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Original Article

Performance analysis of a low-power-consumption electric arc welding machine constructed using cost effective materials

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Abstract

Electric arc welding is a widely used fusion welding method. Electric power is supplied to the primary winding of the transformer as the input, and due to induction, it is transferred to the secondary winding from which it will be utilized for welding. Most of the villages in developing countries are getting a very low electric power supply, hence the use of a commercially available electric arc machine is challenging. Some countries are unable to manufacture arc welding machines because of technological backwardness. It is expensive for those countries to import the welding machines. In this study, an economical and low-power-consumption electric arc welding machine has been fabricated using only local raw materials. The performance parameters of the arc welding machine, such as output voltage and output current, were measured and good results were obtained.

Keywords: electric arc welding machine, arc welding transformer, economical welding machine, low power consumption electric welding machine

1. Introduction

Welding is a method of melting and joining metal pieces by heating them with electricity or a flame. Arc welding is a method of joining metals by using electricity to generate enough heat to melt the metals, and the molten metals, when cooled down, result in metal binding. In a type of welding, a power supply creates an electric arc between an electrode and the base material in order to melt the metals at the welding point. Arc welding processes can be manual, semi-automatic, or fully automated (Okandeji, Olajide, Jagun, & Kuponiyi). In its most basic form, a metal arc welding machine (MAWM) provides the electric circuits that generate the arc required in arc welding (Ahmad, Sheikh, & Nazir, 2019). A step-down transformer provides the welding power from an arc welding machine. This means that the incoming voltage, which could be in the 220-240 Volt range, is stepped down to 30-100 Volts (Hagedorn, Sell-Le Blanc, & Fleischer, 2018). The A.C. arc welding machine has a current control regulator in the transformer, which allows the operator to select the correct current (Amp) for the size of electrode being used. Ethiopia is a developing country where technology is underutilized. More than 85 percent of Ethiopians live in rural areas where electricity is not widely distributed. Various technologies, such as arc welding, have yet to be introduced. Even when projects are investigated by different scholars in different countries, welding is the key to joining metallic materials in any type of use. Arc welding is accomplished through the use of electricity.

However, power is still lagging in Ethiopia. As a result of the high power required to weld metals, the welding problem remains unsolved. People living in both rural and urban areas will benefit from joining metals for various purposes when welding machines run on simple power. As a result, when people become accustomed to using metals rather than wood, the destruction of plants naturally decreases. And, one can save metals from rust and wastage. This study aimed to develop a new arc welding process for the problem of joining metals in various applications. The research study differs from locally manufactured products in that it has been thoroughly analyzed, designed, and modeled. It also ensures high efficiency, low cost, easy maintenance and repair, and

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low power consumption. With a single-phase power (220 v and 9 kW) and as output result of this research, the manufactured machine can cut strong high-duty metals such as H.S.S.

2. Materials and Methods

2.1 Materials

The following desirable characteristics were taken into account in the material selection for this design of a local arc welding machine. Modulate strength, toughness in working conditions, sustain vibration caused by rotating parts, appealing appearance, light weight, retain strength under loading, economical, and available in Ethiopian markets as given in Table 1.

Table 1. Materials used for parts of the welding machine

Machine components	Materials used
Core of transformer	Iron sheet metal
Primary coils	Copper wire
Secondary coils	Copper wire
Sticky purpose	Cola
Loss resister sheet	Classer
Non-conductive purpose	Varnish
Cover of cores	Wood plank
Frame	Cast iron
Body of frame	Wood

2.2 Primary and secondary winding materials

The authors have considered numerous criteria while choosing the correct material, including weight. This research study examines and compares the physical qualities of various copper and aluminum materials, which may influence their selection for transformer winding (Muhammad, Selvakumar, Iranzo, Sultan, & Wu, 2020).

While copper has a lower resistivity than aluminum, copper has a far higher mass density than aluminum. Copper has a lower expansion coefficient than aluminum, yet copper has a higher heat conductivity than aluminum. It's also worth noting that copper has a higher tensile strength than steel. Some of the most essential physical features of copper and aluminum are compared in the Table 2. When two materials have the same resistance, it's fascinating to compare their pricing. For the same power, the length of an aluminum winding will be somewhat longer than the length of a copper winding. However, as compared to the effects of area, price, and mass density, the influence of length is minor. The copper wire has been chosen for the primary and secondary windings of the core type transformer based on the physical qualities listed above.

