Efficient SMAW Arc Controller for Wide Range Applications and also for Emerging Economies

Arun Kumar Paul[1] and Mangesh Waman[2]
Research and Development, Electronics Devices World Wide Private Limited
22 Mistry Industrial Estate, Cross Road A, MIDC, Mumbai 400093. Maharastra, India
Email: [1]arunp26@iitbombay.org, [2]mangesh.waman@gmail.com
Corresponding Author: Arun Kumar Paul

DOI : 10.22486/iwj/2019/v52/i4/186786

ABSTRACT

Due to simplicity of arrangement, initial-cost implication and ease of process learning the shielded metal arc welding process (SMAW) is more popular in developing and underdeveloped countries. Apparently, this manual process needs simple constant current power source. Large number of welding consumables have made the arc characteristics of the process quite diverse; the current range for this non-linear process is wide. The input energy source to feed the arc controller could have diverse output characteristics, it could be from infinite bus i.e. the national grid or moderate size diesel generators in isolated locations (e.g. for pipeline welding) or from mini and micro grids in emerging economies. To make the power controller ideally compatible to the process behavior, that includes the wide range non-linear arc characteristics, as well as to the varied input source, it should be able to create requisite joint characteristics drawing minimum input current from the input source. This article details the features of arc controller meeting the wide range applications in the presence of source constraints and details one such equipment with experimental details. It also details the design of mini grid compatible arc controller.

Keywords: Arc characteristics; mini grid; micro grid; power electronics topology; robust control technique; second order sliding mode (SOSM) control; soft-switching converter.

1.0 INTRODUCTION

From the points of view of productivity and quality of welding joint, prospect of all metal welding, energy efficiency, automation flexibility, comfort level to welder, environmental and health issues, etc. the GMAW [1], [2] process has been proven to be much superior. SMAW process [3]-[10] is still popular due to following reasons:

1. The process is simple and can create quality joints suitable for wide range applications
2. Its controller is simple and cheap
3. It is popular in emerging economies because, apart from process simplicity, its total infrastructure involves minimum cost [3]
4. Pipe welding joints use SMAW method to create root pass welding, etc.

The complete arrangement of SMAW process consists of welding consumables, workpiece, welders and the power controller. Not so long ago, depending upon applications as well as affordability aspects of the users the configuration of power controller used to be different ranging from welding transformers to high-end power electronics controllers. The parameters for optimizing the equipment change in applications.

Scope of controllers for SMAW process could be dictated [3], [5] by the characteristics of input energy source, geographic locations, economic conditions, characteristic requirements of welding joint, etc. Input energy source, in certain part of the

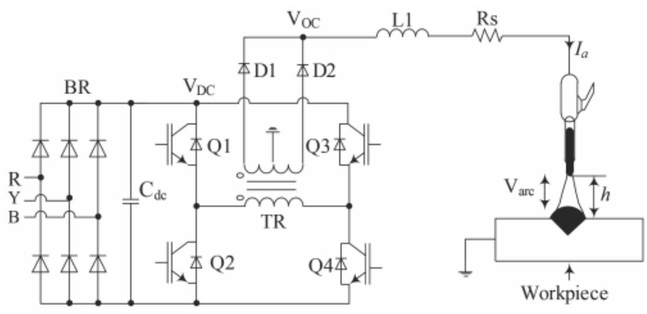

Fig. 1 : Arc Controller using inverter technology

world, in particular, could play significant role on choice of power controller. It is estimated that by year 2030 around 60% of world's population would rely on mini or micro grid fed by renewable sources [11], [12]. Their capacity could be as low as a few kW where power drawn by SMAW controller could play a spoiler to the performance of the mini or micro grid. Even, in India, majority percentage of weld metal deposition is through SMAW. In emerging economies the process is most popular where E6013 electrodes are preferred, the process is controlled by welding transformer. Its optimization needs efficient design of magnetic circuit [3] to tackle the non-linearity of the welding arc. The process characteristics are complex due to the need of wide range current, different types of electrodes and their coating compositions, etc.

