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Neutral earthing in an industrial HV network

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HV electrical networks can be earthed in different ways. This document analyzes the constraints imposed by the different parameters of the installation (overvoltages, network, receivers) and calculates the fault currents.
Different protection modes are described along with the settings and adjustments suggested according to the requirements.

contents

1. introduction

When designing an industrial HV network, a suitable neutral earth arrangement must be selected: the neutral can either be insulated, or it can be connected to earth. The use of an insulated neutral in an HV network has the advantage of ensuring operational continuity since it does not trip on the first fault, however the network capacitance must be such that an earth fault current is not likely to endanger personnel or damage equipment.
On the other hand, an insulated neutral implies the following:

- the risk of high overvoltages likely to favourize multiple faults,
- the use of superinsulated equipment,
- compulsory monitoring of the insulation,
- protection against overvoltages, which will become compulsory in the near future,
- the need for complex, selective protection against earth faults which cannot usually be ensured by simple current-measuring relays. An earthed neutral generally implies mandatory tripping on the first fault, however:
- it reduces overvoltages,
- it provides a simple, reliable, selective means of protection,
- it allows the use of equipment, and in particular cables, with lower insulation levels than for an insulated neutral.

2. earthing

The purpose of this study is not to compare the different neutral earth arrangements, but rather, once the neutral earth solution has been adopted, to determine the earthing mode by finding a compromise between three often contradictory requirements:

- to sufficiently damp overvoltages,
- to limit damage and disturbances caused by an earth fault,
- to provide simple, selective protective devices.

Earthing can be of different types:

- direct (without impedance-dependent current limiting),
- through a reactor,
- through a resistor.

direct earthing

This type of earthing is the most efficient in limiting overvoltages; protection selectivity presents no difficulties.
However, in the event of an earth fault, the current is not limited, damage and interference occur and there is considerable danger for the personnel during the time the fault persists.
This solution is not used for HV distribution.

earthing through a reactor

Tuned reactor (Petersen coil)
This solution is sometimes used for public HV networks. It is rarely used for industrial distribution.
Protective relays sensitive to the active component of the residual current must be used to obtain selectivity.

Current limiting reactor
This solution can result in serious overvoltages, as demonstrated by Le Verre (the Research and Development division of the E.D.F.) [1]. It can be used only where there are low limiting impedances.

earthing through a resistor

This is often the most satisfactory solution.

A study is necessary to choose between these two earthing, (through a reactor or through a resistor) :
accurate determining of these earthing modes depends on the voltage level, the size of the network and the type of receivers.
Depending on the earthing mode, a criterion then determines a maximum impedance value corresponding to the overvoltage problem.
Next, it is necessary to check its compatibility with the requirements of the network and the receivers.

[1] See bibliography

3. requirements imposed by overvoltages

earthing through a current limiting reactor

(see fig. 1)

The study of overvoltages that occur when short-circuits are eliminated from networks with the neutral earthed through a reactor gives the following results:

- let, $I_0\omega$ be the earth fault current limiting reactance,
- and $L\omega$ the network three-phase short-circuit reactance.

The neutral-to-earth overvoltage occurring when short-circuits are eliminated is:

$\frac{\Delta V}{V} = \frac{1}{\sqrt{2}}\sqrt{\frac{I_0}{L}}$ for a radial field cable network,

$\frac{\Delta V}{V} = \frac{1}{2}\sqrt{\frac{I_0}{L}}$ for all other cases.

In practise, the earth fault current is limited to at most 10 % of the three-phase short-circuit current, as applied by the EDF to its HV power distribution network.

earthing through a resistor

As recommended by EDF for hydroelectric power networks. The resistance value r is détermined in order to obtain a total active power loss : $\frac{U^2}{3r}$ equal to or greater than the capacitive power $2C\omega U^2$ in the event of a phase-earth fault, i.e.:

$$\frac{U^2}{3r} \geq 2C\omega U^2 .$$

When dividing by $\frac{U}{\sqrt{3}}$, this become

$$\frac{U}{\sqrt{3}\,r} \geq 2 . 3C\omega \frac{U}{\sqrt{3}}$$

where:

- $\frac{U}{\sqrt{3}\,r}$ is the value of the earth fault current I_L in the earthing connection,
- $3C\omega \frac{U}{\sqrt{3}}$ is the network capacitive current I_C in the event of an earth fault.

