Arc Controllers for TIG Welding Applications : A Review

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ABSTRACT

An arc welding joint could utilize the features of discretely different arc welding methods to obtain the desired joint characteristics. The continuous improvement in arc welding controllers has helped redefine the need of proper parametric control of the process. For efficiency and productivity improvement, modern arc controllers come handy to re-define various aspects of the process (e.g. metal transfer, arc stiffness, etc.). One fascinating outcome is the virtual convergence of complete multi-functional arc welding process to GMAW. Still, there are applications where SMAW and TIG welding processes are regularly being used. Like other welding methods, TIG welding, as well, consists of several derivative approaches. For example, for creating joints of reactive metals (aluminum or magnesium), the AC-TIG welding is commonly employed. Here, the role of arc controller is to generate consistent pattern of desirable rectangular shape AC current waveform through the arc gap. It could cause severe stress (during polarity transition) in all secondary side components of the controller. This review, using indigenously designed peripheral interface controller (PIC) based arc welding inverter, explains the role of arc controllers to handle issues of majority of TIG welding applications.

Keywords: Gas metal arc welding; shielded metal arc welding; alternating current tungsten inert gas welding; HF TIG; arc shape control; joining reactive metals.

1.0 INTRODUCTION

The arc welding process is used to create metal joints. Based on characteristics of arc and metal transfer modes, the process consists of several methods. Each method [1-2] carries certain benefits. Since its introduction for control of arc energy as well as for controlled metal transfer, the growth of GMAW method has been phenomenal and steady. The process is most productive, energy efficient and welder and automation friendly [1-4]. It is continuously being fine tuned for further improvement. Still, due to its overall simplicity and lower cost of infrastructure, the SMAW process is preferred in many applications. Similarly, in many applications, TIG welding process [5-19] is preferred to obtain desired joint characteristics for joining stainless steel. AC-TIG [16-19], on the other hand, is used to create welding joints using reactive metals.

The electric arc is the source of heat energy and arc force. They could be effectively changed dynamically by controlling the waveform of current and arc voltage of weld gap. To suit applications suitably and based on the waveform pattern required for current and voltage of arc the TIG welding process is sub-divided into four major derivative methods. They are,

1. DC TIG
2. Pulse TIG,
3. High frequency (HF) TIG
4. AC TIG

In TIG the majority of joints are made using DC current (DC TIG). When joints are created using DC current the energy transferred to the weld pool is not controlled. Particularly, to make good weld joint on thin sheets, the DC current is often pulsed (Pulsed TIG) at low frequency to control the energy input. And to increase the arc efficiency and process productivity with increased depth of penetration the pulsing frequency is drastically increased to several kHz (in HF TIG) [10-15]. The methods mentioned above are, in general, unsuitable for welding reactive metals where reactions take place between the molten weld metal and the ambient atmosphere. This makes an insulated slag thereby putting obstacles to subsequent welding operation. This slag requires removal from the weldment continuously. If welding is done using AC current, removal of slag through passing current in opposite (reverse) direction becomes inherent to the system. The magnitude and width of current within each polarity are corresponding to the AC characteristics of current. The width of current pulse for removing slag is relatively smaller. The current waveform is mostly rectangular.

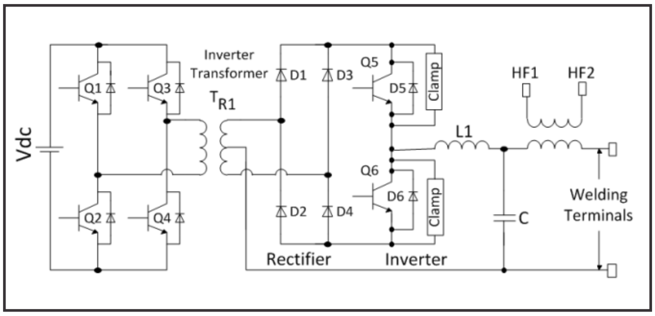


Fig. 1 : Schematic diagram of power controller to feed TIG arc

Fig. 1 shows the schematic diagram of power circuit capable of feeding the arc gap for majority type of TIG welding applications. The origin of current control is activated at the primary side by using an inverter technology. **Table 1** illustrates the pattern, popularly used, for gating different power switching devices of **Fig. 1**. Transformer TR2 is used to ignite the arc gap for arc initiation while welding in non-contact mode.