The design of power controller for control of constant current (CC) SMAW process appears to be simple [5]. To cater wide range applications with high energy efficiency and power density the inverter technology is essentially used. Schematic diagram of full bridge inverter based power controller for control of SMAW process is shown in **Fig. 1**. Affordability, sound knowledge base and easy availability of components for manufacture and or easy access to service and repair help decide the configuration of arc controller for several customers. This is particularly true for emerging economies. This article, using comparative analysis proposes a control function dominant simple full bridge inverter topology to cater the applications of complete customer base of SMAW process. The rest of the article is organized as follows: Section 2 defines the spectrum of energy source that could feed an arc controller. Section 3 briefly discusses the dynamic behavior of SMAW process. Section 4 discusses different power controllers used for control of CC arc. Section 5 details the proposed power controller configuration. Section 6 elaborates practical implementation of proposed power controller with requisite experimental results. Finally, Section 7 details the configuration of mini or micro grid compatible controller for creating quality welding joints.

2.0 INPUT ENERGY SOURCE

The customer base as well as application domain of SMAW process is in many ways quite different from other popular arc welding processes. The input energy source for feeding the SMAW controller could be one of the following:

1. Infinite bus or the national electrical grid
2. Insolated source such as diesel generator
3. Mini or micro grid where more than one small to moderate size sources are synchronized

The national grid is the ideal energy source for feeding power electronics controllers for control of non-linear loads. Its output parameters (voltage and frequency) are robustly stable. It has been experienced with practical data that, when compared with the same available from installations in American and European continents, the failure rate of power controllers is more in emerging economies and developing countries. It could be attributed to fluctuation of electrical parameters of the energy source.

The nature of input source of electrical power is fast changing. Thanks to renewable energy sources it is estimated that by year 2030 majority of households will be fed with electrical power involving micro or mini grid. The capacity of each mini grid could be small. Therefore, the preferred power electronic converters connected to mini grid should be such that they do not create much disturbance to the mini grid performance.

3.0 SMAW PROCESS

In SMAW, for quality welding joint the amount of heat energy (H) reaching out to the base metal is,

$$H = \frac{\eta V_{arc} I_a}{R} \qquad \text{...... (1)}$$

R is speed of manually-fed electrode tip, V_{arc} is arc voltage at current I_a and η is arc efficiency. The expression of V_{arc} is

$$V_{arc} = V_A + V_C + Eh + R_a I_a \qquad \text{...... (2)}$$

Five parameters such as anode drop V_A, cathode drop V_C, arc length (h) factor E and arc resistance R_a define the arc. Their respective value changes with operating point of arc, electrode material and coating used in it. The coating has major influence on arc characteristics. E.g. the set current for E6010 electrodes is small where V_{arc} is needed is more.

In the manual CC process the arc length h is not constant. In order to have control over H the process follows the CC characteristics. If connected to positive terminal, the melting rate vm of electrode is

$$v_m = C_1 V_A I_a \qquad ..... (3)$$

For a particular electrode the melting rate constant C_1 and V_A are considered constant.

The quality of welding joints created by SMAW depends on the stability of arc [8]. For smooth metal transfer at reduced welding fumes and spatters, the parameter F should be minimum [9].

$$F = KI_a^2, \ K \text{ is constant} \qquad ..... (4)$$

For F to be minimum, the form factor of I_a should be ideally unity. The ripple I_r in I_a should be minimum. It is clear from (1) – (4) that the designed controller should be such that the good welding joints are created at a particular value of I_a achieving optimal form factor i.e. the ripple current $I_r \approx 0$. Moreover, the controller should be able to generate requisite arc force and the material transfer process from electrode tip to weld pool should be spatter free.

