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Course KEE/PDS

Transmission and distribution grids

Neutral Earthing

NEUTRAL EARTHING/GROUNDING ARRANGEMENTS

Literature:
Metha: Principles od Power Systems, chapters 26.4 – 26.11
Kasiski: Short Circuits in Power Systems, chapter 7
Kiank, Fruth: Planning Guide for Power Distribution Plants, chapter 6.2
Lakervi: Electricity Distribution Network Design, chapter 3.5 and 3.7.3
Kock: Practical Power Distribution for Industry, chapter 6.1
Wadwha: Electrical Power Systems, chapters 1.1-1.4

Source: Murari Mohan Saha, Jan Izykowski ,Eugeniusz Rosolowski : Fault Location on Power Networks, Springer-Verlag London Limited 2010, ISBN 978-1-84882-885-

2.5 Distribution Networks

2.5.1 Basic Principles of Distribution Systems

Distribution systems, also called medium voltage (MV) systems deliver the electrical energy to final step-down transformers at voltages below 132 kV (this value may be different in particular systems). The MV networks provide supplies direct to large customers, but the vast majority of consumers are connected at low voltage via distribution transformers (MV/LV) [73, 87, 327]

A scheme of a typical distribution system is presented in Fig. 2.33. The MV networks are supplied from HV/MV-transforming substations. The electrical energy is then transported via a series of underground-cable and overhead-line circuits to the customers. In some cases a dispersed generation (DG) can be connected to the network. The particular line sections are of length from a few hundred meters to some dozens of kilometers. The distribution voltages in a specific service territory are likely similar because it is easier and more cost effective to stock spare parts when the system voltages are consistent. Although due to different loads and the network development, separate feeders are made up of sections with different technical data: varying cable cross-sections and overhead-line parameters.

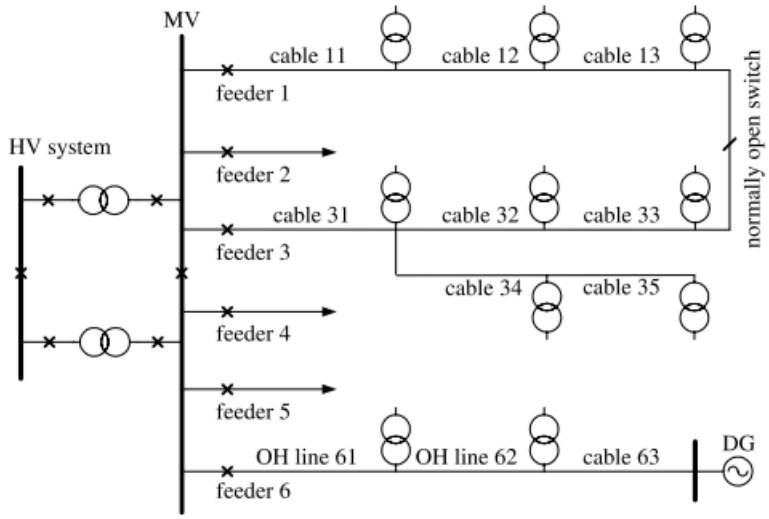


Fig. 2.33 Typical configurations of MV network

The configuration layout and complexity of distribution networks vary widely depending on the application. From that point of view one can specify: rural systems; suburban systems; urban systems, and industrial systems.

Apart from the application, typically the distribution system is radial in nature, including feeders and laterals. Some loads directly in MV level or in LV level are one- or two-phase loads. The majority of distribution circuits are three phase, although in some rural areas single-phase circuits may be used.

Generally, distribution networks are radial systems supplied from one step-down point. However, sometimes also closed-loop networks are used. Moreover, more and more frequently DG sources are connected to distribution networks. A similar effect is observed during a fault introducing motor loads. This is due to the fact that motors behave as generators just after the fault inception. Similarly, if there are motor load taps along a radial distribution line it is equivalent to a line connected to multiple energy sources [327].

6.1 Importance of neutral earthing

The most common fault in all distribution systems is a line-to-earth fault. Fault statistics collected over many years show that 70 % to 90 % of all power system disturbances start as a line-to-earth fault, that is, as a puncture in the insulation of a conductor to earth [6.1 to 6.5]. On occurrence of a line-to-earth fault, three processes occur simultaneously within a very short time (µs < t < ms) [6.6]:

- *The line-to-earth voltage* of the line affected by the earth fault collapses. In the case of a dead short circuit to earth, this voltage drops to zero.
- *The instantaneous values of the line-to-earth voltages* of the two lines without earth faults jump to the instantaneous value of the assigned line-to-line voltage (delta voltage).
- *The instantaneous value of the displacement voltage* suddenly increases from the normal level (less than 10 % of the nominal voltage) to a value that, in the case of a dead short circuit to earth, corresponds to the instantaneous value of the line-to-neutral voltage (star voltage).

The sudden change in the voltages in the three-phase three-wire system is accompanied by short high-frequency oscilllation (transient condition, igniting oscillation) that adds up to the fundamental of the displacement voltage. This short transient condition can produce high voltage surges if damping is not provided. The effects of an earth fault on system operation are considerably influenced by whether and how the neutral point of the system supply is connected to earth. Practically, the fault currents occurring on faults to earth and voltage stress of the equipment depend only on the method of neutral earthing. Because of the high percentage that earth faults represent in the total number of faults, the neutral earthing also has a major influence on the supply reliability in the event of disturbances in the distribution system. For reliable operation of MV industrial power systems, choosing the most advantageous neutral earthing is therefore very important.

2.5.2 Methods of Neutral Grounding

The fault current during a fault depends on the fault-loop impedance and the equivalent supplying voltage. In the case of a phase-to-phase fault the fault loop has small impedance and the fault current reaches a relatively high level. The total fault-loop impedance is basically determined by the longitudinal parameters of the line sections covered by the fault.

Phase-to-ground fault characteristics significantly depend on the type of the network neutral grounding (grounding). System grounding, or the intentional connection of a phase or neutral conductor to ground, is used for the purpose of controlling the voltage to ground (earth), within predictable limits. It also provides for a flow of current that will allow detection of an unwanted connection between system conductors and ground (a phase-to-ground fault). The question of how the network neutral shall be grounded is determined by particular regulations. Local utility practice also influences the choice of the neutral-grounding arrangement on the MV circuits. The general purpose of grounding is to protect life and property in the event of faults and transient phenomena resulting from switching operations. Another reason for adequate grounding of the network is to allow high sensitivity of the relays operation. Fault detection and location invariably relies on the presence of a considerable amount of fault current and this is met in the solidly grounded networks or when the grounding impedance is small – as far as a fault between one or more phases and ground is considered.

Regarding the method of the neutral grounding, the MV networks can be divided into the following categories [96, 97, 265, 327]:

- directly or solidly grounded;
- network grounded through impedance; and
- isolated network.

Adequate method can be assured by grounding the star point delta/wye step-down transformer (Fig. 2.34a). In the case when the MV side of the transformer has delta connection, a separate grounding zigzag connected transformer is applied as a, generally, more efficient solution (Fig. 2.34b).

