

Calculation of overvoltages and interference voltages

When installing telecom or computer systems close to heavy current equipment or traction power supplies, careful thought has to be given to the possibility of overvoltages or interference voltages that could be caused by power lines or system frequency phenomena. The coupling that is possible between the interfering and affected lines is usually of an electrical and/or magnetic nature. Analysis of galvanic, capacitive and inductive coupling, plus the calculation of possible overvoltages and interference voltages, helps industrial operators to make their electrical installations safe and immune to such phenomena.

Electrical apparatus and systems manufactured and/or sold within the European Union require certification that shows that they conform to EU requirements. Before a product is allowed to carry the CE marking proving conformity, it has to satisfy a number of conditions. EU directives exist for the certification. The first one – the directive for machines – has been valid since January 1, 1995. The second is the EMC directive, which went into force as regards CE marking on January 1, 1996. The third directive, which deals with the electrical safety of low-voltage apparatus, will become effective with regard to CE marking on January 1, 1997. All electrical and electronic equipment, systems and installations intended for the European market have to meet the requirements laid down in the relevant EMC directives.

In recent years, interference voltages have been the cause of numerous disturbances in airport control towers and rail traffic control centers. In view of the potential danger of such interference, it is clearly essential for equipment to satisfy at least the minimum requirements of the pertinent EU directives.

Overvoltages that could occur in instal-

lations sited close to power lines and traction power supply systems have to be calculated in advance of their occurrence to ensure the required level of electrical safety and electromagnetic compatibility (EMC).

The overvoltages occurring as a result of capacitive, resistive and inductive coupling are calculated separately and the resultant overvoltage obtained by vectorial addition of the individual values.

Limits for the permissible overvoltages

Overvoltages that occur on control or communications cables are not allowed to diminish safety (protection against electric shock must be ensured), impair the installation or interfere with its operation.

The conditions regarding protection against electric shock are fulfilled in Sweden through compliance with the following limits specified for telecom, signal and control cables:

- $U_{rms} \leq 50 \text{ V}; t \geq 1 \text{ s}$
- $U_{rms} \leq 430 \text{ V}; 0.5 < t < 1 \text{ s}$
- $U_{rms} \leq 650 \text{ V}; t \leq 0.5 \text{ s}$

The permitted limits with regard to equipment protection are specific to the particular apparatus and as such are a component of its design. Permitted values for undisturbed operation also depend on the design of the apparatus and how it is run.

Telecommunications systems present a special problem, since they work with very low voltages and in a wide frequency band. The permitted limits for telephone lines are defined by so-called psophometric values. Psophometric coefficients take account of the way in which frequencies affect the human ear. The psophometric total voltage U_p is given by the following relationship:

$$U_p = \frac{1}{\rho_{800}} \cdot \sqrt{\sum(\rho_i U_i)^2} \tag{1}$$

In the above equation, U_i is the voltage for the frequency f , ρ_i the psophometric weighting factor for f , and ρ_{800} the psophometric weighting factor for the frequency 800 Hz.

Telephone calls are transmitted within a frequency band lying between 300 and 3,400 Hz. The permitted psophometric limits for telephone lines are 230 mV for the common mode voltage (CMV) and 0.5 mV for the normal mode voltage (NMV).

The calculation of the psophometric normal mode voltage depends on the connected equipment. If the circuit configuration is not known, it will not be possible to determine NMV.

In **1**, the psophometric weighting factor according to CCITT is shown by the red curve, the weighting factor used in the USA by the blue curve. The difference between the two curves is minimal.

