9. INTRODUCTION

The protection and control equipment in power plants and substations is influenced by various of environmental conditions. One of the most significant environmental factor is the disturbance voltage at the control and protection terminal.
The disturbance voltages are coupled to the terminals via the control circuits. To control the disturbance voltage the design of the control circuits is of outmost importance. By the control circuits design the coupling can be influenced and disturbance voltages can be rejected from the relay equipment.

10. DISTURBANCE VOLTAGE WITHSTAND CAPABILITY

The disturbance voltage can affect the relay by destruction of the equipment or interference with the operation of the relay. The disturbance can cause both loss of operation and false operation.

The withstand voltage against destruction is defined and tested by dielectric and impulse voltage withstand tests. The substation protection and control equipment is mostly tested according to following standards:
IEC publication 60255-5, insulation tests for electrical relays,
5.0 kv 1,2/50 μs 0.5 J as well as 2 kV (resp 2.5 kV for analogue circuits) 1 minute and the Insulation test >100 Mohm at 500 VDC.

The withstand capability against interference with the operation is tested according to:
IEC publication 60255-22-1 Class III, frequency disturbance test, 2.5 kV, 1 MHz damped oscillatory wave.
ANSI C37.90 Surge withstand capability tests, 2,5-3 kV 1 MHz damped oscillatory wave.
IEC publication 60255-22-4 Fast transient test Class IV 4kV.
IEC publication 60255-22-2 Electrostatic discharge test Class III 8 kV.

IEC publication 60255-22-3 Class III, IEEE/ANSI C37.90.2 Radiated electromagnetic field disturbance.

The disturbance voltage at the relay terminal must under all operational and primary fault conditions be within the limits set by the tests to achieve the full reliability of the protection and control equipment. Due to the practical impossibility to test or calculate all conditions to estimate the maximum overvoltage in a plant some margins are required between the estimate overvoltage and the test value. A 40% margin is often used and recommended by ABB if not the estimated maximum voltage is very well confirmed.

The latter can be the case with pilot wire protection relays with the pilot cable in a well defined geometrical position to the high voltage conductors for most of the pilot cable length.

11. SOURCE OF TRANSIENTS

In the power system transients are caused by lightning strokes, primary apparatus switching and short circuits or ground faults. The primary transients are of different magnitude and frequency.

The transient voltages caused by a lightning stroke is of impulse type. The impulse voltage 1.2/50 μs used at the tests is a good representation of this primary transient.

Transients are generated both at closing and opening of a breaker and a disconnector.The switching generates transients with a frequency content equals to a wavelength of four times the line or bus that is energized or de energized and lower frequencies caused by capacitance in CVT and other capacitive apparatus. The frequency is in most cases in the range 50 kHz to 1 MHz. The oscillation is normally damped to half the initial value after 3-6 oscillations.The oscillating transient is repeated when the arc in the breaker or disconnector restrikes. When the switching is performed with a disconnector the oscillating transients repeated with a frequency of approximately 300 MHz.

Control Cabling

The energizing of capacitor banks can cause very severe transients and especially when another capacitor banks is connected to the same busbar and damping reactors are not installed.

Short circuits and ground faults are associated with a sudden decrease of voltage in the faulty phases. This decrease of voltage is actually a transient with negative sign and a high frequency component together with a fundamental component.
The magnitude of the voltage transient is always less than the peak value of the operational voltage.
The rise can be approximately 1 μs which represents a frequency of 1 MHz.
Short circuits and ground faults in solidly grounded system will cause high fault currents of fundamental frequency. Ground faults in high impedance grounded systems are associated with high frequency current transients. The magnitude of these current transients can reach several kA and with a frequency content of some kHz to some MHz.

An additional source of transients is switching in the control circuits. When inductive loads as contactors and relay coils are de energized high transients can be generated.
These transients have magnitudes of several kV and a frequency content of 10 kHz to 10 MHz. These transients can be suppressed by diodes over the coils, when DC coils are used, or capacitances, when AC coils are used.
The amplitude of the transients can be limited by the installation of zener diodes or MOV's over the coil or the contact.

