A Realistic Breaker Model for Simulation of Prestrike/Restrike in Circuit Breakers

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***Abstract*—This work presents a circuit breaker model for the simulation of prestrike and restrike. The paper proposes a nonlinear representation of the relation linking time and withstand voltage of the gap between contacts during breaker operation.**

The proposed model is compared to the conventional model which assumes a linear relation between time and withstand voltage of the gap distance. Simulation results reveal differences in prestrike/restrike waveforms. It is observed that the conventional breaker model can fail to represent the breaker's behavior during opening or closing faithfully.

***Keywords*: Electromagnetic Transients, Prestrike, Restrike, Switching, Vacuum Circuit Breaker.**

1. Introduction

Modern simulation tools, such as EMTP [1], are capable of predicting network performance under various operating conditions and assist engineers in taking informed decisions. The reliability of predictions depends on several factors such as the level of detail in the modeling of network components. For instance, in switching transient studies, modeling of circuit breakers is crucial when investigating transient phenomena such as breaker prestrikes or restrikes. The evaluation of these transients is highly important due to their influence on switching overvoltages [2]. For vacuum circuit breakers for instance, it has been shown that the dielectric strength of contact gap, although potentially high, can be very unstable [3]. On the one hand, prestrike may occur when the breaker is closing; it is an arc that appears prior to the mechanical touch of the contacts [2]. Prestrike may cause excessive erosion and contact welding [4]. Prestrike may also impact the probability distribution of overvoltages [5]. On the other hand, restrike may occur when the breaker is opening; it is an arc that appears within the contacts after interruption resulting from competing dielectric strength and transient recovery voltage [2]. Restrike may cause overvoltage and intensify the insulation deterioration [6]. Multiple restrikes may also become a severe source of electromagnetic disturbance [7].

Many challenges should be considered in modeling a breaker to assess prestrike/restrike in simulation software. One challenge is accounting for the relation between time and withstand voltage between contacts during switching operation. This challenge is addressed in this paper. Most of breaker models, such as the ones discussed in [5],[8],[9],[10],[11] assume a linear dependency of dielectric strength (withstand voltage) and distance between contacts. However, the dependency of dielectric strength with time is expressed differently. In [5], the withstand voltage is expressed by a t^2 law whereas in [8],[11],[12],[13] it is expressed by a t law. Both models are not correct as they fail to faithfully represent the nonlinear movement of breaker contacts. A more realistic model is proposed in [2]. The proposed model accounts for nonlinear movement of the contacts by modeling the contact displacement curve over time. The obtained mathematical equation is called the travel curve. However, this approach is difficult to implement as it may face the issue of data availability from breaker catalog. Also, this approach uses polynomial fitting functions to derive the travel curve, which increases its complexity.

Other challenges in breaker modeling for prestrike/restrike assessment include: (i) the probabilistic nature of the withstand voltage, (ii) the electrical characteristic of the arc, and (iii) the difference between withstand voltage of the cold gap and withstand voltage of a gap which has reignited [9] (in the latter case, residual charge carriers exist near breaker contacts and a breakdown could occur at lower voltages [12]). These aspects are not considered in this paper for the following reasons. Modeling the probabilistic nature of the withstand voltage requires additional data related to statistical distribution, which may not be available. Modeling the arc also requires specific data and is no common practice, in addition the arc voltage is orders of magnitude smaller than the system voltage [9]. Differentiating between a cold gap and a gap that has reignited is very complicated as it requires knowledge of the amount of residual charge carriers following arc interruption.

This work presents a new, realistic and relatively easy to implement breaker model. A nonlinear representation between time and withstand voltage of the gap is proposed. This is achieved by modeling the nonlinear movement of the contacts caused by the variation over time of the speed of the moving contact during operation.

Section II of this paper recalls the conventional modeling of breakers to assess prestrike/restrike, section III describes the proposed new modeling approach. Section IV presents two demonstration examples in which the proposed model is compared to the most used conventional model.

