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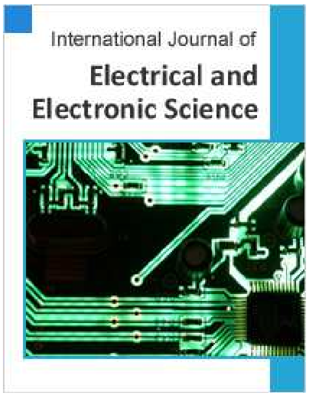

Behaviour of Multi-Break Vacuum Circuit Breakers at High Voltage Capacitor Banks Switching-Off

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Abstract

Multi-break vacuum technology has a high dielectric strength restoration during switching-off processes. Based on this technology, vacuum circuit breakers have more efficient breaking capability than single break during current interruption processes. In this paper, numerous simulations of transitional processes conditioned by high voltage capacitor banks switching-off were performed using multi breaks of 110kV vacuum circuit breaker. In the present work the vacuum circuit breaker is modelled by the use of PSCAD/EMTDC program. Dielectric strength of the circuit breaker based on real inter-contact distance of the multi-break vacuum has taken into account in this research. The results obtained demonstrate that, use of triple-break vacuum leads to notable decreasing of switching overvoltages and allows in the same time to meet the dielectric requirements for vacuum circuit breakers in high voltage applications more than 110kV.

1. Introduction

Interruption of capacitive currents of capacitor banks is one of the most duties expected out of the high voltage circuit breakers. Disconnection of capacitor banks which have a highly capacitive behaviour can lead to some dangerous overvoltages that represent a very high dielectric stress condition for the circuit breakers. Therefore a full model of the circuit breaker during switching-off processes is required to insure a reliable opening operation [1, 2]. For modeling circuit breaker during capacitor banks switching-off there are numerous parameters that affect the transitional overvoltages and must be taken into consideration. These parameters are dielectric strength restoration law, chop current, and full operation time of the circuit breaker [3].

Attending to the medium and the method used for the interruption of the current, circuit breakers can be classified into air magnetic, air blast, oil, SF_6, and vacuum. Vacuum and SF_6 are the modern breaking techniques used in the circuit breakers for medium and high voltage applications. They appeared in the 1960's and quickly developed during the 1970's [4].

Since SF_6 has better dielectric strength restoration than vacuum, it has generalized as insulating and as arc quenching medium. But 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. Hence, there is an urgent need to study a new generation of high voltage circuit breakers that not environmentally harmful [5-7].

As it is known in vacuum circuit breakers (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 [8, 9]. The problem of using VCB in high voltage applications is related to the high voltage capability of a single gap between electrodes. To solve this problem, it is suggested to use multi-break of VCBs in high voltage applications [6-9]. Note that the combined gap length of the multi-break is lower than in a single-break of the VCB [10-12]. This principle must be taken into consideration while medelling the dielectric properties of the VCB to have a more accurate and reliable results during switching processes.

The main purpose of this research is to investigate the behaviour of 110kV VCBs with single, and multi breaks during capacitor banks switching-off processes. A simulation results were performed using PSCAD/EMTDC program. In all simulations the real inter-contact distance of multi-break VCBs were considered. The transitional overvoltages and overcurrents are compared in deferent interruption conditions in this research.

2. Theoretical Bases of the Case Under Study

The connection scheme and equivalent electrical network for the case under study (capacitor banks switching-off) are shown in figure 1. The capacitor banks under consideration with jet powers 37-112 MVAr are connected to the 110kV busbars fed by transformer with rated apparent power 200 MVA.

The numerical values of the connection scheme parameters for single phase representation used for computer simulation are shown in table 1.

