Solving Critical Issues at Low Current in TIG Welding by Controlling Levels of Saturation at the Input of the Inverter

Arun Kumar Paul & Nimesh Chinoy
Electronics Devices

ABSTRACT

The operating current range for TIG welding is wide. Welding at very low current in TIG mode is common. However, managing low current operation in dynamic situation is critical. High frequency inverter has the extra ability to take care some of these problems to a great extent. To meet such requirement(s), the amplifier for the inverter is normally a 'P+I' controller with large DC gain. The bandwidth of this type of inverters is limited by the presence of lag compensating elements of the controller. However, lag compensator with 'controlled peak current mode control' can develop, to our advantage, 'wind-up' in the controller to bring benefits on the dynamical aspects for TIG welding inverters at lower current setting. This paper would discuss the issues of TIG welding at low operating current and also demonstrate how wind-up is created to eliminate the problematic issues. It is absolutely critical for non-contact TIG welding inverter.

Key Words : Full Bridge Inverter, Low Current TIG Welding, Integral Wind-up, Transition Process.

INTRODUCTION

Arc welding inverter is one of the critical power electronics equipments for the fabrication industry as it provides compact and energy efficient means of performing welding operations with improved current and voltage control features. With the introduction of DSPs or High-end Micro-controllers or with FPGAs in control loop, it is possible to meet with one inverter the characteristic needs of MMA, TIG and MIG. The design and control needs for these configurations, however, are different. MMA and TIG inverters work on constant current mode, whereas MIG inverter needs simultaneous close control on both weld voltage and current. In MMA, the welding characteristics shift with the metallurgical content of a particular electrode. The requirement of minimum welding current in MIG and MMA is around 30Amp, whereas it is necessary for TIG welding equipment to feed the weld gap a stable low current as low as 2-3Amp. Ideally, stable arcing at current much less than 1Amp is practicable. Design issues get complicated to include features of all modes of arc welding into one. Operation of TIG welding inverter is complex due to following reasons:

i) Requirement of wide range (3-400A) of current control

ii) Complex starting mechanism, particularly in non-contact TIG initiation mode, and

iii) Complex working mechanism (Pulse TIG and AC TIG).

The requirement to latch on to stable smooth low current in TIG welding is important due to following reasons:

i) Normal welding at low current value,

ii) At start while in up-slope.

iii) At the end of down slope.

iv) Base current in Pulse TIG welding

v) Near zero crossing in AC welding, and

vi) Smooth transition (in case of high frequency initiation) to welding current immediately after the spark in non-contact TIG operation.

The controller requirement at low current in each case as mentioned above could be different as their operating conditions are different. Parametric uncertainties and their drifts of the analog circuit along with circuit tolerances create problem in achieving smooth control of welding current with small reference (? 3Amp) setting. Ground loop noise at low control reference is also a serious concern. Proper circuit layout is key to have reliable welding there. The current reference is ramped from zero while initiating TIG welding with lift arc feature. Hence, the error voltage even with high gain controller also gets ramp-

