Influence of extended grading capacitor for suppressing secondary arc on the transient recovery voltage of multi-break circuit breaker

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Funding information
National Natural Science Foundation of China, Grant/Award Number: 52077068; Hunan Natural Science Foundation, Grant/Award Number: S2019JJQNJJ0386

Abstract
The extended grading capacitor (EGC) is a cost-effective technique to suppress secondary arc. However, whether the use of EGC would weaken the interrupting capability of circuit breakers (CB) or not is still undetermined. In this work, an equivalent circuit model for ultra-high voltage transmission line was established. The expressions of transient recovery voltage (TRV) across the contact gap of CB are derived, and hence the rate of rise of recovery voltage (RRRV). Then, a series of simulations have been performed, including the long-line fault, the short-line fault (SLF) and the terminal fault. It is found that the RRRV had approximately linear downward trend with the increase of the capacitance of EGC under long-line fault but had approximately index downward trend under SLF. The SLF poses the strictest requirements to the CB. In addition to suppressing secondary arc current, the use of EGC would mitigate the interrupting severity and enhancing the interrupting performance of CB.

1 | INTRODUCTION

Single-phase trip and autoreclosure (SPAR) can not only improve the transient stability and reliability of power system, but also reduce the switching overvoltages and shaft torsional oscillation of large thermal units [1]. As most faults on transmission lines are single-phase to ground type, the SPAR scheme is widely used in UHV power system. Since the rated voltage of UHV line is extremely high, and the line length is hundreds of kilometres. The coupling effect is very severe; the secondary current which is caused by the capacitive and inductive couplings among the healthy and faulted phases is very large and the arc is difficult to be self-extinguished. However, the reclosing time is often set about 1 s in order to guarantee the transient stability of power system. It contains the relay action time, the opening and closing times of CBs etc. The main risk lies to the secondary arc extinction time. The reliable extinction of secondary arc is a crucial challenge for UHV power system and plays a role in SPAR [2]. Otherwise, the CB may be reclosed on ground fault, aggravating the severe damage to the associated expensive equipment and even give rise to the unsynchronism of power system [3–4]. The investigation on the mechanism and physics of secondary arc is of great significance.

The secondary arc current and the recovery voltage are the vitally important factors which determine the extinction time. The existing suppressing methods for secondary arc are mainly directed towards minimizing their magnitudes [5]. The methods include the four-reactor bank, the modified four-reactor bank with neutral switch and high-side reactor switches, the high-speed grounding switches, the hybrid single-phase trip scheme etc [1]. However, the neutral end of phase reactor must have a high insulation, and it may not work on closely coupled parallel lines for the four-reactor bank due to the possibility of resonance; the modified reactor bank costs high and requires a complex protection and control strategy; the hybrid single-phase trip scheme cannot be used where the phase is needed to maintain synchronism between the system and the remote generating plant. In practice, the double-break structure is commonly used for CB [6, 7]. Compared with single-break type, its contact is divided into two gaps. As a result, the risk of insulation breakdown is considerably minimized, without increasing the operating energy substantially. A capacitor is connected in parallel with each unit to ensure the uniform recovery voltage distribution [8]. The capacitor can be used to suppress secondary arc by increasing the capacitance only, forming the so-called EGC. Its use can completely neutralize the capacitive coupling effect
between faulted and un-faulted phases. It is simple, flexible and almost free of the shunt reactor installation [9]. This method can be also applied to existing EHV lines to address the secondary arc issue.

The integration of EGC alters the topology of the system. Presently, the influence of normal grading capacitor on the electromagnetic transients of power system has been extensively discussed [10, 11]. A ferroresonance involving an inductive voltage transformer and CB grading capacitor in a 400 kV substation is investigated; the field test results are compared and validated through EMTP simulation [12]; the grading capacitor interacts with the residual magnetic flux of transformer core when the equipments form a loop; its presence affects the charging process of transformer during the CB operation and can easily excite some special inrush current [13]; a number of accidents and insulation defects on grading capacitor body have been reported, including the breakdown, the explosion and the perforation; the measurement method for the dielectric loss of grading capacitor is also studied.

