Research on the Magnetic Field Space-time Distribution in the Air-core Pulse Transformer

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Abstract— In the large-scale pulsed power device, the transient strong magnetic field, which is caused by transient high current, may have effects on the insulation property of the whole system. Therefore, in order to investigate the magnetic field space-time distribution and the influence generated by the axial magnetic field on the insulation performance in the pulsed power device, circuit simulation and transient magnetic field simulation are utilized. It can be found that the coupling coefficient makes much influence on the phase difference between the magnetic field and the load voltage. As the coupling coefficient reduces appropriately, the magnetic field in the vicinity of the peak load voltage increases greatly. The magnetic field distribution in the space is much related to the structure of transformers. In the air core of the transformer, the magnetic field is uniform along the radial, but a little higher near the rim. Besides, the magnetic field decreases relatively faster along the axial when it approaches the edge of the coils. Finally, an air-core pulse transformer with a coupling coefficient of 0.8 is constructed, and the magnetic field space-time distributions in the air core and the area between primary and secondary coils are measured. The experimental results correspond with the theoretical simulation results. The conclusions in the paper are favorable to use the transient strong magnetic field reasonably and to improve the insulation property in this type of transformer.

1. INTRODUCTION

The air-core pulse transformer has been applied generally in the pulsed power system. As there isn't any magnetic cores in air-core pulse transformer, it has great advantages, such as light weight and no magnetic saturation effect [1, 2]. Besides, the internal space of the transformer can be used to place other devices, which makes the pulsed power system compact. However, there is a high-intensity transient magnetic field in the region, and it may have effect on the insulation property. Especially in vacuum, the insulation strength of high voltage transformer can be improved with the high-intensity magnetic field [3], and the magnetic field can also be used to restrain the vacuum creepage flashover [4]. Therefore it is necessary to analyse and measure the magnetic field space-time distribution in the air-core pulse transformer if the internal space of the transformer is to be used. In this paper a simulation method of analyzing the magnetic field space-time distribution in the air-core pulse transformer is presented, and the phase relation between the magnetic field and the load voltage is discussed. Finally, the simulation result and the measurement result of the magnetic field space-time distribution in an air-core pulse transformer with coupling coefficient of 0.8 are given.

2. SIMPLIFIED MODEL OF THE AIR-CORE PULSE TRANSFORMER

The schematic of air-cored pulse transformer is given in Figure 1. The primary winding is in single turn, and the cone secondary winding of 300 turns is placed in the primary winding. The radial width of the transformer is 360 mm, and the axial length is 400 mm. In Figure 1 the transformer consists of three regions, the region I is the air core of the transformer, and region II is the space between the primary winding and the secondary winding, and region III is the external of the transformer. The discharge circuit of pulse transformer is given in Figure 2, the circuit parameters are as follows: primary capacitance $C_1 = 1680\,\mu\text{F}$, primary loop equivalent resistance $R_1 = 0.005\,\Omega$ equivalent inductance $L_1 = 0.05\,\mu\text{H}$, primary winding inductance $Lp = 0.3\,\mu\text{H}$. In the secondary circuit capacitance $C_2 = 10\,\text{nF}$, secondary winding equivalent resistance $R_2 = 30\,\Omega$, secondary winding inductance $Ls = 20\,\text{mH}$.

3. SIMULATION OF THE PHASE RELATION OF CURRENT AND LOAD VOLTAGE

The magnetic field generated by the primary winding current and secondary winding current in the transformer are both approximately axial, so the primary winding current and secondary winding current can be added to estimate the combining magnetic field. With the combining current, the phase relation between the magnetic field and the load voltage can be compared.

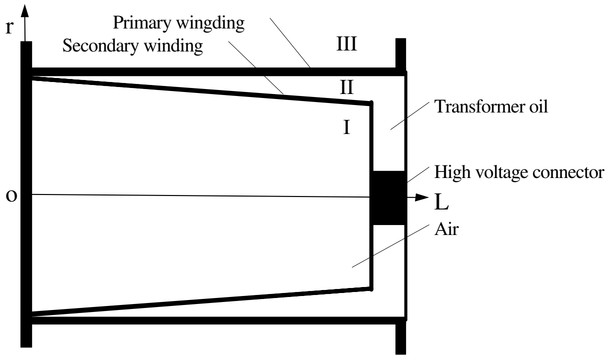


Figure 1: Schematic of air-cored pulse transformer.

