

Second Stage Half Bridge Inverter Design in AC TIG Welding Machines

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Keywords: Half bridge inverter, TIG welding, coupled inductor

Abstract

In AC tungsten inert gas (TIG) welding machine application, there are two kinds of commonly used topologies of the second stage half bridge inverter circuit. This paper analyses and compares these two topologies. In addition, in the second topology, more investigations have been made to show the factors that can affect the changing rate of the output current as well as the factors that can affect the current transformation ratio in the coupled inductor. High changing rate and high current transformation ratio are the two important requirements of the electrical power source for AC TIG welding, however, in the conclusion of the analysis, it is difficult to meet these requirement at the same time. Therefore, a solution by adding extra voltage sources across the rectification circuit is proposed to maintain the high changing rate of the output current as $7A/\mu s$ and achieve about 100% current transfer in the coupled inductor.

1 Introduction

AC TIG welding is a TIG welding process for aluminium and its alloy. Different from DC TIG welding of steel and other metals, in which only negative voltage is required on the electrode in the welding torch, TIG welding for aluminium requires a positive voltage portion to get rid of the aluminium oxide. The aluminium oxide has much higher melting temperature and can inhibit proper TIG welding process if not removed [1]. An output current waveform of an AC TIG welding machine can be illustrated in Fig. 1.

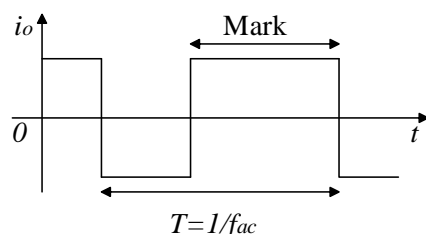


Fig. 1. Output current waveform of the AC TIG welding machine.

As shown in Fig. 1, mark is the time duration of the positive portion in one switching period, T . The percentage of the time

duration of mark in one period is normally called as mark space ratio. According to different welding requirements, such as welding beam width, penetration and etc., the AC frequency can be set within a range from 10 Hz to 300 Hz, and the mark space ratio can be set within a range from 30% to 70%. In AC TIG welding, the current direction will change when the polarity of the output voltage changes. During the change of the current direction, there must be a moment that the current flow is zero. At this moment, it is difficult to keep the arc ionized. Therefore, the arc may be lost during the change of the polarity. In order to keep the arc, the changing rate of the current during the change of the polarity needs to be fast enough, for example, $5A/\mu s$, to make the duration of the low or zero current as short as possible. The AC TIG welding can have undesirable cease or even cannot be proceed when the changing rate of the output current is slow.

Both half bridge inverter and full bridge inverter topologies can realize the DC/AC conversion at the second stage inverter circuit. There are three kinds of commonly used topologies, full bridge inverter, half bridge inverter with single inductor, and half bridge inverter with coupled inductor as shown in Fig. 2. As shown in Fig. 2, the isolated DC/DC converter provides the regulated output current, while the second stage inverter convert the DC power to AC [1-3].

In comparison, half bridge inverter topologies are more power efficient and cost effective. This is because, the output current of the welding machine can be as high as several hundred ampere and there are two semiconductor switches in the second stage full bridge inverter conducting current at a time, while there is only one semiconductor switch in the second stage half bridge inverter conducting current at a time. The advantage of the full bridge inverter topology is that the changing rate of the output current during the change of the output polarity is very fast. The topology with single inductor shown in Fig. 2(b) has slow changing rate, therefore, an auxiliary circuit is required to provide high voltage for arc re-ignition. The topology shown in Fig. 2(c) applies the coupled inductor which can provide a much faster changing rate of the output current compared with the topology with single inductor [4-6]. However, it is lack of analysis that what factors can determine the changing rate of the output current. In addition, high current transformation ratio in the coupled inductor is also desired in this topology. However, it is lack of analysis that what factors can determine the current transformation ratio in the coupled inductor. Furthermore, the current paths of the half bridge topologies shown in Figs. 2(b) and 2(c) are integrated with the

rectification circuit of the DC/DC converter. Therefore, the operation of these circuit topologies are more complicated than the operation of the full bridge topology. Therefore, this paper will undertake a further investigation on the half bridge inverter topologies to address the aforementioned problems.

