Analysis of average-closing-speed for medium-vacuum circuit breaker from theoretical calculation aspects

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Abstract. Average closing speed is an important indicator for evaluating the performance of CB, in order to calculate the average closing speed of the spring operating mechanism of the medium voltage vacuum circuit breaker, the paper establishes a simplified model of CB mechanism, combined with the kinetic energy theorem, and obtains the average closing speed by analyzing the equivalent mass and energy of the mechanism. In order to verify the correctness of the proposed method, the paper establishes a CB simulation model to obtain the simulated average closing speed. In the calculation of the energy of the open-off phase, the paper adopts a segmentation calculation method, which divides the closing process into the open-distance phase and the over-travel phase, and the calculated average closing speed is more accurate. This theoretical calculation method provides a theoretical basis for the research and development of the medium-voltage vacuum CB spring operating mechanism, and plays a positive role in related research and development work.

1. Introduction
The average closing speed of CB refers to the moving speed of the moving contact of CB during the closing process [1]. In the actual design, the average closing speed is usually taken as the average speed of the moving contact at the 70% distance from the opening distance to the point of the closing point. If the average closing speed is too fast, it will cause some damage to the vacuum interrupter, which is an important indicator for evaluating the performance of the circuit breaker.

At present, the research on the average closing speed is mainly through calculating the energy change of the whole closing process, and using the kinetic energy theorem to calculate the closing speed [2]. This is a full-scale averaging method that can only be used for approximate calculations. The spring operating mechanism is complicated, and the average closing speed obtained by the whole-average calculation method is far from the actual closing speed, which can not meet the needs of the current design.

The closing process is divided into two stages: open distance and overtravel. Firstly, the paper establishes a simplified model of the circuit breaker mechanism, and then calculates the energy change from the start of the closing to the displacement of the moving contact to 70% of the opening distance, the change of the mechanical energy from the start of the closing to the closing point, and the equivalent mass of the mechanism. Finally, the article uses the kinetic energy theorem to calculate the average closing speed. This calculation method divides the closing process into several stages and can calculate the average closing speed more accurately.
2. Establishment of simplified model for spring operating mechanism of medium voltage vacuum circuit breaker

The article selects a spring operating mechanism of medium voltage vacuum circuit breaker with a rated voltage of 12kV and rated short circuit breaking current of 31.5kA as the research object. Firstly, the simplified model of the circuit breaker mechanism is established by using the 3D modeling software SolidWorks. After that, in order to facilitate the calculation, the connecting rod is simplified into a straight line, and finally a simplified model of the circuit breaker transmission mechanism is obtained, as shown in Figure 1:

![Figure 1. Simplified model of circuit breaker mechanism.](image)

In the Figure 1: 9 represents the energy storage spring; 8 represents the link 8; 2, 3, 4, 5, 6, and 7 represent links 2, 3, 4, 5, 6, and 7; 10 represents the opening spring; 1 represents the moving contact portion.

During the closing process, after the circuit breaker receives the closing command, the energy storage spring releases the energy to push the connecting rod 8 to rotate. The link 8 drives the main shaft to rotate through the four-bar mechanism. When the main shaft rotates, the insulating rod is driven by the four-bar mechanism to move the moving contact. Move upward until the closing operation is completed, and at the same time, the opening spring is elongated with the rotation of the main shaft, and the opening spring stores energy to store energy for the mechanism opening [3].

3. Theoretical calculation of average closing speed of medium voltage vacuum circuit breaker

3.1. Calculation of speed ratio

Since the research goal of the article is to calculate the average closing speed of the moving contact, the article takes B point as the equivalent point and calculates the speed ratio of the remaining points relative to point B.

In the calculation, the fixed points A, E and I are used as fulcrums, and the speed ratio calculation is not involved. The speeds of points B, C, D, F, G and J are represented by \( v_B \), \( v_C \), \( v_D \), \( v_F \), \( v_G \) and \( v_J \). According to the different transmission modes of the mechanism, the mechanism transmission can be divided into two types:

1. The link rotates at the same angular speed of the same rotating shaft
   At this time, the speed of the mechanism is inversely proportional to the length of the mechanism [4]. Since the points A, E and I are the rotating shafts, We can get:
\[ v_c = \left( \frac{L_2}{L_{AB}} \right) v_b \]  
(3.1)

In the formula: \( L_2 \) represents the length of the link 2; \( L_{AB} \) represents the distance from point A to B.

\[ v_f = \left( \frac{L_5}{L_4} \right) v_d \]  
(3.2)

In the formula: \( L_5 \) represents the length of the link 5; \( L_4 \) represents the length of the link 4.

\[ v_j = \left( \frac{L_8}{L_7} \right) v_k \]  
(3.3)

In the formula: \( L_8 \) represents the distance from point I to J; \( L_7 \) represents the length of the link 7.

(2) Four-bar linkage

In the organization, ACDE and EFGI are two four-bar mechanisms. We can use the closed triangle rule to find the speed ratio of the transmission rod [5].