4.0 POWER CONTROLLER FOR SMAW

The primary aims of the controller is to feed ripple free current and the response time should be small. The dynamic equation for controlling the process [7] is

$$V_{OC} = L_1 \frac{dI_a}{dt} + R_S I_a + V_{arc} \qquad ..... (5)$$

L_1 is inductance of controller and R_S is its resistance. Input to the process V_{oc} is related to power controller through the duty cycle D of the inverter,

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

V_{dc} is voltage of DC bus, n is turns ratio of TR (**Fig. 1**). The maximum open circuit voltage $V_{OC}(\max)$ is

$$V_{oc}(\max) = \frac{D_{\max} V_{dc}}{n} \qquad ..... (7)$$

The power delivered to arc is

$$P_{arc} = V_{arc} I_a \qquad ..... (8)$$

For controller's universal acceptance and for optimized performance of the process [10], the optimization of the controller is important. The parameter to be optimized is quantified as Goodness Factor GF

$$GF = \frac{\eta_{eq} pf}{W \tau_S} \qquad ..... (9)$$

Where pf, η_{eq}, W and τ_S respectively are input power factor, efficiency, weight of controller and settling time of the controller. The design of the controller is such that the first two parameters are maximized and the last two minimized. The value of W and τ_S are reduced through increase in switching frequency and also by reducing the power loss. Moreover, the controller should,

1) Be affordable to users anywhere globally
2) Be able to weld all type of applications
3) Have negligible failure rate
4) Have minimum component count and they should be easily and cheaply available.
5) Be compact and light weight
6) Controller's output characteristics should assist the welder to get desired joint quality

Over the years, several type of controllers have been used. They are listed as below:

1. Welding transformer
2. Welding rectifier
3. Full bridge (FB) inverter
4. Resonant controller
5. Soft-switched inverter
6. Robust power controller

4.1 Welding Transformer and Rectifier

Welding transformer [3] is the simplest and cheapest power source for feeding SMAW process. Its component count is minimum but its application potential is limited. E.g. It is suitable for welding using E6013 electrodes, etc. where arc re-ignition during current reversal of AC waveform is not a problem. It is not directly compatible to DC grid as well. It is most popular in emerging economies.

Rectifier technology could resolve several weakness of welding transformer. However, it is too sluggish (τ_S: large) to take care of fast changing dynamics of welding arc. Its power density as well as efficiency is poor. For a particular value of I_a, it draws large current from input source. It is not suitable for mini grid.

4.2 Full Bridge Inverter

To make arc controllers compact, energy efficient and effective to handle dynamic issues of the process the inverter technology [10] was introduced. Among several available topologies the full-bridge inverter (**Fig. 1**) is able to effectively handle the complete range of operating conditions of arc. Its component count is moderate, they are affordable and easily available. It is compact and efficient. Power density and settling time could further be improved if the switching frequency is increased, it is restricted due to large high-frequency losses. There are components available [13] that efficiently switch the inverter at high frequency; they are costly and difficult to source, at least, for customers from emerging economies.

The conventional FB inverter uses proportional plus integral (PI) control functions where due to asymptotic time convergence the value of τ_S tends to be large. As shown in **Fig. 2** that, for 20 kHz FB inverter, while welding using E6010 electrodes, in particular, there was oscillations in current i.e. the value of ripple current I_r was large. Repeated arc breaks were noticed. The frequency of occurrence of arc breaks was reduced when the value of V_{OC}(max) was increased.

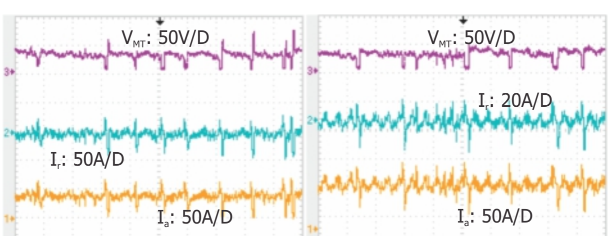

Fig. 2: Waveforms for (a) 3.15mm mm E6010 at 20m, (b) 3.15 mm E6010 at 110m, [VMT: Terminal voltage of controller, Time: 50ms/D]

4.3 Resonant and Soft-Switched Converters

Resonant [14] or soft-switched [16] inverter topologies are used to reduce the high-frequency component of power loss in welding inverters. Here, the power switching devices are turned on or off in such a way that during switching transitions the power loss in each semiconductor device is minimized.

