Investigation of Arc Reignition Duration under Varied VCB Interrupter Dielectric Strength

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***Abstract*- The switching behavior of vacuum circuit breaker (VCB) is different from other circuit breaks. Vacuum Circuit Breakers (VCB) have excellent interruption and dielectric recovery characteristics. This characteristic causes the arcing during breaker opening to be unstable. The arcing instability produces high frequency current which superimpose on the line frequency current. The interruption of high frequency currents can lead to re ignitions during breaker opening. The arc reignition is influenced by many parameters such as current chopping value, dielectric strength of the vacuum gap, opening time and quenching breaker capability of high frequency current. This paper focuses on a medium vacuum circuit breaker model in PSCAD that represents the vacuum breaker characteristics. The model takes into account the impacts of a random nature of opening time before the next current zero, current chopping and dielectric strength of the breaker on arc reignition duration. The developed breaker model for a single phase VCB and the results are shown in this paper.**

Keywords—Current chopping, Reignitions, TRV, VCB, RRDS, PSCAD.

I. INTRODUCTION

The main purpose of circuit breaker is to protect the network from damages during fault. The other function is for normal loads and capacitor switching. They play a significant role in sub transmission and distribution network reconfiguration, more than 60% of the switching devices applied in medium voltage (MV) are vacuum interrupters. VCB is popular because it has lowest environmental impact over the entire product life cycle. In addition VCB can withstand higher number of switching with minimum maintenance requirement [1], [2] [3][4]. When a vacuum circuit breaker is opened, an electric arc is struck and in normal circuit breaker, the arc extinguishes at a natural current zero. But in vacuum the arc is extinguished before current reaching zero causing the arc to be instable. This instability could lead to very high frequency oscillations of the breaker current that superimpose on the power frequency current. Vacuum circuit breakers have ability of interrupting currents which having high time derivative (di/dt). The high frequency current can be interrupted through one of the high frequency excursions during zero crossing. The breaker only recovers to be reignited once again when the transient recovery voltage (TRV) exceeds the dielectric strength of the interrupter gap and failure will occur [5]. On the other hand a failure occurs when a VCB is unable to withstand a voltage after current interruption, and a new arc is formed, through which the current continues to flow. VCBs have experience failures due to reignition overvoltage, the resulting failure during interruption current, it is expected that because of arcing reignition caused by the TRV which has exceeded the dielectric strength of VCB interrupter. PT PLN reported around five failures of VCB during its switching operation for one year service [6].

II. OVERVOLTAGES DURING VCB OPENING

Resulting overvoltage during opening of a VCB can be a different nature than those generated in the same situations by switchgears that use another type of the medium breakers (air, SF6, oil, etc.), due to the ability of VCB chopping the arc current at higher value. The interruption of currents in a VCB is often escorted with high voltage transients and high frequency current. When the current is below than the current chopping value (I_{ch}), the arc through the VCB becomes unstable and extinguishes. The value of the current chopping depends on the contact material type, form and level of the current to be interrupted. when current chopping has occurred, Current clearly falls to zero and the voltage being proportional to the product of circuit inductance and current time derivative (di/dt), will be higher as the current change suddenly to zero[1], [7]. As shown in Figure 1.

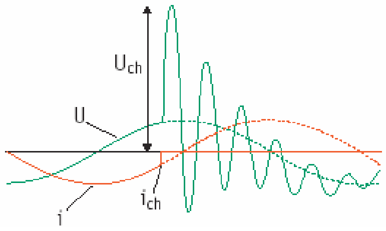

Figure1: TRV and the current chopping phenomenon

III. SWITCHING CHARACTERISTICS OF VCB

There are mainly different parameters, which are important to consider, in order to model and simulate the phenomenon that appears when switching off a VCB [5]. Some of the parameters are as listed below:

- The random nature of opening time before the next current zero (arcing time)
- The ability of the breaker to chop the current before its natural zero
- The characteristic recovery dielectric strength between contacts when breaker opening
- The quenching capability of high frequency current at zero crossing below certain value of di/dt.

When the breaker contacts mechanically open, the dielectric strength between the gap will rise as a function of time, therefore the race between the dielectric strength and the transient recovery voltage develops. Once the TRV exceeds the dielectric strength, the signal is sent to close the switch, and at that time reignition is occurred. If the quenching capability (rate of change of the current at current zero) has a lower value than the critical value, an opening signal is sent to the switch and reopening can occur. If this suppression is followed by a new reignition, this process repeats again until the dielectric strength between the breaker contacts can withstand the TRV [5].

