MODELLING AND SIMULATION FOR A VERSATILE CONTROLLABLE POWER SUPPLY CONFIGURATION APPROPRIATE FOR MAGNETICALLY IMPELLED ARC BUTT (MIAB) WELDING

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ABSTRACT

This article presents the design and development of a power source for industrial applications, focusing on improving energy efficiency, control, and reliability. The study is primarily focused on designing an optimized electrical power source for Magnetically Impelled Arc Butt (MIAB) welding, which is a solid-state welding process characterized by specific current requirements. MIAB welding involves variation of current in two stages of the welding sequence. The objective of this study is to propose an appropriate power supply configuration that meets the precise amperage control and also ensures machine compactness and automation of the process. Utilizing state-of-the-art simulation tools, the research explores various design parameters and configurations to achieve the desired current modulation efficiently. The inverter-based welding power source is tested for the welding of tubes of MS1018 material by implementing parametric variations to validate its workability and performance. The findings indicate that the proposed power supply configuration can enable the required control and also provide a compact power supply unit for MIAB welding, paving the way for its broader industrial adoption and implementation. This research contributes to the advancement of welding technology by providing a robust solution to the challenges associated with arc dynamics and amperage modulation in MIAB welding, ultimately leading to improved weld quality and process efficiency. The proposed power supply design demonstrates potential applications well beyond MIAB welding, offering versatility for any process requiring controlled amperage variation during its operation cycle.

KEYWORDS: MIAB, arc, power source, welding, MATLAB

1. INTRODUCTION

Magnetically Impelled Arc Butt (MIAB) welding is a solid-state welding technique extensively used in industrial applications for joining ferrous tubes. Arc is formed between the faying surfaces which get impelled by the external magnetic field and rotate along the tube periphery [1]. Current flow is maintained in the form of an arc which heats the surfaces, eventually causing them to coalesce on being forged together.

MIAB welding requires precise control of current levels resulting in various arc rotation speeds in the different stages, graphically depicted in Fig. 1:

A. Initiation of the arc
B. Arc rotation
C. Arc acceleration
D. Stable arc and fusion

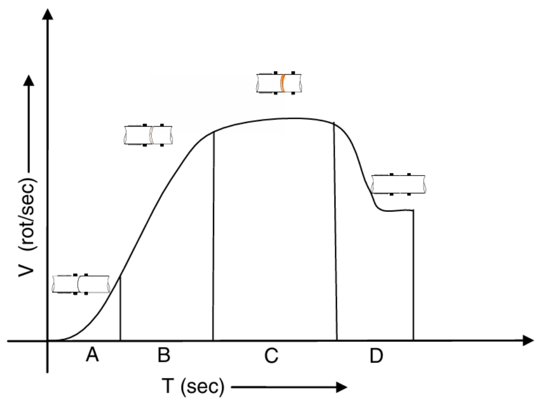

Fig. 1. Graphical representation of stages in MIAB welding [1]

Arc rotation velocity is governed by the impelling force experienced by the arc and the specifications of

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the arc, Eq. 1 and Eq. 2.

$$v_{arc} = \frac{F}{k}\left(1 - e^{-\frac{kt}{m}}\right) \quad (1)$$

where F-Lorentz Force (N), is given by

$$F = B.I.l \quad (2)$$

k-constant of air resistance,
m-mass of the arc(Kg),
t-time duration (s),
B-Magnetic flux density produced by external magnetic field,
I-arc current,
l-length of the arc.

The arc formed by the separation of tubes rotates around the periphery of the weldments. It acts as a moving heat source and causes the faying surfaces to experience an increase in temperature due to the heat transfer from the arc. The heat energy required for raising the temperature of the weld tubes to the solidus temperature depends upon the material characteristics and the temperature change, given by equation 3.

$$Q = m * c * \Delta T \quad (3)$$

where m-mass, c-specific heat, ΔT-change in temperature.

The energy released by the arc is controlled by the arc voltage and current, Eq. 4

$$Q = V_{arc} * I_{arc} \quad (4)$$

where V_{arc} -arc voltage, I_{arc}-arc current.

Arc current and voltage are the significant control parameters that govern the heat generated and transferred to the weld surfaces for increasing its temperature to the required temperature for forging to happen. The final phase of forging requires a 40-50% current higher than the arc heating current. This current enables a steady increase in temperature and consequently ejection of impurities along with the application of force necessary to create the weld.

The experimental work was carried out for the welding of ferrous tubes of MS1018 material. It is a Medium low-carbon steel, has good weldability and slightly better machinability than the lower carbon steels. The chemical composition of MS1018 is provided in Table 1.

