Effect of Pre-Insertion Resistor on Energization of Long Lines.

Sangeeta.S.M[1], Manjula S Sureban[2]

1. PG Scoholar , Department of Electrical and Electronics Engineering , SDMCET, Dharwad ,India.
2. Asst. Professor ,Department of Electrical and Electronics Engineering , SDMCET, Dharwad ,India.

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. Methods to prevent zero-missing phenomenon are still being studied and compared to see which countermeasure works the best. Technically the best way to avoid zero-missing phenomenon produces very high switching overvoltages, making the operator to choose to either avoid the zero-missing phenomenon or to minimize the switching transients. This paper presents a method of determining an optimal value of the resistance of the pre-insertion resistor that results in minimizing both the zero-missing phenomenon and switching overvoltages simultaneously and to study the voltage and inrush current behvaviour while charging the line and also to understand the effetivness of transient mitigating devices.

Index Terms — Current zero-crossing missing, Switching Transients, Circuit Breaker, Pre-Insertion Resistor, Shunt Reactor, Compensated transmission line.

1 Introduction

Switching transients are caused by the operation of breakers and switches in a power system. The switching operations represent two main categories: i) energization phenomena and ii) de-energization of the system elements. The former category includes energization of transmission lines or cables, transformers, reactors, capacitor banks etc. The latter category includes fault clearing and load rejections and so on.

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. Because of this high capacitance, it is required to connectshunt reactor(s) in parallel to the cables, in order to compensate the reactive power generated by them.

If the shunt reactors are compensating all the reactive power generated by the cable, the AC component of the current in the cable has opposite phase angle to AC component of the current into the shunt reactors, therefore they cancel out each other. As the transient of the shunt's reactor current contain both AC and DC components, during transient conditions (as for instance energization of a cable compensated with shunt reactors) under ideal conditions only DC component would remain.

During energizing, the cable has no load and it is open in the far end. As the resistance of the system (cables+shunt reactors) is very small, it may take several seconds for the DC component to be damped. As the current does not cross zero during those seconds, it is not possible to open the circuit breaker without risking damaging it, unless it is prepared to interrupt DC currents or currents with several amperes [3]. If in the meanwhile, a single-phase or two-phase fault occurs on the cable, the circuit breaker will be able to open the faulted phases but not the healthy phase(s) because of the lack of zero-crossings of the current. This can leads to a damage of the circuit breaker.

A method that can be used to damp the DC component in just half of cycle, is to use circuit breakers equipped with pre-insertion resistors.

Due to the complexity of the mathematical representation of the equipments involved, digital simulation using an electromagnetic transients simulation program plays an important role in the study of switching transients.

The results from such studies are useful for:

- Insulation co-ordination to determine overvoltages stresses on equipment
- Determining the arrester characteristics
- Determining the transient recovery voltage across circuit breakers.
- Determining the effectiveness of transient mitigating devices, e.g., pre-insertion resistors, inductors and controlled closing devices.

The structure of this paper is as follows. Section 2 describes phenomena of current zero-crossing mising and the 3 CB model with a pre-insertion resistor. Section 4 outlines a generic model for the EMT study. The simulation scenarios are demonstrated in Section 5 to analyze the bypassing transients of the pre-insertion resistor.Section 6 concludes.

2 . 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.

3. Calculation Of Pre-Insertion Resistor Value

A pre-insertion resistor consists of resistor blocks that are connected in parallel with the circuitbreaker's breaking chamber, and close the circuit 8-12ms before the arcing contacts (in this paper the time considered is 10ms).

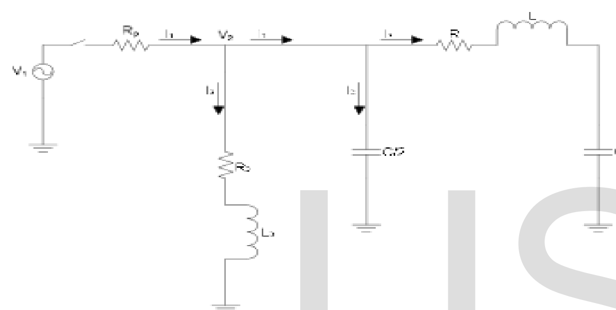

Fig. 1 System model: V-Voltage Source; Rp-Pre-insertion resistor; Rs-Shunt reactor resistor; Ls-Shunt reactor inductor; R-Cable's series resistor; L-Cable's series inductor; C-Cable's shunt capacitor .

