Journal of Magnetics 21(3), 374-378 (2016)

ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
http://dx.doi.org/10.4283/JMAG.2016.21.3.374

A Study on the Transformer Design considering the Inrush Current Reduction in the Arc Welding Machine

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(Received 9 March 2016, Received in final form 21 April 2016, Accepted 27 April 2016)

The transformer used in an inverter type arc welding machine is designed to use high frequency in order to reduce its size and cost. Also, selecting core materials that fit frequency is important because core loss increases in a high frequency band. An inrush current can occur in the primary coil of transformer during arc welding and this inrush current can cause IGBT, the switching element, to burn out. The transformer design was carried out in A_P method and amorphous core was used to reduce the size of transformer. In addition, sheet coil was used for primary winding and secondary winding coil considering the skin effect. This paper designed the transformer core with an air gap to prevent IGBT burnout due to the inrush current during welding and proposed the optimum air gap length.

Keywords : arc welding machine, ferrite & amorphous core, inrush current, air gap core

1. Introduction

Recent inverter arc welding machine systems can have high speed switching by using high performance switching elements and are controlled in high frequency. Power IC and circuit, transformer, and reactor for switching take up the largest volume among the components of arc welding machine. Therefore, since the capacity of transformer and reactor is inversely proportional to frequency, it is necessary to operate them in high frequency [1, 2].

Since the capacity of transformer is influenced by magnetic flux density value and the magnetic flux density is determined by core materials, selecting appropriate materials is important. In general, the core materials that are usable in a high frequency band are ferrite, amorphous. When they have the same capacity, the differences of two materials are magnetic flux density, production cost, core loss, etc. This paper designed the transformer based on the information mentioned above.

1) The basic design of transformer was carried out using the A_P method.

2) The secondary winding coil was formed in a parallel circuit as it has low voltage and high current.

3) PSP coil and sheet coil were used for coil method considering the skin effect and proximity effect.

4) To minimize the size of transformer core, it was made in different materials (ferrite and amorphous) and then compared.

Due to the nature of welding machine, when the transformer core is saturated after the welding rod is in touch with a base metal, then a high current above 1000A flows in the primary winding of transformer. This current is called inrush current and the power IC can be burned out due to the inrush current. Thus, it is important to choose the core size of transformer considering the inrush current during design. The methods to prevent inrush current are as follows.

1) Make the size of core big so that the transformer is not saturated.

2) Maintain the size of transformer core as it is and increase the number of the turns of coil instead.

This paper uses an air gap to prevent the saturation of core while maintaining the size and number of turns of core [3, 4].

2. Transformer Design Method for Welding Machine

2.1. Area Product Design

A_P design method is one of the methods of transformer

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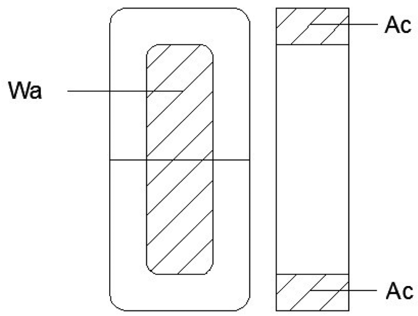

Fig. 1. A_P Design Method.

design and is expressed by the multiplication of W_a and A_c. A_P method can be expressed in formula 1, formula 2, and Fig. 1. The standard for determining the area of W_a depends on the core shape. A_P design method can be shown as in Fig. 1 [5-7].

$$A_P = W_a \times A_c \quad (1)$$

$$A_P = (P_t \times 10^4) / (B_m \times f \times J \times K_f \times K_u) \quad (2)$$

The P_t is a total power, B_m is the residual magnetic flux, K_f is a waveform coefficient, K_u is a window utilization factor, f is the switching frequency, J is a current density. The maximum window size of A_P method must be made considering the space factor of coil, so that there is no interference between each other when the coil is winded inside the window. A_P is proportional to A_c and is inversely proportional to f, B_m, and J. That is, the volume of transformer core gets smaller when it is designed in high frequency and magnetic flux density [8]. Since the switching current through the IGBT flows in the transformer primary, A_P must be designed with about 10% margin [9]. Figure 2 shows the inverter arc welding machine system.