Generally, the interrupting capability of CB depends on both the dielectric strength and the TRV across the contacts [14]. The former rises in the subsequent two or three cycles after the current crosses zero; on the other hand, the latter have a quick and oscillating growth. A diversity of 3D finite element models combined with detailed Navier–Stokes equations for double and triple-break chamber, either horizontal or U-shaped arrangement, have been established so far [15, 16]. Meanwhile, the breaking capability is estimated by means of arc model, the parameters of which are determined through current zero measurement. Koenig et al. investigated the impact of normal grading capacitor on voltage regulation and further improvement of the performance [17, 18]. Considerable tests with simultaneous opening of two tube contacts are performed [19]; however, the efforts are mainly devoted to vacuum CB type. The capacitance of EGC is far larger than normal one. The installation of EGC can directly change the electromagnetic transient. More importantly, the TRV as well as the RRRV have not been quantitatively valued; whether the use of EGC will weaken the interrupting capability or not is still undetermined, and that is the main concern of our work.

2 PRINCIPLE OF EGC FOR SUPPRESSING SECONDARY ARC

2.1 Equivalent circuit for CB with EGC

To multiply the interrupting strength, most of UHV circuit breaker employs the double-break structure, as depicted in Figure 1(a). The comparison of EGC with the four-reactor bank scheme is illustrated in Figure 1(b) [20]. Clearly, the EGC is flexible and almost free of the installation mode of shunt reactor. The reactor can be installed either on busbar or line terminal. If the shunt reactor is installed on busbar, it can be shared by a number of lines, and it would cost much less. The EGC can replace the neutral reactor, and does not require special protection. Since the capacitor can completely neutralize the capacitive coupling effect between faulted and un-faulted phases, the suppressing performance is superior to traditional methods; its performance is also less impact by fault location and line length. The use of EGC can also enhance the transient stability to some extent.

Under normal condition, the interrupters K1 and K2 are kept closed, and the EGC has little influence on the power system. Supposing a single-phase-to ground (1LG) fault takes place on phase A, as illustrated in Figure 2(a), the CB would operate. Then, the EGC will be inserted into the system [20]. The sound phases B and C can contribute a current, denoted as \( I_1 \), through the electrostatic coupling between phases. Meanwhile, the fault phase A would inject a current into the fault point, denoted as \( I_0 \). Since the EGC is capacitive, as depicted in the phasor diagram, \( I_1 \) lags \( E_A \) by 90°; on the contrary, \( I_2 \) leads \( E_A \) by 90°. The presence of EGC can compensate the coupling current \( I_2 \). According to Kirchhoff’s voltage law [21],

\[
\begin{align*}
I_0 Z_0 + I_2 Z_2 &= E_A \\
I_1 Z_1 + I_2 Z_2 &= -0.5E_A \\
I_0 + I_1 &= I_2 \\
I_2 Z_2 &= I_4 R_{\text{arc}}
\end{align*}
\]
FIGURE 2  Equivalent circuit model for UHV line with EGC. (a) Original circuit. (b) Simplified circuit for secondary arc current and recovery voltage. (c) Phasor diagram. $C_1$ and $C_0$ represent the positive-sequence and zero-sequence line capacitance, respectively; $I_p$ represents the shunt reactor; $I_f$ and $U_r$ are the secondary arc current and recovery voltage, respectively

\[
\begin{align*}
Z_0 &= \frac{1}{j\omega C_0} \\
Z_1 &= \frac{3}{2j\omega(C_1-C_0)} \\
Z_2 &= \frac{j\omega R_{arc}I_p}{j\omega L_p + R_{arc}(1-\omega^2C_0L_p)} \\
I_f &= \frac{C_1 - C_0}{3}
\end{align*}
\]

Then, $I_f, U_r \approx 0$

The total secondary arc current and recovery voltage would be minimized to zero.

