Miniaturization design of closing electromagnet for fast contact mechanism of DC circuit breaker in power grid

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Abstract. The newly designed DC circuit breaker closing electromagnet must meet the requirements of small size and fast action. This article focuses on the design index of the electromagnet, and carries on the preliminary design based on the empirical formula. On this basis, with the smallest volume as the objective function, a steady-state simulation design is carried out using BOBYQA's optimization algorithm. The design results are input into the transient simulation model to solve and analyze the characteristic changes of the solenoid coil voltage and current. The simulation and prototype test results show that under AC220V 50Hz full-wave rectification excitation, the moving iron core starts to move in 18.8ms and completes a 6mm stroke in 30.8ms; the peak coil current during the continuous flow is 4.15A, which meets the design index requirements of the electromagnet. The new scheme provides a reference for the design of DC circuit breaker closing device.

1. Introduction
The newly designed closing electromagnet for DC circuit breaker must meet the requirements of small size and fast action. This article focuses on the design index of the electromagnet, and carries on the preliminary design based on the empirical formula. On this basis, with the smallest volume as the objective function, a steady-state simulation design is carried out using BOBYQA's optimization algorithm. The design results are input into the transient simulation model to solve and analyze the characteristic changes of the solenoid coil voltage and current. The simulation and prototype test results show that under AC220V 50Hz full-wave rectification excitation, the moving iron core starts to move in 18.8ms and completes a 6mm stroke in 30.8ms; the peak coil current during the continuous flow is 4.15A, which meets the design index requirements of the electromagnet. The new scheme provides a reference for the design of the closing device of the DC circuit breaker.

2. Mechanical motion equation during closing process
The closing action process of the contact mechanism is: after the electromagnet coil is energized, electromagnetic attraction is generated, the locking device is opened, the intermediate shaft and the movable contact fall vertically downwards, and the closing operation of the circuit breaker is realized. In the process of closing and tripping, this article ignores the elastic deformation of each component,
and considers that the tripping frame and the moving iron core as an integral part move rigidly in the vertical direction. The force situation is shown in Figure 1. It can be seen from Figure 1 that the moving iron core of the electromagnet and the trip frame are connected by screws to form a rigid whole; the trip frame and the bilateral trip lock device form a set of interacting precision mechanical linkage devices. See equation (1) for the mechanical motion equation of closing action.

\[
\begin{aligned}
\frac{dz}{dt} &= \nu \\
F_d &= m_d \frac{d\nu}{dt} \\
F_d &= F_m - F_k
\end{aligned}
\]

(1)

In the formula, \(m_d\) is the mass of the moving parts composed of the moving iron core and the tripping frame; \(z\) is the vertical displacement of the moving iron core; \(\nu\) is the vertical velocity of the moving iron core; \(F_d\) is the difference between the electromagnetic attraction force \(F_m\) and the resistance \(F_k\) received by the moving iron core difference.

![Figure 1](image.png)

**Figure 1.** Schematic diagram of the force of the closing action of the moving iron core.

### 3. Design of electromagnet based on empirical formula

#### 3.1. Restrictions

**3.1.1. Starting electromagnetic attraction.** According to the force analysis of the closing action in Figure 1, it is assumed that the starting coil is DC 2A, and the electromagnetic attraction force of the moving iron core is 160N.

**3.1.2. Limit post.** Select the limit column height \(h_{lim}=1\text{mm}\), the limit column radius \(r_{cu}=3\text{mm}\), as shown in the yellow part in Figure 1. Its function is to limit the moving position of the moving iron core, and prevent the moving iron core and the static iron core from colliding multiple times, causing the upper end pier of the moving iron core to be coarsely deformed.

**3.1.3. Initial position working air gap.** Select the total stroke \(l_e=6\text{mm}\) of the moving iron core. The initial position of the air gap height \(h_0=7\text{mm}\).

\[
h_0 = l_e + h_{lim}
\]  

(2)
3.1.4. Core material. In order to ensure that the movable iron core does not undergo plastic deformation during long-term operation, and to avoid the deformation and failure of the precision mechanical coordination mechanism between the trip frame and the bilateral trip lock device, this article chooses to sacrifice part of the magnetic performance of the electromagnet closing action. The 45# steel with excellent mechanical properties is selected as the core material.