2.2. Parallel Circuit

The winding method using parallel circuit is as in Fig. 3. X represents the start point of coil and X' represents the end point of coil. In the primary size, AA' and BB' are connected in series. The CD of secondary winding coil is coiled in the forward direction and EF is coiled in the reverse direction. Also, coil C is connected to F and D is connected to E, thereby making a total of 2 parallel circuits. C'D'E'F' are connected together. Since the secondary winding coil has low voltage and high current (77V, 389A), the current is divided into two through 2 parallel circuits and thus the current density is halved [10].

2.3. PSP Winding and the Sheet Coil

PSP winding method and sheet coil are used to reduce

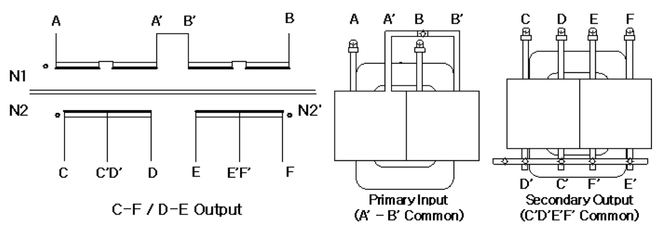

Fig. 3. Winding Method using Parallel Circuit.

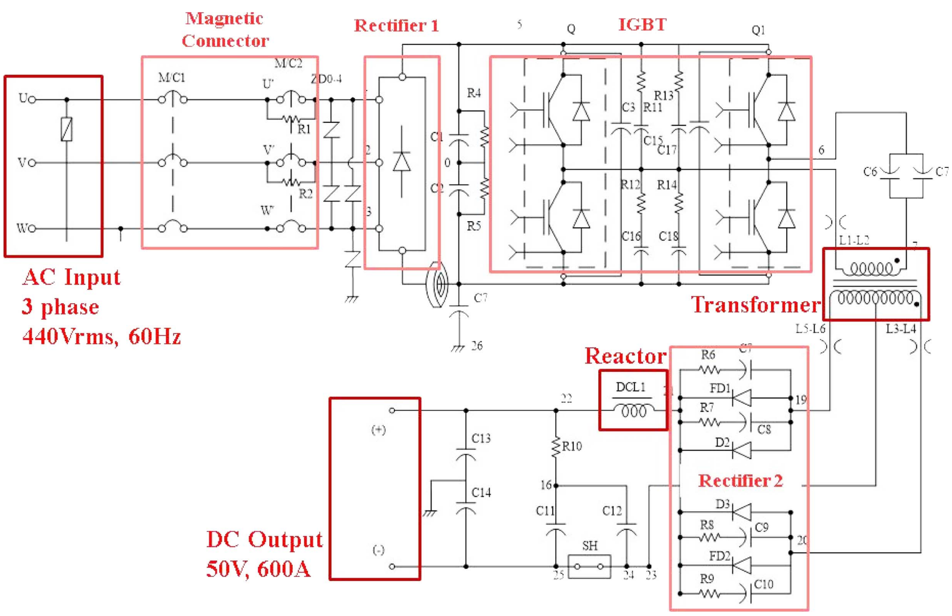

Fig. 2. (Color online) Overview of Inverter Arc Welding Machine System.

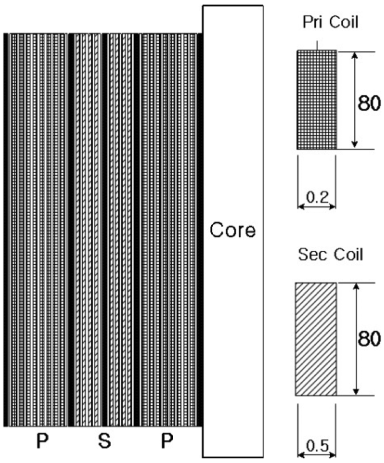

Fig. 4. PSP Winding Method and Sheet Coil.

the influence of proximity effect and skin effect.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{3}$$

μ is a permeability of the coil, σ is a conductivity of the coil.

