Research on 750kV Vacuum Circuit Breaker Composed of Several Vacuum Interrupts in Series

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Abstract- **The paper first introduced the recent research work on super high voltage vacuum circuit breakers (VCB) in China and abroad. It proposed that the research and fabrication of supper high voltage VCB should be accelerated in China to meet the demands of developing 750kV super high voltage power systems. The advantage and significance of applying several vacuum interrupters in series as a super high voltage VCB were stated. The theoretical analysis and experimental test were also conducted to a several single-break vacuum interrupters in series as a super high voltage VCB.**

I. INTRODUCTION

The research on applying VCB by several vacuum interrupters in series as a high voltage and super high voltage VCB has been concerned nationally and internationally. The Electric Arc Research Center in Xi'an Jiaotong University started this work in 1995. At presented, 39[th] international power system conference in Paris on 25-30,August, 2002, the paper discussion about VCB could be developed to higher voltage VCB by using several vacuum interrupters in series. Meantime, it also suggested that the capacitor charging energy could be used to operate VCB. Since the research and fabrication techniques on high voltage VCBs are very matured in China, the VCBs of 126kV, 252kV and other higher voltage levels such as 750kV can be developed independently.

There has been 60-70 years since the vacuum was used for insulating and extinguishing arc dielectric in VCBs. VCBs have dominated in medium voltage level systems. They are also practically used in high voltage systems, for example in 126 kV systems. Currently Toshiba is working hard on developing VCBs for super high voltage systems [1]. In 2004, the 750kV network will be built in northwest of China; hence it is critical to take this opportunity and to develop super high voltage VCBs.

II. DEVELOPMENT OF SUPER HIGH VOLTAGE VCBS USING SEVERAL VACUUM INTERRUPTERS IN SERIES

Zhou Jiyan, an expert on vacuum arc theory in China, has been studying on interrupting characteristics, dynamic recovery and statistic probability for VCBs. He presented that using vacuum interrupters in series was the unique way for VCBs to be applied to super high voltage power system, which is consistent with the previous studies.

A. Breakdown Characteristics of Multiple Interrupters [2]

The breakdown of vacuum gap is very complicated, which is caused by the action of several factors simultaneously rather than a single factor. Therefore it is hard to describe and distinguish it accurately. However the main factor resulting in the breakdown is associated with electrodes, such as the tips on the surface of electrodes, the metallic or non-metallic particles stuck to the surface of electrodes, as well as the weak discharge between electrodes. Hence the concept of "breakdown weak points" is introduced to describe the source resulting the breakdown. These weak points exist on the surface of electrodes, representing all the possible factors that can cause the breakdown under the electric field stress. Obviously the no uniform distribution of recovery voltage along multiple interrupters of VCB enhances the activity of these breakdown weak points. The weak points are distributed arbitrarily on the surface of electrodes, and are changed by the electric field stress. However they comply with a sort of statistics. For double interrupters of VCB the weak points are distributed between the two interrupters.

The multiple interrupters of VCBs take the advantage of the good insulation of vacuum. For the same total vacuum gap, it is more advantage to divide the gap into multiple interrupters than a single one. The maximum increased times of breakdown voltage can be derived:

There are two relationships between the breakdown voltage and the gap distance between electrodes. The breakdown voltage is linear with the distance when it is small. When the gap distance is big, and the relationship becomes

$$U_b=k \quad S^{\alpha} \tag{1}$$

Where α is a very important factor, ranging from 0.4-0.7; S is the gap distance between electrodes; k is a constant.

The design idea of double interrupters VCBs is to use good insulation of small vacuum gaps and to put them in series to achieve high withstanding ability. In the ideal conditions, the relationship between the breakdown voltage and gap distance for double interrupters VCB is

$$U_{double}=2k \quad S^{\alpha} \tag{2}$$

As the gap is a single interrupter VCB is increased one time of the gap in a double interrupters VCB, the relationship between the breakdown voltage and electrode distance for a single interrupter VCB is

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$$U_{single}=k\quad(2S)^{a} \tag{3}$$

The maximum increasing times of the breakdown voltage for double interrupters VCB can be obtained from (2) divided by (3)

$$K_2=\frac{U_{double}}{U_{single}}=2^{(1-a)} \tag{4}$$

Furthermore, the maximum increasing times of the breakdown voltage for the VCB having several interrupters in series can be obtained

$$K_n=\frac{U_n}{U_{single}}=n^{(1-a)} \tag{5}$$

B.Statistic Probability of Static Breakdown [2]

Fig.1 shows the equivalent circuit diagram of double interrupters VCB. When two in series gaps are for two interrupters in series separately, the event *A* and *B* are appeared if they are discharged. Supposed that *P (A)* and *P (B)* are known, when both are in series, the A^* and B^* are appeared if *A* and *B* are discharged.