Hence the relation $I_L \geq 2\ I_C$.

Determination of the cable capacitance values depends on their design (see appendix for this calculation).

fig. 1 : a zigzag or neutral point coil provides an earth fault current limiting reactor.

4. requirements imposed by networks

The above criterion is used to define the lower limit of the phase to earth fault current.

To determine the upper limit, it is necessary to check that the fault current does not cause damage along its path and in particular to the cable shields. The maximum current withstood by the cable shields may be specified by the constructors. As a general rule, the value used is between 500 and 3 000 A for 1 second.

5. requirements imposed by receivers

In HV networks, receivers are transformers which have no particular requirements as concerns the neutral earthing in a power supply network. However, industrial HV networks can supply rotating machines with voltages between 3 kV and 15 kV, most frequently 5.5 kV in France; the earth fault current should not exceed 20 A in order to avoid damage to the steel plating of the machines, for if reworking a winding is a regular repair, repairing a machine when the metal plating is damaged is much more time consuming and more costly.

6. calculating fault currents

The currents in the different circuits are easily calculated using a simple approximative method.
This consists in ignoring the short-circuit impedance of the source and the coupled impedances with respect to the neutral earth impedance and the network capacitances. In other words, we consider that earth fault currents are much lower than three-phase short-circuit currents (see fig. 2).
To calculate the neutral-to-earth potential, the sum of the currents flowing to earth is considered to be zero (see diagram).

$$I_N + I_{rD} + \Sigma\, I_{rS} = 0$$

$$0 = g\, V_N + [G + j\omega\, C]\,(V_N + E) + j\omega C\,(V_N + a^2E) + j\omega C\,(V_N + aE)$$

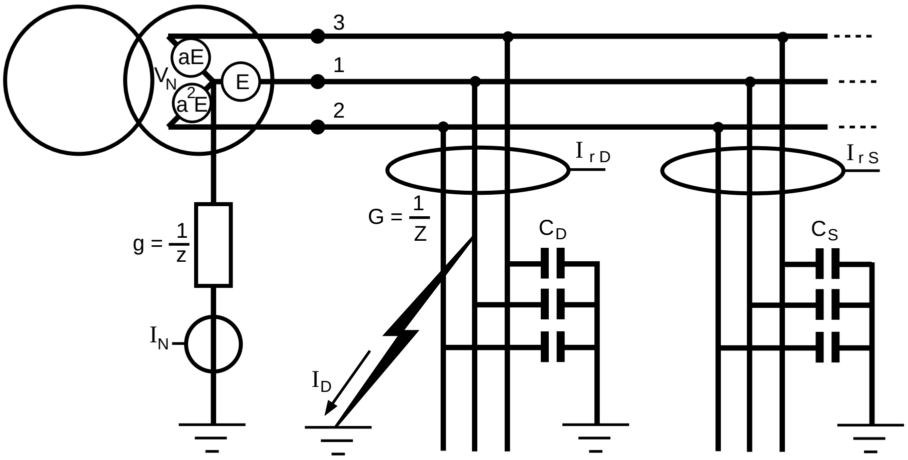
$$0 = V_N\ [g + G + 3j\omega C] + GE + j\omega\, CE\,(1 + a^2 + a)$$

Since $1 + a^2 + a = 0$

This gives:

$$V_N = \frac{-\,GE}{g + G + 3\,j\,\omega\, C}$$

where $V_N = \dfrac{-\,zE}{z + Z + 3\,j\,\omega\, C\, z\, Z}$



$z = \frac{1}{g}$	Neutral earth impedance
$Z = \frac{1}{G}$	Phase to earth fault impedance
C_D	Phase to earth capacitanc e of the faulty outgoing feeder
C_S	Phase to earth capacitance of a sound outgoing feeder
$C = \Sigma\, C_S$	Total phase to earth capacitance of the network
E	Network phase voltage
V_N	Neutral point to earth potential
I_N	Neutral to earth current
I_D	Fault current
I_{rD}	Residual current of the faulty outgoing feeder
I_{rS}	Residual current of a sound outgoing feeder

fig. 2: Earth fault current calculation parameters.