The skin depth δ of coil from formula 3 is 0.554 mm, and a coil much thinner than skin depth must be used (Primary coil is 0.2 mm, Secondary coil is 0.5 mm). In addition, in the high frequency band by the proximity effect, the size and status of current changes greatly depending on the location of the two parallel coils of secondary winding. Therefore, the parallel coil of secondary winding must be interleaved with the primary coil and have the same locations. Such placed parallel coil have the same magnetic flux and magnetic field distribution around it and prevents current unbalance [11]. As a result, PSP and SPS coil, not PS or SP coil, must be used. Figure 4 shows the PSP coil method and Fig. 5 shows the specifications of transformer designing.

The two coil methods in Fig. 6 represents the layer coil and sheet coil, and both methods have the same current density. The two models operate for an hour and their

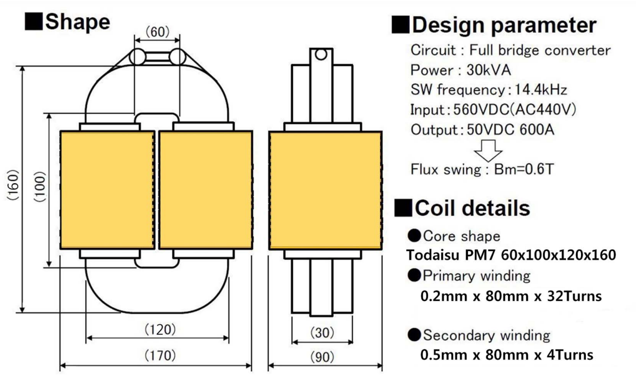

Fig. 5. (Color online) Specifications of Transformer Designing.

temperature saturation was confirmed. Copperplate coil and the coil method of PSP model were used based on the result of Fig. 6.

2.4. Comparison according to Core Materials

To minimize the optimum of the same allowable fre-

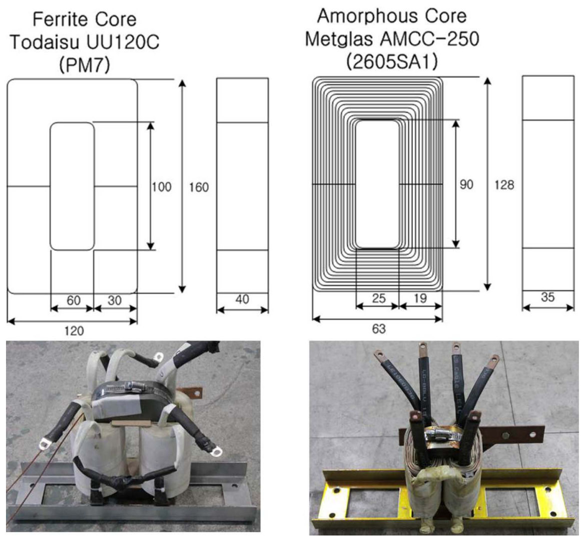

Fig. 7. (Color online) Transformer made by using Ferrite and Amorphous Core.

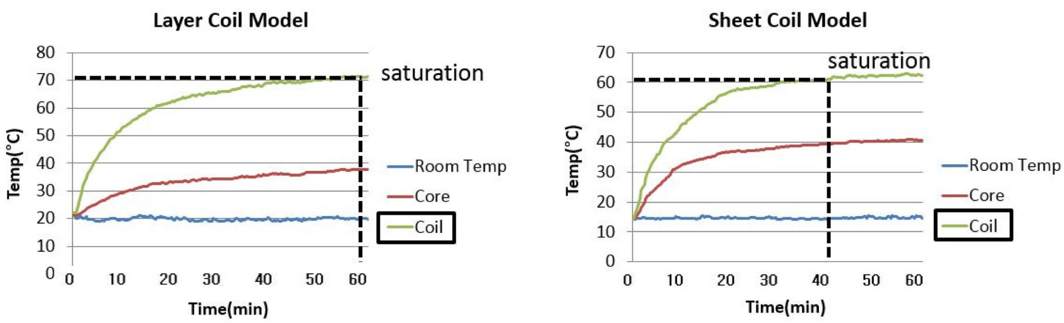

Fig. 6. (Color online) Temperature Saturation Curve in the Layer Coil and Sheet Coil Model.

Table 1. Specifications of the Ferrite and Amorphous Core of Transformer.