If the discharge happens in double interrupters VCB with grading capacitors, it can be analysed by the relationship of independent discharge of two gaps.

The reference [3] presented that the breakdown of a vacuum gap was associated with weak points on the surface of cathodes, and the number of weak points in the unit area of the surface of cathodes was related to the electrode voltage and surface field strength of positive pole, which is the electric field stress $x=U^2/s$ (where s is gap distance). Therefore x is to describe breakdown characteristics of a vacuum gap. Obviously the breakdown occurs in the weakest place when the area of an electrode is increased. Hence the probabilistic distribution of electric field stress x in a vacuum gap is a minimum distribution. The experiments [3][4] show that the breakdown weak points in a vacuum gap comply with Weibull distribution under impulse voltages, and the Weilbull distribution is a popular extreme distribution.

Interrupter 1: $x_A \backsim W(x_{oA}, \eta_A, \delta_A)$

Interrupter 2: $x_B \backsim W(x_{oA}, \eta_B, \delta_B)$

Where x_{0A}, x_{0B} are the location constant of the Weibull function, η_A, η_B are the dimension constant of the Weibull function, and δ_A, δ_B are the shape constant of the Weibull function. These constants are determined by the material and surface of electrodes.

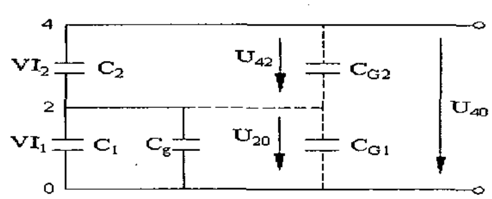

Fig.1. Equivalent circuit diagram of a double interrupters VCB

C_1,C_2: equivalent capacitor; C_{G1},C_{G2}: grading capacitor; c_g:ground capacitor;VI_2,VI_1: interrupters

When two interrupters are in series, the breakdown of one of the interrupters cannot result in the breakdown of the whole breaker. Only when the two interrupters are all broken down, the breaker is considered to be the breakdown. Therefore the relationship is:

$$\begin{aligned} A^* &= A\overline{B}+AB=A \\ B^* &= \overline{A}B+AB=B \\ C &= A^*B^*=AB \end{aligned} \tag{6}$$

Then can be derived: P(C)=P (A*B*)=P (AB)=P (A) P (B)

Because of

$$F(\chi_A)=\begin{cases} 1-exp\left[\left(\frac{\chi_A-\chi_{OA}}{\eta_A}\right)^{\delta_A}\right] & \chi_A \rangle \chi_{OA} \\ 0 & \chi_A \leq \chi_{OA} \end{cases} \tag{7}$$

$$F(\chi_B)=\begin{cases} 1-exp\left[\left(\frac{\chi_B-\chi_{OB}}{\eta_B}\right)^{\delta_B}\right] & \chi_B \rangle \chi_{OB} \\ 0 & \chi_B \leq \chi_{OB} \end{cases} \tag{8}$$

Where x_A, x_B are the electric field stress. Therefore the breakdown statistic distribution function of two interrupters VCB can be derived:

$$F_{double}(x)=F(x_A)\quad(x_B) \tag{9}$$

In particularly, the statistic distribution function for interrupter 1 and 2 can be considered as the same when the material and the surface of electrodes of the two interrupters are the same under the ideal conditions, which is

$$F_{single}(x)=F(x_A)=F(x_B) \tag{10}$$

By using the electric field stress x to represent x_A, x_B, the Weibull function location constant x_0 to represent x_{OA}, x_{OB}, η to represent η_a, η_b, and the Weibull function shape constant δ to represent δ_a, δ_b, the distribution function for two interrupters VCB can be simplified as

$$F_{double}(\chi)=F^2_{single}(\chi)=\begin{cases} \left(1-exp\left[-\left(\frac{\chi-\chi_0}{\eta}\right)^{\delta}\right]\right)^2 & \chi \rangle \chi_0 \\ 0 & \chi \leq \chi_0 \end{cases} \tag{11}$$

It also can be further extended to multiple interrupters VCB, which is

$$F_n(\chi)=F^n_{single}(\chi)=\begin{cases} \left(1-exp\left[-\left(\frac{\chi-\chi_0}{\eta}\right)^{\delta}\right]\right)^n & \chi \rangle \chi_0 \\ 0 & \chi \leq \chi_0 \end{cases} \tag{12}$$

It is shown that the breakdown probability for double interrupters or multiple interrupters VCB is less than that of single-interrupter VCB. Furthermore, the more interrupters are in series, and the less probability is. Therefore the insulation a vacuum gap can be improved by using two or multiple interrupters, and further the withstanding voltage is increased. This has been verified by many research results [5][6].