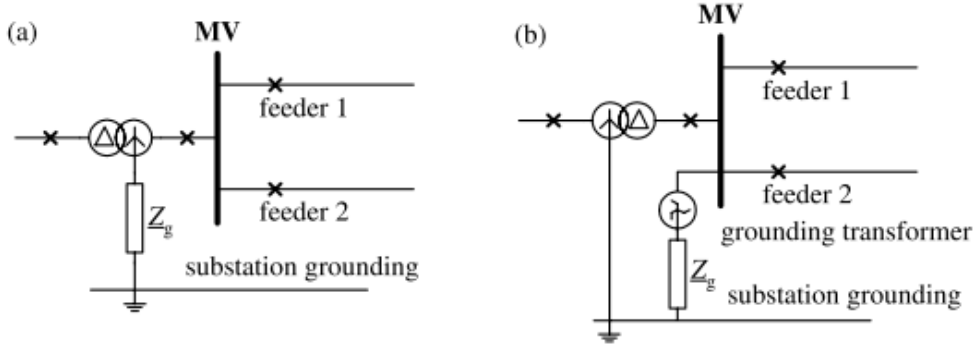


Fig. 2.34 Methods of MV network grounding: (a) with delta-wye step-down grounding transformer; and (b) with grounding zigzag connected transformer; Z_g – grounding impedance

1. Power system with solidly / directly grounded neutral

In the solidly grounded network the only impedance between the neutral and ground is that represented by the grounding transformer impedance, grounding conductor and the ground plate itself (Fig. 2.34). Solid neutral grounding is cheaper as it requires no extra equipment but can lead to high ground-fault currents that may cause damage and high step or touch voltages. On the other hand, this solution establishes a low-impedance path for ground-fault currents and hence satisfactory operation of relay protection.

Advantages

- Neutral held effectively at ground potential
- Phase-to-ground faults of same magnitude as phase-to-phase faults so no need for special sensitive relays
- Cost of current-limiting device is eliminated
- Size and cost of transformers are reduced by grading insulation toward neutral point N.

Disadvantages

- As most system faults are phase-to-ground, severe shocks are more considerable than with resistance grounding
- Third harmonics tend to circulate between neutrals.

In accordance with HD 63751, a network with low impedance neutral point grounding (Figure 7.3) is present only when the neutral point of one or more transformers is directly grounded and the network protection is designed so that in the event of a short circuit to ground at any arbitrary fault position automatic cut-off must take place (protection by cut-off).

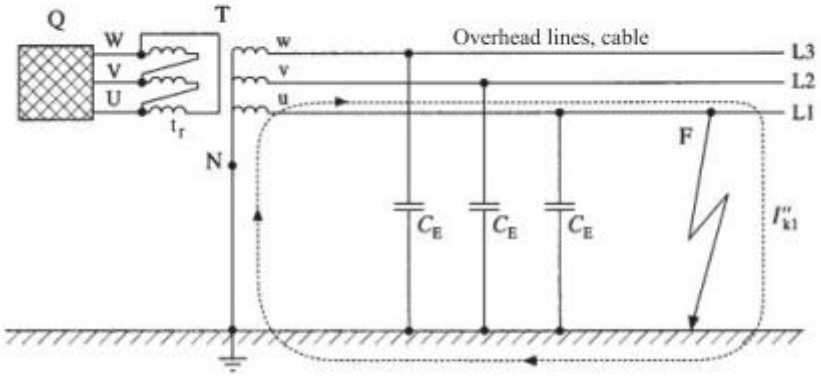


Fig. 7.3: Low-resistance grounded network

The fault to ground is described as a short circuit to ground and the fault current as short circuit current to ground or single-pole short circuit current. The short circuit currents to ground are however limited by the neutral point impedance (Z_S = 20 ⋯ 60 Ω) to values below 5 kA. The ground fault factor $\delta = \frac{U_{LE}}{U/\sqrt{3}}$ will be introduced here to describe the voltage conditions for the neutral point treatment, where U_{LE} is the conductor-to-ground voltage for a fault and U the operating voltage before the fault occurs. For a single-pole short circuit current, then:

$$\bar{I}_F = \frac{\sqrt{3} \cdot \bar{U}_n}{\bar{Z}_1 + \bar{Z}_2 + \bar{Z}_0 + 3R_F}$$

Ground fault in three-phase systems

MV grids without a directly grounded neutral point (distribution systems)
→ single-phase ground fault has a different character than short-circuits (small capacitive current).

Fault current proportional to the system extent.

$I_p > 5$ A → arc formation → conductors, towers, insulators burning →
→ 2ph, 3ph short-circuits (mainly at cables)

Interrupted GF → overvoltage up to 4÷5 U_{ph} on healthy phases

GF compensation → uninterrupted system operation (until the failure clearance, short supply break), arc self-extinguishing

Ground fault

- resistive (100x Ω), metal and arc (x Ω)
- momentary (up to 0,5 s), short-term (up to 5 min), interrupted (repeating), permanent (x hours)

2. Power system with isolated neutral

Insulated neutral point – systems of a small extent, Ip (I_F) ≤ 5 A (Czech Republic)

An isolated network is one in which there is no intentional connection between the circuit and ground (Fig. 2.37). The currents during single phase-to-ground faults are low and depend mostly on the phase to ground capacitances of the lines.

The voltage between faulted equipment and ground is small, which improves safety. However, transient and power-frequency overvoltages can be higher than those obtained for other type of neutral grounding. Moreover, a one-phase grounding results in the full line-to-line voltage appearing on the other two sound phases. This situation can frequently cause failures in motors and transformers, due to insulation breakdown. There are known difficulties in detecting and locating the first line-to-ground fault: the overcurrent principle is not suitable here because the capacitive current in a sound line may be even greater than that measured at the faulted line [95, 97].

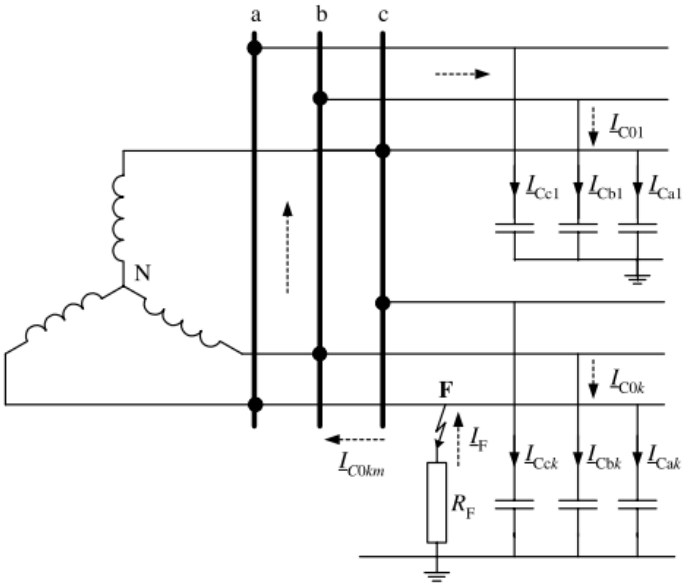


Fig. 2.37 Equivalent scheme of the isolated network; dotted lines show path for the fault current

Power system with isolated neutral [6.2, 6.5, 6.7 to 6.18]

A power sytem with isolated neutral (Fig. B6.2) is defined as a power system in which the neutral points of transformers and generators are either not connected to earth or only connected to earth through measurement and protective devices with a very high impedance or through an overvoltage protector. Operation with isolated neutral is the simplest form of earth-fault-oriented neutral-point connection. In the event of an earth fault, voltage displacement to earth occurs. This voltage displacement which is shown in Fig. B6.3 as a vector diagram, is characterized by the fact that the neutral point of the system (transformer neutral point) accepts the full star voltage to earth and the lines without faults increase their voltages to earth from the star voltage to the delta voltage. The line-to-line voltages of the earth-faulted power system, on the other hand, do not change. Because of this, no reaction arises that is disadvantageous for the loads connected to the power system and operation can be maintained even in the event of an earth fault.

