Research on 10kv Quick Vacuum Circuit Breaker with Double Opening and Closing Coils

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Abstract. This paper introduces the development history of vacuum circuit breakers. According to the low reliability of the vacuum circuit breakers with single opening and closing coil, this paper proposes a new type of 10kV quick vacuum circuit breaker with double opening and closing coils. This new type circuit breaker has two opening and closing coils, which together act on the metal disc of the circuit breaker to ensure the reliability. Then, the electromagnetic repulsion force of the metal disk is deduced using the equivalent calculation method. On this basis, mathematical analysis and calculation are performed on the electromagnetic repulsion of the circuit breaker's metal disc. Thereby the reliablity of the quick vacuum circuit breaker with double opening and closing coils is proved.

1. Introduction

With the rapid growth of China's economy, the scale of the power system has become larger and larger and the load is increasing. The safe and reliable operation of the power system is inseparable from the circuit breaker. When the power grid fails, the circuit breaker acts to quickly cut off the short-circuit current to prevent further accidents from expanding. Therefore, the performance of the circuit breaker directly affects the normal operation of the power grid [1].

Conventional circuit breakers generally employ springs or electromagnetic operating mechanisms. The spring mechanism can store energy through a low-power motor and is suitable for AC operation. But the mechanical structure of the device is complicated, the production cost is high, and its accuracy and reliability is low. The electromagnetic structure relies on electromagnetic force for switching, which has high reliability. However, large electromagnets and large cables are required, and the closing time is long [2].

In 1972, the concept of a quick electromagnetic repulsive force mechanism was first proposed. By applying a pulsed current to the excitation coil, the repulsive force copper disk induces a large repulsive force under the effect of eddy current, which in turn promotes the rapid action of the moving contacts of the circuit breaker. In 1999, the first 15kV vacuum circuit breaker based on the fast repulsive mechanism was produced by Mitsubishi Corporation. Today, vacuum circuit breakers based on fast repulsive structures have been rapidly developed in many countries, especially in Japan and
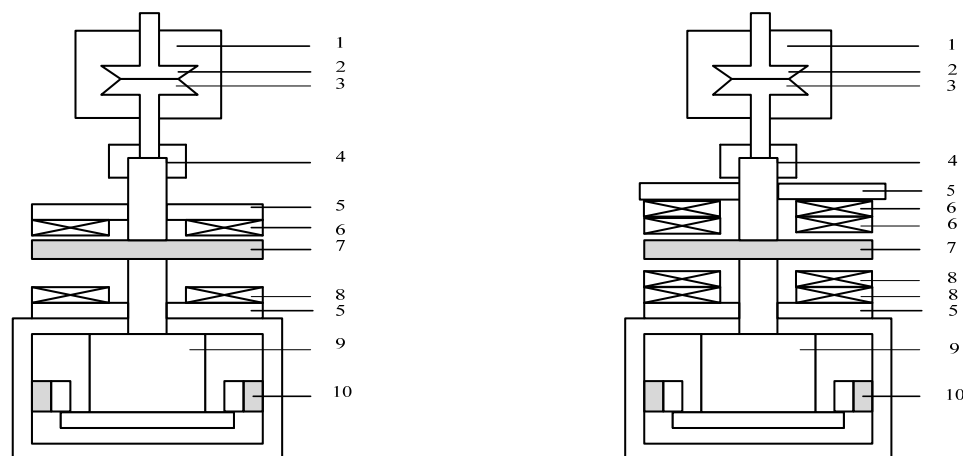
Germany. They have developed a series of quick circuit breakers using the principle of electromagnetic eddy current repulsion. Domestic scholars also study on this topic. Shandong University Qingmin Li developed a fast high-voltage fast transfer switch that uses two-way electromagnetic thrust to perform the operation. Its closing time is 2.3ms, and the opening time is 0.8ms, which satisfies the requirements of fast switching [3].

2. New 10kV quick vacuum circuit breaker with double opening and closing coils

At present, the structure of a vacuum circuit breaker based on fast repulsion is shown in Figure. 1(a). It is mainly composed of a vacuum interrupter, a connecting rod, a metal repulsion disk, an opening and closing coil, and a permanent magnet. The closing coil acts on the metal repulsion disk to generate repulsion. The conventional circuit breaker has only one set of opening and closing coil. Once it fails, it will cause the circuit breaker to be disconnected, which will cause serious consequences.