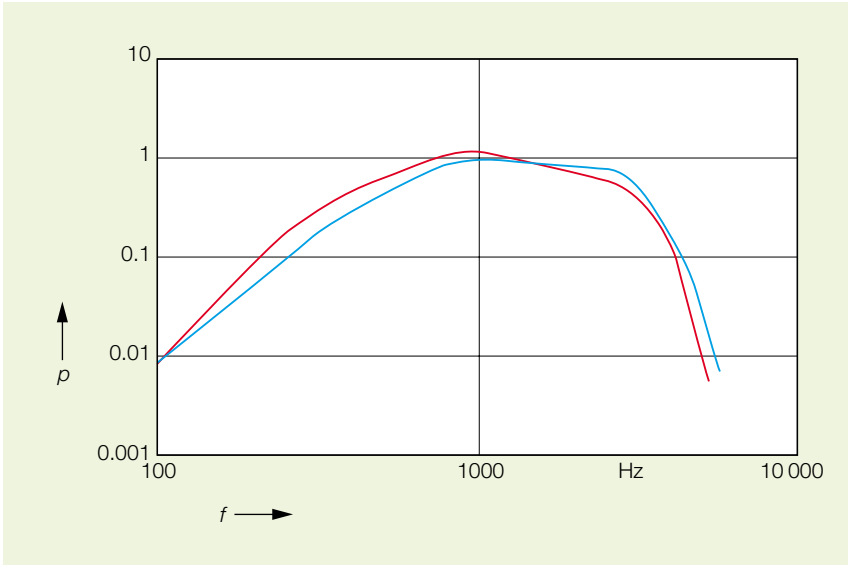
Galvanic coupling

A galvanic coupling is established when two circuits have a common coupling impedance. A typical case is shown in **2**.

$$U_x = U_G \cdot \frac{Z_C}{Z_G + Z_L} \tag{2}$$

In practice, the common coupling imped-

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Psophometric weighting factor p according to the CCITT (red), and the US equivalent (blue)

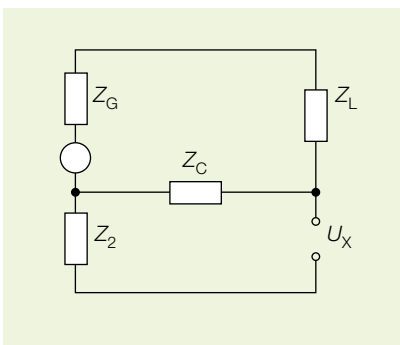
f Frequency

ance Z_C is made up of the resistance and reactance and has a much lower value than the sum of the impedances Z_G and Z_L ($Z_C \ll Z_G + Z_L$).

Capacitive coupling

The consequences of capacitive coupling are greatest in analyses of high-frequency conditions. A lack of knowledge of their effect or inattention to the problem during the installation of equipment can lead to serious disturbances occurring later. It is therefore immensely important to understand this kind of coupling and to be able to calculate the coupling conditions on the basis of the coupling impedance.

Galvanic coupling via a common impedance Z_C



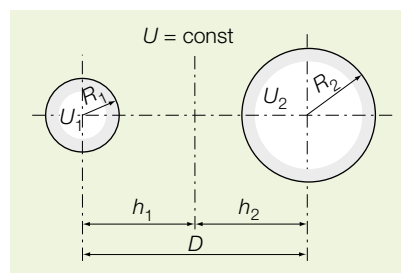
The capacitance between two conducting components depends on the value of their charge and on the potential difference. When calculating the capacitance, only the potential differences are considered. When analyzing the relationships between two conductors, two infinitely long cylinders are assumed for the purpose of calculation.

Capacitance between two parallel conductors

If ϵ is the dielectric constant and the two radii R_1 and R_2 are both much smaller than the distance D between the conductors **3**, the capacitance is given by:

Capacitance between two parallel conductors

- D Distance between conductors
- R Conductor radius
- U Voltage
- h Distance to 'U = const'



$$C = \frac{\pi \epsilon l}{\ln \frac{D}{\sqrt{R_1 R_2}}} \tag{3}$$

With identical thin conductors having the same cross-sectional area ($R_1 = R_2 = R$), the capacitance is:

$$C = \frac{\pi \epsilon l}{\ln(D/R)} \tag{4}$$

Capacitance between concentric conductors

The capacitance between two cylinders **4** is given by the relationship:

$$C = \frac{2\pi \epsilon l}{\ln(R_2/R_1)} \tag{5}$$

Capacitance between two conductors laid above the earth

The easiest way to calculate the capacitive coupling in such a case is to analyze two mirror-inverted conductors **5**.