Table 1 : Switching Logic of Power Devices

Devices	Q1-Q4	Q5	Q6
DC TIG	ON	OFF	ON
Pulse TIG	ON	OFF	ON
HF TIG	ON	OFF	ON
AC TIG - Welding	ON	OFF	ON
AC-TIG Cleaning	ON	ON	OFF

This article, through practical analysis, details the basic design approach of arc controller to cater the complete application range of TIG welding applications. The application range gets wider through use of different shielding gas mixtures as well. It further elaborates an already designed controller to meet a few of these applications. The flow of the article is as follows: Section 2 discusses arc initiation mechanism. Section 3 details the process characteristics for controlled actuation of complete TIG welding process. It, as well, discusses and practically demonstrated the DC TIG and low frequency pulsed TIG welding. Section 4 elaborates the functioning of HF TIG welding process. Finally, Section 5 details the operation, control and practical implementation of AC TIG welding process using 300A rated power controller.

2.0 ARC INITIATION AND RE-IGNITION

Stable arc is pre-requisite to make quality welding joints. Welding arc is said to be established when desired current pattern is maintained at a particular arc voltage (arc length >0). The arc ceased to exist when either current or arc length is zero.

To protect the tungsten electrode from erosion and oxidation, whenever the electrode touches the weld pool or work piece the inverter is switched off. Therefore, to protect the life of electrode the process is not self-starting type. It functions in non-contact mode [9]. The process needs an external support to initiate the welding. The arc is initiated by applying burst of high voltage pulses to arc gap whose frequency is very high [8], [9]. In majority of TIG welding applications, the ignition circuit is energized only once per welding cycle. The ark striking phase should be small because it emits lot of electromagnetic radiations. Typical arc striking circuit is shown in **Fig. 2**. The high-frequency soft-switched primary circuit charges the capacitor C2 to high voltage. When its voltage crosses the breakdown voltage of GDT (gas discharge tube), it discharges through TR2 **(Fig. 1)**.

In AC TIG welding, the problem of maintaining stable arc gets aggravated because during polarity reversal of current wave the arc gets extinguished in each half-cycle. Literally, the process needs extra support for re-ignition twice in each cycle. The problem is severe because, at large current, the energy stored in inductor L1 **(Fig. 1)** and in inductance of welding cable prior to current reversal is large. There are circuit topologies with switching pattern [15], [17] available to divert this energy to the arc gap along with taking care of self re-ignition. The preferred is to utilize the energy in the weld gap [15], [17] in such a manner that it assists the arc re-ignition process. However, assistance of arc initiator is recommended for wide range applications (10-500A) using different shielding gas mixture. Self re-ignition under He shielding, in particular, is difficult because it needs much larger voltage to sustain arc. The characteristic of stable arc under different environment is shown in **Fig. 3**. Current reversal could as well be problematic when the waveform is different from square wave.

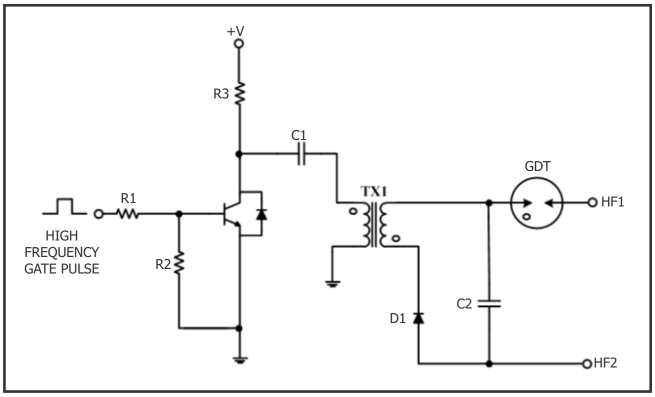


Fig.2 : Soft-switched flyback converter based hybrid (active + passive) arc initiation circuit. [GDT: Gas discharge tube]

