# Effects of Pre-insertion Resistor on Energization of Compensated Lines

Lina He, Ronald Voelzke

***Abstract*—Shunt reactors are commonly applied as a cost-effective way to provide inductive reactive power compensation for transmission lines. When energizing transmission lines with high compensation levels, current zero-crossing missing phenomena often appear due to the excessively long arcing time caused by the generated dc components from shunt reactors. The resulting possible circuit breaker (CB) failure can endanger power system security in extreme situations. One of the effective countermeasures, the pre-insertion resistor, has been applied in industry to prevent current zero-crossing missing. However, the insertion time of the pre-insertion resistor and the corresponding transients are seldom discussed in the current studies. In order to analyze the corresponding impact on the CB performance, this paper develops a generic electromagnetic model on the Siemens PTI software PSS®NETOMAC. An energization case of a compensated line is simulated. A mathematical method is proposed to estimate the amplitude of the dc component generated during energization. The simulation results show that the insertion time of the pre-insertion resistor has a significant impact on the CB performance. It is significant to identify an appropriate insertion time to ensure a successful CB operation.**

***Index Terms*—Current zero-crossing missing, pre-insertion resistor, CB, compensated transmission line, dc component current.**

## I. INTRODUCTION

WHEN a transmission line is loaded below its surge impedance loading (SIL), the transmission line experiences a voltage rise due to its natural shunt capacitance drawing the charging current through its series inductance [1][2]. In order to avoid the unexpected voltage rise, shunt reactors are usually installed at the end(s) of transmission lines to provide inductive reactive power compensation [3].

In an electrical circuit, the current flowing through a shunt reactor lags its crossing voltage by almost 90° due to a high X/R ratio of the shunt reactor. When the shunt reactor in one phase is switched on at a zero-crossing of its phase-to-ground voltage, the resulting initial ac component current in this phase is the maximal. In order to maintain the current continuity, a dc component current with the opposite amplitude of the initial ac component current has to be generated simultaneously at the switching-on time.

When a compensated transmission line is energized by switching-on the CB at one end, the resulting ac component current flowing through the shunt reactor has the opposite phase angle of the capacitive charging current of the transmission line. It makes the amplitude of the ac component current flowing through the CB be reduced. A current zero-crossing will not appear until the amplitude of the dc component generated by the shunt reactor is lower than that of this ac component [4]. In case the compensation level of the transmission line is equal to 100%, the ac component current of the shunt reactor is cancelled by that capacitive charging current of the transmission line. The remaining current flowing through the CB only involves the dc component. This dc component can take seconds to be damped [5]. Before that, it is not practicable for the CB to interrupt the current successfully.

Theoretically, current zero-crossing missing phenomena can be avoided by limiting the compensation levels of transmission lines below 50%. However, this is not a common method for the system operators to address the problem. One typical countermeasure in industry is to equip the CB with a pre-insertion resistor. A few literatures related to this topic have been found. The study of [5] analyzes the current zero-crossing missing problem during the energization of a cable. It utilizes an insulation coordination study to find a safe energization switching time. The corresponding methods to minimize zero-missing phenomena are discussed in [6]. Regarding the method of the pre-insertion resistor, reference [7] reports a mathematical way to determine the resistance of the pre-insertion resistor. To the best of the authors' knowledge, the insertion time of the pre-insertion resistor and the corresponding transients have not been analyzed currently.

When a pre-insertion resistor is bypassed by closing the paralleled CB after a selected insertion time, a new transient current is generated. This transient current has a significant impact on the CB interrupting performance. In order to analyze the relationship between the insertion time and the CB interrupting performance, this paper proposes a generic electromagnetic model that is developed on the Siemens PTI software PSS®NETOMAC. This software has been widely applied for power system transient analysis in time domain. A realistic energization case of a compensated line is studied in the simulation. In addition, a mathematical method is presented to estimate the amplitude of the dc component during energization.

The structure of this paper is as follows. Section II describes phenomena of current zero-crossing missing and the CB model with a pre-insertion resistor. Section III outlines a generic model for the EMT study. The simulation scenarios

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are demonstrated in Section IV to analyze the bypassing transients of the pre-insertion resistor and the corresponding impact on the CB performance. Section V concludes.