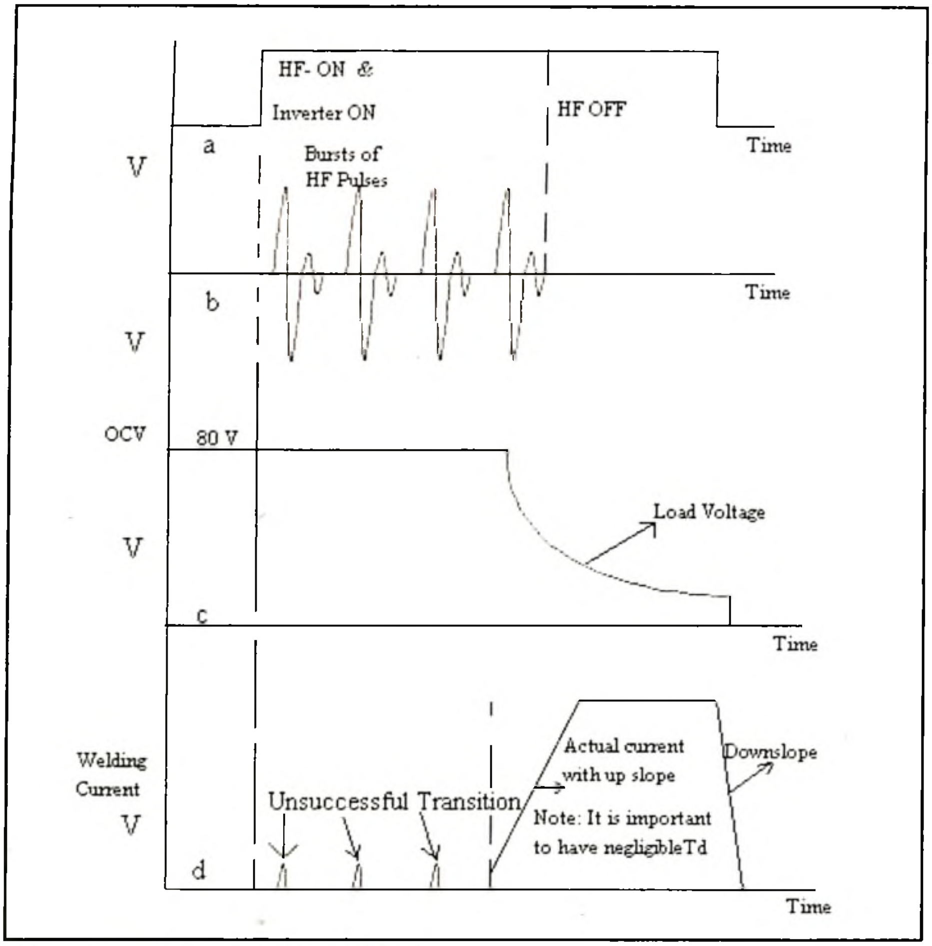

Figure 1. Non-contact TIG welding Sequence

ed up with an intention to avoid current oscillation around reference. Still it is critical for high gain system. Control at small current reference at upslope is important as tungsten electrode is cold during initial start up.

More critical issues are involved in non-contact TIG welding mode. Here, TIG initiation is achieved with the help of high frequency (HF) generator [1] to ionize the weld gap. The duration of HF pulses should be as small as possible. Transition from sparking (spark generator) to arcing (welding inverter) is, therefore, crucial. These two events are controlled by two independent circuits. They have distinctly different characteristics in terms of frequency of signals and time of occurrence. Moreover, transition takes place at low current. The resistance of the weld gap is relatively large even after sparking. In a sense solving the transition process optimally at low current for non-contact TIG welding inverter takes care of all other issues occurring in TIG mode as listed above. There are various approaches [1, 2 and 4] for tackling the transition process. Sequence of non-contact TIG welding process is shown in Fig 1. Sparking till arcing is required to be produced to initiate the welding process. There are topologies available to apply high frequency high voltage waveforms across the gap. Waveforms of three of the commonly used topologies are shown in Fig.2. In Fig.2a, high voltage sinusoidal pulses are continuously applied. In Fig.2b, burst of HF sinusoidal pulses are applied for longer duration and in Fig.2c, one cycle bursts are applied. The transition process is more definite in first two cases. However, they need separate high frequency inverters. High frequency inverters are loss prone and need to be soft-switching type. These 'high frequency resonant' inverters are