Table 1. *Connection scheme parameters for single phase representation (R, L, C and G are resistance, inductance, capacitance and conductance accordingly. Index "s" concerns to source parameters, "l"- to load parameters, "c"- to capacitor banks parameters).*

R_s [Ω]	L_s [mH]	G_l [s]	C_l [μF]	G_c [s]	C_c [μF]			
					37 MVAr	56 MVAr	75 MVAr	112 MVAr
0.2	23	10^{-3}	1.5	10^{-7}	10	15	20	30

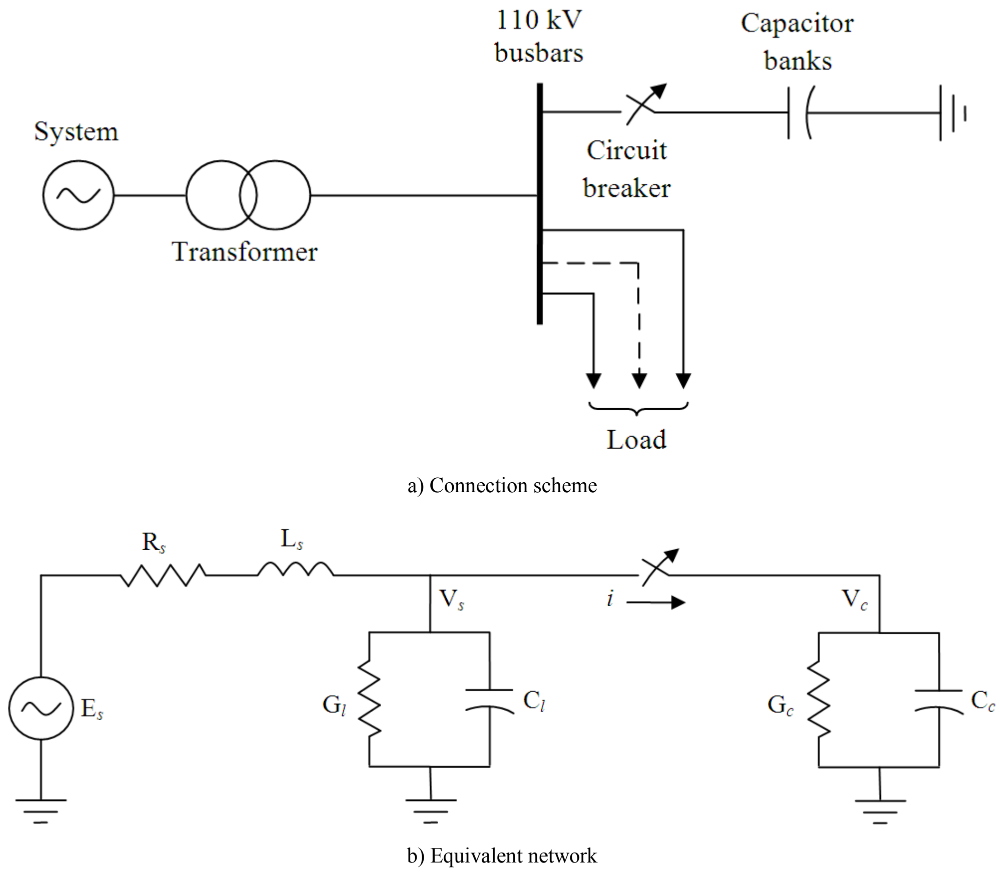


Figure 1. *Scheme and equivalent network of capacitor banks switching-off.*

While carrying out the present research we had applied a mathematical model described in [13]. The known phenomenon of current chopping was modeled in accordance with [2, 13]. Electrical strength and breakdown voltage of VCBs had been given in the numerical models in accordance with [3].