Table 1. Chemical composition of the MS1018 tubes

Element	C	Si	Mn	P	S	Fe
Wt%	0.14-0.20	0.15	0.6-0.9	0.04 (max)	0.05(max)	98.8-99.3%

For one specific sample of MS1018 ferrous tubes of 27mm outer diameter and 3 mm thickness, the current required is 150A for 4 seconds in the initial stage and a forging current of 300A in the second stage [2,3]. A stable arc ensures consistent heat input, which is essential for achieving high-quality welds. Modern power sources offer advanced controls for adjusting welding parameters such as voltage, current, and magnetic field [4]. This control allows welders to configure the welding process to the specific requirements of the job, leading to better weld quality and productivity. For mobile welding applications or field repairs, portable power sources are essential. The power source is a critical component in welding operations, influencing arc stability, welding parameter control, energy efficiency, process compatibility, portability, safety, and overall weld quality. Choosing the right power source for a welding application is essential for achieving successful and efficient welding operations. This paper presents a simulation study aimed at designing an optimized power source for MIAB welding, that can be reconfigured for various applications requiring amperage variation during their operation cycle. The key literatures that facilitated this research is briefly presented in the following section.

Welding is a crucial process in manufacturing and construction industries, enabling the joining of materials for various applications. The efficiency and quality of welding heavily depend on the power source used. Over the years, different power sources have been developed to cater to the diverse needs of welding processes [5,6,7]. Previous studies have explored different aspects of welding power sources, including the influence of magnetic fields on arc stability, current control, and the mechanical properties of the welded joints. Modelling and simulation shed light on power source control to better understand interdependent parameters

Paranchuk, Y., et al [8] proposed a thyristor welding power source to improve electromagnetic compatibility by adjusting AC welding arc current. Various power source configurations were analyzed for the study of harmonics and current distortion. Results showed decreased distortion with the connection of thyristor-reactor groups. Tsujimura, Y. et al [9] modelled Tungsten Inert Gas arc behavior with Constant Voltage (CV) and Constant Current (CC) power sources. For CV, plasma temperature and current increase as arc length decreases, significantly changing arc power. For CC, arc voltage changes but plasma temperature stays constant, with arc power decreasing. CC power sources provide more stable heat input. Bouafassa, A. et al [10] present a bridgeless PFC modified SEPIC converter for arc welding power supplies, combining a modified SEPIC PFC converter with a buck converter of full bridge configuration. Simulated and real-time tests show improved power quality, maintaining constant current and stable arc, which ensured reliable standards of power quality and regulation of voltage. Jabavathi, J.D. and Sait, H. [11], designed a cost-effective design and a simulation model for an IGBT gate inverter driver board for welding power sources. The proposed method was analyzed and tested on an 18kW inverter, and it exhibited durability and techno-economic viability. Zhengqiang, Z. et al [12] introduced a mathematical model for a thyristorised rectifier suitable for arc welding power sources. The simple model structure accurately represents the Voltage-Amperage characteristic for the required power and predicts current and short circuit performance under varying conditions, enhancing the effectiveness of limited measuring data.

A simulation study of power control uses a temperature-controlled resistor to adjust current flow amperage and duration [13]. To determine the operating range of process parameters, several experimental trials were made [14]. Chaturvedi, M et al [15] analyzed simulation models to study magnetic effects on arc dynamics and to simulate MIAB welding process. This explains process variations including arc displacement, electric potential dispersion, and AlNiCo magnet self-demagnetization. Multi-process power sources capable of supporting different forms of arc welding techniques provide versatility and cost-effectiveness in diverse fabrication scenarios. Studies by Jones and Brown [16] evaluate the performance of multi-process power sources in various welding applications, highlighting their adaptability and efficiency.

Pulse power sources, including pulse-width modulation (PWM) and high-frequency pulse systems, offer superior control over heat input and arc stability, particularly in thin-sheet welding applications. Research conducted by Zhang et al. [17] demonstrates the advantages of pulse power sources in reducing distortion and spatter while enhancing weld penetration and fusion zone morphology. Investigations by Patel et al. [18] explore the feasibility of renewable energy-powered welding systems, emphasizing their potential to reduce carbon footprint and energy costs in the welding industry.

Overall, the choice of welding power source depends on factors such as the welding process, material thickness, and desired welding characteristics [14,19, 20]. It's important to select a power source that is suitable for the specific welding application to achieve optimal results. However, limited research has been conducted on the design and optimization of the power supply systems tailored to the specific current requirements of MIAB welding. The MIAB welding process offers significant advantages over traditional welding methods, such as reduced thermal distortion and higher joint integrity [13]. This research work presents a cost-effective, inverter-based power supply circuit for MIAB welding experiments, including modelling and experimental study. This study has thus utilized simulation tools to design and analyze the power supply system required for MIAB welding. The design parameters were determined based on the amperage requirements of the MIAB welding process.

2. METHODOLOGY

Simulation analysis was planned with the following objectives:

- Analysis of the working of inverter-rectifier power converter circuit
- Control of the arc current as required for the two stages of the MIAB weld sequence
- Observation of the arc voltage variation from its formation stage up to the duration for which it sustains between the tube faces
- Study of the behavior of an ideal arc
- Study of arc behavior when it is formed by the opening of the electrical contacts

The simulation was conducted using MATLAB/Simulink, which provided a comprehensive environment for modelling the electrical components and their interactions. The MIAB welding process has the following requirements of amperage and time durations [3]:

- Stage 1: 150A for 5 seconds;
- Stage 2: 300A for 0.3 seconds.