## II. CURRENT ZERO-CROSSING MISSING AND A TYPICAL COUNTERMEASURE

### *A. Phenomena of Current Zero-crossing Missing*

As known, the decay rate of a dc component current depends on the R/X ratio of the corresponding circuit. In case the R/X ratio of a faulted circuit is not sufficient to damp the generated dc component within the CB allowed maximal arcing time, the current zero-crossing missing phenomenon appears. When a compensated transmission line experiences an unbalanced short-circuit fault during its energization, the healthy phase is more likely to experience a current zero-crossing missing than the faulted phase due to its low R/X ratio. Therefore, unbalanced short-circuit faults usually have more severe current zero-crossing phenomena than three-phase short-circuit faults.

During the energization of a compensated transmission line, the worst case with current zero-crossing missing is the “no fault” case. One of the possibilities resulting in the no fault case, is that the protection of the compensated transmission line is activated to trip its CB that should not be tripped. In this situation, all the three-phase R/X ratios are with the low values that can induce current zero-crossing missing phenomena on all the three phases of the CB.

### *B. CB with Pre-insertion Resistor*

One typical countermeasure to prevent current zero-crossing missing is to apply the CB with a pre-insertion resistor. Its model is illustrated in Fig. 1. As seen, the pre-insertion resistor is in parallel with the CB. A switch s1 is applied to control the connection of the pre-insertion resistor.

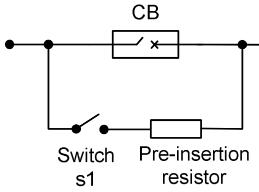

Fig. 1 Model of CB with a pre-insertion resistor

**CB switching-on**

When the CB receives the switching-on signal to energize a transmission line, the pre-insertion resistor is inserted first by switching on s1. The inserted resistor helps to damp the generated dc component during energization. After a selected insertion time, the CB is switched on to bypass the pre-insertion resistor. The status of the switch s1 in the studied CB is not changed after the CB is switched on, i.e., the pre-insertion resistor remains connected during operation.

**CB switching-off**

For a closed CB, no current flows through the pre-insertion resistor theoretically. In case the CB receives a switching-off signal, the switch s1 is disconnected firstly. After a defined time delay, the CB starts to be switched off. If the defined time delay is not considered, the CB with a pre-insertion resistor during its switching-off operation behaves like a normal CB. It has to be noted that no arcing phenomenon occurs during the disconnection of s1, since no current is interrupted by s1.

## III. GENERIC MODEL

For a compensated transmission line, shunt reactors are normally located at its end(s). When the compensated line is energized from one end, its other end needs to be disconnected. A generic model is developed in this section to analyze the energization transients of a compensated transmission line. Its configuration is shown in Fig. 2. It is noted that the further lines connected to the same busbar of the studied line, are not necessary to be considered if there is any, due to their low impact on the transient current performance of the studied line.

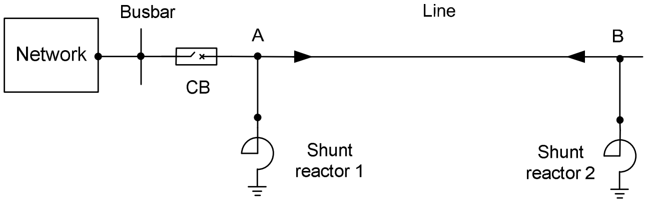

Fig. 2 Generic model for energization transient analysis of a compensated transmission line

In the generic model, the network is represented by a Thevenin equivalent circuit. It is connected to a compensated transmission line by a CB. A series-connected Pi circuit is applied to model the transmission line. Each Pi circuit corresponds to a segment of the transmission line with a short length.