Value	Ferrite Core TR (PM7)	Amorphous Core TR (AMCC-250)
Core Weight (kg)	3.48	2.23
Coil Weight (kg)	3.79	2.47
Turn Ratio	32:4	24:3
Flux Density (T)	0.11	0.45
Switch Freq. (kHz)	14.4	14.4
Core Loss (W)	56.84	57.32
Coil Loss (W)	20.22	10.11
Efficiency (%)	97.74	96.96

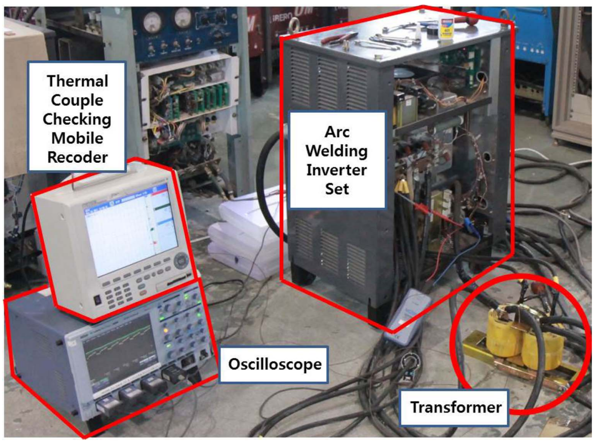

Fig. 8. (Color online) Experiment System of Arc Welding Machine.

quency, magnetic flux density needs to be higher. Therefore, the transformer was made with ferrite and amorphous core that can be used in a 14.4 kHz section. The specifications of each transformer are as in Table 1 and Fig. 7.

Since the amorphous has a magnetic flux density that is three times higher than that of ferrite as in Table 1, it has lower weight and number of turns of coil within the same frequency. Amorphous is better in terms of performance, but it requires more precision in production than ferrite because multilayered core is made by molding powder due to the nature of amorphous production. The two models were applied inside the arc welding machine for the experiment and the output was satisfying. The experiment environment is as in Fig. 8.

3. Air Gap Core Method

A very high current flows inside a welding machine as its switch repeats shortening and opening. The output current of welding machine is as in Fig. 9. The time must

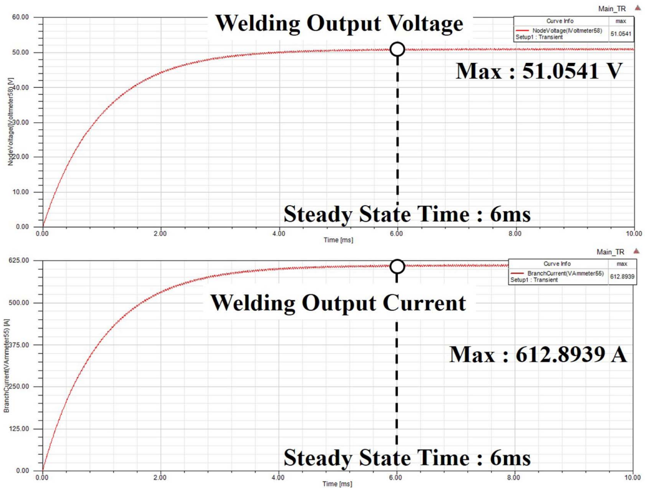

Fig. 9. (Color online) Output Voltage and Current Waveform during Load.

be more than 6 ms since shortened to satisfy the rated current at 600A during the load.

The inrush current of transformer primary winding occurs when the load is connected to the secondary winding of transformer and the switch is on. During the rated load of welding machine, welding works normally after 5 ms. The maximum welding time must be within the allowable current of the switching element that the inrush current of primary winding can endure. If the maximum welding time is exceeded, the switching element is burned

