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Theory of Shielding and Grounding of Control Cables to Reduce Surges

THEORY OF SHIELDING AND GROUNDING OF CONTROL CABLES TO REDUCE SURGES

by

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INTRODUCTION

Previous authors have discussed the nature of surges in control circuits of power stations, their causes, and the various techniques which both the utility engineer and the equipment designer can apply to minimize surges and their effects on control equipment. This paper will discuss the basic theory of shielding and grounding of control cables as one of several techniques for reducing surge voltage levels in control circuits.

SOURCES OF SURGES

There are two general sources for surges found in control circuits on switching stations. These are, first, switching phenomena on the high voltage system, and second, switching on any of the low voltage electric systems in the station including the control system itself. The subject of cable shielding is concerned chiefly with sources outside the control circuit, the most severe being those originating on the high voltage system.

CHARACTERISTICS OF SURGES

The nature of surges originating on the H.V. system is of particular importance. Briefly, they usually have a high frequency oscillatory nature, lightly damped and are produced during operation of various switching devices in the station. Frequencies from a few hundred kilohertz to several megahertz are common. They originate in a sudden redistribution of trapped charges on various lumped and distributed capacitances in high voltage equipments during restriking and clearing of switching devices. The self inductances of bus sections, vertical connections to equipments, and portions of the station ground system are also involved in determining the surge characteristics and also to a large degree establish the location and severity of the surge coupled into the control circuit.

The high voltage system in a station along with the various capacitance paths (in equipments) to the ground mat, and the mat itself together form a large cage-like three dimensional matrix as shown in Figure 1. During a surge, large transient oscillatory currents and voltages exist in this structure. These are accompanied by very strong, rapidly changing electric and magnetic fields.

COUPLING TO THE CONTROL SYSTEM

Threading through the high voltage matrix near the surface level routed to the various high voltage equipments, are the control cables. They are literally immersed in the intense transient electric and magnetic fields in this region during a surge. This proximity accounts for the coupling between the two systems which is responsible for the transfer of surge energy from the high voltage system to the control system.

Coupling in this region is mainly a function of the geometrical relationship between the two systems. This suggests proper control of this relationship as a means of reducing the coupling. This is a feasible, but not 100 percent effective technique, because there are also many other factors affecting station layout which may at times conflict with low coupling requirements. Nevertheless, physical location and routing of control cables, especially near high voltage equipments, is an important factor, which should be carefully considered in designing low surge level stations.

ELECTRIC FIELD COUPLING

Figure 2 shows the electric field mode of coupling between a transient voltage on a high voltage bus element and a parallel control cable beneath the bus. The transient electric field between the bus and the ground mat impinges on the control cable as well as on about every other metallic object in the vicinity. This results in establishing the control cable at some intermediate transient potential. From the circuit point of view we say there exists capacitance between the bus and the control cable, and between the control cable and the ground mat. These capacitances act like a voltage divider connected to the control cable.

MAGNETIC FIELD COUPLING

In Figure 3 the transient magnetic field associated with the transient current in the bus links the area between the control cable and the ground mat. Because of the high frequency of the surge current, the rate of change of this magnetic field is extremely rapid. This makes it possible to induce a rather large transient voltage in a modest size loop some distance from the bus.

SUPERPOSITION

The previous several paragraphs have illustrated by simplified diagrams, the presence simultaneously of two modes of coupling to the control circuit. Since the same surge on the high voltage bus produces both modes simultaneously, one might wonder if and how they add together in the control circuit. Actually, the complexity of a real system makes it dangerous to extend simple picture theory to answer this question. Fortunately we do not need to answer it in order to explain the operation of a cable shield. This explanation can deal with the effect of the shield on each coupling mode separately. In short, the principle of superposition applies.

TERMINATING DEVICE CAPACITANCE

Control cable circuits in switchyards terminate at the outdoor end in some type of electrical device such as a simple switch, a coil on an electromagnetically operated valve, a transformer secondary winding, an auxiliary relay coil, etc. All of these terminating devices have capacitances to the local ground. The value is small, a few hundred picofarads being typical. However this small capacitance is only a few hundred ohms impedance at typical surge frequencies and it closes the circuit from the control cable to the ground mat allowing transient currents to flow between the ground mat and the cable.