3. Vacuum Circuit Breaker Dielectric Strength Restoration

It is known that as the current reaches the chopping level, the arc becomes unstable and the circuit breaker breaks the current. 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 reaches the dielectric withstand of the circuit breaker, a voltage breakdown (first repeated re-ignition) occurs and resulting in a high frequency current. When the magnitude of the high frequency current drops to the value matched by the quenching capability of the circuit breaker, the circuit breaker breaks this current and the TRV starts building up again. At the same time the circuit breaker builds a higher dielectric withstand as a result of the further opening of the contacts. If the TRV reaches the dielectric withstand of the circuit breaker again, the second repeated re-ignition will be occurs. This process continues until the TRV can't be able to reach the higher dielectric strength of the circuit breaker and then achieves a successful interruption. Therefore the dielectric strength of the circuit breaker is a significant parameter for the switching analysis.

For modeling the dielectric properties of the inter-contact spaces in VCBs it's important to take into account the physical nature of vacuum inter-contact gaps (decreasing of dielectric strength at increasing of inter-contact distances). Dielectric strength restoration of VCBs with single break is modeled in accordance to the empirical formula presented in [3]. This formula takes into account both inertia of contact and inconstancy of dielectric strength of vacuum gaps. The dielectric strength restoration of 110kV VCB with single break is given by the following empirical formula:

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

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.

In case of considering n breaks of VCB connected in series and having the same equivalent spacing of single break, the gap length of each break assumed equal to X_m/n. The formula of dielectric strength restoration of VCB with n breaks is given by computing the dielectric strength of each break multiplied by the number of breaks as given in [7]. The dielectric strength restoration of 110kV VCB with multi breaks is given as following:

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

where:

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

The dielectric strength characteristics of multi-break VCB that obtained by using formula (2) are based on theoretical assumption and not accurately enough to model the dielectric properties of real VCBs in power systems. To obtain a more accurate characteristic while modeling the VCB dielectric strength, the real inter-contact distance parameter of the multi breaks must be considered. The following section describes how this parameter affects the dielectric strength characteristics of the VCBs.

4. Inter-Contact Distance of Multi-Break Vacuum Circuit Breaker

Theoretically it is assumed that, multi-break of VCBs have the same equivalent spacing of single-break [7, 12]. But practically the real VCBs are produced with total inter-contact distances of multi-break less than that used in single-break [8, 12]. Therefore during switching processes it is very important to take into account the inter-contact distances of multi-break VCBs.

In order to get the dielectric strength formula of VCBs based on the real inter-contact distances of multi-break, let us consider that the gap length of each break is X_{break} and less than X_m/n. In this case the formula of real dielectric strength restoration for multi-break 110kV VCB is given by,

$$V_{str\_real}^{multi}(t) = (191.43)(n)\log\left\{1 + 5.75\, X_{break}\left\{1 - \cos\left[\frac{\pi(t - t_{off})}{T_{full}}\right]\right\}\right\} \tag{3}$$

where:

$X_{break} < X_m/n$ is the real inter-contact distance for each break of multi-break VCB.

To obtain the real dielectric strength gain, a comparison between multi-break and single-break from the point of view dielectric strength restoration can be obtained as below. By dividing formulas (3) and (1), the expression of real dielectric strength gain of multi-break VCB is given by,

$$K = \frac{\log\left\{1 + 5.75\, X_{break}\left\{1 - \cos\left[\frac{\pi(t - t_{off})}{T_{full}}\right]\right\}\right\}^{n}}{\log\left\{1 + 5.75\, X_m\left\{1 - \cos\left[\frac{\pi(t - t_{off})}{T_{full}}\right]\right\}\right\}} \tag{4}$$

where:

K is the real dielectric strength gain for n breaks of VCB.