3.1.5. Coil thickness. The thickness of the selected coil former $w_{sk}$ is 2mm, as shown in the green part in Figure 1, which provides support for coil winding.

3.1.6. Lateral air gap. The unilateral side air gap $w_{air}$ is selected to be 0.3mm. In order to ensure the pull-in movement of the electromagnet moving iron core, it can be smoothly completed in the slideway on the inner surface of the wire frame, and a certain unilateral side air gap is reserved.

3.1.7. Ignore temperature rise. The electromagnet designed in this paper belongs to a short-term work system, that is, the coil's power-off time is much longer than the on-time, and the coil temperature has enough time to drop to the ambient temperature after the power is off. Therefore, the influence of the heating of the electromagnet on the movement characteristics is negligible.

3.2. Design of structure parameters of electromagnet

After determining the constraints of the electromagnet design, according to the approximate magnetic circuit theory, engineering experience values, geometric dependence, the geometric dimensions of the electromagnet and the coil parameters are sequentially calculated. The solution process is as follows:

3.2.1. Assumed working air gap magnetic flux density modulus $B_{\delta}$. This paper considers that the magnetic surface of the electromagnet moving iron core at the initial position is perpendicular to the magnetic force lines, and the magnetic force lines are evenly distributed on the surface where the moving iron core contacts the air gap. It is assumed that the magnetic flux density mode of the working air gap is $B_{\delta}=0.5T$.

3.2.2. Solve the moving iron core cross-sectional area $S_{move}$, moving iron core outer diameter $D_{move}$.

Only consider the electromagnet attraction equation of the scalar magnitude of the electromagnetic force:

$$F_{m} = \frac{B_{\delta}^2}{2\mu_0} S_{move}$$  \hspace{1cm} (3)

In the formula, $F_{m}$ is the starting electromagnetic attraction force of 160N on the moving iron core; $\mu_0$ is the vacuum permeability. From equation (3), the cross-sectional area of the movable iron core $S_{move}=1609\text{mm}^2$. According to the circular geometric relation:

$$D_{move} = 2\sqrt{\frac{S_{move}}{\pi}}$$  \hspace{1cm} (4)

By formula (4), the outer diameter of the movable iron core $D_{move}=45.3\text{mm}$.

3.2.3. Solve for the inner diameter of the coil winding $d_{rz}$, the outer diameter of the coil winding $D_{rz}$, and the width of the coil winding $w_{rz}$. Only consider the electromagnet attraction equation of the scalar magnitude of the electromagnetic force:

$$d_{rz} = D_{move} + 2w_{air} + 2w_{sk}$$  \hspace{1cm} (5)
In the formula, \( w_{air} \) represents the air gap width of 0.3mm on one side, and \( w_{xk} \) represents the thickness of the bobbin 2mm. According to formula (5), the inner diameter of the coil winding \( d_{rz} = 49.7 \text{mm} \). The electromagnet designed in this paper has a larger outer diameter and a smaller height. At the same time, in order to avoid the shape of the electromagnet from being deformed, the ratio of the inner diameter \( d_{rz} \) of the coil winding to the outer diameter \( D_{rz} \) is selected as 0.6 [2]:

\[
D_{rz} = \frac{d_{rz}}{0.6}
\]

\[
w_{rz} = \frac{(D_{rz} - d_{rz})}{2}
\]

Calculate the outer diameter of the coil winding \( D_{rz} = 82.8 \text{mm} \) by formula (6). Calculate the coil winding width \( w_{rz} = 16.6 \text{mm} \) by formula (7).

3.2.4. Calculate the width of the static core \( w_{Fe} \). The width \( w_{Fe} \) of the static iron core designed in this paper is equal everywhere, according to the principle of equal area of the main magnetic circuit in the iron core, that is, the cross-sectional area of the moving iron core is equal to the annular cross-sectional area of the outer static iron core [3]:

\[
\frac{\pi}{4} \left( (2w_{Fe} + D_{rz})^2 - D_{rz}^2 \right) = \frac{\pi}{4} D_{move}^2
\]

After simplification:

\[
w_{Fe} = \frac{( \sqrt{D_{move}^2 + D_{rz}^2} - D_{rz} )}{2}
\]

Solve the static core width \( w_{Fe} = 5.8 \text{mm} \).