TABLE 1  Standard value for TRV of 1100 kV UHV CB

| Test mode | Interrupting current | Peak value of TRV (MV) | RRRV (kV/µs) |
|-----------|----------------------|------------------------|---------------|
| T100      | $I_R$                | 1.635                  | 2.0           |
| T60       | 0.6 $I_R$            | 1.751                  | 3.0           |
| T30       | 0.3 $I_R$            | 1.786                  | 5.0           |
| T10       | 0.1 $I_R$            | 1.786                  | 10.0          |
| OP1-OP2   | 0.125 $I_R$          | 2.5                    | 1.54          |

Note T100-T10 represents the interrupting current ranging from 100% to 10% rating; OP1 and OP2 represent out-of-phase interruptions; $I_R$ is the rated interrupting current.

FIGURE 3  Simulation model. $I_s, R_s, C_s$ are the source inductance, resistance and capacitance, respectively; $L_1, C_1$ are the line inductance and capacitance per-unit line, respectively; $x$ is the distance between the fault point and the line terminal

2.2  Standards for CB

The TRV and RRRV are the key parameters to evaluate the interrupting performance of CB, and the rated value for 1100 kV CB are stated in IEC 62271-100 [22, 23]. Under normal condition, it is generally determined by the first peak value of TRV. Due to the relatively slow recovery of dielectric strength when the arc current crosses zero, the RRRV also governs the interrupting burden. By means of the four-parameter method, the standard values for the UHV CB are listed in Table 1.

3  METHODOLOGY

In order to determine the influence of EGC on the interrupting performances of CB, the TRV and RRRV across CB are computed. The equivalent circuit diagram is depicted in Figure 3. Since the line resistance is far less than the reactance, it is ignored in this work to facilitate the analysis.

3.1  CB without EGC

In the event of ILG long line fault, the equivalent circuit diagram is illustrated in Figure 3 [24].
The steady-state value of fault current is [24]

\[ I_s = \frac{E}{\sqrt{R_i^2 + (\omega L_i + \omega L_A x)^2}} \]  

(5)

where \( \omega \) is the angle frequency of power source. Before the extinction of switching arc \( (t = 0^+) \), \( u_A \) and \( u_B \) are equal; at the arc extinction moment \( (t = 0^-) \), \( u_A \) and \( u_B \) reach their peak values, \n
\[ U_A = U_B = \frac{E_m\omega L_A x}{\sqrt{R_i^2 + (\omega L_i + \omega L_A x)^2}} \]  

(6)

When the fault current passes zero \( (t = 0^+) \), the circuit diagram can be divided into two individual parts, as illustrated in Figure 4.

The equivalent circuit for voltage \( u_A \) is depicted in Figure 4(a); the voltage \( u_B \) can be derived based on travelling wave theory, among which the initial voltage distribution in line BO section is depicted in Figure 4(b). The TRV across CB is

\[ u_{tr} = u_{AB} = u_A - u_B \]  

(7)

Here, \( u_A \) can be determined by the following equations

\[ L_i C_i \frac{d^2 u_A}{dt^2} + R_i C_i \frac{du_A}{dt} + u_A = E_0 \]  

(8)

As the TRV is very short, the power source voltage can be regarded as a constant during this stage, i.e. \( E_0 = E_m \sin \varphi \), where \( \varphi \) is the power angle determined by \( L_i, R_i \) and \( C_i \). Equation (8) can be solved

\[ u_A = E_0 \left[ 1 - e^{-\delta t} \left( a \cos \omega_1 t + b \sin \omega_1 t \right) \right] \]  

(9)

Applying the initial conditions: \( u_A = U_{Am} \) and \( i_A = 0 \) when \( t = 0 \), \( a \) and \( b \) are obtained, and the equation can be rewritten as

\[ u_A = E_0 \left\{ 1 - e^{-\delta t} \left[ \left( 1 - \frac{U_{Am}}{E_0} \right) \cos \omega_1 t + \frac{\delta}{\omega_1} \left( 1 - \frac{U_{Am}}{E_0} \right) \sin \omega_1 t \right] \right\} \]  

(10)

where \( \delta \) is very small,

\[ \omega_1' \approx \omega_1, e^{-\delta t} \approx 1 \]  

(11)