UNSHIELDED CABLES

Figure 4 shows an equivalent circuit of an unshielded control cable. In this circuit, Vr is the transient voltage between the cable conductors and the local ground at the receiving end. Vm is a voltage source which represents the magnetically induced transient voltage in the ground loop circuit composed of the control cable, the control device capacitance C3 and the ground mat. The magnitude of this voltage is:

$$V = M \frac{dIs}{dt}$$

where M is the mutual inductance between the cable circuit ground loop and the primary surge loop. With this equation we can estimate the approximate severity of magnetically induced voltages on unshielded cables. If we assume the following typical values:

M = 1.0 microhenry
Is = 500 amperes
f = 1.0 megahertz,

then $Vm = (10^{-6})(500)(2\pi)(10^{6})$
$= 3141$ volts

Also shown in Figure 4 is a capacitor C1 which represents the capacitance between the bus and the control cable. C2 is another capacitor representing the total distributed capacitance of the cable to the ground mat system. These two capacitors, with C3 the terminating device ground capacitance, form a voltage divider. In typical stations it may have a step down ratio of about 100. This means a 300 kV surge on the high voltage bus would result in a surge on the control cable of about:

$$Vr \approx (.01)(300 \times \omega^{3}) \approx 3000 \text{ volts}$$

THE SHIELDED CABLE

The equivalent circuit is shown in Figure 5. This is essentially the same circuit as Figure 4, but with the addition of a shield over the secondary cable with switches shown to allow various grounding arrangements to be made. The distributed capacitance between the cable and the shield is C4. It depends on the length and size of the cable. A good average figure is about 0.01 microfarad for a shielded cable 500 feet long.

CABLE SHIELD GROUNDED AT THE SENDING END

Assume that switch SW-l is closed so that the shield is connected to the apparatus ground wire at the sending end. The fact that the shield completely encloses the cable prevents the transient electric field from terminating on the cable. Thus the displacement currents to the shield through C1 are diverted to ground at the sending end. For all practical purposes this eliminates the transient voltage on the cable due to the electric field.

An entirely different situation prevails for the magnetically induced potential Vm. With SW-1 closed this potential appears directly on the shield and is capacitively coupled to the cable via C3 and C4 in parallel. Grounding the shield at the sending end has no effect on the magnetically induced transient.

CABLE SHIELD GROUNDED AT THE RECEIVING END ONLY

Closing only SW-2 grounds the shield at the receiving end. Again the shield prevents the electric field from reaching the cable, so the electric field component is eliminated. The displacement currents to the shield now flow to the ground mat at the receiving end.

For the magnetically induced component we now find that C3 is the only circuit element between Vm and the cable. The cable-to-shield capacitance C4 is now connected between the cable and ground so that C3 and C4 form a voltage divider. This reduces the surge voltage on the cable somewhat, the amount of reduction being more the longer the cable.

Summarizing, for the shield grounded at the receiving end, the electric-field-induced component is eliminated and the magnetic-field-induced component is only partially reduced.

CABLE SHIELD GROUNDED AT BOTH ENDS

In this case for the electric-field-induction the displacement currents to the cable through C1 are diverted to ground at each end and no transient voltage appears on the cable.

With grounds on the shield at both ends, a closed loop is completed in the cable and ground mat system. The transient magnetic field linking this loop induces the potential Vm which in turn causes a transient secondary current to flow in the loop. The magnetic field due to this induced current opposes the primary field so that the net field in the, loop is just sufficient to induce the total resistive and reactive impedance potential drop around the current loop. This current flows axially along the shield of the cable. Does the flow of this shield current affect the cable potential?

A path can be traced from the receiving end, along the cable to the sending end, through C3 to the shield, along the shield back to the receiving end ground. Does this path link any transient magnetic flux? If so, there could be a magnetically induced transient at Vr. There are only two locations for magnetic flux linkage in this loop: inside the shield between the cable and shield, and at the sending end in the small loop near C3. Let us assume we can eliminate the small loop at C3. We are left with the question of the possibility of flux linkages inside the shield.

Referring to Figure 6, we see a conducting cylinder, the shield, carrying a current along its length in the Z axis direction. The current is assumed to be uniformly distributed around the circumference of the cylinder. The cylinder is sufficiently long so that any end effects may be neglected.

Because of the orthogonal relation between a current and its associated magnetic field we can safely assume there is no magnetic field component anywhere in the Z direction. Also because of symmetry and orthogonality, it is possible to show the current produces no field component in the radial, r, direction. This leaves only the tangential, 0, component.

