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GE Power Management

Control Circuit Transients

Control Circuit Transients - Part 1

Application of solid-state controls to EHV systems requires an understanding of surges. Here is an explanation of how surges are caused and how you can cope with them.

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It has been well established by field experience that transient potentials of significant magnitudes (several kv) can be induced in the secondary cables and d-c control wiring in switching stations. These overvoltages may be present during ordinary operating conditions. Commonly, they have been referred to as surges.

With the introduction of high-speed solid-state relay equipment and other solid-state control equipments, the normal presence of these surges has taken on increased importance. This is due to both the fast response of semiconductor devices and their susceptibility to damage by surges. Concurrent with the advent of solid-state relays has come the introduction of higher and higher voltage systems. This also has affected the situation adversely, because the magnitude of surges in station control circuits on EHV systems tends to be more severe than on lower-voltage systems. Successful application of solid-state equipment and controls to EHV systems requires, therefore that engineers understand surges – what causes them, how they get into control circuits, and what can be done to prevent false operation or damage to the protective relay system.

We will deal here with the theoretical aspects of one of the most common causes of surges. In particular, the various ways by which surges from this source can be coupled into the control circuit will be examined in detail. For purposes of discussion, consider that there are two classes of electrical conductor systems in a high-voltage switching station. These are described as follows:

1. EHV Power Circuits: All of the EHV buses and apparatus, primary circuits of instrument transformers and devices and all circuits operating at high potential; also, the ground grid and apparatus grounds.

2. Control Circuits: All instrument transformer secondary circuits, all

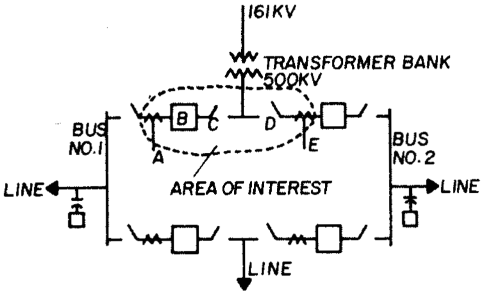

Fig. 1. One-line diagram of typical 500-kv switching station.

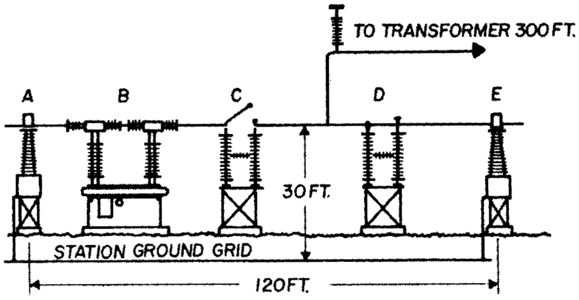

Fig. 2. Elevation view of part of EHV station.

battery, d-c control, a-c auxiliary power, protective relaying and communication circuits; normally, these circuits will operate at potentials of only a few hundred volts or less.

Of necessity, these two classes of conductor systems are located in near proximity (with due regard for insulation distances). They can be quite close inside of EHV apparatus such as current and potential transformers (CT's and PT's). They can also be quite close in the ground system. A consequence of this proximity is that both intentional and stray electromagnetic coupling will exist between these systems. It follows, therefore, that an electrical disturbance in one of the systems will result in a coupled or induced effect in the other.

A disturbance in the EHV system, even though small, can result in a relatively large effect in the control-circuit system. The transient potentials and currents resulting can be orders of magnitude greater than the normal operating values for the control circuit. Another consideration is the effect of disturbances in one control circuit on another, or upon equipment in the same circuit. This generally causes transient of lesser magnitude [7, 8, 9, 10].

Sources of transients

A number of phenomena that occur on EHV systems give rise to transient electromagnetic field disturbances and induce transient potentials in secondary or control circuits. Some of these sources are: (a) switching of shunt capacitor banks in parallel, (b) flashover of protective gaps due to overvoltages; (c) restriking of a circuit breaker and (d) switching a section of EHV bus by an air break disconnect switch.

