Review of 72.5kV double-break vacuum circuit breaker based on rapid repulsion actuator

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Abstract. 72.5kV double-break vacuum circuit breakers based on rapid repulsion actuator remain blank in China. Based on the theoretical analysis and experimental results from researchers, the design of 72.5kV double-break vacuum circuit breakers based on rapid repulsion actuator was presented. It takes the form of double-break, using two standard 40.5kV vacuum interrupter in series at the bottom, which adopt a permanent magnetic repulsion actuator. The permanent magnetic repulsion actuator consists of rapid repulsion actuator and magnetic retentivity actuator. On the basis above, we produced the prototype, and the superiority of the design was verified through the experiments.

1. Introduction

The rapid development of China's power system greatly promoted the development of high-voltage vacuum circuit breakers. Especially in recent years, because of the research and application of the multi-power and non-disturbance fast switching device for high voltage power network, the action speed of the high-speed switch has been put forward higher requirements. At present, the relevant units at home and abroad has made progress in the development of 110kV high voltage vacuum circuit breakers, such as the breaking performance and the mechanism design of the vacuum interrupter chamber. But the 72.5kV double-break vacuum circuit breakers based on rapid repulsion actuator remain blank in China. Independent research and development should be made to the related key technologies and the equipments\cite{1}.

Because there is a saturation effect between the break voltage of the breaker and the gap length of the fracture, when the length of the vacuum gap is longer than usual, simply increasing the length of the vacuum gap can't improve the pressure level of vacuum circuit breakers. When the relatively long vacuum gap is divided into several relatively short vacuum gaps, and put them in series, you can improve its pressure level. Actually, this is the basis of using the multi-break vacuum circuit breaker technology to obtain high-voltage circuit breakers. In order to promote the vacuum circuit breaker to a higher voltage level of development and application, using the advantages of multi-break vacuum circuit breaker is a more sensible choice.

Due to the stray capacitance, the partial pressure of the multi-break circuit breaker is not uniform, which will make the breaking performance of circuit breakers greatly worse. Therefore, this paper also discusses the approach of the domestic and foreign researchers using on the fracture of the pressure equalization.

Based on the theoretical analysis and experimental results from researchers, the design of 72.5kV double-break vacuum circuit breakers based on rapid repulsion actuator was presented. It takes the form of double-break, using two standard 40.5kV vacuum interrupter in series at the bottom, which adopt a permanent magnetic repulsion actuator. The permanent magnetic repulsion actuator consists of
rapid repulsion actuator and magnetic retentivity actuator. On the basis above, we produced the prototype, and the superiority of the design was verified through the experiments.

2. Theoretical basis of 72.5kV double-break high voltage vacuum circuit breaker

2.1. Pressure saturation effect of vacuum gap

Vacuum gas molecules in the air gap is minimal. As the breakdown of vacuum air gap by a variety of factors, the physical process is very complex[2]. After researchers repeated theoretical analysis and experimental demonstration several times, the relationship between the breakdown voltage and the vacuum gap length is obtained[3]. When the length of the vacuum gap is relatively small, generally less than 0.5cm, the breakdown voltage will proportionally increase as the length of the vacuum gap increases. When the vacuum gap length is large, generally more than 1cm, the breakdown voltage does not increase proportionally as the length of the vacuum gap increases, showing a pressure saturation characteristics. The relationship is:

\[ U = \begin{cases} Kd, & d \leq 0.5cm \\ Kd^\alpha, & d \geq 1.0cm \end{cases} \]  

(1)

Where \( U \) is the breakdown voltage in kV; \( K \) is the proportional constant; the exponential factor \( \alpha \) is usually in the range of 0.4 to 0.7; \( d \) is the length of the vacuum gap in cm.

Physical principles of multi-break vacuum circuit breaker, in essence, is the use of multiple small vacuum gap in series. Then make full use of the advantages of the short vacuum gaps. So we will obtain a vacuum circuit breaker of higher tolerance voltage level. Under ideal circumstances, the researchers assumed that the voltage of each interrupter in a multi-break vacuum circuit breaker was evenly distributed. The relationship between the breakdown voltage and vacuum gap length is:

\[ U_n = nKd^\alpha \]  

(2)

Where \( U_n \) is the multi-break vacuum circuit breaker breakdown voltage. The meaning of the other physical quantities is the same as above. Under ideal circumstances, assuming that the interrupter vacuum gap length of a single-break vacuum circuit breaker is \( n \) times the interrupter vacuum gap length of a multi-break vacuum circuit breaker. The breakdown voltage of single-break vacuum circuit breaker is:

\[ U_1 = K(nd)^\alpha \]  

