Flyback snubber, , Isolated bidirectional Dc-Dc converter, Leakage inductance, Voltage spikes*

I. INTRODUCTION

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. Applications of renewable energy sources have been getting more awareness. Because of the increasing demand of the renewable energy sources like fuel cell, solar energy etc, batteries are necessary for storing and supplying energy. For charging and discharging of the batteries a converter which can operate in both directions is required. Bidirectional converters are the main part of a system where it is necessary to interface an energy storage device to a renewable energy sources like fuel cell , solar cell etc. Therefore bidirectional converters are getting more importance for past decades. Bidirectional converters can be isolated and nonisolated. Both of them have its own advantages and disadvantages. In applications where high power is required , bridge-type bidirectional converters are become an important [5-7] . A dual full-bridge configuration is usually used for raising the power level and its low side and high side are configured with boost type and buck-type topologies, respectively. Isolation is used for isolating the low voltage and high voltage side. There is many problems associated with these topologies.

Most important problem is due to the leakage inductance of the isolation transformer, which will result in high voltage spike during switching transition. And the current freewheeling due to the leakage inductance will increase conduction loss. A passive or an active clamp circuit can be used to solve this problem. Passive and active clamping circuits can be used to suppress the voltage spikes due to the current difference between the current-fed inductor and leakage inductance of the isolation transformer . To clamp the voltage, *RCD* passive snubber can be used, which is a simple method. The energy absorbed in the clamping capacitor is dissipated on the resistor. But the disadvantage is the reduction efficiency due to the power loss in the resistor. A flyback snubber can be used to recycle the absorbed energy in the clamping capacitor [1]. The current does not circulate through the full-bridge switches, their current stresses can be reduced. Then it improves system reliability significantly. Additionally, during start-up, the flyback snubber can be controlled to precharge the high-side capacitor, improving feasibility significantly.

The main objective of this work is to simulate an isolated bidirectional converter with and without flyback snubber and compare the simulation results . Also implement the hardware of the converter in boost mode with flyback snubber and compare it with the simulation results.

II. OPERATION OF THE CONVERTER

An isolated bidirectional dc- dc converter without flyback snubber is shown in fig 1 and without flyback snubber is shown in fig 2. The isolated bidirectional converter can be operated in two modes . buck mode and boost mode. Figure 2 consists of a current-fed switch bridge, a flyback snubber at the low-voltage side, and a voltage-fed bridge at the high-voltage side.
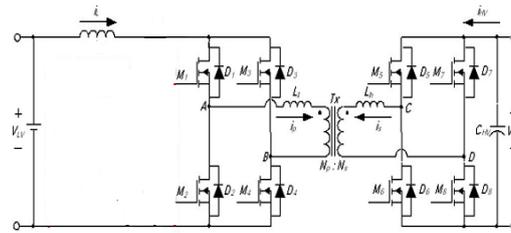
Figure 1.Isolated Bidirectional Dc-Dc Converter Without A Flyback Snubber

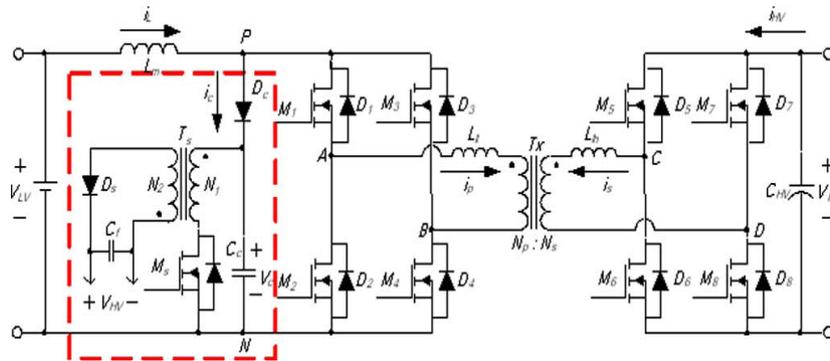
Figure 2. Isolated Bidirectional Dc-Dc Converter With A Flyback Snubber