Doubtless, the list should be much longer. The sources given merely serve to illustrate types of phenomena which can induce control circuit transients. They are given in their approximate order of severity; the most severe, but not the most prevalent, is switching of parallel EHV capacitor banks. This phenomenon has been known to induce transient potentials of about 8 kv in control circuits.[1]

Probably the most prevalent source of surges is (d) – the switching of a section of EHV bus by an air break disconnect switch. Several papers have been written on this subject.[2, 3, 4, 5.]

However, it is still one of the most elusive of the phenomena that occur in a switchyard. Some rather elaborate explanations have been proposed relating the frequency (wavelength) of the transients generated to the length of the buses. Actual frequencies measured in the field, 300 kHz to 1.5 MHz, do not, however, lend support to these explanations, as they

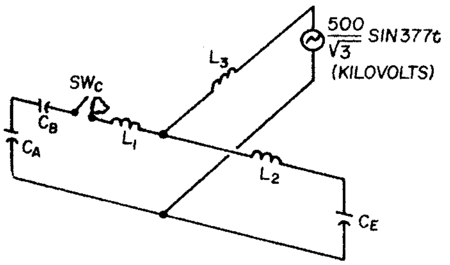

Fig. 3. Equivalent circuit.

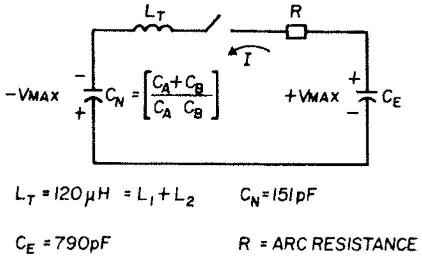

Fig. 4. Approximate equivalent circuit.

would indicate unusually long bus structures. It is more probable that other parameters, in addition to the length of the buswork, also affect the character of these transients, notably the shunt capacitance to ground of various apparatus. For example, the capacitance of coupling capacitor potential devices (CCPD's) and bushing capacitances of CT's, trans-formers, circuit breakers, etc. In fact, when these parameters are included in the analysis, rather good agreement is obtained with actual field data.

Role of the shunt capacitance of EHV apparatus can be illustrated by an example. Consider the EHV switching station shown in one-line diagram form in Fig. 1. It consists of a ring bus structure. Notice the area of interest encircled on the diagram. It contains two current transformers, A and E; a circuit breaker, B, and two disconnect switches, C and D. Consider the case where all of the breakers are open, all of the disconnect switches in the station are open except C and D, and the transformer bank is excited from the 161-kv side.

Switch C is then opened. Figure 2 shows an elevation view of the area of interest. The dimensions shown are important. The two CT's are 120 ft apart and the EHV conductor connecting the apparatus is 30 ft above the ground grid. Only one phase is shown, but similar arrangements exist for the other two phases.

Disconnect switch C is opened and a restriking arc occurs between its arms, making and breaking the charging current flowing into the open-breaker voltage-dividing capacitance and the CT-bushing capacitance in series. This transient disturbance causes a train of damped oscillatory currents to flow around a loop in the vertical plane consisting of the two CT bushings, the open-breaker capacitance, and the loop inductance in series. Figure 3 shows the equivalent circuit. In this circuit the total self inductance of the loop in the vertical plane between the CT's is represented by L1 and L2 in series, as shown. The bushing capacitances of the CT's are CA and CE. The capacitance across the open circuit breaker (the built-in voltage equalizing capacitors) is CB. The inductance of the long loop back to the transformer bank is shown as L3. The 60-Hz voltage source equivalent of the transformer is also shown.

Using the dimensions given in Fig. 2 and assuming that all of the conductor diameters are 1 in., the loop inductances L1, L2, and L3 can be calculated approximately as 60 μh, 60 μh, and 268 μh respectively.[13]

Now consider the phenomenon occurring when the disconnect switch is opening. As in line dropping by a circuit breaker, capacitors CA and CB in series are left with a trapped charge so that the static potential on one side of the switch will be V max. Meanwhile, a half cycle later the 60-Hz source will have reversed the potential on the opposite pole of the open switch causing the potential across the switch to be 2 x V max. Assume that the switch cannot withstand this difference of potential and the gap breaks down. Then an oscillatory discharge will occur giving rise to high frequency currents in the vertical plane loops. For the case illustrated, the dominant oscillation occurs in the loop between the two CT's.

