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Dielectric Strength Restoration Velocities of Multi-Break Vacuum Circuit Breakers

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Abstract
A multi-break interrupters of vacuum circuit breakers has become the most requirements of high voltage circuit breakers with high breaking capacity that not environmentally harmful. In this article the dielectric properties of multi-break vacuum circuit breakers were considered. Velocities of dielectric strength restoration of multi-break vacuum interrupters were analyzed.

1. Introduction

A circuit breaker is an electrical switch designed not only to interrupt the high magnitude short-circuit currents; switching of different loads, capacitor banks, reactors and unloaded cables or transmission lines are some of the duties whose requirements are not only different but might even conflict with those of the high current interruption [1].

During switching-off processes the movable contacts of circuit breakers begin to separate and the arc is produced. This arc needs to be extinguished, in order to retain the breaking capacity of the circuit breakers. SF_6 circuit breakers stretch the arc and use the dielectric strength of the sulfur hexafluoride (SF_6) to quench the stretched arc. In vacuum circuit breakers (VCB), the electrical contacts are enclosed in a vacuum out of which one is fixed and the other is movable. During switching-off processes, the movable contacts pulls away from the fixed contacts and minimal arcing is produced [1, 2].

According to the dielectric strength, SF_6 has better behavior than vacuum. That is why SF_6 has generalized as insulating and as arc quenching medium. Under normal conditions, SF_6 is an inert, non-flammable, non-corrosive, odorless, and non-toxic gas. However, at temperatures over 1000°C, SF_6 decomposes to gases including S_2F_{10} which is highly toxic. Fortunately, the decomposition products recombine abruptly after arc extinction (when the temperature goes down) [2, 3]. SF_6 has been labeled as one of the major global warming gases, since the 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change [4, 5]. Hence, there is an urgent need to study new generation of high voltage circuit breakers that not environmentally harmful.

Note in this view that, there are many efforts being made to find an alternative gas to SF_6 and to minimize the utilization and leakage of SF_6 in circuit breakers. The attempts to find an alternative gas to SF_6 have not yet borne fruit. It means that vacuum and SF_6 circuit breakers are staying the preferable ones [5, 6].

As it is known in VCBs the quenching media is a vacuum, so there is no risk for the environment. Another advantage of VCBs is the higher dielectric strength restoration after current zero in comparison with other types of circuit breakers. The problem of using VCB in high voltage applications is related to the high voltage capability of a single gap between electrodes. The breakdown characteristics have very high dependence of electrode area, and the dielectric strength with the contact gap. On this way, in vacuum breakdown, the breakdown voltage is proportional to the square root of the gap length. Thus, a longer gap is necessary for the vacuum interruption. But this technology makes the circuit breaker bigger and leads to the problem of arc control. It appears a high arc voltage noise, which indicates that the vacuum arc is unstable in a long gap [2, 4].

The study of circuit breakers based on the vacuum interrupters in series began in the 1960s. During the past period the patent applications were made by several manufacturers in the USA and Japan but none was applied in the industry because of technical conditions. Note that, series connection of vacuum interrupters has also a few disadvantages like complex mechanism and non-uniform voltage distribution across each interrupter due to the stray capacitance. To keep the uniform voltage distribution, grading capacitors would require to be connected across each break [5, 7, and 8]. With the development of large-capacity VCBs, a new round of research is proceeding in the 21st century [4, 5, and 7].

The main purpose of this research is to compare between multi and single breaks of 110 kV VCBs from the point of view dielectric properties and velocities of dielectric strength restoration.

2. Vacuum Circuit Breaker Dielectric Strength Restoration

It is known that when the circuit breaker contacts starts to separate from each other the dielectric strength of the gap starts to increase. After the arc has been extinguished, the race between the transient recovery voltage (TRV) and the dielectric withstand of the circuit breaker begins. When the TRV exceeds the dielectric withstand of the circuit breaker a breakdown occurs and creates a conducting path between the two circuit breaker contacts. Then the TRV jumps back to zero and does not start to rise again before the arc is extinguished [3, 9, and 10]. Therefore the dielectric withstand of the circuit breaker is a significant parameter for the switching analysis.