A. opening time before the next current zero (Arcing time)

The arcing time of the breaker is the time between the contacts separation and the following current zero, and it's random in nature for the different switching operations of VCB [1]. The opening time could be located at any point of electrical period, and it depends on the moment of the contact separations, the higher the arcing time, the longer the time provided to the breaker to achieve its dielectric strength, and this can lead to the successful interruption of the current at the first current zero. If the opening time before the next current zero is short, then the dielectric strength of the gap won't have time to reach a high value before the arc is extinguished and the probability of reignition is longer.

B. Current Chopping

Current chopping is a phenomenon that can lead to overvoltage, it happens when capacitive and inductive currents are interrupted. The real current chopping is non deterministic, while earlier researches have established different mean chopping levels for different load currents and contact material of the breaker. The mean current chopping is calculated according to the following equation [8], [1]:

$$I_{ch} = (\omega .\ i .\ \alpha .\ ß)^{q} \qquad (1)$$

Where, ω Angular frequency

$\omega = \mathbf{2} .\ \pi .50Hz$

i Amplitude of the current

α, ß, q Parameters that dependent on the contact material

α = 6.2e-16 sec

ß = 14.3

q $= (1 - ß)^{-1}$

It is depending on the amplitude of the load current and also on the moment of the contact separations. The closer the contact opens to current zero, the higher the chopping current. The chopping currents giving to this equation related to those of modern vacuum breakers, which use Cu/Cr contacts (3- 8 A at small load currents). Because of the statistical character of the chopping level, a value calculated with (1) is varied by a normal distribution with 15% standard deviation [8].

C. Dielectric Strength

In the VCB there are two breakdown mechanisms exist [5], [8]: The first one is the cold gap breakdown. The dielectric strength of vacuum gap increases linearly after the contacts of VCB separate. The reignition will occur, when the TRV exceeds the dielectric strength. This phenomenon is called cold gap breakdown and it dependents on the recovery of dielectric strength. The second one is the hot gap breakdown. When reignition occurs, the temperature and the pressure of vacuum gap increase. When the arc is quenched, the vacuum gap might still have metal vapors and different ions. These remaining particles make the breakdown voltage reduce. This paper is considered only the cold gap breakdown. A linear dependency of contact distance and dielectric strength is assumed [5], [1].

$$U = A\,(t - t_{open}) + B \qquad (2)$$

Where, U Dielectric strength of vacuum gap

t_{open} moment of contact separation

A Rate of rise of dielectric strength

B Intercept of the function

TABLE I: Three Typical Breakdown Voltage Characteristics of the Vacuum Circuit Breaker [9]

BV Type	A(V/s)	B(V)
High	1.70E7	3.40E3
Medium	1.30E7	0.69E3
Low	0.47E6	0.69E3

When the contacts of the breaker mechanically open, the dielectric strength between the contacts increases as a function of time. The signal is sent to close the switch, after the transient recovery voltage (TRV) exceeds the dielectric strength, then a reignition is established and arc interruption has failed [1].

D. High frequency quenching capability

A reignition will occur when the TRV exceeds the dielectric strength of the breaker contacts. The actual frequency of the high frequency current related with arc stability of the breaker is determined by a model containing inductance and capacitance. This high frequency current superimpose on the power frequency current. When the high frequency current comes to be bigger in magnitude than the power frequency current, it can force current zeros. Vacuum circuit breaker has the capability of quenching the high frequency current and then the current could be quenched at any of its zero crossing at high frequency. The high frequency quenching capability of model vacuum circuit breakers has found in the range of numerous hundred A/µs. The quenching capability of VCB is calculated by using the equation [5], [8]:

$$di/dt = C\,(t - t_{open}) + D \qquad (3)$$

Where t_{open} is the moment of contact separation, C and D are constants. The values of the constants for three typical di/dt characteristics are shown in Table II. As given in [9]. When the absolute value of the rate of change of the current open at current zero is higher than di/dt, the arc extinction will not occur.

TABLE II: Three Typical di/dt Characteristics of the Vacuum Circuit Breaker

di/dt Type	C(A/s²)	D(A/s)
High	-0.34E11	255.0E6
Medium	0.31E12	155.0E6
Low	1.00E12	190.0E6

IV. SIMULATION OF A SINGLE PHASE VCB

One of the ways of performing the simulation of arc reignition duration in VCB is to use PSCAD/EMTP. To characterize the various behaviors of the VCB model that mentioned before, the single phase test circuit as shown in Figure 2 is used based on J. Helmer, M. Lindmayer and Juan A. Martinez Velasco [8][10] with some simplification. The model simulates a 14KV RMS single phase system, which can be taken as a representing a medium voltage industrial supply
system where transient conditions may occur. The VCB is modelled by PSCAD/EMTP with different values of coefficients A, B, C, and D as reported by Mietek T. Glinkowski [9].