2.1. Simulation Setup

A three-phase rectifier inverter power source is a sophisticated welding power source that utilizes both rectification and inversion techniques to supply stable and efficient power for welding operations. This technology offers several advantages over traditional welding power sources, including improved energy efficiency, precise control of welding parameters, and reduced harmonic distortion. The first model simulated in SIMSCAPE was of the rectifier-inverter power source configuration (Fig. 2).

In the first stage of operation, the incoming three-phase AC voltage from the power supply is converted into DC voltage through a rectifier circuit. This rectification ensures a smooth and continuous DC power supply, which is essential for maintaining a stable welding arc. The DC voltage is then inverted back into the AC voltage of the desired frequency using high-frequency switching techniques. IGBTs are used as the high-speed switching device in the inverter circuit and is controlled using the PWM mechanism. The AC voltage signal thus obtained is then transformed using High-frequency transformers. These are much smaller than their counterparts at lower frequencies. A suitable step-down is applied to the transformer output. Fast recovery diodes can then be, used to rectify this reduced AC voltage. This output is suitable in the process of MIAB welding. The inversion process allows precise control over the output waveform, including voltage, current, and frequency facilitating optimal performance in various welding processes. The rectifier inverter power source can convert and regulate power more efficiently. Inverter technology allows for a more compact and lightweight design owing to the high-frequency transformer, making the power source portable and suitable for various welding applications, including fieldwork.

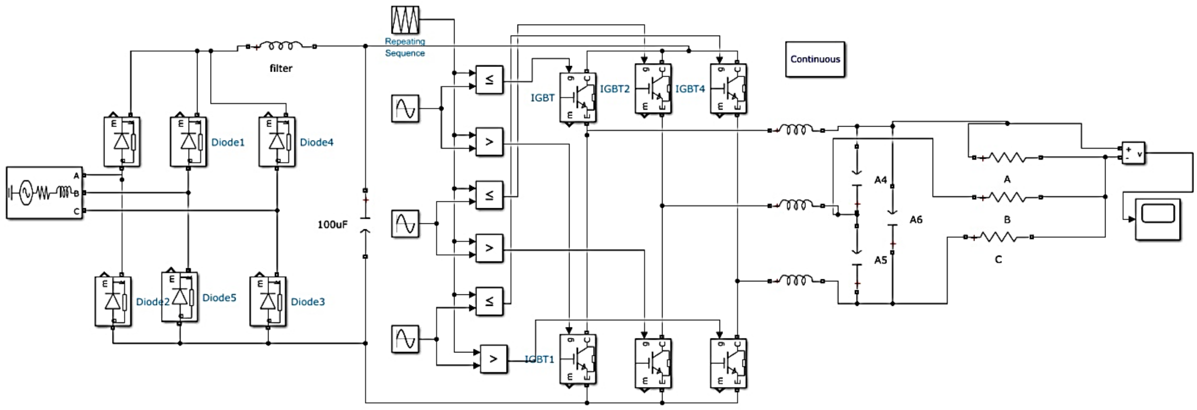

Fig. 2. Simulation circuit of the designed inverter power source

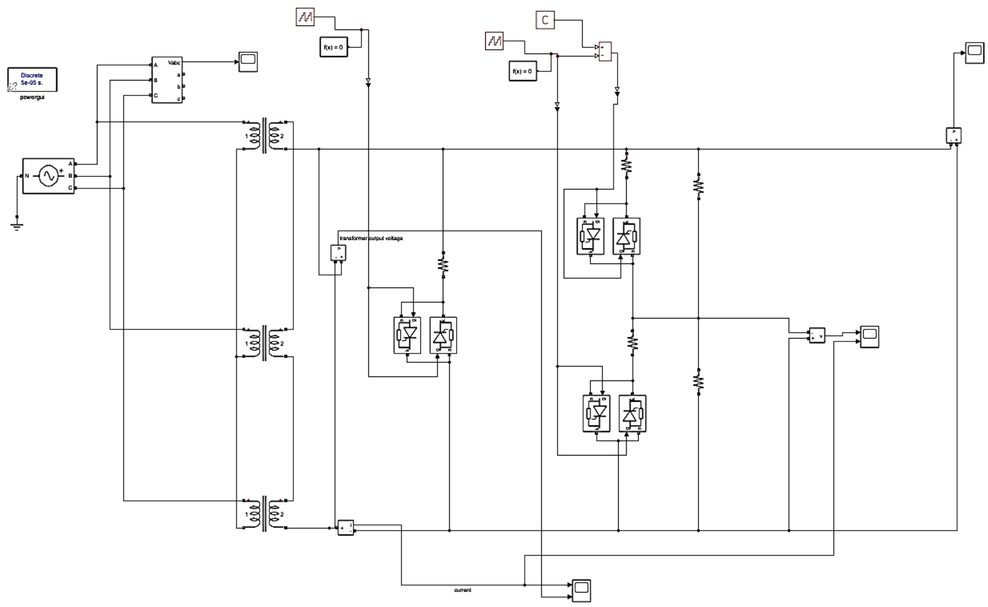

Fig. 3. Model for observing control of current and variation of voltage during the weld sequence