Since we know V_N, the different currents (I_N neutral to earth current, I_D fault current, I_{rD} and I_{rS} residual currents in outgoing feeders) are calculated as shown below:

- $$I_N = gV_N \frac{-gGE}{g+G+3j\omega C}$$
$$= \frac{-E}{Z+z+3j\omega CzZ}$$

- $$I_D = G\left(V_N + E\right) = \frac{g+3j\omega C}{g+G+3j\omega C}\ GE$$
$$\frac{1+3j\omega Cz}{Z+z+3j\omega CzZ}$$

- $$I_{rD} = I_D + 3j\omega C_D V_N$$
$$= \frac{g+3j\omega\left(C-C_D\right)}{g+G+3j\omega C}\ GE$$
$$= \frac{1+3j\omega\left(C-C_D\right)z}{Z+z+3j\omega CzZ}\ E$$

- $$I_{rS} = 3j\omega C_S V_N$$
$$= \frac{-3j\omega C_S}{g+G+3j\omega C}\ GE$$
$$= \frac{1-3j\omega C_S z}{Z+z+3j\omega CzZ}\ E$$

In the event of a short-circuit Z = 0, the above formulae become:

$$V_N = -E$$

- $$I_N = \frac{-E}{z}$$

- $$I_D = \left[\frac{1}{z} + 3j\omega C\right] E$$

- $$I_{rD} = \left[\frac{1}{z} + 3j\omega\ \left(C - C_D\right)\right] E$$

- $$I_{rS} = -\ 3j\omega C_S E$$

7. earth protection mode

The neutral earthing impedance affects the required method of protection against phase to earth faults.
As a general rule, the higher the fault currents, the easier they are to detect; the lower they are, the harder they are to detect .

Moreover, it is advisable, even essential, to ensure protection not at one single point, but in all branches of the network, since the relays operate selectively.

Phase to earth protection is provided by overcurrent relays supplied by the earth current.
This current can be measured as follows:

- either by a core balance transformer around the three phase conductors and which directly detects the sum of their currents (zero if no earth fault) ;
- or by three current transformers the secondary windings of which are connected to form a neutral conductor through which the sum of the three currents flows.

The core balance transformer solution is the most accurate, however it can only be installed on cables, not on busbars or overhead lines. The 3 current transformers solution is often used, in particular when these 3 transformers are already required for another application. But the measurement obtained is degraded by the inaccuracies of all three transformers, in particular in the event of transient overcurrents when the transformers become saturated.

earth protection setting

This must be adjusted according to the measurement accuracy. It must ensure maximum protection and authorize selectivity.

If the measurement is carried out using the sum of the secondary currents of the three transformers, it will be degraded by the dispersion of the transformers. In particular, a residual current is measured if there is no earth fault when the transformers become saturated.
Saturation is caused by excessive amplitude of the phase current, but more specifically by the DC component induced in a short-circuit or unbalanced inrush current.

Note that, in transient conditions, the DC component can induce saturation of the transformers even though the peak value of the transient current is around 10 times less than the saturation value for a steady-state balanced current. An earth protection device supplied by 3 transformers must therefore include a time delay in order to avoid spurious triggering resulting from transients. The current setting must not be lower than 6 % of the transformer rating at best, or 15 or 20 % of the transformer ratings in the most unfavourable cases.
Moreover, if an earth fault occurs in a star winding near a neutral point, the maximum fault current is only a small part of the maximum fault current which is limited by the neutral earth impedance. For this reason, the current setting is usually 20% of the maximum current limited by the neutral earth in order to protect 80% of the windings.