If there is no pre-insertion resistor (Rp=0), the current I1isthe sum of Is, Ic and I3, whose mathmatical solution can be easily found in a circuitstheory book. But when using a pre-insertion resistor the mathematical resolution is much more complicated, as the system is described by morecomplex differential equations (1)

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

To calculate the pre-insertion resistor value, there are two techniques that can be used:

•Use the Energy Equations;

•Use the Differential Equations;

A. Energy Equations

This method is based on some approximations and it is not 100% accurate, but by other hand it is much easier and faster than solve the differential equations. The energy equations method calculates the energy that should be dissipated on the pre-insertion resistor, in order to damp the DC component (2):

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

The energy dissipated in the pre-insertion resistor is calculated by the integral on (3), whose limits are the time during which the pre-insertion resistor is connected, 0s to 10ms:

$$W = \int P dt \Leftrightarrow \int_0^{0.01} R_p I_1^2 dt \qquad (3)$$

Considering that the current I1 decreases linearly (this is an approximation, but as Rp is large the error is small), and neglecting Rs (it is dozens of times smaller than Rp), (3) can be substituted by (4), and the value of Rp is calculated using (6).

$$W = 0.01 R_p \left(\frac{I_1(0)}{2}\right)^2 \qquad (4)$$

$$0.01 R_p \left(\frac{I_1(0)}{2}\right)^2 = \frac{1}{2} L_s \left(I_s^{DC}\right)^2 \Leftrightarrow 0.01 R_p \left(\frac{1}{2}\right)^2 = \frac{1}{2} L_s \qquad (5)$$

$$R_p = \frac{2L_s}{0.01} \qquad (6)$$

Because of the simplifications made this method is not very accurate, and while for a situation of maximum DC component the error is not very big, when the DC component is reduced the error increases.

B. Differential Equations

Unlikely in previous method, in the method based on the differential equations no simplifications are made. The system is modelled by (1), and the equations presented in appendix are used in the calculations.

To calculate the value of Rp a Matlab code was written. It consists on an iterative process, where in each iteration Rp is increased, until it reaches a value for which the DC component is damped in 10ms.

To verify that the DC component was damped, it is calculated the peak value of IS 10ms after the connection. To that value be equal to the amplitude of the AC current, it is required to have the DC component equal to zero, so if the calculated value is equal to (7) plus a small tolerance the iterative process stops.

$$I_s^{peak} = \frac{V_2}{\sqrt{R_s^2 + \left(\omega L_s\right)^2}} \qquad (7)$$

The value of the pre-insertion resistor depends on the initial value of the DC component, but the DC component depends of the connection moment, which is unknown. So it was decided to solve the equations for the worst case scenario, maximum DC component, to that case the calculated value of Rp is ideal, to the other cases there is a small error.

4. 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 trasients 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.

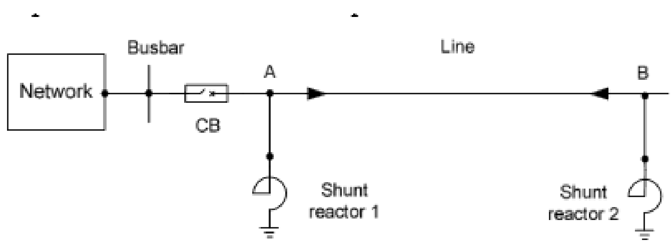

Fig. 2 Generic model for energization transient analysis of a compensated transmission line

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,

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

Here, the symbols of Q 1SR and Q 2SR correspond to the rated reactive power of shunt reactors 1 and 2. The symbol of Qline represents the rated capacitive charging power of the transmission line that is given by,

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

the symbols of Vr and fr 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.