However, the voltage displacement to earth causes the capacitive earth-fault current I_{CE} of the entire power system to flow through the earth fault location. This earth-fault current, which is largely determined by the earth capacitance of the lines C_E, has the magnitude $I_{CE} \approx 3 \cdot \omega \cdot C_E \cdot U_{LE}$.

For reliable operation of industrial cable networks with isolated neutral, a fault current range of $10\ A < I_{CE} \leq 30\ A$ is recommended. In this range, it can be expected that both the risk of intermittent earth faults with high transient overvoltages and the thermal effect of the earth-fault arc are relatively minor. Due to the comparatively low thermal stress at $I_{CE} < 30\ A$, the earth-fault arc can burn for longer without destroying the insulation of the intact conductors. Destruction of this insulation would entail a serious danger of the earth fault developing into a double earth fault or short circuit. Danger of fault propagation and the risk of a double earth fault can only be prevented with

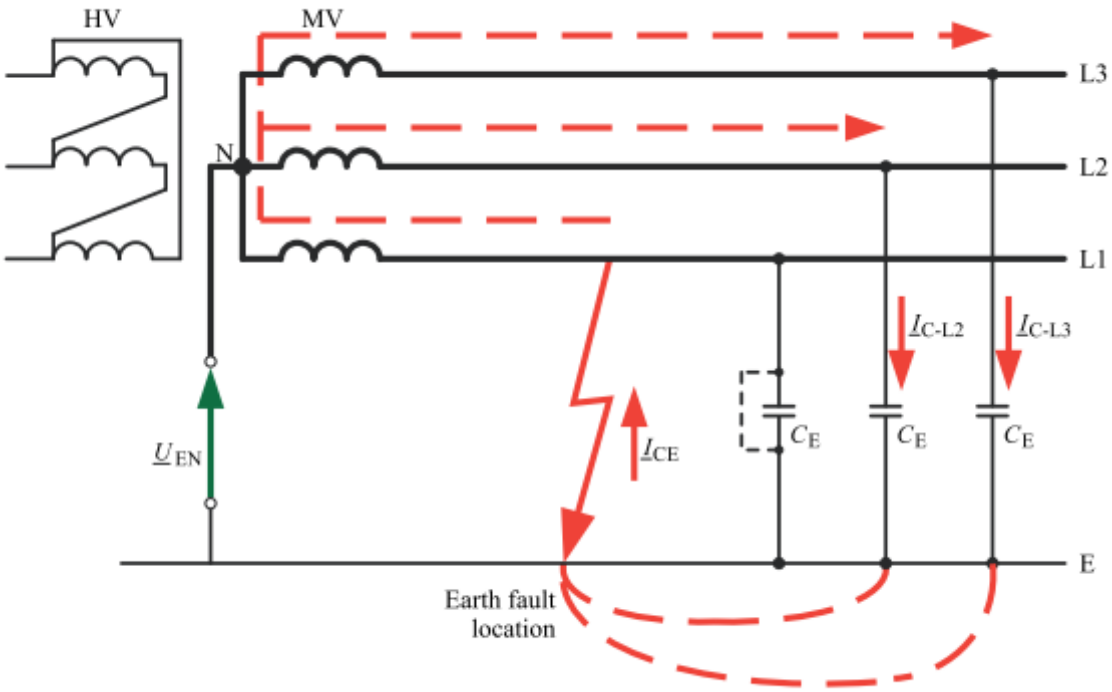


Fig. B6.2 MV system with isolated neutral during an earth fault of line L1

small earth-fault currents if the earth fault is detected selectively and operation is continued only for a limited time. Generally, a time limitation of 3 h for continued operation should be sufficient to create the necessary conditions for earth-fault clearance without any adverse effect on the production process.

Despite its negative side-effects (relaxation oscillations, high transient and long-lasting power-frequency overvoltages), operation with isolated neutral is very important for industrial power supplies. This method of neutral earthing is preferred in small cable networks and those without $(n-1)$ redundancy.

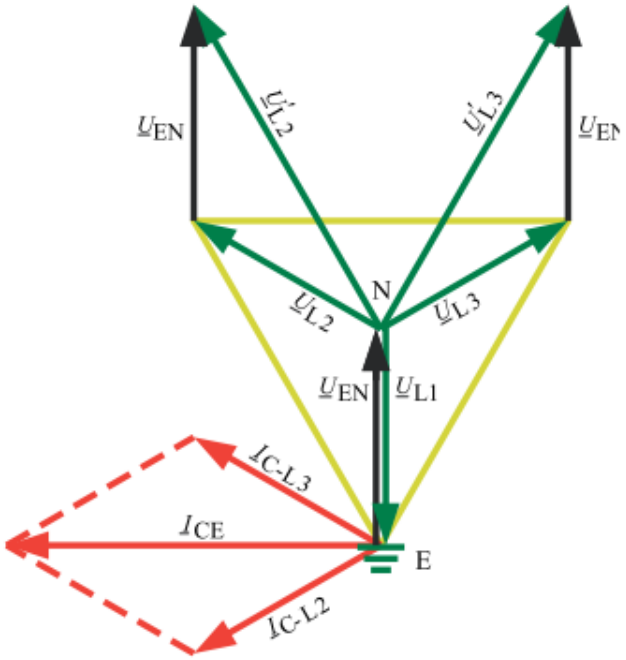


Fig. B6.3
Vector diagram of the voltages and currents during an earth fault of line L1 in a system with isolated neutral

$\underline{U}_{L1}$, $\underline{U}_{L2}$, $\underline{U}_{L3}$	Star voltage of lines L1, L2, L3
$\underline{U}'_{L2}$, $\underline{U}'_{L3}$	Star voltage on the faultless phases L2 and L3 raised by the factor $\sqrt{3}$ (power-frequency overvoltage)
$\underline{U}_{EN}$ or $\underline{U}_{en}$	Neutral-point displacement voltage
$\underline{I}_{C-L2}$ or $\underline{I}_{C-L3}$	Capacitive charging current of line L2 or L3
$\underline{I}_{CE}$	Capacitive earth-fault current at the fault location