According to the analysis of relevant statistics, the failure of the operating mechanism of the circuit breaker accounts for about 70% of all circuit breaker failures [1, 4]. The performance of the circuit breaker operating mechanism will affect the safety and stability of the entire power system. In order to improve the reliability of the circuit breaker, the structure of the above circuit breaker has been improved in this paper, as shown in Figure. 1(b).

(a) Ordinary quick vacuum circuit breaker   (b) New quick vacuum circuit breaker

Figure 1. Structure diagram of ordinary and new quick vacuum circuit breaker.

(1-Vacuum interrupter; 2-Static contact; 3-Moving contact; 4-Connecting rod; 5-Fixed plate; 6-Opening coil; 7-Metal repulsion disk: 8-Closing coil: 9-Moving iron core: 10-Magnet.The role of components can refer to literature [5])

The new quick vacuum circuit breaker adopts two sets of independent opening and closing coils to jointly act on the metal repulsion disk. Each set of opening and closing coils has an independent discharge capacitance. When one opening and closing coil fails, the other can normally act on the metal repulsion disk to produce repulsion. Thereby, it can guarantee the effectiveness of the operating mechanism and avoid loss.

3. Electromagnetic repulsion calculation

According to the electromagnetic force calculation method in literature [6], the metal repulsion disk is considered to be equivalent to several rings, and two opening and closing coils work together on the metal disk, as shown in Figure. 2. N_1 and N_2 are the number of turns of the coils of winding 1 and winding 2, and N_0 is the equivalent number of rings of the metal disk. The equivalent circuit equation of the repulsion mechanism is as equation (1):
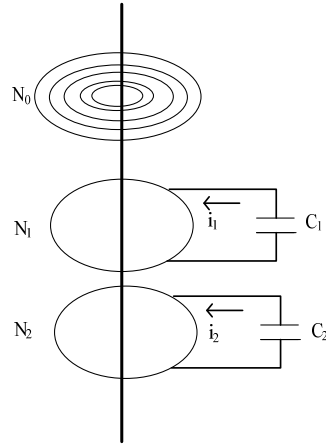
Figure 2. Two independent coils work together on a metal repulsion disk.

$$
\left\{
\begin{aligned}
E_1 &= \frac{1}{C_1}\int_0^t i_1 \mathrm{d}t + i_1 \sum_{m=1}^{N_1} R_{1m} + \frac{\mathrm{d}i_1}{\mathrm{d}t}\sum_{m=1}^{N_1}\sum_{n=1}^{N_1} L_{1mn} \\
&\quad + \frac{\mathrm{d}i_2}{\mathrm{d}t}\sum_{m=1}^{N_1}\sum_{n=1}^{N_2} M_{12mn} + \sum_{m=1}^{N_0}\sum_{p=1}^{N_1} M_{01mp}\frac{\mathrm{d}i_{mm}}{\mathrm{d}t} \\
E_2 &= \frac{1}{C_2}\int_0^t i_2 dt + i_2 \sum_{m=1}^{N_2} R_{2m} + \frac{\mathrm{d}i_2}{\mathrm{d}t}\sum_{m=1}^{N_2}\sum_{n=1}^{N_2} L_{2mn} \\
&\quad + \frac{\mathrm{d}i_1}{\mathrm{d}t}\sum_{m=1}^{N_1}\sum_{n=1}^{N_2} M_{12mn} + \sum_{m=1}^{N_0}\sum_{p=1}^{N_2} M_{02mp}\frac{\mathrm{d}i_{mm}}{\mathrm{d}t} \\
0 &= R_{11}i_{11} + \frac{\mathrm{d}i_1}{\mathrm{d}t}\sum_{m=1}^{N_1} M_{01m1} + \frac{\mathrm{d}i_2}{\mathrm{d}t}\sum_{m=1}^{N_2} M_{02m1} \\
&\quad + \sum_{q=1}^{N_0} L_{0qq}\frac{\mathrm{d}i_{qq}}{\mathrm{d}t} \\
0 &= R_{22}i_{22} + \frac{\mathrm{d}i_1}{\mathrm{d}t}\sum_{m=1}^{N_1} M_{01m2} + \frac{\mathrm{d}i_2}{\mathrm{d}t}\sum_{m=1}^{N_2} M_{02m2} \\
&\quad + \sum_{q=1}^{N_0} L_{0qq}\frac{\mathrm{d}i_{qq}}{\mathrm{d}t} \\
&\qquad\qquad\qquad\vdots \\
0 &= R_{N_0 N_0}i_{N_0 N_0} + \frac{\mathrm{d}i_1}{\mathrm{d}t}\sum_{m=1}^{N_1} M_{01mN_0} + \frac{\mathrm{d}i_2}{\mathrm{d}t}\sum_{m=1}^{N_2} M_{02mN_0} \\
&\quad + \sum_{q=1}^{N_0} L_{0qq}\frac{\mathrm{d}i_{qq}}{\mathrm{d}t}
\end{aligned}
\right.
\tag{1}
$$