By rearrangement formula (4), the empirical expression of real inter-contact distance for each break of multi-break VCB is given by,

$$X_{break}^{real}(t) = \frac{\left\{1 + 5.75\, X_m \left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\}^{\frac{K}{n}} - 1}{5.75\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}},$$

$$t_{off} < t \le t_{off} + T_{full} \quad (5)$$

From formula (3), it is clear that the highest characteristic of VCB dielectric strength were got at full time of contact separation ($t\text{-}t_{off} = T_{full} = 40\ ms$). The real inter-contact distance of multi-break VCB that satisfies the highest characteristic of dielectric strength can be obtained as below. The simplified formula of real inter-contact distance for each break of multi-break 110kV VCB is given by,

$$X_{break}^{real} = \frac{[1+11.5\, X_m]^{\frac{K}{n}}-1}{11.5} \quad (6)$$

As presented in [7], the dielectric strength gains for 110kV VCB with double and triple breaks were 1.402, and 1.698 respectively. The real inter-contact distance for each break that satisfies these gains can be determined by using formula (6). For 110kV VCB with multi breaks, the total real inter-contact distances of double and triple breaks are 2.4 cm, and 2.0 cm respectively. Note that the real inter-contact distances of the multi breaks VCB are less than the gap length of single break ($X_m = 4\ cm$).

According to the values of real inter-contact distances, it is evident that the real dielectric strength of double and triple breaks has reduced characteristics compared with that obtained theoretically in [7]. But the dielectric strength characteristics of multi breaks still the highest comparing with that obtained in single break VCB. At the same time, the rate of rise of real dielectric strength of multi breaks VCB is enough and capable to deal with the steep rising part of the TRV.

5. Results and Analysis

In this section numerous simulations of capacitor banks switching-off by using single, and multi breaks of 110kV VCB were carried out. The model of multi breaks VCB is obtained by connecting the model of double or triple vacuum breaks in series. Each vacuum break was modeled by the respective contact resistance before contact separation and by the respective dielectric strength restoration after contact separation. In all simulations the real inter-contact distances of double and triple breaks of VCB were considered.

The results of capacitor banks switching-off with rated jet powers of 37-112 MVAr are presented below. The transitional voltages and currents in cases of single, double, and triple breaks are shown in tables 2, 3, 4 respectively. Note that the contacts in cases of multi breaks were simultaneously separated. As shown in tables the overvoltages values for all cases do not exceed the rated amplitude's triple value which is the maximum allowable for 110kV insulation level. From the results shown it's clear that, the cases of multi breaks VCB has less magnitude of overvoltages, inter-contact recovery voltages, and overcurrents than single break. Moreover the recovery voltage is not great influencing the voltage divisors (capacitive and resistive ones) that connected between poles of circuit breakers.

As shown in table 4, switching-off capacitor banks by using triple breaks of VCB has the minimum transitional voltages and currents. It means that, triple breaks of VCB have more efficient breaking capability during current interruption process. As a result the behaviour of 110kV VCB with triple breaks is better than double and single breaks.

Table 2. *Overvoltages and overcurrents in case of single break of 110kV VCB for range of jet powers.*

capacitor bank [MVAr]	capacitor bank voltage [p.u]	breaker voltage [p.u]	breaker current [p.u]
37	2.51	2.15	9.73
56	2.64	2.34	8.53
75	2.67	2.39	7.78
112	2.84	2.68	6.70

Table 3. *Overvoltages and overcurrents in case of double breaks of 110kV VCB for range of jet powers.*

