Modeling of Circuit Breaker
for Controlled Switching Applications using
EMTDC/PSCAD

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Abstract—Circuit breaker is an important part of the electrical network. It makes or breaks the network to transmit the electrical energy from one point to another. But every operation of the circuit breaker is associated with switching transients. Switching transients degrade the quality of power transferred through the power system. Controlled switching is a well known methodology used for mitigation of transients during switching operations. This paper deals with the electrical and mechanical modeling of circuit breaker in PSCAD/EMDTC environment. This model can be used to verify the performance of controlled switching in case of different loads. The model can also be used to study different switching transient that can appear during the breaker operation.

I. INTRODUCTION

In a power system network, circuit breaker plays a significant role in making and breaking the circuit. Every switching operation is associated with exchange of energy between capacitive and inductive elements of the circuit. This exchange of energy causes high frequency over-voltage and currents and thus compromises the quality of power that is being transferred in the system. This affects the life cycle of the equipment present in the system. These transients can be mitigated by the use of additional components like pre-insertion resistor, inductors and surge capacitors[1]. Controlled switching is one of the other ways to mitigate the transients[2][3][4][5]. In controlled switching application the instant of switching is controlled in such a way that the stress across the circuit breaker can be minimised. Therefore, the performance of controlled switching depends upon how accurately the desired switching instant has been realised in a real circuit breaker. Therefore, to ensure the applicability of a proposed algorithm in real field, rigorous testing is required simulating realistic scenarios.

This is achieved by modeling the electrical and mechanical characteristics of the circuit breaker upon which the controlled switching algorithms can be verified. The authors in [6] has explained the modeling of circuit breaker that simulates randomness in arcing time, dielectric strength, current chopping phenomenon and also incorporates the arc quenching phenomenon. In [7] the authors have modeled yet another phenomenon of multiple re-ignitions in a circuit breaker for a low inductive current. Both of these models have modeled only electrical characteristics of circuit breaker and application of these models for controlled switching applications has not been discussed. This paper will present electrical as well as mechanical modeling of circuit breaker along with the application of this model in respect with controlled switching.

The paper is organized as follows. Section II gives a brief review of closing and opening characteristics of circuit breaker and subsequently section III describes the modeling of these characteristics in PSCAD/EMDTC environment. Section IV presents the simulation studies of the modeled circuit breaker with reactor and capacitor loads and finally section V concludes the paper.

II. CIRCUIT BREAKER OPERATION CHARACTERISTICS

Circuit breakers(CB) are the key components of any transmission and distribution network. They are not only used for interrupting current during fault conditions but are also used for normal load switching operations. For controlled switching applications that mainly comes under load switching, circuit breaker characteristics plays an important role in determining the instants of closing and opening because controlled switching is methodology with the intention to control the switching instant dynamically by varying the command release instant to the circuit breaker. The accuracy that is desired for this application is 1 millisecond or less[5]. The key parameters that can affect the accuracy of circuit breaker switching instant are:

1) Operating time of physical contacts of circuit breaker
2) Rate of decay of dielectric strength (RDDS) and Rate of rise of dielectric strength(RRDS)
3) Arcing time

The effects of each of these parameters on to the circuit breaker have been classified in terms of closing and opening characteristics and their modeling has been described as followed.

1) Closing Characteristics of Circuit Breaker: The operating time of real circuit breaker gets affected by variations in the environmental and physical factors. The key factors that affect the operating time of primary as well as auxiliary contacts are DC control voltage level, spring charge, temperature, hydraulic pressure of \( S_F^0 \) and other variable factors. The variations in the closing times are more due to change in environmental factors compared to opening times[5]. For testing controlled
switching applications the variations in the operating times are utmost important factor as they effect the instant of switching.

Considering that the circuit breaker is subjected to close operation, as the gap between the primary contacts of circuit breaker decreases, the dielectric strength between the contacts decreases. When the voltage across the gap is high enough to match the dielectric strength of the gap, the current starts flowing through the circuit breaker contacts. This will happen even before breaker contacts touch each other. The time interval between this electrical making of current and mechanical touch of contacts depends on the Rate of Decay of Dielectric Strength(RDDS). RDDS shows the dielectric strength between the gaps of circuit breaker contacts[8].