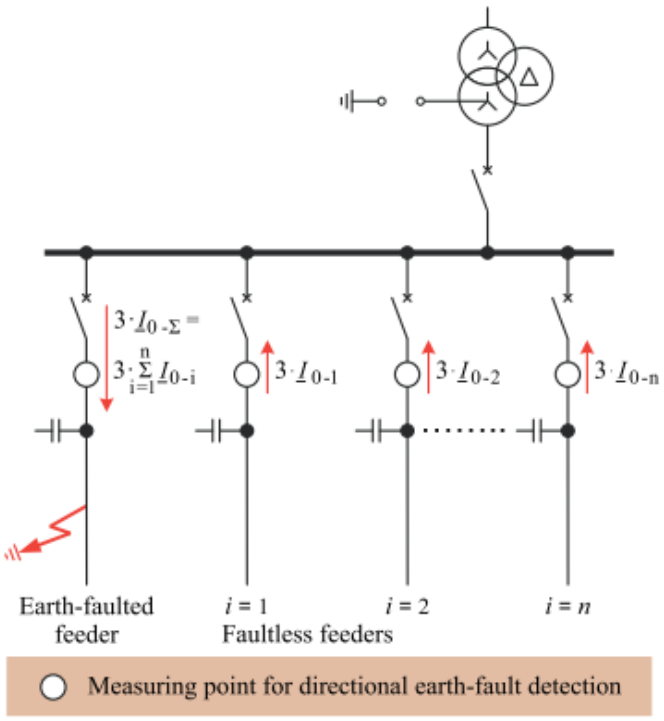


Fig. B6.4
Distribution of the residual currents on an earth fault in a system with isolated neutral

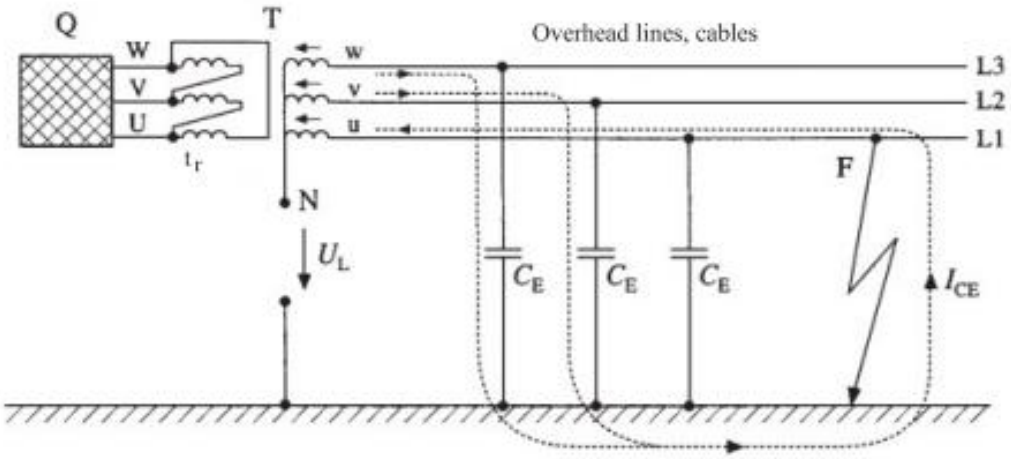


Fig. 7.1: Isolated network

The short circuit current to ground flows through the capacitances to ground C_E of the uninterrupted conductors (Figure 7.1). The short circuit currents to ground are small in this case and in small networks are usuallyself-quenching, although large transient overvoltages can occur. The potential of the neutral point relative to ground is determined by the capacitances C_E. The short circuit current to ground I_{CE} at the position of the short circuit is given by:

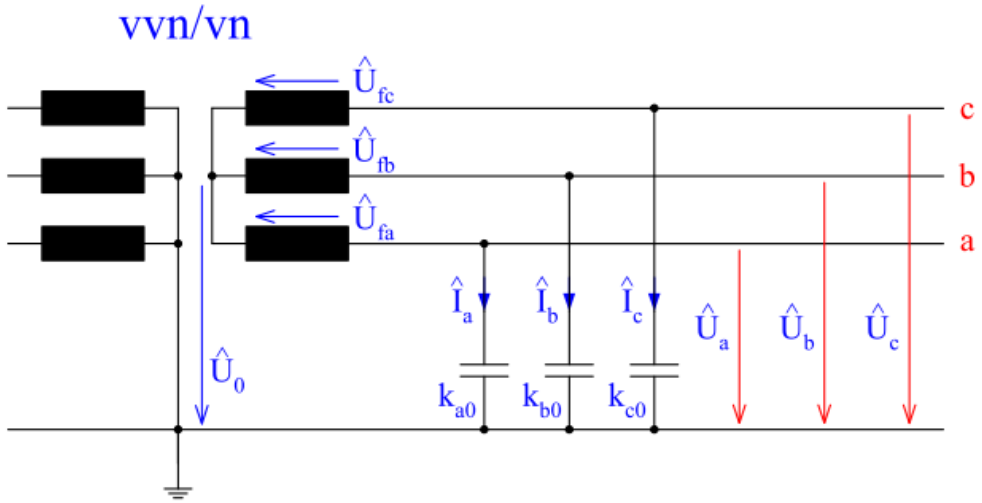
$$I_{CE} = 3 \cdot w \cdot C_E \frac{c \cdot U_n}{\sqrt{3}}. \qquad (7.1)$$

The short circuit current to ground increases with the length of the conductor, so that the operation of this type of network is restricted to smaller networks (up to 30 kV). The limiting value of the short circuit current to ground is around 35 A, since otherwise the arcing is no longer self-quenching.

Not 35 A but 5 A in the Czech Republic.

Conditions in a system with insulated neutral point (theory)

Before the earth fault



$$\hat{U}_a - \hat{U}_0 - \hat{U}_{fa} = 0 \qquad \hat{I}_a = j\omega k_{a0}\hat{U}_a$$
$$\hat{U}_b - \hat{U}_0 - \hat{U}_{fb} = 0 \qquad \hat{I}_b = j\omega k_{b0}\hat{U}_b$$
$$\hat{U}_c - \hat{U}_0 - \hat{U}_{fc} = 0 \qquad \hat{I}_c = j\omega k_{c0}\hat{U}_c$$

System with insulated neutral point

$$\hat{I}_a + \hat{I}_b + \hat{I}_c = 0$$

Symmetrical source

$$\hat{U}_{fb} = \hat{a}^2\hat{U}_{fa}, \quad \hat{U}_{fc} = \hat{a}\hat{U}_{fa}$$

Neutral point voltage

$$\hat{U}_0 = -\frac{k_{a0} + \hat{a}^2 k_{b0} + \hat{a}k_{c0}}{k_{a0} + k_{b0} + k_{c0}}\hat{U}_{fa}$$

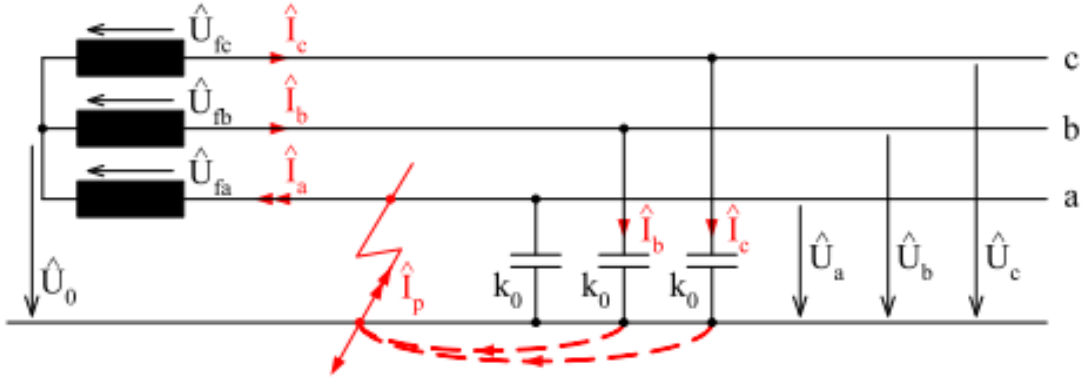
Unbalanced capacities

$$\hat{U}_0 \neq 0$$

Symmetrical capacities

$$k_{a0} = k_{b0} = k_{c0} = k_0 \quad \Rightarrow \quad \hat{U}_0 = 0$$

During the earth fault



Fault current composed of 2 capacitive currents in the disaffected phases.

