Methods to Minimize Zero-Missing Phenomenon

F. Faria da Silva, C. L. Bak, U. S. Gudmundsdottir, W. Wiechowski and M. R. Knardrupgård

Abstract—With the increasing use of high-voltage AC cables at transmission levels, phenomena such as current zero-missing start to appear more often in transmission systems.

Zero-missing phenomenon can occur when energizing cable lines with shunt reactors. This may considerably delay the opening of the circuit breaker, leaving the system unprotected and vulnerable to failures.

Methods to prevent zero-missing phenomenon are still being studied and compared in order to identify effective countermeasures. This paper contributes to these efforts, by presenting several countermeasures that can be applied to reduce the hazards of zero-missing phenomenon.

The authors discovered that this phenomenon can be eliminated, merely by using an extra circuit breaker or a pre-insertion resistor.

Index Terms—Power Cables, AC Circuit Breaker, Shunt Reactor, Switching Transients, Level-crossing problems

I. Introduction

ZERO-MISSING phenomenon is defined as an AC current not crossing zero value during several cycles. If a current does not cross zero value it is not possible to open the circuit breaker without risk of damage, except if the circuit breaker is designed to interrupt DC currents or open at a non-zero current value [1][2].

Because of the large capacitive reactive power of HVAC cables, shunt reactors are needed for power compensation. For unloaded cable systems, the shunt reactor current is almost in phase opposition to the current in the cable, reducing the amplitude of the resultant AC component through the circuit breaker. As the current in the shunt reactor has a transient DC component, the resulting current in the circuit breaker may have a DC component larger than its AC component. When this happens, the current passing through the circuit breaker does not cross zero until the DC component becomes smaller than the AC component.

During its energization the cable is unloaded, and the resistance of the system (cable+shunt reactor(s)) is very small. As a result, the DC component may take several seconds to be damped, period during which the circuit breaker cannot be opened.

This paper is an extension of [3], and for a 50 Hz power frequency it describes zero-missing phenomenon and presents countermeasures that can be used to avoid it. The countermeasures are divided into two types: Cases where the shunt reactor is directly connected to the cable and cases where the shunt reactor is connected to the cable via a circuit breaker.

II. Zero-Missing Phenomenon and Switching Overvoltages

A. Basic Circuit: Inductor in Parallel with a Capacitor

An easy way of understand zero-missing phenomenon is by analysing an inductor in parallel with a capacitor of equal impedance. In this situation the currents in the capacitor and inductor have equal amplitude and are in phase opposition. The current in the inductor can also have a DC component, whose value depends on the voltage at moment of connection.

If the inductor is connected at peak voltage the current at $t(0^+)$ is zero, if it is connected for zero voltage the current has a peak value at $t(0^+)$. As the current in the inductor must maintain its continuity, and it was zero at $t(0^-)$, if the voltage is not at a peak value during connection, a DC component will appear in the inductor current to maintain its continuity. The DC component is equal to minus the value of the AC component at $t(0^-)$ [4].

If there is no resistance in the system, the DC component is not damped and it will be maintained infinitely. In reality there is always some resistance and the DC component disappears after some time.

Fig. 1 shows an inductor in series with a resistor, both of them in parallel with a capacitor. The resistance is 100 times smaller than the inductor reactance, which is equal to the capacitor reactance. Fig. 2 shows a simulation of Fig. 1. The circuit breaker closes when the voltage is crossing zero, and therefore the DC component in the inductor is maximum. The inductive and capacitive AC components cancel out (IL and IC

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have equal amplitude and are in phase opposition) and the current I1 contains only the decaying DC component

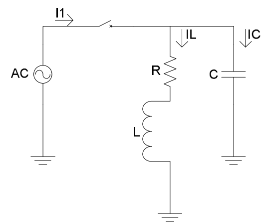

Fig. 1 Equivalent scheme of an inductor in series with a resistor, both in parallel with a capacitor

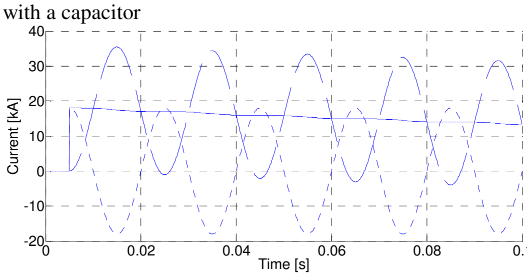

Fig. 2 Current in the inductor (IL, dashed line), in the capacitor (IC, dotted line) and the sum (I1=IL+IC, solid line)

The behaviour of a system consisting of a shunt reactor and a cable is not very different from the one depicted in Fig. 1. The shunt reactor can be modelled as an inductor in series with a resistor, and the cable is mainly a capacitive shunt element [5]. There are, however differences between the behaviour of a simple RLC circuit and a physical cable/shunt reactor system, as for instance switching overvoltages.