Where, E_1, E_2-the initial value of the charging capacitance of the opening and closing winding 1 or winding 2

R_{1m}, R_{2m}- the resistance of each turn of winding 1or winding 2

R_{mm} - the resistance of each equivalent ring of the metal disc

i_1, i_2-the current in winding 1 or winding 2

i_{mm}-the current in each equivalent ring of the metal disc

L_{1mn}-The self-inductance of each turn of the winding 1

L_{2mn}-the self-inductance of each turn of the winding2

M_{12n}-the mutual inductance between the winding 1 and the winding 2

M_{01mp}-the mutual inductance between the winding 1 and the equivalent ring of the metal plate

M_{02mp}- the mutual inductance between the winding 2 and the equivalent ring of the metal plate

It can be organized as equation (2):

$$
\begin{bmatrix} i_1 \\ i_2 \\ i_{11} \\ i_{22} \\ \vdots \\ i_{N_1N_1} \end{bmatrix} = \begin{bmatrix} \dfrac{E_1 - \dfrac{1}{C_1}\displaystyle\int_0^t i_1 \mathrm{d}t}{\displaystyle\sum_{m=1}^{N_1} R_{1m}} \\ \dfrac{E_2 - \dfrac{1}{C_2}\displaystyle\int_0^t i_2 \mathrm{d}t}{\displaystyle\sum_{m=1}^{N_2} R_{2m}} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} - \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} \dfrac{\mathrm{d}i_1}{\mathrm{d}t} \\ \dfrac{\mathrm{d}i_2}{\mathrm{d}t} \\ \dfrac{\mathrm{d}i_{11}}{\mathrm{d}t} \\ \dfrac{\mathrm{d}i_{22}}{\mathrm{d}t} \\ \vdots \\ \dfrac{\mathrm{d}i_{N_1N_1}}{\mathrm{d}t} \end{bmatrix}
\tag{2}
$$

Where, **A** is an N_2+2 dimensional inductance coefficient matrix. Rewrite equation (2) as a matrix vector as (3)-(7).

$$
\mathbf{I} = \mathbf{E} - \mathbf{A}\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}t}
\tag{3}
$$

$$
\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}t} = \mathbf{A}^{-1}\left(\mathbf{E} - \mathbf{I}\right)
\tag{4}
$$

$$
\mathbf{I}_{j+1} = \mathbf{A}^{-1}\left(\mathbf{E}_{j+1} - \mathbf{I}_{j+1}\right) \bullet \Delta t + \mathbf{I}_j
\tag{5}
$$

$$
F = \sum_{m=1}^{N_1}\sum_{p=1}^{N_0} i_1 i_{pp}\frac{\mathrm{d}M_{01mp}}{\mathrm{d}x} + \sum_{m=1}^{N_2}\sum_{p=1}^{N_0} i_1 i_{pp}\frac{\mathrm{d}M_{02mp}}{\mathrm{d}x}
\tag{6}
$$

$$
m\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = F - f\left(x\right)
\tag{7}
$$

Where, $f(x)$ is the resistance during the movement, and it can be regarded as zero with respect to the short-term huge electromagnetic repulsion F.

Together, the double-iteration of time and displacement can be used to solve the dynamic process of energized coil current, copper disk eddy current, copper disk displacement and electromagnetic repulsive force [7].