It is very easy to estimate the magnitude and frequency of this current. An approximate equivalent circuit is shown in Fig. 4 in which the loop to the transformer is eliminated because it has a minor effect. CN is the equivalent of CA and CB in series. The potentials on CN and CE just before the switch restrikes are -V max, +V max, respectively. The resistance of the arc is represented by R. Analysis of this circuit gives the equation and waveforms shown in

Fig. 5, which shows that a transient damped oscillatory current of 830 amp peak value and a frequency of 1.3 MHz will flow in the loop.

Referring back to Fig. 2, it can be seen that these high-frequency transient currents flow not only in the buswork, but also in the CT's and their ground connections, and in the ground grid. Because the high-frequency currents flow in the ground grid, there exists both capacitive and magnetic couplings to secondary and control wiring due to their proximity to the ground conductors.

Coupling to control circuits

Both capacitive and magnetic coupling of surges from EHV circuits to the control circuits can take place inside of various EHV apparatus (notably in CT's, PT's and CCPD's), and external to these equipments by distributed mutual inductance (flux linkages) and capacitance between the two systems. In any given installation all modes of coupling are present to various degrees. Switchyard designers are becoming increasingly aware of the need to minimize external coupling by proper routing of cables, shielding, and attention to grounding practices. However, the coupling which is internal to EHV apparatus is beyond

$$I = \left(\frac{2V_{MAX}}{\sqrt{\frac{L_T}{C_T}}}\right) \epsilon^{-\frac{Rt}{L}} \; SIN \frac{1}{\sqrt{LC}}\, t$$

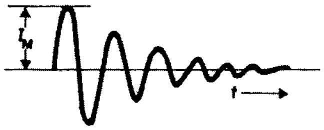

Fig. 5. Waveform of oscillatory current.

$$I_M = 830 \text{ AMPERES}$$

$$f = \frac{1}{2\pi\sqrt{L_T C_T}} = 1.3 \text{ MHZ}$$

$$C_T = \frac{C_N + C_E}{C_N \; C_E} = 127 pF$$

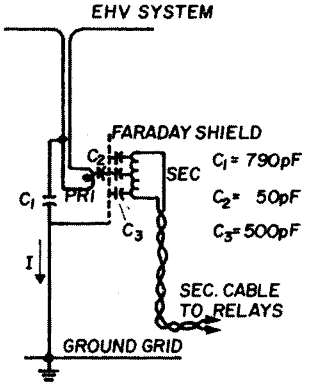

Fig. 6A. High frequency equivalent of EHV transformer.

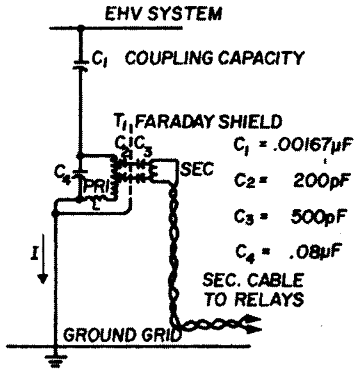

Fig. 6B. High frequency equivalent of EHV coupling capacitor potential device.

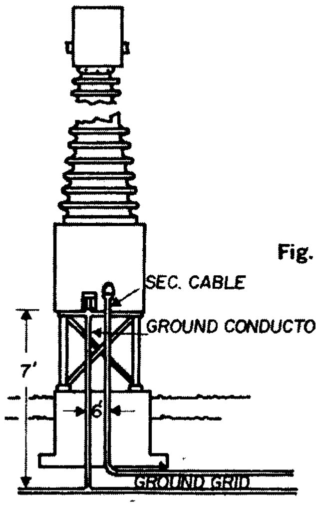

Fig. 7. EHV current transformer installation.

their control. It seems reasonable for theoretical reasons, that this internal coupling may be a major factor in determining the surge level on the control circuits, even when good shielding has been provided. The arcing-disconnect surge source will be used again as an illustration.