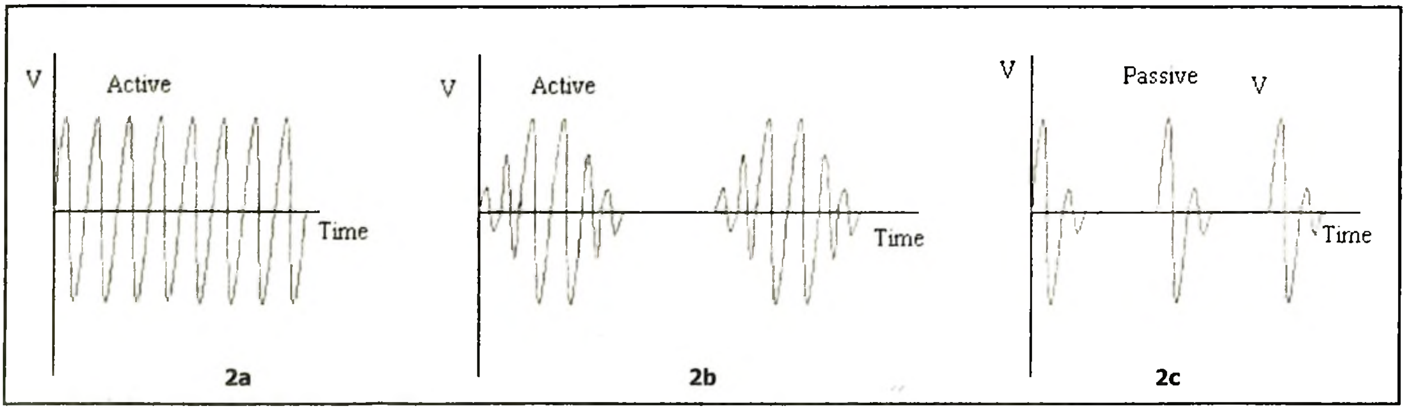

Figure 2a. Continuous Sinewave Actively Control **2b.** Sinewave with burst Actively Control **2c.** Single pulse Passive Controlled

complex and costly. They invite reliability issues as well. The transition process is complicated for the third type though it is simple, compact, reliable and cheap. If single pulse transition is ensured, it is ideal for TIG as HV pulse generation, in such case, is mostly passive [8]. The control and power circuit for HG generation works at low voltage and at low frequency (sometimes 50Hz). In this case soft switched flyback circuit controls the spark generation. We would investigate in this discussion on the impact of control system behavior on initiation and subsequent transition to stable welding at the start of upslope.

CONTROLLER STRUCTURE OF WELDING INVERTER

During welding, fast switching of current and voltage of the welding inverter may not have direct cycle-by-cycle qualitative impact on welding characteristics. The response of end parameters such as energy input to the weld pool, temperature rise etc. is relatively sluggish. The control bandwidth need not be large for such an operating requirement. Still, over the years there have been topological transformations in the design of welding equipment. Since the early days of electric arc welding, the 50/60Hz power source or its controlled rectification has been put to use to feed the welding gap quite efficiently. Subsequently, inverter based equipments have started replacing these rectifiers. With the introduction of soft switching techniques the achieved switching frequency of IGBT based welding inverter is high. The bandwidth of the control system [3] is directly linked to the switching frequency of the inverter. It plays important role in current control and in the transition process. There are other definite benefits of high frequency welding inverters.

A simple schematic circuit diagram of the secondary side of welding inverter is shown in Fig. 3. The inverter is IGBT based with full bridge configuration. The capacitor C_t is more for decoupling the HF unit from the inverter, rather than any DC filtering applications. However, C_t plays a major role during initial transition process. The otherwise insignificant value of C_t helps ignoring one pole in the transfer function of the system. Reduction of one pole makes the controller design simpler. The primary side current transformer (not shown in Fig. 3) 'T_1' is used for protection of IGBTs and it helps in flux balancing in cores. In actual design practice T_1 is programmed to allow maximum rated welding current undisturbed from the equipment.

The designed value of the output inductor 'L', the inverter switching frequency 'f_s' along with arc characteristics in TIG welding mode makes the equipment behave like a current source. As the current range is wide (>100:1) average current mode control topology [5] is more suitable. Current mode control topology provides fantastic line regulation, and is fast and inherently more stable. It provides cycle-by-cycle current limiting. In average current mode control, the welding current i.e. the output inductor current is averaged and is dynamically compensated in an error amplifier to generate control input 'V_c'. 'P + I' compensation network allows the system's states to behave in a sluggish manner. To achieve accurate current control over a wide range, high gain feedback (normally P + I) system [4] is employed. High gain system saturates the amplifier even with small current reference. The high gain current controller with lag compensator causes large current overshoot. The overshoot magnitude is function of current reference value and bandwidth of the controller. It is difficult to add further non-linear compensation [6], otherwise useful at times, on lag network because of wide welding requirement in TIG as well as in MMA modes. Fig. 4 shows apparent behavior of the welding inverter at the beginning of the TIG cycle to various current reference levels. Though there exists a definite sequence for TIG welding process, the eventual process initiation is decided by the sparking moment. Sparking across the weld gap opens the gate for current flow. It is presumed qualitatively that the control input voltage 'V_c' is same (saturated) at start in all cases due to presence of high gain (added with integral action of controller) system. The duration for sparking in capacitor discharge mode is in microsecond(s). However, the bandwidth of the compensated control system of the welding inverter is limited. Hence fast i.e. microsecond level correction to achieve continuous current flow through the weld gap is extremely difficult. It is clear from Fig. 4 that lower the current reference larger is the percent overshoot. This is because the current surge is limited only by the set current limit. Overshoot is associated with undershoot. The undershoot level at very small current reference makes welding current zero. The circuit enters into discontinuous conduction mode. Hence, the arc stops. The system waits for multiple arc-striking i.e. by applying burst of 'HF' pulses. Burst of pulses help as the tungsten gets hotter, and probability of transition improves. Electron emission for tungsten electrode is more at higher temperature. However, multiple arc-striking invites EMI problems and disturbs the controller and nearby equipments.