The protection relays are tested according to IEC fast transient test to verify the capability to withstand the transients caused by switching of secondary circuits. When class III with showering arc tests of 4-8 kV is fulfilled there is normally no needs to include extra components to limit the transient voltage.

12. COUPLING OF THE TRANSIENTS TO THE RELAY CIRCUIT.

The primary transients coupled to the relay circuits results in common mode and transverse mod disturbance voltages. Common mode voltages arises between ground and a conductor in the circuit.
Transverse mode voltages arises between conductors in the circuit. See figure 1. The common mode voltage is stressing the isolation to ground in the various equipment in the circuits. The transverse mode voltage is added to the signal in the circuit and can be characterized as noise in the signal. Common mode voltages are transformed to transverse voltages if the circuit is unbalanced to ground.

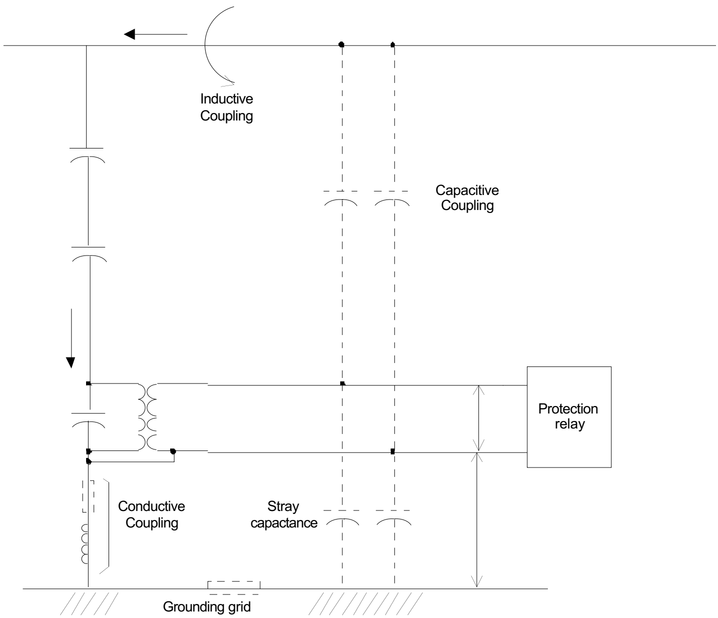

Figure 13. Coupling of primary transients to the relay circuit.

The coupling of the primary transient to the relay circuit takes place by inductive coupling, capacitive coupling and conductive coupling, see figure 1.

The primary transient current I_T is inductively coupled to the relay circuit by mutual inductance M_k. The mutual inductance that cause the transverse voltage U_T is by twisting of the wires in the cable reduced to a value that makes the transverse mode voltage negligible in normal relay circuits.

In most cables for relay circuits the twisting of different pairs of wire contra each other is insignificant. Current transients in one pair of wires will therefore be inductively coupled to other pairs of wires in the cable and cause transverse voltages.
The mutual inductance between the HV conductor and the loop formed by the ground plane in the station and a cable is relatively high. This mutual inductance can be reduced by locating the cable close to the ground wire in the ground grid system.
By using screened cables and grounding the screen in both ends, the mutual inductance to the cable wires can be heavily reduced. The inductive coupling to the loop between ground and the cable causes a common mode voltage U_C, see figure 1.
The common mode and transverse mode voltages capacitive coupled from the HV conductor to the relay circuits are low and can be neglected in most relay circuits due to a small coupling capacitance C_G, see figure 1.