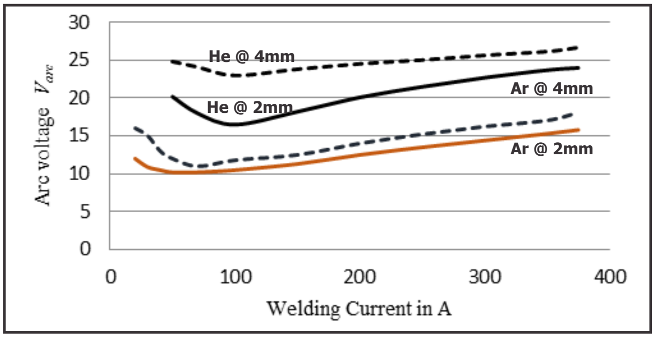


Fig. 3 : TIG arc depending on shielding environment and arc length

2.0 PROCESS CHARACTERISTICS FOR TIG

In TIG the joints are made using energy in arc. The process does not involve metal transfer from the electrode. It mostly follows the constant current arc characteristics. Considering that the issues of arc initiation is resolved then the control of the process involves, primarily, current control whose waveform pattern, depending upon applications, changes. The control involves maintaining the desired arc decided by the joint characteristics. The expression of arc at particular welding current Ia is characterized by the following expression.

$$V_{arc} = V_{AC} + +Eh + R_a I_a \qquad \text{... (1)}$$

V_{arc} is arc voltage, and its parameters are constant voltage drop V_{AC}, arc length (h) factor E and arc resistance R_a. The value of each parameter could change with arc temperature, operating point of arc and shielding **(Fig. 3)**. In TIG the shielding mostly consists of helium, argon or suitable combination of both. **Table 2** [12] lists down the value of arc parameters under two popular gas shielding.

Table 2 : Arc Parameters and Shielding Gas

Shielding	I_a (A)	V_{AC} (V)	E(V/mm)	Ionizing Potential (eV)
Argon	100	13.4	≤1.0	15.8
Helium	140	16.7	2.0	24.6

Compared to GMAW process, in TIG welding, the current density used in the electrode is much less. Moreover, there is no metal transfer involved. For a particular speed R (mm/s) of tungsten tip the heat input H (J/mm) per unit length to weld pool is expressed as

$$H = \frac{\eta V_{arc} I_a}{R} \qquad \text{... (2)}$$

Where η is arc efficiency. To guarantee controlled heat input H, the TIG process require constant current arc. Further fine control is possible by adopting suitable pulsing technique.

By applying open circuit voltage V_{oc} (available at collector of Q6 in **Fig. 1**) to deliver power to arc, the dynamic equation for controlling the first order constant current DC TIG process is

$$V_{oc} = (L_1 + L_C)\frac{dI_a}{dt} + (R_S + R_C)I_a + V_{arc} \qquad \text{... (5)}$$

L_1 and L_C are inductance of controller and high frequency ignition circuit respectively. R_S and R_C are resistance of power controller and welding cable respectively. Input to the process V_{oc} is related to power controller through the duty cycle D of the inverter,

$$V_{oc} = \frac{DV_{dc}}{n} = DV_{OC}(\max) \qquad \text{... (6)}$$

V_{dc} is voltage of DC bus (**Fig. 1**), n is turns ratio of transformer TR_1 and V_{OC}(max) is maximum value of V_{OC}. The objective of the controller is to actuate the duty cycle D to achieve requisite control of dynamic profile of current I_a. The power control objective of DC TIG and Pulsed TIG is quite different from that HF and AC TIG, because they need fast response time. For AC TIG, in particular, the re-ignition of arc, during polarity reversal of current in each half cycle, is essential.