Also because of cylindrical symmetry, we can assume correctly that the Θ component of the field has no change in the Θ direction. This means that whenever the Θ component exists, its magnitude is constant for that radial distance from the Z axis. Mathematically, these relationships are expressed as follows:

$$H_z = 0$$

$$Hr = 0$$

$$\frac{\partial H\Theta}{\partial \Theta} = 0$$

$$\therefore H\Theta = \text{a constant}$$

Going now to Figure 7 we make use of Amperes Law to examine the behavior of HO. Figure 7 shows an end view of the cylinder. It shows two dotted circles, one outside the cylinder and one inside. These circles are the paths to be taken for a line integral as defined in Amperes Law, which states:

$$O\ H \cdot d\ 1 = I$$

where I is the current enclosed by the path. If there is no current enclosed, the integral must be zero.

For the circle outside the cylinder which does enclose the shield current, we get

$$0\ HO \cdot d\ 1 = HO\ (2\pi r) = I$$

or the field is $HO = \frac{I}{2\pi r}$

For the circle inside the cylinder, the path of the integral does not enclose any current, so

$$0\ H \cdot d\ 1 = HO\ (2\pi r) = 0$$

But this cannot be true unless HO = 0. Therefore, there is no tangential field inside the cylinder or shield. Also since the Hr and H_z components were zero everywhere, there is no magnetic field at all inside the shield and therefore, there can be no magnetic flux linkages, transient or otherwise, in this area. It follows, of course, that there is no magnetically induced transient voltage between the cable and the shield at the receiving end.

There is, however, one small transient potential caused by the magnetic field which is still present. This is the I R drop along the shield due to the flow of shield current. This appears in series with C3 and the cable. Generally it amounts to only a few volts if the shield is a good conductor.

Grounding the shield at both ends is a very effective means for greatly reducing the surge voltage level on control cables. It simultaneously eliminates both the electric-field and magnetic field-induced transients.

PROTECTING THE SHIELD

With the shield grounded at two points greatly separated, there is a risk that large potential gradients in the ground mat system during faults may cause large shield currents to flow, sufficient to damage the shielded cable. This is because the shield is generally not a very robust conductor. In such a case it has been found satisfactory to run a separate heavy conductor in parallel with the control cable and connected to the two shield ground points. This diverts the fault-induced currents away from the shield, preventing damage.