In current and voltage transformers however the coupling capacitance between the HV winding and the secondary winding is of such an order that a grounding of the secondary winding is necessary to avoid destructive common mode voltages.
The detractive coupled disturbance voltage is caused by currents to ground and the potential increase in the ground grid system at the point of current injection, see figure 1. To control the voltage the coupling impedance Z_K have to be small. By the cross section of the wired in the ground system Z_K can be controlled for high frequency transients. For high frequency switching transients is practically the wave impedance of the ground wire and Z_K can not be kept low only by a large cress sections. Parallel ground conductor is the best mean to control the Z_K

The high frequency ground current transient IG is coupled from the HV conductor via the stray capacitances in the HV apparatus. Measuring transformers are mostly a big capacitance to ground and the conductive coupling must be noticed. The high frequency common mode voltage can be reduced at the relay equipment by use of screened cables with the screen grounded at both ends.

13. CONTROL OF DISTURBANCE VOLTAGE IN RELAY CIRCUITS

13.1 GROUNDING OF SECONDARY CIRCUITS

Grounded circuits that are galvanically connected must be ground connected at one single point of the system. The power frequency and high frequency voltage between different points in the ground system at primary faults and switching condition would otherwise cause transverse voltages in the circuit and currents in the control cable. This current will induce high transverse voltages between wires in the cable. Due to this coupling the grounding of spare conductors in a cable have to be avoided.

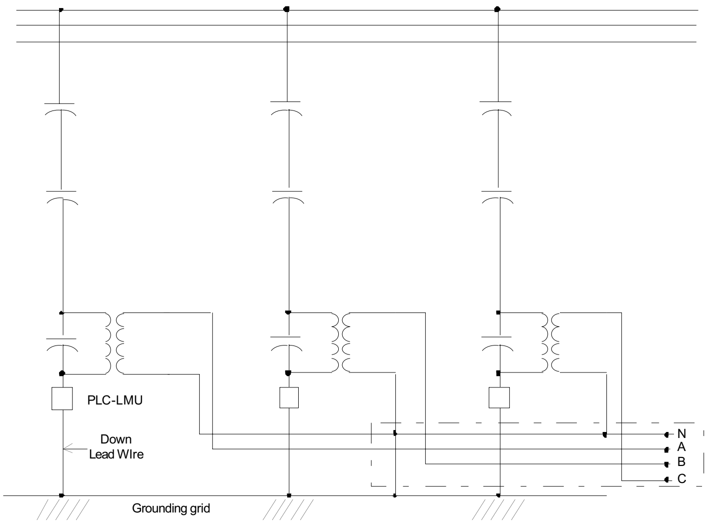

Figure 14. Grounding of a three phase group of capacitive voltage transformers.

To minimize the conductive coupling the grounding of control circuits and of primary capacitive apparatus as shunt capacitors, capacitive voltage transformers etc. have to be separated. Different down lead conductors to the ground grid is favorable and grounding of control circuits at a cross point in the ground grid system is preferred. Figure 2 shows the grounding of a capacitive voltage transformer group as an example.

13.2 SEGREGATION OF CIRCUITS IN CONTROL CABLES.

All wires in a single circuit must be within a single cable. In a circuit with wires in different cables the inductive coupling to the loop formed by the cables will give a considerable transverse voltages in the circuits. Figure 3 shows the dc-circuits as an example.

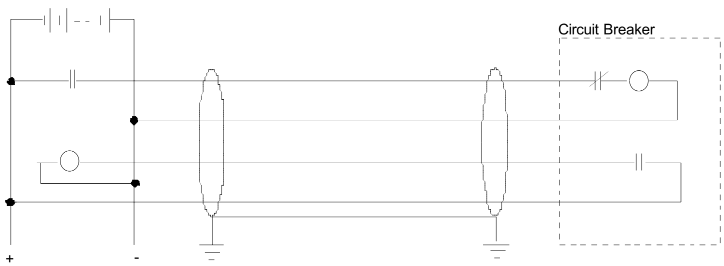

Figure 15. The circuits should be provided in a single cable. Mixing in different cables should be avoided.