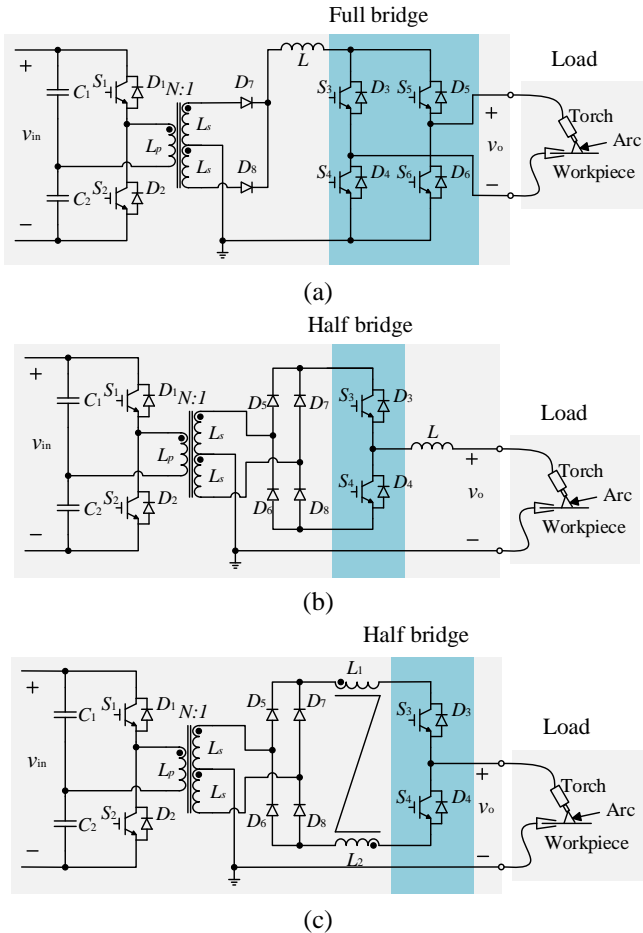


Fig. 2. Circuit diagrams (a) full bridge inverter, (b) half bridge inverter with single inductor, and (c) half bridge inverter with coupled inductor, as the second stage inverter in the AC TIG welding machine application.

This paper is organised as follows. In section 2 the half bridge inverter with single inductor is discussed and an auxiliary current path circuit is proposed for voltage spikes reduction and safe operation. In section 3, the operation of the half bridge inverter with coupled inductor is analysed and the factors that determine the changing rate of the output current and the current transformation ratio in the coupled inductor is derived and discussed. Finally, conclusions are provided within Section 4.

2 Half bridge inverter with single inductor

The operation of the second stage half bridge inverter with single inductor can be illustrated by some key waveforms as shown in Fig. 3. As shown in Fig. 2(b), there is no current path

when S_3 or S_4 turns off. Therefore, as shown in Fig. 3, S_1 and S_2 need to be turned off for a few cycles to let the output current drop to zero before turning off S_3 or S_4 . Otherwise, a large voltage spikes will be generated across S_3 and S_4 and cause damage. Ideally, S_3 or S_4 turns on or off when the inductor current reaches zero. After that, S_1 and S_2 start to operate again to transfer power to the load.

However, it is difficult to estimate the time when the inductor current reaches zero during operation. Therefore, there are three scenarios. Case 1 is ideal as shown in Fig. 3. In case 2, S_3 and S_4 turns on or off after the inductor current reaches zero. In case 3, S_3 and S_4 turns on or off before the inductor current reaches zero. When it is in case 3, the remaining inductor current can still cause large voltage spikes across S_3 and S_4 .