(3)

The gain multiplies of breakdown voltage of the multi-break vacuum circuit breaker are:

\[ K_n = \frac{U_n}{U_1} = n^{(1-\alpha)} \]  

(4)

As can be seen from equation (4), for a double-break rapid vacuum circuit breaker, if the exponential factor is 0.5, the breakdown voltage gain factor is 1.414. Under ideal circumstances, compared with single-break vacuum circuit breakers, multi-break vacuum circuit breakers have higher pressure level. It can be seen that multi-break rapid vacuum circuit breakers have the following advantages: The voltage applied to each of the break ports can be reduced by the configuration of a plurality of ports, and the arc-gap recovery voltage of each port can be reduced. The arc is divided into a plurality of small arc segments by a plurality of fractures, then connect them in series. As the same contact stroke, the tensile arc of multi-break structure is longer than the single break structure, which is mean that arc gap resistance becomes larger. Circuit breaker opening speed has been improved, while accelerating the recovery speed of the media. Circuit breaker control mechanism has reduced mechanical energy, laying the foundation for its manufacturing.
2.2. Dynamic properties of the multi-break vacuum circuit breaker
The insulation properties and changes of the multi-break vacuum circuit breakers in a variety of practical situations are called the dynamic insulation properties of the multi-break rapid vacuum circuit breaker, including the medium strength and the post-arc re-breakdown ability of the circuit breaker in a high-current breaking. That is reflecting the ability of the vacuum breaker to break current. The dynamic insulation characteristics of the multi-break fast vacuum circuit breaker are closely related to the reliability of the circuit breaker operating safely and stable in power system. So it has been the focus of researchers.

In paper [3], the breaking performance of the double-break circuit breaker was tested by using two single-break vacuum circuit breakers. Using the arc time to reflect the circuit breaker breaking capacity, it is concluded that the breaking performance of the double-break vacuum circuit breakers are better than the single-break fast vacuum circuit breakers. In paper [4], two 24kV fast vacuum circuit breakers are connected in series, the experimental results are analyzed. It is found that the breaking performance of the double-break vacuum circuit breakers is 1.3 times higher than that of the single-break vacuum circuit breakers.

3. Fracture pressure equalization technique of 72.5kV double-break vacuum circuit breakers
Due to the stray capacitance, the fracture partial pressure of the multi-break circuit breaker is not uniform. The way by increasing the installed equalizing capacitor is mainly taken at home and abroad, thereby enhancing the uniform distribution properties of the multiple-break fast breaker's fracture voltage. In paper [5], the breaking time of the circuit breaker is used to characterize its breaking performance. It is proved by experiments that increasing the voltage equalizing capacitor has a positive effect on improving the breaking performance of the double-break vacuum circuit breakers. Throughout the course of the experiment, when no additional installation of voltage equalizing capacitor, the successful breaking of the double-break vacuum circuit breaker was happened 2.8ms after the arcing. At the same time, there is no clear dispersion region in the whole experiment. After equipping with a 100pF equalizer capacitor, there is a clear dispersion region in the whole experiment. In particular, when the arc time beyond 2.3ms, each fracture of the double-break vacuum circuit breaker can successfully break.

In paper [6], the experimental results show that the distribution of the recovery voltage on each fracture is more uniform when there is a equalizer capacitor. But the capacity of the equalizer capacitor is not the bigger the better. Because it may cause that the arc time of two vacuum interrupter is different, leading to the breakdown of the double-break vacuum circuit breaker. So the breaking performance of the double-break vacuum circuit breakers is deteriorated.

In paper [7], the positive impact of the installation of the equalizer capacitors on the multi-break fast break circuit breakers and the negative issues followed by the installation is comprehensively overviewed. At the same time, the theory of the positive influence and the new problem is studied. Some existing theoretical and experimental research limitations are put forward. And the preliminary analysis results are given. Based on the above theoretical research, the author gives some constructive suggestions on the reasonable value of equalizing capacitance of multi-break vacuum circuit breakers, playing a positive role in the further development of the equalizer capacitors of the multi-break vacuum circuit breakers. In paper [8], the negative effects caused by using the equalizer capacitors are demonstrated in theory and experiment.