5. SIMULATIONS

A.ONLY LINE ENERGIZATION

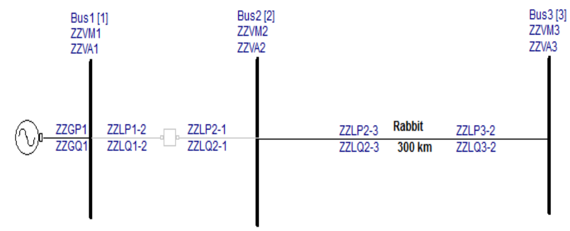

Figure 3: Network Considered For Simulation

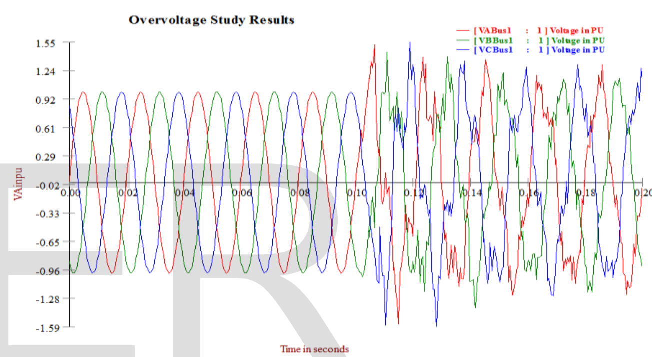

Figure 4: Phase voltages at receiving end bus.

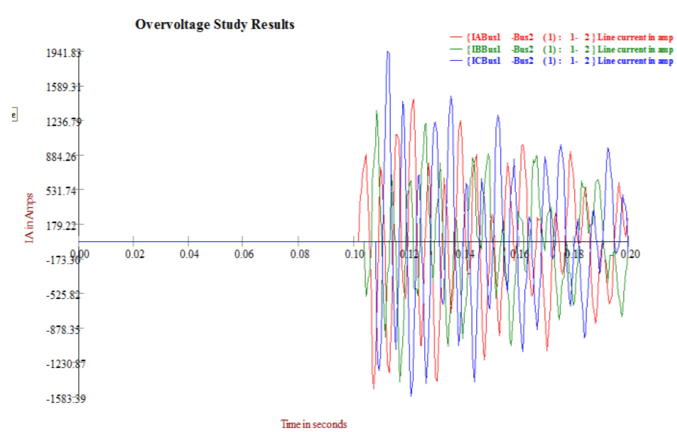

Figure 5: Phase inrush current drawn by line

B. LINE ENERGIZATION WITH PRE INSERTION RESISTOR

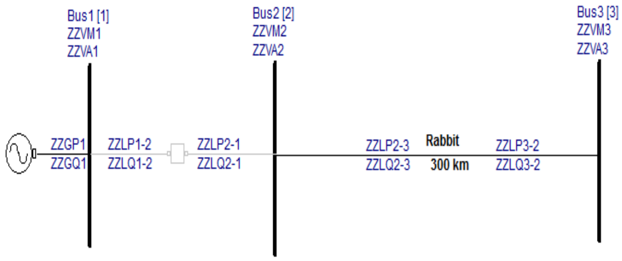

Figure 6: Network Considered For Simulation

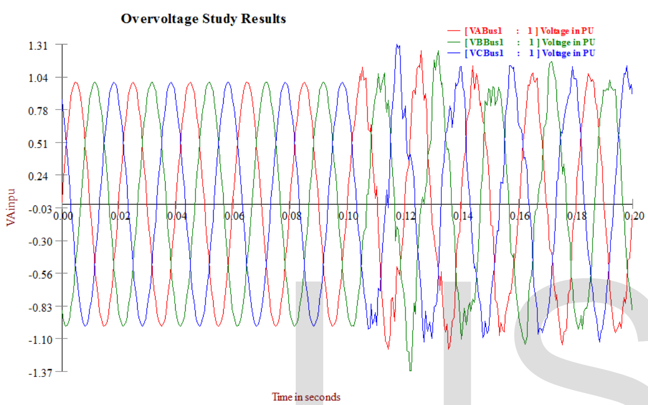

Figure 7: Phase voltages at receiving end bus.