For VCBs the most of authors use linear restoration law [11, 12]. But this law is not quite suitable to the physical nature (decreasing of strength at increasing of inter-contact distances) of vacuum inter-contact gaps [13, 14]. Therefore for modeling the dielectric properties of the inter-contact spaces we used the logarithmic law of dielectric strength restoration in VCBs presented in [15]. This law takes into account both inertia of contact and inconstancy of strength of vacuum gaps. The logarithmic restoration law for dielectric strength of 110 kV VCB with single-break is given by the following empirical formula;

$$V_{str}(t) = (191.43)\log\left\{1 + 5.75x_m\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}, \quad t_{off} < t \le t_{off} + T_{full} \tag{1}$$

where:

$V_{str}(t)$ is the acceptable law of circuit breaker's dielectric strength restoration;

X_m is the maximum distance between contacts of single-break VCB;

t is time;

T_{full} is the full switch-off time of circuit breaker;

t_{off} is the initial instant of contact separation [13, 15].

In order to reach the high dielectric strength, double-break or more connected in series of VCBs are used. In case of considering double-break of VCBs, the gap length of each break assumed equal to $X_m/2$. Then the formula of dielectric strength restoration is given by computing the dielectric strength of each break multiplied by the number of breaks as following;

$$V_{str}^{double}(t) = (191.43)(2)\log\left\{1 + (5.75)(\tfrac{X_m}{2})\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\} \tag{2}$$

Theoretically to get the same dielectric strength obtained from formula (2) while using of VCB with single-break, the contact distance supposed have twice the value of X_m. So the formula of dielectric strength restoration of single-break VCB have twice the gap length is given by,

$$V_{str}^{single}(t) = (191.43)\log\left\{1 + (5.75)(2X_m)\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\} \tag{3}$$

In order to get the dielectric strength gain, a comparison between double and single breaks dielectric strength can be obtained as following. By dividing formulas (2) and (3) the dielectric strength gain of double-break VCB (K_2) is given by,

$$\frac{V_{str}^{double}(t)}{V_{str}^{single}(t)} = K_2 = \frac{\log\left\{1+(5.75)(\frac{X_m}{2})\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}^2}{\log\left\{1+(5.75)(2X_m)\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}} \tag{4}$$

In general form the formulas (2) and (4) for VCB with multi breaks connected in series can be written as following,

$$V_{str}^{multi}(t) = (191.43)(n)\log\left\{1 + (5.75)(\tfrac{X_m}{n})\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\} \tag{5}$$

$$\frac{V_{str}^{multi}(t)}{V_{str}^{single}(t)} = K_n = \frac{\log\left\{1+(5.75)(\frac{X_m}{n})\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}^n}{\log\left\{1+(5.75)(nX_m)\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}} \tag{6}$$

where:

n is the number of breaks connected in series of VCB;

K_n is the dielectric strength gain of the n breaks of VCB.

From formula (5), it is clear that the maximum value of the dielectric strength were got at full time of contact separation (t-$t_{off} = T_{full}$). So for 110 kV VCB ($T_{full} = 40$ ms, $X_m = 4$cm), the dielectric strength gains of double and triple breaks are 1.402, and 1.698 respectively. These results have a great agreement with that obtained in [16, 17]. From the analysis above, double or triple breaks have higher dielectric strength characteristic than single break for 110 kV VCB.

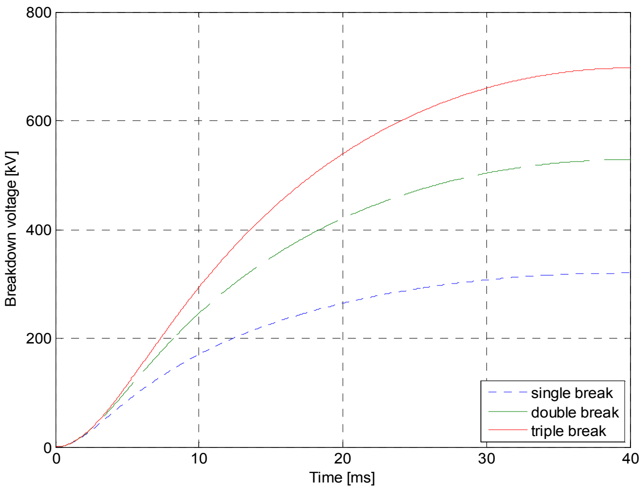

Fig 1. *Dielectric strength restoration of 110 kV VCB with single, double, and triple breaks.*