$$\hat{U}_a = 0$$
$$\hat{I}_p = \hat{I}_a = \hat{I}_b + \hat{I}_c$$
$$\hat{I}_b = j\omega k_0\hat{U}_b \qquad \hat{I}_c = j\omega k_0\hat{U}_c$$
$$\hat{U}_a - \hat{U}_0 - \hat{U}_{fa} = 0 \quad \Rightarrow \quad \hat{U}_0 = -\hat{U}_{fa} \ !$$

$$\hat{U}_b - \hat{U}_0 - \hat{U}_{fb} = 0 \quad \Rightarrow \hat{U}_b = \hat{U}_0 + \hat{U}_{fb} = \left(-1 + \hat{a}^2\right)\hat{U}_{fa} = -\sqrt{3}e^{j30^\circ}\hat{U}_{fa} \quad !$$

$$\hat{U}_c - \hat{U}_0 - \hat{U}_{fc} = 0 \quad \Rightarrow \hat{U}_c = \hat{U}_0 + \hat{U}_{fc} = \left(-1 + \hat{a}\right)\hat{U}_{fa} = -\sqrt{3}e^{-j30^\circ}\hat{U}_{fa} \quad !$$

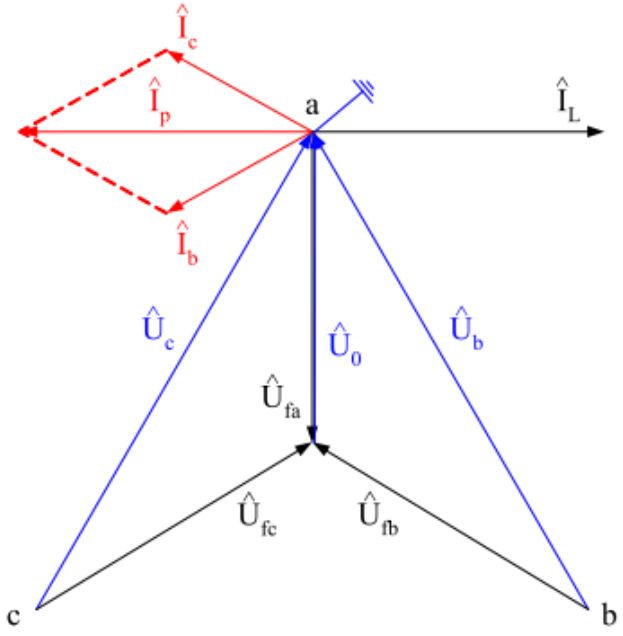
→ affected phase voltage – zero
neutral point voltage – phase-to-ground value
disaffected phases voltage – phase-to-phase value

Ground fault current

$$\begin{aligned}\hat{I}_p = \hat{I}_b + \hat{I}_c &= j\omega k_0\left(\hat{U}_b + \hat{U}_c\right) \\ &= j\omega k_0\left[\left(-1 + \hat{a}^2\right) + \left(-1 + \hat{a}\right)\right]\hat{U}_{fa} \\ &= j\omega k_0\left(-2 + \hat{a}^2 + \hat{a} + 1 - 1\right)\hat{U}_{fa}\end{aligned}$$

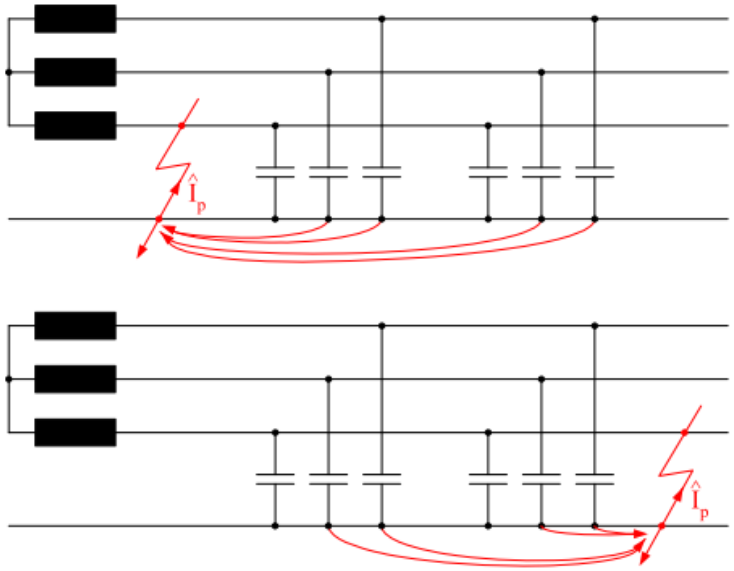
$$\hat{I}_p = -3j\omega k_0\hat{U}_{fa} = 3j\omega k_0\hat{U}_0 \quad \left(A; s^{-1}, F, V\right)$$

Voltage and current conditions



Fault current depends on the total system extent and almost doesn't depend on the fault point distance from the transformer.

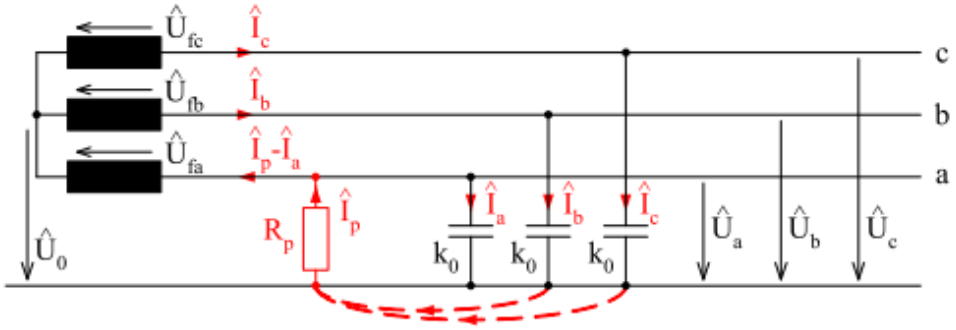
$$I_p = 3\omega k_{01} l U_f \quad \left(A; s^{-1}, F/km, km, V\right)$$



Note: overhead 22 kV – current c. 0,06 A/km
cables 22 kV – current c. 4 A/km

Note: MV system can be operated also with GF, on LV level again 3-phase supplying due to transformers MV/LV D/yn (Y/zn)

