Optimal Design of Magnetic Components in Plasma Cutting Power Supply

J F Jiang¹, B R Zhu¹, W N Zhao², X J Yang² and H J Tang²

¹Electric Power Science Research Institute, Shanghai Electric Power Company, State Grid, Shanghai, China.
²Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China.

Email: *247721794@qq.com

Abstract. Phase-shifted transformer and DC reactor are usually needed in chopper plasma cutting power supply. Because of high power rate, the loss of magnetic components may reach to several kilowatts, which seriously affects the conversion efficiency. Therefore, it is necessary to research and design low loss magnetic components by means of efficient magnetic materials and optimal design methods. The main task in this paper is to compare the core loss of different magnetic material, to analyze the influence of transformer structure, winding arrangement and wire structure on the characteristics of magnetic component. Then another task is to select suitable magnetic material, structure and wire in order to reduce the loss and volume of magnetic components. Based on the above outcome, the optimization design process of transformer and dc reactor are proposed in chopper plasma cutting power supply with a lot of solutions. These solutions are analyzed and compared before the determination of the optimal solution in order to reduce the volume and power loss of the two magnetic components and improve the conversion efficiency of plasma cutting power supply.

1. Introduction

Cutting and welding has been one of the key technology of many industries such as bridge, construction, machinery, ships, aircraft carriers, railway and power generation equipment industry. The development of modern industry is inseparable from the cutting device and the requirement of cutting quality and cutting efficiency is higher [1]. At present the main metal thermal cutting
methods include flame cutting, plasma cutting and laser cutting. Flame cutting has disadvantages of low speed, rough cutting surface and poor cutting accuracy. These problems can be solved through laser cutting and the cutting quality can be significantly improved. But the cost of laser cutting is very high and its cutting thickness is usually limited to 20 mm. However plasma cutting has both advantages of flame cutting and laser cutting, which can achieve faster cutting speed, better cutting quality and low cost at the same time [2-4].

From the beginning of the 1960s, plasma cutting technology continue to progress with the development of power electronic semiconductor devices, from silicon rectifier, thyristor rectifier power supply to chopper type plasma cutting power supply and high power inverter plasma cutting power supply[5]. Among them the chopper type plasma cutting power supply has advantages of simple control circuit, high switching frequency, good control performance and high reliability, so it is commonly used in high power system more than 20kW[6]. In the chopper type plasma cutting power supply, the power transformer and the DC reactor are needed. Due to the high power and high current level the loss of magnetic components may be more than several kW, which will seriously affect the conversion efficiency. For DC reactor the loss is mainly determined by core material and wire type, but when designing transformer its connection mode and winding arrangement should be taken into account.

This paper optimizes the design of phase shifting transformer and the DC reactor based on operation parameters of 45 kW chopper type plasma cutting power supply to decrease volume and power loss of two magnetic components and improve the efficiency of power supply. The second section briefly introduces the topology and the principle of the chopper type plasma cutting power supply. The third section, the influence of different magnetic material, transformer structure, winding arrangement and wire structure on the characteristics of magnetic components is compared, and the suitable material and structure are selected. In the fourth section, the design procedure of the DC reactor and the power transformer is described, and several design schemes are compared to select optimal design result. The last section is the experimental verification.

2. Principle of Plasma Cutting Power Supply

The topology of chopper type plasma cutting power supply is shown in Fig.1. The chopper type plasma cutting power supply has many advantages, such as simple control circuit, high switching frequency, good control performance and high reliability, so it is the ideal choice in high power plasma cutting power supply [6]. In this paper the power of plasma cutting power supply is set to be 45kW. Because of the high power and large current, a two-channel DC-DC buck converter in parallel operation as shown in Fig.2 is designed. This parallel structure can help partake the system capacity, reduce current stress of switch and improve the system stability. When the output current of plasma cutting machine is less than 130A only one buck DC-DC converter is working and the other one is backup. When the required current is greater than 130A the two converter works at the same time to share the current. In Fig.2, 1 and 2 represent the two channel Buck DC-DC converter. Their input DC voltage is $i_{u1}$ and $i_{u2}$. Their DC output current is $i_{L1}$ and $i_{L2}$. The output current of the power supply is the sum of output current of each channel and it can be adjusted from tens A to 260A continuously according to the type and thickness of the work piece. 3 in Fig.2 represents double secondary winding step-down transformer and 4 means the work piece, cutting torch and arc device.
3. Optimal Selection of Magnetic Components