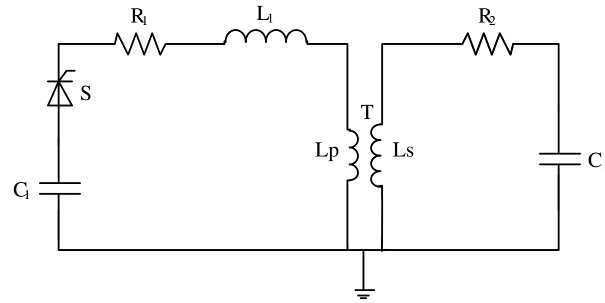


Figure 2: The discharge circuit of pulse transformer.

In the current simulation it can be found that the primary and secondary winding current is in the opposite direction, and the magnetic field in region I is mostly counteracted when the coupling coefficient is nearly 1. Besides, it exists 90° phase difference between the peak of load voltage and the peak of the magnetic field. The result is that the magnetic field nearly disappears when the load voltage approaches its peak. Thus, the transformer with high coupling coefficient can be influenced little by the magnetic field. However, it is different in the transformer with low coupling coefficient such as the air-core pulse transformer. The phase relation among the primary and secondary winding current and the load voltage will change with different coupling coefficient, and those results in the change of the magnetic field. Besides, other parameters like capacitance and inductance have effect on the frequency of the magnetic field, and the resistance and the charging voltage have effect on the size of the magnetic field, but all of them have little effect on the phase difference. Therefore the coupling coefficient is the key factor of changing the time distribution of the magnetic field.

Figure 3 shows the waveform of the primary and secondary current with different coupling coefficients. Ip is the primary winding current, and Is is the secondary winding current. The secondary winding current is multiplied by -300. As Fig. 3 shows, both of the current amplitude decreases with the reducing of coupling coefficient, and Ip decreases more in the forward direction and less in the reverse direction. Especially in the transformer with the coupling coefficient of 0.8, the primary and secondary current are in the same direction at some moments. At the same time, the phase difference between Ip and Is increases when the coupling coefficient falls. That means the Is can't weaken the magnetic field in time. As a result, the magnetic field can reach a rather high level.

The net current I_0 is defined to estimate the magnetic field: $I_0 = Ip + 300 \times Is$. And in order to analyze the magnetic field characteristic in the vicinity of the peak load voltage, the net current and the load voltage with different coupling coefficient are presented in Fig. 4.

As shown in Fig. 4 the net current is incremental before the load voltage reaches its peak. That means the magnetic field increases with the load voltage going up. If the magnetic field is strong enough, such magnetic field time distribution is useful to improve the insulation property. Besides, the net current increases obviously when the coupling coefficient decreases, also the peak of the

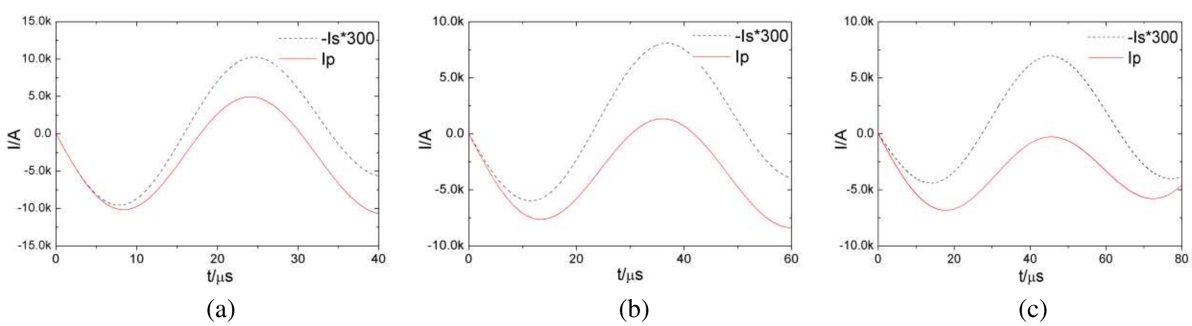
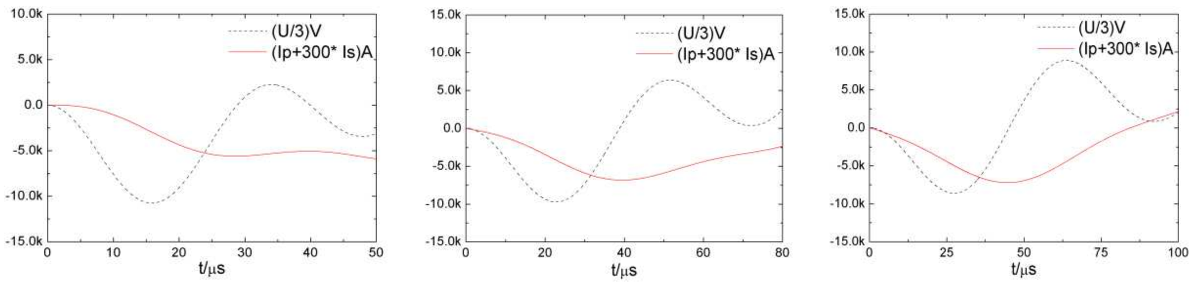