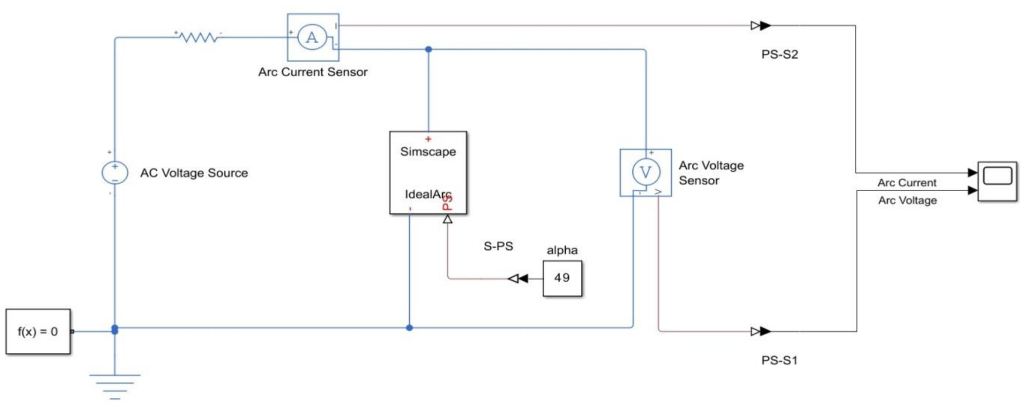

Fig. 4. The simulation model for representing an ideal ARC

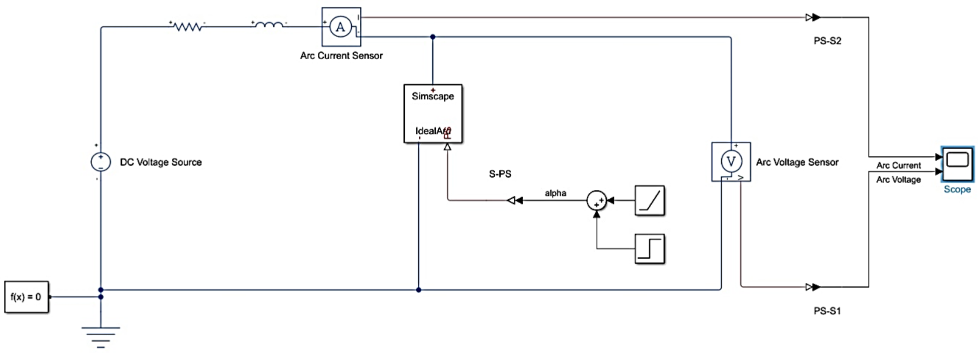

Fig. 5. Simulation model representing arc formation by the opening of the contacts

The second model, Fig. 3 was designed for the control of arc current as required in the two stages of the MIAB weld sequence. The ability to precisely control welding parameters such as voltage, current, and waveform shape enables greater flexibility and customization, leading to improved weld quality and productivity. The model also displays the variation of voltage as experienced in the welding sequence during the formation and stabilized condition of the arc.

Three-phase supply is given as input to the three-phase transformer with a specific winding connection. The output obtained from this transformer is a single-phase supply of reduced magnitude, depending on the winding ratio. A switching potentiometer, implemented with two TRIACs (TRIODE for AC) and series resistors is then used for simulating the variation of arc voltage. Counter-logic with parallel switch and a resistor is used to implement the variation of current by controlling the gates of TRIAC. The parallel connection of the time-controlled switch enables the control of current as required for the two stages of MIAB welding.

The third simulation model, Fig. 4 was studied for analysis of an ideal arc. The arc initiation, formation, evolution, extinction, and subsequent contact separation and recovery processes play crucial roles in the reliable operation of electrical switching devices. Understanding these phenomena is essential for designing and maintaining efficient and safe electrical systems. The internal conditions of the arc are intricate and to study the electrical characteristics of the arc, the differential equation model is commonly used to represent the arc. The arc model defines the interaction between the arc and the circuit during the current interruption. This is significant to the MIAB Welding study since the formation of arc happens by the creation of an open circuit and the arc behavior, henceforth, affects the electrical and thermal characteristics of the tubes in between which the arc is formed.

Arc current and voltage were observed for the ideal arc which is simulated using mathematical equations that describe the arc characteristics [18,19,20]. The Simulink model of ideal arc is described in terms of the following equation:

$$v + \tau_v . \frac{dv}{dt} = (a. R_c . i_t)/[R_c * i_t * \tan^{-1}(x)] \quad (5)$$

Where: a= input voltage to the arc model,
x= time varying parameter dependent on material coefficient and arc voltage, current;
R_c=corona resistance; τ_v=arc time constant for voltage; i_t=time varying current.