Switching overvoltages occur due to the charging of the cable's capacitance and energy oscillation between the cable's capacitance and inductance [6]. As for zero-missing phenomenon, the value of switching overvoltages depends on the voltage value when connecting the cable/reactor system. However, to avoid zero-missing phenomenon the connection should be made when the voltage is at its peak, whereas the opposite applies when it comes to avoiding switching overvoltages [2][7].

According to [8], when the shunt reactor is directly connected to the cable it is necessary to choose between avoiding either zero-missing phenomenon or switching overvoltages. This paper will show that it is possible to avoid both by applying specific countermeasures.

B. System using Cable's Pi-model

For analysis purposes the shunt reactor had been modeled as an inductor in series with a resistor and the cable is represented by its equivalent pi-model (see Fig. 3).

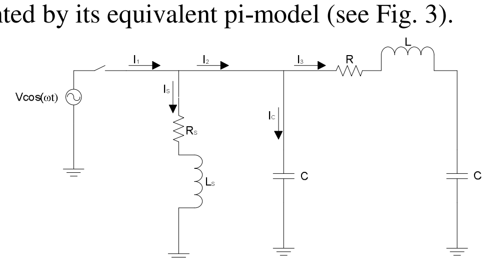

Fig. 3 Equivalent scheme of a shunt reactor and a cable: V_1-Voltage Source; R_S-Shunt reactor resistor; L_S-Shunt reactor inductor; R-Cable's series resistor; L-Cable's series inductor; C-Cable's shunt capacitor

The system of Fig. 3 is described by (1). The circuit breaker current I_1, equal to $I_S+I_C+I_3$, is obtained from (1) and shown in (2).

$$\begin{cases} V\cos(\omega t) = L_s \dfrac{dI_s}{dt} + R_s I_s \\ V\cos(\omega t) = \dfrac{1}{C}\int I_c dt \\ V\cos(\omega t) = RI_3 + L\dfrac{dI_3}{dt} + \dfrac{1}{C}\int I_3 dt \end{cases} \tag{1}$$

$$\begin{aligned} I_1(t) = {} & \frac{V}{\sqrt{R_s^2+(\omega L_s)^2}}\cdot\cos\left(\omega t - \arctan\left(\frac{\omega L_s}{R_s}\right)\right) + I_{sA}\cdot e^{-t\frac{R_s}{L_s}} + \\ & + \frac{V}{\sqrt{R^2+\left(\omega L-\frac{1}{\omega C}\right)^2}}\cdot\cos\left(\omega t - \arctan\left(\frac{\omega L-\frac{1}{\omega C}}{R}\right)\right) + \\ & + I_{3aux}\, e^{-\frac{R}{2L}t}\cdot\cos\left(\sqrt{\omega_0{}^2-\left(\frac{R}{2L}\right)^2}\, t\right) + V\cdot\cos\left(\omega t+\frac{\pi}{2}\right)\cdot\omega C \end{aligned} \tag{2}$$

Where I_{sA} is the initial value of the DC component and is calculated by (3). I_{3aux} is related with the energization of the inductor and capacitor and is calculated by (4). Both depend on the moment when the shunt reactor is connected.

$$I_{sA} = -\frac{V}{\sqrt{R_s^2+(\omega L_s)^2}}\cdot\cos\left(\omega t - \arctan\left(\frac{\omega L_s}{R_s}\right)\right) \tag{3}$$

$$I_{3aux} = -\frac{V}{\sqrt{R^2+\left(\omega L-\frac{1}{\omega C}\right)^2}}\cdot\cos\left(-\arctan\left(\frac{\omega L-\frac{1}{\omega C}}{R}\right)\right) \tag{4}$$

The equations can be confirmed using EMTDC/PSCAD to simulate the system. Fig. 4 shows the current in the circuit breaker using both EMTDC/PSCAD and (2) for a single phase cable, and a 400 kV voltage source. The parameters used in the simulation are based on a 400 kV, 50 km cable from SAGEM [9]: C=3.929 µF; L=25.7 mH; R=15.05 Ω; for the shunt reactor the parameters are: L_S=1.29 H; R_S=0.3003 Ω.

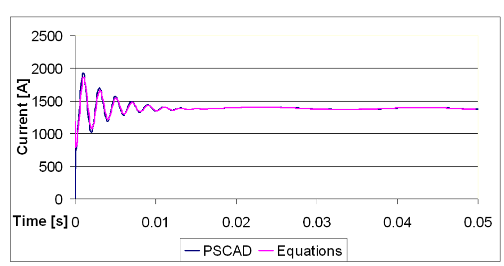

Fig. 4 Current I_1 during 0.05s for 100% reactive power compensation

In order to have more accurate results for the simulations instead of using a pi-model the cable will be simulated by a PSCAD-EMTDC frequency dependent phase model, as it is currently the most precise method to simulate cables [10]. The electrical cable parameters are equal to the ones previous mentioned for the pi-model.

