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Capacitor switching phenomenon for EHV circuit breaker

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While, shunt capacitor bank are extensively used to improve loading of the transmission lines as well as to support system voltages. As these capacitor banks are frequently switched in and out of duty, enegisation and de-energisation of these bank causes transient voltages are produced. The concerns on energisation are overvoltage and inrush current, while for de-energisation is restriking.

Switching of capacitor bank, Capacitor bank because of their concentrated capacitance, in contrast with distributed capacitance, generally draws much more current than unloaded cable or line- in practical cases up to several hundred of ampere. Switching of Capacitor bank causes a very high rate of rise of transient recovery voltage across circuit breaker contacts. With improvements in circuit breaker technology, modern SF6 circuit breakers have been designed with less number of interrupter per pole. This causes, modern circuit breaker operates with higher voltage stress in the dielectric recovery region after current interruption. Catastrophic failures of circuit Breaker during shunt reactor and capacitor bank de-energisation. In those cases, evidence of cumulative re-strikes has been found to be the main cause of interrupter failure.

Keywords: *Capacitor switching, line switching, circuit breaker, switching transients.*

1.0 INTRODUCTION

The interruption of capacitive current is a very normalin switching case, unlike the making and braking of faults current. The usual cases, in which a capacitive current is switched,are:

a) Switching of unloaded overhead transmission lines. In this case, capacitiveload current is still flowing in thesystem, to be interrupted depends upon onthe voltage level and the values vary from 9.1 nF per km for single conductor overhead lines to 14nF per km for a four conductor bundle [1]. The current is to be interrupted is in the range of several amperes at medium voltage to several hundred of ampere at high voltage, which corresponds to a line of a few tens to hundreds of kilometers.

b) Switching of local substation components. Some substation components also draw capacitive current, current transformer typically have 1 to 1.5 nF of stray capacitance, Capacitive Voltage Transformer (CVT) [1].

c) Switching of cables. Due to the relatively high capacitance of cables (compared to overhead lines), the current to be interrupted is higher.

d) Capacitor Bank Switching, Regarding the interruption of current, switching of capacitor banks is principally no other switching duty than line- or cable

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switching. The main difference is the frequency of switching: whereas the switching of unloaded lines and cables is a rare event, the switching of capacitor banks is a very frequent operation, since capacitor banks are installed to supply reactive power one night/day varying basis. Thus, the switching performance of capacitor banks has to be considered on a statistical basis, taking into consideration a very large number of switchingoperations.

1.1 Energizing a capacitor bank:

When a capacitive load is energized, it usually draws a certain inrush current. In the case where a lumped uncharged capacitor is connected to a voltage source, the sudden change of the capacitor voltage from zero to a certain source voltage value involves a very large dv/dt and surge impedance of capacitor banks is far smaller than that of cables and lines leading toan inrush current [6]. The inrush current is inversely proportional to the surge impedance of the load circuit. Because of their distributed nature, cables and lines have impedance from several ten (cables) to several hundred of ohms (lines).Due to the low inductance of cable circuit, however, a very steep rate of rise of inrush current in cable systems is possible.

Energisation of capacitor banks, however, having surge impedance of just a few ohms, may lead to very large inrush currents if no current limiting measures have been taken [1].

The challenge of capacitor bank inrush current is two-fold:

i) For the switching device, the inrush current starts to flow at the moment of pre-strike, before contact touch. Due to the high-frequency of the inrush current, the peak values of the current (and normally several periods) are easily reached during the pre-arc duration. This causes a stress to the interrupter. In gas, shock waves can result, and damage of internal parts (e.g. holes in nozzles in SF6 breakers) is observed from time to time [1]. For vacuum breakers, during inrush current, the contacts are closing under intense arcing, causing the contacts to weld. Subsequent contact separation breaks the welds and draws micro-protrusions. When there is no or little arc activity after contact separation to "burn" these whiskers away, voltage withstand can be a challenge.

ii) For the system, depending on the capacitor bank's topology, voltage transients can arise at the station bus, potentially causing power quality issues [5].