3.2.5. Calculate the working air gap reluctance at the initial position of the moving core \( R_{\delta} \). In this paper, it is approximately considered that the cross-sectional area of the air gap magnetic circuit is equal to the cross-sectional area of the iron core, and the reluctance formula is obtained:

\[
R_{\delta} = \frac{h_{\delta}}{\Phi_{\delta} R_{\delta}} \left( \mu_0 S_{move} \right)
\]

Solve the working air gap magnetoresistance \( R_{\delta} = 3.46 \times 10^6 \text{H}^{-1} \).

3.2.6. Calculate the starting total magnetomotive force \( IN \), the number of coils turns \( N \). According to Ohm’s law of the magnetic circuit, the magnetic potential equation of the main magnetic circuit of the electromagnet is established as:

\[
IN = N \cdot I = \Phi_{\delta} R_{\delta} + \sum H_{li}
\]

Where \( IN \) is the magnetomotive force generated by the electromagnet; \( I \) is the starting coil current 2A; \( \Phi_{\delta} R_{\delta} \) is the magnetic potential consumed in the working air gap; \( \sum H_{li} \) is the sum of the magnetic potential consumed in the non-working air gap and each segment of the permeable magnet, approximately 25% of the total kinetic magnetic potential [4]:

\[
IN = N \cdot I = 1.33 \Phi_{\delta} R_{\delta} = 1.33 B_{\delta} S_{move} R_{\delta}
\]
From equation (12), the number of coil turns \( N = 1852 \) turns.

3.2.7. Select the outer diameter of the wire \( D_{\text{coil}} \). According to the current density limit condition of the solenoid coil of the short-time working system, the wire diameter \( D_{\text{coil}} = 0.4 \) mm is selected.

3.2.8. Calculate the number of wire layers in the coil frame \( m \), the number of wires in each layer \( n \), and the height of the coil frame \( h_{rz} \). According to the geometric dependence of the wires in the coil frame in Figure 2(a):

\[
n = \frac{D_{rz} - d_{rz}}{2D_{\text{coil}}} \quad (13)
\]

It can be solved by formula (13) in turn, each layer contains \( n = 41 \) turns of wire.

\[
m = \frac{N}{n} \quad (14)
\]

Solved by equation (14), the number of wire layers inside the coil frame \( m \) is 45 turns.

\[
h_{rz} = mD_{\text{coil}} \quad (15)
\]

Solved by formula (15), the height of the coil frame \( h_{rz} \) is 18 mm.

3.2.9. Calculate the height of the moving iron core \( h_{\text{move}} \), the outer diameter of the electromagnet \( D_{z} \), the height of the electromagnet \( H_{z} \), and the volume of the electromagnet \( V \). According to the geometric dependency shown in Figure 2(a):

\[
h_{\text{move}} = w_{Fe} + h_{rz} + 2w_{sk} \quad (16)
\]

Solve in turn, the height of the moving iron core \( h_{\text{move}} \) = 26.8 mm.

\[
D_{z} = D_{rz} + 2w_{Fe} \quad (17)
\]

Solve the electromagnet outer diameter \( D_{z} \) = 94.3 mm.

\[
H_{z} = h_{rz} + 2w_{Fe} + w_{sk} \quad (18)
\]

Solve the height of the electromagnet \( H_{z} \) = 33.6 mm.

\[
V = 0.25\pi D_{z}^{2}H_{z} \quad (19)
\]

Solve the volume of electromagnet \( V \) = 2.35E-4 m\(^3\).

To sum up, according to the flow from equation (3) to equation (19), the calculation results of the electromagnet parameters are shown in Table 1. According to the constraints, combined with the electromagnet design results based on the empirical formula in Table 1, a three-dimensional geometric model of the electromagnet is constructed, as shown in Figure 2(b).
4. Steady-state simulation design of electromagnet

The accuracy of electromagnet design based on empirical formula is not high, and it can only be used as the basis of magnetic field simulation design. There are many design parameters of electromagnets, and the influence of different moving iron core shapes on electromagnetic force is more complicated; the functional relation between electromagnet volume $V$ and moving iron core outer diameter $D_{move}$ and other variables is difficult to accurately express by analytical expression. Therefore, studying the change law of a certain parameter alone has little effect on solving the objective function. It is necessary to find the optimal solution of the combination of multiple independent variables.