As expected there are small differences between the two simulations, mainly in the moments following the connection of the cable/shunt reactor.

C. *Circuit Breaker*

Two different circuit breakers types can be used. A first type that closes all the phases at the same time, and a second type called single-pole mode, which closes the three phases at different moments [11].

A circuit breaker operating in single-pole mode is similar to three different single-phase circuit breakers operating independently. In Fig. 5 an example is shown of the closing of a circuit breaker operating in this mode, phase R closes at 0 ms, phase T at 3.3 ms and phase S 6.7 ms after phase R.

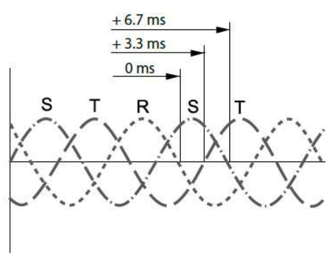

Fig. 5 Example of a single-pole mode operation [11]

The type of circuit breaker used has an influence on the energizing transient. Fig. 6 and Fig. 7 show the differences between the two modes. In Fig. 6 all the phases close when the voltage is zero in the respective phase, therefore the DC component is maximum and the switching transient minimum in all the phases. In Fig. 7 all the three phases are closed at the same time, with phase R having a maximum DC component and the other phases having a lower DC components but also larger switching overvoltages.

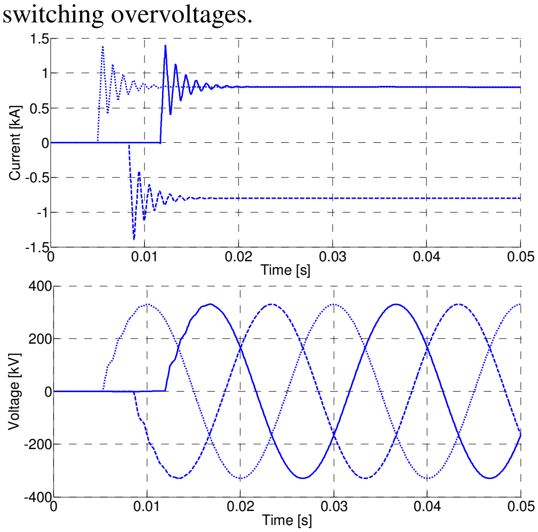

Fig. 6 Current I1 and voltage at the sending end of the cable in a three-phase system for a circuit breaker operating in single-pole mode (phase R: dotted line; phase S: solid line; phase T: dashed line)

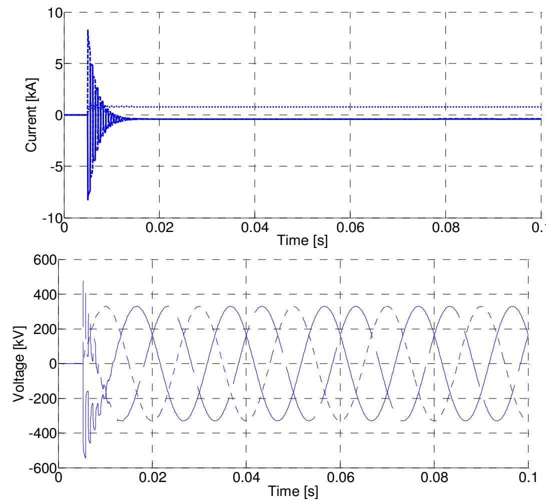

Fig. 7 Current I_1 and voltage at the sending end of the cable in a three-phase system for a circuit breaker closing the three phases at the same time (phase R: dotted line; phase S: solid line; phase T: dashed line)

III. Countermeasures when the Shunt Reactor is Connected Via a Circuit Breaker

Depending on the system load, it may be necessary to connect and disconnect shunt reactors [12]. In such situations the shunt reactors will be connected to the cable via a circuit breaker instead of being directly connected. In this situation it is possible to eliminate/reduce the initial DC component simply by controlling the circuit breaker closing.

A. *Shunt Reactor Connection for a Voltage Peak*

As explained before, the DC component is zero for a shunt reactor energized at voltage peak. For direct connected shunt reactors, the cable and shunt reactor are energized simultaneously, and it is not possible to use this method because of switching overvoltage. But if the shunt reactors are connected via circuit breakers, it is possible to connect the cable when the voltage is zero, and after a short period connect the shunt reactors when the voltage is at a peak value.

For this countermeasure to be completely effective, the circuit breaker associated to the shunt reactor must operate in single-pole mode, or it would not be possible to connect all the phases at peak voltage.

B. *Disconnecting the Shunt Reactor before the Cable*

Zero-missing phenomenon only becomes problematic if it is necessary to disconnect the cable shortly after its energization. So instead of eliminating zero-missing phenomenon, a possible countermeasure could be to find a method of opening the circuit breaker when desired.