Because of reduced switching losses the operating frequency can be increased in series resonant (SRC) or parallel resonant (PRC) converters [14]-[16]. But, they are less suitable for wide range arc welding applications where the load characteristics is extreme because short circuit, open circuit and arcing – all are valid operating point. It is difficult to maintain both zero current at turn off and zero voltage at turn on under all operating situations. Secondly, the controller characteristics (e.g. switching frequency) also shift with change in loading condition. The number of high frequency critical component count increases. Each power device (Q1-Q4) needs separate gate drive. Sourcing certain critical passive power components at low cost is not easy even for countries such as India.

Though the basic inverter block for power delivery in soft-switched welding controller is the full bridge inverter (**Fig. 1**), their switching pattern is different [17]. In soft-switched inverter the power loss in each high frequency active power component is minimized by ensuring out of phase transitions of voltage and current [18], [19] during switching transitions. It generates optimal performance of the process because each power switching device can enjoy either zero current or zero voltage during switching transitions. The recovery loss in D1 and D2 can as well be minimized. The switching frequency of these inverters could be more than 100 kHz. These inverters are equipped to weld wide range applications with increased efficiency. The controller could be designed to optimize its goodness factor GF. However, to minimize the high frequency losses the active and passive power components' count is more than resonant inverter discussed above. Their availability at low price in developing countries is poor.

5.0 ROBUST SMAW CONTROLLER

It has been realized that the design of high frequency converter for effectively and efficiently handling the arc load may not be a real challenge. Manufacturing them in a cost effective manner with all components sourced from outside the country of origin is a big problem. It has been already proposed and experimentally verified [7] that the choice of robust control function for effective actuation of arc control could resolve several issues of welding inverter. The high frequency inverter can handle many dynamic issues of arc load effectively because the settling time is reduced. The robust control concepts (e.g. SOSM), contrary to PI control idea, on the other hand, could achieve finite time convergence of the controlled variable i.e. the arc current. There by, the value of τ_S is inherently reduced even when the inverter is switched at 20 kHz. When SOSM control [22] is used, the natural choice of sliding surface for first order constant current process [7], [21] is the current error e is

$$e = (I_{ref} - I_a) \quad ..... (10)$$

Using suitable control function u_{SOSM} the following two conditions are satisfied, i.e.

$$e = I_{ref} - I_a = 0 \quad \text{and} \quad \frac{de}{dt} = 0 \Rightarrow \frac{dI_a}{dt} = 0 \quad ..... (11)$$

The two pre-requisite conditions (11) make SOSM control ideally suited for control of SMAW. The second condition, in particular, ensures that the ripple current I_r is minimized. For constant value of reference I_{ref},

$$\dot{e} = -\frac{dI_a}{dt} = -\frac{1}{L_1}(V_{oc} - V_{arc} - R_S I_a) \quad ..... (12)$$

As $\dot{e}$ contains input V_{oc} (5), therefore, for robust control performance, popularly used super twisting control [22] is applied. The control input u_{SOSM} is expressed as

$$u_{SOSM} = \rho_1 |e|^{0.5} \operatorname{sgn}(e) + \rho_0 \int \operatorname{sgn}(e) d\tau \quad ..... (13)$$

Where ρ_0 and ρ_1 are gains of the SOSM controller. The inverter output V_{oc} is linearly related to u_{SOSM}.

5.1 Implementation of Fractional Order Control Function

Though, now a days, in most control applications the controller implementation is mostly through microcontrollers [20], here, for simplicity, hardware approach was considered. A control idea is considered to be friendly to design engineer if it is easily implementable both in hardware and software domains. Here, an analog-switch (S1-S4) based basic circuit for generating PWM signals from error is shown in **Fig.3**. Translating fractional-order function (13) in simple hardware circuits appears to be problematic. At small error the dominant first part of (13) could be approximated through addition of a few more structures as shown in **Fig.3**. The structure or gain switching takes place in such a manner that as error moves towards origin the impact of nonlinear part is increased. Then, (13) could be simplified as,

$$u_{SOSM} = \rho_0 k_e e + \rho_1 \int \operatorname{sgn}(e) d\tau = \rho_0 (e) e + \rho_1 \int \operatorname{sgn}(e) dt \quad ..... (14)$$