The transmission line is assumed to be equipped with a shunt reactor at both ends. The resulting compensation level of this transmission line can be calculated by,

$$\varphi = \frac{Q_{SR1} + Q_{SR2}}{Q_{line}} \tag{1}$$

Here, the symbols of $Q_{SR1}$ and $Q_{SR2}$ correspond to the rated reactive power of shunt reactors 1 and 2. The symbol of $Q_{line}$ represents the rated capacitive charging power of the transmission line that is given by,

$$Q_{line} = V_r^2 * \omega * C' * L = V_r^2 * 2\pi * f_r * C' * L \tag{2}$$

the symbols of $V_r$ and $f_r$ represent the rated voltage and frequency of the power grid. The symbols of $C'$ and $L$ indicates the positive sequence capacitance per length and length of the transmission line.

## IV. CASE STUDY

### *A. Simulation Data*

The generic model is developed on the software PSS$^{®}$NETOMAC (Version 11.5) for time-domain simulation. An energization case is studied in this section to investigate the performance of a CB with the pre-insertion resistor of 400 Ohm. The insertion time of the pre-insertion resistor is between 8 and 12 ms. The applied grid data is provided by a

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realistic TSO, including the network, the transmission line and two shunt reactors. The corresponding details are listed in Appendix.

The studied grid is operated at a nominal voltage of 500 kV with a rated frequency of 50 Hz. As discussed in Section III, the transmission line is modeled as a series-connected Pi circuit. Each Pi circuit in the simulation model corresponds to a transmission line with a length of 2 km. The two shunt reactors are with identical parameters. Their rated reactive power is 180 Mvar. The resulting compensation level of the studied transmission line according to (1) is 120%. It is noted that the neutral points of both shunt reactors are grounded.

### *B. Energization of Compensated Line*

It is assumed that the studied CB is equipped with a pole switching device (PSD) that enables the switching time of each CB pole to be controlled separately. When a CB is switched on by the point-on-wave (PoW) strategy during energization, the resulting dc component is with the highest amplitude. With the PoW strategy, the three-phase poles of the CB are switched on at the zero-crossings of their phase-to-ground voltages, respectively. The switching time of phases B and C are behind phase A by 120° and 240°, respectively. In some references, this switching strategy is also called the single-pole mode [6].

The PoW strategy is applied to switch on the CB to energize the compensated transmission line. During the CB operation, the pre-insertion resistor is connected first. After a selected insertion time, say, 8 ms, the CB is switched on to bypass the pre-insertion resistor. The simulation results are reported in Fig. 3, including the busbar voltage and the energization current flowing through the CB. As seen, the CB phase A is switched on at a zero-crossing of its phase-to-ground voltage. After 1/3 and 2/3 cycles, the CB phases B and C are switched on, respectively.

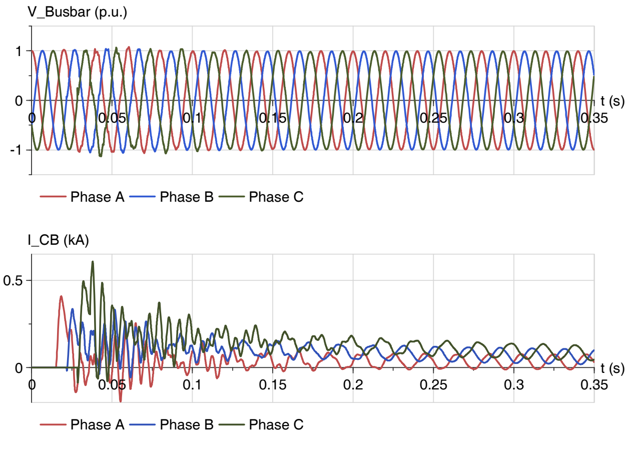

Fig. 3 Busbar voltage and current flowing through CB during energization

It is seen in Fig. 3 that the energization current starts to oscillate with a high amplitude when the CB is switched on. The oscillation frequency is related to the inductance and capacitance of the transmission line [7]. The maximum current peak value is up to 0.61 kA. Afterwards, the amplitude of the oscillation current is reduced rapidly. After about 0.3 s, the high frequency oscillation component is almost disappeared, and only the fundamental frequency and dc components remain.