Even for a maximum DC component, the current on the shunt reactor (I_S) always has a zero crossing. It is therefore always possible to disconnect the shunt reactor from the cable. When the shunt reactor is disconnected both the DC component and inductive AC component disappear. As the cable's circuit breaker current now only has an AC component the circuit breaker can be disconnect when desired.

One advantage of this countermeasure is that it does not require a circuit breaker operating in single-pole mode.

Fig. 8 shows an example of countermeasure effectiveness. The shunt reactor circuit breaker opens at 0.05 s and the cable circuit breaker at 0.08 s. As a circuit breaker can only open when the current is crossing zero, a delay is required between the two opening orders. But as can be observed, after the disconnection of the shunt reactor there is only AC current without DC offset, and therefore the cable can be disconnected without any risks for the circuit breaker.

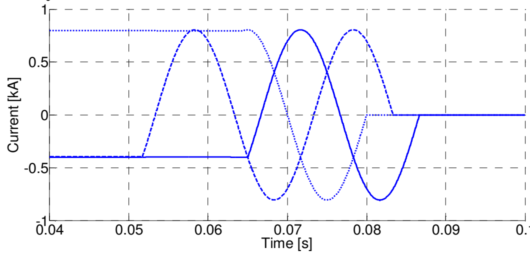

Fig. 8 Current I_1 when the shunt reactor is disconnected before the cable

C. *Use of Several Shunt Reactors*

If more than one shunt reactor is used to compensate for the reactive power, it is possible to synchronize their energization thus reducing the risks of zero-missing phenomenon occurring. For zero-missing phenomenon to occur, a shunt reactor has to compensate more than 50% of the reactive power generated by the cable. When a cable is compensated by several shunt reactors, all with the same compensation level, it is necessary to have more than one connected to have zero-missing phenomenon (unless if it is necessary to compensate more than 100% of the generated reactive power).

This countermeasure is demonstrated for a system with two shunt reactors, each compensating half of the reactive power. The reasoning is similar for systems with more shunt reactors.

This countermeasure involves connecting the second shunt reactor after the DC component caused by the first one has been completely damped.

When a shunt reactor compensates 50% of a cable's reactive power, the amplitude of its AC component is half of the amplitude of the cable's AC component. As these two currents are in phase opposition, the resulting current I_1 has an AC component whose amplitude is equal to that of the shunt reactor's current. The initial DC component is never larger than the amplitude of the shunt reactor AC component, and in the worst case scenario the minimum peak value of the current I_1 is therefore zero.

Fig. 9 gives an example of the currents in the shunt reactor, cable and circuit breaker, for a situation where the initial DC component is maximum.

After the DC component caused by the first shunt reactor is damped, the second shunt reactor is connected. Because there already is one shunt reactor connected, the amplitude of I_1 prior to the connection of the second shunt reactor is half that of the cable's current and equal to the current in the shunt reactors (see Fig. 9). Therefore, when the second shunt reactor is connected its AC current cancels out the AC current of the system, and only the DC component of the second shunt reactor remains. This DC component value is half of what it would have been if only one shunt reactor had been used, whereas the AC component continues to have the same amplitude, and as such the current crosses zero sooner.

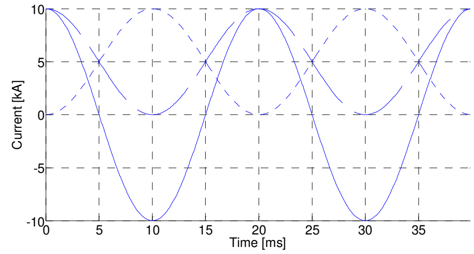

Fig. 9 Currents for a maximum DC component for a shunt reactor compensation half of the cable's reactive power: Solid line: Current in the cable; Dotted line: Current in shunt reactor; Dashed line: Current in the circuit breaker (I_1)

Fig. 10 and Fig. 11 show the current I_1 before and after the connection of the first and the second shunt reactor. Note that as expected the DC current in Fig. 11 is only half of the indicated in Fig. 8, as was expected.

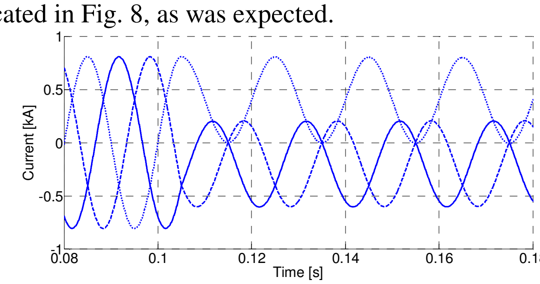

Fig. 10 Current I_1 in the circuit breaker after the connection of the first shunt reactor (phase R: dotted line; phase S: solid line; phase T: dashed line)

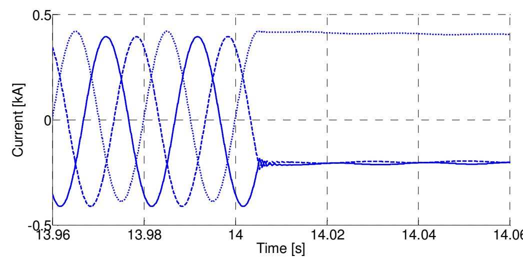

Fig. 11 Current I_1 in the circuit breaker after the connection of the second shunt reactor (phase R: dotted line; phase S: solid line; phase T: dashed line)

This countermeasure does not eliminate zero-missing phenomenon, it merely reduces its duration. It is therefore still not possible to open the cable circuit breaker in the moments following the energizing of the second circuit breaker. On the other hand when a cable is energized, problems are more likely to occur immediately after the connection of the cable. As this countermeasure results in no zero-missing phenomenon until the second shunt reactor is connected, the risks to the system are reduced.