Table 2. Comparison of copper and aluminum materials

Physical property	Copper	Aluminum
Resistivity, Ʊ-mm^2/m	2.4	3.21
Mass density, kg/dm^3	8.89	2.7
Expansion coefficient, mm/ (m ^{0}C)	16.7	23.86
Thermal conductivity, W/ (m K)	398	210
Tensile strength, MPa	124	46.5
Melting point, ^{0}C	1084.88	660.2
Specific heat, J/ (kg K)	384.6	904
Body of frame	Wood	

2.3 Methods

It is easy to recognize the needs of rural and urban societies, such as how much they need to reduce power loss and low-cost availability of welding machine based on information from the primary data of interviews and their desire is to focus on modernizing the country's technological system within the next few years. As a result, this research study chose to create a local arc welding machine utilizing the following methods.

2.4 Construction and analysis of arc welding transformer

Arc welding processes use an electrical power supply to create and maintain an electric arc between an electrode and the base material in order to melt metals at the welding point. Electric arc welding involves the formation of low-voltage, high-current arc between an electrode and the metallic work piece. There are three methods for lowering the power: system voltage transformer method, rectifier method, and the motor generator method (Kalair, Abas, Kalair, Saleem, & Khan, 2017). A transformer is a stationary device that converts electric power from one circuit to electric power of the same frequency in another. It has the ability to increase or decrease the voltage from the supply based on the requirements, and a constant power is maintained by adjusting the current. Step-up and step-down transformers are the two types of transformer (Li, Li, He, Xu, & Wu, 2011). Because welding requires a high current, a step-down transformer was chosen for this design of a local arc welding machine: the transformer reduces voltage while increasing the current.

The physical basis of a transformer is mutual induction between two circuits connected by a common magnetic flux. In its most basic form, it consists of two inductive coils that are electrically separated but magnetically linked by a low reluctance path. The mutual inductance of the two coils is extremely high. When one coil is connected to an alternating voltage source, an alternating flux is created in the laminated core, the majority of which is linked with the other coil, producing mutually-induced electric motive force (Gladyshev, Gladyshev, & Okrainskaya, 2020; Krishnan, 2017). When the second coil circuit is closed, a current flows through it, transferring electric energy (magnetically) from the first coil to the second coil. The first coil, into which electric energy is fed from the alternating current supply mains, is known as the primary winding, and the second coil from which energy is drawn is known as the secondary winding. The primary and secondary coils are positioned around the laminated core differently in two types of transformers. Core-type and shell-type are the two types (Rao, Lenine, & Sujatha, 2020). A core type transformer is constructed in this research study.

2.5 Arrangement of primary and secondary circuits of the arc welding transformer

The laminated core is comprised of rectangular 0.5 mm thick iron steel sheet metal in both the limp and the yoke parts. The rectangular arc welding transformer was completed after the half L-shaped single limp and yoke were installed. The dimensions of standard 2 m × 1 m sheet iron steel metal were cut out in rectangular pieces as shown in Table 3 below.

The steel laminate is insulated with a non-conducting substance like varnish before being molded into a core. Iron ore steel has a significantly better ability to conduct magnetic flux than air. Permeability refers to the ability to carry flux. When alternating current circuits for energy distribution were originally established, steel cores were employed in power transformers. Yokes connect the two limbs and are equal to or larger than the limbs in the number of laminate layers. The quantity of parts involving iron steel in each limp and yoke of a local arc welding machine is listed in Table 4 below. Two hundred twenty pieces of iron were used to construct a full rectangular shaped transformer limp and yoke core for this research study.

Table 3. Dimensions of core parts of the transformer

Core part	Dimensions in mm	Shape of part
Right limp	80 × 600	Rectangular
Left limp	80 × 600	Rectangular
Top yoke	80 × 300	Rectangular
Bottom yoke	80 × 300	Rectangular

Table 4. Quantity of iron steel pieces in laminated core

Core part	Quantity of pieces	Material
Right limp	80	Iron steel
Left limp	80	Iron steel
Top yoke	40	Iron steel
Bottom yoke	40	Iron steel

The existence of a magnetic flux, which provides mutual linkage between the two electric circuits, namely the primary and the secondary windings operating at the same frequency, is required for the operation of a transformer. When a load is connected across the secondary terminals, the secondary current produces a demagnetizing effect according to Lenz's law (Lowe & Nave, 1973). As a result, there is no secondary current when there is no load, and the secondary winding then has no effect on the primary current. The primary winding behaves like a choice, with a very low resistance and a very high inductance. In addition, arc welding is an AC process that uses a single-phase transformer (Moreira, da Silva, & Paredes, 2018).