Since the single break of VCBs with longer gap distances have a few disadvantages that mentioned previously, a comparison from the point of view dielectric strength restoration characteristics between multi-break and single-break with the same equivalent spacing were performed below. In other words for multi-break it is assumed that, the gap length of a single-break (X_m) is divided into n parts and the length of every gap is X_m/n. The curves of dielectric strength restoration of 110 kV VCB with single, double, and triple breaks are presented in figure (1).

From the curves shown in figure (1), it is clear that the triple or double breaks connected in series have higher breakdown voltage than single break of VCBs with the same equivalent spacing. At the same time, the triple or double breaks of VCBs are not breakdown simultaneously at a moment. Thus, the multi breaks of VCBs are more reliable in high voltage applications than single break that have larger gap distance.

3. Velocities of Dielectric Strength Restoration

In modern high voltage vacuum interrupters it's very important to have ability to withstand the steep rising part of the TRV, in order to minimize the probability of repeated re-ignitions. It means that the vacuum interrupters should have a high rate of velocity of dielectric strength restoration more than the TRV. This underlines the importance of dielectric strength restoration velocities of the circuit breakers. So in this section a comparison between triple, double, and single breaks of VCBs from the point of view dielectric strength restoration velocities were performed.

Since the dielectric strength restoration formula of VCB has a non-linear character, the mathematical differentiation is the easy way can be used to get the expressions of velocity and acceleration. In other words differentiation of dielectric strength and velocity with respect to time allows determination of the rate of change of dielectric strength (velocity), and the rate of change of velocity (acceleration) respectively.

For multi-break VCB, the function of dielectric strength restoration velocity can be obtained by differentiating the formula (5) with respect to time as following;

$$v_{str}^{multi}(t) = \frac{d}{dt}V_{str}^{multi}(t) = (191.43)(n)\frac{d}{dt}\log\left\{1 + (5.75)\left(\frac{X_m}{n}\right)\left\{1-\cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}$$

$$= (83.136)(n)\frac{d}{dt}ln\left\{1 + (5.75)\left(\frac{X_m}{n}\right)\left\{1-cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}$$

Then use a rule on differentiation the logarithm a function of function such as $\frac{d}{dt}\ln[f(t)] = \frac{f'(t)}{f(t)}$ and get,

$$v_{str}^{multi}(t) = (478.032)\left(\frac{\pi X_m}{T_{full}}\right)\left\{\frac{sin\left[\frac{\pi(t-t_{off})}{T_{full}}\right]}{1+(5.75)\left(\frac{X_m}{n}\right)\left[1-cos\frac{\pi(t-t_{off})}{T_{full}}\right]}\right\} \quad (7)$$

To get the maximum value of dielectric strength restoration velocity, it needs to get at first the function of acceleration and then finding the time instant of maximum velocity which occurs at zero derivatives.

$$\frac{d}{dt}v_{str}^{multi}(t) = (478.032)\left(\frac{\pi X_m}{T_{full}}\right)\frac{d}{dt}\left\{\frac{sin\left[\frac{\pi(t-t_{off})}{T_{full}}\right]}{1+(5.75)\left(\frac{X_m}{n}\right)\left[1-cos\frac{\pi(t-t_{off})}{T_{full}}\right]}\right\} = zero$$

At this instant of time the numerator of the derivative obtained equal to zero, then

$$cos\frac{\pi(t-t_{off})}{T_{full}} = \frac{(5.75)(X_m)}{n+(5.75)(X_m)} \quad (8)$$

And correspondingly,

$$sin\frac{\pi(t-t_{off})}{T_{full}} = \frac{\sqrt{1+(11.5)\left(\frac{X_m}{n}\right)}}{1+(5.75)\left(\frac{X_m}{n}\right)} \quad (9)$$