Where, $k_e = 1/\sqrt{e}$

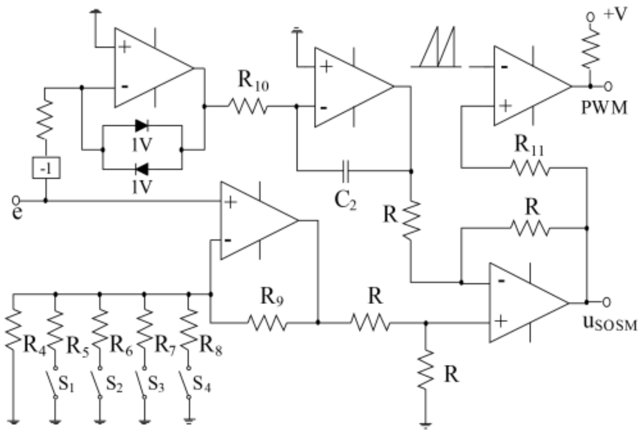

Fig. 3 : Circuit to design the SOSM control function

6.0 PRACTICAL EXPERIMENTATION AND RESULTS

Capability of 400A rated SOSM controller to weld wide range welding applications was addressed in [7], [21]. Unlike PI control (**Fig. 2**), the performance of controller for value of V_{OC}(max) at 80 V was satisfactory for each type of electrodes. The range of current performed was from 30A to 350A without any quality issue. There was no problem even when the length of welding cable was increased. This proved that the cable inductance hardly played any role. The form factor of I_a was close to unity. Under such conditions the welding quality appeared to be good and spatter free. To further study the robustness features, more welding experiments were performed at reduced value of V_{OC}(max) at 57.6V. There was no degradation in performance in the current range from 35A till 310A. It essentially means that the controller could robustly handle arc nonlinearity and parametric variations caused by change in cable length, operating conditions, change in electrode material, change in welder, etc. A few experimental results are shown in **Fig. 4** and **Fig. 5**, where it appears clear that the robust arc controller could achieve superior current control and the ripple content in it was negligible. Therefore, SOSM based arc controller for CC process could be regarded as an ideal for creating high quality wide range welding joints.

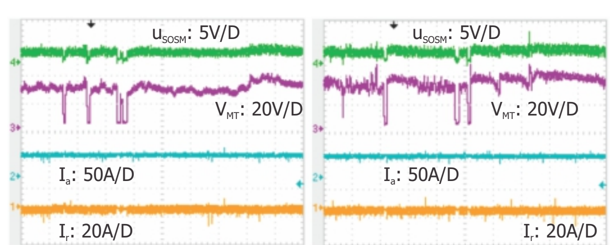

Fig. 4 : Waveforms under SOSM control for 2.5 mm E6010 electrode (a) at 20 m at 35A, (b) at 110 m at 35A, [Time: 50ms/D]

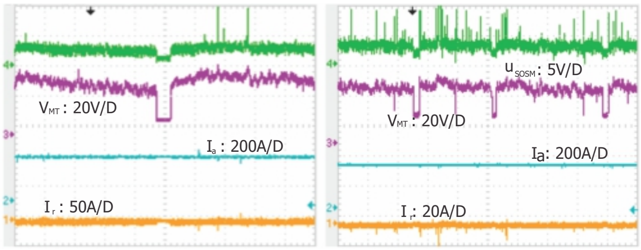

Fig. 5 : Waveforms for (a) 6.3 mm E7018 at 20m, (b) 6.3 mm E7018 at 110m, [VMT: Terminal voltage of controller, Time: 50ms/D]

The impact of controller performance or the influence it makes could be felt on three fronts – process, controller and the welder. It is clear from **Fig. 4** and **Fig. 5** that, when compared with performance to PI (**Fig. 2**), the arc stability feature was superior [7], [21] even when different electrodes were used. The comparative performance of two controllers is listed in **Table 1** [21]. It is also clear from **Table 2** that welders' comfort level in SOSM control would be superior to PI and generating better process performance.