But, as the calculation shows, in the event of a fault, a residual capacitive current flows through the sound parts of the network. So, to prevent the protective device of a sound line from tripping spuriously, the threshold must be set to 30% higher than the capacitive current flowing through this sound line when a phase to earth short-circuit affects the network.
Moreover, we must take into account the possible presence of voltage harmonics likely to produce currents

which increase as the order of the harmonics increases. Note that 3rd harmonics and multiples of 3 exist even in steady-state conditions. Finally, the neutral earth impedance characteristics must be coordinated with the protective devices so that this impedance itself is not degraded by the fault current before it is eliminated.

Note: that this concerns circuit protection and not personnel protection.

Conclusion: when the earthed neutral solution is selected for a medium voltage network, it is advisable to use earthing through a resistor rather than other systems.

Calculating r and I_L

This resistance r and the maximum current $I_L = \frac{U}{\sqrt{3r}}$ are determined taking the following requirements into account:

- the current I_L must be greater (or equal) to twice the network capacitive current in the event of an earth fault $I_L \geq 2\ L_C$ in order to limit overvoltages,
- the current I_L must be less than the maximum overcurrent that can be withstood by the cable shields, normally between 500 and 3 000 A, depending on the cable cross section,
- in a network containing HV motors, it is preferable to respect the relation: $5\ A \leq I_L \leq 20\ A$ but, if this is incompatible with the first condition, I_L can be up to 50 A,
- in order to ensure correct protection of receivers, the I_r threshold settings should not exceed 0,2 I_L, i.e. $I_r \leq 0{,}2\ I_L$,
- in order to ensure selectivity with regard to sound connections, the relation $I_r \geq 1{,}3\ I_C$, must be respected, where I_C is the capacitive current of the line when a phase to earth fault occurs,
- if the earth current is measured by 3 transformers of rating I_n, then I_r must be $\geq 0{,}06\ I_n$,
- the thermal withstand of resistor r must allow for current I_L to flow during the maximum fault clearing time required (1 to 1.5 s) or, conversely, the earth fault must be cleared sufficiently rapidly to avoid damaging the resistor.

earthing with accessible neutral

The resistor is connected to the neutral output terminal and to the earthing system, either directly, or through a single-phase transformer the secondary winding of which is loaded by an equivalent resistance, as is used in networks supplied through a transformer which has a star-connected secondary winding with accesible neutral and for AC generators with accessible neutral (see fig. 3).

If the network is supplied through several transformers or AC generators, it is advisable to have one single neutral earth connection to prevent the maximum earth fault current from varying with the number of sources in service.

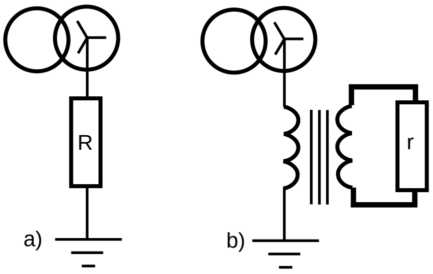


fig. 3: neutral earthing at the secondary winding of a star-coupled transformer, through a resistor either connected directly (a) or connected through a single-phase transformer (b).

earthing with an artificial neutral

If the neutral of the source is inaccessible (as for delta-connected windings), or if there are several parallel-connected sources, earthing can be ensured by an artificial neutral (see figs. 4 and 5) (or earthing transformer)