Directly put (8) and (9) into the formula (7) and obtain expression for maximum velocity such as,

$$v_{str}^{multi,max} = (478.032)\left(\frac{\pi}{T_{full}}\right)\frac{X_m}{\sqrt{1+(11.5)\left(\frac{X_m}{n}\right)}} \quad (10)$$

From the formula (8) find now the time instant corresponded to the maximum value of velocity.

$$\frac{\pi(t-t_{off})}{T_{full}} = arccos\frac{(5.75)(X_m)}{n+(5.75)(X_m)}$$

$$t_{v_{max}} = t - t_{off} = \left(\frac{T_{full}}{\pi}\right) arccos\frac{(5.75)(X_m)}{n+(5.75)(X_m)} \quad (11)$$

The curves of corresponding velocity functions are presented in the figure (2). This figure shows the velocity curves of triple, double, and single breaks of 110 kV VCB with the same equivalent spacing.

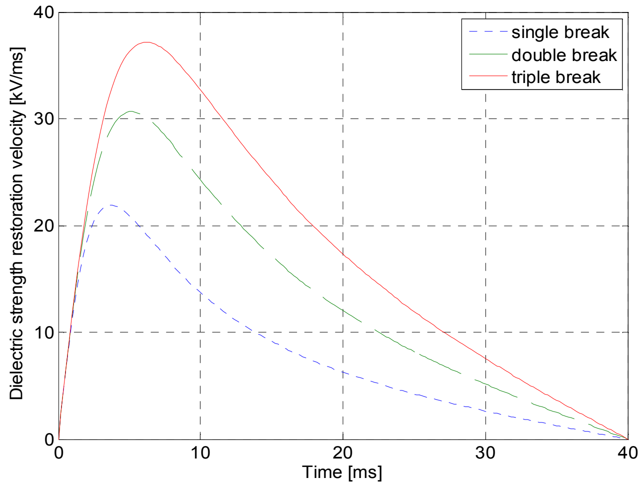

Fig 2. *Dielectric strength restoration velocities of triple, double, and single breaks of 110 kV VCB.*

As shown in figure (2), the character of triple or double breaks has a high rate of dielectric strength restoration velocity more than single break of VCB with the same equivalent spacing. It means that, the multi-break can withstand the steep rising part of the TRV efficiently more than single-break of VCBs and consequently have higher breaking capability during switching-off processes.

The velocities and corresponding time instants for 110 kV VCB with single, double, and triple breaks shown in table (1).

Table 1. *Velocities (maximum, average) and corresponding time instants for 110 kV VCB.*

number of breaks, n	maximum velocity [kV/ms]	average velocity [kV/ms]	instant of maximum velocity [ms]
1	21.9	8.0	3.7
2	30.7	13.2	5.1
3	37.2	17.4	6.2

From the results shown in table (1) it's evident that, triple breaks of 110 kV VCB have the higher values of velocities. Note that, the average velocities have little values due to the non-uniformity of dielectric strength in inter-contact gap. It means that the dielectric strength of VCB is conditioned by taking into account decreasing of dielectric strength of vacuum gap with increasing of its length.

4. Conclusion

Multi-break of vacuum circuit breakers has a high rate of dielectric strength restoration velocity. It means that it has an excellent ability to deal with the steep rising part of the transient recovery voltage more than single break, which makes it faster in the current interruption processes. The success and development of multi-break vacuum technology, give confidence to meet the dielectric requirements of vacuum circuit breakers to use it with high voltage applications.

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Biography

Esam Saafan was born in El-Mansoura, Egypt in 1977. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Faulty of Engineering, University of El-Mansoura, Egypt in 2001 and 2007 respectively. He obtained the Ph.D. degree in High Voltage Engineering in 2012 from Azerbaijan Technical University, Baku. From 2001 to 2012 he worked in the Electrical Engineering Department, University of El-Mansoura, Egypt as a Lecturer Assistant. Since 2012, he has been a Lecturer in the same university.

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