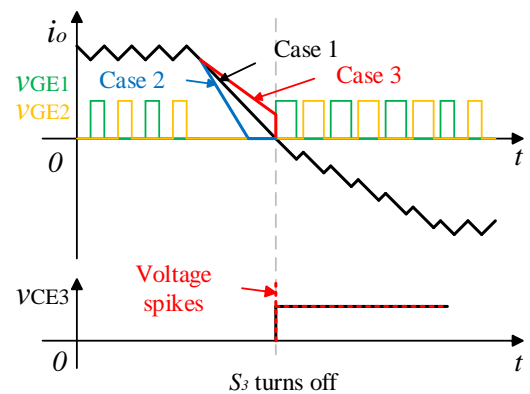


Fig. 3. Key waveforms of the operation in the second stage half bridge inverter with single inductor.

To solve this problem, the output current can be compared with zero to indicate the time when S_3 and S_4 can operate. This paper proposes another approach that is simple in implementation and robustness.

In this method, a capacitor, C_a , and a resistor, R_a , are added across the half bridge switches as shown in Fig. 4. These two components provide a current path when S_3 or S_4 turns off. When S_3 turns off, the current will go through C_a and D_4 as indicated in red arrow line in Fig. 4. When S_4 turns off, the current will go through D_3 and C_a in dashed red arrow line. At the same time, the energy stored in C_a is discharged by R_a as indicated in blue arrow line.

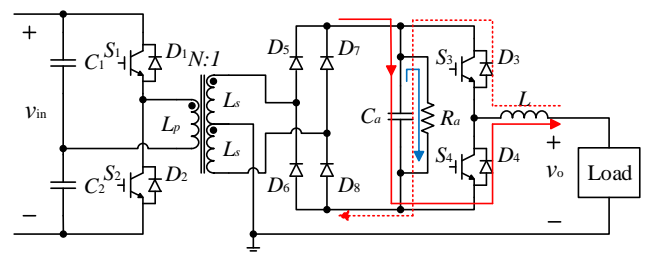


Fig. 4. Circuit diagram of the half bridge inverter with an auxiliary current path circuit.

A prototype machine as shown in Fig. 5 was built to verify the effectiveness of this method. In the experiment setup, $v_{in} = 310V$, $N = 2$, $L = 30\mu H$, $C_a = 40\mu F$, $R_a = 1.2k\Omega$, and the output current, $i_o = 50A$. The experimental results are shown in Fig. 6. From Fig. 6, it can be found that even though the output current, i_o , which is the same as the inductor current, i_L , is about 25A when S_3 turns off, there is no voltage spikes across S_3 .

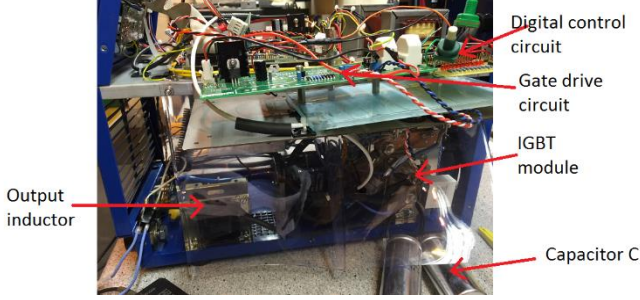


Fig. 5. Experimental setup of the half bridge inverter with single inverter.