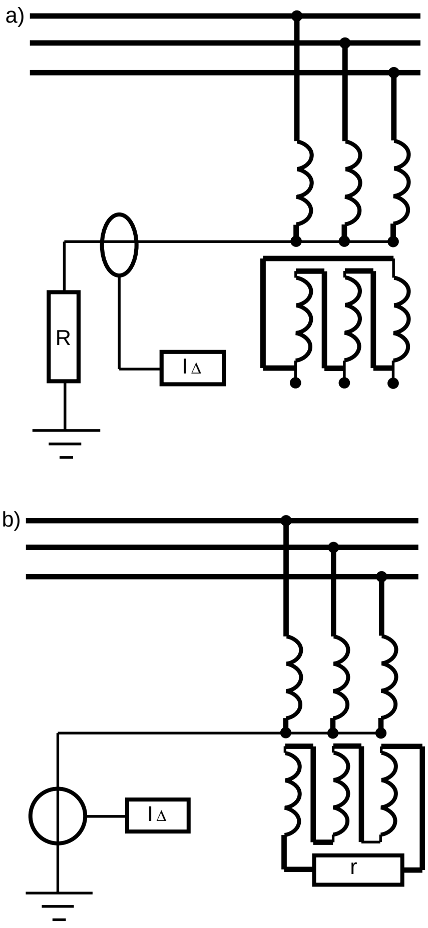


fig. 4: earthing a network neutral by means of a star-delta transformer associated to:
a) a resistor connected to the HV side; in this case the transformer secondary winding can supply the auxiliaries;
b) a resistor series-connected to the secondary winding.

Several solutions are possible:

- a star/delta transformer with a resistor;
- a zigzag coil (see figs. 1 and 6): this is used in cases where the maximum earth fault current is limited to values over 100 A;
- or, a special transformer, since to set up an artificial neutral it may be more economical to use the transformer which supplies the substation LV auxiliaries (see figs. 7 and 8).

fig. 5: special transformer for neutral earting

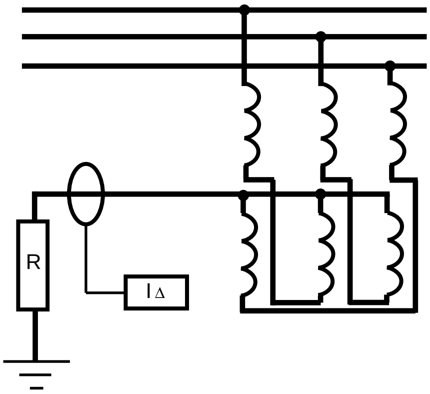


fig. 6: neutral earthing by means of a zigzag coil.

The resulting impedance :
$r_o + jI_o\omega$ appears as a resistance
if $r_o \geq 2I_o\omega$,
with r_o and I_o referenced to the same voltage.

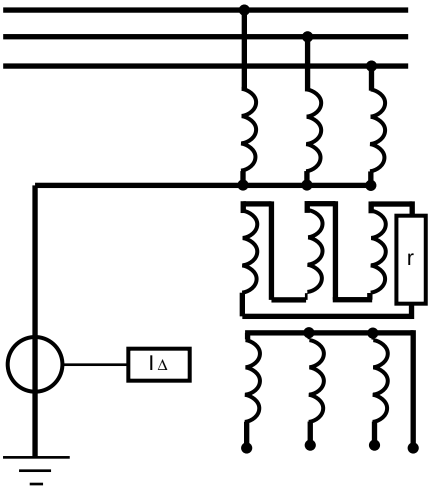


fig. 7: neutral earthing by means of a double-star transformer with compensating delta windings around a resistor.

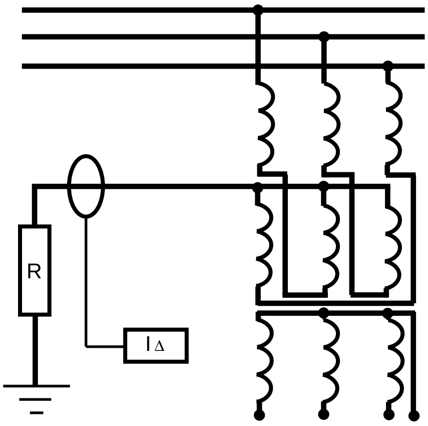
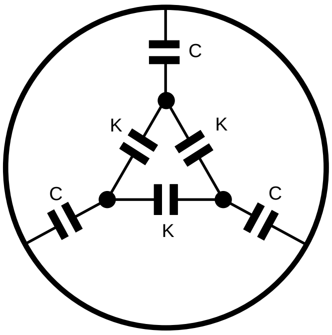


fig. 8: neutral earthing by means of a zigzag transformer.

appendix 1:how to determine the capacitance values of a network

The capacitance of the cables depends on their design:

- **single-pole cable**
The conductor is surrounded by a shield and the capacitance C is that measured between the conductor and the earthed shield.
- **three-pole radial field cable**
Each conductor is surrounded by a shield and the capacitance C is that measured between each conductor and its earthed shield.
- **three-pole belted type cable**
A single shield surrounds the three conductors. There is a capacitance K between conductors and a capacitance C between each conductor and the earthed shield.