The primary winding of the step-down transformer has more turns than the secondary winding, and the secondary voltage is lower than the applied voltage in the primary winding, opposite to a step-up transformer (Yamane, de Moraes, Espinosa, & Tenório, 2011). Furthermore, because the current in the primary winding is lower than the current in the secondary winding, the secondary winding has fewer turns than the primary winding.

2.6 Analysis of voltage and turn ratio

The ratio of number of turns in the primary winding to the number of turns in the secondary winding on the laminated core is referred to as the turns-to-turns ratio (Katargin, 1966). The output voltage will be lower than the input voltage if the primary winding has more turns of wire than the secondary winding. The following formula is used to compute the turn ratio of a local arc welding transformer.

$$\textit{Turn}\ \text{ratio} = \frac{N_1}{N_2} \tag{1.1}$$

where N_1 = number of turns in primary limp winding
N_2 = number of turns in secondary limp winding

The primary winding of the transformer is wound with 2.5 mm diameter copper wire to ensure the performance of the arc welding equipment. The total number of turns in the lips pole was 204 in primary winding and 68 in secondary winding. Because the purpose of the study is to weld heavy-duty metals, 2.5 mm diameter copper wire plays a significant part in the transformer's primary and secondary windings. On both the primary and secondary sides of step-up and step-down transformers, the power rating is always the same. The secondary voltage and current can be calculated using the turns ratio as follow:

$$\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{I_2}{I_1} \tag{1.2}$$

where E_1 = voltage in primary (in V)
E_2 = voltage in secondary (in V)
I_2 = current in secondary (in A)
I_1 = current in primary (in A)

Alternative materials can be chosen to create a two-sided limp transformer, other than copper wire. To prevent short circuits and for safety, the wires must be electrically isolated from each other and from the environment. The majority of wire and cable insulations are made of polymers with a high resistance to electric current flow. The primary function of the jacket on a cable is to protect the insulation and conductor core from external physical pressures or chemical deterioration. The following materials are utilized as insulators for safety: alkalized varnish, cotton cloth (jodi/Abujedi), carton, classer, and wood plank.

The wood planks shown in Figure 1 aid in forming a strong link and preventing them from connecting with one another. The classer is a heat-resistant paper that takes a long time to disintegrate as shown in Figure 2. The magnetizing current is flowing in the primary winding as shown in Figure 3. When voltage is provided to the exciting or primary winding of the transformer, this current creates a flux in the core. The flux flow in a magnetic circuit is comparable to a current flow in an electrical circuit. Losses occur when the flux passes through the steel core.

When the flux runs through the iron steel core, the steel suffers from two types of losses. These are losses due to eddy currents and to magnetic hysteresis. The cyclic reversal of flux in the magnetic circuit causes hysteresis losses, which can be mitigated by metallurgical management of the steel

Figure 1. Wood planks on laminated core

Figure 2. Classer paper

Figure 3. Primary winding of right limp of a transformer

(Aliyu, Ahmed, Stannard, & Atkinson, 2019). Eddy current losses is created by induced currents within the steel, caused by the passage of magnetic flux normal to the width of the core, and these can be reduced by reducing the thickness of the steel laminates or by applying a thin insulating coating (Hamzehbahmani, Anderson, Hall, & Fox, 2013). The use of varnish and white cola to cover this coating stage is a well-researched subject.

As indicated in Figure 4, the primary and secondary windings are assembled using a machine. Moreover, in this research the machine designed was air cooled, as shown in Figure 5. This type cooling uses the surrounding air to transfer heat away from the welding gun. Moreover, due to the high temperatures in a heavy duty welding gun, air cooling is more appropriate than water cooling. The air-cooling system for the machine was assembled using a commercial fan system.

2.7 Analysis of power selectors

In this study the machine output was separated into five sections, each with a constant voltage but with varied resistances. The power selectors have varied power stages

Figure 4. Primary and secondary windings in the machine

Figure 5. Air cooling system

based on the metal characteristics. Metals have varied quality, ranging from sheet metal to high carbon metal, and their strength varies. To weld the metals, the power must be balanced according to the strength of the metals. As a result, the following patterns were employed to develop each of the machine's five power choices. It is self-evident that power is equal to the product of current and voltage (Kock, Taconis, Bolhuis, & Gravemeijer, 2015).

$$V = R \times I \tag{1.3}$$

where R = resistance of material

$$R = \frac{\rho \times L}{A} \tag{1.4}$$

where ρ = resistivity of the copper
L = length of the circulating copper wire
A = area of the copper wire

It is possible to calculate the area of a wire since the cross section of copper wire is circular and standard with 2.5 mm diameter. According to new research, when cotton cloth (Jodi/Abujedi) varnishes copper, it becomes hard and sufficiently strong during welding operations, even if the mechanic has been using it for a long period. Because of the ticked materials, the machine cannot get heated.

$$A = \frac{\pi \times d^2}{4} \tag{1.5}$$

where d = diameter of the copper wire.