Resistive ground fault



Affected phase voltage non-zero

$$\hat{I}_p = -\hat{U}_a / R_p = \hat{I}_a + \hat{I}_b + \hat{I}_c$$

Neutral point voltage

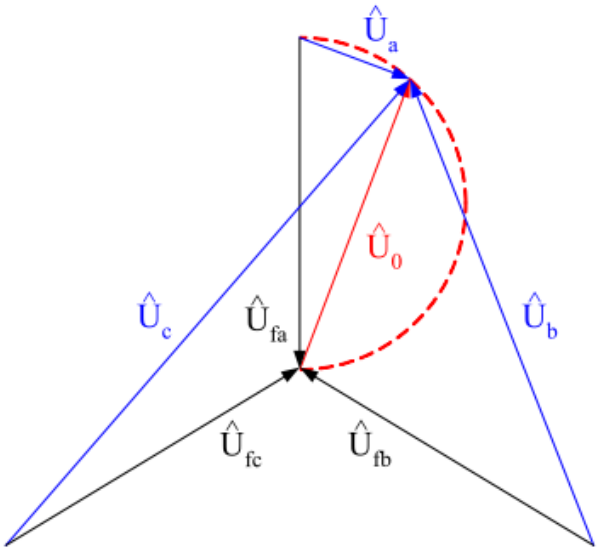
$$\hat{U}_0 = -\frac{j\omega\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right) + R_p^{-1}}{j\omega\left(k_{a0} + k_{b0} + k_{c0}\right) + R_p^{-1}} \hat{U}_{fa}$$

Circle equation in the Gauss plane

$$\hat{U}_0 = -\frac{\hat{A} + R_p^{-1}}{\hat{B} + R_p^{-1}} \hat{U}_{fa}$$

$R_p = 0 \qquad \hat{U}_0 = -\hat{U}_{fa}$

$R_p = \infty \qquad \hat{U}_0 = 0$ (for symmetrical capacities)



Disaffected phase voltage can be higher than the phase-to-phase value.

3. Power system with indirectly grounded neutral (grounded trough impedance)

If the grounding impedance $\underline{Z}_g$ is intentionally selected for reducing a phase-to-ground fault, the grounding becomes non-effective (Fig. 2.35). For high grounding impedance the network capacitance plays a significant role.

There are two types of impedance grounding [96, 278]:

- grounding through resistor; and
- grounding through arc-suppressing coil (Petersen coil).

Resistance grounding is broadly dividing into two categories: high-resistance (when the fault current is limited to about 10 A) and low-resistance grounding (with fault current of some hundreds of amps). Generally, the high grounding resistance decreases the selectivity of the protective relays because the fault detection and the fault-place estimation are less accurate.

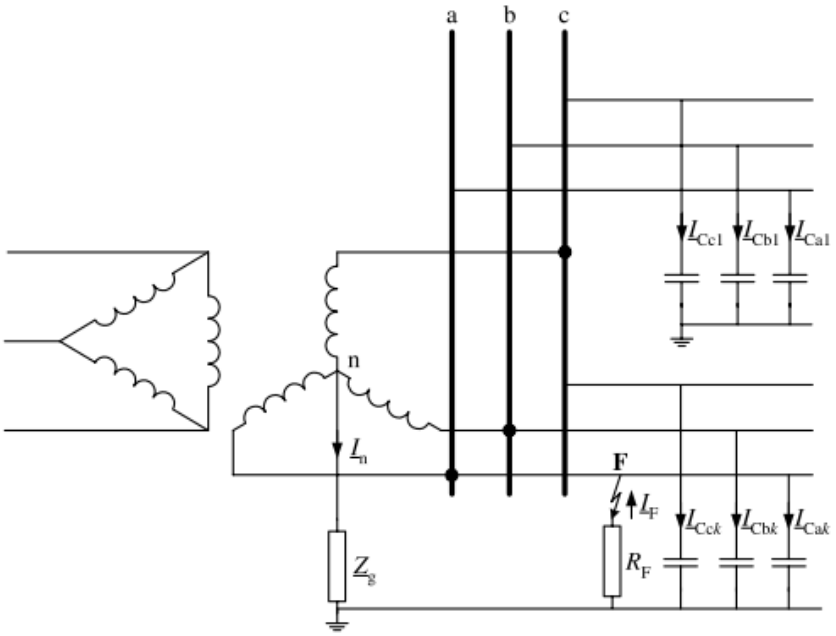


Fig. 2.35 Equivalent scheme of network grounding through impedance

Grounding through arc-suppressing coil (Petersen coil)

Power system with resonant neutral earthing [6.2 to 6.5, 6.7, 6.21 to 6.46]

A system with resonant neutral earthing or earth-fault compensation (Fig. B6.9) is a power system in which the neutral point of one or more transformers is earthed through an arc-suppression coil (Petersen coil) with inductance L_{ASC}. The resulting inductance of the arc-suppression coil(s) is essentially coordinated with the line-to-earth capacitances of the power system. Coordination is undertaken in such a way that the power-frequency inductive alternating current $\underline{I}_{ASC}$ that flows through the arc-suppression coils during a line-to-earth fault largely compensates for the power-frequency capacitive component $\underline{I}_{CE}$ of the earth-fault current $\underline{I}_F$.

The residual earth-fault current $\underline{I}_{resi}$ that remains after compensation of $\underline{I}_{CE}$ reduces the thermal load at the earth-fault location.

Its magnitude $|\underline{I}_{resi}| = I_{resi}$ can be calculated as follows:

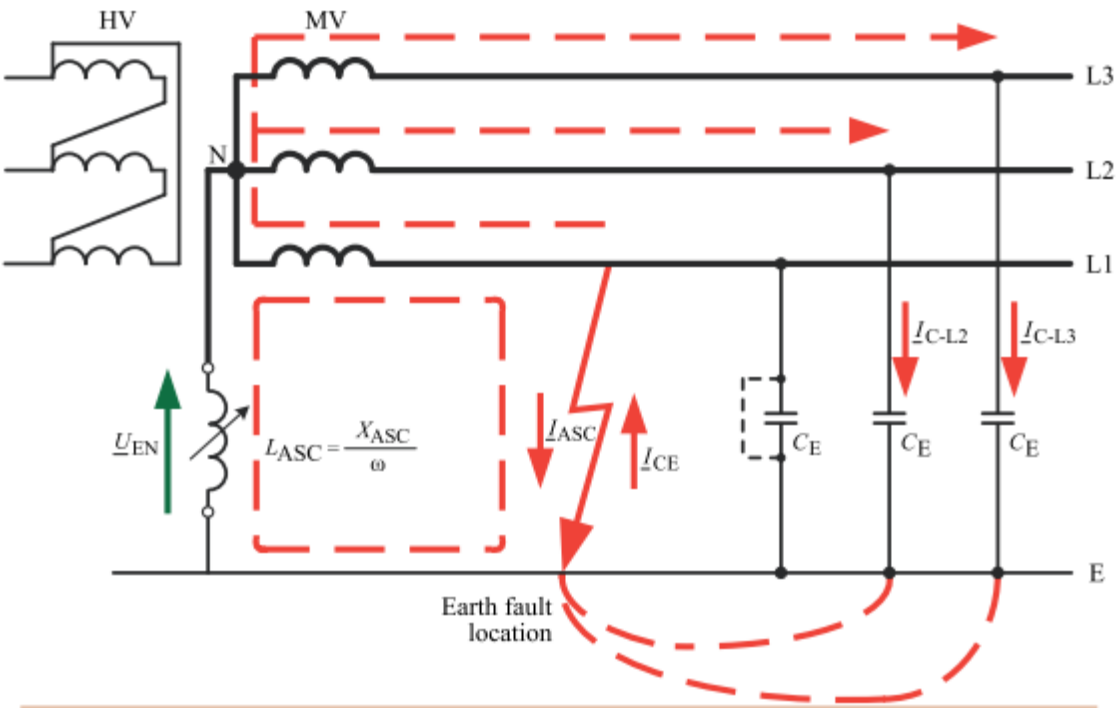
$$I_{resi} = \sqrt{(I_{CE} - I_{ASC})^2 + I_R^2 + \sum_h I_h^2} \tag{6.3}$$