Figure 3: Simulated result of primary and secondary current with different coupling coefficient. (a) Coupling coefficient of 1. (b) Coupling coefficient of 0.9. (c) Coupling coefficient of 0.8.



(a) (b) (c)

Figure 4: Simulated result of net current and load voltage with different coupling coefficient. (a) Coupling coefficient of 1. (b) Coupling coefficient of 0.9. (c) Coupling coefficient of 0.8.

Table 1: Net current with different coupling coefficient at $0.9U_m$.

Coupling coefficient	1	0.9	0.8	0.7
$0.9U_m$/kV	29.035	26.252	23.211	20.170
Net current/kA	1.82	2.98	3.77	4.30

net current and the load voltage gets closer. The net current with different coupling coefficient at $0.9U_m$ are compared as shown in Table 1, and it indicates that the magnetic field distribution generated by the transformers with low coupling coefficient is more likely to be used.

4. COMPARISON OF SIMULATION AND EXPERIMENT

According to the analysis above, the transformers with low coupling coefficient can get more advantaged magnetic field distribution. Here the magnetic field in a transformer with coupling coefficient of 0.8 was simulated and measured.

The waveform comparison of magnetic field B_y and the net current I_0 is shown in Fig. 5, and they are similar in the time distribution on the whole. It proves the rationality of the analysis method above. And in Fig. 6 three moments are chosen to compare the magnetic field strength in region I and region II before the magnetic field reaches its first peak. And the three moments are $t = 45$ μs when the magnetic field B_y reaches its peak, $t = 26$ μs when the load voltage U reaches its peak, and $t = 20$ μs when the load voltage $U = 0.8U_m$. It can be found that the magnetic field in the region I and region II may reach 0.015 T, however in different moment. But both the magnetic field in the region I and region II can reach 0.01 T at the same time when $U = U_m$. That means the magnetic field strength in the transformer can reach a high level when the system is under high voltage.

Referring to Fig. 7, the magnetic field space distribution in an air-core transformer is simulated as shown in (a)–(c) and measured as shown in (d)–(f). The experiment result practically accords with the simulation. The magnetic field in region I is uniform along the radial, while a little higher

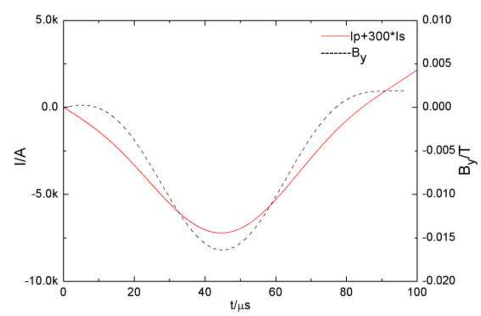


Figure 5: Contrast of net current and B_y waveform.

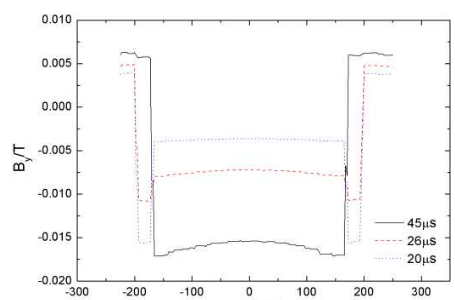


Figure 6: Radial distribution of B_y at different moment.

near the rim. It is also uniform along the axial but decreases fast relatively when it approaches the edge of the coils. The magnetic field distribution in region II is similar.

As shown in Fig. 8, the experimental magnetic field waveform is almost the same with the simulated prediction magnetic field waveform. And the difference in (b) is mainly caused by the nonuniform distribution of the current in the primary winding.