3.1 Magnetic Material. Magnetic component is indispensable key element in high power supply, which can realize energy delivery, storage or work as filter. Its volume and weight generally account for 20% to 30% of the whole power supply system and its loss may account for 30% of total loss. Core loss of magnetic component consists of magnetic hysteresis loss, eddy current loss and residual loss and it can be influenced by magnetic core material, operating frequency, AC magnetic flux density and the waveform. Core loss under sine excitation can be calculated by Steinmetz formula in equation (1):

$$ P = K \cdot f^{\alpha} \cdot B_{ac}^{\beta} $$  \hspace{1cm} (1)

Where, $K \cdot \alpha$ and $\beta$ are determined by the material and the working condition of core and they can be obtained by referring to manual provided by manufacturer or fitting after testing [7]. Core loss under non-sinusoidal excitation can be calculated by correction based on the above formula or Fourier series decomposition [8].

DC reactor in plasma cutting power supply can be divided into two types according to magnetic material of core. One is single magnetic material reactor, the other is mixing magnetic material reactor. For single magnetic material reactor high permeability material with air gap or magnetic powder can be used as core material. In addition, the magnetic core can made from combination
of high-permeability and low-permeability material or high-permeability and permanent magnet material. The volume, cost, loss and inductance of the above four structures is shown in Table 1. Considering these factors select high permeability magnetic material with air gap as magnetic core of DC reactor in this article.

Table 1 Design method comparison of magnet structure

| Core material | high-permeability magnetic material with air gap | magnetic powder | combination of high-permeability and low-permeability material | combination of high-permeability and permanent magnet material |
|---------------|-----------------------------------------------|-----------------|-------------------------------------------------------------|-------------------------------------------------------------|
| volume        | small                                         | big             | medium                                                      | small                                                      |
| cost          | low                                          | medium          | medium                                                      | high                                                       |
| loss          | medium                                        | medium          | low                                                         | high                                                       |
| inductance    | linear                                        | nonlinear       | nonlinear                                                   | linear                                                     |

3.2 Phase-shifted Transformer. Three-phase bridge rectifier is always needed in chopper type plasma cutting power supply. The rectifier is a strong nonlinear and time-varying circuit, which will produce a large amount of harmonic current pollution in the power system and reduce the power factor of the grid. This may lead to distortion of voltage and current and adversely affect other electricity users. Phase-shifting transformer can raise the ladder count of the primary current superposition by increasing number of pulse so as to minimize the harmonic content. Improving power factor by phase-shifted transformer has advantages of easy to realize and high reliability, so it is suitable for high current power supply, high voltage frequency converter and high voltage DC transmission system [9].

Phase-shifting transformer used in plasma cutting power supply in this paper can be divided into two types as shown in Fig.3. One is called 12-pulse phase-shifting transformer, and the other one is 24-pulse phase-shifting transformer. 12-pulse phase-shifting transformer is of simple structure and easy to produce, but the harmonic distortion of current in grid side is 15.22% which means the current distortion is still high. While using 24-pulse phase-shifting transformer the harmonic distortion of current in grid side can be reduced to 7.5%. So the effect of 24-pulse phase-shifting transformer in improving power factor is much better than 12-pulse transformer. But its structure is complex so 24-pulse transformer is fabricated complicatedly. After comprehensive comparison select 12-pulse phase-shifted transformer in this paper.

(a) 12-pulse phase-shifting transformer
3.3 Winding Arrangement of Transformer. The common winding arrangement of transformer is shown in Fig.4. Here P means primary winding and S means secondary winding. The × in Fig.4 indicates that the current direction is inflow while · means outflow direction. H is the magnetic field strength.