C. Probability of Rebreakdown After Arc

The high over voltage can be generated when double interrupters VCB is rebreakdown, which is the great threat for personal and equipment in the network. Therefore it is necessary to study the rebreakdown mechanism for double interrupters VCB. Based on the study of the static breakdown statistics of two interrupters VCB in Section 2.1, the probability and time distribution is further studied considering the action of recovery procedure and transient recovery voltage.

As the discussion above, the static breakdown statistics of double interrupters VCB can be described by (11). The insulation of a vacuum gap is enhanced as the time increasing in the process of recovery. In other words, the minimum electric field stress χ_0 withstand by double interrupters VCB is a function of time. It is zero in the beginning of recovery, and increased to χ_0 at the time of full recovery. Hence the re-breakdown probability of double interrupters VCB in the period of dielectric recovery can be derived

$$F_{double}(\chi) = F_{single}^2(\chi) = \left(1 - exp\left[-\left(\frac{\chi-\chi_0}{\eta}\right)^\delta\right]\right)^2 \qquad (13\text{-a})$$

The experimental results shown that the function between electric field stress and time can be described approximately by an exponential function, which is

$$\chi_0(t) = \chi_0\left[1 - exp\left(-\frac{t}{\tau}\right)\right] \qquad (13\text{-b})$$

Where τ is time recovery constant.

The rebreakdown probability of double interrupters VCB is less than that of single interrupter VCB can be shown by (13-a) and (13-b).It can be well explained by the theory and analysis proposed in this paper. When one of the two interrupters is rebroken down, the other one may not be broken and can still withstand the recovery voltage for a short period. It waits until the first interrupter gets a certain recovery voltage, and then completes whole interruption. Therefore double interrupters VCB may not have the rebreakdown.

It can be derived that the more interrupters are in series, the less breakdown probability is. The breakdown model after arc for n interrupters in series is

$$\begin{cases} F_n(\chi) = F_{single}^2(\chi) = \left(1 - exp\left[-\left(\frac{\chi-\chi_0(t)}{\eta}\right)^\delta\right]\right)^n \\ \chi_0(t) = \chi_0\left[1 - exp\left(-\frac{t}{\tau}\right)\right] \end{cases} \qquad (14)$$

III. Analysis And Study On Main Components Of 750kV Super High Voltage VCBs

A. The Types of Super High Voltage VCBs

There are two types of super high voltage VCBs, post type and tank type. The comparisons between them are described as follows.

The post type of a single-phase 750kV super high voltage VCB diagram is laid out in Fig.2, which is composed of six 126kV interrupters 1 in series. There is grading capacitor 3 paralleled with each interrupter. Under the control box 2, there are six porcelain posts 4 in series to insulate with ground, and the steel base 6 is used underneath. To ensure the VCB working reliably and stably, insulating wires 5 are used to tighten it. The high voltage source is supplied through terminals A to B. The control box shown in Fig.3 is installed in one side of each interrupter.

VCB can be operated by optoelectronic and electronic devices to close, open and re-close etc for VCB automatically and remotely.

The tank type of single phase 750kV super high voltage VCB diagram is laid out in Fig.4 [7], which is composed of six 126kV interrupters in series and located in the middle of the tank. There are six grading capacitors corresponding to each of the six interrupters. The permanent magnetic actuator and charging capacitors are installed underneath the interrupters. Optoelectronic control box consists of signal receiver, electronic board, anti-jamming equipment, sensors and other accessories. It controls closing and opening as well as the protection equipments of power system. In addition, there are isolate switches and surge arresters in the tank. Current transformers can be installed on the bushing, and all the components of the VCB are flooded by silicon oil for insulation.