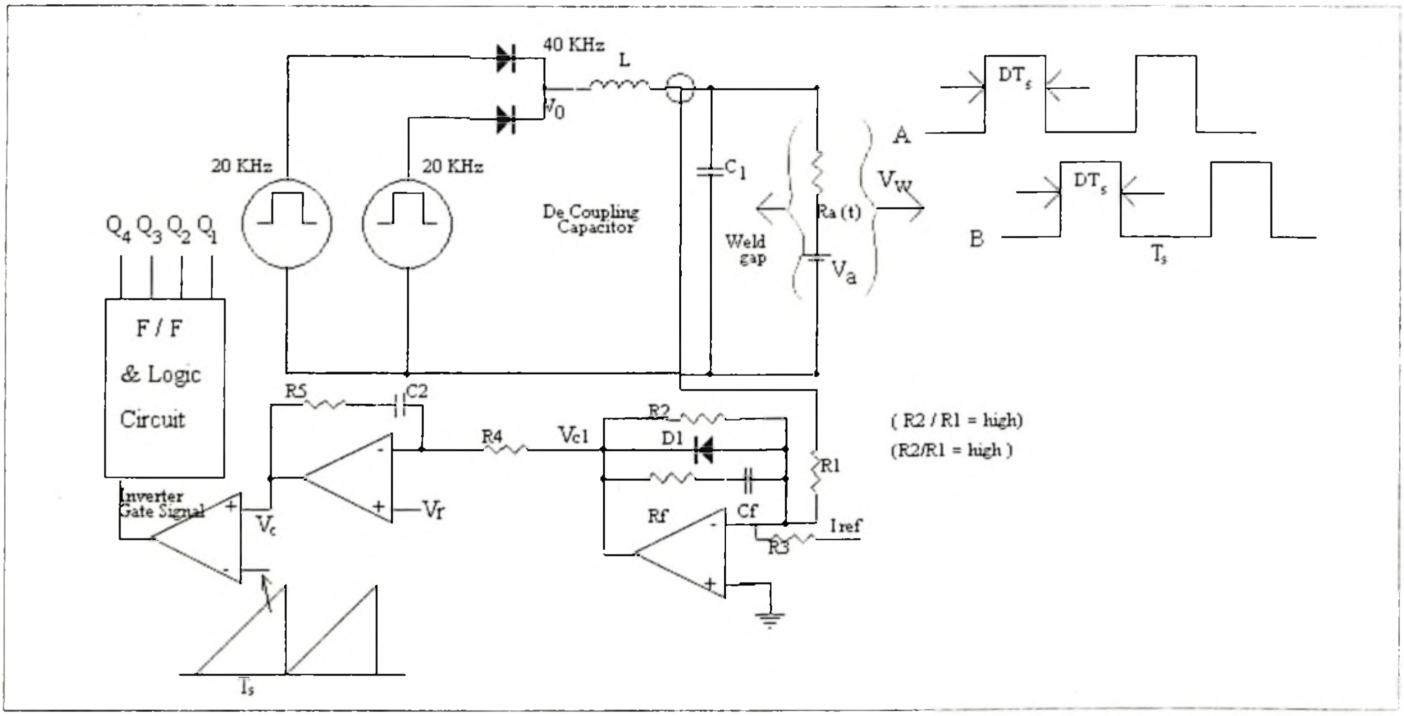

Figure 3. Secondary side of welding inverter

A particular solution to avoid multiple arc-striking has been detailed in [4]. Another possible approach is to effectively latch on to initial transition i.e. by 'C_1'. As discussed earlier, the undershoot value of current at low setting (i.e. the real situation in TIG) stops the arc. It should be avoided in an efficient way. Therefore the job of the controller is to avoid the oscillation at low current level. One approach is to control the gain of the system as control voltage 'V_{C1}' is directly related to the initial error and the DC gain. Gain scheduling approach in the forward path is difficult to activate when the transition process is very fast. The bandwidth does not allow the impact of changed gains to be effective so fast. Other approach [7] is through controlling the saturation levels at the input. The real time pulse-by-pulse input control is realizable through peak current mode control. This is achieved by shouldering another responsibility to current limit protection circuitry which is placed at the primary of the inverter transformer. As per the schematic, average current mode logic is available at the secondary and current limit for IGBT protection is in place at the primary. If we can logically transfer the current limit logic to the secondary, peak current mode control is attainable.