Consider the high-frequency equivalent circuit of a typical EHV CT as shown in Fig. 6A. At a frequency of 1.3 MHz, the stray capacitances of the windings to shield, core, case, etc., become important parameters in determining the overall surge performance. The capacitor C1 represents the bushing capacitance (790 pf). C2 represents the capacity of the primary to the internal shield (about 50 pf), and C3 is the distributed capacity of the secondary winding to the shield, core, and case (about 500 pf). The surge current, I, flows to ground via the ground connection to the CT. This ground connection plays a very important role in the surge picture. Its physical relation to the secondary cable determines the surge voltage which is impressed between the secondary cable and the ground mat.

Capacitance C3 closes the loop (for the surge frequencies) around the area between the ground connector and the secondary cable. When the surge current flows in the ground lead, high-frequency magnetic flux encircling the current links this loop, giving rise to a high-frequency transient voltage in the loop. The magnitude of this transient voltage depends on the frequency and magnitude of the surge current, the size of the loop, and the size of the various conductors. An accurate analysis is not feasible because of the complexity of the geometry in actual installations; however, a few simplifying assumptions can be made to permit simple calculations giving usable *ball park* answers.

The voltage induced in this loop and coupled to the cable via C3 appears on both secondary conductors with respect to ground. This is the so-called longitudinal or common mode. If C3 is not distributed uniformly, both secondary cable conductors will not have the same potential impressed upon them, and the lateral or transverse mode will be present in addition to the common mode. This is often the case.

Similar effects are present in coupling capacitor potential devices. Figure 6B shows the high-frequency equivalent of a potential device. Here again C3 is the capacitance which closes the loop between the ground connection and the secondary cable. Because CCPD’s are generally mounted on higher pedestals than CT’s, this loop tends to be larger than for CT’s. It is easy to see that proper routing of the secondary cable to follow the ground connection closely would reduce the loop greatly in either case and, hence, cause a reduction of the common mode surge voltage.

Consider now the question of how much voltage would be induced in this loop at the base of a CT or CCPD in a typical installation during restriking of the disconnect switch. Assume that a CT is installed as shown in the sketch of Fig. 7. Calculations are simplified considerably by neglecting the proximity of the steel support structure, and the magnetic flux around the ground conductor is assumed to have simple cylindrical geometry. In this sketch the horizontal distance between the CT-housing ground conductor and the secondary cable is 6 in. The ground conductor is assumed to be 300 MCM cable. The base of the CT box is 7 ft above the ground grid. Magnetic flux surrounding the surge current in the ground threads through the area between the secondary cable and the ground conductor. The time rate of change of the flux linkages in this area gives the induced voltage:

$$V_{max} = -\frac{d\phi}{dt} = \frac{d}{dt}$$

$$\left[2 \times 10^{-7}\, l \left(\log_e \frac{D}{r}\right) I_{max}\right] \quad (1.0)$$

$$V_{max} = 4\pi f\, I_{max}\, l$$

$$\left(\log_e \frac{D}{r}\right) 10^{-7} \text{ volts} \quad (1.1)$$

where
f = surge frequency (hertz)
I_{max} = max. value of surge current (amperes)
l = length of ground conductor (meters)
D = distance between the ground conductor and the secondary cable (meters)
r = radius of ground conductor (meters).

Substituting values in equation 1.1 we get:

$$V_{max} = 8500 \text{ volts.}$$

This is a substantial voltage! It appears in the common mode between the secondary cable and the ground grid via the stray capacitance of the CT secondary winding to the Faraday shield, core, and case.