$$I_R = I_{R\text{-}ASC} + I_{R\text{-}CE} \tag{6.3.1}$$

I_{resi}	residual earth-fault current
I_{CE}	capacitive earth-fault current of the system
I_{ASC}	inductive arc-suppression coil current
I_R	residual active current ($I_R = (0.02...0.05) \cdot I_{CE}$ in MV cable networks)
I_h	harmonic currents, caused by magnetization currents of the transformers
$I_{R\text{-}ASC}$	residual active current due to ohmic losses of the arc-suppression coil
$I_{R\text{-}CE}$	residual active current due to leakage and dielectric losses of the lines

In a system ideally tuned to resonance (detuning factor $v = 1 - I_{ASC}/I_{CE} = 0$), only the power-frequency residual active current $\underline{I}_R$ (50-Hz currrent) and a higher-frequency harmonic residual current $\underline{I}_h$ (e.g. 250-Hz current) flow through the fault location. The tuning to resonance has no direct influence on the voltage conditions in case of an earth fault. Practically, the same voltage conditions to earth occur in a power system with resonant neutral earthing as in a power system with isolated neutral. Fig. B6.10 shows the vector diagram of the power-frequency voltages and currents during an earth fault of line L1 in a resonant neutral earthed system.

The necessary resonance tuning in power systems with resonant neutral earthing is best achieved with the use of plunger-core arc-suppression coils. Standardized nominal powers Q_{rASC} with the corresponding reactive current ranges $I_{min\text{-}ASC} \le I_{ASC} \le I_{rASC}$ are listed in Table B6.11. Plunger-core arc-suppression coils are used in conjunction with a



Fault current: $I_F = I_{resi} = (I_{CE} - I_{ASC}) + I_R + I_h$; $I_R = I_{R\text{-}ASC} + I_{R\text{-}CE}$

$|I_{resi}| \approx 0.03 \cdot |I_{CE}|$ to $0.11 \cdot |I_{CE}|$; $|I_{CE}| = 3 \cdot \omega \cdot C_E \cdot U_{LE}$

U_{EN}	Neutral-point displacement voltage	I_{CE}	Capacitive earth-fault current
U_{LE}	Line-to-earth voltage ($U_{LE} = U_{LL}/\sqrt{3}$)	I_{resi}	Residual earth-fault current
U_{LL}	Line-to-line voltage ($U_{LL} = U_{nN}$)	I_{ASC}	Arc-suppression coil current
L_{ASC}	Inductance of the arc-suppression coil	I_R	Residual active current ($I_R = (0.02 \cdots 0.05) \cdot I_{CE}$ in MV cable systems
X_{ASC}	Reactance of the arc-suppression coil ($X_{ASC} = U_{LL}/\sqrt{3} \cdot I_{ASC} \approx 1/3 \cdot \omega \cdot C_E$)	$I_{R\text{-}ASC}$	Residual active current due to ohmic losses of the arc-suppression coil
ω	Angular frequency ($\omega = 2 \cdot \pi \cdot f$)	$I_{R\text{-}CE}$	Residual active current due to leakage and dielectric losses of the lines
C_E	Line-to-earth capacitance	I_h	Harmonic current

Fig. B6.9 MV power system with earth-fault compensation or resonant neutral earthing (RESPE)

resonant neutral earthing controller that automatically tunes the inductive arc-suppression coil current I_{ASC} for the prevailing system conditions. The maximum displacement voltage (voltage between the neutral point and earth) functions as the closed-loop control setpoint during fault-free operation. The displacement voltage during fault-free operation is caused by the unequal line-to-earth capacitance of the individual phases.

With precise resonance tuning ($I_{ASC} = I_{CE}$), this voltage reaches its maximum value. In resonant-earthed cable networks, the maximum displacement voltage is only small. Due to the great symmetry of the line-to-earth capacitances, cable networks have only relatively small displacement voltages and flat resonance curves.

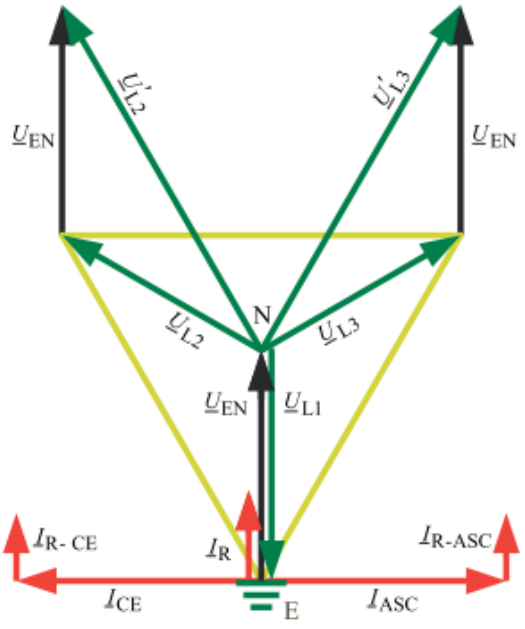


Fig. B6.10
Vector diagram of the voltages and currents during an earth fault of line conductor L1 in a system with earth-fault compensation or resonant neutral earthing (RESPE)

$\underline{U}_{L1}$, $\underline{U}_{L2}$, $\underline{U}_{L3}$	star voltage of lines L1, L2, L3
$\underline{U}'_{L2}$, $\underline{U}'_{L3}$	star voltage on the faultless phases L2 and L3 raised by the factor $\sqrt{3}$ (power-frequency overvoltage)
$\underline{U}_{EN}$ or $\underline{U}_{en}$	neutral-point displacement voltage
$\underline{I}_{CE}$	capacitive earth-fault current of the system
$\underline{I}_{ASC}$	inductive arc-suppression coil current
$\underline{I}_R$	resultant residual active current
$\underline{I}_{R-CE}$	active component of $\underline{I}_{CE}$
$\underline{I}_{R-ASC}$	active component of $\underline{I}_{ASC}$

If resonance curves are too flat, controllability of the plunger-core arc-suppression coils used for the resonant neutral earthing must be questioned. The only remedy may be to increase the displacement voltage using artificially produced capacitive system unbalance. One good way of adjusting the setpoint of the resonant neutral earthing controller based on measurements is an artificial increase in the capacitive system unbalance by 3-pole disconnection and 1-pole reclosing of selected cable routes.