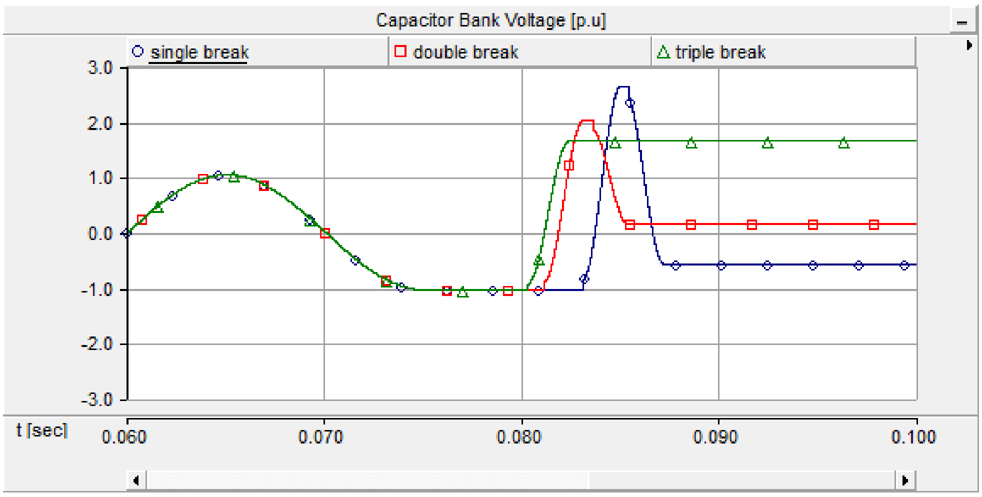
capacitor bank [MVAr]	capacitor bank voltage [p.u]	voltage across each break [p.u]	breaker current [p.u]
37	1.99	0.99	8.06
56	2.03	1.00	6.82
75	2.26	1.07	6.69
112	2.40	1.14	5.43

Table 4. *Overvoltages and overcurrents in case of triple breaks of 110kV VCB for range of jet powers.*

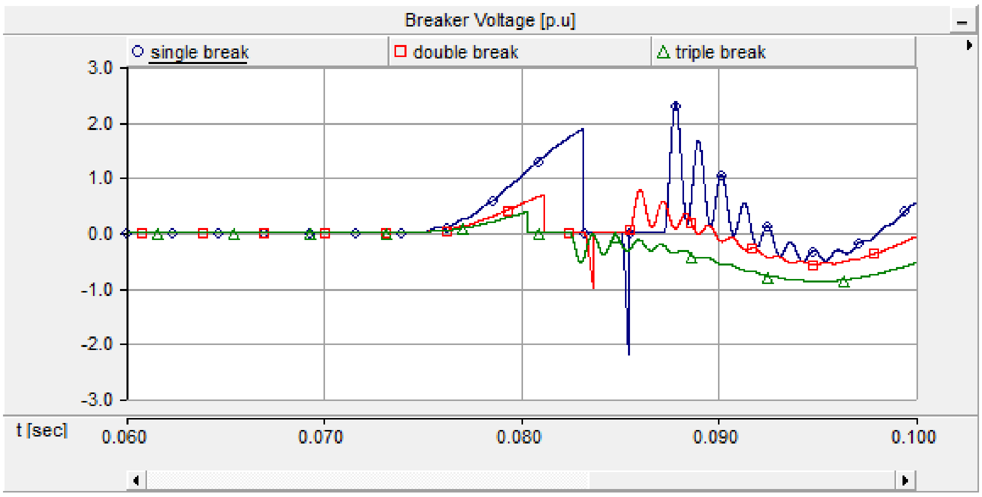
capacitor bank [MVAr]	capacitor bank voltage [p.u]	voltage across each break [p.u]	breaker current [p.u]
37	1.36	0.79	6.17
56	1.65	0.89	5.84
75	1.05	0.68	1.04
112	1.08	0.69	1.00

Some calculated transitional voltages and currents taken place at capacitor banks switching-off with jet powers of 56 and 112 MVAr are presented in figures 2, 3 respectively. Note that the recovery voltages shown in figures for each break in case of multi-break VCB. As shown in figures, we had two or more repeated re-ignitions in the cases of single and double breaks of VCB. But in case of triple breaks we had only one repeated re-ignition (see figure 2). In some cases there is no repeated re-ignitions occurs during capacitor banks switching-off while using VCB with triple breaks (see figure 3). This is due to the recovery voltage that divided across the triple breaks can't be able to reach the higher dielectric strength of the VCB. It means that, using of VCB with triple breaks may also reduce the probability of repeated re-ignitions during switching-off processes.