And,

\[ u_A = E_m \sin \varphi - E_m \left( 1 - \frac{U_{Am}}{E_m} \right) \sin \varphi \cos \omega_1 t \]  

(12)

Usually, the power factor \( \varphi \) tends to be low for short circuit faults, \( \cos \varphi < 0.15, \sin \varphi \approx 1, \varphi \approx \pi/2 \). We have

\[ u_A = E_m - (E_m - U_{Am}) \cos \omega_1 t \]  

(13)

Regarding \( u_B \), it is the sum of two travelling waves, i.e. a forward wave \( u_{B1} \) and a reverse wave \( u_{B2} \), as illustrated in Figure 5. It can be easily derived that \( u_{B1} = u_{B2} = \sqrt{2L_i \omega L_A x} / 2 \), \( u_B = u_{B1} + u_{B2} = \sqrt{2L_i \omega L_A x} \), respectively. The propagation velocity of travelling wave is given by \( v = 1/\sqrt{L_i C_i} \), and the time required to propagate from B to O is \( x/v \). The evolution of travelling wave along line BO is illustrated in Figure 5 [25].

\[ u_{B1} = \beta u_{B1} \]  

(14)

where \( \beta \) refers to the reflection coefficient.
At \( t = \pi / \nu \), the travelling wave would pass to the fault point. Here, \( \beta = -1 \). The reflection voltage \( a_{B2} = -a_{B1} \), and \( a_{B} = a_{B1} + a_{B2} = 0 \). As the travelling wave passes to point B, \( \beta = 1 \), and \( a_{B} = 2a_{B2} = 2a_{B1} \). The expression of \( a_{B} \) is determined, as presented in Equation (17)

\[
\begin{align*}
  a_{B} = U_{Bn} (1 - \nu / \pi) & = \sqrt{2} j \omega L_s x (1 - \nu / \pi), 0 \leq t \leq 2 \nu / \pi \\
  a_{B} = U_{Bn} (3 - \nu / \pi) & = - \sqrt{2} j \omega L_s x (3 - \nu / \pi), 2 \nu / \pi \leq t \leq 4 \nu / \pi \\
  a_{B} = U_{Bn} (5 - \nu / \pi) & = \sqrt{2} j \omega L_s x (5 - \nu / \pi), 4 \nu / \pi \leq t \leq 6 \nu / \pi
\end{align*}
\]

(17)

Clearly, \( a_{B} \) has an oscillating sawtooth waveform, the frequency of which is \( \nu / 4x_s \), as depicted in Figure 6(b). Substituting Equation (15) and (17) into (7), the TRV can be obtained

\[
\begin{align*}
  a_{B} = E_{m} - (E_{m} - U_{Am}) \cos \omega t \quad & a_{B} = U_{Bn} (1 - \nu / \pi), 0 \leq t \leq 2 \nu / \pi \\
  a_{B} = E_{m} - (E_{m} - U_{Am}) \cos \omega t \quad & a_{B} = U_{Bn} (3 - \nu / \pi), 2 \nu / \pi \leq t \leq 4 \nu / \pi \\
  a_{B} = E_{m} - (E_{m} - U_{Am}) \cos \omega t \quad & a_{B} = U_{Bn} (5 - \nu / \pi), 4 \nu / \pi \leq t \leq 6 \nu / \pi
\end{align*}
\]

(18)

Initially, when the fault current passes zero, the TRV rises rapidly, and then drops slowly; on the contrary, the dielectric strength across the fault point develops slowly at the early stage but approximately has an exponential growth trend at the later stage. Consider the maximum value of RRRV and TRV in the period of \( 0 \leq t \leq 2 \nu / \pi \). Regarding the oscillation period of \( a_{B} \), represented as \( T_1 \), since \( 2 \nu / \pi < T_1 < 2 \pi \sqrt{L_s C_s} \), \( a_{B} \) also changes slowly, so the RRRV across CB is expressed in Equation (19)

\[
\begin{align*}
  \text{RRRV} = \frac{\omega}{E_{m}} - \frac{d}{dt} & \left[ E_{m} - (E_{m} - U_{Am}) \cos \omega t - U_{Bn} (1 - \nu / \pi) \right] \\
  = \omega (E_{m} - U_{Am}) \sin \omega t + \frac{U_{Bn}}{L_1} & = \sqrt{2} j \omega L_s x \\
  = \sqrt{2} j L_s \omega = E_{m} / \sqrt{R_1^2 + (\omega L_s + \omega L_A x)^2}
\end{align*}
\]