IV. Countermeasures for a Shunt Reactor Directly Connected to the Cable

The drawback of the countermeasures presented in the previous section is that the shunt reactor must be connected to the cable via a circuit breaker. As a circuit breaker is an expensive piece of switchgear, it will only be installed if it is absolutely necessary. A common design choice is to connect the shunt reactor direct to the cable and energize both cable and shunt reactor at the same time.

This section presents two countermeasures that can be used to avoid zero-missing phenomenon when the shunt reactor is directly connected to the cable.

A. Pre-insertion Resistor

A pre-insertion resistor consists of resistor blocks connected in parallel with the circuit breaker's breaking chamber, and closes the circuit 8-12 ms before the arcing contacts [11] (in this article the time considered is 10 ms).

A pre-insertion resistor can damp the entire DC component in 10ms, thus eliminating zero-missing phenomenon. But for this happen the pre-insertion resistor value has to be precise.

The inclusion of this resistor changes the system layout, see Fig. 12 and compare with Fig. 3. Just this little change is sufficient to change the system behaviour so that it is no longer described by (1), but by (5).

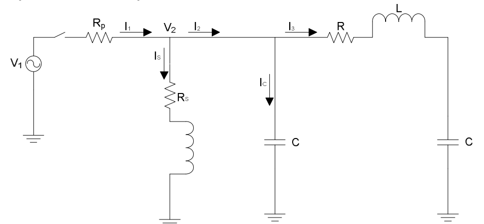

Fig. 12 Equivalent scheme of the shunt reactor and the cable when using a pre-insertion resistor (R_P)

Unlike the differential equation in (1), (5) is not analytically solvable in the time domain [13]. It is therefore necessary to do a Laplace transformation in order to solve it.

$$\begin{cases} V_2 = L_s \dfrac{dI_s}{dt} + R_s I_s \\ V_2 = \dfrac{1}{C}\displaystyle\int I_c dt \\ V_2 = R \cdot I_3 + L\dfrac{dI_3}{dt} + \dfrac{1}{C}\displaystyle\int I_3 dt \\ I_1 = I_2 + I_3 + I_c \\ V_2 = V_1 \cos(\omega t) - R_p \cdot I_1 \end{cases} \tag{5}$$

It is though possible to introduce some simplifications in order to obtain a first approximation of the pre-insertion resistor value. This is done by calculating the energy that the pre-insertion resistor should dissipate (6).

$$W = \frac{1}{2} L_s \left(I_s^{DC}\right)^2 \tag{6}$$

The energy dissipated in the pre-insertion resistor is calculated by the integral in (7), whose limits are the time during which the pre-insertion resistor is connected.

$$W = \int P dt \Leftrightarrow \int_0^{0.01} R_p I_1^2 dt \tag{7}$$

The objective is to calculate R_p, where both I_1 and I_S^{DC} depend on the connection moment and are unknown. For 100% reactive power compensation, the AC components of the shunt reactor and cable's currents cancel each other out, and at the moment of connection the current I_1 is equal to I_S^{DC}, whereas both should ideally be zero after 10ms.

Considering that the current I_1 decreases linearly (this is an approximation, but as R_p is large the error is small), and neglecting R_S (which is much smaller than R_p), (7) can be simplified to (8), and the value of R_p is calculated by (10).

$$W = 0.01 R_p \left(\frac{I_1(0)}{2}\right)^2 \tag{8}$$

$$0.01 R_p \left(\frac{I_1(0)}{2}\right)^2 = \frac{1}{2} L_s \left(I_s^{DC}\right)^2 \Leftrightarrow 0.01 R_p \left(\frac{1}{2}\right)^2 = \frac{1}{2} L_s \tag{9}$$

$$R_p = \frac{2L_s}{0.01} \tag{10}$$

Because of the simplifications this method is not always accurate. If the DC component is maximum the error can be disregarded, but if the DC component is smaller, the error increases.

The use of differential equations allows a more accurate calculation of the pre-insertion resistor value, but an iterative process is required to calculate the value of R_p. Part of the equation solution is presented in appendix.

To perform the iterative process, a small program was written in Matlab. The program increases R_p, until it reaches a value at which the DC component is damped in 10ms.