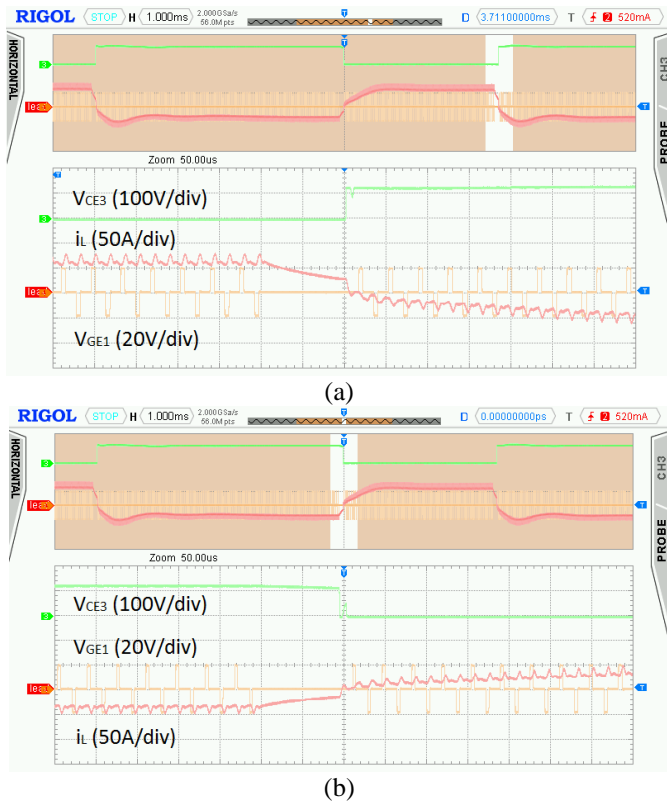


Fig. 6. Waveforms of collector-emitter voltage of S_3 , v_{CE3} , gate-emitter voltage of S_1 , v_{GE1} , and inductor current, i_L (a) zoomed-in diagram when S_3 turns off, (b) zoomed-in diagram when S_3 turns on.

3 Half bridge inverter with coupled inductor

As can be found in Figs. 3 and 6, the half bridge inverter with single inductor topology has slow changing rate of the output

current during the change of the polarity. This is because, when the output current changes direction, the magnetic flux of the output inductor will change the direction as well. Therefore, in this topology, auxiliary circuit is required to provide high pulse voltage on the output voltage just after the change of the polarity to keep the arc.

In order to achieve high changing rate of the output current during the change of the polarity, half bridge inverter with coupled inductor has been proposed as shown in Fig. 2(c). L_1 and L_2 are the output inductors and they share the same magnetic core. A circuit diagram with more details is shown in Fig. 7. As shown in Fig. 7, L_1 is the leakage inductance of L_1 and L_2 . L_c is the parasitic inductance of the welding cable. When S_3 turns off, there is no current path to conduct the current in L_1 and L_c . Therefore, similar to the solution for half bridge inverter with single inductor topology, an auxiliary current path circuit is required to be added across the second stage half bridge circuit. As shown in Fig. 7, C_b and R_b consist the main part of the auxiliary current path circuit.

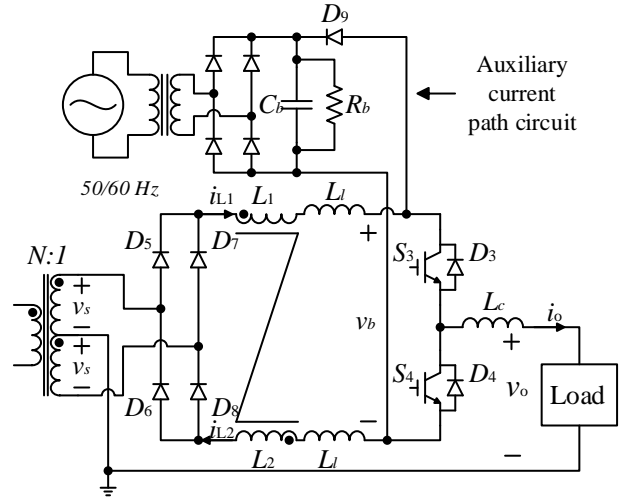


Fig. 7. Second stage half bridge inverter circuit with coupled inductor and the auxiliary current path circuit.