![Fig. 1. Closing operation of circuit breaker](image1)

Fig. 1 shows the characteristic curve of gap voltage and RDDS during closing operation. According to the figure, at time $t_{clc}$, primary contacts starts moving for closing operation. At time $t_{op}$, the gap voltage across the circuit breaker has become $V_{CB}$. At this instant the dielectric strength is equal to the gap voltage. When the primary contacts touches each other the dielectric strength becomes zero and this condition occurs at time $t_e$. Here, it can be clearly observed that the operating time of primary contact is the time interval between the instant of close command $t_{comm}$ and contact touch $t_e$. It has been denoted by $T_{pri}$ in Fig.1. The time interval between electrical energization and mechanical contact touch has been denoted by $T_l$.

Fig. 2 shows the effect of RDDS on the operating time of circuit breaker during close operation.

The voltage across the circuit breaker with three different RDDS characteristics have been plotted. It can observed that for $RDDS_1 > RDDS_2 > RDDS_3$ and the time interval between electrical energization and mechanical touch for respective RDDSs follows the relation $T_{l1} < T_{l2} < T_{l3}$. This shows that RDDS effects the electrical and mechanical operating times of CB therefore, it proves to be an important factor for control switching application and this parameter needs to be modeled.

2) Opening Characteristics of Circuit Breaker: The current and voltage across the contact gap can vary depending on the instant of current interruption. In a circuit breaker the current is normally interrupted at current zero crossing. Therefore, it is desirable that the current should be interrupted at zero crossing of current to avoid stressing of circuit breaker from high gap voltage and current.

Mechanical and electrical interruptions take place at different time instances. This is because even after mechanical separation of primary contacts, the current continues to flow in the form of arc between the contacts. This current will be interrupted at the current zero crossing. The time interval between the mechanical contact separation and final current interruption is called arcing time. If the arcing time is sufficient enough to extinguish the arc (by building up enough dielectric strength), current will stop flowing through the contacts and it gets interrupted. But if this arcing time is not enough to build up the required dielectric strength then the current will again start flowing through circuit breaker and this phenomenon is termed as restrike or re-ignition depending on the duration after which the current will start flowing.

Fig.3 and Fig.4 clearly depict the phenomenon of re-ignition and and re-strike respectively. Fig.3 shows the current and voltage waveform across the circuit breaker and also the dielectric strength across it [9]. In Fig.3 current is interrupted before its natural current zero instance leading to the phenomenon of current chopping. Due to this chopping phenomenon, the TRV(Transient recovery voltage) of the system exceeds the dielectric strength between the breaker contacts (gap) which causes the current to flow through the gap again. If this current starts flowing before one quarter cycle from the current interruption instance, this phenomenon is termed as re-ignition.

Similarly, Fig.4 shows the source voltage with peak of $V_{in}$ volts, source current, voltage across capacitor and voltage across circuit breaker(difference between source voltage and capacitor voltage) along with RDDS characteristics. After two quarter cycles from current interruption the voltage across circuit breaker exceeds the dielectric strength between the breaker contacts (gap) which causes the current to flow through the gap again, this phenomenon is termed as re-strike.
The CB models that are available in various simulation tools do not include the effect of RDDS (Rate of Decay of Dielectric Strength), arcing time and physical parameters on circuit breaker operation. Therefore, to obtain the actual response of Circuit Breaker during switching operations, opening and closing characteristics need to be modeled.

The main purpose of this paper is to accurately model the behavior of CB under switching operations and to study the impact of change of RDDS and arcing time on the behavior of CB during opening and closing operations so that accurate DRs(Disturbance records) can be generated for testing purpose.

III. CIRCUIT BREAKER MODELING

This section describes the modeling of circuit breaker in PSCAD/EMTDC environment. To simulate open and close behaviour of circuit breaker the resistance across the CB has been varied. In open condition a very high resistance \( R_o \) has been kept across CB so that no current can flow through the CB. Similarly in closed condition of circuit breaker a low resistance \( R_c \) has been kept across circuit breaker to allow the flowing of current.

The modeling of electrical and mechanical properties of circuit breaker during open and close operation has been described in the following sections.