To verify that the DC component is damped, the peak value of I_S is calculated 10 ms after connection. For that value be equal to the amplitude of the AC component, the DC component must be equal to zero. So when the calculated value is equal to (11) plus a small tolerance the iterative process stops.

$$I_s^{peak} = \frac{V_2}{\sqrt{R_s^2 + \left(\omega L_s\right)^2}} \tag{11}$$

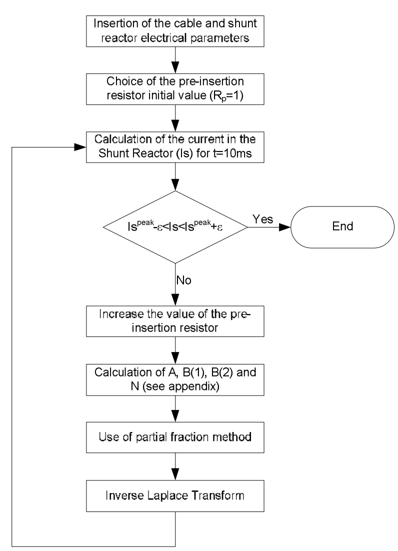

Fig. 13 - Flowchart of the iterative process for the calculation of the pre-insertion resistor value

The value of the pre-insertion resistor depends on the initial value of the DC component. As this value depends on the connection moment, it was decided to solve the equations for the worst case scenario, maximum DC component. For that case the calculated value of R_p is ideal, whereas for the other cases the error is small.

Solving the differential equations, using the system described before, it is obtained 295 Ω as ideal value for the pre-insertion resistor.

Fig. 14 and Fig. 15 show two simulations of a circuit breaker equipped with a pre-insertion resistor. In Fig. 14 the circuit breaker operates in single-pole mode and closes each phase for the maximum DC component in the phase. In Fig. 15 the circuit breaker closes the three phases at the same time for maximum DC component in just one of the phases.

In Fig. 14 all the three phases are zero during connection. In this situation the pre-insertion resistor completely damps the DC component in 10 ms and there is no zero-missing phenomenon. As the connection in all the phases is made for zero voltage, the switching overvoltage in the three phases is minimum.

For the situation depicted in Fig. 15 it is not possible to have zero voltage in the three phases when the circuit breaker closes, and therefore it is neither possible to eliminate the DC component nor completely minimize the switching overvoltages. In one of the phases though there is neither a DC component nor switching overvoltage; this phase is the one where the voltage is zero at the connection moment. When comparing Fig. 15 with Fig. 7, it can be seen how the DC component in the other two phases is smaller when the pre-insertion resistor is used (80 A instead of 400 A) and that there is no switching overvoltage (maximum 1 pu or 326 kV instead of 1.58 pu or 516 kV).

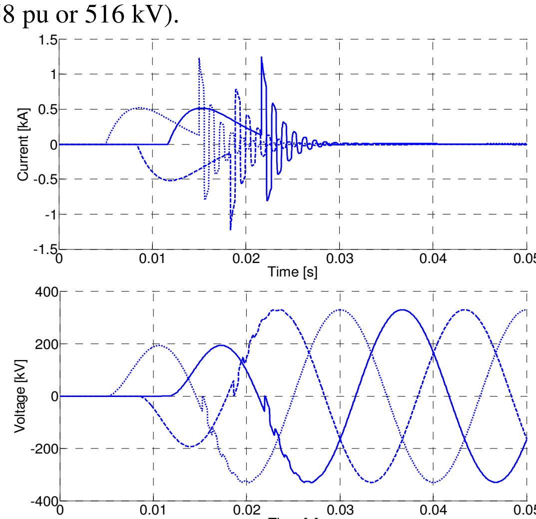

Fig. 14 Simulation of cable energizing, for a circuit breaker operating in single-pole mode and using pre-insertion resistor (phase R: dotted line; phase S: solid line; phase T: dashed line)

Even if the value of the resistor is not ideal, the DC component of the shunt reactor current is always reduced, and it will be lower than a given maximum. Fig. 16 shows the value of the DC component after 10 ms for different resistor values when the cable and the shunt reactor are connected for zero voltage.

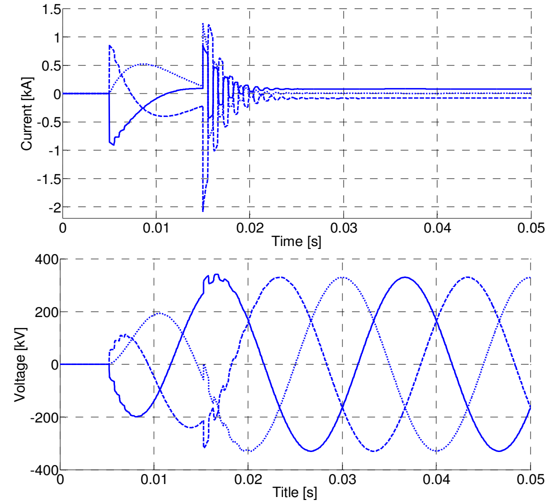

Fig. 15 Current in the circuit breaker and voltage on the sending end of the cable for a situation of maximum switching overvoltage, using a pre-insertion resistor (phase R: dotted line; phase S: solid line; phase T: dashed line)

The curve in Fig. 16 is non-linear, and for pre-insertion resistor values close to the ideal, the DC component is very small, but for larger differences there is still zero-missing phenomenon during long periods of time.