In average current mode control the average duty cycle at low current reference is small. Hence, the contribution of magnetizing current in the primary of the transformer is negligible, and quite naturally magnetic saturation in the core is absent. Therefore, the current in primary as well as in secondary are linearly related through turns ratio (n) of the inverter transformer.

The duty cycle 'd' of the inverter in each half cycle acts as input to the inverter. The output of the inverter is related to the applied input voltage i.e. rectified DC 'V_{IN}' as $V_O = d * V_{IN}/n$ ------ (1)

In peak current mode control the PWM duty cycle 'd' is defined [3] as

$d = V_{C1}/(S_n + S_e)$, ----- (2)

where S_e is external ramp for PWM generation and S_n is sensed current ramp. If the circuit for generating 'S_n' is disabled, the inverter follows characteristics of voltage mode control. On the other hand, large value of S_n reduces the duty cycle of the inverter. The duty cycle has direct reflection on output voltage. Reduced duty cycle has the ability to contain overshoot of current. With inner loop control through S_n, it is possible to control the duty cycle instantaneously. The welding current in TIG mode is decided in two stages as per the equations

1.IGBTs are ON (for period $d.T_S$):

$L*di/dt = V_O - V_W \approx$

V_O ($V_a + R_a(t)*i$) -----(3)

Or,

$L*di/dt + R_a(t)*i \approx V_O\ V_a$, and,

2.IGBTs are OFF (for period $(1 - d.T_S)$):

$L*di/dt + R_a(t)*i \approx V_a$ ------(4)