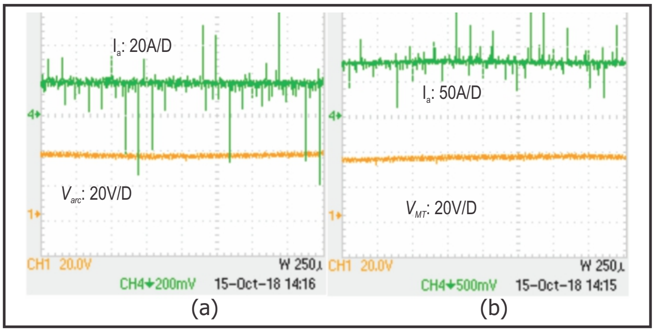
The waveforms of V_{arc} and I_a for two DC TIG applications are shown in **Fig. 5**. The welding was performed using 20 KHz, 400A full-bridge inverter suitable for majority of TIG welding applications. The indigenous power controller suitable for many TIG welding applications is shown in **Fig. 4**. The details of the power controller is listed in **Table 3**.

Table 3 : Parameters of Power Controllers

D_{max}	0.9	D1, D2	150EBU04, 3 each
Ratio TR1	21:3:3	Q1-Q4	2MBI075VA-120
V_{OC}(Max)	80V	Q5, Q6	SKM600GB060
$L_1 + L_C$	35 µH	Max. value of f_{AC}	150 Hz
f_s	20 kHz	D5, D6	400A, 600V

Note: f_{AC} is frequency of current in AC welding

Fig. 4 : Water-cooled 300A power controller for multi-functional TIG welding applications



(a) (b)

Fig. 5 : Waveforms of V_{arc} and I_a while welding in DC TIG mode, at, (a) 20A; (b) 75A. [Time axis: 250ms/D]

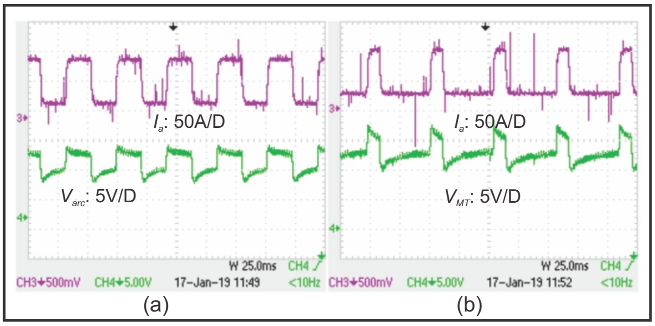
For constant current arc, it is difficult to have control on V_{arc}. The power to the arc or the heat input H (2) to weld pool is uncontrolled. At large current, it could create quality issues in many applications. For better control of joint characteristics low frequency pulsing of current (<50Hz) is employed. In pulse mode the pulse frequency f_{Pulse} is decided by the following relation,

$$f_{Pulse} = \frac{1}{t_p + t_b} \qquad \text{... (3)}$$

Where t_p and t_b are peak and base time respectively and during those two time intervals the respective values of current are I_p and I_b. Then the heat input H_{pulse} could be expressed as,

$$H_{pulse} = \frac{\eta f_{Pulse}}{R}(V_p I_p t_p + V_b I_b t_b) \qquad \text{... (4)}$$

V_p and V_b are value of V_{arc} during t_p and t_b respectively. **Fig. 6** shows the waveforms of arc gap variables, for two applications, during low frequency pulsing.



(a) (b)

Fig. 6 : Waveforms of V_{arc} and I_a while welding using Pulsed TIG mode at f_{Pulse}: 25Hz with, (a) I_p: 100A, I_b: 30A @duty cycle: 50%, and (b) I_p: 100A, I_b: 30A @duty cycle: 30%. [Time axis: 25 ms/D]

2.0 HF TIG WELDING

If the pulse repetition frequency f_{Pulse} in Pulse-TIG is increased many fold to several kHz then it is considered that the welding operation is performed under HF TIG mode. HF pulsing helps increase the arc force and the arc shape is constricted, making it more directional; thereby the weld penetration is deeper and the heat affected zone is much smaller. The productivity is enhanced with improved energy efficiency and joint quality. For a particular HF TIG application [11] the impact of frequency of current pulsing on arc force and weld appearance is listed in **Table 4**.