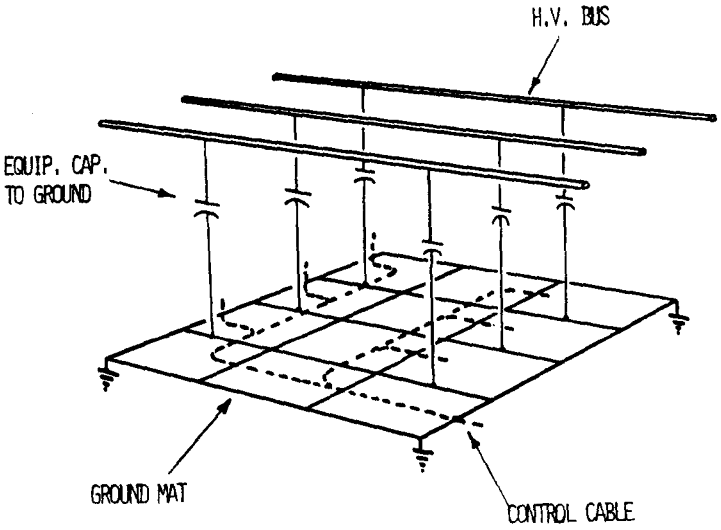


Figure 1. The H.V. Structure

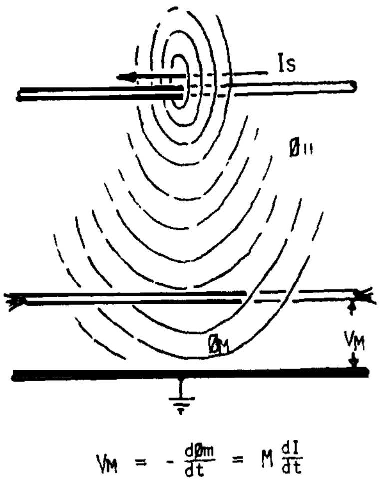


Figure 3. Magnetic Coupling

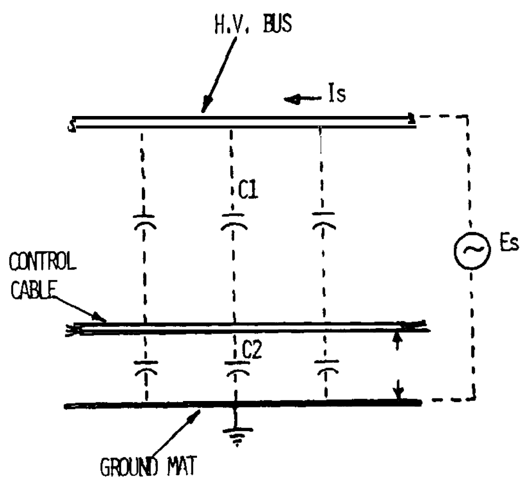


Figure 2. Electric Field Coupling

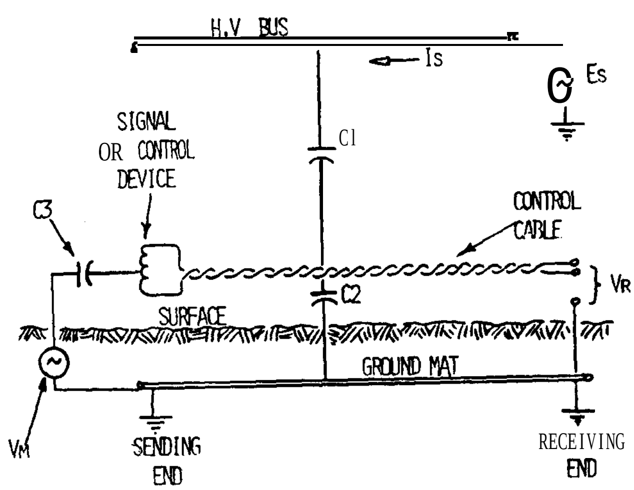


Figure 4. Unshielded Control Cable

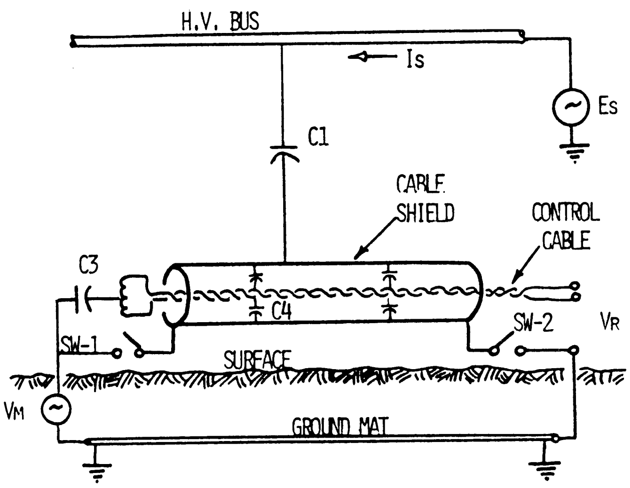
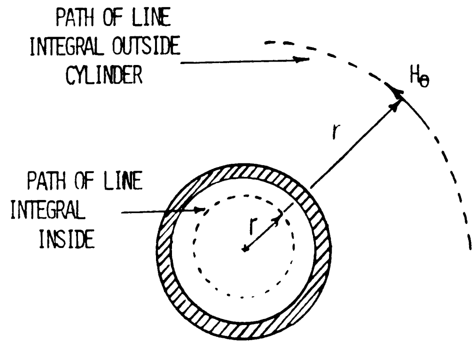


Figure 5. Shielded Control Cable



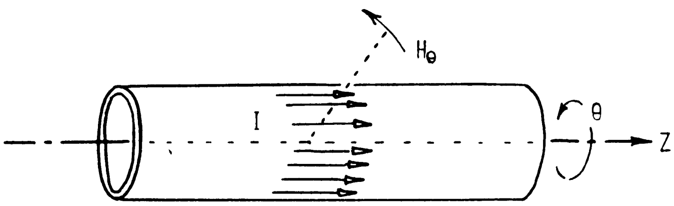
From Amperes Law, $\oint H \cdot d1 = I$, the current enclosed outside the shield: $\oint H\Theta \cdot d1 = H\Theta\,(2\pi r) = I$

so $H\Theta = \dfrac{I}{2\pi r}$

Inside, there is no current enclosed: $O\ H\Theta \cdot d1$
$= H\Theta\,(2\pi r) = 0$

But, if $H\Theta$ must be a constant, $H\Theta = 0$

Figure 7. The Magnetic Field Inside the Shield



With uniformly distributed axial current:

$H_z = 0$
$Hr = 0$ axial current only

$\dfrac{\partial H\Theta}{\partial \Theta} = 0$ by symmetry,

therefore $H\Theta$ = a constant

Figure 6. Magnetic Field Near a Conducting Cylinder

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