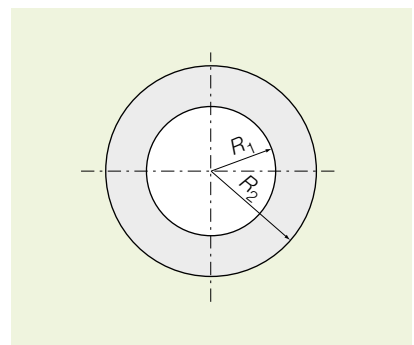
The formula used to calculate the capacitance C between two conductors laid above the earth **6** is as follows:

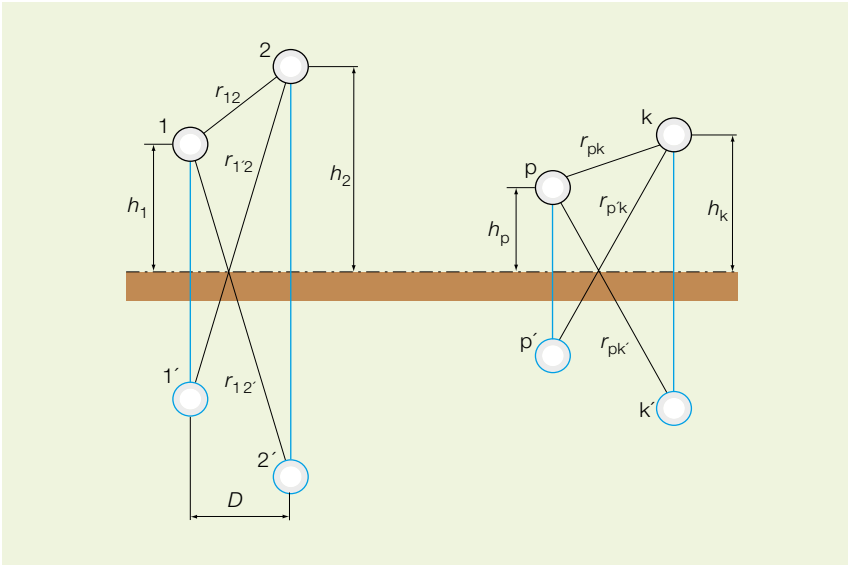
$$C = \frac{\pi \epsilon l}{\ln(D/R)} \tag{6}$$

This is identical to eqn (4). If the conductor radii are given by R_1 and R_2 , and their height above the earth by h_1 and h_2 , respectively, **5** then:

$$C = \frac{2\pi \epsilon l}{\ln \frac{2h_1}{R_1} \cdot \frac{2h_2}{R_2} - \ln \frac{(h_2 + h_1)^2}{(h_2 - h_1)^2 + D^2}} \tag{7}$$

Capacitance between concentric conductors





General analysis carried out with the help of mirror-inverted conductors (1', 2' and p', k') 5

- D Distance between conductors
- h Distance between conductors and earth
- r Distance between mirror-inverted conductors

Common mode voltages produced by inductive means

Common mode voltages produced inductively require special attention during the calculation of overvoltages and interference voltages caused by power frequency phenomena. The overvoltages and interference voltages caused by capacitive coupling to 'live' conductors, on the other hand, can be neglected – at least when the cables are shielded. In addition to the capacitive coupling to live conductors, resistive coupling also occurs. The predominant case here is the coupling caused by the earthing resis-

tance of the transformer substation (increased earth potential).

The induced electromotive force (EMF) is given by:

$$E_2 = \omega M I_1 k \tag{8}$$

In this relationship E_2 is the induced EMF in the conductor of the control cable in V, $\omega (= 2\pi f, f$ in Hz) is the angular frequency and M is the mutual inductance in H between the interfering conductor and the control cable. It is assumed that the cables' sheaths and the adjacent metallic conduc-

tors, if any, are insulated from one another. I_1 is the worst-case current in the interfering line and k a reduction factor used to take account of cable sheaths and conductors lying in close proximity.

If the connected equipment is sensitive to frequencies lying above the fundamental frequency, the harmonic currents in the power line have to be calculated. Such a calculation is very complex and yields unreliable results. Measurement of the induced EMF is therefore recommended.

The current in the interfering circuit

The interfering and the affected circuit consist of one or more conductors, with the earth acting as the return conductor. (The case in which the earth does not act as the return conductor will be dealt with later.) When considering a high-voltage three-phase AC power line, this applies only to the zero-sequence component of the current. The positive- and negative-sequence components do not return via the earth, and their consequences are minor due to the relatively small distance between the outer conductors. As a rule, I_1 is used to designate the sum of the zero-sequence currents ($= 3I_0$) providing the control cable does not lie immediately next to the power line. If it does lie in close proximity to the line, different inductions for each outer conductor must be reckoned with when sensitive equipment has been installed.