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2. Conventional Breaker Modeling For Prestrike/restrike

2.1. Basic considerations

Several international standards describe breaker ratings for power system applications [14] to [16]. Most simulation tools model the breaker as an ideal switch. When the switch is closed, the voltage between its terminal is zero. When the switch is opened, the current flowing through is zero. Capabilities such as current chopping, cold gap breakdown (prestrike/restrike) or current quenching are accounted for by adding additional constraints to the breaker opening or closing conditions. For instance, to account for current chopping, the condition:

$$|i(t)| \le I_{chopping} \tag{1}$$

should be satisfied before the breaker is opened. In (1), $i(t)$ is the instantaneous current flowing through the breaker and $I_{chopping}$ is the chopping current value of the breaker.

2.2. Withstand voltage of the gap between contacts

Two parameters are crucial to model a breaker for prestrike/restrike assessment [5]: the open contact withstand voltage of the breaker U_C, and the contacts' operating time T_C. It is usual to assume that U_C is constant, even though its value depends on the interaction of many variables, such as voltage polarity [5]. For T_C, it usually ranges in milliseconds. Depending on its value, the breaker can be identified as slow or fast contact closing breaker. Conventional breaker models assume a linear dependency of dielectric strength and distance between contacts. However, the dependency between dielectric strength and time is expressed differently in the literature.

In [5], it is assumed that the breaker contacts operate according to a t^2 law where t is time measured from the instant when the contacts commenced to move. For breaker closing, the withstand voltage across the closing contacts v_w is expressed by

$$v_w(t) = U_C\left(1 - \frac{t^2}{T_C^{\,2}}\right) \tag{2}$$

The formulation for breaker opening is expressed by

$$v_w(t) = \frac{U_C}{T_C^{\,2}} t^2 \tag{3}$$

In [8],[12],[13] it is assumed that the breaker contacts operate according to a t law. This formulation is the most used in the literature and is referred to hereinafter as the conventional model. For breaker closing, the withstand voltage is expressed by

$$v_w(t) = U_C\left(1 - \frac{t}{T_C}\right) \tag{4}$$

The formulation for breaker opening is expressed by

$$v_w(t) = \frac{U_C}{T_C} t \tag{5}$$

Equations (2) to (5) respect the boundary conditions stated in (6) and (7). For breaker closing,

$$v_w(0) = U_C \;\; and \;\; v_w(T_C) = 0 \tag{6}$$

For breaker opening,

$$v_w(0) = 0 \;\; and \;\; v_w(T_C) = U_C \tag{7}$$

2.3. High frequency currents quenching

As explained in [8] and [11], the capability to quench high frequency currents following a re-ignition is expressed by the slope SL of the current at its zero crossing, which is calculated as follows:

$$SL(t) = C\,t + D \tag{8}$$

where C (in $A\,\mu s^{-2}$) is the rate of rise of the quenching capability, D is the quenching capability prior to contact separation, and t is time measured from the instant when the contacts commenced to move. Some values of C and D for vacuum circuit breakers are given in [11].

Following a re-ignition, at any instant $t = t_s$ located at or near zero crossing, the breaker is allowed to open only if the actual slope of the current di/dt is lower than the slope calculated using (8), that is:

$$\left.\frac{di}{dt}\right|_{t=t_s} \le SL(t_s) \tag{9}$$

2.4. Prestrike/restrike conditions

When simulating breaker operation (opening or closing), at each time $t \in [t_0, t_0 + T_C]$ (t_0 is the instant at which breaker operation is initiated), the computed value of $v_w(t)$ is compared to $v(t)$, the measured voltage across the breaker contacts to decide whether the breaker should be opened or closed in the simulation software. If the breaker is opened, the closing condition is given by

$$v_w(t) \le v(t) \tag{10}$$

If the breaker is closed, the opening condition is given by (11), (1) and (9) that should all be true:

$$v_w(t) > v(t) \tag{11}$$

Therefore, the prestrike condition is as follows: during breaker closing, if $v_w(t)$ calculated using (2) or (4) satisfies (10), the breaker is effectively closed in the model. After closing, if at any subsequent instant $t < t_0 + T_C$, (11), (1) and (9) are all satisfied, the breaker is effectively opened in the model. Similarly, the restrike condition is as follows: during breaker opening, if $v_w(t)$ calculated using (3) or (5) satisfies (10), the breaker is effectively closed in the model. After closing, if at any subsequent instant $t < t_0 + T_C$, (11), (1) and (9) are all satisfied, the breaker is effectively opened in the model. It is worth pointing out that when the breaker is closed in the model, $v(t)$ becomes exactly 0 if the arc resistance is not modeled. Also, prestrike or restrike could occur several times in the interval $[t_0, t_0 + T_C]$. Prestrike/restrike conditions described above are illustrated in the flowchart of Fig. 1.