For traditional arrangement, the magnetic field strength H in primary winding increases with the the number of ampere-turns of the winding and reaches maximum in the junction of primary and secondary winding, then H gradually decreases to zero in secondary winding. This traditional arrangement causes great adjacent effect and leakage inductance.

Fig.4 (b) is a sandwich arrangement which can significantly reduce adjacent effect and leakage inductance. The maximum magnetic field strength under sandwich arrangement is about half of that in traditional structure. Fig.4 (c) and Fig.4 (d) are staggered winding and they can help further decrease adjacent effect and leakage inductance. However staggered winding is complex to produce and the parasitic capacitor may increase.
3.4 Structure of Wire. Considering the skin effect and the adjacent effect under high frequency, the current distribution in wire is not average, causing the copper loss increased. The copper loss of wire under high frequency is closely related to the structure of wire so it is necessary to select suitable wire to reduce copper loss. The common used wire in magnetic components includes copper foil, round wire and stranded wire. Stranded wire can realize minimum AC copper loss because its wire diameter is small and stranding techniques can be effective against the skin effect and adjacent effect. But its producing process is complex and the cost is high. The loss of thin copper foil is low in the case of fewer turns, but increasing the number of turns will cause AC loss rise rapidly because of adjacent effect. Round wire is of medium AC loss and has advantages of easy to produce and low cost. But limited by maximum wire diameter and skin effect round wire is not suitable for large current reactor. After comprehensive assessment select copper foil to make DC reactor used in plasma power supply in this paper because it has advantages of moderate cost, small AC loss and good heat dissipation.

4. Design Procedure of Magnetic Components

4.1 Design of DC Reactor. The calculation method of DC reactor is mainly using the AP method, but due to large dc offset the inductance of DC reactor must be enough high to meet the requirement of the ripple with short-term maximum current operating condition. The design procedure of DC reactor is shown in Fig.5.

When designing DC reactor the input electrical parameters are voltage, the maximum current, rated current, ripple current, frequency and so on. Number of turns, wire diameter, magnetic chip...
width, thickness and air gap length are selected as design variables. Besides cabinet install size, temperature-rise limit should be added as boundary conditions. The design procedure searches for the scheme which can realize minimum loss or minimum cost. Setting the percentage of loss and cost as design target can make trade-off parameters.

Fig.5 Design procedure of DC reactor

The inductance of DC reactor in plasma cutting power supply is determined by ripple current and working frequency. Keeping working frequency constant, the inductance is inversely proportional to ripple current. Assuming the operating frequency of plasma cutting power supply is 10 kHz, the influence of ripple current on weight, loss and overall dimensions of DC reactor is shown in table 2. Increasing ripple current contributes to smaller inductance, lighter DC reactor in weight, smaller loss and smaller dimensions. After comprehensive assessment the current ripple coefficient is set to 5% to ensure stable operation of DC power supply and reduce the weight, volume, loss and cost of DC reactor in plasma cutting power supply. Similarly when the ripple current is fixed inductance of DC reactor is inversely proportional to working frequency. The current ripple coefficient is set to 5% then change working frequency and analyze weight, loss and dimension of DC reactor, as shown in table 3. Increasing frequency contributes to smaller inductance, lighter DC reactor in weight, smaller loss and smaller dimensions. However due to high power rating of plasma cutting power supply too high working frequency will cause large switching loss. Besides for high power switch IGBT its operating frequency is limited by its switch speed. After comprehensive assessment set switching frequency to be 20kHz. Then the optimal DC reactor design scheme is determined. The inductance of DC reactor is 1 mH and the weight of coil and core are 1.6 kg and 27.1 kg. Its dimension is 156×144×222 mm. The DC coil loss is 163.3 W, while AC coil loss is 1.7 W, and core loss is 32.5 W.
4.2 Phase-shifted Transformer. The design procedure of phase-shifted transformer is shown in Fig.6. When designing phase-shifted transformer the input electrical parameters are voltage rating, voltage ratio, rated current, leakage inductance and so on. Number of turns, wire diameter, magnetic chip width, airway distance and airway number are selected as design variables. Besides cabinet install size, temperature-rise limit should be added as boundary conditions. The design procedure searches for the scheme which can realize minimum loss or minimum cost. Setting the percentage of loss and cost as design target can make trade-off parameters.