The operation of the circuit can be illustrated in Fig. 8. The switches, S_1 and S_2 , in the first stage half bridge DC/DC converter turn on and off to transfer the power to the secondary side of the transformer. Before t_1 where S_3 is on, the current flows from the secondary side of the transformer to the load through D_5 and D_7 , L_1 , L_l , S_3 , and L_c , i.e., $i_o = i_{L1}$, and $i_{L2} = 0$. During this time, L_1 works as an output inductor to smooth the output current. At t_1 where S_4 turns on and S_3 turns off, the current stored in L_1 transfers to L_2 due to the effect of the magnetic flux in the inductor core. Then, the current flows from the load to the secondary side of the transformer through S_4 , L_l , L_2 , and D_6 and D_8 , $i_o = -i_{L2}$, and $i_{L1} = 0$. During this time, L_2 works as an output inductor to smooth the output current. At t_3 , S_3 turns on and S_4 turns off, the current stored in L_2 transfers to L_1 and repeat the above procedure. Due to the fact that the current in L_1 or L_2 can be transferred to each other

very quickly, the changing rate of the output current can be very fast.

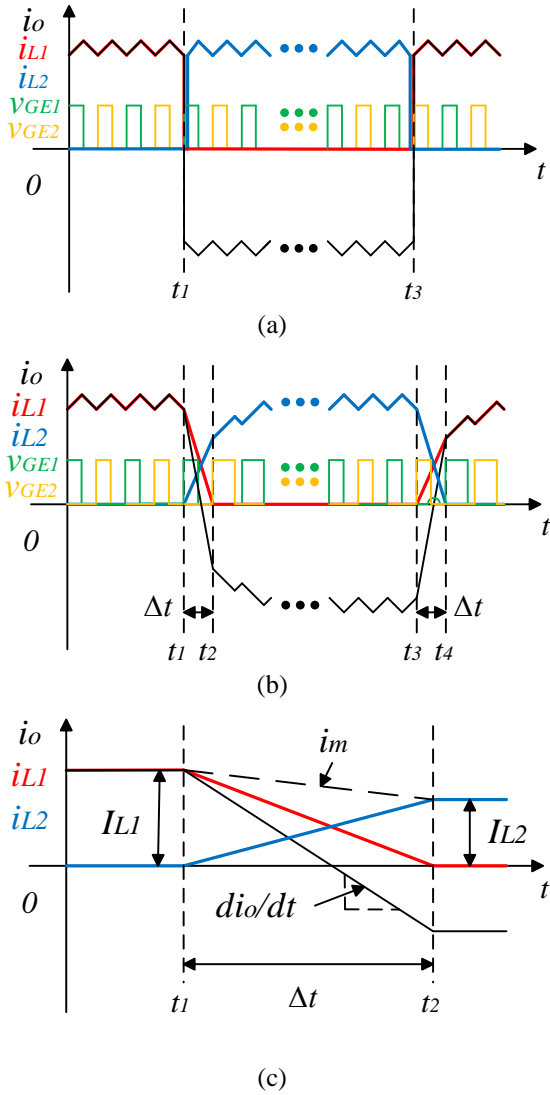


Fig. 8. Waveforms of the output current, i_o , the current of L_1 , i_{L1} , the current of L_2 , i_{L2} , the gate-emitter voltage of S_1 , v_{GE1} , and the gate-emitter voltage of S_2 , v_{GE2} . (a) in ideal operation, (b) in real operation, and (c) the details of the waveforms in the real operation from t_1 to t_2 .

In the ideal situation, $L_c = 0$, and the coupling factor of L_1 and L_2 is 1, i.e., $L_l = 0$. In this case, the current transfer between L_1 and L_2 at t_1 and t_3 will be instantaneously as shown in Fig. 8(a). However, in the real situation, due to the effect of L_l and L_c , it takes a certain time, Δt , for the output current to change the direction during the change of the polarity as shown in Figs. 8(b) and 8(c). In addition, at t_2 , i_{L2} is less than i_{L1} at t_1 , i.e., the current in the L_1 is not fully transferred to L_2 . As a result, the output current loses its amplitude during the change of the polarity. Due to the fact that high value of di_o/dt during the change of the polarity is important to the continuity of the arc, and the high current transformation ratio in the coupled

inductor is also desirable. Therefore, it is worth of investigating the factors that determine these specifications.

