Simulation analysis of thermal management of inductor applied to PFN under continuous discharge condition

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Abstract. The pulse forming network (PFN) is an important component of the electromagnetic launch system, and its continuous discharge performance at same frequency is of great significance for the development of electromagnetic launch system. Pulse inductor is one of the key components of PFN, which has a decisive influence on the amplitude, pulse width and wave front time of discharge current. In order to study the thermal management scheme that could meet the temperature control requirements of pulse inductors under continuous discharge condition, an electromagnetic-thermal-fluid coupling model is established, and the temperature change of pulse inductor under the condition of liquid cooling and natural cooling is analyzed. It is concluded that the natural cooling scheme cannot meet the temperature control requirements, while the liquid cooling scheme can meet it. But the disadvantage of the liquid cooling scheme is that the maximum temperature difference inside the inductor will be increased.

1. Introduction

Electromagnetic launch technology is the inevitable trend of new concept launch technology development. The power supply applied to electromagnetic emission technology needs to have enough energy and high power, as well as the characteristics of short discharge time and precise regulation of discharge current. The pulse forming network (PFN), which is composed of several capacitor energy storage pulse forming units (PFU), can meet the above requirements. It is widely used in the experimental research of electromagnetic emission and becomes one of the most possible power supply schemes for engineering application [1-6].

Pulse inductor is one of the key components of PFN, which has a decisive influence on the amplitude, pulse width and wave front time of discharge current [7]. In the design of PFN, the columnar solenoid inductor is mostly used, which is poured by epoxy resin. Its structure is shown in figure 1. The gap between the turns of solenoid is fixed and insulated by filling epoxy resin. In addition, the epoxy resin has viscoelasticity, which is helpful to reduce the vibration of pulse inductor during operation and extend its service life [8].
Based on the operation characteristics of PFN, a large amount of Joule heat will be generated during the operation of pulse inductor, while epoxy resin is a bad conductor of heat, the heat generated is not easy to be dissipated. Under the condition of continuous discharge, the heat would accumulate in the inductor and lead to temperature rise; while the long-term overheated operation of the equipment will accelerate the aging of the insulation layer and reduce the service life. In serious cases, it will cause insulation failure and lead to major accidents such as explosion and fire. Therefore, cooling measures must be taken to keep the temperature of the pulse inductor within the allowable range.

Based on the structural characteristics of the pulse inductor, the inductor wound by hollow coil is generally used in the project, as shown in figure 2. The temperature of the inductor is controlled by passing cooling water in the coil.

In the following, the electromagnetic thermal flow coupling simulation technology is used to analyze the temperature changes of pulse inductors with cooling measures and without cooling measures under the condition of continuous discharge, verify the effectiveness of the cooling scheme, and put forward suggestions for improvement.

2. Circuit model of PFU

The circuit model of 250kJ PFU is shown in figure 3, and parameters of each component are shown in table 1.
Figure 3. Circuit Model of 250kJ PFU.

Table 1. Component parameters of 250kJ PFU.

| Name                                      | Equivalent circuit parameters |
|-------------------------------------------|-------------------------------|
| Capacitor Capacitance C/mF               | 10                            |
| Capacitor Initial Voltage uC/kV          | 10                            |
| Inductor Inductance L/μH                 | 25                            |
| Equivalent internal resistance of capacitor branch Rc/mΩ | 4                             |
| Equivalent internal resistance of inductance branch RL/mΩ | 4                             |
| Equivalent internal resistance of diode branch RD/mΩ | 2                             |
| Load Inductance L0/μH                    | 0.5                           |
| Load Resistance R0/mΩ                    | 2                             |

After SCR was turned on, the PFU first carried out the RLC 2nd order discharge. Due to \((R0 + Rc + RL) < 2\sqrt{(L + L0)/C}\), This process is underdamped oscillation discharge, the governing equation is as follows:
The zero point of \( t_1 \) was when SCR was turned on, and under ideal conditions, \( i_L(t_1) \) reached its peak value when \( u_C(t_1) \) decreased to zero. At the same time, D was turned on, and the PFU carried out the RL 1nd order discharge. The governing equation is as follows:

\[
\alpha = \frac{R_L + R_R + R_0}{2(L + L_0)} \quad , \quad \omega_0 = \frac{1}{\sqrt{(L + L_0)} \cdot C} \quad , \quad \omega_d = \sqrt{\omega_0^2 - \alpha^2} \quad , \quad \cos \beta = \frac{\alpha}{\omega_0}
\]

The zero point of \( t_2 \) was when D was turned on, and \( I_0 \) was the value of \( i_L(t_1) \) when D was turned on.

Using MATLAB Simulink module, 250kJ PFU was simulated and analyzed, and its discharge current curve was as shown in the figure 4.