A. Modeling of CB during closing operation

Circuit breaker has two types of contacts, one remains fixed and the second one moves during CB operation. During closing operation of circuit breaker, the moving contact of circuit breaker travels towards the fixed contact with a certain velocity. As the gap between the contacts reduces, the dielectric strength between the gap decreases. When this dielectric strength falls below the circuit breaker gap voltage, the current starts flowing through the gap. This premature initiation of current is called prestrike. This means that electrical path is completed before instant of mechanical contact touch of circuit breaker. The time difference between electrical making of current and mechanical contact depends on the rate of decay of dielectric strength (RDDS). From Fig.1 the time lapse between the electrical making and mechanical interaction of contacts can be determined by (1)

\[
T_i = \frac{V_{CB}}{RDDS}
\]

where,

\( T_i \) = time lapse between electrical and mechanical making

\( V_{CB} \) = voltage across CB(illustrated in Fig.1)

If the close command is given to the breaker at \( t_{comm} \) then to simulate the behavior of circuit breaker under closing operation following steps are followed:-
1) As per the given breaker’s RDDS and (1), the pre-arcing time (time gap between the electrical making and mechanical touch) $T_l$ in Fig. 1 has been evaluated.

2) The operating time of the primary contacts ($T_{pri}$) has been determined from breaker library.

3) The electrical operating time instant ($t_{op}$) has been then determined from (2)

4) After the final calculation of electrical time instant ($t_{op}$) the simulation time has been monitored after $t_{comm}$ and the resistance across the circuit breaker has been made to $R_c$, which corresponds to closed resistance across circuit breaker.

$$t_{op} = T_{pri} - T_l$$

$$\Rightarrow t_{op} = t_t - t_{comm} - T_l$$

(2)

B. Modeling of CB during opening operation

During opening operation of circuit breaker, the moving contact moves away from fixed contact. During the opening operation of CB, the time lapse between the instant of de-energising and instant of mechanical contact separation, is termed as arcing time. After the mechanical contact separation, arc continues till the next current zero instance or until current gets chopped, whichever is earlier.

For opening operation, the following two phenomena have been modeled in PSCAD:

1) Current interruption with arcing time.
2) Restrike and reignition phenomenon.

In Fig. 5, let $t_{cmd}$ be the instant at which the primary contacts starts separating. This time instant is given in terms of angle from reference zero crossing. It can be expressed by (3)

$$t_{cmd} = t_{ZC} + \alpha$$

(3)

where,

$t_{ZC}$=time instant of zero crossing

$\alpha$= instant of mechanical contact separation

In this model both of the above mentioned parameters are given as setting so that user can adjust the instant of command arrival to the circuit breaker.

If $T_{arc}$ is the arcing time, then the total time after which the current interruption will happen($T_{tot}$) is given by (4)

$$t_{tot} = t_{cmd} + T_{arc}$$

(4)

After determining the current interruption time($t_{tot}$) which also includes arcing time, current waveform is monitored and following operations are performed accordingly with the assumption that circuit breaker is previously in closed position with resistance across it as $R_c$

1) If $t_c < t_{tot}$ and current zero is not detected, then the resistance across the CB is kept as it i.e. $R = R_C$

2) If $t_c < t_{tot}$ and current zero is detected then make $R = R_O$

3) If $t_c > t_{tot}$, then make $R = R_O$

where $t_c$ is the simulation time.

For re-strike or re-ignition phenomenon, as soon as the current interruption happens, start monitoring the voltage across the circuit breaker $V_{CB}$ and execute the following steps

1) If $V_{CB} > V_{CB-rated}$, store the time instant of this condition as $t_{delay}$, and make $R = R_c$. This will make the current to flow through the circuit breaker illustrating in simulation the reignition or restrike. phenomenon.

2) After $t_{delay}$, monitor the current waveform. If zero crossing is detected make $R = R_O$ making the current to stop flowing through the circuit breaker.

3) Repeat the above two steps to simulate multiple reignitions if any.

In Fig.5 the time interval($T_{delay}$) between current interruption and $t_{delay}$ determines whether this re-flowing of current through circuit breaker is reignition or restrike.