In paper [4], in order to avoid the risk of the installation of equalizing capacitor, a new design of the double-break circuit breakers is obtained. The rational use of fracture structure is arranged so as to optimize the allocation of two fracture partial pressure. Because the connection distance between the two vacuum interrupters is very small and the position at which the fracture is connected is far away from the ground, generally more than 1000mm, the port dispersion capacitance of the conductor at the junction is very small, which can be ignored. So its equivalent circuit can be shown in Figure 1.
Figure 1. The equivalent circuit of the new double-break vacuum breaker.

Where $U$ is the supply voltage; $U_1$ and $U_2$ are the fracture voltage; $C_d$ is the fracture capacitance, usually 1000pF to 2000pF; $C_0$ is the capacitance to the ground, usually 20pF to 60pF. It can be seen that, in this form of structure, the fracture voltage is basically the same, because $C_d$ is far greater than $C_0$.

4. Structure design of the double-break high voltage vacuum circuit breaker

4.1. Appearance structure design of 72.5kV double-break vacuum circuit breaker

When designing the appearance structure of the double-break vacuum circuit breaker, the "H" type structure and inverted "A" type structure are generally used. The drive mechanism of the inverted "A" type fast vacuum circuit breaker must be equipped with a rotating part to turn the force of vertical movement to a certain angle oblique force. Not only will it affect the circuit breaker opening and closing speed, but also affect the operating force. As can be seen from the above, using "H" type structure can make full use of its structural advantages to achieve the fracture pressure. In this paper, the form of double-break is taken, and two standard 40.5kV vacuum interrupter are used in series at the bottom. It can be shown below in Figure 2.

Figure 2. Appearance of the single-phase rapid vacuum breaker.

In Figure 2, X and Y are designed in accordance with the 72.5kV voltage level. $X_1$ and $Y_1$ are the drive dimensions that match the 72.5kV vacuum circuit breaker. And sealing should be considered for outdoor installation. Considering the insulation standard of relevant voltage grade, the final design dimension of X is 650mm, Y is 1050mm, $X_1$ is 850mm, $Y_1$ is 400mm.

4.2. Actuating mechanism structure design of 72.5kV double-break vacuum circuit breaker

Overview of actuator. The main performance of the rapid vacuum circuit breaker is directly presented in the opening and closing action time and speed of the static and dynamic contact of the circuit breaker. Opening and Closing action must be completed directly by the operating mechanism. Therefore, the performance of the selected operating mechanism will directly affect the stability and reliability of the high-voltage vacuum circuit breaker[9,10].
The energy is stored in the traditional spring operating mechanism by the built-in elastic properties of the spring. And it does not require high-powered DC power as operating power. However, the mechanical structure of the device is complicated, and the production cost is high. Also the precision is low, the reliability cannot be guaranteed. The electromagnetic mechanism structure drive is simple and reliable. But in order to provide greater operating power, it usually requires a larger traction electromagnet, power supply unit and large area cable. It need to be equipped with expensive battery, leading to the heavy structure and long action time. The traditional permanent magnet actuator has many problems, such as the large cumulative motion tolerance of each control link and the slowly action response. So the action of each breaker of the circuit breaker is not synchronized. Thus, the traditional multi-break vacuum circuit breaker is not widely used in practice. Therefore, the development of higher voltage single-break fast vacuum circuit breakers has become a problem that many researchers need to solve[11-14].

At present, the study of the circuit breaker operating mechanism using eddy current electromagnetic repulsion principle has been flourishing. In this way, the requirements can be completed in a very short period of time to quickly drive the load. Therefore, many researchers pay close attention to this aspect of the study. Currently many countries in the world have the corresponding development in the field of quick vacuum circuit breaker based on electromagnetic repulsion mechanism, especially in Japan, Germany and so on. They are using electromagnetic eddy current repulsion principle to design the quick circuit breaker at a series of voltage grade, and developed relative products by use of this principle. Repulsion mechanism has obvious advantages. Repulsion mechanism does not require mechanical off and locking device, so there is few sources of failure. Thus, it can safely and reliably operate for a long time[15-20]. It is particularly worth mentioning that the movement of its operating mechanism can be accurate to the microsecond level. If this technology is applied to multi-break vacuum circuit breaker, the control accuracy and synchronization of the sub-closing points of the multi-break fast vacuum circuit breaker control mechanism will increase. In China, such research is still in its infancy. But it is reported that the vacuum contactor interrupter and high-speed eddy current repulsion agency have been used in the production of rapid circuit breaker. However, the research of high speed vortex repulsion mechanism in high voltage circuit breaker has not yet appeared. So this article has a good application prospects.