![Discharge current curve of 250kJ PFU.](image)

3. Theoretical model of coupling analysis

3.1 Theoretical model of electromagnetic field

When the time-varying current flows through conductor, a time-varying magnetic field will be generated in the plane perpendicular to the conductor. The time-varying magnetic field will induce eddy current in source conductor and conductors parallel to source conductor [9]. The induced eddy current field equation is as follows:
\[ \nabla \times \left( \frac{1}{\mu_r} (\nabla \times A) \right) = (\sigma + j\omega \epsilon) \cdot (-j\omega A - \nabla \phi) \quad (4) \]

Where \( A \) is vector magnetic potential, \( \phi \) is scalar potential, \( \mu_r \) is relative permeability, \( \mu_0 \) is vacuum permeability, \( \omega \) is angular frequency of excitation, \( \sigma \) is conductivity, \( \epsilon \) is dielectric constant.

The induced eddy current will hinder the propagation of magnetic field in conductors and only allow the magnetic field to penetrate a certain depth. This effect is called skin effect and the depth of penetration is called penetration depth, which is expressed by \( \delta \).

\[ \delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}} \quad (5) \]

Due to the influence of skin effect, current is concentrated near the surface of conductors. When penetration depth is exceeded, current will decay rapidly. And with the increase of excitation frequency, the penetration depth decreases. While the skin effect of solid conductor is not only related to the frequency of excitation, but also to the relative position between conductors. Based on the Maxwell equation, the total current density in the conductor is [10]:

\[ J = -\sigma \left( \frac{dA}{dt} + \nabla \phi \right) \quad (6) \]

\[ \nabla \times \left( \frac{1}{\mu_r} \nabla \times A \right) = \sigma \left( \frac{dA}{dt} - \nabla \phi \right) \quad (7) \]

\[ \nabla \cdot \left[ \sigma \left( \frac{dA}{dt} - \nabla \phi \right) \right] = 0 \quad (8) \]

### 3.2 Theoretical model of electromagnetic-thermal coupling

Assuming that the heat generated in the pulse inductor is Joule heat, the theoretical model of electromagnetic thermal coupling is as follows [11]:

\[ \rho c \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \frac{1}{\sigma} |J|^2 \quad (9) \]

A third kind of boundary condition is applied on the outer surface of epoxy resin to simulate the convective heat transfer between pulse inductor and air.

\[ -\kappa \left( \frac{\partial T}{\partial n} \right)_w = h \left( T_w - T_a \right) \quad (10) \]

Where \( \rho \) is density, \( c \) is specific heat, \( T \) is temperature, \( t \) is time, \( \kappa \) is thermal conductivity, \( h \) is convective heat transfer coefficient between pulse inductor and air, \( T_w \) is outer surface temperature of pulse inductor, \( T_a \) is air temperature near outer surface of pulse inductor.

### 3.3 Theoretical model of heat-flow coupling

In each simulation time step, the wall temperature was transferred to fluid domain solver from solid
domain solver, and the fluid temperature near the wall and convective heat transfer coefficient were transferred to solid domain solver from fluid domain solver.

Fluid Domain Control Equation:

\[ \nabla \cdot U = 0 \]  \hspace{1cm} (11)

\[ \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uU) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} \]  \hspace{1cm} (12)

\[ \frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho vU) = \nabla \cdot (\mu \nabla v) - \frac{\partial p}{\partial y} \]  \hspace{1cm} (13)

\[ \frac{\partial (\rho w)}{\partial t} + \nabla \cdot (\rho wU) = \nabla \cdot (\mu \nabla w) - \frac{\partial p}{\partial z} \]  \hspace{1cm} (14)

\[ \frac{\partial (\rho T)}{\partial t} + \nabla \cdot \left( \rho UT \right) = \nabla \cdot \left( \gamma \nabla T \right) \]  \hspace{1cm} (15)

Solid Domain Control Equation:

\[ \rho c \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) \]  \hspace{1cm} (16)

The third boundary condition is used to simulate the convective heat transfer between the pulse inductor and cooling water.

\[ -K \left( \frac{\partial T}{\partial n} \right)_w = h \left( T_w - T_f \right) \]  \hspace{1cm} (17)

Where \( U \) is velocity vector; \( u, v, w \) are the component of velocity in \( X, Y, Z \) direction; \( \mu \) is viscosity of water; \( p \) is pressure, \( T_w \) is inner surface temperature of pulse inductor, \( T_f \) is fluid temperature near inner surface of pulse inductor.