4.1. Steady-state simulation model construction

According to engineering experience, the boss yoke structure of the electromagnet can effectively improve the magnetic field distribution of the working air gap [2] which is beneficial to reduce the volume of the electromagnet. As shown in Figure 3 (a) in the finite element simulation software, a two-dimensional axisymmetric geometric model of an electromagnet with a boss structure is constructed. Except the geometric parameters in the constraint conditions are assigned specific values, the other parameters are set as function variables. Set the moving iron core outer diameter $D_{move}$ as an independent variable, and according to the functional relation expressed by equations (5) ~ (16), set the winding inner diameter $d_{rz}$, winding outer diameter $D_{rz}$, winding width $w_{rz}$, static iron core width $w_{Fe}$, and coil frame height $h_{rz}$, the height of the moving iron core $h_{move}$ is a function of the outer diameter of the moving iron core $D_{move}$. 

![Diagram of two-dimensional axisymmetric structure of electromagnet](image1)

![Diagram of 3D model designed based on empirical formula](image2)

**Figure 2.** Three-dimensional model of electromagnet designed based on empirical formula.
4.2. **BOBYQA optimization algorithm design**

In order to reduce the volume of the electromagnet and improve the efficiency, this paper adopts the BOBYQA numerical optimization algorithm to find the objective function Objective as the minimum volume of the electromagnet, and find the local optimal combination solution of multiple independent variables such as the moving iron core outer diameter $D_{move}$ [5-8]. Taking the model shown in Fig. 3 as the starting point of the iteration, within a small range of trust region variation, and under constraints such as electromagnetic force limitations, interpolation points and quadratic approximation functions are used instead of objective calculations [9]. The BOBYQA optimization algorithm does not need to know the function expressions of multiple independent variables such as $V$ and $D_{move}$ and calculate their derivatives, and is suitable for solving the non-differentiable "black box" optimization problem [10-13].

4.2.1. **BOBYQA optimized module settings.** The BOBYQA optimization module settings of the finite element software are as follows:

1. Set the objective function. According to formula (19), the volume $V$ of the electromagnet is set as the function expression of the outer diameter of the moving iron core $D_{move}$. The minimum value of the total volume of the electromagnet $V$ is the objective function, as shown in equation (20)

   $\text{Objective} = \min V(D_{move})$  \hspace{1cm} (20)

2. Set the independent variable and value range. Select 4 geometric independent variables and their trust variation ranges, and set the initial value of the moving iron core diameter $D_{move}$ to 45.3mm and the variation range from 38mm~48mm; the initial value of the short side width $w_1$ of the boss is 3mm, ...
and the variation range is introduced. The initial value of the boss height \( h_1 \) is 6mm, and the variation range is 4mm~8mm; the initial value of the boss angle \( \theta \) is 110°, and the variation range is 105°~145°.

(3) Determine the constraints. Set when the coil current is excited \( I=2A \), and the moving iron core is at the bottom dead center, the electromagnetic attraction force \( F_m>160N \). According to formula (17) and formula (18), set the electromagnet outer diameter \( D_z \) and the electromagnet height \( H_z \) as the function expression of \( D_{move} \), set \( D_z <118\text{mm} \), \( H_z <50\text{mm} \).

4.2.2. Optimization Results. In order to facilitate the production and processing of the prototype, after calculation by the BOBYQA solver, the selected results of the fine-tuned prototype are shown in Table 4, and the three-dimensional model constructed according to Table 1 is shown in Figure 4. The movable iron core is subjected to electromagnetic attraction \( F_m=163N \); in order to connect with the trip frame, the height of the movable iron core is increased by 2mm.