1.2 De-energizing a capacitor bank:

Capacitivecurrentsgenerallyrequire very short arcing times which mean that the actual contact gapis very short and in some cases, when the magnitude of the recovery voltage exceedsthe dielectriccapability of this small gap, it leads to restrikes. It was indicated earlier that typical minimum arcing timefor capacitance switching withSF6 circuit breakers is about 2.5 milliseconds and 1.5 millisecond for vacuum interrupters. Since it is not indispensable that the opening of the contacts coincides with the minimum arcing time but rather that it should be longer than that which is considered minimum, a satisfactory choice would be to part the contacts at a point thatis at least 4 milliseconds prior to therent zero [1]. Consequently the controls for this type of application need not be that sophisticated again all that is needed is that the contacts separate efficiently ahead of the current zero. It was said before, with the advent of the new technologies of high voltage circuit breakers there is basically no need for synchronous opening of the capacitor banks and that this mode of operation should only be considered in very special occasions when it is known that there is a real possibility of restriping.

The typical features of capacitive load switching are:

- Current leads the voltage by 90 degrees, this means that at current zero the supply voltage is close to maximum.

- The load capacitance is charged to the voltage; it had at current interruption and keeps this as a DC voltage. This implies that recovery voltage is basically a "1-cosine" wave shape having power frequency [2].
- Current is much smaller than the rated (short-circuit) breaking current of the breaker. This implies that it is very easy for the breaker to interrupt the current (at least initially) even very shortly after contact separation, in those cases that contact separation is very close to current zero;
- For capacitor bank switching, the number of switching operations is very high, estimated as 120 switching operations per year [3];
- For capacitor bank switching, there exists a considerable inrush current upon energization.The combination of short contact gap at current zero and high recovery voltage makes it possible for the breaker to re-strike (a breakdown of the open(ing) gap later than a quarter power frequency cycle after current interruption) at re-strike, the sudden release of the energy stored in the load, can lead to damage of the breaker's contact system. Also, re-strike can lead to voltage escalation [2] that maybe harmful for other station equipment.

2.0 RECOVERY VOLTAGE AND TRANSIENT BREAKDOWN VOLTAGE DURING CAPACITIVE CURRENT INTRRUPTION.

In case of capacitor switching the circuit breaker has to interrupt the currents which are of the order of few hundred amperes, which in turn contribute less energy to the arc. Hence this dutyis considered as a pure dielectric duty. The recovery voltage after current interruption is expressed as equation (1) according to the specification of capacitive current switching.

$$v(t) = v_{max}(1 - \cos \omega t) \quad ....(1)$$

Where,

$$v_{max} = 1.2 \left(\sqrt{2}/_{\sqrt{3}} \right) v_n \quad ....(1.1)$$

vn is the rated applied voltage,

$\omega = 2\pi f$,

f is frequency in Hz, and

t is time in msec.

The critical breakdown voltage aftercurrent interruption depends on the gas pressureand electric field stress.

$$v_{bd} = f(E, \rho) \quad ... (2)$$

Where,

v_{bd} dis critical breakdown voltage,

ρ is gas density, and

E is electric field intensity.

More precisely, the breakdown voltage is inversely proportional to Electric field stress and directly proportional to gas density or gaspressure. Hence E and ρ needs to be optimized to get better performance during capacitive current switching [7].

$$v_{bd} = \left(\frac{\rho}{E} \right) \quad ....(3)$$

3.0 EXPERIMENTAION RESULTS

In EHV system, when line is charged, the stray capacitance appears throughout the line, and when Circuit breaker open the line, 1- cosine voltage wave appear across contacts of circuit breaker. In case 1- cosine wave, rate of rise is very large and circuit breaker has to be capability to build up dielectric strength with respect to Rate of rise of Transient recovery voltage (TRV) of system.

Two classes of circuit-breakers are defined according to their restrike performances:

Class C1 : low probability of restrike during capacitive current breaking;

Class C2 : very low probability of restrike during capacitive current breaking [8].