In HF TIG welding, the effective current I_{eff} (**Table 4**) is expressed as

$$I_{eff} = \sqrt{D_{Pulse} I_p^2 + (1 - D_{Pulse}) I_b^2} \qquad \text{...(7)}$$

Where D_{pulse} is the duty cycle of each HF pulse and is expressed as

$$D_{Pulse} = \frac{t_p}{t_p + t_b} \qquad \text{...(8)}$$

The frequency of current I_a in HF TIG is high, could be upto several tens of kHz [7]. The controller design for such waveform control is complex. During transitions from I_b to I_p and vice versa, the transient response of I_a in high frequency current pulsing should be very fast. It needs a highly sophisticated controller with a capacity to achieve the current slew rate of the order at 50A/µs or more. The slew rate of current of arc controller of **Fig. 1** is expressed as

$$\frac{dI_a}{dt} = \frac{1}{L_C + L_1}(V_{OC} - (R_S + R_C) I_a - V_{arc}) \qquad \text{...(9)}$$

Apparently, for controller of **Fig. 1**, large slew rate could ideally be achieved through proper choice of V_{OC} and its actuation mechanism and (L_1 + L_C) of which L_C resides outside the controller. There are three approaches adopted in industry to achieve the desired slew rate of current, they are:

1. Secondary control by configuring the secondary side to behave as chopper controller (**Fig. 1**)
2. Primary control in the inverter; in this mode the power circuit of **Fig. 1** could be used. However, the switching frequency of the inverter needed is large [20]-[21] to cater moderate range of HF TIG upto a few kHz. The topology could achieve slew rate upto 5A/µs.
3. Employing two inverters [11] – one (Inv_b as shown in **Fig. 7**) for feeding the base current and the other for supplying peak current (Inv_p as shown in **Fig. 7**). Using soft switching technique, both inverters operate at very high frequency. For instantaneous current switching, it additionally needs large current switching network, mostly IGBT based, to enable current swing from I_b to I_p and vice versa. The response time of current is small and very large value of slew rate (>50A/µs) of current could be achieved. The power rating of the second inverter is comparatively less as it is used to boost the current during peak time. It needs to maintain the differential voltage to arc.

Depending upon the requirement of applications, moderate value (≤ 5A/µs) of slew rate of current could be achieved by adopting different configuration of power circuit. The bottle-neck for achieving fast response time of I_a comes from the overall inductance the controller faces as well as switching frequency of power controller. For secondary control, it is dictated by L_1 and L_c. In the second case, for primary control, the leakage inductance of TR1 is also included. For moderate value of slew rate first two methods could be useful. Primary control is cost effective, power density of the controller is also large. For $L_1 >> L_C$, the switching frequency of the power controller (either at primary or secondary) helps decide the slew rate. For very high frequency TIG applications the third approach is preferred. In this method the two independent high frequency soft switched constant current controllers (**Fig. 7**) are deployed. The first inverter maintains the arc at constant base current. The second inverter is always enabled, in constant current mode, to feed the differential requirement (I_p-I_b) instantaneously. During current switching, the current in inductor L2 (=L1) is constant.

Table 4 : Arc Force and Weld Appearance: Impact of Frequency of Welding Current

Freq. f_{Pulse} (kHZ)	Condition	Vare (V)	Arc force (mN)	Weld Appearance	
				Depth (mm)	Width (mm)
DC TIG	I_{dc}: 100A	9.8	3.2	2.47	7.61
20	I_{eff}: 98.5A	10.1	9.2	2.81	7.13
40	I_p: 130A	10.3	11.8	2.9	6.8
60	I_b: 50A	10.5	16.0	3.0	6.5
80	D_{pulse}: 50%	10.7	17.1	3.33	6.11