It is feasible to relate voltage and current using Ohm's law after computing each parameter of resistance and wire area. Finally, each selector's power should be discovered.

$$P = V \times I \quad (1.6)$$

$$V = I \times R \quad (1.7)$$

$$P = I^2 \times R \quad (1.8)$$

where P = power of output selector.

The five output power selectors can be easily determined with constant output voltage as shown in Figure 6.

$$P_1 = I_1 \times V$$
$$P_2 = I_2 \times V$$
$$P_3 = I_3 \times V$$
$$P_4 = I_4 \times V$$
$$P_5 = I_5 \times V$$

Here P_1, P_2, P_3, P_4, and $P_5$are the output powers of the local arc welding machine.

And I_1, I_2, I_3, I_4, and I_5 are the output selector currents.

If a power transformer had a solid core, the losses would be quite significant, and the temperature would be excessive. To lower the thickness of the individual sheets of steel normal to the flux and hence reduce losses, cores are laminated from very thin sheets, such as 0.23 - 1 mm. To prevent shorts between the laminations, each sheet is covered with a very thin insulation. It's difficult to calculate eddy current loss from resistance and current data, but experiments have proven that the eddy current power loss in a magnetic material may be calculated using the equation below (Wang, Wu, Chen, & Yang, 2021).

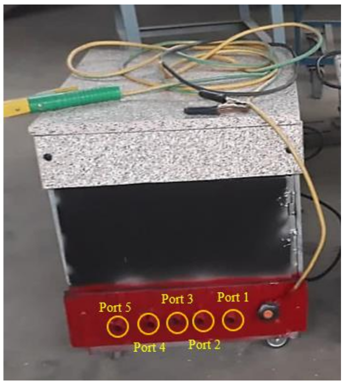

Figure 6. Fabricated arc welding machine with five output powers

$$P = K \times B^2 \times t^2 \times f^2 \times v \quad (1.9)$$

where K = eddy current coefficient.
B = maximum value of flux density (in wb/m^2)
t = thickness of lamination (in meters)
f = frequency of the magnetic field (in Hz)
v = volume of magnetic material (in m^3)

However, in large capacity transformers, the most cost-effective use of core material necessitates that the core be ideally a circular, because a circle has the smallest periphery for a given area, and thus the windings that are placed around the core have the shortest mean turn, resulting in a lesser amount of conductor material and thus a lower cost and reduced copper losses.

3. Results and Discussion

The three-welding transformer local arc welding machines are constructed in the Dire Dawa University basic workshop based on the design specifications of this research. Each step-down transformer consists of a laminated, smooth iron steel core carrying two coils that are not electrically connected. The input supply is connected to the first copper coil (primary coil). When a voltage is put across the first coil, it induces a voltage in the second coil due to the magnetic induction field generated by the primary coil. The ratio of turns in the primary and secondary turn coils determines the secondary (induced) voltage. A 2.5 mm diameter copper coil with 204 turns was wound on the surface of smooth iron sheet metal, and a 2.5 mm diameter multi twisted copper coil with 68 turns was employed in each secondary winding. Then, using equation (1.2), a primary voltage of single-phase power supply 220 V induced a secondary voltage of 73.33 V.

$$\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{204}{68} = \frac{220}{E_2} = 73.33\,\text{V}$$

The output voltages are multiplied by the output currents of each of the five terminals of selector to calculate the power into those local arc welding machines. Here 50 A is a standard current supply at 220 V, then maximum current output can be computed theoretically using equation (1.2).

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{220}{73.33} = \frac{I_2}{50} = 150 \text{ A}$$

The welding machine's power is computed by multiplying the volts by the amps and stated as equation (1.6).

$$P = V \times I$$

$$P_1 = V_1 \times I_1 = 220 \times 50 = 11 \text{ kw}$$

$$P_2 = V_2 \times I_2 = 73.33 \times 150 = 10.99 \text{ kw}$$

The total power input into the machine is almost equal to the power output. Therefore, this local arc welding machine is theoretically 99.9 **%** efficient. As a result, the transformer's copper wire winding and iron steel sheet laminated transformer had very low losses.

$$\eta = \frac{power \text{ output}}{power \text{ input}} \times 100\%$$

$$= \frac{10.99}{11} \times 100\% = 99.9 \text{ \%}$$

where η = theoretical efficiency of the machine.