Inductor Lm at the low voltage side performs output filtering when power flows from the high-voltage side to the batteries, which is denoted as a buck mode. On the other hand, it works in boost mode when power is transferred from the batteries to the high-voltage side. Also clamp branch capacitor C_C and diode D_C are used to absorb the current difference between current-fed inductor Lm and leakage inductance L_{ll} and L_{lh} of isolation transformer Tx during switching commutation. The flyback snubber can be independently controlled to regulate V_C to the desired value . Thus, the voltage stress of switches M_1–M_4 can be limited to a low level. The major merits of this bidirectional converter configuration include no spike current circulating through the power switches and clamping the voltage across switches M_1–M_4, improving system reliability significantly. Note that high spike current can result in charge migration, over current density, and extra magnetic force, which will deteriorate in MOSFET carrier density, channel width, and wire bonding and, in turn, increase its conduction resistance.

A bidirectional dc–dc converter has two types of conversions: step-up conversion (boost mode) and step-down conversion (buck mode). In boost mode, switches M_1–M_4 are controlled, and the body diodes of switches M_5–M_8 are used as a rectifier. In buck mode, switches M_5–M_8 are controlled, and the body diodes of switches M_1–M_4 operate as a rectifier. To simplify the steady-state analysis, several assumptions are made, which are as follows.

1) All components are ideal. The transformer is treated as an ideal transformer associated with leakage inductance.
2) Inductor Lm is large enough to keep current i_L constant over a switching period.
3) Clamping capacitor C_C is much larger than parasitic capacitance of switches M_1–M_8 .

III. Step-Up Conversion

In boost mode, switches M_1–M_4 are operated like a boost converter, where switch pairs (M_1 , M_2) and (M_3 , M_4) are turned ON to store energy in Lm. At the high-voltage side, the body diodes of switches M_5–M_8 will conduct to transfer power to V_{HV} . When switch pair (M_1 , M_2) or (M_3 , M_4) is switched to (M_1 , M_4) or (M_2 , M_3), the current difference i_C (= i_L – i_p) will charge capacitor C_C, and then, raise i_p up to i_L . The clamp branch is mainly used to limit the transient voltage imposed on the current-fed side switches. Moreover, the flyback converter can be controlled to charge the high-voltage-side capacitor to avoid over current. The clamp branch and the flyback snubber are activated during both start-up and regular boost operation modes.

In this converter V_C (R) represents the regulated V_C voltage , fs is the switching frequency, and Lm >>Leq. Power will be transferred to the high-side voltage source through the flyback snubber, and the snubber will regulate clamping capacitor voltage V_C to V_C (R) within one switching cycle Ts (=1/fs). Note that the flyback snubber does not operate over the interval of inductance current i_p increasing toward i_L. The processed

power by the flyback snubber is typically around 5% of the full-load power for low-voltage applications. With the flyback snubber, the energy absorbed in C_C will not flow through switches M1–M4 , which can reduce their current stress dramatically . Theoretically, it can reduce the current stress from $2i_L$ to i_L. For reducing conduction loss, the high-side switches M_5–M_8 are operated with synchronous switching. The operation waveforms of step-up conversion are shown in Fig 4. A detailed description of a half-switching cycle operation is shown as follows.

Mode 1 [$t_0 \leq t < t_1$]:

In this mode, all of the four switches M_1–M_4 are turned ON. Inductor Lm is charged by V_{LV} , inductor current i_L increases linearly, and the primary winding of the transformer is short-circuited. The equivalent circuit is shown in Fig 3(a)

Mode 2 [$t_1 \leq t < t_2$]:

At t_1 , M_1 and M_4 remain conducting, while M_2 and M_3 are turned OFF. Clamping diode Dc conducts until the current difference ($i_L (t_2) - ip (t_2)$) drops to zero at t = t_2 . Moreover, the body diodes of switch pair $(M_5$, $M_8)$ are conducting to transfer power. During this interval, the current difference ($i_L (t) - ip (t)$) flows into clamping capacitor C_C . The equivalent circuit is shown in Fig 3(b) .