Table 1 : Gain in 400A SMAW Arc Controller

Parameter	Conventional FB Inverter	Robust FB Inverter
V_{oc}(max) needed	>80V	≤ 64V
Peak power rating	28.8 kW	23 kW
Maximum delivered power	8.74kW @280A	10.0kW @310A
Power utilization	30.34%	43.6%
Maximum current @ 100% duty cycle	280 A	310 A
Maximum efficiency at 100% duty cycle	88% @ 280A	92.0% (at same loading as in PI)
Weight	32 kg	28 kg

7.0 ARC CONTROLLER FOR EMERGING ECONOMY

Mini grids fed from renewable energy sources are emerging as a solution to feed electricity to consumers in remote areas. The capacity of each mini grid in emerging economies is not large. The industrial activities in those places could be presumed to be small. With emergence of mini grids, now there is hope for small-scale industrial activities coming up on remote areas. Till the industrial activity is in full swing, the metal joining process there could mostly be relying on SMAW process. The preferred electrode could be E6013 having maximum diameter of

Table 2 : Welders' Comfort Level and Gain in Process

Parameter	Conventional FB Inverter	Robust FB Inverter
Welders' comfort zone	Needs more voltage	Good at small voltage
Ripple I_r @ 110m	10% at 280A	<1% at 310A
Ripple I_r @ 110m	20% at 250A	4.5% @ 35A
Arc Break	Prominent at small current	Nil
Art stability	Poor due to arc non-linearity and also by cable drop at large current	Good and robust in entire current range
Arc radiation	More	Less

3.15mm. Ideally, 130A capacity arc controller would be good enough to cater applications in those areas. The ideal controller should draw minimum current from the source to feed requisite power P_{arc} to arc for welding. For a controller with large value of GF (9), if the ratio of V_{arc} to V_{oc}(max) is maximized then the power drawn from the source is minimized. It has been noticed in earlier Section that the robust controller could improve the ratio greatly. Similar design exercise is performed here as well.

It is easy to make weld joints using E6013 electrode. The welding can be made using controlled DC source of either polarity, the process set up is friendly with AC power source as well. It essentially means that the contribution of space charge voltages V_A and V_C (2) is less significant from arc ignition point of view. The arc, as if, behaves more like a resistive load. Therefore, when fed from the DC source, for a particular application setting, the controller may be optimized by minimizing the value of V_{oc}(max) where the robust controller have an edge.

Using the power controller used in Section 5.0 a few more experiments were conducted to study the characteristic need of E6013 electrode. It was noticed that for welding full capacity of 3.15 mm E6013 electrode the value of V_{oc}(max) needed was 33V.

7.1 SMAW Controller Compatible to Mini Grid

The capacity of power controller for feeding 3.15 mm 6013 electrode is approximately 3.0 kW, it is fed from single phase supply. The power circuit is shown in **Fig. 9**, its major components are listed in **Table 3.** The DC link capacitor C_{dc} is chosen in such a manner that the permissible ripple in V_{dc} is around 25-30 %, it results in improved input power factor. The RMS current handling ability of C_{dc} needs to be large, the power loss in it should be negligible. In full bridge configuration the selection of Q1-Q4 is important. The turn off loss in this topology is negligible. Therefore, the losses occurring during conduction and turn-off are major. Moreover, the small secondary DC voltage of around 33V allows Schottky diodes could be used for D1, D2 for secondary rectification. Their conduction loss is small and reverse recovery loss is negligible. With such power circuit configuration, the efficiency of the controller is very high.