(19)

where \( Z \) is the line wave impedance which is equal to \( \sqrt{L_1 / C_1} \). The maximum value of TRV occurs at the instant of \( t = 2 \nu / \pi \) as the value of RRRV is larger than zero. Since the period \( 2 \nu / \pi \) is short, the value of \( \cos \omega t \) is approximately equal to 1. Consequently, the maximum value of TRV at \( 0 \leq t \leq 2 \nu \) can be obtained as follows

\[
U_{B\text{max}} = 2U_{Am} = 2U_{Bn} = 2 \sqrt{2} j \omega L_s x
\]

(20)

**3.2 CB with EGC**

Using EGC, the capacitor is automatically connected to the system when 1 LG fault happens, and the equivalent circuit model is depicted in Figure 7(a). The initial charge for \( C_s \) can be computed by Equation (6) and (15). It is equal to \( \sqrt{2} j \omega L_s x \), and it can be represented by a DC source. Due to the short interval at this period, the rate of change of the initial electric potential on the line side, which is equal to \( \sqrt{2} j \omega L_s x \), according to Equation (17), is remarkably high. Consequently, the power source inductor \( L_1 \) would exhibit a great impedance to the wave, which can be regarded as an open circuit. Figure 7(a) can be simplified into Figure 7(b). According to Kirchhoff’s voltage law,

\[
\frac{1}{C_s} \int i dt + \frac{1}{C_G} \int i dt + iz = \sqrt{2} j \omega L_{A} x t
\]

(21)

Applying the time differentiation on both sides of above equation, and substituting \( L_s x = Z \) into Equation (21),

\[
\frac{Z C_s C_G}{C_s + C_G} \frac{di}{dt} + i = \sqrt{2} j \omega Z C_s C_G
\]

(22)

The current can be obtained,

\[
i = i' + i''
\]

(23)

where \( i' = \frac{C_s + C_G}{Z C_s C_G} \), \( i'' = \frac{\sqrt{2} j \omega Z C_s C_G}{C_s + C_G} \).

When \( t = 0, i = 0 \). It can be easily derived \( a = \frac{\sqrt{2} j \omega Z C_s C_G}{C_s + C_G} \).

Hence,

\[
i = \frac{\sqrt{2} j \omega Z C_s C_G}{C_s + C_G} \left[ 1 - e^{-\frac{t}{C_s}} \left( \frac{1}{C_s} + \frac{C_G}{C_s + C_G} \right) \right]
\]

(24)

\[
\sqrt{2} j \omega L_{A} x (1 - \nu / \pi)
\]
The TRV across CB can be expressed as

\[ u_{tr} = \frac{1}{C_G} \int i dt + b \]

\[ = \frac{1}{C_G} \left\{ \int_0^{t_{max}} \sqrt{2k_0} Z C_G \left[ 1 - e^{-\frac{1}{2} \left( \frac{1}{C_G} + \frac{1}{C_S} \right)} \right] dt \right\} + b \]  

(25)

\[ = \frac{\sqrt{2k_0} Z C_S}{C_S + C_G} \left[ t + \frac{Z C_G C_S}{C_S + C_G} - \frac{Z C_S C_G}{C_S + C_G} e^{-\frac{1}{2} \left( \frac{1}{C_G} + \frac{1}{C_S} \right)} \right] + b \]  

(26)

Applying the initial condition: \( t = 0, u_{tr} = 0, \)

\[ b = -\frac{\sqrt{2k_0} Z^2 C_G^2}{(C_S + C_G)^2} \]