Mode 3 [$t_2 \leq t < t_3$]:

At t_2 , clamping diode Dc stops conducting, and the flyback snubber starts to operate. At this time, clamping capacitor Cc is discharging and flyback inductor is storing energy. Switches M_1 and M_4 still stay in the ON state, while M_2 and M_3 remain OFF. The body diodes of switch pair (M_5 , M_8) remain ON to transfer power. The equivalent circuit is shown in Fig 3(c).

Mode 4 [$t_3 \leq t < t_4$]:

At t_3 , the energy stored in flyback inductor is transferred to the high-voltage side. Over this interval, the flyback snubber will operate independently to regulate V_C to V_C (R) . The switches M_1 and M_4 and diodes D_5 and D_8 are still conducting to transfer power from V_{LV} to V_{HV} . The equivalent circuit is shown in Fig 3 (d).

Mode 5 [$t_4 \leq t < t_5$]:

At t_4 , capacitor voltage V_C has been regulated to V_C (R) , and the snubber is idle. Over this interval, the main power stage is still transferring power from V_{LV} to V_{HV} . It stops at t_5 and completes a half-switching cycle operation. The equivalent circuit is shown in fig 3(e).
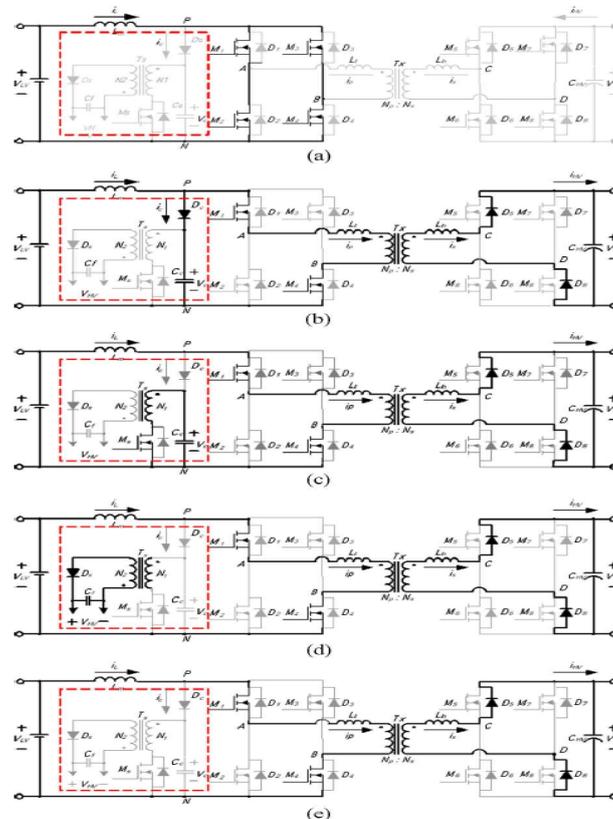

Figure 3. Operation Modes Of Step Up Conversion

IV. Step-Down Conversion

In this mode leakage inductance of the transformer at the low-voltage side is reflected to the high-voltage side. In the step-down conversion, switches M_5–M_8 are operated like a buck converter, in which switch pairs (M_5, M_8) and (M_6, M_7) are alternately turned ON to transfer power from V_{HV} to V_{LV}. Switches M1–M4 are operated with synchronous switching to reduce conduction loss. For alleviating leakage inductance effect on voltage spike, switches M_5–M_8 are operated with phase-shift manner. There is no need to absorb the current difference between i_L and ip .

Figure 4. Operation Waveforms of Step Up Conversion

The operation waveforms of step-down conversion are shown in Figure 6. A detailed description of a half-switching cycle operation is shown as follows.