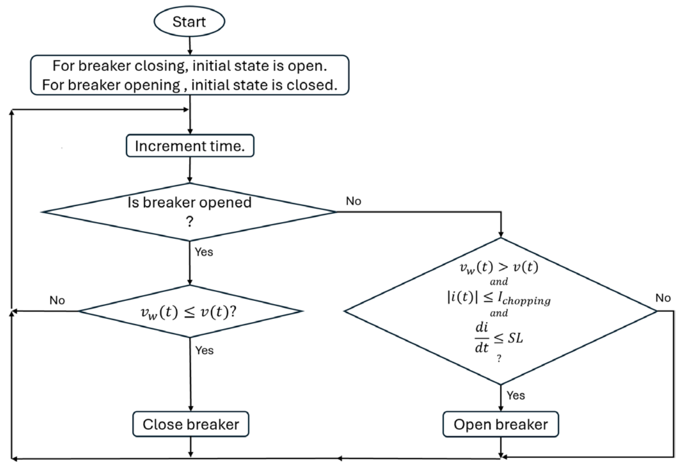

Fig. 1. Prestrike/restrike modeling during breaker operation.

3. PROPOSED BREAKER MODEL

3.1. Overview

This section proposes a new and more realistic formulation of breaker contact withstand voltage, which is also relatively easy to implement. As stated above, the conventional breaker representation presented in section II assumes a linear dependency of dielectric strength and distance between contacts. In some models, the dependency of dielectric strength with time is quadratic [5] whereas in other models, this dependency is linear [8],[12],[13]. In either case, the model is not realistic enough because it implies that the dependency of distance between contacts with time is either quadratic (for models such as the one in [5]) or linear (for models such as the ones in [8],[12],[13]). In fact, the dependency of distance between contacts with time is a sequential mix of quadratic and linear behavior. This paper proposes to decompose the speed of the moving contact of a breaker during opening or closing into 3 zones, as illustrated in Fig. 2.

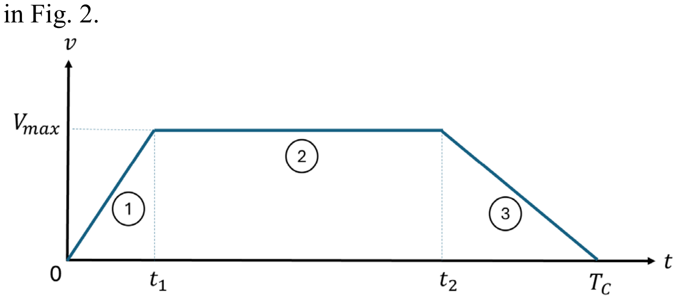

Fig. 2. Variation of the speed of the moving contact during breaker operation.

In zone 1, the speed moves from 0 to its maximum value $V_{\max}$ reached at instant t_1. In zone 2, the speed keeps its maximum value until time t_2. In zone 3, the speed decreases from $V_{\max}$ to 0. The proposed new model is based on this realistic behavior of the speed of the moving contact during breaker operation. The theoretical foundation behind this more realistic behavior comes from the fact that physically speaking, to move from a state of rest at point A to another state of rest at point B (this is the movement of the circuit breaker contact during opening or closing), it is more realistic to assume that the movement between A and B is made up of a phase of acceleration, followed by a phase of constant speed, and finally followed by a phase of deceleration, rather than to assume that the movement is made up of a phase of acceleration only or a phase of constant speed only (as the traditional models presented in [5], and [8],[12],[13] do assume).