Basically in circuit breaker dielectric strength is depends upon following parameter,

3.1 Gas pressure :

Electrical Breakdown voltage is function of density, as pressure into gas circuit breaker increases, increases. density increases, hence breakdown voltage

3.2 Contact profile :

uniform electric field, withstand more voltage levelthan non uniform or strongly non uniform field, so by changing contact surface area or profile in such way that electric field approximately uniform, which gives better voltage withstand capability.

3.3 Nozzle profile:

Normally circuit breaker nozzle made of Teflon or MOS2 material, which is relative permittivity is around 6 F/m, while gas has 1 F/m relative permittivity, so by changing nozzle internal Diameter or nozzle area, breakdown phenomenon can improve.

When the contacts are in motion during opening operation, compressed gas is blasted between them after being guided by an insulating nozzle. The gas pressure fluctuates greatly in the contact region. The study suggests that this pressure fluctuation causes transient breakdownvoltages to have lower values than in a static gascondition.

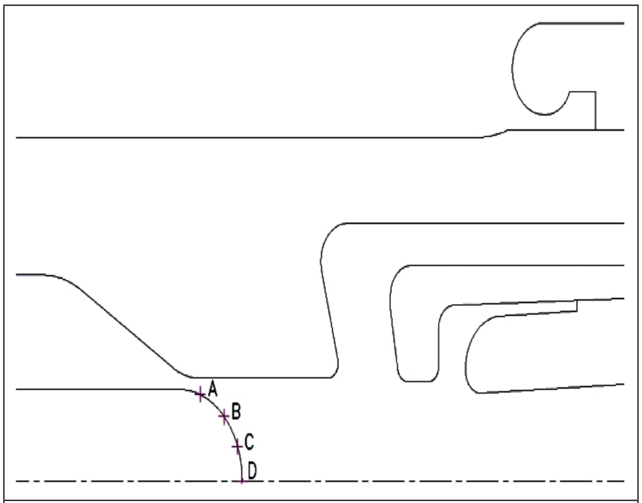

FIG. 1 POINTS FOR CALCULATION ON CONTACT TIP

Moreover different nozzle shapes produce different pressure fluctuations and different transient breakdown voltages. The typical nozzle shape used in the analysis is shown in the Figure 2. The observation shows that, during the opening operation, when point A on the fixed arcing contact as shown in Figure 1, reaches end of the nozzle throat, the gas flow fully develops to the supersonic flow (Mach No. >1) and it is adequate to make the shock wave between the nozzle wall and the tip of fixed arcing contact as shown in Figure 3. The shock wave rapidly decreases the density on the surface of the fixed arcing contact and which in turn causes the breakdown at lower voltages.

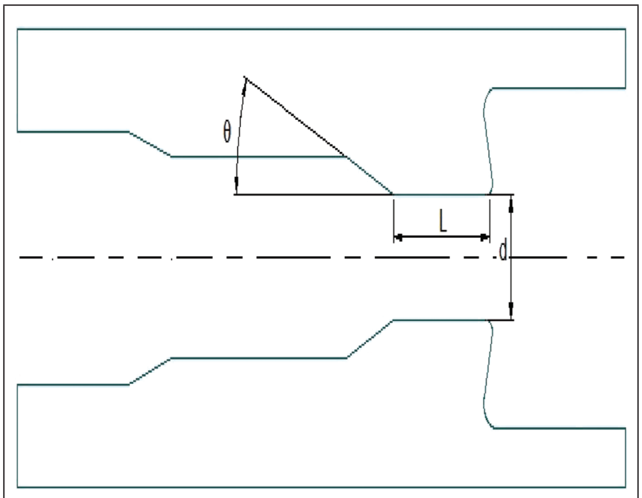

FIG. 2 TYPICAL NOZZLE USED FOR ANALYSIS

The angle θ is varied from 10° to 90° to see the effect on pressure fluctuation on the tip of the fixed arcing contact at point 'A'. The gas flow field is calculated by solving the twodimensional axis-symmetric Euler equations using FVFLIC method.