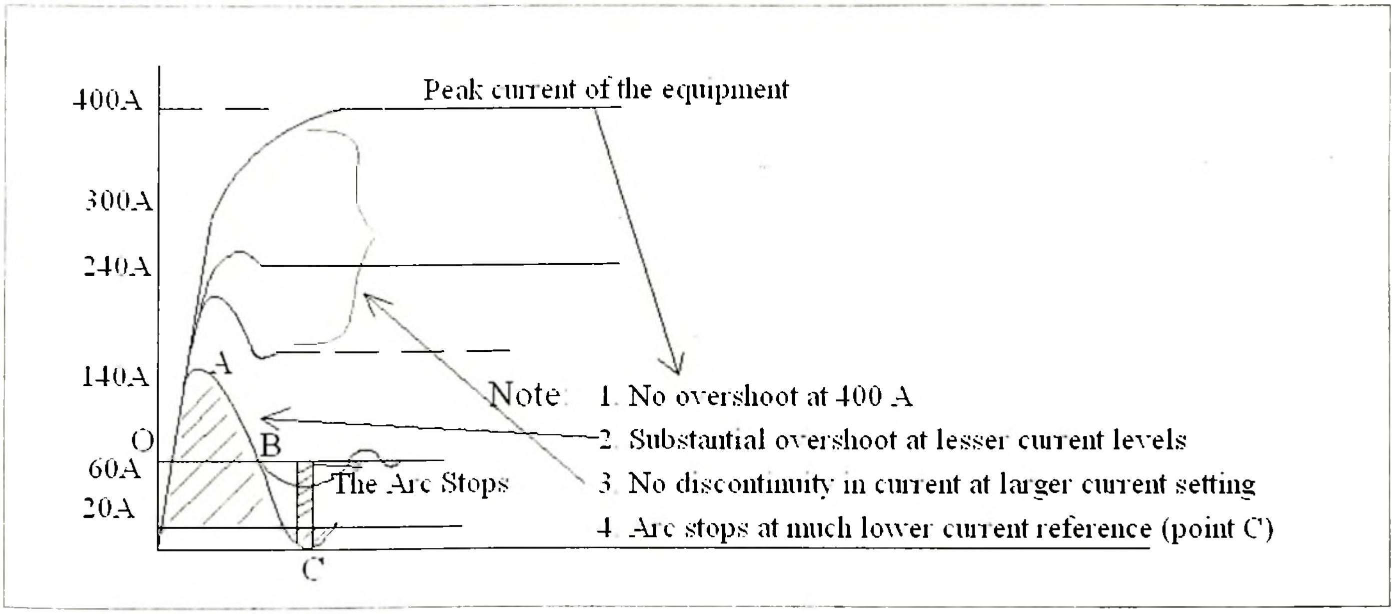

Figure 4. Apparent response of welding current at start in TIG mode

where V_w is the weld terminal voltage, V_a is the drop in electrode regions, $R_a(t)$ is dynamic resistance of the arc column, and T_S is half-cycle time period. Eqn. (1), (3) and (4) together relate output current to duty cycle. The rectified secondary voltage V_O oscillates at '$2f_s$'. Solutions of the above equations in each state together decide the peak and valley of welding current. Substantial value of V_a puts constraint on minimum duty cycle. However, in TIG the small value of V_a/V_O (<1:8) allows duty cycle control over considerable range. The duty cycle of the inverter, while in current limit mode, is influenced by the peak current through the IGBTs. Higher 'f_s' allows reduced value of 'L'. It enables smoother transition process as 'di/dt' rating of the inverter is improved. The critical value of S_n is decided in such a way that the stable welding current is limited to less than the set value till following conditions are satisfied:

i) Tungsten rod is sufficiently hot to emit electrons efficiently (Thermionic emission)

ii) Welding current is maintained stably at a value less than the minimum rated one to generate positive current error in 'e_I'. Integral action further increases the total error as given below

$$V_{C1} = K_P * e_I + K_I * \int e_I dt \qquad \text{------(5)}$$

to keep the inverter in running and thereby current flow is somewhat 'latched'. The second part in the above expression is called 'wind-up'. If e_I is positive for long time, V_{C1} is dominated by the wind-up value. In this way V_c is deliberately kept positive and current limit circuit takes control of the transition process. With controlled peak current mode control topology, integral wind-up is inherently created and maintained. Wind-up, in this case, works favorably in transferring control from sparking (passive control) to stable arc welding (active control). Prolonged wind-up in TIG is not a serious problem as upslope phase is about to start. The current reference is constantly increased, and controlled peak current limit circuitry is bypassed once transition phase is over.

IMPLEMENTATION PROCEDURE, EXPERIMENTAL SET UP & RESULTS

Each current mode control IC for PWM generation is equipped with current limit feature. The tolerance band of threshold for current limit in these ICs is tight and accurate. It makes implementation procedure easier. It is known that the IGBT gate pulses are instantly taken off due to current limit (I_{LIM}) when

$$R_B * I_{LIM} \geq V_{I\text{-}LIM} \qquad \text{----------(6)}$$

$$\text{i.e. } R_B \geq V_{I\text{-}LIM} / I_{LIM} \qquad \text{---------(7)}$$

and at small welding current (i.e. when magnetizing current is negligible)

$$I_{LIM} = I_{WELD\text{-}PEAK}/n \qquad \text{---------(8)}$$

where R_B is the bleeder resistor across current transformer T_1 and $I_{WELD\text{-}PEAK}$ is peak value of welding current. Bleeder resistor R_B is directly related to S_n. Hence, in order to have large S_n the value of R_B needs to be increased accordingly.

Flexibility of the controller increases when programmable devices are used for control. The programmed current reference to the inverter is generated by the micro-controller. It monitors the set voltage fed to the inverter and accordingly generates 4-bit output to switch the resistor network to modify R_B. However, as explained in Fig. 4 that current undershoot at large reference is not critical. The 4-bit resistance controlled network is therefore segmented into two categories. In first category, three resistors are switched to saturate the duty cycle i.e. the input between 3amp and 40Amp. The fourth resistor is for current limit of IGBT and to prevent core saturation. The value of the resistor is set maximum at minimum value of welding current. Incremental change in R_B over wide range in current setting is cumbersome, and is not necessary. The undershoot value at large current reference may not be significantly large to take the inverter into discontinuous current conduction mode. The photograph of the actual welding inverter is shown in Fig. 5. The course of experimentation was organized to look into transition process at various low current settings. The set current values were 3Amp, 10Amp and 20Amp. Though the operating frequency of the inverters was 20kHz, the switching frequency was deliberately kept at 13kHz to see the impact of reduced bandwidth. Secondly, it helped the see the differential impact on the duty cycle of the inverter as the time period of the inverter was more and magnetizing current was also more. Welding current was sensed with hall current transformer where as IGBT current was sensed with Rogowsky coil. The scale for welding current was set kept at 16mV per Amp where as the same for the IGBT current was 100mV/A

Various waveforms at various low current situations have been taken to verify on the performances with respect to the conceptual ideas.