3.2. Mathematical formulation

The curve in Fig. 2 allows to formulate the equation of the velocity (speed) $v(t)$ of the moving contact in each zone:

$$v(t)=\begin{cases} v_1(t)=\dfrac{V_{\max}}{t_1}t, \ for\, t<t_1 \\ v_2(t)=V_{\max}, \ for\, t_1\le t<t_2 \\ v_3(t)=-\dfrac{V_{\max}}{T_C-t_2}\left(t-T_C\right), \ for\, t_2\le t\le T_C \end{cases} \tag{12}$$

Then, (12) is used to derive in each zone, the expression of $d(t)$, the gap length between breaker contacts with respect to time t elapsed since the beginning of breaker operation:

$$d(t)=s\int_{t_i}^{t}v(u)\,d(u)+D_i \tag{13}$$

where t_i and D_i are respectively the initial time and gap length values, $s=1$ for breaker opening and $s=-1$ for breaker closing.

Finally, the expression of the breaker withstand voltage $v_w(t)$ is determined, assuming a linear dependency between withstand voltage and gap length:

$$v_w(t)=K\,d(t) \tag{14}$$

where K is a constant.

The gap length in zone 1 is calculated using (13) in which v is expressed by $v_1(t)$ from (12) and $t_i=0$. This gives:

$$d_1(t)=s\int_0^t\frac{V_{\max}}{t_1}u\;d(u)+D_{i1}=\frac{s}{2}\frac{V_{\max}}{t_1}t^2+D_{i1} \tag{15}$$

For breaker opening, $s=1$, $D_i=0$ and (15) becomes:

$$d_1(t)=\frac{1}{2}\frac{V_{\max}}{t_1}t^2 \tag{16}$$

For breaker closing, $s=1$, $D_i=D_C$ (the maximum gap length between contacts when breaker is fully opened); (15) becomes:

$$d_1(t)=-\frac{1}{2}\frac{V_{\max}}{t_1}t^2+D_C \tag{17}$$

The gap length in zone 2 ($t_i=t_1$) is given by:

$$d_2(t)=s\int_{t_1}^{t}V_{\max}d(u)+D_{i2}=sV_{\max}\left(t-t_1\right)+D_{i2} \tag{18}$$

where $D_{i2}=d_1(t_1)$, calculated using (16) or (17). For breaker opening, (18) becomes:

$$d_2(t)=V_{\max}\left(t-\frac{1}{2}t_1\right) \tag{19}$$

For breaker closing, (18) becomes:

$$d_2(t)=-V_{\max}\left(t-\frac{1}{2}t_1\right)+D_C \tag{20}$$

The gap length in zone 3 ($t_i = t_2$) is given by:

$$d_3(t) = s\int_{t_2}^{t} -\frac{V_{max}}{T_C - t_2}\left(u - T_C\right)d(u) + D_i = -\frac{sV_{max}}{T_C - t_2}\left(t - t_2\right)\left[\frac{1}{2}\left(t + t_2\right) - T_C\right] + D_{i3} \quad (21)$$

where $D_{i3} = d_2(t_2)$, calculated using (19) or (20). For breaker opening, (21) becomes:

$$d_3(t) = V_{max}\left\{-\frac{t - t_2}{T_C - t_2}\left(\frac{1}{2}\left(t + t_2\right) - T_C\right) + \left(t_2 - \frac{1}{2}t_1\right)\right\} \quad (22)$$

For breaker closing, (21) becomes:

$$d_3(t) = V_{max}\left\{\frac{t - t_2}{T_C - t_2}\left[\frac{1}{2}\left(t + t_2\right) - T_C\right] - \left(t_2 - \frac{1}{2}t_1\right)\right\} + D_C \quad (23)$$

In the proposed formulation, V_{max} should be determined so that the total breaker operation time remains equal to T_C. The total distance traveled by the moving contact should be equal to D_C . This means the following: for breaker opening, $d_3(T_C) = D_C$ using (22); for breaker closing, $d_3(T_C) = 0$ using (23). The result is the same in both cases:

$$D_C = V_{max}\left[\frac{1}{2}T_C + \frac{1}{2}t_2 - \frac{1}{2}t_1\right] \quad (24)$$