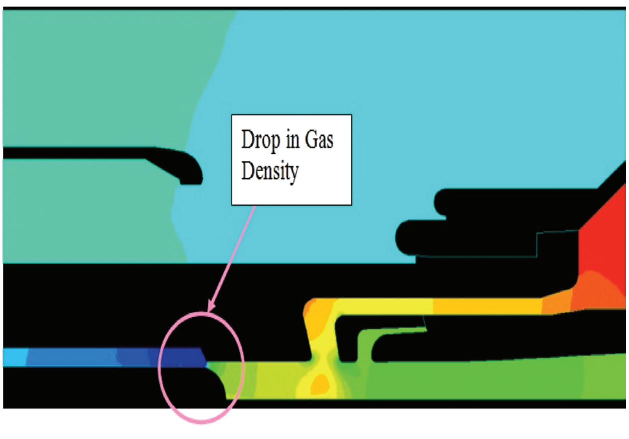

FIG. 3 PRESSURE DISTRIBUTION PLOT

Figure 3 represent the analytical result forgas pressure variation on fixed arcing contact tipfor different diffuser angle during opening operation at point 'A". The resultshows that thetransient pressure drop is much smaller when the Diffuser angle θ is kept from 50° to 90°. Figure 4 represent the analytical result for gas pressure variation on fixed arcing contact tip for different diffuser angle during opening operation at point 'A".

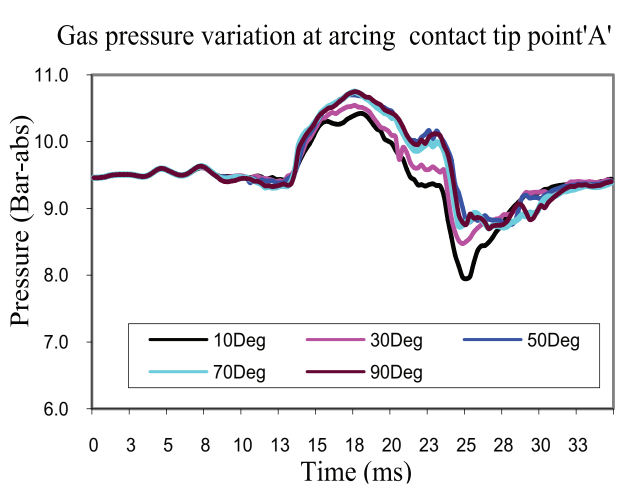

FIG. 4 GAS PRESSURE VARIATION AT ARCING CONTACT TIP POINT 'A'

The result shows that the transient pressure drop is much smallerwhen the diffuser angle θ is kept from 50° to 90°.

3.4 Opening speed of circuit breaker :

In case capacitor switching, Transient recovery voltage (TRV) is '1- cosine' wave, its rate of rise is very higher than rated power frequency.