The fourth simulation model illustrated the formation of an arc due to the opening of the electrical contacts, Fig. 5. In this welding process, an arc is formed due to the interruption of the electrical current flow. When the current is abruptly interrupted, the phenomenon of arc discharge, occurs, causing a localized ionization of the air or insulating medium between the contacts.

The ideal arc component is simulated to analyze open circuit arc formation using a combination of a ramp and step input function. A step signal is generated at the specified contact separation time to control the start time of contact and separation of the arc-generating device. The ramp function is configured to have a slope of 1000 and a start time of 0.01s, while the step signal has a step time of 0.01 to rise from an initial value of zero to a final value of 24 [18].

The simulation circuits were analyzed to meet the objectives and the observations made are described in the following section.

3. SIMULATION RESULTS

The simulation results demonstrated that the proposed power supply design could reliably provide the required current levels for MIAB welding. In the first model, Fig. 2, a rectifier inverter configuration has been analysed. A phase ac supply is given as input to the power converter circuit (Fig. 6). This supply given as input to the rectifier, generates the below signal (Fig. 7). The DC voltage is then fed into the inverter where the switching device is triggered based on the PWM technique. The voltage generated out of the controlled inverter circuit is shown in figure 8.

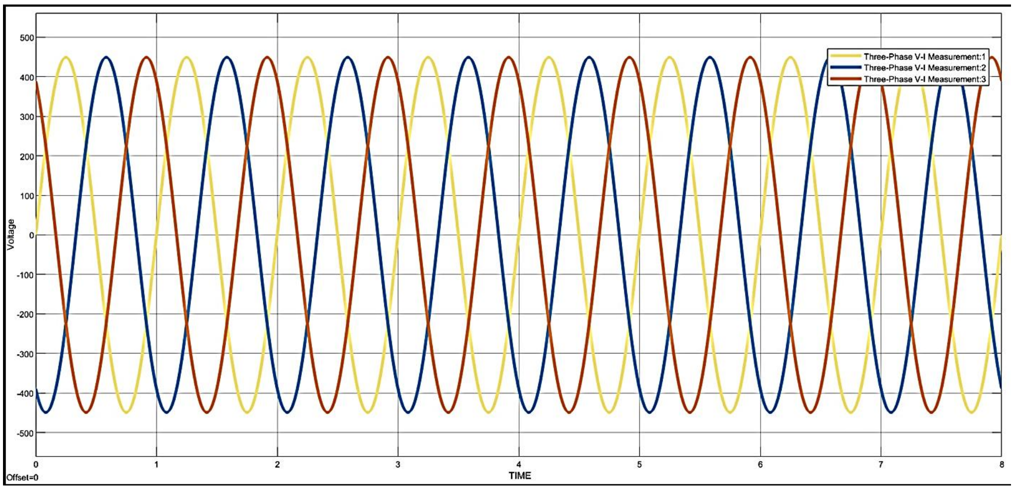

Fig. 6. Three-phase input supply waveform

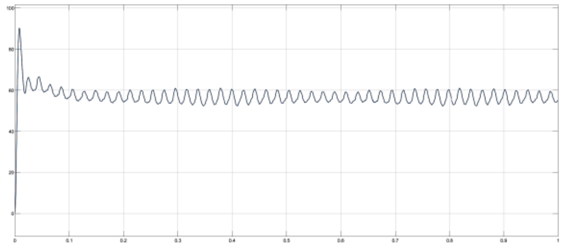

Fig. 7. Rectifier Output of the power supply design

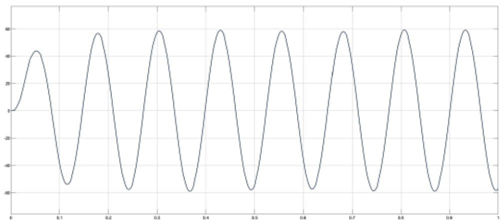

Fig. 8. Inverter output waveform

In the second simulation model, Fig. 3, a three-phase supply is given to the three transformers, and a single-phase supply is obtained in the below-shown range, Fig. 9. A Switching potentiometer with a time counter logic has been utilized for obtaining variation of voltage and the current. The current is controlled to vary from 190 A for 4 seconds to 320A further. The switching potentiometer gets the single-phase supply from the transformer output. The voltage obtained at the circuit output is observed to dip from 60V for the first 1.5s to 24V,

Change in the voltage levels can be considered the same as the voltage drop in the arc from the formation to the cvasistationary phase (Fig. 9.) The third simulation model, Fig. 10, simulates the ideal arc to understand and analyze the behavior of the welding arc in welding processes. While actual welding arcs exhibit complexities and variations, the ideal arc representation provides a simplified framework for studying fundamental arc characteristics. The current and voltage in the ideal arc are represented in Fig. 10.