Let α and β be defined such that:

$$t_1 = \alpha T_C \text{ and } t_2 = \beta T_C \quad (25)$$

Using (25), (24) can be rewritten as follows:

$$\frac{D_C}{T_C} = V_{max}\left[\frac{1 + \beta - \alpha}{2}\right] \quad (26)$$

Let $V_C = D_C / T_C$, the constant speed of the moving contact in the conventional breaker model, and let γ :

$$\gamma = \left(1 + \beta - \alpha\right)/2 \quad (27)$$

Equation (26) could be rewritten as:

$$V_{max} = \left(1/\gamma\right)V_C \quad (28)$$

Equation (28) reveals how V_{max} is obtained in the proposed formulation. Coefficients α and β defined in (25) represent new parameters in the proposed breaker model.

Now, the dielectric strength during breaker operation can be derived using (14). The coefficient K is determined as follows: when the breaker is fully opened, $v_w = U_C$ and $d(t) = D_C$. This gives:

$$K = \frac{U_C}{D_C} \quad (29)$$

The dielectric strength in zone 1, calculated with (14), and using (29), (16), (17), (25) and (28) gives:

$$v_{w1}(t) = A_1 t^2 + B_1 \quad (30)$$

for breaker opening

$$A_1 = \frac{U_C}{2T_C^2\gamma\alpha},\ B_1 = 0 \quad (31)$$

for breaker closing

$$A_1 = -\frac{U_C}{2T_C^2\gamma\alpha},\ B_1 = U_C \quad (32)$$

The dielectric strength in zone 2, calculated with (14), and using (29), (19), (20), (25) and (28) gives:

$$v_{w2}(t) = A_2 t + B_2 \quad (33)$$

for breaker opening

$$A_2 = \frac{U_C}{\gamma T_C}, B_2 = -\frac{1}{2}\frac{\alpha}{\gamma}U_C \quad (34)$$

for breaker closing

$$A_2 = -\frac{U_C}{\gamma T_C}, B_2 = U_C\left(1 + \frac{1}{2}\frac{\alpha}{\gamma}\right) \quad (35)$$

The dielectric strength in zone 3, calculated with (14), and using (29), (22), (23), (25) and (28) gives:

$$v_{w3}(t) = A_3 t^2 + B_3 t + C_3 \quad (36)$$

For breaker opening:

$$A_3 = -\frac{U_C}{2\gamma T_C^2(1-\beta)}, B_3 = \frac{U_C}{\gamma T_C(1-\beta)}, \quad C_3 = \frac{U_C}{\gamma}\left[\frac{\beta\left(\frac{1}{2}\beta - 1\right)}{1-\beta} + \beta - \frac{1}{2}\alpha\right] \quad (37)$$

For breaker closing:

$$A_3 = \frac{U_C}{2\gamma T_C^2(1-\beta)}, B_3 = -\frac{U_C}{\gamma T_C(1-\beta)}, \quad C_3 = U_C\left[-\frac{1}{\gamma}\left(\frac{\beta\left(\frac{1}{2}\beta - 1\right)}{1-\beta} + \beta - \frac{1}{2}\alpha\right) + 1\right] \quad (38)$$

Equations (30) to (38) represent the proposed formulation for the withstand voltage in each zone when the breaker operates.

3.3. Model evaluation

The proposed formulation for the breaker model is a generalization of the conventional formulation presented in section II, with the addition of 2 new parameters. The new parameters α and β allow to account for the nonlinear movement of the contacts of the breaker during operation. For instance, for $\alpha = 0$ and $\beta = 1$ (only zone 2 in Fig. 2 exists), (27) yields $\gamma = 1$. In such case, (33) matches (5) and (4) for breaker opening (using (34)), and for breaker closing (using (35)) respectively. For recall, (5) and (4) represent the conventional breaker model which assumes that the breaker contacts operate according to a t law. Also, for $\alpha = 1$ and $\beta = 1$ (only zone 1 in Fig. 2 exists), (27) yields $\gamma = 1/2$. In such case, (30) matches (3) and (2) for breaker opening (using (31)), and for breaker closing (using (32)) respectively. For recall, (3) and (2) represent the breaker model which assumes that the breaker contacts operate according to a t^2 law.