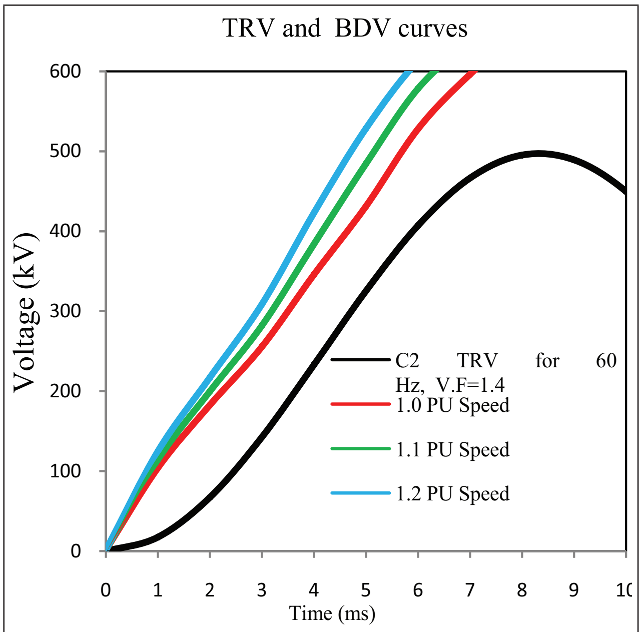

FIG. 5 TRV AND BDV CURVES FOR DIFFERENT OPENING SPEED

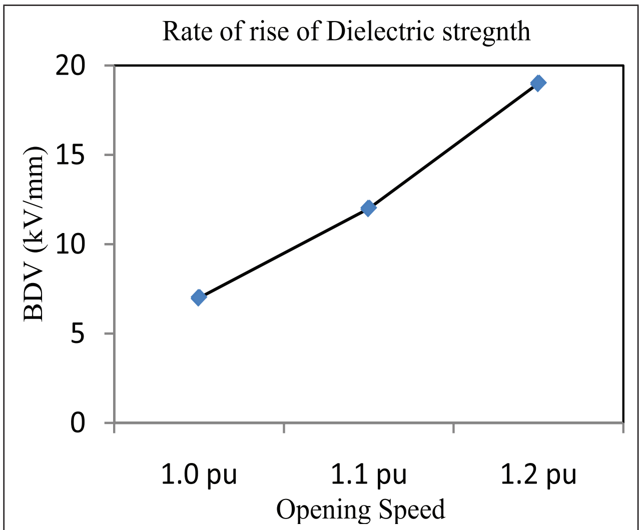

FIG. 6 SPEED VS RATE OF RISE OF DIELECTRIC STRENGTH.

While remaining lines are showing Developed dielectric strength across circuit breaker contacts. By increasing opening speed during rate of rise zone of TRV, dielectric performance can improve as shown in Figure 5 & Figure 6.

TABLE 1 DIFFERENCE BETWEEN TRV WAVE & DEVELOPED DIELECTRIC STRENGTH (%)			
TRV Voltage (kV)	**1.0 PU Speed**	**1.1 PU Speed**	**1.2 PU Speed**
0.00	0.00%	0.00%	0.00%
17.46	397.87%	437.85%	477.43%
67.38	180.85%	197.91%	214.99%
142.75	119.42%	131.77%	144.26%
232.98	98.95%	109.87%	121.06%
325.41	88.34%	99.28%	108.27%
407.05	86.45%	94.70%	100.37%
466.44	85.19%	91.04%	94.80%
495.23	87.56%	91.67%	95.34%
489.38	93.52%	97.66%	102.81%
449.71	106.06%	112.37%	120.15%
381.80	132.63%	143.04%	155.60%
295.17	182.92%	200.91%	216.03%
202.01	267.27%	293.56%	315.66%

Figure 5 showing that, as openingspeed increases, rate of building of dielectric strength increases. TRV appear across circuit breaker contacts is showing by black line and remaining line showing developed dielectric strength for different speed.

Table 1 showing that, Profile of developed dielectric breakdown strength for different speed; in short we can say that, it is margin or factor of safety. As difference between TRV and developed dielectric strength by circuit breaker increases, probability of failure decreases.

4.0 CONCLUSION

1. Capacitor switching duty is very severe duty because rate of rise of transient recovery voltage (TRV) in capacitor switching is very high, so circuit breaker should be capable to build up dielectric strength in smaller time with higher distance contact gap.In short circuit breaker should have capability to build up high dielectric strength during high rate of rise of TRV zone e.g. From 2 ms to 8 ms, for 50 Hz from contact separation.
2. Diffuser angle θ is play important role in density compensation; we observed that transient pressure drop is much smaller when the diffuser angle θ is kept from 50° to 90°.
3. Circuit breaker opening speed during rate of rise of TRV important, as speed increases in this zone gives better performance for capacitor switching application.as speed increases, and gap between TRV & BDV increases. As per 'race theory', if rate of rise of dielectric strength curve crosses the TRV curve, it means restrikes occur or test fail.

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