Two conductors located at the same height above the earth 6

- D Distance between conductors
- h Distance between conductors and earth

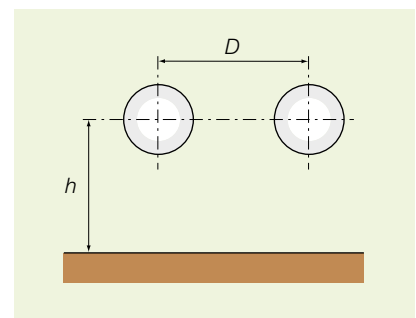
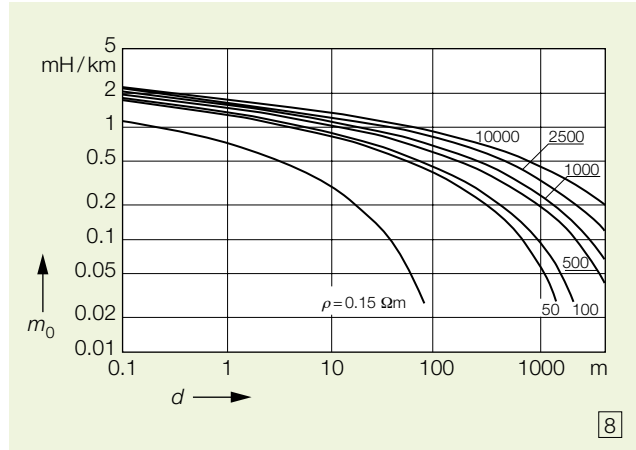
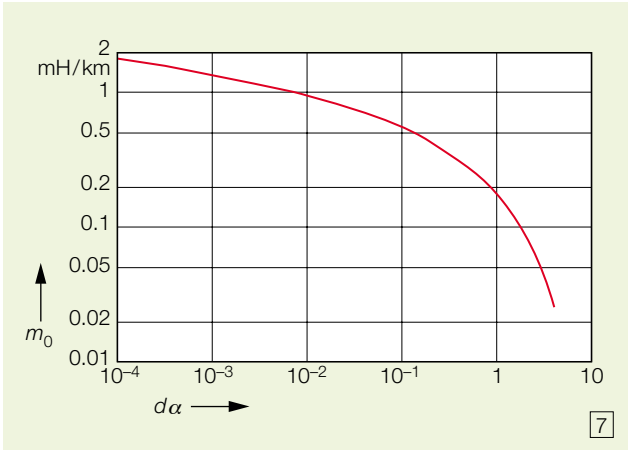


Table 1: Approximate values for the resistivity ρ

Soil type	ρ in Ωm
Carbon, mineral layer	1–3
Light clay, alluvion	5–20
Chalk, marl, clay without alluvion	20–100
Quartz, limestone, sandstone, clay slate	100–1,000
Rocks, slate, granite, pebbles	1,000–10,000



Mutual inductance as a function of $d\alpha$

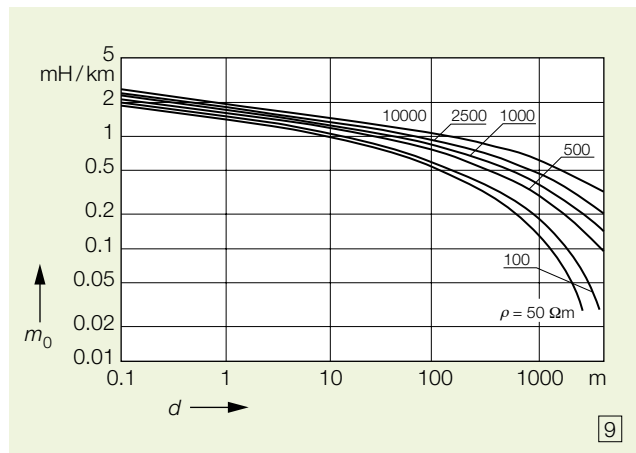
7

- m_0 Mutual inductance/length
- d Distance between interfering and affected line
- α See eqn 10

Mutual inductance as a function of d at 50 Hz

8

- m_0 Mutual inductance/length
- d Distance between interfering and affected line
- ρ Soil resistivity



Mutual inductance as a function of d for 16 2/3 Hz

9

It is assumed that the zero-sequence currents occurring at various fault locations in the installation being considered are known. Often, calculations have to be carried out for several fault locations in order to determine the maximum EMF.