The repulsion mechanism composition of 72.5kV double-break vacuum circuit breakers. In this paper, considering the characteristics of high voltage circuit breaker, a new design scheme is proposed for the repulsive force operating mechanism. The repulsive mechanism proposed in this paper is composed of a permanent magnet holding mechanism, a bidirectional repulsion mechanism and a vacuum interrupter. The schematic diagram of the circuit breaker is shown in Figure 3.

![Figure 3. Appearance of the repulsion actuator of the double-break vacuum breaker.](image)

In figure 3:
1. Vacuum interrupter: vacuum excellent insulation through the tube so that the circuit can quickly cut off the power supply and inhibit the current arc.
2. Static contact: a fixed contact that connects or disconnects a power line.
3. Moving contact: movable contact that connects or disconnects a power line.
4. Connecting rod: the whole connecting rod, used to move the moving contact action.
5. Fixed plate: used to fix opening and closing coil.
6. Opening coil: opening excitation coil, issued by the opening command to generate electricity and metal repulsion force down the repulsion.
7. Metal repulsion disk: metal copper disk, with the excitation coil to produce upward or downward repulsion, play a role in moving the moving contact.
8. Closing coil: closing excitation coil, issued a closing instruction when the power supply and metal repulsion plate upward repulsion.
9. Moving iron core: the active iron core, function with the magnet as the maintenance role.
10. Magnet: used to fix moving core.

The working principle is that the electromagnetic repulsion works as the driving force by the permanent magnet magnetic circuit in the permanent magnet to provide retention force. Self-retention is accomplished by the use of a magnet and a moving iron core structure. After opening and closing, the magnet retains the moving core by means of a magnetic force so as to achieve the self-retaining effect. The basic operation process is that the thyristor controls the charged capacitor that discharges to the coil of the repulsion mechanism, so that the coil produces a transient magnetic field. Then copper disk induces eddy current to form a reverse magnetic field, resulting in repulsive force which drives the rod movement, and then the interrupter moving contact moves, so as to achieve the effect of circuit opening and closing.

The main factors affecting the repulsive force are the thickness and the radius of the metal repulsion disk, the number of the excitation coil turn, and the parameters of initial air gap. In this paper, the parameters of the prototype components are calculated, especially the method and structure of the wound coil coil are studied deeply. Finally, the repulsion mechanism is designed. The relevant design parameters are shown in Table 1.

| Item                              | Unit | Parameter |
|-----------------------------------|------|-----------|
| the thickness of the metal repulsion disk | mm   | 10        |
| the radius of the metal repulsion disk | mm   | 100       |
| initial air gap                   | mm   | 0.2       |
| the number of excitation coil turn| turn | 100       |
| drive current                     | A    | 1500      |

4.3. Performance test of 72.5kV double-break vacuum circuit breaker

Test of closing and opening time. In this paper, the testing platform of the closing and opening time of the prototype is established. One channel of the dual channel oscilloscope records the pulse start time, and the other channel records the stop time. The experimental results are shown in Fig.4 and Fig.5. From the experimental results, the circuit breaker opening time of 18ms, closing time of 27ms. Therefore, the closing and opening speed of the circuit breaker prototype designed in this paper is fast. And the breaking capacity of the circuit breaker is good.
Mechanical properties test. Connect the movable part of the linear displacement sensor to the moving lever of the circuit breaker and connect the potentiometer output voltage to the oscilloscope. By analyzing the change of the output voltage, the relationship between the stroke variation and the time of the circuit breaker is obtained. The length of the sliding rheostat is 50mm, the travel range of the breaker moving rod contact is 20mm. In this test, the charging voltage of a single charging module is 860V, when the charging modules are connected in series, the closing and opening capacitor voltage is 1700V. Then get the sub-closing circuit breaker mechanical characteristics, as shown below in Fig.6 and Fig.7.

From the figure we can see that the total time of the breaker closed from the beginning to the stability is 30ms, in fact, there is a bottom near 27ms. When open the breaker, there is a bottom near 18ms, then jump to 30ms for stability.

In summary, compared to other solutions, the circuit breaker designed in this paper has certain advantages, such as short closing and opening action time, good mechanical properties, successfully broken in many voltage level.

5. Conclusion

Based on the theoretical analysis and experimental results from researchers, the design of 72.5kV double-break vacuum circuit breakers based on rapid repulsion actuator was presented. It takes the form of double-break, using two standard 40.5kV vacuum interrupter in series at the bottom, which adopt a permanent magnetic repulsion actuator. The opening time of the circuit breaker prototype is 18ms, and the closing time of the circuit breaker prototype is 27ms. Circuit breaker can be successfully broken with a certain superiority, and the mechanical characteristics are excellent. But the structure of circuit breakers only can be applicated in the transmission grid after the type test. The 72.5kV double-break high-speed vacuum circuit breaker developed by high-speed repulsive mechanism, can meet the high-speed requirement of high-voltage power supply without disturbance. So it has a very wide application prospect.