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Control Circuit Transients-Part 2

Conclusion of a discussion of voltages induced into control circuits by surges in EHV systems. Progress is called for in the design of equipment and station layout

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For high frequency common mode surges which are coupled to the secondary cable, the cable appears as a two wire transmission line with respect to the ground grid. At the frequencies of interest, its length is an appreciable fraction of a wavelength. If we assume that it is a uniform distance from a ground conductor lying in the cable trough, then we can calculate its surge impedance approximately by making some assumptions as to its effective diameter. Also, the loop at the base of the CT has self inductance which must be considered as well as the internal capacitance of the CT (C3). Let it be assumed that the cable from the CT to the relays is 500 ft long and is spaced 12 in. from a 300-MCM ground grid conductor along its length. Assume also that the secondary cable bundle has an effective diameter of about 0.63 in., the same as the 300-MCM cable. Figure 1 then shows .he complete high-frequency equivalent circuit of the secondary cable/base loop for common mode voltages. Making use of the lossless transmission line equations, it is now a simple matter to calculate the open circuit voltage and short circuit current available at the receiving end (at the relays). The following relations are useful:

(1) surge impedance to two conductor line, ohms

$$Z_O = 120 \log_e \frac{2D}{d}$$

(2) sending end impedance with receiving end open, ohms

$$Z_{S\text{-}OC} = Z_O \frac{l}{\tan \beta l}$$

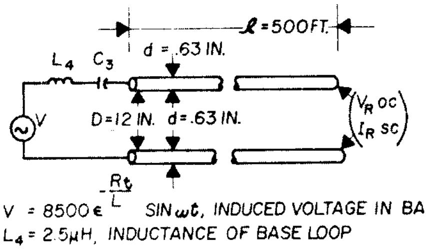
(3) sending end impedance with receiving end shorted, ohms

$$Z_{S\text{-}SC} = Z_O \tan \beta l$$

(4) phase constant, radians/meter

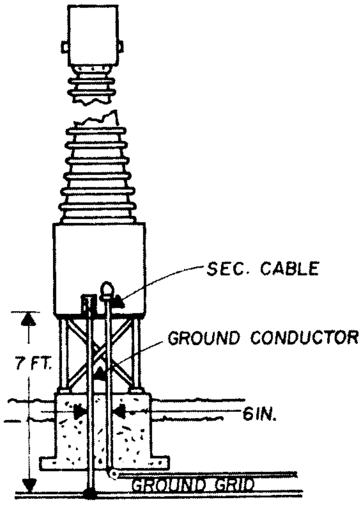
$$\beta = \sqrt{ZY}$$

(5) series impedance per unit length, ohms/meter



$V = 8500\epsilon^{-\frac{Rt}{L}} \sin\omega t$, INDUCED VOLTAGE IN BASE LOOP
$L_4 = 2.5\mu H$, INDUCTANCE OF BASE LOOP
$C_3 = 500pF$, CAPACITANCE OF C.T. SECONDARY

1. Equivalent circuit of the secondary cable system.



2. EHV current transformer installation.

$$Z = \omega \left[2 \times 10^{-7} \log_e \frac{2D}{d} \right]$$

(6) shunt admittance per unit length, mhos/meter

$$Y = \omega \left[\frac{1}{36 \times 10^9 \log_e \frac{2D}{d}} \right]$$

(7) angular frequency of surge voltage, radians/sec.

$$\omega = 2\pi f$$

(8) source impedance, ohms

$$Z_1 = j \left(\omega L_4 - \frac{1}{\omega C_3} \right)$$

where:

1 = cable length, meters
D = distance between cable and ground conductor, meters
d = diameter of cable and ground conductor, meters

In Figure 1 the source voltage, V, is the induced voltage in the base loop. The receiving end voltage, open circuit, is then given by:

$$V_{R\text{-}OC} = V \left[\frac{Z_O}{Z_1 \, j \sin \beta l + Z_O \cos \beta l} \right] \quad (2.0)$$

For the example given: VR = 9500 v and the receiving end short circuit current is:

$$I_{R\text{-}SC} = \frac{V}{Z_1 \cos \beta l + Z_O \, j \sin \beta l}$$

For the example given: IR = 29.8 amp.