If, for instance the value of the pre-insertion resistor value was calculated using the energy equations (10) instead of the differential equations, the initial DC current would be about 51 A, which is 16 times lower than the value of the initial DC component when no pre-insertion resistor is used (800 A). It can therefore be concluded that the method applied in the energy equations can be used to obtain a first approximation of the final resistor value.

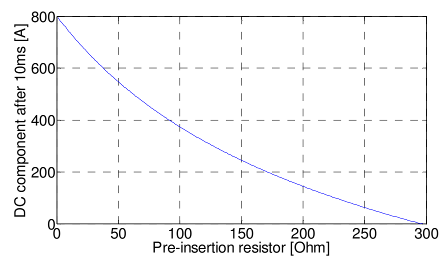

Fig. 16 Initial value of the DC component after bypassing the pre-insertion resistor for different R_p values, for a phase closing when the voltage is zero

B. *Cable Energized from Both Ends*

In the previous countermeasures it was considered that the cable is energized only at one end while the other end was open. It is also possible to energize the cable from both ends simultaneously.

When the cable is energized from one end only, there is a 1 pu voltage drop between the cable and the ground, and almost all the voltage drops are due to the cable capacitance to the ground (see Fig. 3).

When the cable is energized from both ends, the cable resistance and inductance become more relevant, and part of the reactive power is compensated by the grid instead of being solely compensated by the shunt reactor.

Therefore the current in the cable is no longer fully cancelled out by the shunt reactor current, and there is an AC component in the current going through the circuit breaker.

Fig. 17 shows a simplified model for a cable being energized from both ends. By Ohm's law the current I_{C2} only depends on V_2, whereas the current I_3 depends more on the cable resistance and inductance. If, however the cable was energized from one end only, it would be the cable capacitance to define most of the current I_3 value.

The current I_1 has the same DC component as before, but now it also has an AC component, reducing the minimum value of I_1. The current in the second generator (I_f) has an AC amplitude that is almost equal to the one of I_1 but without the DC component (the shunt reactor is in the other cable's end). Therefore it is possible to open the circuit breaker connected to the second generator at any time.

In real cables the capacitance is spread along the cable, and it is not possible to do a so simplistic analysis, but the reasoning is similar.

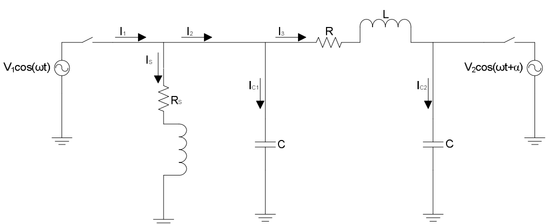

Fig. 17 Model for a cable energized from both ends

Fig. 18 shows the current I_1 for a voltage that is the same at both terminals terminals. I_1 is shown both for cable energization from one end and both ends, respectively.

It can be observed that the DC component is equal in both situations, but for the cable energised from both ends there is also an AC component whose amplitude is about half that of the cable's AC current.

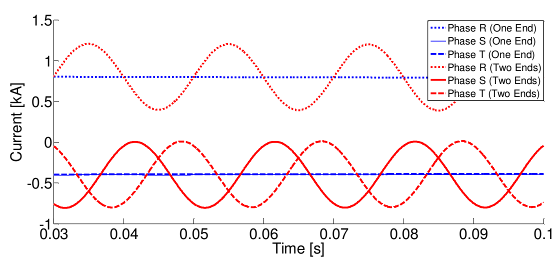

Fig. 18 Current in the circuit breaker when the cable is energized from both ends and the voltage is equal in both terminals (oscillating lines) or just from one end (flat lines)

Zero-missing phenomenon does not disappear by energizing the cable from both ends. But, if the voltage is not the same in the two cable ends, the AC component is larger and at a point it becomes even larger than the DC component. The question is: What should the minimum difference between the sending and receiving end voltages (amplitude and/or phase angle) be in order to prevent zero-missing phenomenon?

There is no definitive answer to this question, since it depends on the system parameters: Voltage level, cable impedance, cable length, etc….

As an example Fig. 19 and Fig. 20 show the minimum values of the difference between the phase angles and the amplitudes required to prevent zero-missing phenomenon. For instance, a 40 km cable should have an energising voltage with a 0.0156 pu amplitude difference between the two ends or a 2º phase angle difference.