Thus,

\[ u_{tr} = \frac{\sqrt{2k_0} Z C_S}{C_S + C_G} \left[ t + \frac{Z C_G C_S}{C_S + C_G} - \frac{Z C_S C_G}{C_S + C_G} e^{-\frac{1}{2} \left( \frac{1}{C_G} + \frac{1}{C_S} \right)} \right] \]

(27)

The RRRV can be expressed as

\[ \text{RRRV} = \frac{du_{tr}}{dt} = \frac{\sqrt{2k_0} Z C_S}{C_S + C_G} \left[ 1 - e^{-\frac{1}{2} \left( \frac{1}{C_G} + \frac{1}{C_S} \right)} \right] \]

(28)

\[ \approx \sqrt{2k_0} Z \left( 1 - e^{-\frac{2}{C_S C_G}} \right) \]

Considering \( 0 \leq t \leq 2x/n, \) the RRRV is greater than zero, indicating that \( u_{tr} \) increases monotonously during this period. When \( t = 2x/n, \) the maximum value of TRV is

\[ U_{\text{trmax}} = 2 \sqrt{2k_0} Z L_A \times + \sqrt{2k_0} Z L_A t Z C_G \left( 1 - e^{-\frac{2x}{C_S C_G}} \right) \]

(29)

Suppose a 1LG occurs on the line, the RRRV and the first peak value of TRV \( (U_{\text{trmax}}) \) of CB are 4.45 kV/\( \mu \)s and 2065.11 kV, respectively. The variations of RRRV and \( U_{\text{trmax}} \) versus \( C_G \) are plotted in Figure 8. Clearly, the use of EGC can effectively reduce the RRRV. When \( x = 50 \text{ km} \), the RRRV shows an approximately linear downward trend with the increase of \( C_G \) whereas \( U_{\text{trmax}} \) has a nonlinear growth trend with the increase of \( C_G \); the growth speed of \( U_{\text{trmax}} \) slows down, and eventually tends to be stable. The results suggests that when the value of \( C_G \) increases, the peak value of arc voltage rises before the arc extinction and the dielectric strength is improved, which would contribute to the successful interruption of CB.

4 SIMULATION STUDY

In order to verify the aforementioned analysis, a practical UHV line of China was selected, that is, the Jingdongnan–Nanyang line. The simulation model was established in the environment of EMTP. Then, the TRV and RRRV across CB are systematically studied. Three cases are considered in our work, that is, a long-line fault, a short-line fault and a terminal fault. Here, the simulation time step is set to be 0.01 \( \mu \)s. As presented in Figure 9, the RRRV is defined as

\[ \text{RRRV} = \frac{dU_{tr}}{dt} = \frac{U_{\text{trmax}}}{t_{\text{m}} - t_0} \]

(30)

where \( t_{\text{m}} \) is the corresponding time of \( U_{\text{trmax}} \), and \( t_0 \) is the initial time of the recovery voltage.

4.1 Long-line fault

Suppose a 1LG fault occurs 50 km away from the sending end, the fault arc initiates quickly and the tripping command
4.2 Short-line fault

Suppose a 1LG fault occurs 5 km away from the sending end, the waveforms of TRV are shown in Figure 11. Comparing Figure 11(a) with Figure 10(a), the oscillating frequency of latter is much greater than that of the former. This is because the oscillating frequency $f_{\text{SLF}}$ (power source side) is considerably larger than $f_{\text{LLF}}$ (line side), and the oscillating frequency of $u_2$ is mainly determined by $L_2$. It can be observed that $f_{\text{SLF}}>f_{\text{LLF}}$. Under short-line fault (SLF) condition, the short-circuit current $I_S$ becomes greater, and the amplitude of $u_2$ has an increasing trend. However, on the basis of Equation (6) and (15), the increasing trend slows down with the decrease of fault distance $x$. According to Equation (17), the smaller $x$ is, the greater the decrease of oscillating amplitude of $u_2$ will be. As a result, the peak value of $u_2$ after superposition is decreased, whereas the decrement is slight. In this case, $U_{\text{rrmax}}=1269.12$ kV, $RRRV_{|\text{LLF}}=32.54$ kV/$\mu$s $>RRRV_{|\text{SLF}}$. It should be noted that the RRRV is far beyond the allowable value stated in existing standard [22, 23]. On one hand, when $x$ becomes smaller, the increase of RRRV is supposed to be greater. Furthermore, according to Equation (5), the steady-state value of short-circuit current is larger. Hence, the interruption condition of CB would become more severe. SLF is a rigorous fault type to evaluate the interrupting performance for CB.