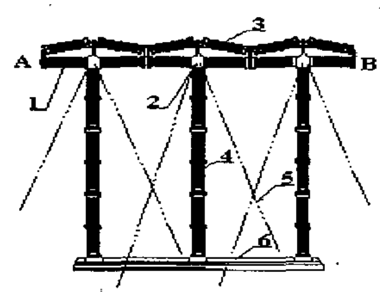

Fig.2.The porcelain post type of 750kV super high voltage VCB

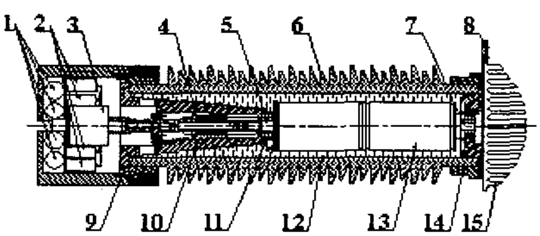

Fig.3 control box and interrupter
1-optoelectronic auto-control equipment;2- capacitors;3- permanent magnetic actuator; 4—super stroke spring; 6-porcelain insulate; 7—stationary contact rod;8-up terminal;9-down terminal;10- current carrying support.;11-down plum type spring contact;12-silicon oil;13--vacuum interrupter;14- up plum type spring contact;15-cooling duct cap

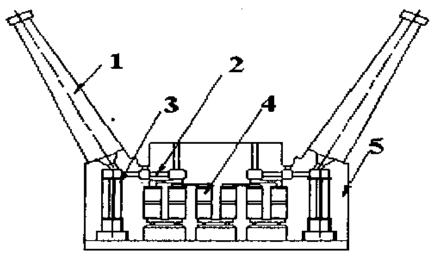

Fig.4 Tank type of 750kV super high voltage VCB
1--bushing; 2—surge arrester; 3—isolate breaker;
4—vacuum interrupters; 5—silicon oil

The advantages of the porcelain post type of 750kV super high voltage VCB are low cost, simple structure, and easy installation. The parts of a VCB are easy to be changed when damaged, because it is exposed to the air.

The tank type of 750kV super high voltage VCB can be operated safely because all the parts are in the tank, and the current transformer, surge arrester, and isolator can be installed together. It occupies less space than the post type VCB. However, the fabrication is more expensive and the installation is more complicated. Furthermore it is hard to maintain and to set the optoelectronic control equipment inside in the tank.

B. Discussion on Applying The Permanent Magnetic Actuator to Super High Voltage VCB

The permanent magnetic actuator for 126kV interrupters were tested and simulated "unpublished"[9]. It was shown that the characteristics of output force and velocity were suitable to be applied to 750kV super high voltage VCB. Fig5 shows the configuration of permanent magnetic actuator for 126kV VCB. The maximum moving stroke can achieve to 80mm. The load stress at the closed position is approximately 7000n per each interrupter. The maximum velocity of opening contact is about 4m/s. The closing coil and opening coil in the permanent magnetic actuator has its own capacitor of 0.1F and pre-charge voltage 100V. For a 750kV super high voltage VCB composed of six 126kV interrupters in series, it can be operated by permanent magnetic actuator in parallel. The asynchronous time during opening operation is less than the range of 100μS. It is proved that the permanent magnetic actuator can meet the requirement of 750kV super high voltage VCB.

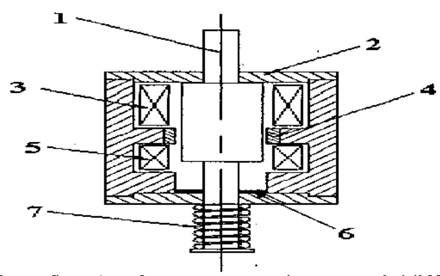

Fig.5 The configuration of permanent magnetic actuator of 126kV interrupter
1--moving iron core; 2-stationary iron coil; 3-closing coil; 4-permanent magnetic actuator; 5-opening coil, 6-padding; 7-opening accelerate sprinp

C. Preliminary Design of Super High Voltage VCB Using Auto-control and Remote Control

Auto- and remote-control equipment has an optoelectronic controller to receive optical signals and optoelectronic capacity. It is located on one side of the permanent magnetic actuator, shown in Fig.3. It controls pre-charged capacitors to discharge to the closing and opening coils so that the interrupters are closed and opened. This auto-control equipment can also receive signals through special telephone line to control VCBs.

Optoelectronic auto-control equipment has electro-magnetic shielding to protect interferences. The permanent magnetic actuator, super stroke spring, and optoelectronic auto-control are installed in a seal cabinet, and integrated into a unity. It is characterized by the proper design, compact installation, and convenient operation.

IV. CONCLUSION

Six 126kV interrupters in series can build the 750kV super high voltage VCB. The closing and opening of VCB are able to be operated by the permanent magnetic actuator and optoelectronic auto-control equipment of each interrupter, which greatly simplified the set up. The 750kV super high voltage VCB is a creative product and characterized by simple fabrication, low cost, and long life.

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