The output power, voltage, and current listed above are the maximum values theoretically calculated. The selector, on the other hand, is ready to regulate the induced voltage of 73.33 Volts to various ports depending on the performance of metallic strengths. As a result, five ports with varying output powers have been prepared. Then, on each of the three transformer machines, experimental tests were conducted using a wattmeter. Short circuit and open circuit tests are the two most prevalent types of conversion tests performed on transformers. The machine output current and voltage were measured using Digital Clamp Multi-meter, shown in Figure 7.

3.1 Short circuit (impedance) test of the manufactured local welding machine

The supply was gradually fed via the other side of the transformer winding up to the full load rating of the transformer once one side of the transformer winding was short circuited. The wattmeter (W), ammeter (A-1.), and voltage meter (V-1.) readings were recorded, as shown Figure 8.

3.2 Open circuit (no load) test of the machine

The high voltage side received normal rated voltage, which caused heating in the primary winding. The MAA and W meter readings were recorded. Considering the fact that copper has resistance losses, in an open circuit the I^2R power can be ignored, and the no load input will be the normal core loss as shown in Figure 9.

3.3 Efficiency of the real manufactured local arc welding machine

A voltmeter and an ammeter were used to measure the input current, input voltage, output voltage and maximum current.

$$P_1=V_1xI_1=220x50= 11kw$$

$$P_2=V_2xI_2=143.1x70=10.017kw$$

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \text{ x } 100$$

$$\text{Efficiency} = \frac{10.017}{11} \text{ x } 100 = 91.06\%$$

The results show that the true power efficiency of the local arc welding machine was 91.06%.

4. Conclusions

In this study an electric arc welding machine was fabricated to address some power and cost issues. The machine was designed to work using single phase power and was prepared using locally available low-cost materials. The primary winding of the transformer had 204 turns of 2.5 mm diameter copper wire, and the secondary winding had similar diameter coil wiring with 68 turns. Due to the compact construction of the transformer, optimal material selection, and fan cooling system, the real local arc welding machine efficiency was assessed at 91.06 percent when working on a single-phase power supply. This result reflects no additional losses under welding conditions. With 8.94 **%** output losses, the machine's total power requirement is 11 kW. When compared to an externally supplied three phase arc welding machine with the same metal thickness, the local arc welding machine has a power differential of 6.7 kW from a single phase power supply. Finally, this constrained local arc welding machine has the best significant value in terms of both power reduction and long-term duty. And, when compared to commercially available welding machines, the cost of the equipment was also considerably reduced by use of the local materials.

Figure 7. Measurement of the output parameters using a digital clamp multi-meter

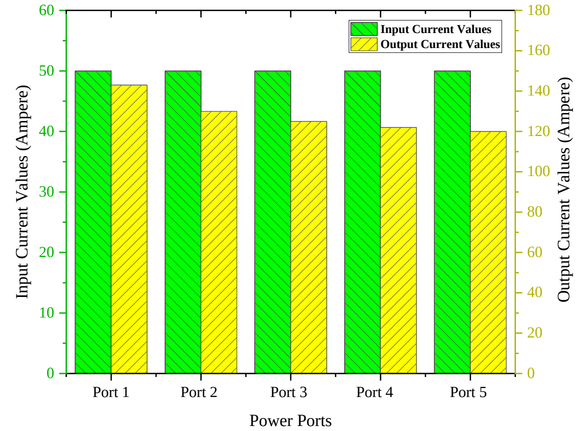

Figure 8. Impedance (short circuit) results for the fabricated machine

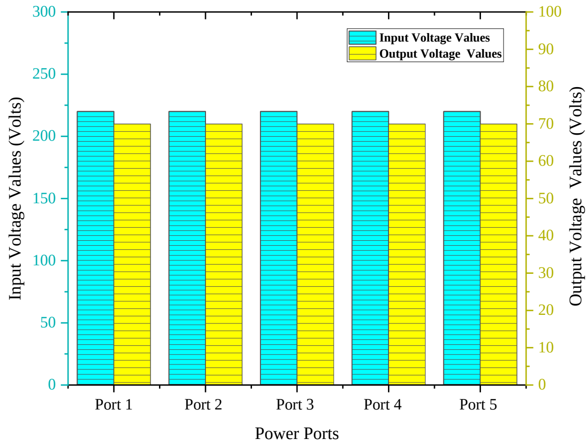

Figure 9. No load test of the fabricated machine

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