Using EGC, the waveform of TRV is plotted in Figure 11(b). Here, $C_G=0.5$ $\mu$F, $U_{\text{rrmax}}=1570.11$ kV and the RRRV is reduced to 7.92 kV/$\mu$s. The peak value of $u_2$ is increased, but the RRRV is greatly reduced, which weakens the interrupting severity for the CB. To further verify the effects of EGC on RRRV, the line parameters are substituted into Equation (28), we obtain

$$RRRV = \begin{cases} \frac{97.30}{3+C_G} \left[1 - e^{-\frac{(0.144+0.048)}{C_G}}\right] & x = 5 \text{ km} \\ \frac{16.17}{3+C_G} \left[1 - e^{-\frac{1.44+0.48}{C_G}}\right] & x = 50 \text{ km} \end{cases}$$

Referring to the related literature, $C_S$ is taken as 3 $\mu$F [24]. It can be concluded that under SLF and LLF, the RRRV decreases with the increase of $C_G$. In the case of SLF, it has an approximately exponential downward trend. The variation of RRRV versus $C_G$ is depicted in Figure 12.

When $C_G=0.5$ $\mu$F, $RRRV=7.93$ kV/$\mu$s, which is almost the same as the simulation result. In the event of LLF ($x = 50$ km),

\[\text{FIGURE 10 Voltage waveforms under LLF. (a) } u_A, u_B \text{ and } u_0 \text{ without EGC, (b) Comparison of } u_0 \text{ before and after using EGC}\]

\[\text{FIGURE 11 Voltage waveforms under SLF. (a) } u_A, u_B \text{ and } u_0 \text{ without } C_G, (b) u_0 \text{ with the use of EGC}\]
the value of \( C_G \), in the exponential part of Equation (31), has a small impact on RRRV, it has approximately a linear decreasing trend, and the degree of reduction is less than that under SLF.

### 4.3 Terminal fault (TF)

Suppose a fault occurs at the terminal of CB, the steady-state value of fault current can be mathematically expressed as

\[
I_S = \frac{E}{\sqrt{R_S^2 + (\omega L_S)^2}} \quad (32)
\]

If the CB is not equipped with EGC, since \( u_B \) is equal to zero at the moment of arc extinction, \( u_{tr} \) can be approximately considered as the voltage on point A. According to Equation (15)

\[
\begin{align*}
  u_{tr} &= E_m (1 - \cos \omega_1 t) \\
  \text{RRRV} &= \frac{du_{tr}}{dt} = E_m \omega_1 \sin \omega_1 t
\end{align*} \quad (33)
\]

Using EGC, on the contrary, \( u_{tr} \) satisfies,

\[
L_S (C_G + C_S) \frac{d^2 u_{tr}}{dt^2} + R_S (C_G + C_S) \frac{du_{tr}}{dt} + u_{tr} = E_0 \quad (34)
\]

In practice, \( R_S \) is lower than \( 2\sqrt{L_S/(C_G + C_S)} \), \( u_{tr} \) occurs in the form of oscillation. At the instant \( t = 0 \), \( u_{tr} = U_{A0} = 0 \) and \( i_A = 0 \). The equation can be solved

\[
\begin{align*}
  u_{tr} &= E_m (1 - \cos \omega_1 t - \frac{\delta}{\omega_1} \sin \omega_1 t) \\
  \text{RRRV} &= E_m (\omega_1 \sin \omega_1 t - \delta \cos \omega_1 t)
\end{align*} \quad (35)
\]

As the capacitance of EGC increases, \( \omega_1 \) decreases and as well as the term \( \omega_1 \sin \omega_1 t \). On the contrary, the second term \( \delta \cos \omega_1 t \) rises as the EGC capacitance increases. The RRRV is equal to the first term minus the second term. As a consequence, the RRRV value drops as the EGC increases. In principle, the use of EGC can smooth the TRV waveform and the RRRV drops as the capacitance increase. It suggests that the RRRV drops with the installation of EGC. Considering \( \delta \) is quite small, \( u_{tr} \) changes mildly. In the case of TF, the waveforms of TRV are illustrated in Figure 13.