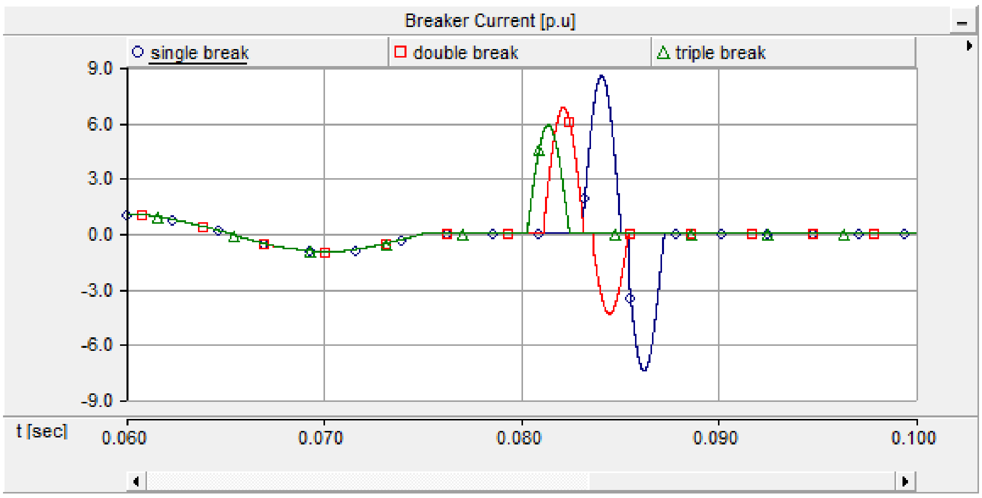
Finally it must be noted that, if any break of the multi breaks switched-off before the others, during this time interval the first break switched-off will be withstand the total TVR alone. So it's important to mention that, when the contacts of the multi-break VCB are not simultaneously separated, the performance is not significantly differing from the case of single break switching-off.