Taking the point D speed as an example: \( v_c \) is perpendicular to the link 2, \( v_d \) is perpendicular to the link 4, we make the vertical speed so that it is perpendicular to the link 3, and construct a triangle by using the vertical speed and \( v_c, v_d \), as shown in Figure 2:

![Figure 2. Closed triangle rule.](image)

Then we can use the closed triangle rule to find \( v_d / v_c \).

Similarly, we can use \( v_f, v_g \) and the vertical velocity of the link 6 to construct a closed triangle, then we can find \( v_f / v_f \).

By substituting the various institutional parameters into the formula, we can find the speed ratio of the circuit breaker closing process, as shown in Table 1:

| Node number | Node speed | speed ratio | ratio |
|-------------|------------|-------------|-------|
| B           | \( v_b \)  | \( v_b / v_b \) | 1     |
| C           | \( v_c \)  | \( v_c / v_b \) | 2.59  |
| D           | \( v_d \)  | \( v_d / v_b \) | 5.08  |
| F           | \( v_f \)  | \( v_f / v_b \) | 2.08  |
| G           | \( v_g \)  | \( v_g / v_b \) | 2.56  |
| J           | \( v_j \)  | \( v_j / v_b \) | 1.93  |

### 3.2 Equivalent mass calculation

#### 3.2.1 Substitute quality

From a theoretical point of view, according to the different modes of movement of components, the substitution quality can be divided into the following three types:

- **Parts for linear translation:** the substitute quality of such parts can be considered to be concentrated at any point of the part. For example, the mass of part 1 can be directly equivalent to point B.
- **Parts that rotate around a fixed axis:** According to the principle of conservation of moment of inertia, the alternative quality of such parts can be concentrated at any point of the part. For example, The mass of the link 2, 4, 7 can be equivalent to points C, D, G.
- **Complex parts that do parallel plane motion:** These parts are usually approximated and the mass
is equivalent to both ends of the part[6]. For example, The mass of the link 3 can be equivalent to points C, D; The mass of the link 6 can be equivalent to the points F, G.

3.2.2 Node quality
The two components are connected together by a pin. We call the pin joint a node. By calculating the replacement mass, most of the parts can be concentrated on the nodes[7].

3.2.3 Equivalent quality
By calculating the mass of the substitute and the mass of the node, the mass of the part is concentrated on several nodes, and the motion of each node is \( v_a, v_b, \ldots \), then the kinetic energy of the whole moving part is[8]:

\[
A_d = \frac{1}{2} m_A v_A^2 + \frac{1}{2} m_B v_B^2 + \frac{1}{2} m_C v_C^2 + \cdots = \frac{1}{2} \left[ m_A + m_B \left( \frac{v_B}{v_A} \right)^2 + m_C \left( \frac{v_C}{v_A} \right)^2 + \cdots \right] v_A^2 = \frac{1}{2} m v_A^2 \tag{3.4}
\]

In the formula: \( m \) is the equivalent mass to be calculated. Through the SolidWorks software, the mass and moment of inertia of each component, axle pin, spring, etc. can be obtained. Combined with the above-mentioned equivalent mass solution method, the node quality is shown in Table 2:

| Table 2. Node quality. | Components |
|----------------------|------------|
| Node                | 1 | 2 | 3 | 4 | 6 | 7 | 8 | 9 |
| B                   |   |   |   |   |   | 5.1 |   |   |
| C                   | 0.41 | 1.24 |   |   |   |   |   |   |
| D                   |   |   | 1.24 | 0.35 |   |   |   |   |
| F                   |   |   |   |   |   |   | 0.03 |   |
| G                   |   |   |   |   | 0.03 | 0.03 |   |   |
| J                   |   |   |   |   |   |   |   | 0.11 | 0.32 |

Known node mass and mechanism speed ratio, according to the equivalent mass formula:

\[
m = m_A + m_B \left( \frac{v_B}{v_A} \right)^2 + m_C \left( \frac{v_C}{v_A} \right)^2 + \cdots \tag{3.5}
\]

The equivalent mass of the available circuit breaker mechanism at point B is 62Kg.

3.3 Energy calculation
There are mainly five kinds of forces in the closing process to provide energy for closing. The energy storage spring and the contact self-closing force are used to drive the circuit breaker to close, and the opening spring, gravity and overtravel spring block the circuit breaker to close. The overtravel spring acts in the overtravel phase of the circuit breaker and does not need to be considered in the calculation of the energy in the open phase[9].

Through the simplified model of the circuit breaker established by SolidWorks, we can analyze the change of the length of the energy storage spring and the opening spring when the moving contact is at different positions, and then find the energy provided by each load force for closing.

In the article, the distance of the circuit breaker is 12mm, and the length of the energy storage spring and the opening spring are analyzed when the contact is started at the closing, displacement is 8.4mm, and the joint is just closed. As shown in Table 3.