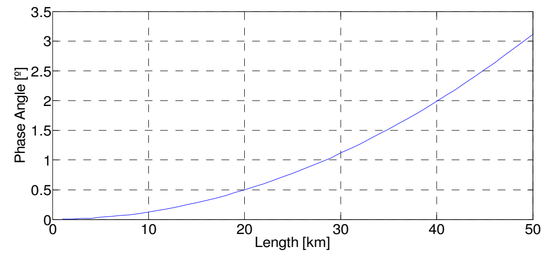

Fig. 19 Minimum difference between phase angles to prevent zero-missing phenomenon for different cable lengths

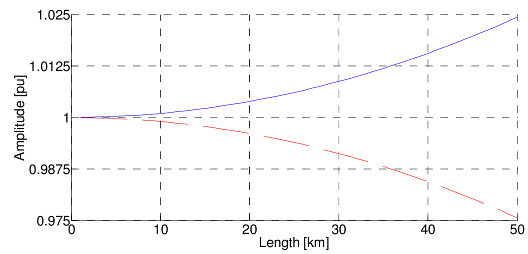

Fig. 20 Minimum difference between the amplitudes to prevent zero-missing phenomenon for different cable lengths (solid line: V_2>1pu; dashed line; V_2<1pu)

V. Conclusions

Zero-missing phenomenon is a non-desirable effect that can occur when energizing cable lines with shunt reactors. The phenomenon can lead to the degradation or even destruction of the cable circuit breaker. With the increasing use of long high-voltage cables, this problem becomes more relevant, and countermeasures for it are necessary.

This paper presents several countermeasures that can be applied for different conditions/systems, reducing/eliminating zero-missing phenomenon. An analysis of all the countermeasures proposes that two of them be considered as the most effective:

- Connect the shunt reactor when the voltage is at a peak value (when the shunt reactor is connected to the cable through a circuit breaker);
- Use of a pre-insertion resistor (when the shunt reactor is connected direct to the cable);

If correctly applied these two countermeasures completely eliminate zero-missing phenomenon, something that it is not granted when the others countermeasures are applied.

As the system parameters change from case to case, it is always necessary to analyse the system to see which countermeasure should be applied.

APPENDIX

$$V_1 = V_2 \left(\frac{A}{N} + \frac{B(1) + B(2)}{N} \right) \quad (12)$$

$$\begin{aligned} A = {} & s^5 L L_s C \omega^2 + s^4 \left(L_s R C \omega^2 + L C R_s \omega^2 \right) + \\ & s^3 \left(L_s \omega^2 + R C R_s \omega^2 + L L_s C \omega^4 \right) + \\ & + s^2 \left(L_s R C \omega^4 + L C R_s \omega^4 + R_s \omega^2 \right) + \\ & + s \left(L_s \omega^4 + R C R_s \omega^4 \right) + R_s \omega^4 \end{aligned} \quad (13)$$

$$\begin{aligned} B(1) = {} & s^4 L C \omega^2 + s^3 R C \omega^2 + \\ & + s^2 \left(\omega^2 + L C \omega^4 \right) + s R C \omega^4 + \omega^4 \end{aligned} \quad (14)$$

$$\begin{aligned} B(2) = {} & s^6 L C^2 L_s \omega^2 + s^5 \left(L C^2 R_s \omega^2 + R L_s C^2 \omega^2 \right) \\ & + s^4 \left(R R_s C^2 \omega^2 + 2 C L_s \omega^2 + L L_s C^2 \omega^4 \right) + \\ & + s^3 \left(2 C R_s \omega^2 + L R_s C^2 \omega^4 + R L_s C^2 \omega^4 \right) + \\ & + s^2 \left(R R_s C^2 \omega^4 + 2 C L_s \omega^4 \right) + s 2 R_s C \omega^4 \end{aligned} \quad (15)$$

$$\begin{aligned} N = {} & s^3 L L_s C \omega^3 + s^2 \left(L_s R C \omega^3 + L C R_s \omega^3 \right) + \\ & + s \left(L_s \omega^3 + R C R_s \omega^3 \right) + R_s \omega^3 \end{aligned} \quad (16)$$

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BIOGRAPHIES

Filipe Faria da Silva was born in Portugal in 1985 and received his MSc in Electrical and Computers Engineering in 2008 from Instituto Superior Técnico (IST), Portugal.
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Wojciech Wiechowski received the M.Sc. degree from Warsaw University of Technology in 2001 and the Ph.D. degree from Aalborg University, Denmark in 2006. From 2001 to 2002 he worked for HVDC SwePol Link as a Technical Executor. In the period from 2002 to 2006 he was with the Institute of Energy Technology, Aalborg University, first as a PhD Student and later as an Assistant Professor. Since 2006 he has been employed in the Planning Department of the Danish TSO Energinet.dk. His current responsibilities include various power system analysis tasks related to the planning of the transmission network with extensive use of long AC cable lines and wind power generation. He is a Senior Member of IEEE.

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