a) Capacitor bank voltages

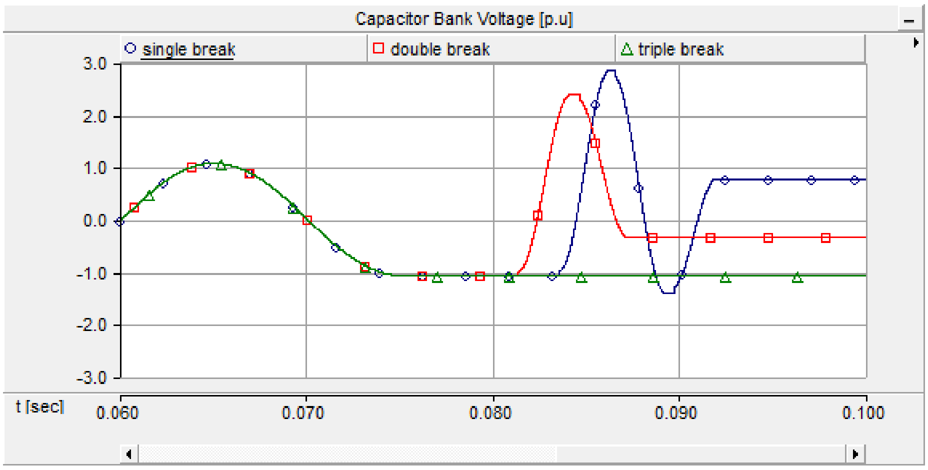


b) Recovery voltages across each break

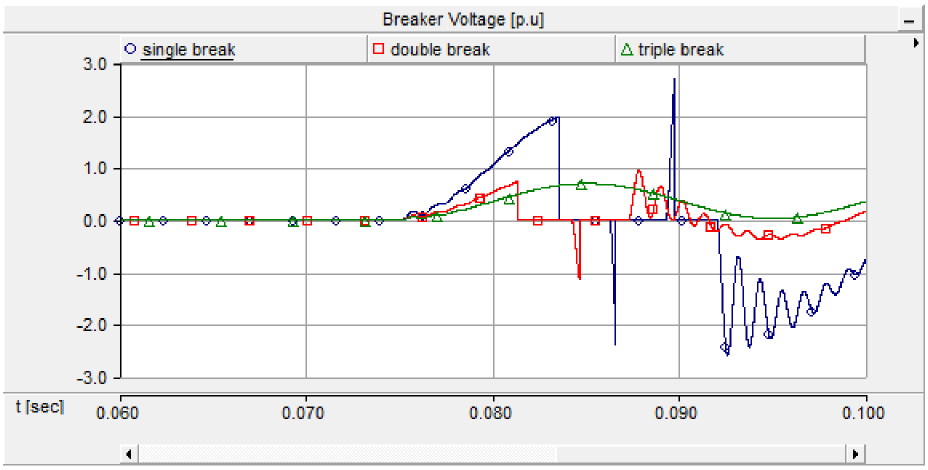


c) Breaker currents

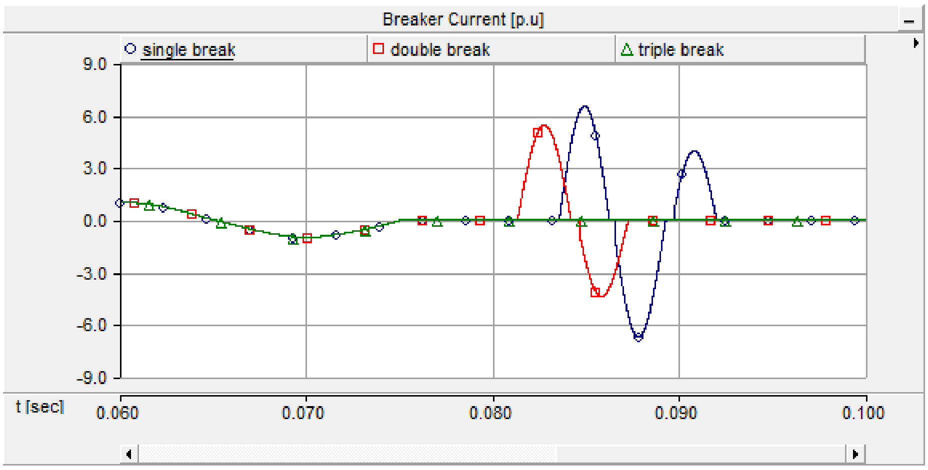
Figure 2. *Transitional voltages and currents conditioned by 56 MVAr capacitor banks switching-off by using single, double, and triple breaks of 110kV VCB.*



a) Capacitor bank voltages



b) Recovery voltages across each break



c) Breaker currents

Figure 3. *Transitional voltages and currents conditioned by 112 MVAr capacitor banks switching-off by using single, double, and triple breaks of 110kV VCB.*

6. Conclusion

Multi-break of 110kV vacuum circuit breakers with the real inter-contact distance has a higher rate of rise of dielectric strength than in a single break during capacitive current Interruption. Moreover the recovery voltage that divided across the multi breaks vacuum has been weakened enough and can't able to reach the higher dielectric withstand of the circuit breaker. As a result triple breaks of VCBs can reduce the probability of repeated re-ignitions and consequently the transitional overvoltages and overcurrents.

In case of repeated re-ignition occurred the reductions are equal to 46%, 63%, and 37% for capacitor bank voltage, recovery voltage, and breaker current respectively. Note that using of double breaks can also improve the behaviour of VCBs but this improvement is not enough and may cause some dangerous effects to the electric equipments especially in high voltage applications. Therefore triple breaks of VCBs have the better behaviour during high voltage capacitor banks switching-off. These results indicate that, the technology of multi-break vacuum makes the VCBs more reliable in high voltage applications more than 110kV.

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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.
Dr. Esam Saafan research areas include transitional processes in power electric systems and their computer simulation, power systems electromagnetic compatibility.