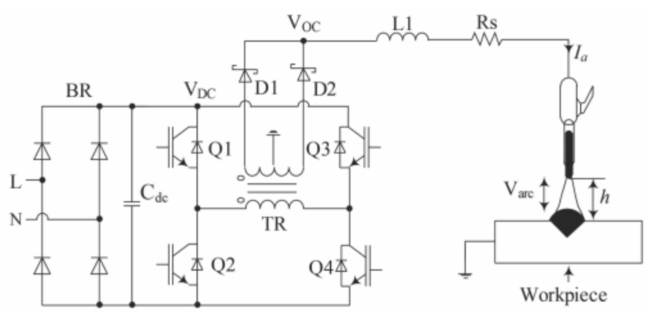

Fig. 6 : Arc Controller for mini grid application

Table 3 : Parameter of Full-Bridge Controller

D_{max}	0.90	D1+ D2	DSS 2X160-01A
fs	20 kHz	Q1-Q4	IKW50N60T
V_{OC}(Max)	33V	L1	40μH, 130A
C_{dc}	400μF, 400V	TR1	Turns Ratio: 9:1:1

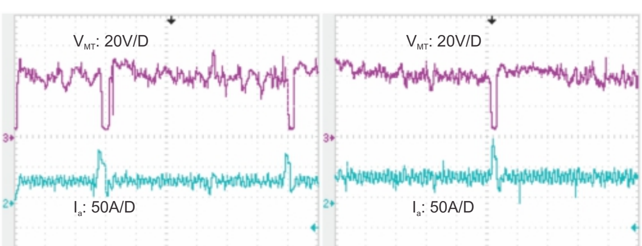

Fig. 7 : Waveforms under SOSM control for 2.5 mm E6013 electrode (a) at 60 m at 80A, (b) at 20 m at 80A, [Time: 25ms/D]

Several experiments were conducted to validate the single phase robust controller. Both 2.5 mm and 3.15 mm sized E6013 electrodes were tested. As shown in **Fig. 7** that the current control was smooth at 80A when 2.5 mm electrode was used. There was no arc breaks noticed as well. It was demonstrated and shown in **Fig. 8** that for value of Voc(max) merely at 33V DC the controller could make good welding joint (**Fig. 9**) at 120A. There was no problem in welding when the length of the cable was increased.

Optimized use of V_{OC}(max) allowed intelligent choice of materials. The high frequency power components such as for D1, D2 low voltage high current Schottky diode were used. The conduction loss was reduced and high frequency reverse recovery loss was negligible. Similarly, equivalent series resistance of MKP dielectric for C_{dc} was also negligible. The conduction loss of anti-parallel diodes and turn-off loss of Q1-Q4 for this topology are also small. The major power losses taking place in Q1-Q4 could be attributed to conduction loss and turn-on loss. The choice of these devices was based on lower value of V_{CE}(sat) and smaller turn on loss. Therefore, the efficiency and power density of the proposed controller would be high.

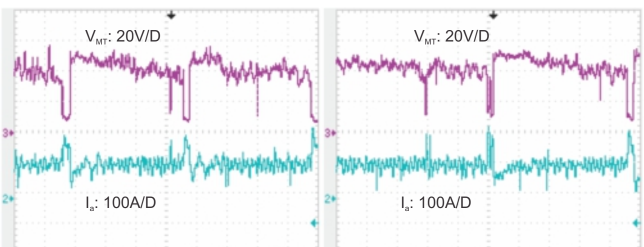

Fig. 8 : Waveforms under SOSM control for 3.15 mm E6013 electrode (a) at 20 m at 120A, (b) at 60 m at 120A, [Time: 25ms/D]

Fig. 9 : Spatterless welding joint made using 3.15mm E6013 electrode at current 120A

8.0 CONCLUSION

In this article, a robust control function based wide range arc controller suitable for welding using complete range of consumables for SMAW process was detailed. It was established that, for a particular application, the controller ensured optimal use of open circuit voltage, thereby, the controller could draw minimum current from the source. Using this feature, a new power controller was designed to ensure its compatibility to mini grid. The controller inherently optimized the energy use for applications in SMAW. The component count of this active controller was minimum, they were easily available. Features such as compatibility to mini grid, high operating efficiency, easy availability of components, high reliability feature made the controller attractive for applications in remote areas. The controller was otherwise simple where commonly available components were used. The repairability aspect was also high.

REFERENCES

[1] Parslow MA (2012); Reducing the ecological impact of arc welding, Welding Journal, 91(12), pp. 24 – 27.