Mutual inductance

Assuming that the earth is homogeneous and that the interfering and the affected line run parallel to each other, the mutual inductance will be:

$$M = m_0 l = 10^{-7} \left[\ln \left(1 + \frac{0.6\rho \cdot 10^6}{fd^2} \right) \right] \cdot l \quad (9)$$

In this equation, M is the mutual inductance in H, m_0 the quotient of the mutual inductance/length in H/m (also a function of $d\alpha$), l the length of the parallel run, and d the distance between the interfering and the affected line in m.

$$\alpha = \sqrt{\omega\mu_0/\rho} \quad (10)$$

In eqn (10), ω is the angular frequency ($= 2\pi f$, f in Hz), μ_0 ($= 4\pi \cdot 10^{-7}$) the permeability in empty space in H/m and ρ the soil resistivity in Ωm .

The quantity m_0 is a complex number. As a rule, its phase angle is of no interest and the absolute value is sufficient for the calculation.

The mutual inductance is dependent upon the soil resistivity, measurements of which have been carried out over a number of years. Where there are no values of any practical use available, a mean value can be used. (For most of Sweden, for example, a value of 2500 Ωm may be used. An exception is Scania in southern Sweden, where the mean value is 100 Ωm). Approximate values for the soil resistivity are given in Table 1.

In densely populated areas, a large part of

the return current flows through the pipes and other metallic conductors which are usually buried in the earth. This factor can be taken into account by using a lower, fictitious value for the soil resistivity.

Useful support for the calculations is provided by diagrams showing the mutual inductance as a function of $d\alpha$ **7** or d for different values of soil resistivity (for 50 Hz **8** and 16 2/3 Hz **9**).

If m_0 is not constant over the total length of the control cable (eg, the distance to the interfering line fluctuates), the run has to be broken down into sub-sections and separate calculations performed for each. The partial inductances are afterwards summed.

The values for m_0 are calculated under the assumption that the interfering line is infinitely long. If it is too short in comparison with $1/\alpha$, the actual value for the coupling can be considerably lower than m_0 . In prac-

tice, the same formula is also used for short lines; however, this gives a value for m_0 which is too high.

Special conditions in transformer substations

When an earth-line grid and other metallic conductors are buried in the earth, the major part of the return current will flow through the earthing network. Here, too, the starting point is m_0 , although it has to be multiplied by a reduction factor which depends on the distance d between the interfering and the affected line.

The value of m_0 corresponds to approximately the value of the mutual inductance when it is assumed that the return current flows in a plane at a depth of $1/\alpha$ below the earth's surface. This assumption is largely true for substations with a buried earth-line grid. Measurements carried out in substations have shown that for a value for α of 0.05m^{-1} (corresponding to $\rho = 0.15 \Omega\text{m}$), the mutual inductance will agree closely with the measured values at 50 Hz. Since more comprehensive measurement results are not available, it is recommended that the curve

8 for $\rho = 0.15 \Omega\text{m}$ be used, as for calculations for substations with an earth-line grid.

When the interfering and the affected line lie at different heights, the actual distance between the lines can be used for the calculation since this will assure a sufficient accuracy for d .

Reduction factors

Efforts are made in many installations to reduce the induced voltages. The reduction factor achieved by appropriate measures on the interfering line is designated k_1 , the factor corresponding to the measures taken for the control cable k_2 . In general, the distance between the interfering line and the control cable is so large that the mutual influence of k_1 and k_2 can be neglected. The resultant reduction factor is then the product $k_1 \cdot k_2$.

Providing the equivalent resistance of their earth electrodes is low and the conductivity in the connecting link is good, a good reduction is achieved with top earth lines in substations. However, in many cases the equivalent resistance is so high that for safety reasons a value of $k_1 = 1$ has to be assumed for the calculations.

In a traction power supply system the current flows via the contact (catenary) line to the locomotive, the return current flowing through the tracks and earth. To reduce the current flowing through the earth **10**, so-called booster transformers with a transformation ratio of 1:1 are used. The purpose of these transformers is to force the return current to flow through the tracks or return line. A return line hanging between the masts at about the same height as the contact line produces the best results. The combination of return line and booster transformer gives a value for k_1 of between 0.4 and 0.5.