The transverse voltage will disturb the measurement in current or voltage transformer circuits and different cables must be avoided in a single measuring circuit. When parallel cables must be used a design according to figure 4 must be utilized. Naturally the ground grid system must not be used as return path in any circuit.

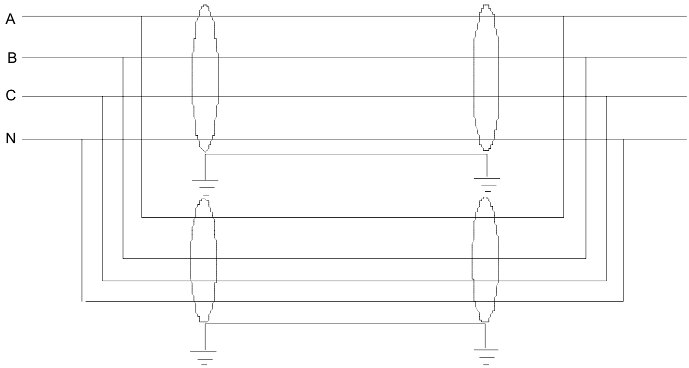

Figure 16. To minimize disturbances the cables should be screened and screened shall be grounded at both ends.

The mixing of current and voltage measuring circuits in a single cable should be avoided due to the inductive coupling between pairs in the single cable. The mixing of current and voltage circuits is as an example less suitable for distance protection without cross polarization due to high currents combined with low measuring voltages for close up faults.

13.3 LOCATION OF SECONDARY CABLES.

The mutual inductance between the HV conductor and the cable is inversely proportional to the distance between the cable and the HV conductor. Locations close to HV conductors or secondary cables must be avoided. HV power cables and secondary cables should have different trenches or cable shelves. The mutual inductance is proportional to the length of the parallelism. The distance the control cables are parallel to HV conductors shall always be shortest possible.

Ground wires parallel and close to the control cables reduces the mutual inductance and thereby the disturbance voltage. By locating the control cables on the same depth as the grounding grid the distance between control cables and ground wires is always kept short. By locating ground wires close to the control cable trenches, the induced voltage can be reduced by a factor 10. It is recommended that all cable trenches with a length over 20 m is followed by a ground wire close to the trench but not inside the trench. The latter to avoid thermal damages to the cables.

13.4 CABLE TYPES.

To minimize the induced transverse voltage, cables with twisted conductors should always be used. Parallel twisted conductor type of cables is satisfactory and individually pair twisted conductors s not necessary.

13.5 SCREENING OF CABLES.

Figure 5 shows the effect of screening of cables and grounding of the screen for induced voltage of different frequency. From the figure can be seen that with the screen grounded at one end the transverse voltage U_T is reduced but not the common mode voltage U_C.

With the screen grounded at both ends both the common mode and transverse mode voltage at high frequency are reduced. At low frequency the transverse voltage is to some extent increased compared with an unscreened cable. These frequency levels are however normally not occurring in a station.

In the vicinity of HV conductors the most serious disturbance are the inductive and conductively coupled high frequency transients. Therefore when screened cables are used in the switch yard the screen **must be grounded at both ends**. Shortest possible conductor to the ground bar shall be used and whenever practical 360 degrees grounding in the grounded bottom plate of the panel should be utilized.