Thanks to the high amplitude of the oscillation component, there are a few current zero-crossings appearing after the CB operation, even on phase C. With the decaying of the oscillation component, the current zero-crossing missing phenomenon starts to appear on both phases B and C. It is seen that the amplitude of the dc component current on phase C is still higher than that of the ac component current at 0.35 s. This dc component will take several seconds to be damped due to its low decay rate.

### *C. Performance of CB in No Fault Case*

As discussed, current zero-crossing missing phenomena usually appear on the healthy phase(s) during the energization of a compensated line, due to the low R/X ratio of the healthy phase (s). The worst case – “no fault” case, is studied in this section to analyze the performance of the studied CB.

The PoW strategy is applied to switch on the CB in this case. Its switching time is identical with that in Section B. After 12 ms, the protection system is activated to trip the CB. With consideration of the inherent time delay of a primary protection, the CB contacts start to be separated at 0.061 s. The inherent time delay of the studied CB includes the relay time delay of 17 ms and the opening time of 17 ms [8]. Based on the information from the manufacture, the caused arc during the separation of the CB contacts needs to be extinguished within 38 ms, to enable a successful current interruption. The corresponding time sequence of the CB operation is illustrated in Fig. 4.

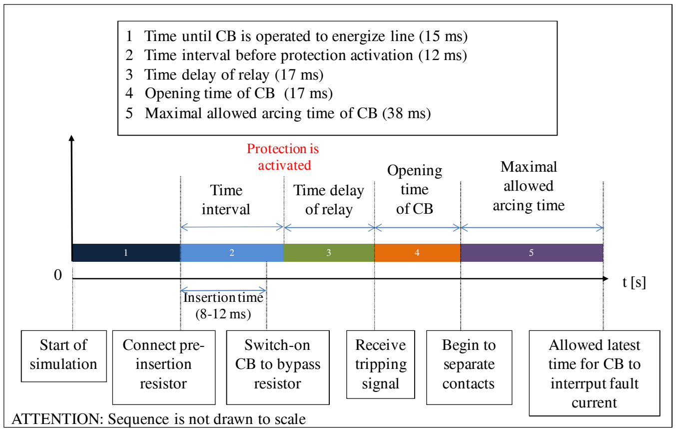

Fig. 4 Operation sequence of CB with a pre-insertion resistor

The selected insertion time of the pre-insertion resistor is 8 ms. The corresponding simulation results are shown in Fig. 5. The time interval between two orange vertical lines in the current plot of Fig. 5 indicates the maximal allowed arcing time of 38 ms. As seen, phases A and B of the current flowing through the CB are successfully interrupted with their zero-crossing appearances between two orange lines. The resulting arcing time on both phases correspond to 1.6 and 1.1 ms, respectively, which are much less than the maximal allowed arcing time. Here, the arcing time represents the time interval between the separation beginning of the CB contacts (i.e., the

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left orange line) and the arc extinguishing time (i.e., the coming current zero-crossing). It is shown in the current plot of Fig. 5 that the phase C experiences a current zero-crossing missing. The corresponding arcing time is 45.2 ms that is longer than the maximal allowed arcing time. The flowing current on this phase cannot be interrupted successfully by the studied CB.

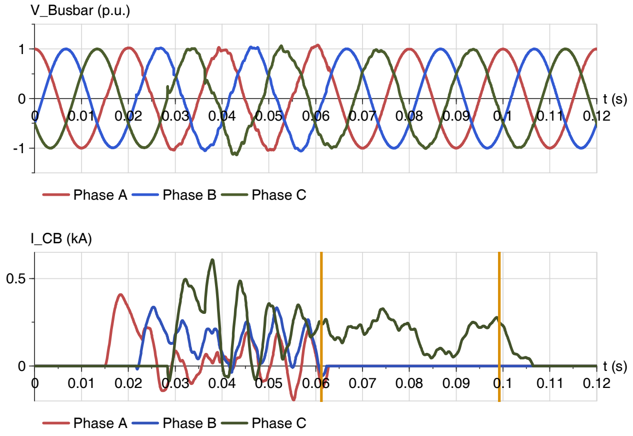

Fig. 5 Simulation results with the insertion time of 8 ms

Varying the insertion time in a step of 2 ms, the corresponding currents flowing through the CB are reported in Figs. 6 and 7, respectively. It is seen that no current zero-crossing phenomenon appears in both cases. Therefore, the CB can interrupt the energization currents successfully in both cases.