Mode 1 [$t_0 \leq t < t_1$]:

In this mode, M_5 and M_8 are turned ON, while M_6 and M_7 are in the OFF state. The high-side voltage V_{HV} is immediately exerted on the transformer, and the whole voltage is exerted on the equivalent inductance Leq and causes the current to rise. With the transformer current increasing linearly toward the load current level at t_1 , the switch pair (M_1 , M_4) are conducting to transfer power, and the voltage across the transformer terminals on the current-fed side changes immediately to reflect the voltage from the voltage-fed side. The equivalent circuit is shown in Fig 5 (a).

Mode 2 [$t_1 \leq t < t_2$]:

At t_1 ,M_8 remains conducting, while M_5 is turned OFF. The body diode of M_6 then starts to conduct the freewheeling leakage current. The transformer current reaches the load-current level at t_1 , and V_{AB} rises. Clamping diode Dc starts to conduct the resonant current of Leq and the clamp capacitor C_C . This process ends at t_2 when the resonance goes through a half resonant cycle and is blocked by the clamping diode Dc . The equivalent circuit is shown in Fig 5 (b).

Mode 3 [$t_2 \leq t < t_3$]:

At t_2 , with the body diode of switch M_6 conducting, M_6 can be turned ON with zero-voltage switching (ZVS). The equivalent circuit is shown in Fig 5 (c).

Mode 4 [$t_3 \leq t < t_4$]:

At t_3 ,M_6 remains conducting, while M_8 is turned OFF. The body diode of M_7 then starts to conduct the freewheeling leakage current. The equivalent circuit is shown in Fig 5 (d).

Mode 5 [$t_4 \leq t < t_5$]:

At t_4 , with the body diode of switch M_7 conducting, M_7 can be turned ON with ZVS. Over this interval, the active switches change to the other pair of diagonal switches, and the voltage on the transformer

reverses its polarity to balance flux. It stops at t_5 and completes a half-switching cycle operation. The equivalent circuit is shown in Fig 5 (e).
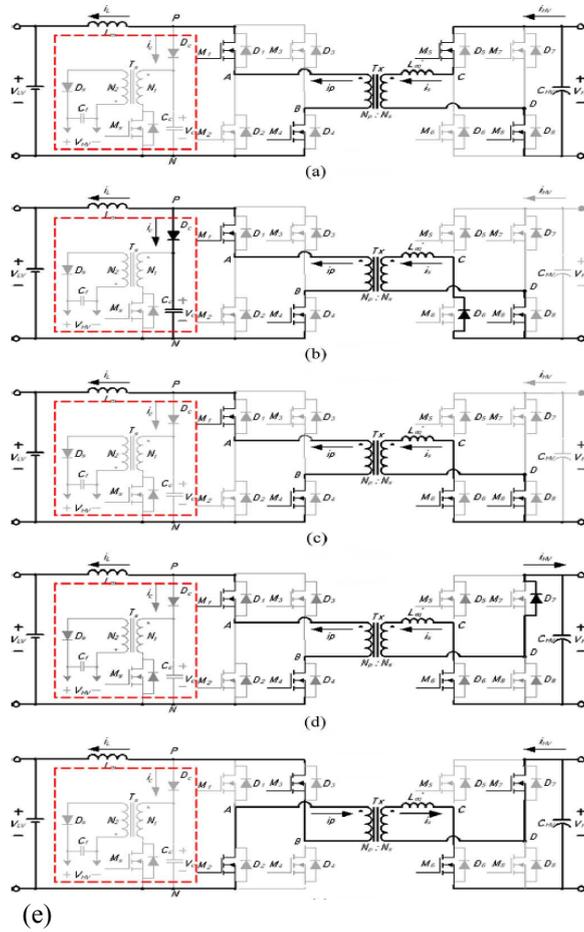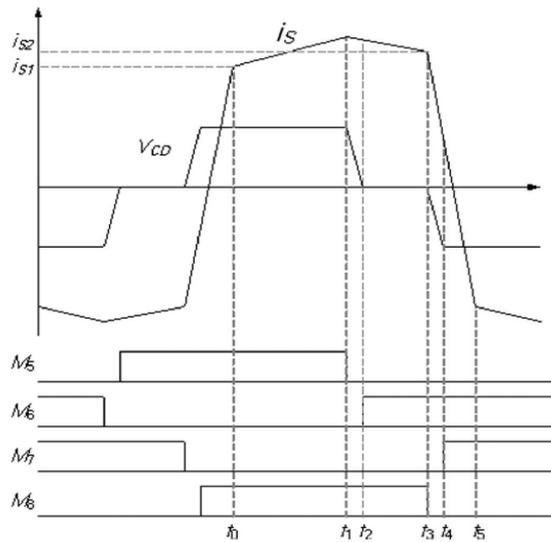