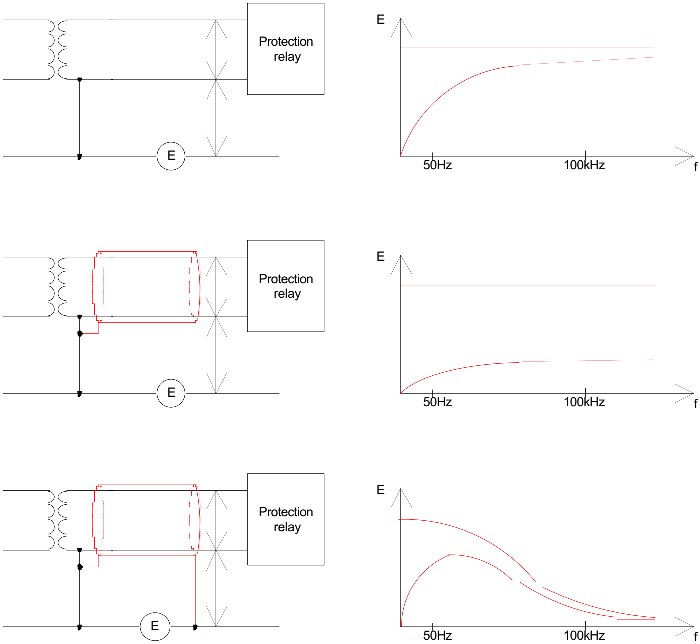

Figure 17. The suppression of disturbance voltages with an unscreened cable respectively with a cable screened with the screen grounded at one respectively both sides. To efficiently avoid the occurring transient voltages the screen must be grounded at both ends.

A screen grounded at both ends is a conductor parallel to the grounding grid and will carry a portion of the fault current at ground faults. The screen connection have to be dimensioned for this current that can be around 370 A/mm^2 when the ground wire is carrying 200 A/mm^2. The values are given as an indication of the magnitude of the current and not a recommendation for the design.

The practical level of the current is low if the grounding grid is correctly dimensioned and all cable screens are grounded at both ends.

13.6 SECONDARY CABLING IN MEASURING TRANSFORMER GROUPS.

The relatively high stray capacitance to ground in both voltage and current transformers produces high frequency voltages of several kV over the transformer ground down leads. This voltage will stress the insulation of the secondary winding that is grounded at another point in the grounding grid, see figure 2. By using screened cable with a screen grounded at both ends between the marshalling box and the individual measuring transformers the later are protected against internal flash-over. This protection is of special interest when high speed protection relays are used as they can malfunction due to flash-over.

14. RECOMMENDATION

The disturbance voltage must under all operational conditions including primary switching and faults be lower than the withstand capability of the protection and control equipment. The primary transient level in a station is not directly proportional to the operational voltage. Field tests have shown that in a 40 kV station about the same disturbance voltages may arise as in a 400 kV station. Naturally the type of switch yard is influencing the transient level. With metalclad or gas insulated switchgear the transient level is low (except very high frequency (100-300 MHz disturbance at operating SF6 disconnectors). The transient level in a conventional open switchyard is a function of the ground system and the latter must be paid special attention to. The general rules below should be followed for all type of stations at all voltages.

- Cable trenches with a length of over 20 m are followed by a ground wire close to, but not within, the trench.
- Galvanically connected control circuits e.g. CVT and CT circuits that have to be grounded are ground connected at only one point.
- The ground wires should not be used as a control path for control circuits
- All wires in a single circuit have to be located in the same single cable.
- The secondary windings in a three phase group of a measuring transformer must be grounded at a single point in the ground wire system and then preferable a cross point.
- The grounding of the capacitive dividers in capacitive voltage transformers must be done via down leads not used to ground the secondary winding.
- All cable should be provided with cable screens and the screen shall be grounded at both ends. Unscreened cables are better than screened cables with screen grounded at one end only.

Operational experiences from many stations have shown that with precautions above and unscreened cables the protection and control equipment have operated properly and have not been destroyed by transients.
But some field tests have shown that a disturbance voltage higher than the test voltage (levels specified in standards) can occur

at the protection or control terminal. In these cases unfortunate combination of ground wire system, ground connection and cable routing have occurred.

A number of tests and measurements of disturbance voltages have shown that with screened cables and the screen grounded at both ends the disturbance voltage is well within the tested withstand capability of the protection and control equipment in a station. Screened cables are not generally necessary in HV plants but with screened cables the disturbance levels are always well within the levels specified in the standards.

Screened cables with the screen grounded at both ends are therefore recommended in MV, HV and EHV plants and specially when capacitive voltage transformers and high speed protection relays are used.