For the single-pole cable and the three-pole radial field cable, there is no ambiguity since there is only one capacitance, C which is a phase-to-earth capacitance. If there is no fault and in three-phase steady-state operating conditions, a capacitive current i_c flows through each phase and is absorbed by the cable capacitance C under the phase voltage V, flowing from phase to earth, at the network frequency:

$$i_c = C\omega V = C\omega\frac{U}{\sqrt{3}}$$

Since this capacitive load is three-phased and balanced, it does not disturb the network and does not affect the protection operation.

On the other hand, if an earth fault occurs in the network, in other words when a phase is earthed, the cable capacitance is equivalent to an unbalanced load composed of the capacitance C between the two sound phases and the earth under phase to phase voltage U.
The two currents CωU which are out of phase by 60° flow through the two sound phases; the sum of these two currents is known as the capacitive current I_C of the network in the event of an earth fault.

$$I_c = 2C\omega V\ \cos\frac{\pi}{6}\ \sqrt{3}\,C\omega U$$

i.e. $I_C = 3\,C\omega V$.

For the three-pole belted type cable, if there is no fault, current i_c flowing in balanced conditions is:

$$i_c = \sqrt{3}\,K\omega U + C\omega V = 3\,K\omega V + C\omega V$$

i.e. $i_c = (3\,K + C)\,\omega\,V$ per phase, and the sum of the currents of the three phases is zero

Cable manufacturers generally give this 3 K + C capacitance value for belted-type cables.
On the other hand, if there is an earth fault in the network, in other words if a phase is earthed, the capacitive load includes:

- the three K capacitance values under the phase to phase voltage which form a balanced load;
- the three C capacitance values, two of which are under phase to phase voltages and are out of phase by 60°; the third under a zero voltage.

The sum of these currents (i_c per phase), known as the capacitive current I_c of the network in the event of an earth fault is:

$$i_c = 2\,C\omega V\cos\frac{\pi}{6} = \sqrt{3}\,C\omega U$$

i.e. $I_c = 3\,C\omega\,V$.

Conclusion: when determining the resistance of an earth connection or the adjustment of an earth protection device, the capacitive current that must be known is therefore:

$I_c = 3\,C\omega\,V$

which only takes into account the capacitance C regardless of the cable type.

In practise, cable manufacturers use the term star connection capacitance, for which they indicate the following:

- the value of C for radial field cables,
- the value of 3 K + C for belted type cables.

They do not normally give this C capacitance value for belted type cables. On request, they give three measurement results for these cables:

- the capacitance C_1 measured between a conducting core and the other cores connected to the metal sheathing; this gives the relation $C_1 = 2\,K + C$,
- the capacitance C_2 measured between the three conducting cores bound together and the metal sheathing; this gives the relation: $C_2 = 3\,C$,
- the capacitance C_3 measured between two conducting cores, with the third connected to the metal sheathing; this gives the relation:

$$C_3 = \frac{3\,K + C}{2}$$

Thus, capacitance C_2 must be known in order to directly obtain the value of:

$$C = \frac{C_2}{3}$$

appendix 2:bibliography

[1] Le Verre: «Overvoltages occurring when elimining short-circuits in networks with the neutral earthed through a resistor». Société Française des Electriciens (French Electricians' Guild) Bulletin, 8th series, Volume 1, No. 4 (April, 1960).

[2] E.D.F.: Memo on protection of hydraulic power generators. NP 69 03.

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