![Diagram of design procedure](image)

Fig.6 The design procedure of phase-shifted transformer

| Ripple coefficient | Inductance (mH) | Wire weight (kg) | Core weight (kg) | Total weight (kg) | Wire loss (W) | Core loss (W) | Total loss (W) | Dimension (mm) |
|--------------------|----------------|------------------|------------------|-------------------|--------------|--------------|----------------|----------------|
| 0.5%               | 20             | 10.4             | 512.7            | 523.2             | 1046.3       | 0.3          | 1046.6         | 416×404×498    |
| 1.0%               | 10             | 6.5              | 264.1            | 270.7             | 655.7        | 6.8          | 662.4          | 328×342×384    |
| 2.0%               | 5.0            | 4.3              | 133.0            | 137.3             | 433.2        | 11.4         | 444.6          | 242×302×305    |
| 3.0%               | 3.33           | 3.8              | 72.2             | 76.0              | 387.1        | 12.6         | 399.7          | 182×288×245    |
| 5.0%               | 2.0            | 3.0              | 37.7             | 40.7              | 298.9        | 16.0         | 314.9          | 164×196×224    |
Table 3 Scheme comparison of fixed ripple current

| Frequency (kHz) | Inductance (mH) | Wire weight (kg) | Core weight (kg) | Total weight (kg) | Wire loss (W) | Core loss (W) | Total loss (W) | Dimension (mm) |
|----------------|----------------|------------------|------------------|------------------|---------------|---------------|---------------|----------------|
| 5.0            | 4.0            | 4.2              | 87.7             | 91.9             | 422.3         | 13.1          | 435.3         | 204×285×262    |
| 7.5            | 2.67           | 3.3              | 57.8             | 61.1             | 331.1         | 25.2          | 356.3         | 182×234×242    |
| 10.0           | 2.0            | 3.0              | 37.7             | 40.7             | 298.9         | 16.0          | 314.9         | 164×196×224    |
| 12.5           | 1.6            | 2.4              | 36.8             | 39.1             | 238.3         | 21.9          | 260.2         | 160×191×222    |
| 15.0           | 1.33           | 2.0              | 35.9             | 37.8             | 197.7         | 28.8          | 226.6         | 156×186×222    |
| 17.5           | 1.14           | 1.8              | 30.9             | 32.6             | 179.0         | 36.2          | 215.2         | 156×162×222    |
| 20.0           | 1.0            | 1.6              | 27.1             | 28.7             | 165.0         | 32.5          | 197.5         | 156×144×222    |
| 22.5           | 0.89           | 1.6              | 21.2             | 22.8             | 163.8         | 30.6          | 194.4         | 148×130×222    |
| 25.0           | 0.8            | 1.5              | 19.1             | 20.7             | 154.4         | 32.2          | 186.6         | 148×119×222    |

Table 4 Scheme Comparison of aluminium and copper phase shifting transformer

| Wire material | Aluminum wire | Copper wire |
|---------------|---------------|-------------|
| Core material | non-oriented silicon steel sheet | orientation silicon steel sheet | amorphous alloy | non-oriented silicon steel sheet | orientation silicon steel sheet | amorphous alloy |
| Weight (kg)   | wire 45       | 42          | 48          | 57          | 53          | 85          |
|               | core 191      | 143         | 169         | 204         | 158         | 154         |
|               | total 286     | 231         | 264         | 319         | 253         | 286         |
| Wire loss (W) | 1422          | 1340        | 1535        | 1397        | 1361        | 1618        |
| Core loss (W) | 300           | 143         | 28          | 278         | 146         | 23          |
| Total loss (W)| 1723          | 1483        | 1562        | 1675        | 1507        | 1641        |
| Dimension (mm)| 580×410×590   | 550×410×560 | 610×430×60  | 550×440×550 | 520×410×530 | 570×410×59  |
| Cost          | 3403          | 4092        | 12584       | 4081        | 4858        | 13475       |