It can be observed that \( u_B = 0 \) and \( u_A = u_{tr} \). \( U_{trmax1} \) and RRRV1 are 1515.8 kV and 7.15 kV/\( \mu \)s, respectively, under such circumstance. Using 0.5 \( \mu \)F \( C_G \), \( U_{trmax2} \) and RRRV2 become 1534.3 kV and 7.02 kV/\( \mu \)s. The simulation result demonstrates that the presence of EGC reduces the RRRV but gives rise to a slight increase of \( u_{tr} \), which further validates the theoretical analysis. The variation of RRRV versus \( C_G \) is plotted in Figure 14. Clearly, the RRRV has a downward trend as \( C_G \) increases from 0 to 0.7 \( \mu \)F. The simulation result, shown in Figure 14, is consistent with the theoretical analysis.

Figure 15 compares the effects of EGC on the TRV and RRRV under different fault conditions.
5 | DISCUSSION

- Clearly, $U_{\text{trmax}}$ is the largest in the case of LLF: It may exceed the allowable value specified in the standard without any overvoltage measures; after installing a 0.5 $\mu$F EGC, $U_{\text{trmax}}$ further increases but the RRRV drops, in turn, it would contribute to the successful interruption of the CB. As far as the SLF, the RRRV is much greater than others. Previously, the SLF is often considered as the most critical condition for CB interruption. After installing EGC, the RRRV is significantly minimized within the standard value despite a slight increase of $U_{\text{trmax}}$. In our case, the SLF condition still tends to be the most severe circumstance for short-circuit interruption. If the CB is capable of meeting the standard under SLF, it is supposed to be met under other fault types.

- When the TF occurs, the steady-state value of short-circuit current is the largest. By contrast, $U_{\text{trmax}}$ and RRRV are moderate and within the standard range simultaneously. Similarly, $U_{\text{trmax}}$ rises whereas the RRRV drops to some extent after installing EGC. From aforementioned analysis, the 1100 kV CB is composed of two 550 kV interrupters in series; the use of EGC can also completely overcome the asymmetrical TRV distribution across each individual one, which is about 1.7 to two times of the average value. The correctness of modelling method is verified by the detailed simulation study.

6 | CONCLUSIONS

- This paper proposes an equivalent circuit model and a mathematical method for the transient recovery voltage study of multi-break CB using the extended grading capacitor. The expressions for the peak of transient recovery voltage and its rate of rise are derived with full consideration of the travelling waveguide process and the fault type. The established mathematical model provides a way to theoretically study and reveal the electromagnetic transient characteristics of multi-break CB. The proposed method can be applied to both EHV and UHV lines.

- It indicates that the use of extended grading capacitor can not only suppress the secondary arc, but also enhance the interrupting capability of CBs. As the rise of grading capacitance, the waveform of transient recovery voltage is greatly smoothed and hence the rate of rise despite a slight increase of the peak value. It shows that the short-line fault tends to be the most severe circumstance for the short-circuit interruption. The detailed simulation study verifies the correctness of this modelling method.

ACKNOWLEDGEMENTS

This work is jointly supported by the National Natural Science Foundation of China under Grant No. 52077068 and Hunan Natural Science Foundation under Grant No. S2019JJQNJ0386.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to cite this article: Sun Q, Xiao Z, Jiang R, Zhong L, Chen S. Influence of Extended Grading Capacitor for Suppressing Secondary Arc on the Transient Recovery Voltage of Multi-Break Circuit Breaker. IET Gener. Transm. Distrib. 2021;15:2127–2136.
https://doi.org/10.1049/gtd2.12162