4. Simulation calculation

According to the calculation method of the above electromagnetic repulsion force, the example simulation analysis is carried out. It calculates a dynamic calculation result of quick vacuum circuit breaker with double opening and closing coils. The calculation parameters are as follows. Copper disk: Inner radius 15 mm, outer radius 55 mm, thickness 5 mm, width 2 mm (copper disk equivalent parameter $N0 = 20$)); coil 1: radius 50 mm, thickness 5 mm, width 2 mm, number of turns $N1 = 4$, charging voltage $E1 = 380V$, discharge capacitance $C1 = 50000uF$; coil 2: radius 50mm, thickness 5mm, width 2mm, number of turns $N2 = 4$, charging voltage $E1 = 400V$, discharge capacitance $C1 = 70000uF$; initial distance of copper disk and coil 1 is 3mm; The distance between the coil 1 and the coil 2 is 10 mm; the stroke of the moving contact of the switch is 10 mm; the mass of the copper disk and the round rod M is 2 kg.

The equation is calculated by programming. The following are dynamic process diagrams (time is 0-5ms) of the current $i1$ of the opening and closing coil 1, the current $i2$ of the opening and closing coil 2, the electromagnetic repulsion force F, and the change of the switching stroke X.

(a)the current i1

(b) the current i2

(c) the electromagnetic repulsion force F

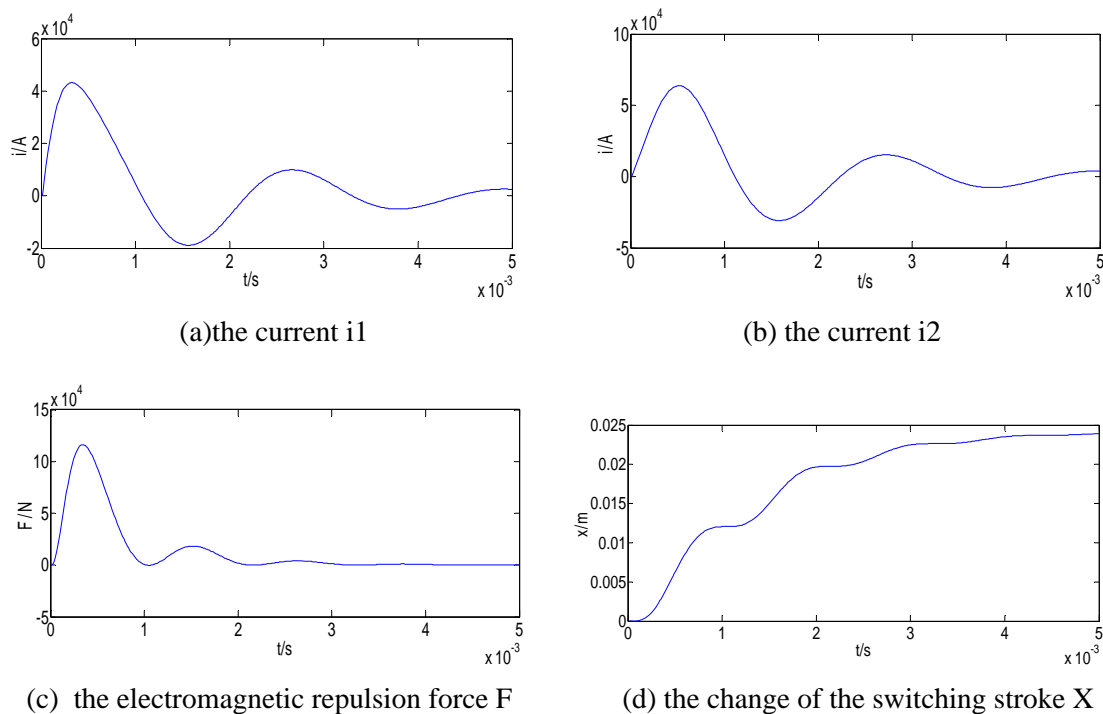(d) the change of the switching stroke X

Figure 3. The process of dynamic change of variables over time.

The switch stroke starts from zero and the displacement is initially zero. When the displacement is 0.01m, the circuit breaker is closed, and the corresponding time is 0.69ms.

5. Conclusion

This paper introduces the development history of vacuum circuit breakers. Due to the low reliability of existing circuit breakers, this paper proposes a new circuit breaker structure with two independent opening and closing coils. The two independent opening and closing coils act independently on the metal disc to ensure the reliability of the operation. On this basis, the electromagnetic repulsion force of the metal disk is deduced using the equivalent calculation method. Finally, the parameters are selected and the closing time of the circuit breaker is 0.69ms through simulation calculation, which satisfies the requirement of quick opening and closing.

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