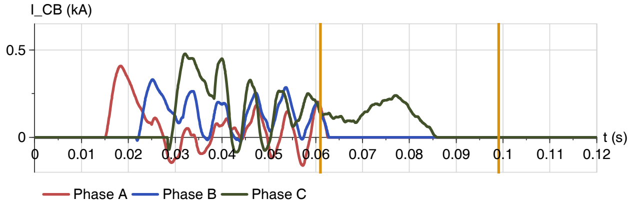

Fig. 6 Current flowing through CB with the insertion time of 10 ms

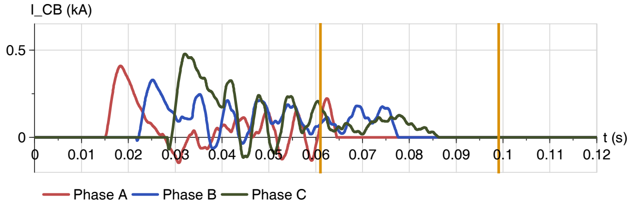

Fig. 7 Current flowing through CB with the insertion time of 12 ms

### *D. Simulation Comparison with Different Insertion Time*

According to the simulation results shown in Section IV C, the current zero-crossing missing only occurs on phase C of the case with the insertion time of 8 ms. With the insertion time increasing in a step of 2 ms, the current zero-crossing missing phenomenon is disappeared.

All the phase C currents with the simulated insertion time are shown in Fig. 8. As seen, the pre-insertion resistor of phase C is connected at 0.028 s in these cases. After 8, 10 and 12 ms, the CB is switched on to bypass the pre-insertion resistor, respectively. With the bypassing of the pre-insertion resistor, a new dc component current has to be generated in each case to maintain the current continuity at this moment. In the meanwhile, the CB operation is accompanied by an oscillation component current with a high amplitude. This oscillation component is decayed rapidly at the beginning. After about 20 ms, both of the oscillation component amplitude and its decay rate are reduced dramatically.

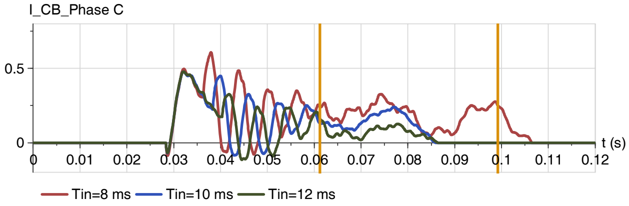

Fig. 8 Phase C currents with the insertion of 8, 10 and 12 ms

According to the CB operation sequence shown in Fig. 4, the arcing time is started to be accounted at 0.061 s, i.e., the time of the first orange line in the current plots. The dc component amplitude at this moment can be estimated as the absolute of the average of the maximal and minimal instantaneous currents within the following period (20 ms), i.e.,

$$I_{dc} = \left|(i_{\max} + i_{\min})/2\right| \tag{3}$$

the symbols of $i_{\max}$ and $i_{\min}$ indicates the maximal and minimal instantaneous currents within the following period. It has been discussed in Section IV B that the energization transient current contains the fundamental frequency, dc and oscillation components. Without consideration of the slow decaying of the oscillation component at this moment, the contribution of the oscillation component on $i_{\max}$ can be cancelled by that on $i_{\min}$, like the fundamental frequency component. As a result, only the dc component remains in the sum of $i_{\max}$ and $i_{\min}$. As noted, the dc component decaying during the studied period is not considered due to its low rate.