In the steady state operation, either L_1 or L_2 in Fig. 7 works as an output inductor to smooth the output current. In the transient operation during the change of polarity, L_1 and L_2 work as a transformer. In order to investigate this problem, Fig. 7 is simplified into a circuit as shown in Fig. 9. As shown in Fig. 9, L_1 and L_2 are illustrated by a transformer with leakage inductance L_l on each side and L_m as the excitation inductance. i_m is the excitation current.

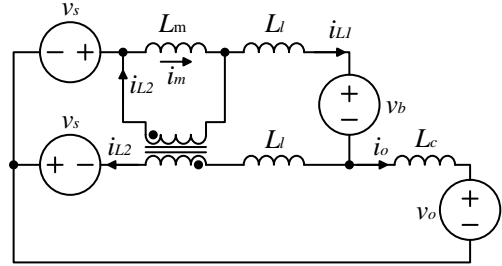


Fig. 9. Simplified circuit of the second stage half bridge inverter circuit and the auxiliary current path circuit during the change of the polarity.

From Fig. 9, by KVL and KCL, the following relationships can be obtained.

$$v_b - 2v_s + L_l \frac{di_{L1}}{dt} + L_m \frac{di_m}{dt} + L_l \frac{di_{L2}}{dt} + L_m \frac{di_m}{dt} = 0 \quad (1)$$

$$L_m \frac{di_m}{dt} + L_l \frac{di_{L2}}{dt} - v_s = L_c \frac{di_o}{dt} + v_o \quad (2)$$

$$i_o = i_{L1} - i_{L2} \quad (3)$$

$$i_m = i_{L1} + i_{L2} \quad (4)$$

By substituting (3) and (4) into (2), we can get

$$\frac{di_{L2}}{dt} = \frac{(L_c - L_m) \frac{di_o}{dt} + v_s + v_o}{2L_m + L_l} \quad (5)$$

By substituting (3)-(5) into (1), we can get

$$\frac{di_o}{dt} = \frac{-v_b - 2v_o}{L_l + 2L_c} \quad (6)$$

From (6), it can be concluded that

1. The changing rate of the output current, i_o , during the change of polarity has proportional relationship with v_b and v_o . Due to the fact that v_o is dynamic during the change of polarity and is relatively small. Therefore, the changing rate of i_o dominantly has proportional relationship with v_b .
2. The changing rate of i_o has inverse proportional relationship with L_l and L_c .
3. The changing rate of i_o does not have relationship with v_s . Therefore, it is not necessary to control v_s by controlling S_1 and S_2 during the change of polarity.

4. The changing rate of i_o does not have relationship with L_m . However, there is compromise in the design of L_m . Because, given that the coupling factor of the coupled inductor is fixed, large L_m can provide small output current ripples, but at the same time, the leakage inductance, L_l will be large.

In general, in order to obtain high value of di_o/dt , L_l and L_c must be kept as low as possible. In addition, v_b can be kept high. Therefore, in the design of the auxiliary current path circuit as shown in Fig. 7, v_b can be kept to a high value by an external voltage source.

An experiment prototype has been built to verify the effectiveness of the analysis. In the experiment setup, $v_{in} = 310V$, $N = 2$, $L_1 = L_2 = 30\mu H$, $v_b = 310V$, and $i_o = 50A$. The experimental result is shown in Fig. 10. From Fig. 10, it can be seen that di_o/dt is about $7A/\mu s$ which meets the requirement and is much faster than the value of di_o/dt as shown in Fig. 6.