After calculating the displacement of the energy storage spring, the opening spring and the moving contact, the energy storage spring is set to work \( W_1 \), the opening spring is \( W_2 \), the contact self-closing force is \( W_3 \), the gravity work is \( W_4 \), according to the spring work formula, The self-closing work formula and the gravity work formula can be used to obtain \( W_1, W_2, W_3, \) and \( W_4 \).

In addition, since the friction of the mechanism will lose some energy during the transmission process, the calculation is complicated. In engineering practice, it is generally expressed as mechanical
efficiency. The average value $\eta$ is generally 0.6 to 1, due to the spring action. There are many parts in the mechanism, and the energy loss in the transmission process is large. Therefore, the article takes $\eta = 0.9$ for theoretical calculation [10].

Table 3. Mechanism displacement.

| Contact displacement (mm) | Energy storage spring length (mm) | Energy storage spring displacement (mm) | Opening spring length (mm) | Opening spring displacement (mm) |
|---------------------------|----------------------------------|----------------------------------------|---------------------------|---------------------------------|
| 0                         | 133.68                           | 0                                      | 189.58                    | 0                               |
| 8.4                       | 142.87                           | 9.19                                   | 213.70                    | 24.12                           |
| 12                        | 148.69                           | 15.01                                  | 24.12                     | 35.54                           |

Therefore, the energy change formula in the closing phase is:

$$W = \eta(W_1 + W_2 - W_3 - W_4)$$

(3.6)

The closing energy of the moving contact at the closing position of the closing position, displacement of 8.4 mm and the position of the just-integrated point is shown in Table 4:

Table 4. Institutional energy change.

| Displacement | $W_1$ | $W_2$ | $W_3$ | $W_4$ | $W$  |
|--------------|-------|-------|-------|-------|------|
| 0            | 0     | 0     | 0     | 0     | 0    |
| 8.4          | 31.64 | 11.36 | 3.02  | 0.43  | 20.58|
| 12           | 53.92 | 18.52 | 4.32  | 0.61  | 35.20|

3.4 Average closing speed calculation

The kinetic energy theorem formula is:

$$W = \frac{1}{2}mv^2$$

(3.7)

In the formula: $W$ represents the energy of the closing; $m$ represents the equivalent mass of the institution; $v$ represents the closing speed.

The closing energy and the equivalent mass of the mechanism have been obtained above, and the data is substituted into the kinetic energy theorem formula, which can be concluded as follows: The speed of the moving contact when the displacement is 70% of the opening distance is 0.83 m/s. The speed at which the movable contact is displaced to the just-engaged point is 1.07 m/s. The movement of the moving contact during the closing phase can be approximated as an equal acceleration motion, and the average closing speed can be approximated as the average of the two, that is, the average closing speed is 0.95 m/s.

4. Simulation analysis of average closing speed based on Adams

The virtual prototype is used to simulate the closing of the spring operating mechanism of the medium voltage vacuum circuit breaker, and the simulation results of the closing speed are obtained. The correctness of the analytical method is verified by comparing the theoretical closing method and the average closing speed obtained by the simulation method.

4.1 Establish a simplified model of medium voltage vacuum circuit breaker

The modeling ability of Adams is weak. It is difficult to guarantee the three-dimensional model of medium voltage vacuum circuit breaker mechanism directly with Adams. Therefore, the article adopts professional 3D modeling software SolidWorks modeling, and then imports into Adams. The simplified model of the circuit breaker established in the paper is shown in Figure 3.
4.2 Adams simulation analysis
Introduce the established circuit breaker model into Adams, add constraints and spring drive to the mechanism, build a virtual prototype, and then simulate and analyze the virtual prototype closing process. The simulation results are shown in Figure 4:

It can be seen from Figure 4 that when the moving contact displacement is 8.4 mm, the closing time is 0.0153 s, and when the moving contact moves to the just-integrated point, the closing time is 0.019 s, so the average closing speed of the simulation is 0.97m/s.
Comparing the calculation results with the simulation results, it can be concluded that the average closing speed obtained by the two methods is very close and the error is within a reasonable range, which verifies the correctness of the theoretical solution method.

5. Conclusion
- The article analyzes the average closing speed of the spring operating mechanism of the medium voltage vacuum CB from the theoretical point of view. Provide a theoretical basis for the design and development of circuit breakers.
- The article establishes a virtual prototype through ADAMS, and verifies the correctness of the theoretical analysis method by simulation.
- In the analysis of energy, a segmentation method is adopted. The article divides the closing process into the open phase and the overtravel phase, and then calculates the energy of different
phases in the open phase. This method of segmentation reduces the error of theoretical calculations.

- There are still many shortcomings in the analysis of the average closing speed. For example, when calculating the friction of the mechanism, the article only approximates the mechanical efficiency. If the friction of the mechanism can be analyzed in detail, the theoretical analysis results will be more accurate.

6. References

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Acknowledgments

This work was supported by the Fujian Provincial Natural Science Foundation Project (GrantNo.2019J01867).