The conditions are different when power and control cables are laid together with a protective earth line. The influence of interference voltages on the control cable is suppressed by:

- Providing shielding, plus armour for the control cable when necessary
- Shielding other control cables in the same run
- Running protective conductors close to the control cable

The reduction factor k_2 is then calculated using the following method: assuming that the shield or the metal sheath is grounded at both ends, and possibly at other locations, a current with the following value passes through them:

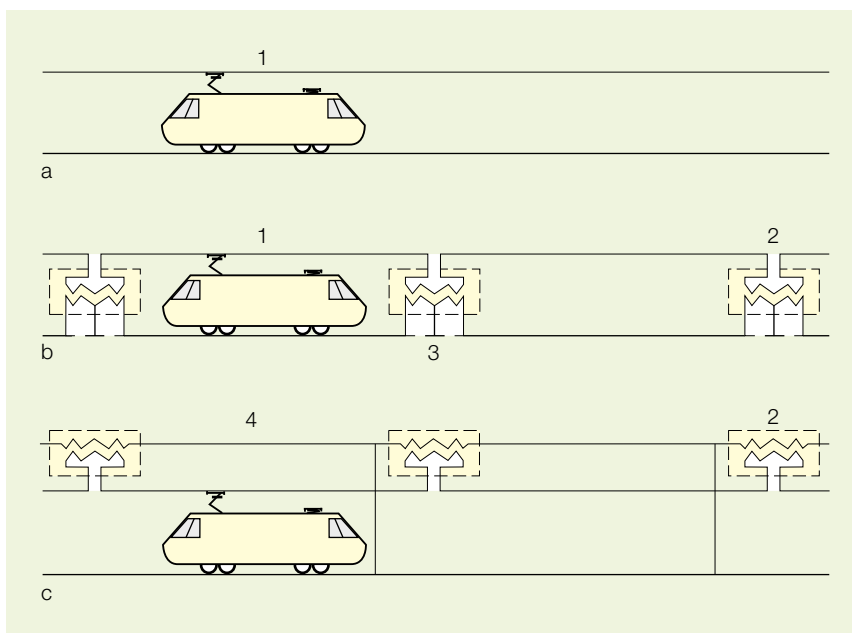
$$I_2 = \frac{E I}{(r_2 + j\omega L_2) \cdot l + R_1} \tag{11}$$

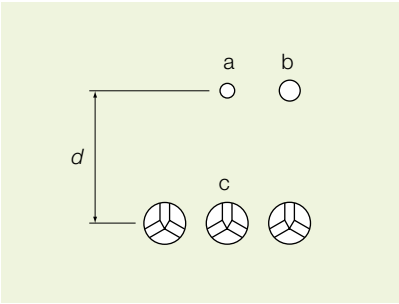
In this equation, $E (= m_0 k_1 I_1)$ is the electrical field strength in V/m in the earth along the length of the control cable (disregarding the reactions caused by the currents in the control cables and in their protective conductors), r_2 the quotient given by dividing the equivalent resistance of the sheath circuit by its length (in Ω/m), L_2 the quotient given by the inductance of the sheath circuit divided by the length (in H/m), R_1 the summated resistance at the earthing locations in Ω and l the length of the control cable in m.

The current I_2 causes an electrical field strength on the inside of the sheath, between it and the conductor, equal to $I_2 \cdot Z_k$, in which Z_k is the quotient of the transfer im-

Different railway electrification systems
Reduction factor $k_1 = 0.4 - 0.5$ in arrangement c

- | | |
|-----------------------|--------------------|
| 1 Catenary | 3 Sectioning point |
| 2 Booster transformer | 4 Return line |





Power and control cables laid in the same cable duct 11

- a Protective earth line
- b Control cable
- c Parallel three-wire cable or groups of single-conductor cables laid closely together in triangular configuration

pedance of the sheath and the length (in Ω/m). At low frequencies this quotient is approximately equal to the quotient of the DC resistance and the length, ie $Z_k \approx r_k$.