Applying (3), the amplitudes of the dc components at 0.061 s in three cases are calculated. The corresponding results are reported in Table I. It is seen that the case with the insertion time of 8 ms has the highest dc component amplitude. Its arcing time is beyond the maximal allowed arcing time of 38 ms. When the insertion time is increased by 2 ms, the amplitude of the dc component is declined dramatically. The resulting arcing time in the case with the insertion time of 10 ms is reduced to 24.8 ms. The current zero-crossing missing phenomenon is disappeared. When the insertion time is increased from 10 ms to 12 ms, the dc component amplitude continues to be reduced. However, the corresponding arcing time is even increased a bit. This shows, besides the fundamental frequency and dc components, the energization transient current must contain another component that can impact the CB performance. According to the discussion of the transient current performance in Section IV B, this component is the oscillation component. The amplitude of the oscillation component is also reduced with the increasing of the insertion time. When the amplitude decline is able to counteract the caused impact by the amplitude decline of the dc component on the current zero-crossing performance, the CB arcing time stops to be reduced.

It is found that the CB arcing time depends on the performances of the dc and oscillation components, which can be affected significantly by the insertion time of the pre-insertion resistor. For a given pre-insertion resistor, it is important to select an appropriate insertion time to make the CB arcing time be within the maximal allowed limit.

TABLE I
AMPLITUDES OF DC COMPONENTS OF THREE CASES AT 0.061 S

| Tin (ms) | $i_{\max}$ (kA) | $i_{\min}$ (kA) | $I_{dc}$ (kA) | Arcing time (ms) |
|---|---|---|---|---|
| 8 | 0.325 | 0.130 | 0.228 | 45.2 |
| 10 | 0.240 | 0.080 | 0.160 | 24.8 |
| 12 | 0.155 | 0.015 | 0.085 | 25.2 |

## V. CONCLUSION

Current zero-crossing missing phenomena often appear on highly compensated transmission lines during their energization. In order to avoid them, the pre-insertion resistor as a typical countermeasure has been applied in industry. A generic electromagnetic model is developed on the Siemens PTI software PSS®NETOMAC to analyze the performance of the CB with a pre-insertion resistor. According to the simulation results, the caused transient current during energization contains the fundamental frequency, dc and oscillation components. Both of the dc and oscillation components have the significant impacts on the performance of current zero-crossings. With the increasing of the insertion time, both the amplitudes of the dc and oscillation components are reduced effectively. The resulting arcing time depends on the relationship of both the amplitude declines. When a CB with a pre-insertion resistor is applied to energize a compensated line, it is significant to determine an appropriate insertion time with consideration of both the impacts of the dc and oscillation components to avoid current zero-crossing missing phenomena.

## APPENDIX

TABLE II
PARAMETERS OF NETWORK

| Symbols | Values | Units | Description |
|---|---|---|---|
| $V_r$ | 500 | kV | Rated voltage |
| $f_r$ | 50 | Hz | Rated frequency |
| $I''_{k3}$ | 9.4 | kA | Three-phase initial symmetrical short-circuit current |
| $l''_{k1}$ | 8.9 | kA | Single-phase initial short-circuit current |
| X/R | 9.9 | - | X/R ratio |
| c | 1 | - | c-factor (According to standard IEC60909) |

TABLE III
PARAMETERS OF TRANSMISSION LINE

| Symbols | Values | Units | Description |
|---|---|---|---|
| L | 157 | km | Length |
| R' | 0.032 | Ω/km | Resistance per km (positive sequence) |
| X' | 0.305 | Ω/km | Inductance per km (positive sequence) |
| C' | 24.14 | nF/km | Capacitance per km (positive sequence) |
| R0' | 0.182 | Ω/km | Resistance per km (zero sequence) |
| X0' | 0.866 | Ω/km | Inductance per km (zero sequence) |
| C0' | 17.25 | nF/km | Capacitance per km (zero sequence) |

TABLE IV
PARAMETERS OF SHUNT REACTORS

| Symbols | Values | Units | Description |
|---|---|---|---|
| R | 10.47 | Ω | Resistance |
| X | 1531 | Ω | Reactance |
| Q | 180 | MVar | Rated reactive power |

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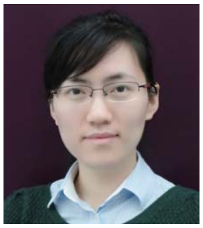

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