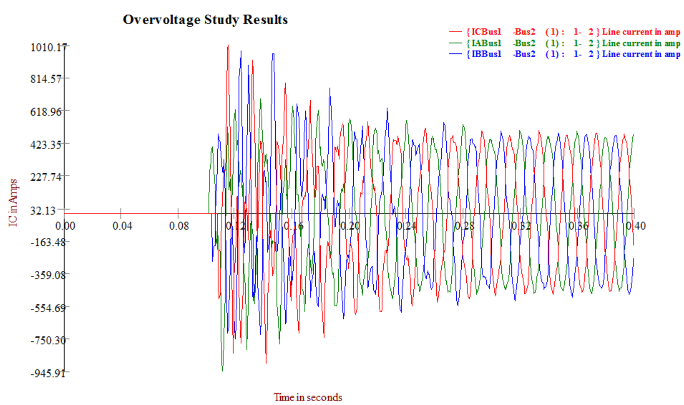

Figure 8: Phase inrush current drawn by line

C. LINE ENERGIZATION WITH SHUNT REACTOR.

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 [1].

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.

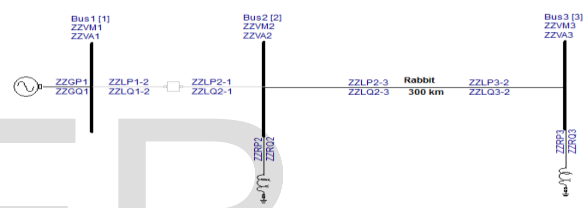

Figure 9: Network Considered For Simulation

Figure 10: Phase voltages at receiving end bus.

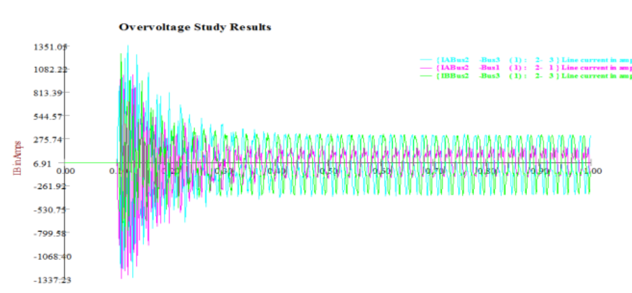

Figure 11: Phase inrush current drawn by line

Observation

For this case study, recorded maximum overvoltage graph is shown in Fig.10, and the maximum overvoltage is 1.54 p.u. Consider the switching impulse level of 400 kV system is 1050 kVp and insulation co-ordination safety margin as 25% i.e. switching overvoltage should not exceed the 80% of 1050 kVp i.e. 840kVp. For this case study, it is observed that the maximum switching overvoltage is 741 kVp and it is less than 840 kVp. However, the switching event is random in nature with point on wave closing. Hence one can carry multiple switching case studies by varying closing time over a cycle to find the maximum switching overvoltage.

It is also observed that, the magnitude of the switching overvoltages is reduced with shunt reactors. However, it is important to note that shunt reactors will be used to control the only steady state overvoltages but not for transient overvoltages. Since switching is random in nature with shunt reactors, may reduce switching overvoltages for few cases and may increase switching overvoltages for few cases (student can prove this by conducting various simulations). Hence, one cannot conclude that shunt reactor will control the switching overvoltages.

It is also observed that form the Fig. 11, the charging inrush current drawn by the line is 1351 peak and it is not harmful to line connected equipment such as breaker rated for usually 40kArms and above.

6. CONCLUSION

Switching overvoltages and zero-missing phenomenon are non-desirable phenomena that can happen when energizing cable lines. The use of a pre-insertion resistor in the circuit-breaker is an effective countermeasure to both overvoltage problems and existence of DC-component in the current of the circuit breaker.Furthermore using a pre-insertion resistor donot introduce any non-desirable effects on the system. As the value of the pre-insertion resistor depend of the closing moment of the circuit breaker it is not possible to have an ideal value for all possible cases. But independently of the closing moment the use of the pre-insertion resistor always substantially reduces the DC component responsible for zero-missing phenomenon, and the switching overvoltages. It is also concluded that if it is possible to control the closing moment of the circuit breaker and it can operates in single-pole mode, it is possible to completely avoid both phenomenon. For that it is required to use a pre-insertion resistor with an accurate value that must be precisely calculated, and use a circuit breaker closing its phases independently when the voltage in each one ofthem is crossing zero.

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