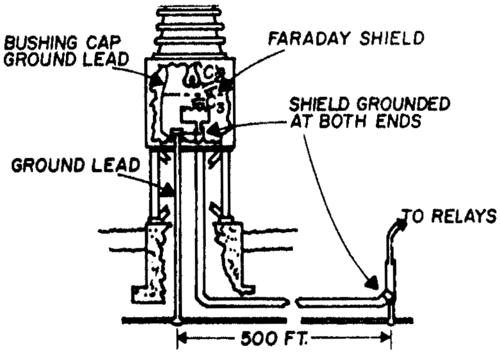
Taking the ratio of the open circuit voltage and short circuit current at the receiving end of the cable-ground pair, the effective source impedance of the common mode surge is obtained:

$$Z_{S\text{-}CM} = Z_O \left(\frac{Z_1 \cos \beta l + Z_O \, j \sin \beta l}{Z_1 \, j \sin \beta l + Z_O \cos \beta l} \right)$$

$Z_{S\text{-}CM}$ = 320 ohms

The foregoing example used many assumptions to simplify the calculations. The effect of these assumptions is to give voltages and currents greater than those actually occurring in practice. For instance, a secondary cable which is buried in earth rather than laid in a trough would have considerable losses at 1.3 MHz for common mode potentials. Other cables laid in the trough were ignored. Their presence will lower the receiving end voltage. The well-defined geometry of the loop at the base of the CT is probably not typical of most installations, and the effect of the conducting support frame on the flux in the loop was ignored. Also, in Fig. 2 only one ground connection for the CT was shown. Two would be more likely. This would divide the ground current, and result in lower induced voltage in the loop. In the primary loop, the presence of parallel phases and their loops was ignored.

For all of these reasons, and others, it is concluded that this analysis gives high values and that actual values may be only a third as much, or even less. On this basis, one could expect common mode surge voltage levels on unshielded secondary cables caused by disconnect switch operation in 500-kv stations to be about 3 kv, with frequency content of about 1 MHz and a source impedance of about 300 ohms.



Effect of shielded cables

What about shielded cables? There has been much discussion pro and con recently about the necessity for using shielded cables in EHV switchyards. In 1960, Berger[1] in the Bulletin of SEV published a very complete study of the effect of shielded cables on surges in CT and CCPD secondary circuits. He published data comparing the measured open circuit voltage (common mode) at the receiving end for unshielded cables and for cables having a conducting shield grounded at both ends. With the shield grounded at both ends the measured voltage was less than 1/400 of the voltage on the unshielded cable. Similar results have been published by others in this country and abroad.[2, 3, 4, 5] There are many EHV stations that do not have shielded secondary cables and others that do. Reports on surge experience do not always correlate with the type of installation. Other variables seem to be at work which confuse the issue.

It will be instructive at this point to apply the method of the previous example to an installation having a shielded secondary cable. Figure 3 shows the installation. It is similar to that of Figure 1 except that the secondary cable has a conducting copper sheath 0.01 in. thick which is grounded at the CT_5 housing and at the relay house. It is pointed out in the reference cited that this shield effectively shorts out the base loop. This gives rise to a circulating transient current in the shield which in turn produces a magnetic field opposing the field around the ground lead. As a result, the only voltage that can be induced in the secondary cable is the induction occurring between the cable conductors and the inside surface of the shield. This is determined by the transient current density on the inside surface of the shield. Skin effect is quite marked at the high frequencies encountered in these surges, and conductivity of the shield is high; hence, the internal field is usually quite low. The shielding is thus very effective. Circulating current in the shield will be the same as the receiving-end short circuit current, i.e. about 29.8 amp. Resistance of the sheath, end to end, calculates to be about 0.094 ohms. The IR drop end to end is then:

$$V_{SH} = IR = 29.8\ (0.094) = 2.8 \text{ volts}$$

At a frequency of 1.3 MHz the skin depth for copper is only about 0.0026 in. Therefore, most of the field is external to the shield and the induced voltage on the secondary cable should be less than one volt.