Neglecting R_p , k_2 has the value:

$$k_2 = \frac{Z_k I_2}{E} = \frac{Z_k}{r_2 + j\omega L_2} \tag{12}$$

Here, r_2 is the equivalent resistance of the sheath under AC conditions. At power system frequency r_2 is approximately equal to the DC resistance of the sheath, this being calculated from the cross-sectional area and the resistivity of the shield and metal sheath.

For cables which have no armour made of flat steel wire, L_2 is given by the following formula:

$$L_2 = \frac{\mu_0}{2\pi} \ln \frac{4}{\alpha D} \tag{13}$$

In this formula D is the diameter of the shield or of the metal sheath in m.

As the logarithmic relationship shows, the equivalent inductance depends only to a relatively small degree on α and on the fluctuations in cable diameter D . For control cables with normal dimensions, the following approximation can be used for the calculation:

- $L_2 = 2.5$ mH/km for $\rho \approx 2500 \Omega m$
- $L_2 = 2.0$ mH/km for $\rho \approx 100 \Omega m$
- $L_2 = 1.6$ mH/km for $\rho \approx 0.15 \Omega m$ (transformer substations)

In the case of shielded, plastic-insulated control cables of types EKFR, r_2 is much greater than ωL_2 , with the result that a reduction factor of $k_2 \approx 1$ is obtained. With cables of type EKFR, EKLR and FKLR, the k_2 values lie between 0.87 and 0.99 for 50 Hz, $\rho = 100 \Omega m$ and $L_2 = 2$ mH/km.

Good k_2 values are obtained when several shielded control cables are run together. At power system frequency, a close approximation of k_2 is given by:

$$k_2 \leq \frac{r_{tot}}{r_{tot} + j\omega(L_2 - \Delta L_2)} \tag{14}$$

Here, r_{tot} is the quotient of the resultant DC resistance and the length in Ω/m when all the shields are connected in parallel. ΔL_2 is then given (in $\mu H/m$) by:

$$\Delta L_2 = \frac{\mu_0}{2\pi} \cdot \ln \frac{2b_m}{D_m} \tag{15}$$

In this equation, b_m is the mean geometric distance between the control cables in the run in m and D_m the mean geometric diameter of the cable shields in m.

Example

- Control cable, type EKFR $4 \times 2 \times 1.5$ mm² + 14×1.5 mm²
- $A_{shield} = 7.5$ mm², $r_k = 2.8 \Omega/km$
- $D_m = 19.5$ mm
- $b_m = 100$ mm
- $L_2 = 1.6$ mH/km (transformer substation)
- $\Delta L_2 = 0.46$ mH/km

The reduction factor k_2 changes with the number of cables. For example, for one cable it is 0.99, and for 20 cables 0.31. The value of k_2 calculated using eqn 14 is also valid for non-shielded cables in the same run.

The conductors in the control cables can be included in the calculation of r_{tot} providing they are grounded at both cable ends. In addition, any number of protective earth lines can be taken into account which are in the same cable run. In the case of heavy-duty protective earth lines (eg, with a cross-sectional area $A_{Cu} = 25$ mm²), the effect of the line inductance is restricted. $k_2 \geq \Delta L_2/L$ is therefore valid for individual control cables run together with such a PE line.

When a protective earth line having a diameter of about 10 mm is laid at a distance of 50 mm from the control cable, $k_2 \geq 0.3$.

If the control cable has armour made of flat steel wire, the inductance of the sheath will be increased considerably. Due to the permeability of steel, the reduction factor depends on the field strength of the earth along the length of the control cable.

When more than one cable are run together, it should be noted that the reduction due to the flat steel wire armour is valid only for those conductors which are enclosed by the armour.

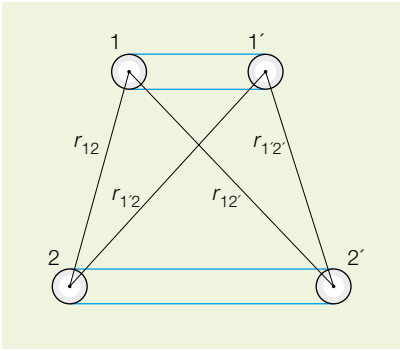
A better value for the reduction factor k_2 is obtained when a heavy-duty protective earth line ($d \leq 0.1$ m) is laid next to the control cable.

If an even larger reduction is required, a special design will be necessary, for example with an increased amount of steel in the armour and improved conductivity for the shielding.