References

[1] Liao Mifu, Duan Xiongying, Zou Jiyan, et al. Dynamic medium recovery and statistical analysis of multi-break vacuum circuit breaker [J]. Proceedings of the Chinese Society for Electrical Engineering, 2003, 22(2): 83-87.

[2] Wang Jimei. Vacuum circuit breaker theory and its application [M]. Xi'an: Xi'an Jiaotong
University Press, 1986.

[3] Wen Hubin, Zou Jiyan, Liao Mifu, et al. Theoretical Analysis of 126kV Double Breaking Vacuum Circuit Breaker [J]. *High-voltage electrical appliances*, 2009, 45 (2): 14-17.

[4] Fugel T., Koenig D. Peculiarities of the switching performance of two 24kV vacuum interrupters in series [C]// *IEEE 19th International symposium on Discharge and Electrical Insulation in Vacuum*. Xi’an: IEEE, 2000: 411-414

[5] BETZ T, KOENING D. Influence of grading capacitors on the breaking capacity of two vacuum interrupters in series [C]// *Proceedings of 18th Int. Symp. on Discharges and Electrical Insulation in Vacuum*, Eindhoven, Holland:[s. n.], 1998:231-238

[6] Fugel T.Koenig D.Influence of grading capacitors on the breaking performance of a 24 kV vacuum breaker series design[J]. *IEEE Trans on Dielectrics and Electrical Insulation*, 2003, 10(4): 569-575

[7] Wu Gaobo, Ruan Jianjun, Huang Daochun, et al. Study on the study of equalizing capacitance of multi - break vacuum circuit breaker [J]. *High Voltage Apparatus*, 2011, 47 (3): 77-81.

[8] Shu Shengwen, Ruan Jiangjun, Huang Daochun, et al. Transient recovery voltage distribution mechanism and equalizing capacitance of double-break vacuum circuit breaker [J].

[9] Wen Huabin, Song Yongrui, Zou Jiyan, et al. Experimental study on design and breaking capacity of new type 126kV high voltage vacuum circuit breaker [J]. *Proceedings of the Chinese Society for Electrical Engineering*, 2011, 31(34): 198-204.

[10] Liu Donghui, Wang Jimei, Wang Zhongyi, et al. Necessity and preliminary research on development of 126kV vacuum circuit breaker in China [J]. *High-voltage electrical appliances*, 2003, 10(4): 26-29

[11] Ma Shaohua, Xu Jianyuan, Wang Jimei. Performance Analysis of Permanent Magnet Actuator Structure and the Possibility of Using High Voltage Vacuum Circuit Breaker [J]. *High Voltage Apparatus*, 2000, 36 (4): 19-23.

[12] Fu Wanan, Song Baoyun. Study on Permanent Magnet Mechanism of High Voltage Circuit Breaker [J]. *Proceeding of the CSEE*, 2000, 20 (8): 21-26.

[13] Zou Jiyan, Wang Ying, Dong EnyuMan. Electronic Actuation Concept and Practice [J] *High Voltage Apparatus*, 2000, 36 (5): 29-31.

[14] Lin Xin, permanent magnet mechanism and vacuum circuit breaker [M]. Beijing: Mechanical Industry Press, 2002.

[15] Li Bo, High-speed repulsion mechanism and fault current fast monitoring device [D]. *Dalian University of Technology* 2006.

[16] Huang Yulong, Zhang Zu’an, Wen Weijie, Gao Shutong, Cheng Tiehan, Liu Jiayu. Study on Electromagnetic Repulsive Fast Actuator in High Voltage DC Circuit Breaker [J]

[17] Liang Zhuangxian, Zhuang Jinwu, Wang Chen, Liu Luhui, Dai Chao. The Simulation Analysis and Design of High Speed Contact Mechanism Based on Electromagnetic Repulsion Principle [J]. *Techniques in Electrical Engineering*, 2011 (08).

[18] Jiang Nan, electromagnetic repulsion mechanism design methods [D]. *China Ship Research Institute* 2013.

[19] Tian Peng, A New Type of High Speed Retarding Mechanism for Permanent Magnet Retention [D]. *Dalian University of Technology* 2011.

[20] Zhao Xia, fast electromagnetic actuator topology and discharge loop optimization study [D].