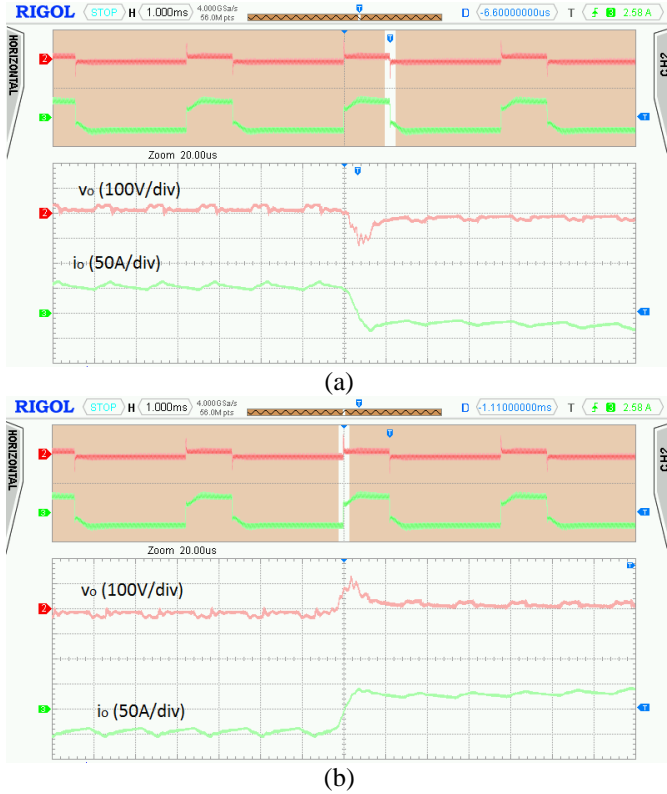


Fig. 10. Waveforms of the output voltage, v_o , and the output current, i_o , (a) zoomed-in diagram when S_3 turns off, (b) zoomed-in diagram when S_3 turns on.

In addition to the analysis of di_o/dt , another concern in the AC TIG welding are that how many percentage of the current can be transferred between L_1 and L_2 , and how to improve it. It can also be derived from the equations (1)-(4).

By substituting (3) and (4) into (1), we can obtain

$$\frac{di_{L1}}{dt} = \frac{(L_c + L_m + L_l) \frac{di_o}{dt} + v_s + v_o}{2L_m + L_l} \quad (7)$$

By substituting (6) into (7), we can get

$$\frac{I_{L1}}{\Delta t} = \frac{di_{L1}}{dt} = \frac{(L_c + L_m + L_l) \frac{-v_b - 2v_o}{2L_c + L_l} + v_s + v_o}{2L_m + L_l} \quad (8)$$

By substituting (6) into (7), we can get

$$\frac{I_{L2}}{\Delta t} = -\frac{di_{L2}}{dt} = \frac{(L_m - L_c) \frac{-v_b - 2v_o}{2L_c + L_l} - v_s - v_o}{2L_m + L_l} \quad (9)$$

From (8) and (9), we can get

$$\frac{I_{L2}}{I_{L1}} = \frac{(L_m - L_c) \frac{v_b + 2v_o}{2L_c + L_l} + v_s + v_o}{(L_c + L_m + L_l) \frac{v_b + 2v_o}{2L_c + L_l} - v_s - v_o} \quad (10)$$

By rearranging (10), we can get

$$\begin{aligned} \frac{I_{L2}}{I_{L1}} &= \frac{(L_c + L_m + L_l) \frac{v_b + 2v_o}{2L_c + L_l} - v_o - v_b + v_s}{(L_c + L_m + L_l) \frac{v_b + 2v_o}{2L_c + L_l} - v_o - v_s} \\ &= \frac{x - v_b + v_s}{x - v_s} \end{aligned} \quad (11)$$

where,

$$x = (L_c + L_m + L_l) \frac{v_b + 2v_o}{2L_c + L_l} - v_o$$

In order to make $I_{L2} = I_{L1}$,

$$v_b = 2v_s \quad (12)$$

This conclusion can also be proofed by Fig. 9 and Equation (1).

From (1) and (4), we can get

$$v_b - 2v_s + (2L_m + L_l) \frac{di_m}{dt} = 0 \quad (13)$$

In order to make $di_m = 0$, Equation (12) must be fulfilled.