Figure 5. Operation Modes Of Step Down Conversion

Figure 6 . Operation Waveforms Of Step Down Conversion

V. Practical Consideration

5.1. Low-Voltage Side

Switch pairs (M_1, M_4) and (M_2, M_3) are turned ON alternately under any load condition. Its minimum conduction time is

$$T_{C(min)} = \frac{L_{eq} i_L}{V_{AB}} \qquad (1)$$

$$L_{eq} = L_{ll} + L_{lh} \times (\frac{N_p}{N_s})^2 \qquad (2)$$

L_{ll} - Leakage inductance of low voltage side

L_{lh} - Leakage inductance of high voltage side

$\frac{N_p}{N_s}$ - Turns ratio

5.2. Clamping Capacitor

For absorbing the energy stored in the leakage inductance and to limit the capacitor voltage to a specified minimal value V_{cl}, capacitance Cc has to satisfy the following inequality

$$C_C \geq \frac{L_{eq}(i_L - i_p)^2}{V_{cl}^{~2}} \qquad (3)$$

VI. Simulation

An isolated bidirectional dc-dc converter with a R load is selected. Its model is simulated with and without a flyback snubber. Simulation model and results of isolated bidirectional dc-dc converter with and without flyback snubber in boost mode is shown in figures 7 to 12. The input dc voltage given is 48V and the output dc voltage obtained is 280V. Simulation models for without and with flyback snubber is shown in figures 7 and 8 respectively. In an isolated bidirectional dc – dc converter without flyback snubber , the voltage spikes are of large values. By comparing the results it can be see that 78% to 80 % voltage spikes can be reduced with a flyback snubber. Simulation parameters are as shown in the Table 1.

Table 1

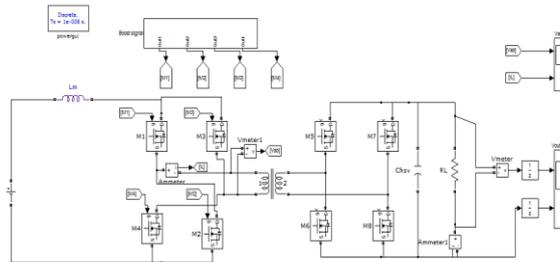| Parameter	Value
Current fed inductor, L_m	500μH
Clamping capacitor, C_c	1μF
Resistor, R	100Ω
Switching frequency , f_s	25kHz