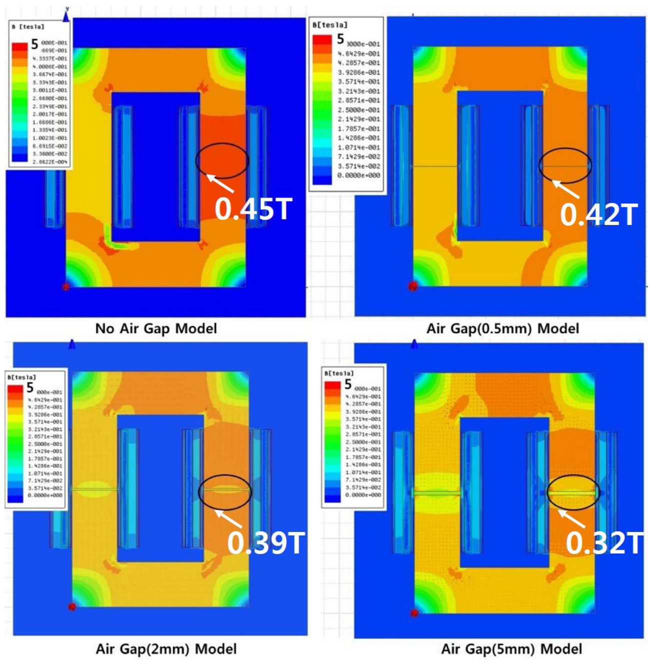

Fig. 10. (Color online) Comparison of Magnetic Flux Saturation according to Air Gap.

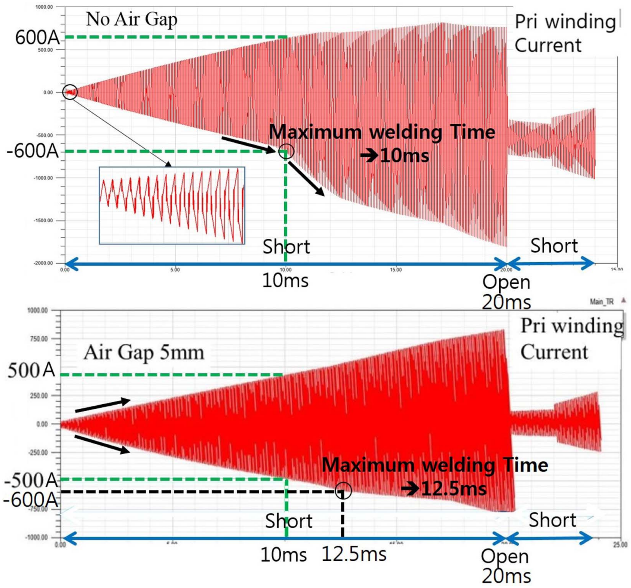

Fig. 11. (Color online) Comparison of the Waveform of Primary Winding Inrush Current according to Air Gap.

out [12, 13]. An air gap (0-5 mm) was given to increase the maximum welding time. The inrush current of primary winding is decreased as the induced voltage becomes smaller by primary winding, since the inductance in the core drops when the air gap increases. However, if the air gap exceeds 5 mm, the average magnetic flux density (amorphous 0.45T) decreases and cannot satisfy the rated output during load. The result of finite element analysis on the differences of air gap are as in Fig. 10.

The highest current that can flow in the used IGBT is −600~600A. The characteristics of the inrush current of primary winding are as in Fig. 11. This waveform shows welding after the welding time was set up to 20 ms and switch open was made.

When the time gets above 12.5 ms, the allowable current of IGBT is exceeded regardless of air gap. Thus, the maximum welding time cannot go beyond 12.5 ms in the used IGBT. The model without an air gap exceeds −600A at 10 ms of welding time, while a model with 5 mm-air gap does not exceed −600A at 10 ms of welding time. This enables welding at up to 10 ms. During welding, the output at load as well as the allowable current of IGBT and maximum welding time must be considered.

4. Conclusion

Since an inverter arc welding machine uses high frequency band, it has an advantage of reducing the size of transformer. It is necessary to reduce the size of transformer core to save cost. However, when the size of core is decreased, magnetic flux is saturated and huge inrush current occurs by the primary winding of transformer. The huge inrush current of primary winding can make IGBT, the switching element, burn out. As a result, since the maximum welding time is proportional to the time of the safe operation of IGBT, the transformer was designed by inserting an airgap to decrease the inrush current of primary welding. It is necessary to appropriately choose the maximum length of air gap as it influences the output of load.

Acknowledgment

This work was supported by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20154030200900).

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT & Future Planning) (No. NRF-2016R1A2A1A05005392).

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