[2] Paul AK (2010); Power electronics help reduce diversity of arc welding process for optimal performance", Proc. IEEE PEDES, pp. 1-7.

[3] Cale J, Lute C, Simon J and DelCore A (2019); Modeling minimally-processed shielded metal arc weld transformers for rural minigrid applications, IEEE Trans Power and Energy Syst. Technol., 6(2), pp. 95-103.

[4] Boussiala B, Nezli L, Mahmoudi MO, Deboucha A (2018); Novel welding machine based on small PMSG wind turbine. Journal of Renewable and Sustainable Energy, 10(5):053304.

[5] Paul AK (2011); Qualitative study of status of indigenous arc welding equipments in India, Ind. Weld. Journal, 44(3), pp. 58 – 66.

[6] Srithorn J, Srithorn P and Danbumrungtrakul M (2017); A control technique for shielded metal arc welding improvement, Suranaree Journal of Science & Technology, 24(3), p. 281-289.

[7] Paul AK (2016); Robust product design using SOSM for control of shielded metal arc welding (SMAW) process, IEEE Trans. Ind. Electron., 63(6), pp. 3717-3724.

[8] Shigeta, M., Ikeda, T., Tanaka, M., Suga, T., Poopat, B., Peansukmanee, S., Kunawong, N., Lersvanichkool, A., Kawamoto, H., Thongdee, S. and Suenaga, K., (2016); Qualitative and quantitative analysis of arc characteristics in SMAW," Weld World, 60, pp. 355 – 361.

[9] Chen JH, Sun ZC and Fan D (1996); Study on the mechanism of spatter produced by basic welding electrodes, Welding Journal, 75(10), pp. 311s-316s.

[10] Paul AK (2013); Sliding surface in 1-sliding boosts multi-objective optimization program of shielded metal arc welding process, IEEE conf. ICAES, Pilani, India, pp. 39 - 44.

[11] Palit D and Sarangi GK (2014); Renewable energy based mini-grids for enhancing electricity access: Experiences and lessons from India, Proceedings of the Int. Conf. Green Energy and Sustainable Development, Pattaya. Thailand.

[12] Bhattacharya SC and Palit D (2016); Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required?, Energy Policy, 94, pp. 166-178.

[13] Paul AK (2012); SiC mosfets with Schottky power diodes help optimize the design of multi-functional arc welding equipment in popular power range, Int. J. of Power Electronics, 4(4), pp. 360 – 377.

[14] Malesani et al (1995); Electronic welder with high frequency resonant inverter, IEEE Trans. Ind. Appl., 31(2), pp. 273-279.

[15] Altanneh NS, Uslu A and Aydemir MT (2019); Design of a series resonant converter GMAW welding machine by using the harmonic current technique for power transfer, Electronics, 205(8), pp. 1-17.

[16] Mecke H, Fischer W and Werther (1997); Soft switching inverter power sources for arc welding, European Conf. Power Electron. and Appln., 4, pp. 333-337.

[17] Jeon SJ and Cho GH (2001); A zero-voltage zero-current switching full bridge DC-DC converter with transformer isolation, IEEE Trans. Power Electron., 16(5) pp. 573 – 580.

[18] Dudrik J and Trip N. (2010); Soft-switching PS-PWM DC–DC converter for full-load range applications, IEEE Trans. Ind. Electron., 57(8), pp. 2807-2814.

[19] Dudrik J, Pastor JM, Lacko M and Zatkovic R (2017); High-freuency soft-switched PWM DC-Dc converter with active output rectifier operating as a current source for arc welding applications, Electric Power Components and Systems, 45 (6), pp. 681–691.

[20] Jabavathi JD and Sait H (2019); Design of a single chip PWM Driver Circuit for Inverter Welding Power Source. IEEE Trans. Circuits Syst. II Exp. Briefs, Early Access.

[21] Paul AK (2016); Decoding the impact of robustness measures of SOSM control in SMAW process, IEEE Conf. Proc. PEDES, Trivandrum, India, pp. 1-66.

[22] Levant A (2005); Introduction to high-order sliding modes, in School Math. Sci., Israel, pp. 1 – 55.