The ideal arc representation serves as a valuable conceptual tool for understanding fundamental arc characteristics and behavior in welding processes. While it may involve simplifications and idealizations, it provides a solid foundation for theoretical analysis, process design, and education in the field of arc welding.

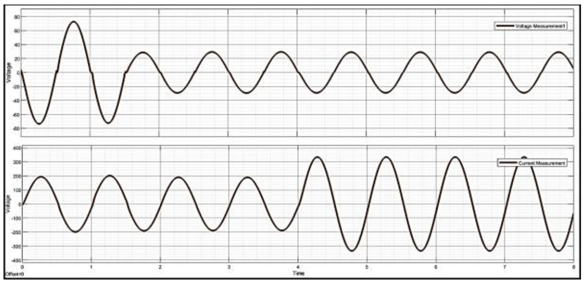

Fig. 9. Transformer output Voltage and Current Waveform

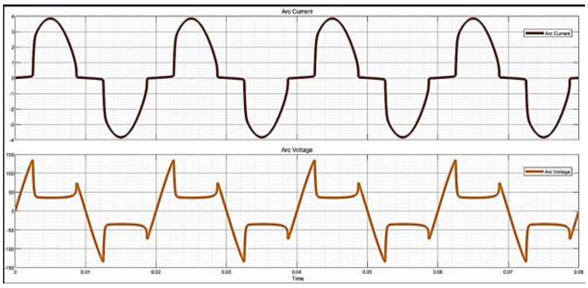

Fig. 10. The simulation result of an ideal ARC

The fourth simulation model is used to analyze the arc behavior when it is formed due to the opening of the electrical contacts. The waveforms show the voltage and the current in case of arc formation by the opening of contacts and sudden interruption of current flow (Fig. 11).

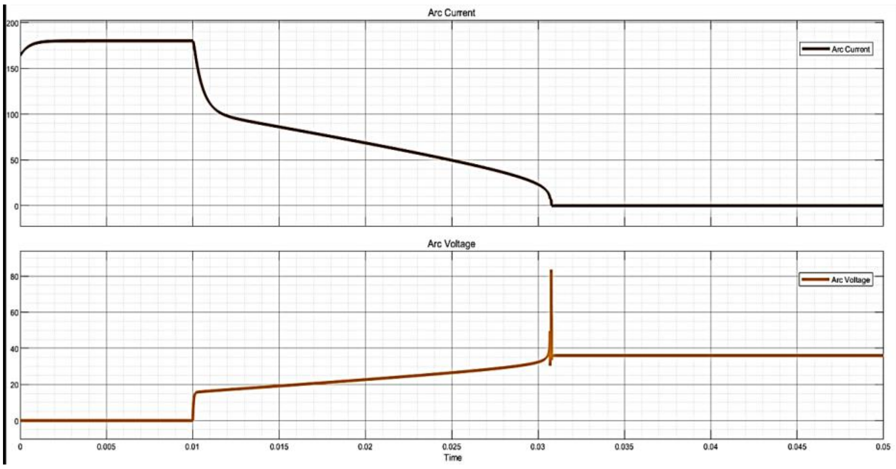

Fig. 11. Current and voltage variation in case of arc formation by the opening of electrical contacts

4. EXPERIMENTAL TRIALS

The observations made from the simulation study of the inverter-based power converter and current control mechanism were utilized in the configuration of PLC and the power supply used in the experimental trials conducted for the welding of two MS1018 tubes in the prototype MIAB welding setup at the Advanced Welding Research Lab at Dayananda Sagar University, Bangalore. Welding was done for tubes of 27mm Outer Diameter (OD) and a 1.5 mm thickness, The MIAB welding setup, Fig 12 was used with the tabulated parameters in Table 1 and the corresponding weld outcomes were obtained. A welding current of 155Aor 160A in stage I ie. the arcing and heating stage followed by a forging current of nearly 250A in stage II are determined to be suitable to establish the weld for the considered geometry of weld tubes, with a gap of 1mm between the tubes. The welding setup comprises the following components: Power Supply, PLC Unit, Welding Assembly, Hydraulic System, Pneumatic System, and Weld Heads with external magnets.

Experimental trials were conducted with parameter values approximately set per previous literature [1, 2, 3, 4] reported for experimental work conducted on similar materials and based on trial and error. The PLC was programmed for the two stages' current amperage and duration. This setting depends on the weld material's properties and its geometry. Several trials were made with the variation of current and time settings. For the experimental material and its properties, the settings made in the PLC are listed in table 2.

Table 2. PLC Configuration for the MIAB welding

Parameters	Stage I	Stage II
Current [A]	155	265
	160	270
Time [s]	4.8	0.3
	5	0.3

Samples welded with this parametric variation were subjected to destructive and non-destructive tests to ascertain the impact on the weld characteristics and to also analyse the inter-dependence of parameters. Results for some of the samples are presented in table 3.