4. Simulation analysis

It is assumed that the specific heat capacity, thermal conductivity, conductivity and other physical parameters of the material are constant and do not change with temperature. The physical parameters of the materials involved in the simulation analysis are shown in table 2.

| Table 2. Physical Parameters of Materials Involved in Simulation Analysis. |
|-----------------|-----------|-----------|-----------|
|                  | Copper    | Epoxy Resin | Water    |
| Conductivity/(S/m) | 5.8e7     | -         | -         |
| Relative Permeability | 0.999991 | 3100      | 998.2     |
| Density/(kg/m³)    | 8933      | 0.2       | 0.6       |
| Specific Heat/(J/kg·K) | 385      | 550       | 4182      |
| Thermal Conductivity/ W/(m·K) | 400    | 0.2       | 0.6       |
| Viscosity/(Pa·s)   | -         | -         | 1.003e-3  |

The simulation condition is 10 discharges per minute with a discharge interval of 6s, and total analysis time is 1min. During discharge interval, solid coil inductor is naturally, while hollow coil is cooled by cooling water. Cooling water flow is maintained at 2L/min, and the temperature of cooling
water is 25 °C. The thermal conductivity of the epoxy resin is 0.2 W/(m·K), and the total simulation time is short, so it could be assumed that the outer surface of the inductance coil is adiabatic. The initial temperature of pulse inductor is assumed to be 40 °C.

Figure 5 is the current density nephogram of pulse inductor at peak current moment. Due to proximity effect, the maximum current density is located at the edge of the inner surface of the inductor; and because the resistance of hollow coil inductor is slightly larger than that of solid coil, the current density of hollow coil inductor is larger than that of solid coil.

Figure 5. Current density nephogram of solid coil inductor (left) and hollow coil inductor (right).

Figure 6 shows the average Joule thermal power nephogram of pulse inductor during the discharge process, which is consistent with current density distribution. Similarly, the Joule thermal power of hollow coil inductor is larger than that of solid coil inductor.

Figure 6. Average joule thermal power nephogram of solid coil inductor (left) and hollow coil inductor (right).

Figure 7 shows the temperature nephogram at the end of the 1st, 4th, 6th, 8th and 10th discharge of solid coil inductor. The temperature of solid coil inductor increases with the increase of discharge
times. The peak temperature is close to 145 °C, which exceeds allowable peak temperature of pulse inductor, indicating that the natural cooling conditions cannot meet the temperature control requirements of continuous discharge of designed PFU.

![Figure 7. Temperature nephogram at the end of the 2st, 4th, 6th, 8th and 10th discharge of solid coil inductor.](image)

Figure 7. Temperature nephogram at the end of the 2st, 4th, 6th, 8th and 10th discharge of solid coil inductor.

Figure 8 shows the temperature nephogram at the end of the 1st, 4th, 6th, 8th and 10th discharge of hollow coil inductor. The temperature of hollow coil inductor changes little after the 4th discharge, that is to say, from the fourth discharge, the temperature of inductor tends to be stable. The peak temperature is not more than 85 °C, indicating that the cooling scheme can meet the temperature control requirements of continuous discharge of designed PFU. Meanwhile, the inner surface temperature is higher than the outer surface temperature, and temperature gradient in the water inlet area is larger, and gradually decreases with the distance from the water inlet.

![Figure 8. Temperature nephogram at the end of the 2st, 4th, 6th, 8th and 10th discharge of hollow coil inductor.](image)

Figure 8. Temperature nephogram at the end of the 2st, 4th, 6th, 8th and 10th discharge of hollow coil inductor.

Figure 9 shows the curves of maximum and minimum temperature of solid coil inductor and hollow coil inductor with time during continuous discharge. The maximum and minimum temperature of solid coil inductor and their difference rise with the increase of discharge times, and the maximum difference is about 20 °C. With the increase of discharge times, the maximum temperature of hollow coil inductor rises slowly, while the minimum temperature decreases slowly. Both of them tend to be stable from the 4th discharge, and the maximum difference between them is about 50 °C.
Figure 9. Curves of maximum and minimum temperature of solid coil inductor (left) and hollow coil inductor (right) with time during continuous discharge.

5. Conclusion
Due to proximity effect, the maximum current density is located at the edge of the inner surface of the inductor; and because the resistance of hollow coil inductor is slightly larger than that of solid coil, the current density and the average Joule thermal power of hollow coil inductor is larger than that of solid coil.

The temperature of solid coil inductor rises with the increase of discharge times. The peak temperature is close to 145°C at the end of 10th discharge, which exceeds allowable peak temperature of pulse inductor, indicating that the natural cooling conditions cannot meet the temperature control requirements of continuous discharge of designed PFU.

When cooling water flow is maintained at 2L/min, the temperature distribution of hollow coil inductor tends to be stable after 4th discharge, and the peak temperature is not more than 85 °C, indicating that the cooling scheme can meet the temperature control requirements of continuous discharge of designed PFU. Temperature gradient of inductor near the water inlet is larger, and gradually decreases with the distance from the water inlet. It should be noted that after stabilization, the maximum temperature difference inside the inductor is close to 50°C.

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