Figure 5. Actual Welding Inverter

The waveform as shown in Fig 6 depicts the impact of wind-up (deliberately created) in the transition process. The current reference was 20A and designed R_B allowed 18A of welding current. The ratio of bleeder resistances with respect to nominal rating i.e. $R_{B\text{-}400}/R_{B\ 18}$ was kept as 1:35. While in upslope the (refer figure no. 1) the error voltage

(refer Fig. 3) V_{C1} was controlled due to ramped reference in upslope. This was similar to reference ramping in lift arc and had resemblance to the one for controlling oscillations in mechanical systems [7].

Subsequently, wind-up contributed to saturation of the error amplifier ($\approx$0.7V) and overshoot was avoided. Experimental results at various low current references are shown in Fig. 7, Fig. 8 and Fig. 9. Fig. 7 is with current reference 3Amp, while Fig. 8 is with 10Amp reference and Fig. 9 is with 20Amp reference. Each figure contains two waveforms with two different scales. One (the top one) is the average welding current and the other (the bottom one) the corresponding IGBT current at the primary. No upslope was present and no overshoot occurred at 3Amp. The ratio of bleeder resistances $R_{B\ 400}/R_{B\ 3}$ was kept at 1:130. Similarly, at 10Amp gentle upslope took place (Fig. 8). The ratio of bleeder resistances $R_{B\ 400}/R_{B\ 10}$ was kept at 1:49. Similar was the case at 20Amp reference. However, the ratio of bleeder resistances $R_{B\text{-}400}/R_{B\ 20}$ was kept at 1:32. The welding was stable there as well.

The repeatability of successful transition has been verified with various welding conditions such as weld gap distance, welding cable length, welding current setting etc. To crosscheck more about the reproducibility, the process was repeated quite a number of times in cold conditions. It was found that in all cases welding started at the very first pulse. The repeatability in creating the sparking was excellent and the subsequent transition was definite. The logic for switching R_B is however disabled in MMA as well as in MIG modes.

CONCLUSION

The issues related to low amperage welding has been discussed from control system perspective. The most critical among them have been experimentally verified. TIG welding inverter with programmed current slope compensation brings multiple benefits to the equipment, particularly during the transition process in non-contact TIG welding application. Smooth welding at 3Amp where tungsten heating was not that great to take full advantage of thermionic emission signifies the importance of the concept. Deliberately created wind-up achieves current latching with out any discontinuity in current flow. The definiteness of transition from sparking with a single burst for non-contact TIG welding

Parameters of Spark Generator		Parameters of the Inverter		External Parameters	
Output Spark Voltage	≈ 2Kvac	Open Ckt. Voltage	80V	Cable Length	10M
Frequency	≈ 1.0MHz	Topology	Full Bridge Inverter	Argon Gas Flow	5LPM
Method	Capacitive Discharge	Frequency	13kHz for testing purpose only	Gap Length	4mm
Energy Spent per cycle	11mJ	Rating of Equipment	3Amp to 400Amp	Weld Current Setting	3A to 20A
Means for Creating Spark	With Resonating Loops	di/dt at sparking	1.5Amp/μSec	Welding Electrode	Thoriated Tungsten

suitable for inverter based machines is therefore achieved. Moreover, the concept guarantees efficient transition at the very first instance of sparking, the components selected for the HF generator are mostly under utilized. Hence, the reliability parameter of the equipment is enhanced. The EMI issue for single burst, statically, is much less as well.