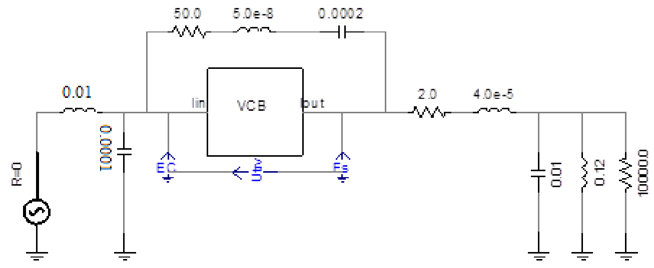

Figure 2: Test circuit for the single phase VCB model

V. SIMULATION RESULTS AND DISCUSSION

A. Effect of RRDS

From the Figure 3 it is shown that, the TRV developed much more than the RRDS developed across the breaker that has led to re ignition. When the RRDS is increased from 6kv/ms breakdown voltage strength to high BV strength, maintaining all other parameters the same, the breaker has successful interrupted of the arc at the first current zero. The plot of TRV and current across the breaker are shown in Figure. 4.

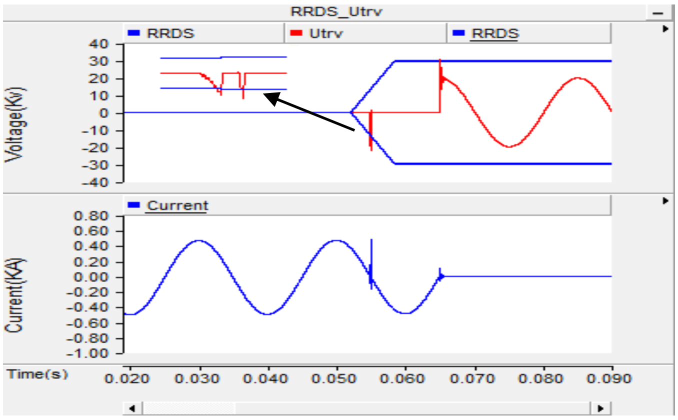

Figure 3: Unsuccessful interruption of the current at first current zero (reignition across the breaker)

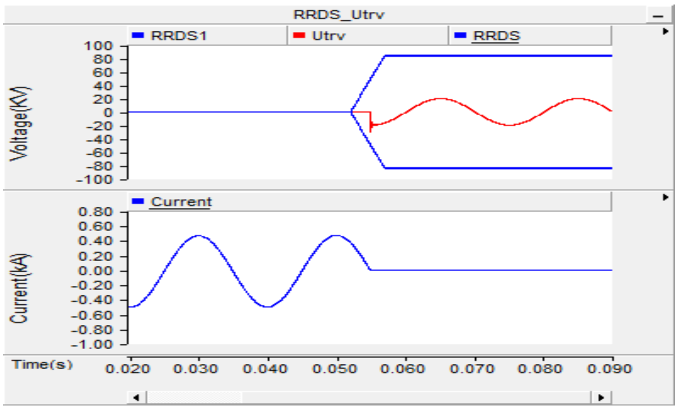

Figure 4: Successful interruption of the current at first current zero (TRV& Current across the breaker)

B. *Effects of Chopping Current Level*

As explained before in section B the current chopping is a phenomenon that can lead to severe over voltages and occurs when inductive and capacitive currents are interrupted before reaching a zero crossing, the existing arc between breaker contacts becomes unstable, causing the current to be interrupted prematurely leading to overvoltage. The VCB with a higher chopping current quenching the current before current zero, the longer the arc reignition duration across the VCB contacts, as displayed in Figure 5. 6, a few reignitions were created when using I_{ch}=5A, and longer reignitions were created when using I_{ch} =20A respectively.

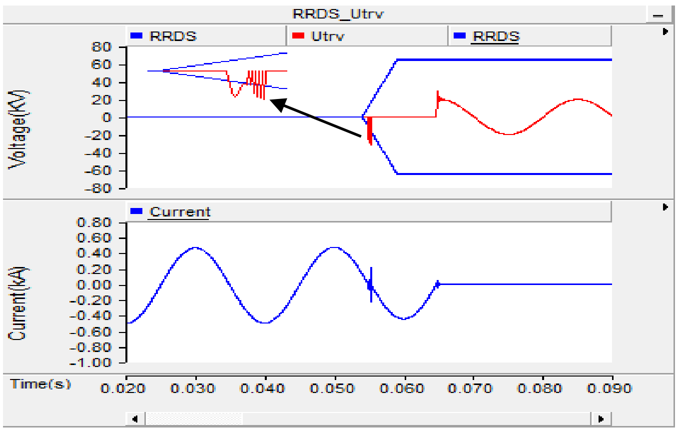

Figure 5: Reignitions lead to unsuccessful interruption of the current at first current zero with I_{ch}=5A when contacts open at 1ms before current zero.