Figure 7. Simulation Model For Boost Operation Without flyback Snubber
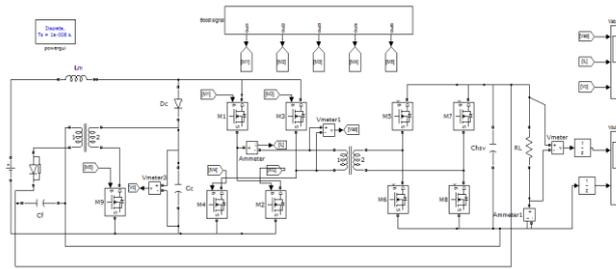
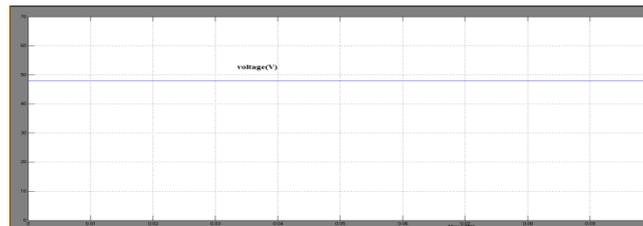Figure 8. Simulation Model For Boost Operation With a flyback Snubber
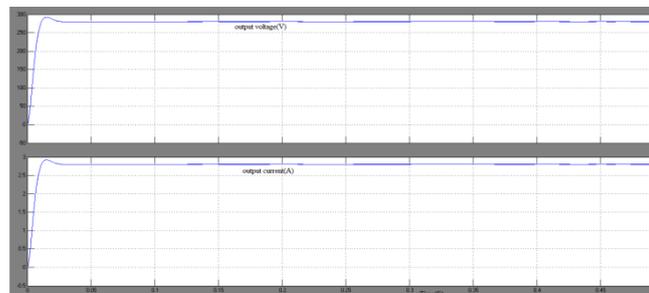

Figure 9. Input Voltage

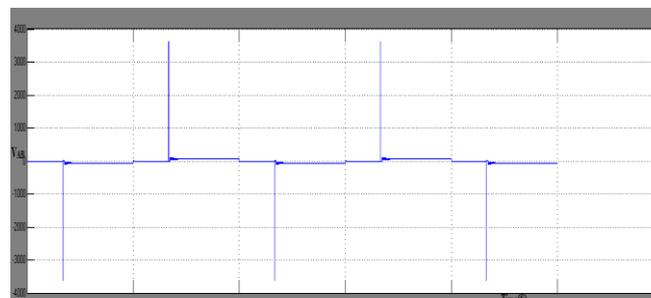Figure 10. Output Voltage And Current V_s Time

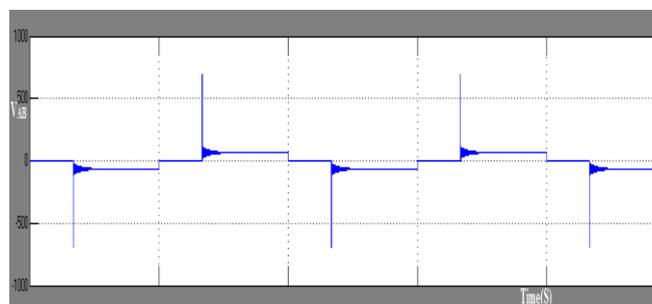Figure 11. V_{AB} (voltage across the primary) for without flyback snubber)

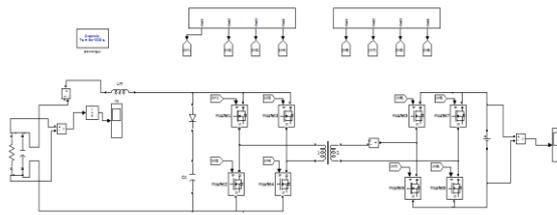Figure 12. V_{AB} (voltage across the primary) for with flyback snubber)