1) If $T_{delay} < $ quater cycle, the phenomenon is called reignition.

2) If $T_{delay} < $ quater cycle, the phenomenon called is restrike.

C. Modeling of physical parameters affecting the operation of circuit breaker

Circuit breaker exhibits variation in operating time due to changes in physical operating parameters viz. control voltage, spring charge, temperature, $SF_6$ pressure etc. These variations differ from one breaker to another. In controlled switching applications where instant of switching plays an important role, these deviations should be taken care of as these can affect the performance of controlled switching applications.

The operating time at a given condition can be given determined on the basic of data collected from sensors/transducers and known operating characteristic obtained from the manu-
The actual operating time of primary and auxiliary contacts is given by (5)

\[ T_{pri-a} = T_{pri} + \Delta T_{\text{compensation}} \]

\[ T_{NO-a} = T_{NO} + \Delta T_{\text{compensation}} \]

\[ T_{NC-a} = T_{NC} + \Delta T_{\text{compensation}} \]

where, 

- \( T_{pri-a}, T_{NO-a}, \) and \( T_{NC-a} \) = average operating time of primary and auxiliary contacts
- \( \Delta T_{\text{compensation}} \) = total variation in the operating time due to physical parameters. The total variation from the nominal operating time, \( \Delta T_{\text{compensation}} \), can be expressed by equation (6)

\[ \Delta T_{\text{compensation}} = \Delta T_V + \Delta T_S + \Delta T_P + \Delta T_T + \Delta T_U \]  

(6)

where,

- \( \Delta T_V \) = Change in operating time due to variation in control voltage
- \( \Delta T_S \) = Change in operating time due to variation in spring charge
- \( \Delta T_P \) = Change in operating time due to variation in pressure
- \( \Delta T_T \) = Change in operating time due to variation in temperature
- \( \Delta T_U \) = Change in operating time due to variation in unknown parameters

Change in operating time due to individual parameters can be found with the help of sensor transducer data and operating characteristics of circuit breaker.

Similar methodology can be implemented to model the effect of physical parameters for open to close operation.

**IV. Simulation**

To demonstrate the characteristics of circuit breaker during closing and opening operation the circuit shown in Fig. 6 with the modelled CB has been simulated in PSCAD along with the following loads.

1) Reactor

Fig. 6.

Fig. 7. Simulation results for the network.
2) Capacitor
Here, the source voltage has been taken as 240 kV with 0.1Ω as source resistance.

Fig.7a shows simulation results with 50MVAR reactive load. Graph at top shows source voltage ($V_a$), load voltage ($VL - a$) and voltage across circuit breaker ($E_a$) which is basically the difference between the given two voltages. The load current is 212.4A RMS. From the results it has been observed that the current has been interrupted at t=0.4049 sec. After current interruption the voltage across the circuit breaker becomes about 1.7 kV. The dielectric strength after the current interruption was not enough to handle this high transient recovery voltage and because of that current got initiated again at t=0.4054 sec with a magnitude of 100A. This current continues for half cycle and is interrupted at subsequent current zero.

Similarly Fig.7b shows waveforms of voltages and current with 50MVAR capacitor load. In the top most waveform source voltage ($V_a$), capacitive voltage ($VL_a$) and voltage across circuit breaker($E_a$) has been shown. In this case load current is 215.5A RMS. It can be observed that the current has been interrupted at t=0.418 sec which corresponds to the negative voltage peak of the voltage across capacitor load. After current interruption the voltage across the capacitor remains constant. When the source voltage reaches positive peak the voltage across circuit breaker becomes maximum(677kV). At this instant the dielectric strength has not been risen enough therefore because of this condition the current got initiated again with a very high magnitude of 8kA.

V. CONCLUSION

This paper proposes the detailed model of circuit breaker during opening and closing operation. This model includes the effect of RDDS on circuit breaker operation and accurately simulates the phenomenon of re-ignition and re-strike when appropriate conditions are provided. This model also includes the effect physical parameters that can alter the operating time of primary and auxiliary contacts.

This model will facilitate generation of accurate disturbance records for various scenarios and cases, which can be further used for testing controlled switching application related functions for hardware in loop environment.

REFERENCES