Power cable and control cable in the same cable duct

When calculating the induced voltages for control cables which are laid in the same duct as power cables, it is not possible to assign independent reduction factors to the different cable sheaths. When the cables are laid as shown in **11**, however, a simple method of calculation can be used under the given conditions. The following prerequisites apply:

- Cable sheaths and protective earth lines are connected together and to the earth at least at each end of the cable.
- The fault occurs close to the far end of the power cable (worst case).
- The influence of flat steel wire armour around the power cables is neglected (the steel is magnetically saturated in the event of short-circuit currents).
- In cases of multiple power cables, the distance between each power cable and the control cable is assumed to be approximately the same.



Configuration with two-wire lines 12

- The protective earth line is located close to the control cable (≤ 0.1 m). The best safety factor is obtained in this way.

The induced voltage is then:

$$E_2 = I_1 r_p k_3 k_2 l \tag{16}$$

In this formula I_1 is the sum of the zero-sequence currents in A and r_p is the quotient obtained by dividing the equivalent resistance by the length of the metal sheath or shielding of the power cable (alternatively, the parallel-connected cable sheaths or shields) in Ω/m . k_2 is the reduction factor for the flat steel wire armour of the control cable. k_2 is determined by first calculating the field strength, given by $I_1 r_p k_3$, the value for k_2 then being taken from the corresponding diagrams [6] (Swedish version). If the control cable has no flat steel wire armour, a value of 1 is used for k_2 . k_3 is a reduction factor which depends on the distance d between the control cable and the power cables, the cross-sectional area A_3 of the protective earth line and the shielding of the control cable. If $A_3 = 100 \text{ mm}^2$ and $d = 0.5 \text{ m}$, a value of approximately 0.5 can be used for k_3 . l is the length of the parallel run in m.

Mutual inductance between two two-wire lines

In the configuration shown in 12 the earth does not serve as the return conductor.

In the first circuit, 1 represents the conductor and 1' the return conductor; the same is true for the second circuit. The lines have the length l .

Providing the length of the lines is much greater than the distance between the conductors, it is possible to neglect the connections at the beginning and end of the circuit (blue lines in 12).

Given these conditions, the mutual inductance will be:

$$M = M_{12} + M_{12'} + M_{1'2'} + M_{1'2} \tag{17}$$

$$M = \frac{\mu_0 l}{2\pi} \cdot \left(\ln \frac{r_{12'} r_{12}}{r_{12} r_{1'2'}} \right) \tag{18}$$

Here, M is the mutual inductance in H, l the length of the parallel lines in m, μ_0 ($= 4\pi \times 10^{-7}$) the permeability in H/m, and r_{12} , $r_{12'}$, $r_{12'}$ and $r_{1'2}$, the distances in m.

The mutual inductance M can have either a positive or a negative value. In the configuration shown in 12, M has a positive value. This means that the currents given in the respective lines have to have the currents induced as a result of the mutual inductance M added to them.

In the event of the actual operating current having an opposite polarity to the assumed current, the mutual inductance M will be negative.

The induced voltage in circuit 2 is calculated as follows:

$$E_2 = I_1 \omega M \tag{19}$$

Summing up

As of January 1, 1996, all electrical and electronic components having a direct function, plus apparatus, systems and installations, have to conform to the European Union EMC directive referred to earlier, ie, the products must be constructed in a way that ensures that they neither cause excessive interference nor are unduly affected by electromagnetic disturbance. The mandatory CE marking shows conformance with all relevant directives.

These minimal requirements, however, do not guarantee interference-free performance of highly complex installations sited close to traction power supplies and power transmission lines. In such cases, it is necessary

to determine the overvoltages in the cables in order to ensure both electrical safety and electromagnetic compatibility.

ABB Industry and Drives has been applying such regulations to its products for a long time. Electrical and electronic components with a direct function, as well as apparatus, systems and installations from ABB satisfy, as a minimum, the requirements set down in the new legislation. And where ABB considers it expedient, the company even employs its own, more rigorous regulations.

In view of this, older ABB apparatus, systems and installations are also designed to satisfy at least the requirements set down in the EMC directive.

ABB has its own in-house EMC test facility in which the appropriate measurements can be carried out. Although it is used primarily to test new ABB equipment and systems, the facility may also be made available to other equipment vendors.

References

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