Figure 13. Simulation Model For Buck Operation

Simulation model for buck operation with R load is also shown in figure13. The effect of flyback snubber is only in boost mode operation. In buck mode it is inactive. The input voltage given is 360 V and the output obtained is 50V.
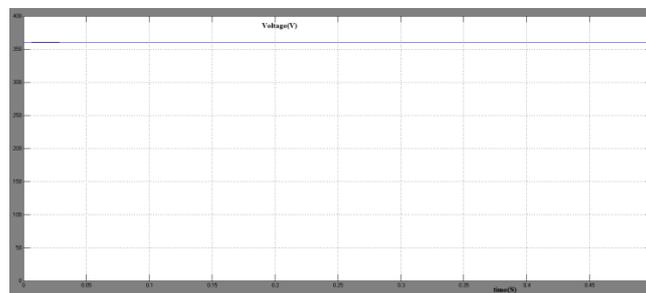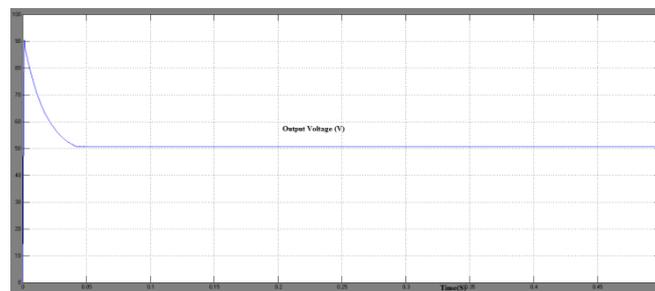

Figure 14. Input Voltage

Figure 15. Output Voltage

VII. Hardware Implementation
Hardware circuit of isolated bidirectional dc – dc converter with flyback snubber in boost mode is implemented and got the boosted dc output and observed the other waveforms. Experimental set up of the hardware of the isolated bidirectional dc-dc converter is shown in fig 16.
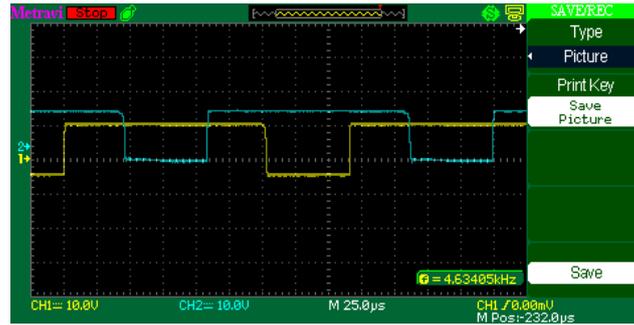

Figure 16. Hardware Setup
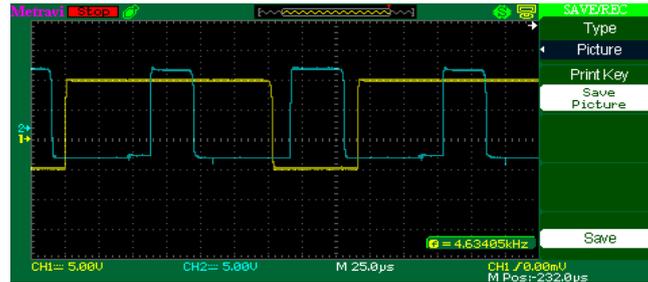
Figure 17. Pulses For MOSFETS M_1 M_4 AND M_2 M_3.

Figure 18. Pulses For MOSFETS M_1 M_4 and M_9

Figure 19. Waveform Of V_{AB}

Figure 20. Output Voltage

The waveforms obtained from the hardware follow the shape of the simulation results. The waveforms are shown in figures 17 to 20. The input given is 10V from a battery. The input is boosted and the output is 39V.

VIII. Conclusion

In this work an isolated bidirectional dc –dc converter is simulated using MATLAB SIMULINK tool . The simulation model includes converter with and without the flyback snubber. Then the simulation results of both of them are compared. From comparison of simulation results it can be observed that the voltage spikes can be reduced to a great extent by using flyback snubber. About 78% to 80% voltage spikes can be reduced. The hardware of the isolated bidirectional dc-dc converter with flyback snubber in boost mode is implemented and experimental waveforms follow the shape of the simulation results. But the hardware results still contains

spikes. From the simulation results and hardware results , it can be concluded that the spikes will be larger in the hardware results if there is no flyback snubber.

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