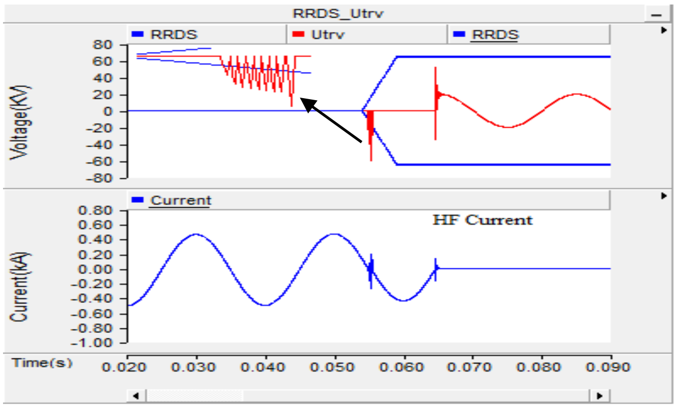

Figure 6: Reignitions lead to unsuccessful interruption of the current at first current zero with I_{ch}=20A when contacts open at 1ms before current zero.

C. *Effect of opening time before the next current zero (arcing time)*

Opening time before next current zero (Arcing time) is a very important parameter for the arcing reignition duration and dielectric strength of the vacuum circuit breaker. As defined before when the contacts separate, an arc appears between the contacts and is maintained until the current zero point. The higher the arcing time, the sufficient is the time provided to the breaker to achieve its dielectric strength leading to the successful interruption of the arc as shown in Figure 7, the breaker opens at 9ms before the next current zero. The shorter the opening time before the next current zero, the longer the reignition duration across the breaker contacts as shown in Figure 8, opening time is 1ms before the next current zero.

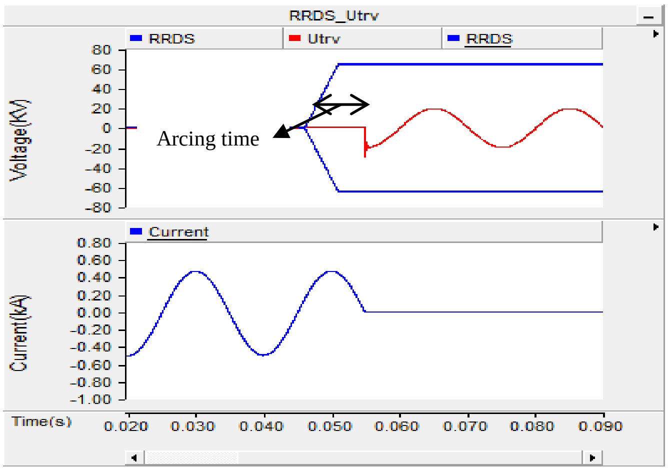

Figure 7: TRV, arcing time and dielectric strength for opening time of 9ms before the next current zero.

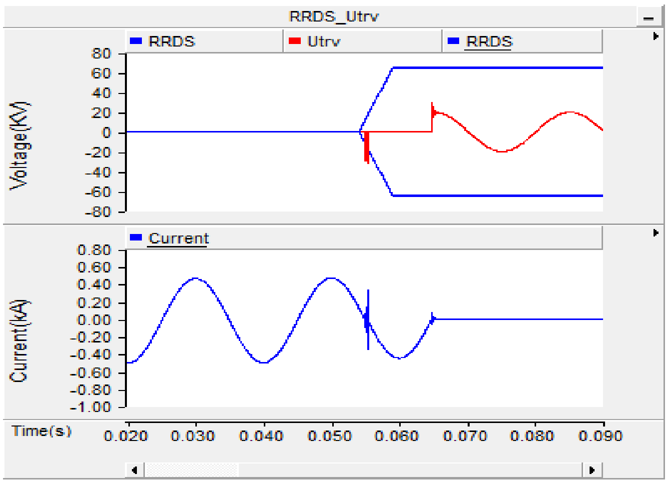

Figure 8: Reignition, dielectric strength for opening time of 1ms before the next current zero.

VI. CONCLUSION

Based on the present investigation of the simulation results, the VCB which has a high RRDS reaches a higher dielectric strength faster and has interrupted the current successfully without any reignition occurs, the lower the dielectric strength of the VCB failed to interrupt the current at first current zero leading to arc re ignition and longer duration of interruption. As expected from the results, a VCB which having a higher chopping current level, experience longer the arc reignition duration across the contacts. The result of random nature of opening time of VCB was also found that, the shorter the opening time before next current zero, leads to the VCB dielectric strength having longer time to recovery, which results in a longer arc reignition duration. Based on this simulation the condition of dielectric strength inside the VCB can be assessed the deterioration of the dielectric strength in VCB if can monitor the behavior of reignition during breaker opening.

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