When designing phase-shifted transformer non-oriented silicon steel sheet, orientation silicon steel sheet or amorphous alloy can be selected as transformer core. Aluminum wire or copper wire can be used to make winding. The selection of magnetic material and wire will have an impact on cost and loss. Table 4 compares transformer made from different magnetic material and wire material on weight, size and cost. It can be seen that amorphous alloy has advantage in reducing core loss but its lamination factor and magnetic saturation is lower than silicon steel sheet which leads to large size of transformer and high cost. Compared with non-oriented silicon steel sheet, orientation silicon steel sheet can reduce loss and volume by 10% to 15% even though the cost increases by about 20%. As for the wire, using copper wire can slightly reduce loss and volume, but cause the cost increase by 20%. So after comprehensive analysis and comparison aluminum wire and orientation silicon steel sheet are selected to produce transformer in this paper.

5. Experimental Results

DC reactor and phase-shifted transformer in plasma cutting power supply based on the above design method is shown in Fig.7.
Fig. 7 Pictures of DC reactor and phase-shifted transformer

The circuit parameters of plasma cutting power supply with two channel buck DC-DC converter in parallel are as described below. Its input is three-phase AC voltage of 380V then after the transformer the voltage is converted to 220V. Each buck DC-DC converter can realize maximum output current of 130A so the overall maximum output current is 260A. The rated output voltage is 150V. The operating frequency is 20kHz and the ripple current peak-peak value of output current should be less than 10A. According to these parameters the inductance of the DC reactor is designed to be 1.0mH. The waveform under different working stage is shown in the following figures. In these figures the green line represents output voltage and the blue line means output current. Fig.8, Fig.9 and Fig.10 are respectively corresponding to the arc striking stage, start-up stage and normal cutting stage.

Fig. 8 Voltage and current waveforms when arcing
6. Conclusions

This paper optimizes design of DC reactor and phase-shifting transformer in chopper plasma cutting power supply. The paper focuses on the influence of magnetic material, transformer structure, winding arrangement and wire structure on the characteristics of magnetic components. Based on this proposes design procedure of DC reactor and phase-shifting transformer and lists a variety of design schemes. After comparison and analysis optimal solution is determined to ensure lower loss of magnetic components and smaller size.

References

[1] Hao R X, Zheng Q L, You X F, Guo W J and Lin F 2007 Characteristic analysis and experimental research on high-power plasma arc heater power supply. Trans. of China Electrotechnical Society V22, Sup.178-82.

[2] Wu J 2010 Research on high-performance plasma cutting power supply system. A thesis in Electrical Engineering for the Degree of Master of Engineering. Nanjing University of Aeronautics and Astronautics March.
[3] Chen Y L 2008 IGBT inverted plasma cutting power supply. A thesis in Electrical Engineering for the Degree of Master of Engineering. *Lanzhou University of Technology* May.

[4] Liu B Q, Duan S X and Li X 2012 An improved double closed loop control strategy for air plasma cutting converter. *Przeglad Elektrotechniczny* 88 278-282.

[5] Ramakrishnan S, Gershenzon M, Polivka F, Kearney T Nand Rogozinski M W 1997 Plasma generation for the plasma cutting process. *IEEE Transactions on Plasma Science, vol. 25, no.* 5937-946.

[6] Yang X J and et al. 2014 Research on two-channel interleaved two-stage paralleled Buck DC-DC Converter for plasma cutting power supply. *2014 International Power Electronics and Application Conference and Exposition, Shanghai* 914-919.

[7] Chas. P S 1984 On the law of hysteresis. *Proc. IEEE* 72 197-221.

[8] Aguglia D and Neuhaus M 2013 Laminated magnetic materials losses analysis under non-sinusoidal flux waveforms in power electronics systems. *Power Electronics and Applications (EPE)* 1-8.

[9] Sikora and Kulesz B 2008 Effectiveness of different designs of 12- and 24-pulse rectifier transformers. *Electrical Machines* 1-5.