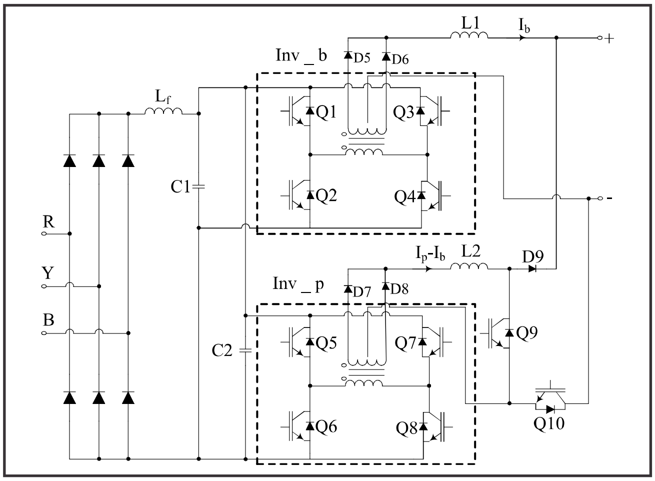


Fig. 7 : Instantaneous current switching circuit for high frequency TIG welding

5.0 AC TIG WELDING

Welding of reactive metals needs alternating current and voltage in the arc gap. The direction of current in is reversed alternately over a wide range of frequency (20Hz $\le f_{AC} \le$ 250 Hz) decided by the features of the joint. When the current is negative the arc energy is used for making a welding joint, and when it is positive then cleaning of oxide layer is performed. The width or duty cycle of current pulse in each half cycle could be different, and so could be their magnitude. The AC waveforms need not be symmetrical.

As shown in **Fig. 1**, the AC TIG welding needs additional secondary side inverter to ensure current reversal. Several design ideas exist for generating requisite AC welding current [14]-[17]. The switching sequences of gate signals of different power devices for both the inverters (**Fig. 1**) are mentioned in **Table 5**. The gating signal of primary and secondary IGBTs and ideal current waveforms are shown in **Fig. 8**. A typical gating circuit to drive Q5 and Q6 for feeding alternating current to arc is shown in 8. Two essential prerequisite for AC welding are:

1. The transition of current during phase reversal should be fast, particularly, for square wave AC welding. The major bottleneck has been the handling of energy E_S stored in the secondary side inductors L1 and Lc
2. The controller needs to ensure re-ignition of arc during current reversal. The requirement of re-ignition is distinctly different in each half cycle. It is relatively much easier for the controller to ensure current reversal when the electrode polarity is changed from positive to negative potential. Prior to this, when the current is positive, for same current, the temperature of the electrode would have been more to help the thermionic tungsten electrode emit thermal electrons when its polarity is reversed. It assists the re-ignition process. However, the work piece does not emit thermal electrons. It makes the re-ignition process difficult when the polarity of electrode is changed from negative to positive.

For one full cycle, the gate waveforms for driving the power controller for AC TIG applications are shown in **Fig. 8**. It also shows the current waveforms having ideal transitions. The inverter at primary operates at high frequency (≥ 20kHz). During current reversal its functioning is disabled and both Q5 and Q6 are switched ON to allow the stored energy in combined inductor freewheel with arc gap. The switching sequence for generating rectangular AC current waveform using secondary side inverter is shown in **Fig. 9**. Overlap time is the time during transition period when both Q5 and Q6 are switched on. In ideal case, once the stored energy is transferred to weld gap the next half cycle begins.