Fig. 12. MIAB Welding setup

Table 3. Observations with established range of process parameters

Sample	Welding current [A]	Upset current [A]	Welding time [s]	HAZ [mm]	Weld	Visual Control
S1	158	265	4.8+0.3	16		Insufficient reinforcement

S2	155	270	5+0.3	18		Non-Uniform bead
S3	155	270	4.8+ 0.2	24		Good Reinforcement

5. RESULTS AND DISCUSSION

The weld samples were subjected to various testing and characterizations. The detailed reports of the tests have been reported in earlier publications [2,3]. Figure 14 shows the microstructural images of the weld region, base metal, and HAZ for a sample. Microstructure did not reveal any micro-cracks or asperities in the fusion zone. Micro-examination in the weld zone revealed the formation of acicular ferrite, while that at HAZ and the base metal exhibited fine grains of ferrite with pearlite. The upset force differentiated the microstructures of the weld and the base metal. This welding method creates hot zones that cover 30% of the weld area. Restricted molecular transformation at the weld contact is the result of reduced bainitic needle development in the upset stage. The upset phase expels overheated coarse grains, which form the reinforcement, leaving the fine grain part of the faying surfaces to create the weld zone.

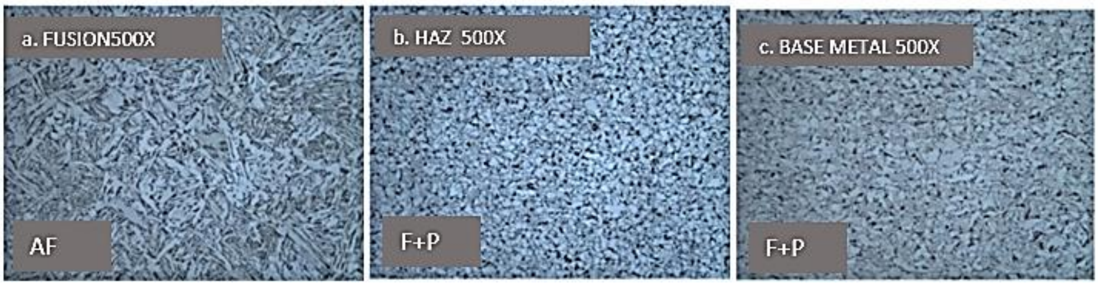

Fig. 14. Microscopic images for sample S1: a. fusion- 500x, b. haz-500x, c. base metal -500x

Table 4. Tensile test results

Sample	Welding current [A]	Upset current [A]	Weld time [s]	HAZ [mm]	Ultimate tensile load [kN]	Tensile strength [MPa]	Test Result
S1	158	265	4.8+0.3	18	117.8	503	Ductile fracture at base metal
S2	158	265	5+0.3	17	124.7	491	Ductile fracture at base metal

Table 6. Radiography Results

Sample Number	Current I_1, I_2 [A]	Time t_1, t_2 [s]	Segment	Observation/ Remark	Result
1	158,270	5,0.3	A	slag inclusion	 Not accepted

2	158,270	5,0.3	B	no significant defect	 Accepted
3	158,270	5,0.3	C	no significant defect	 Accepted

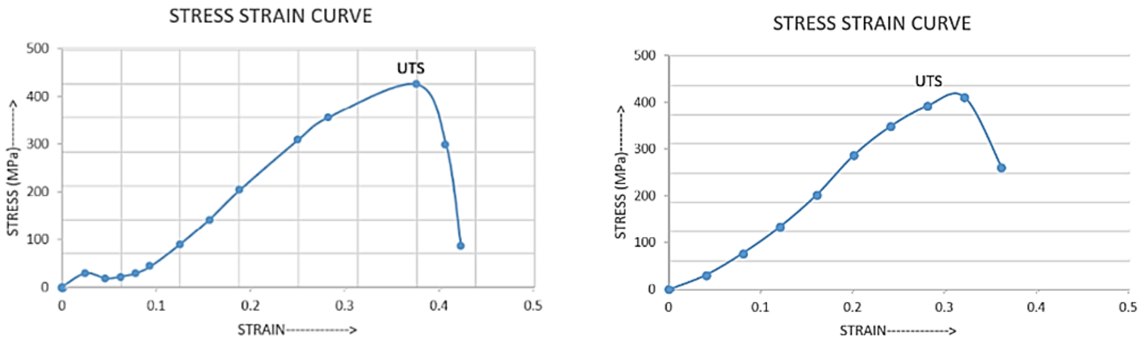

Fig. 15. Stress-Strain Curve of Samples: a) sample S1; b) sample S2

Welding behaviour is considerably affected by hardness. Due to fast heating and cooling, welding causes metallurgical changes. Rapid cooling following the welding upset stage forms hard microstructures of low-temperature bainite in the HAZ.

Hardness testing identifies metallurgical changes in welds. Hardness is determined from indenter penetration. Hardness variations at distinct zones in the weldment are listed in table 5.

Table 5. Hardness test results

Region	**Hardness Value (HV)**			
	Location 1 (HV)	**Location 2 (HV)**	**Location 3 (HV)**	**Average HV**
Weld	189	194	196	193
HAZ	212	205	185	200
BASE	177	174	170	174

The hardness curve shows the variation in hardness for the test sample at increasing distances of 1mm from the weld Fig. 16).