REFERENCES

1. M. Saiepour and J. W. Harry, "Continuous Sinusoidal HF Arc Initiation", Jr. of Phy., Part D, 1990, pp. 1129-1131
2. J. A. Roux, J. A. Ferreira and P. C. Theron, "A Series Resonant Converter for Arc Striking Applications", IEEE PESC, 1995, pp. 723 728
3. R. B. Ridley, "A New Continuous-Time Model For Current-Mode Control', IEEE Trans. On Power Electronics, Vol. 6, No. 2, April 1991, pp. 271 280.
4. Arun Kumar Paul, "Optimizing the Transition Process from Sparking for Non-contact TIG Welding Inverters", Conf. Proc. IEEE ICIT, Dec. 2006, pp. 1413-1418.
5. L. H. Dixon, "Average Current-Mode Control of Switching Power Supplies", Unitrode Power Supply Design Seminar Handbook, 1990
6. G. B. Yundt, "Non-linear Compensation of Self Oscillating Switching Regulators", Con Proc. IEEE PESC, 1985, pp. 368 374.
7. R. Eloundou and W. Singhose, "Saturation Compensating Input Shapers for Reducing Vibration" Conf. Proc. On Motion and Vibration Control, Siatama, Japan, 2002, pp. 625-630.
8. Arun Kumar Paul, " Creating Better Avenuesof Arc Striking for Inverter Based TIG Welding Applications", Conf. Proc. PCIM, Nuremberg, 2006, pp. 409 414.

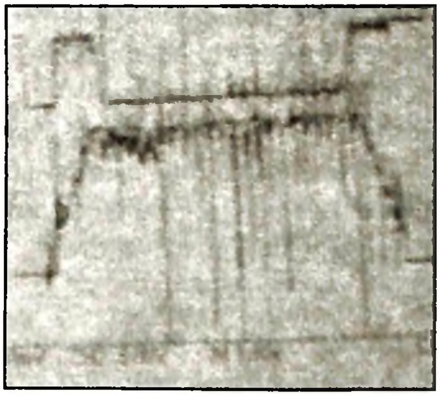

Figure 6. Demonstration of Wind-up

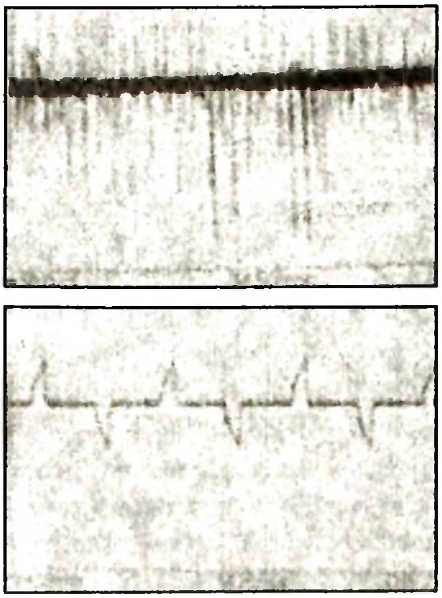

Figure 7. Welding Current and Primary Current at 3A ref.

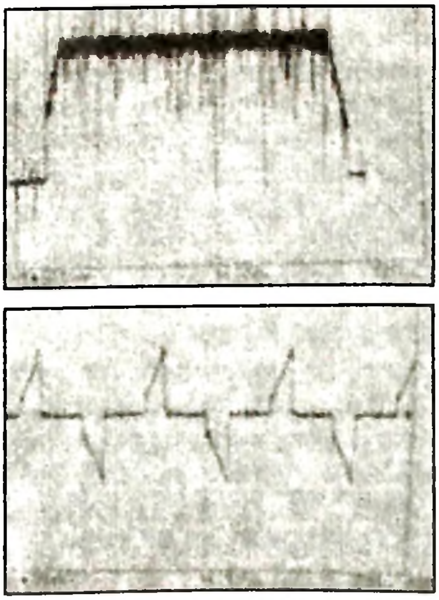

Figure 8. Welding Current and Primary Current at 10A ref.

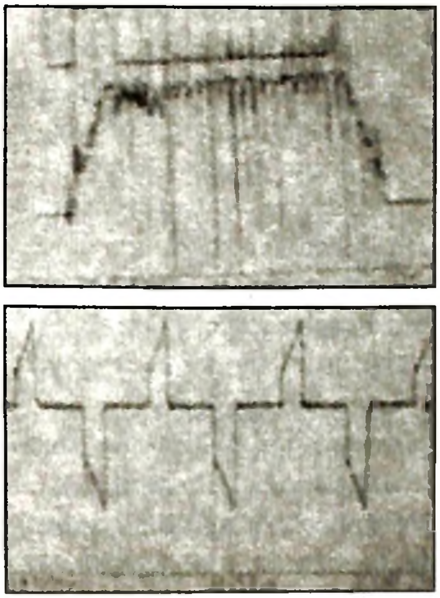

Figure 9. Welding Current and Primary Current at 20A ref.