From Equation (12), Fig. 8(c), and Fig. 9, it can be concluded that the percentage of the current transferred between L_1 and L_2 is related to v_b and v_s . v_s needs to be equal to $0.5v_b$, to make 100% current transfer. However, in the welding machine application, v_s is an AC square waveform with about 75V peak amplitude, while v_b needs to be kept high, for example, 310V, to increase di_o/dt as explained above.

To address this problem, extra voltage sources, v_a , can be added across the rectifier as shown in Fig. 11. In Fig. 11, $v_a = 0.5v_b > v_s$. During the change of polarity, switches S_5 and S_6 will be turned on for a few micro-second. During this time, v_a can replace v_s in Figs. 7 and 9, as a result, the current in L_1 and L_2 can be fully transferred to each other.

A simulation circuit of the second stage half bridge inverter circuit with extra voltage sources circuit as shown in Fig. 11 was built in LTspice, and the simulation results were exported and plotted in Matlab as shown in Fig. 12. From Fig. 12, it can be found that only about 65% of current transferred from L_1 to L_2 when it is without the extra voltage sources circuit. In comparison, with the extra voltage sources circuit, about 100% current can be transferred.

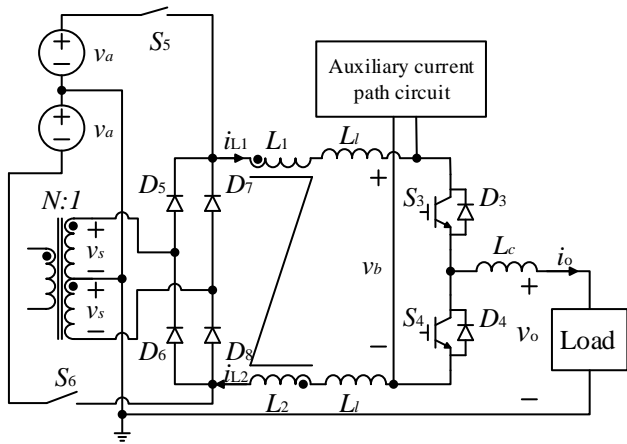


Fig. 11 Second stage half bridge inverter circuit with extra voltage sources circuit.

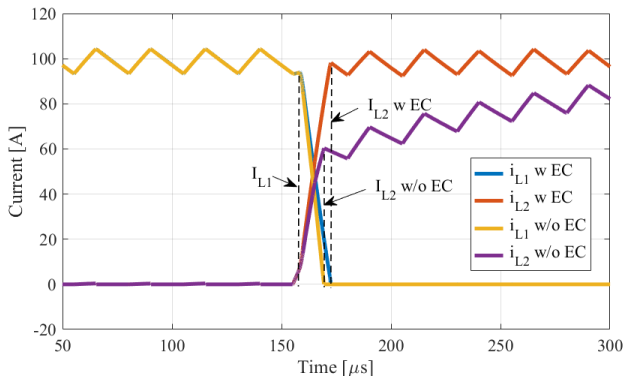


Fig. 12 Waveforms of i_{L1} and i_{L2} with and without the extra voltage sources circuit.

4 Conclusions

In this paper, two half bridge inverter topologies as the second stage inverter circuit have been investigated. In comparison, the half bridge inverter topology with coupled inductor can achieve much faster changing rate of the output current, therefore, it can maintain the arc without extra voltage boost circuit for re-ignition. Investigations have been made to derive that v_b can be kept high to increase the changing rate of i_o . In addition, analysis has also been made to show that both v_b and v_s can affect the current transferring in the coupled inductor. Larger v_b can result in less current transferring. Therefore, in this paper, an extra voltage sources circuit has been proposed to overcome the problem. In this circuit, extra voltage source, v_a , is added across the rectifier, replacing v_s during the current transferring. Therefore, with this circuit, v_b can be kept high to achieve fast changing rate of i_o , meanwhile, v_a can be designed to achieve high percentage of the current transferring in the coupled inductor.

Acknowledgements

The authors would like to thank Innovate UK and Newarc Ltd. for their support.

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