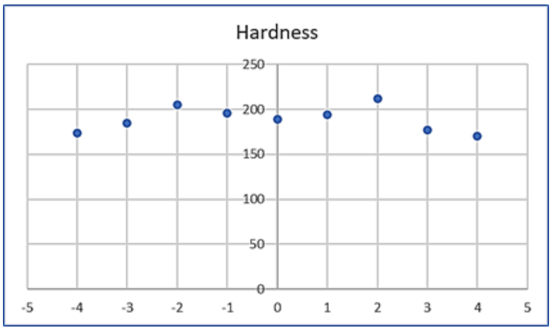

Fig. 16. Sample S II Hardness variation at different locations with respect to distance from the weld

The delayed bainite growth causes reduced hardness in the weld region due to deformation caused to the microstructure in the upset phase. Lowest hardness is found to appear in zones having columnar grains with large secondary dendrite arm spacing. This zone is described by a coarse structure and reduced carbon content in the alloy.

Radiography tests were carried out on MIAB welds with and without the reinforcements. Grinding removes the reinforcement for the latter, and the weld area is cleaned before subjecting to a radiography test. Results of the tests are recorded in Table 6. as per ASME Section VIII Div 1. MIAB welded tube without the reinforcement is as shown in Figure 17. In this sample, the flash/ reinforcement is grinded.

Fig. 17. MIAB Weld Sample without the reinforcement

The samples did not include porosity, slag inclusion at the weld interface, or excessive coalescing surface penetration. Sample porosity is low without reinforcement, indicating significant reinforcement pores but low weld line pores. All impurity-free butt joints with reinforcement removed will have acceptable radiography results. Weld pores may form due to gas molecules interacting during heating and cooling cycles at the weld periphery. These can be avoided with the use of shielding gas in the weld technique. The following results were derived from the various categories of tests:

1. Upset current and its duration - critical for the expulsion of the molten material, impurities and for the flash deposit of the plasticized material at the weld interface. Incomplete expulsion also causes formation of distinct decarburized zone.
2. The arc current, upset current, and duration of both stages are based on the material properties, tube thickness, geometry, and tube gap.
   a. Arc current of 156-158A, for 5 s.
   b. Upset current of 270A, for 0.3 s.
3. NDT of the MIAB weld samples shows acceptability of the samples,
4. Variations in the weld joint formed can be attributed to the following factors:
   a. Irregularities in the weldment;
   b. Variations in upset pressure;
   c. Rate of application of pressure;
   d. Magnetic properties of the AlNiCo or ferrous magnets;
   e. Tube gap length;
   f. Observed Irregularities help in arriving at the parametric range for crack-free weld formation.

The three-phase rectifier inverter power source represents a significant advancement in welding technology, offering enhanced performance, efficiency, and control capabilities. Its ability to efficiently convert and regulate power, coupled with advanced control features, makes it a valuable tool for modern welding operations.

This configuration of power sources finds applications across a wide range of arc welding processes. [21]. The compact and automated nature of the proposed power supply design has been observed to have the following features:

- The inverter rectifier configuration is well-suited for MIAB welding power supply requirements and also for other high-demand industrial environments where control, reliability, efficiency, and quality are paramount
- The automation of current transitions enhances MIAB welding process consistency and reduces the likelihood of human error. The ability to control amperage as required by the application cycle broadens the potential uses of this power supply design beyond MIAB welding.
- The variation of voltage simulated in the model explains the drop in the arc voltage due to variations in the resistance of the arc and the surrounding medium.
- The compact design of power supply unit can facilitate easier adoption of MIAB welding in existing industrial systems, making it suitable for a wide range of material joining requirements.

6. CONCLUSIONS

- This study presents the simulation studies for a compact power supply design for arc welding and is highly suitable for MIAB welding, using inverter-rectifier configuration and current control implemented with the voltage controller circuits to meet the specific amperage requirements of the process. The integration of these technologies not only enhances the precision and stability of the welding current but also contributes to improved energy efficiency and operational flexibility. The following key outcomes were observed from the study:
- The inverter-rectifier configuration provides a reliable power supply for MIAB welding and other industrial requirements, ensuring consistent output even under varying load conditions. This stability is crucial for achieving high-quality welds.
- The implementation of voltage controller circuits enables precise regulation of the welding current, ensuring that it meets the specific amperage requirements of different welding processes. This precise control is essential for maintaining the integrity of the weld and preventing defects.
- The proposed design is compact and automatable, making it a preferred choice for various industrial applications requiring precise amperage control and compact form.
- Dependence of weld characteristics on the power supply variations and control necessitates the design of an accurate, reliable power supply circuit configuration.
- The proposed design of the inverter-rectifier system allows for easy adaptation to various welding processes and materials. This flexibility is beneficial for industries that require versatile welding solutions to accommodate diverse production needs.

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