The values of α and β are to be defined by the user. α should be very small as in breaker operation, the initial acceleration of the moving contact is very high due to the instantaneous release of the mechanical energy stored in the springs. β should be higher than 0.5 as it is reasonable to assume that the speed begins to decrease after reaching the half-opening time. In the equations of the travel curve presented in [2], it is observed that the speed deceleration occurs at roughly 60% of the total operation time. For these reasons, the following settings are recommended:

$$\alpha = 0.01 \ \ and \ \ \beta = 0.6 \tag{39}$$

The most accurate possible values of α and β for a given breaker can be obtained using the breaker travel curve. This curve shows the relationship between gap distance and time during breaker operation. The travel curve can be obtained experimentally by high-speed camera recordings during breaker operation.

The impacts of the proposed breaker model in transient simulation of prestrike/restrike can be predicted using Fig. 3 and Fig. 4. These figures illustrate the differences in withstand voltages between a breaker modeled using the conventional equation (4) and (5), and a breaker modeled using the proposed representation from (30) to (38). Fig. 3 and Fig. 4 are drawn for theoretical illustration, using $U_C = 1\text{V}$, $T_C = 6\,ms$, and (39).

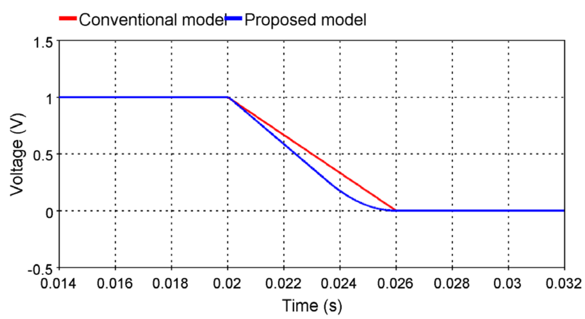

Fig. 3. Variation of the withstand voltage of the gap during breaker closing, for the conventional model and for the proposed model.

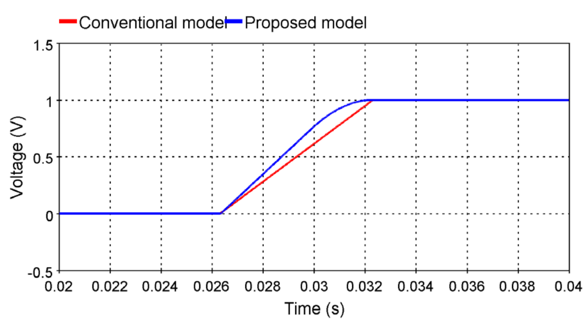

Fig. 4. Variation of the withstand voltage of the gap during breaker opening, for the conventional model and for the proposed model.

Fig. 3 (breaker closing) shows that the curve of the proposed model is beneath the curve of the conventional model. This means that with the new and more realistic model, prestrike will occur sooner than expected from the conventional model. This will have an impact on peak overvoltage measured in the energized circuit, as will be seen later.

Fig. 4 (breaker opening) shows that the curve of the proposed model is above the curve of the conventional model. This means that with the new and more realistic model, restrike is less likely to happen, compared to what would be expected from the conventional model.

Fig. 3 and Fig. 4 reveal that software using the conventional model would fail to reproduce the physical behavior of the breaker faithfully. This will be demonstrated in the next section.

4. DEMONSTRATION EXAMPLES

4.1. Circuit description

The circuit of Fig. 5 is used to demonstrate the effect of the proposed breaker model. This circuit is often used in literature to study prestrike/restrike. Some variants are found in [2], [9], [10] and [12]. Two versions of the breaker device brk1 will be used for simulations: the conventional model built from (4) and (5), and the proposed new model built from (30) to (38). In both cases, it is assumed that $U_C = 23\,kV$, $T_C = 6\,ms$. The proposed model uses the recommended settings defined in (39).