The stored energy E_S prior to the beginning of transition to next half cycle is

$$E_S = \frac{1}{2}(L_1 + L_C)I_a^2 \qquad \text{... (10)}$$

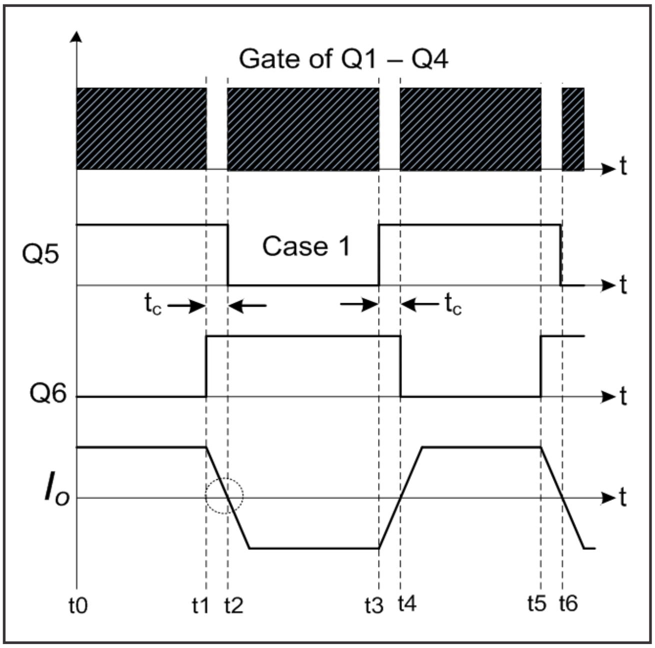


Fig. 8 : Gate signals and desired waveforms of output current in AC TIG welding

Table 5 : Switching Sequence of Power Devices

Duration	Q1-Q4	Q5	Q6	Event(s)
$t_1 - t_0$	ON	ON	OFF	Cleaning oxide layer
$t_2 - t_1$	OFF	ON	OFF	($L_2 + L_C$) discharging + re-ignition + current reversal
$t_3 - t_2$	ON	OFF	ON	Welding
$t_4 - t_3$	OFF	ON	ON	($L_1 + L_C$) discharging + re-ignition + current reversal

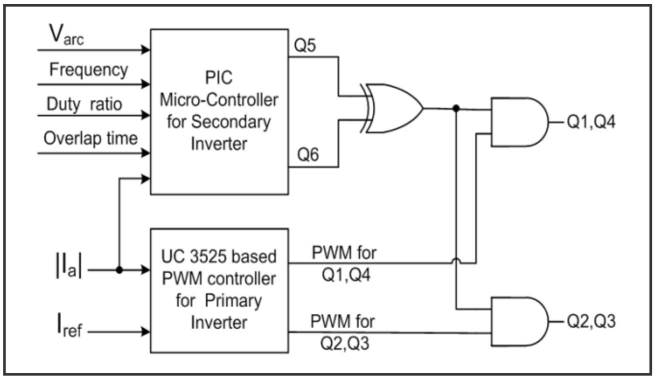


Fig. 9 : Circuit to derive gate trigger signals to drive power devices for AC TIG welding

5.1 Problems in AC Welding

Though AC welding needs low frequency waveforms, its controller design is complex because of following three factors:

1. Fast current reversal with high slew rate of current
2. Handling of stored energy in inductors at the time of current reversal, and, finally,
3. Re-ignition of arc

The inverter of **Fig. 1** is recommended for ideal applications. In actual practice the current waveform of Case 1 (**Fig. 8**) is hardly valid. Rather, chances of occurrence of either Case 2 or Case 3 (**Fig. 10**) is more. In Case 2 the stored energy E_S (10) is exhausted prior to successful transition. It needs exact re-ignition pulses for desired transition that generates quality welding. In Case 3, on the other hand, there is excess energy still available (current is not zero) at the inductor. It would create severe voltage stress in Q5 and Q6. Moreover, the wastage of E_s in each half cycle reduces the efficiency of the controller as well. Improper use of E_S happens because large parametric variations exists, such as,

1. The arc is non-linear (**Fig. 3**), the value of arc parameters depends on operating point of arc
2. Uncertain value and drift in L_1 and L_C
3. Each parameter of V_{arc} (2) changes [12] if shielding environment is changed (**Table 2**). Argon and helium in different combination is popularly used. The parameters also vary with shift in operating point of arc and its temperature.
4. Due to change in ionization potential of shielding mixtures (**Table 2**) the arc stability features are different
5. Uncertain value of L_c caused by length of welding cable, and,
6. In manual process where large fluctuation in arc length h is common, it affects V_{arc} directly.