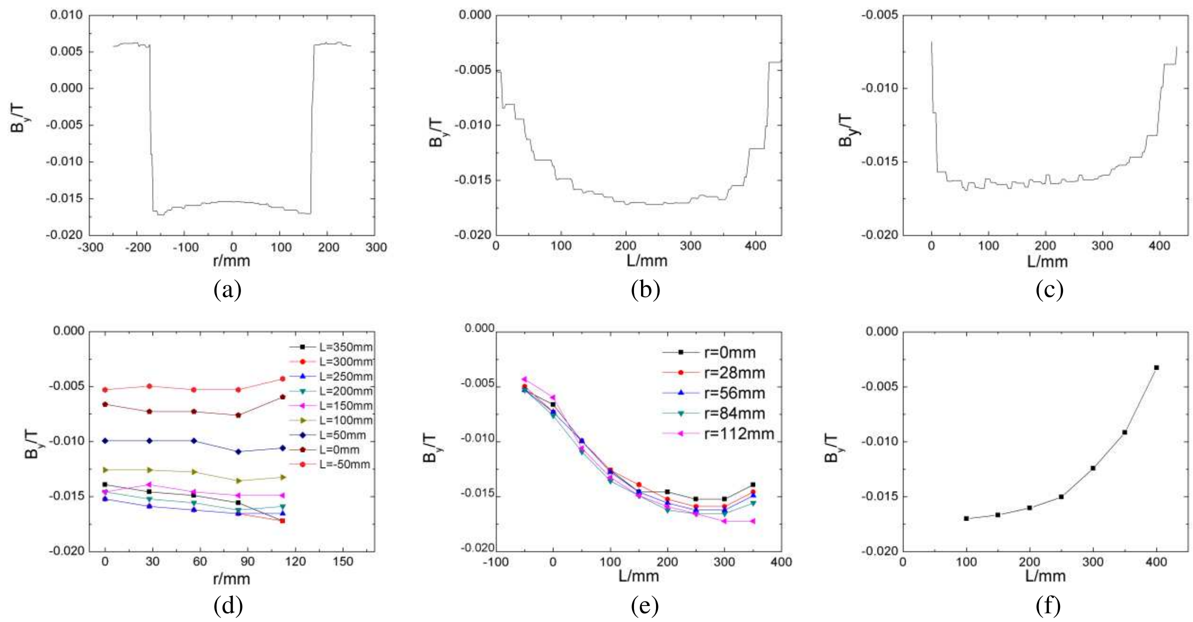


Figure 7: Comparison of simulated and experimental magnetic field space distribution. (a) Simulated radial distribution in I. (b) Simulated axial distribution in I. (c) Simulated axial distribution in II. (d) Experimental radial distribution in I. (e) Experimental axial distribution in I. (f) Experimental axial distribution in II.

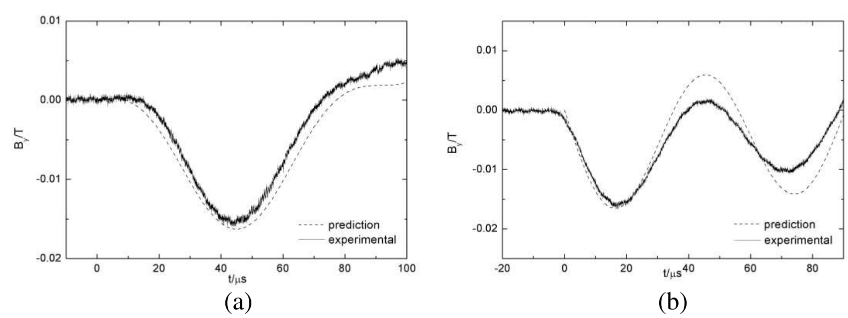


Figure 8: Comparison of simulated and experimental magnetic field time distribution. (a) Magnetic field waveform in region I. (b) Magnetic field waveform in region II.

5. CONCLUSIONS

An approximate method of analyzing the magnetic field space-time distribution in the air-core pulse transformer is presented in this paper. And the coupling coefficient is found to be the key factor influencing the time distribution of the magnetic field, which will determine the phase relation between the transient high voltage and magnetic field. With the coupling coefficient decreasing, the magnetic field increases obviously. The magnetic field space-time distribution in an air-core pulse transformer with a coupling coefficient of 0.8 is simulated and measured, and the experimental results correspond with the simulation result. The magnetic field space distribution is uniform, and it is lower as it's near the top and bottom. The magnetic field strength in the two regions of transformers can reach a high level at the same moment.

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