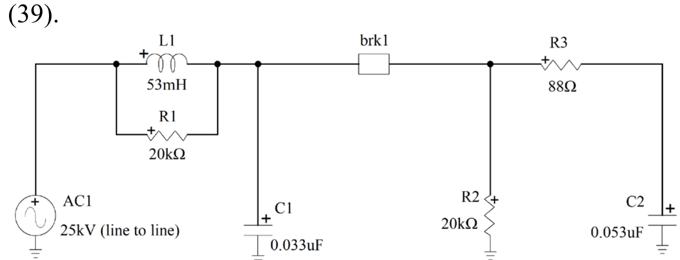

Fig. 5. Testing circuit for prestrike/restrike.

4.2. Example 1: prestrike

In this example, the breaker (initially opened) is closed at 20ms. Two simulations are performed, using the conventional and the proposed breaker model respectively. Results are shown in Fig. 6 and Fig. 7 (only phase a is represented).

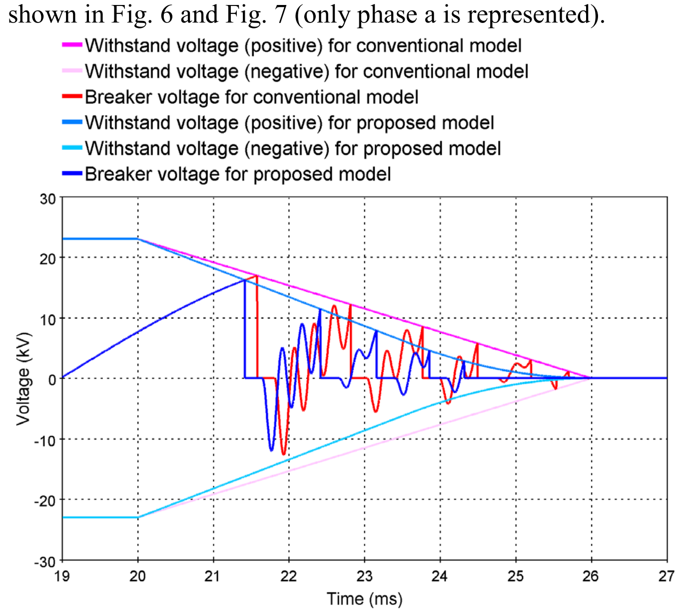

Fig. 6. Voltage across breaker contacts and withstand voltages during breaker closing.

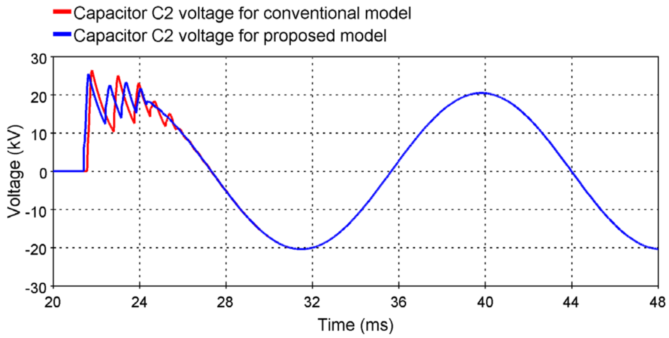

Fig. 7. Voltage across capacitor C2 during breaker closing.

The voltage waveforms across breaker contacts while closing are similar for both models. However, prestrike events do not occur at the same time instants. As shown in Fig. 6, with the conventional model, the first prestrike occurs at $t = 21.58ms$ whereas with the proposed model, it occurs sooner, at $t = 21.42ms$. This phenomenon of varying prestrike moments was forecasted in the explanations given at the end of the section 3.3, which were based on the analysis of Fig. 3. Furthermore, it seems logical to consider that the proposed model better reflects the actual operation process of the circuit breaker because the proposed model assumes a more realistic movement of contact during breaker operation. The difference in prestrike moments has an impact on the peak voltage on energized components such as capacitor C2. As shown in Fig. 7, with the conventional model, the peak voltage is $V_{peak} = 26.44kV$ whereas with the proposed model, the peak voltage is $V_{peak} = 25.49kV$. To better evaluate the difference between the two models, statistical simulations (500 runs) are conducted. The breaker closes according to Gaussian law with a mean value of 20ms and standard deviation of 1.5ms. Results are summarized in TABLE I.