As usual, according to Murphy's law or some other profound physical principle, field data do not always indicate so large a reduction of the common mode voltage by the shield. In fact, some data show potentials of a few hundred volts with the shield in place and grounded at both ends.[2] Except for measurement errors, which do not seem to be evident, there is no explanation of this phenomenon except that there must be additional coupling mechanisms that have not been considered.

All of the flux linkages external to the current transformer have been considered and the grounded shield minimizes these greatly. The only place left is inside of the current transformer case. Figure 3 shows that there are still areas that can be linked by transient magnetic flux inside the case. The ground on the bushing capacitance tap and the ground on the Faraday shield both carry transient magnetic flux. The capacitance of the secondary winding to the Faraday shield C3 again closes the loop. If we assume that this internal loop links one-ninth as much flux as the external base loop, the cable with the grounded shield can still experience a driving potential of almost 1000 volts in series with C3.

Another difference is the lower surge impedance of the cable inside of the shield. This will be about 75 ohms or less. The major element in the source impedance is C3, which is about 245 ohms at 1.3 MHz. It seems reasonable, therefore, to expect that the voltage impressed on the cable will be less than one-fourth the source voltage, or about 250 v. Also, the short-circuit current available between the cable and the shield at the receiving end will be about 4 or 5 amp. Field measurements seem to confirm these approximate values.

Nature of most switching surges in EHV stations is oscillatory. This causes oscillatory transients to be induced in the secondary cables which can have values exceeding several kilovolts.

Physical arrangement of the conductors in a switchyard is a most important factor affecting surge voltage levels. This applies to the EHV conductor system as well as the control system cables. Equally important, however, are the capacitances to ground of the various EHV apparatus such as CT's, PT's, and potential devices. The capacitance of the secondary winding to the internal shield, core, and case is a vital link. It establishes the loops, internal or external to the CT case, in which transient flux linkages produce large transient common mode voltages which are then propagated along the secondary cable.

A lesser factor which influences the common mode surge voltage level is the length of the secondary cable relative to the surge freqeuncy wavelength. Theoretically, except for odd numbered half wavelengths, this causes an increase in the common mode surge voltage. Actually, high-frequency losses tend to mitigate this effect.

It has been well established by theory and field test data that a conducting sheath, grounded at both ends, greatly reduces the common mode surge voltage in a secondary cable. Instances wherein the shield is not highly effective have been reported. It seems probable, according to theory that in these cases additional coupling exists internally in the CT, PT, or potential device. Further field investigation needs to be done to establish the nature of this coupling and to find ways to eliminate it by improved design or corrective approaches on existing apparatus.

An important factor affecting the source impedance of the surges, as seen from the relays, is the capacitance of the secondary winding to shield, core, and case. Another is the common mode surge impedance of the secondary cable and ground grid treated as a length of transmission line. For non-shielded cables, a value of 300 ohms is a good ball park figure. Considering that a 1.0 microfarad capacitor may have only 0.1 ohm reactance at the surge frequency, as a shunt surge suppressor, it should reduce the common mode surge level over 2000 times, if properly installed with short leads.

Looking ahead to the future when transmission voltages of 1000 kv or greater may be common, it appears almost certain, based on past experience, that the surge voltage levels on station control wiring will increase more than proportionally. One author[1] has related it to the third power of system voltage. if so, these surges may be measured in tens of thousands of volts. While it is technically possible to build relay and control equipment including electromechanical relays and secondary cable systems to withstand these voltages, it may not be economically feasible to do so.

Recently, plans have been announced by several power companies to install high-speed digital computers in EHV substations. This places an added emphasis on the need to come to grips with the surge problem if these highly complex data and control systems are to operate reliably.

Progress in solving the surge problem must be made in three areas. First, the equipment manufacturers must continue their present efforts to make their products more immune to surges. Second, the greatest gains can be made by electric utilities in the proper design of station layout with due consideration for transient electromagnetic effects. Finally, methods must be developed to recognize and minimize all parasitic coupling in CT's. PT's, potential devices and other apparatus.

Editor's Note: Part I of this article was in the January issue of Power Engineering.

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