![3D model of moving iron core](image1)

![3D model of electromagnet](image2)

**Figure 4.** Three-dimensional model of the selected result of electromagnet prototype design.

**Table 1.** Comparison of prototype design results of electromagnets.

| Parameter name                  | Parameter symbol | Empirical formula design | Optimized design | Prototype selection | Unit |
|---------------------------------|------------------|--------------------------|------------------|---------------------|------|
| Moving iron core outer diameter | \( D_{move} \)   | 45.3                     | 39.7             | 40                  | mm   |
| Width of the short side of the boss | \( w_1 \)       | -                        | 4.1              | 4                   | mm   |
| Height of boss                  | \( h_1 \)        | -                        | 4.9              | 5                   | mm   |
| Boss angle                      | \( \theta \)     | -                        | 119.8°           | 120°                | /    |
| Height of moving iron core      | \( h_{move} \)   | 26.8                     | 32.6             | 34                  | mm   |
| Static core width               | \( w_{Fe} \)     | 5.8                      | 6.8              | 7                   | mm   |
| Wire diameter                   | \( D_{coil} \)   | 0.4                      | 0.4              | 0.4                 | mm   |
| Coil turns                      | \( N \)          | 1845                     | 1628             | 1584                | turn |
| Coil frame wire layer number    | \( m \)          | 45                       | 44               | 44                  | turn |
| Number of wires per layer       | \( n \)          | 41                       | 37               | 36                  | turn |
| Electromagnet height            | \( H_z \)        | 33.6                     | 38.8             | 41                  | mm   |

5. Simulation of electromagnet closing motion characteristics

During the closing movement of the electromagnet, the eddy current effect in the iron core, the magnetic saturation of the iron core material, the equivalent inductance of the coil, and the air gap magnetic field distribution are complicated. In order to verify the applicability of the selected design results of the electromagnet, a transient simulation analysis is required.
5.1. Transient model construction.  
According to the results of prototype selection in Fig. 4 and Table 1, a transient simulation geometric model is constructed. Set the coil turns to 1584 turns, the wire diameter is 0.4mm, the coil excitation is AC220V 50Hz bridge type full-wave rectification, the moving part mass \( m_d \) is 0.372kg, the starting resistance is 160N, and the return spring stiffness coefficient is 2N/mm.

5.2. Transient simulation results n.  
The electromagnet transient simulation solves the change of coil voltage and current within 0ms~40ms, as shown in Figure 5(a). It can be seen from Figure 5(a) that the coil voltage curve is a full-wave rectified waveform of AC220 50Hz power grid with a period of 10ms; the current waveform gradually increases in a wave-like manner, and the current reaches a peak value of 15A in 37ms. Figure 5(b) shows the electromagnetic attraction force, moving iron core displacement and speed change within 0ms~40ms.

![Coil voltage and current waveform](image1)
![Electromagnetic force, displacement and speed](image2)

(a) Coil voltage and current waveform.  
(b) Electromagnetic force, displacement and speed.

**Figure 5.** Changes of coil voltage and coil current during closing.

![Distribution of magnetic flux density mode in iron core](image3)

(a) 0.2ms Power on.  
(b) 18.8ms Movement start.  
(c) 30.8ms End of exercise.  
(d) 40ms End of power up.

**Figure 6.** Distribution of magnetic flux density mode in iron core

Figure 6(a)–(d) respectively show the 0.2ms coil energization start, 18.8ms moving iron core movement start, 30.8ms moving iron core movement end, 40ms coil energization ends at 4 moments, the magnetic flux density model in the core Distribution.
6. Conclusions
This article focuses on the design index of the electromagnet, carries on the optimization design based on the empirical formula and BOBYQA, and draws the following conclusions:

1) The structure parameters of the electromagnet obtained by the electromagnet design based on the empirical formula have low accuracy and can be used as the basic model of the magnetic field simulation design.

2) On the basis of the preliminary design, the BOBYQA optimization algorithm is used to automatically iteratively calculate the four independent variables of the electromagnet moving iron core diameter, the short side width of the boss, the height of the boss, and the angle of the boss based on the steady-state simulation model. After fine-tuning and rounding, all the design parameters of 92mm cylindrical outer diameter, 41mm height, and the smallest electromagnet volume are obtained. The steady-state simulation results show that when the coil current input is DC 2A, the moving iron core at the bottom dead point receives electromagnetic attraction $F_m = 163N$, which is greater than the starting resistance 160N.

3) The transient simulation results of solenoid closing action show that under the excitation of AC220V 50Hz full-wave rectification, the moving iron core starts to move in 18.8ms and completes a 6mm stroke at 30.8ms, with a maximum speed of 2m/s; 40ms continuous on. During the current flow, the coil current peak value $I_{max}$ is 15A, which meets the design specifications of the electromagnet.

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