TABLE I
STATISTICAL DISTRIBUTION OF THE PEAK VALUE OF THE VOLTAGE ACROSS CAPACITOR C2 FOR THE CONVENTIONAL AND THE PROPOSED MODELS.

Statistical result	Conventional model	Proposed model
Maximum voltage (kV)	30.822	30.822
Standard deviation (kV)	2.590	2.778
Mean voltage (kV)	28.518	28.480
Median voltage (kV)	29.601	29.687

TABLE I shows that the maximum statistical voltage is the same for both models. TABLE I also reveals that the statistical distribution (expressed by the standard deviation, the mean voltage and the median voltage) is not the same for both models. The statistical distribution of overvoltages is very important as it may have an impact on the outcome of some power system studies. An example of such studies is insulation coordination [17].

The results presented above demonstrate the need to use a more realistic breaker model for more accurate results.

4.3. Example 2: restrike

This example uses the circuit of Fig. 5 to simulate the voltage across breaker contacts during breaker opening. The breaker (initially closed) receives an opening order at 20ms. The chopping current is set to 0A. Two simulations are performed, using the conventional and the proposed breaker model respectively. Results are shown in Fig. 8 (only phase a is represented).

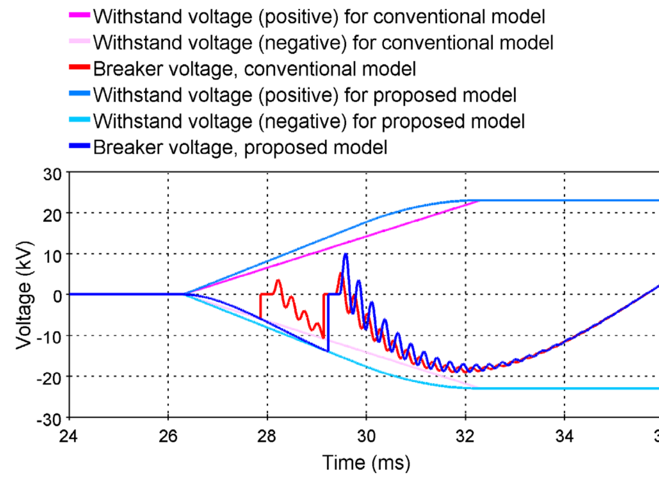

Fig. 8. Voltage across breaker contacts and breaker withstand voltages during breaker opening.

It is observed that the number of restrikes is not the same for both models. In the simulation result obtained using the conventional breaker model, 2 restrikes are observed, at $t = 27.87ms$ and $t = 29.14ms$, respectively. In contrast, in the simulation result obtained using the proposed breaker model, only one restrike is observed, at $t = 29.23ms$. This phenomenon of varying restrike moments was forecasted in the explanations given at the end of the section 3.3, which were based on the analysis of Fig. 3. Furthermore, it seems logical to consider that the proposed model better reflects the actual operation process of the circuit breaker because the proposed model assumes a more realistic movement of contact during breaker operation.

The prestrike and restrike cases presented in this part have revealed that the conventional breaker model may fail to represent the breaker's behavior during opening faithfully.

5. CONCLUSIONS

This paper presented a new breaker model for studying prestrike and restrike. The proposed model is more realistic than available conventional breaker models. This is because it considers the nonlinear displacement of the moving contact during breaker opening or closing. The mathematical formulation of the new model introduces two new parameters that the user could freely vary to mimic different nonlinear behaviors of breaker contacts. This model is relatively easy to implement and does not require complex additional data. Demonstration examples have shown differences between the conventional breaker model and the proposed model. It was observed that the conventional breaker model may fail to faithfully represent the behavior of the breaker during operation. Future works could include experimental validation of this observation. This task could not be accomplished in this paper due to the large number of resources required to conduct experiments.

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