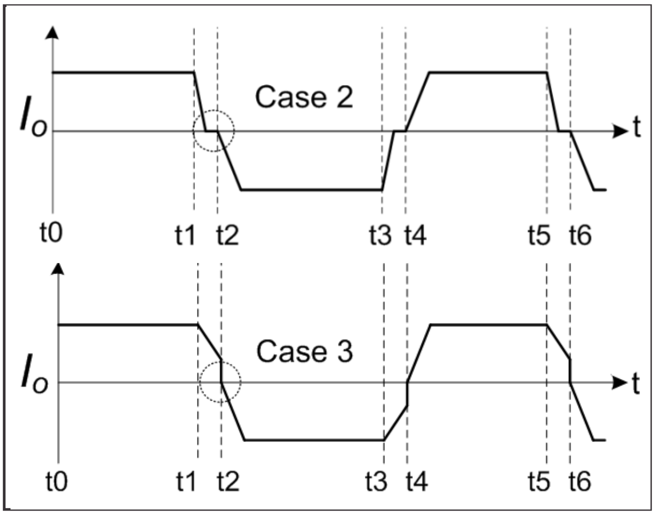


Fig. 10 : AC welding waveforms under non-ideal situations

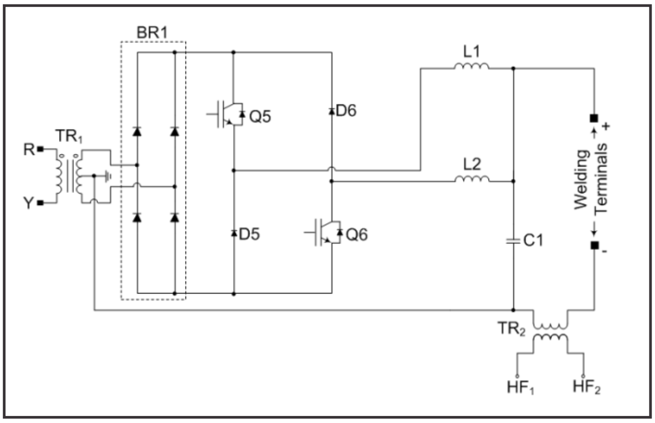
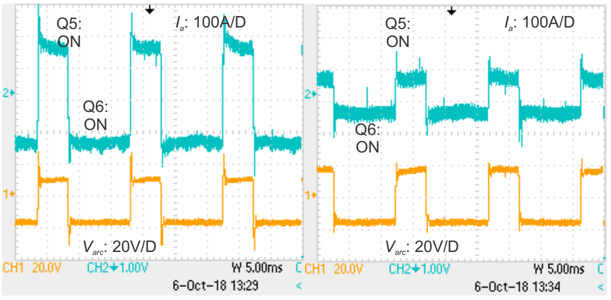


Fig.11 : Schematic diagram of modified secondary side of arc welding controller of Fig. 1

If the secondary side of **Fig. 1** is redesigned through additional use of a few power components, then the problems discussed earlier could be resolved. The modified design for smooth energy efficient AC TIG is shown in **Fig. 11** [15]. The gating signals of **Table 5** as well as its schematic circuit of **Fig. 9** are still valid. The blanking time needed is much less so that Case 3 always exists. Then the current reversal is ensured, depending on the current polarity, by either of D5 or D6.

Certain combination of IGBT Q5 and Q6 and diodes D5 and D6 are used to create requisite AC waveform at the output terminals. However, the secondary power circuit of **Fig. 1** was able to achieve AC welding functions under ideal conditions (**Fig. 8**).

Using AC TIG welding joints were made under argon shielding environment. **Fig. 12** shows the waveforms of arc voltage and current whose conditions are listed in its caption. **Fig. 13** shows one aluminum joint.



(a) (b)

Fig. 12 : Waveforms of arc voltage and welding current in AC welding applications for following conditions : (a) f_{AC} : 70 Hz, duty cycle: 30%, current in both polarity : 80A, and, (b) f_{AC}: 70 Hz, duty cycle: 30%, current in both polarity: 40A

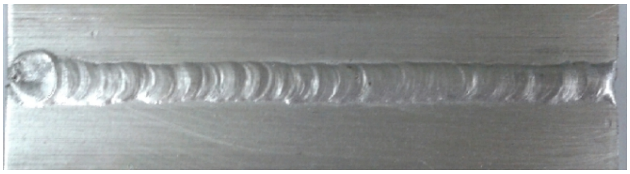


Fig. 13 : Sample of aluminum joint created using AC current and created on 6mm sheets under Argon

6.0 CONCLUSION

TIG welding process and, in particular HF-TIG, is still being used in many critical application areas. The arc characteristics, in each case, differ appreciably and thereby the controller design gets drastically more complex. This article has detailed the basic design criteria of an arc controller capable of feeding the arc gap for all type of TIG welding applications. The article has also discussed the requisite arc initiation mechanism. Along with detailing the characteristic need of the controller, this article, using 300A rated power controller, practically demonstrates the different TIG welding operations for a few applications as well.

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