If resonance tuning is correct, the heat generated at the fault location will be very slight. It is largely determined by the residual active current $\underline{I}_R$ flowing through the fault location. Because the residual active current in cable networks is relatively small, the time that elapses while an earth fault becomes a short circuit can usually be considerably prolonged. The actual advantage of resonant neutral earthing in the operation of cable networks is derived from this extra time. For example, if $(n-1)$ redundancy is limited, it proves advantageous that disconnection of the earth-faulted cable can be deferred until a time that is more favourable for operation even with large capacitive earth-fault currents ($\underline{I}_{CE} > 30$A).

In cable networks, the extensive compensation of the capacitive earth-fault current also has a significant disadvantage: In the case of small residual earth-fault currents $\underline{I}_{\text{resi}}$, the earth faults may suppress themselves. Because XLPE cables do not have a self-healing ability, locations with impaired insulation remain after suppression of the earth fault. These weak points are then not easy to find. Unlocated weak points can later result in chains of multiple earth faults and serious system disturbances in the event of sustained earth faults.

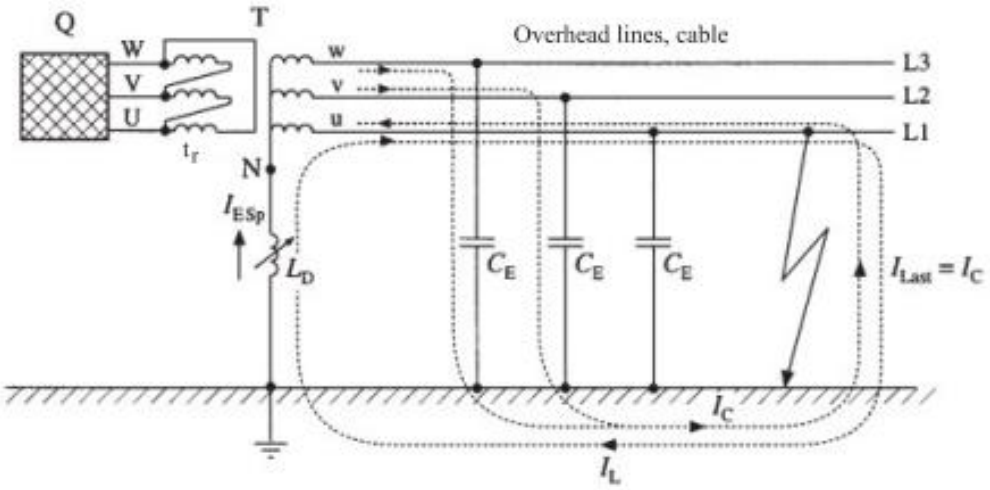


Fig. 7.2: Ground fault neutralizer grounded system

A network with grounding compensation is present when the neutral point is grounded through ground fault coils in such a way that their inductance is matched to the capacitance to ground (Figure 7.2). For the matching condition $I_C = I_L$:

$$I_C = 3 \cdot w \cdot C_E \frac{c \cdot U_n}{\sqrt{3}}, \text{ und } I_L = \frac{c \cdot U_n}{\sqrt{3} \cdot w \cdot L} \tag{7.2}$$

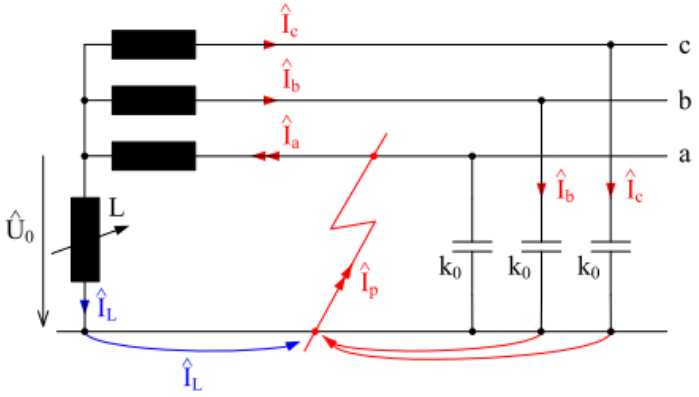
Here, we refer to the ground fault current I_F as the unbalanced residual current. The capacitive short circuit to ground I_C is compensated by the inductive coil current I_L of the ground fault quenching coils apart from a residual current. If the short circuit current to ground exceeds 35 A, the network must be operated with grounding compensation. The residual current should not exceed 60 A for medium voltage networks and 130 A for high voltage networks, in order to ensure the self-quenching of the arcing and to keep the thermal stress under control. If this is not the case, low impedance neutral point grounding must be used. Here too, overvoltages occur as for networks with an isolated free neutral point.

Ground fault current compensation

Compensation in systems where $I_p > 5A$ - suitable

$I_p > 10A$ - necessary

Method: continuously controlled arc-suppression coil (Petersen coil) between the transformer neutral point and the ground (in case of transformers with D winding by means of grounding transformer with Zn, Yn – artificial neutral point)



Faultless state

$U_0 = 0$ - symmetrical capacities

$U_0 \approx x \cdot 0{,}01\, U_f$ - usual unbalance

Perfect ground fault

$$\hat{U}_0 = -\hat{U}_{fa}$$

Arc-suppression coil current

$$\hat{I}_L = -j\frac{\hat{U}_0}{\omega L}$$

Total compensation

$$\hat{I}_L = -\hat{I}_p$$

$$-j\frac{\hat{U}_0}{\omega L} = -3j\omega k_0 \hat{U}_0$$

Hence

$$L = \frac{1}{3\omega^2 k_0} \quad (\mathrm{H};\ \mathrm{s}^{-1},\ \mathrm{F})$$

Coil power (reactive inductive)

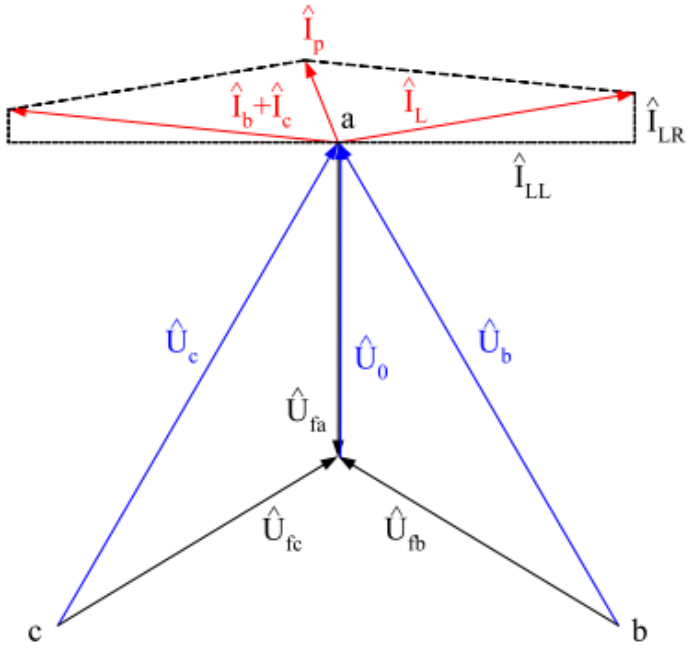
$$\hat{S} = \hat{U}_0 \hat{I}_L^* = 3j\omega k_0 \hat{U}_0 \hat{U}_0^* = j\omega k_0 U^2 = Q_L$$

Ideal compensation: $I_p = 0$ in the fault point

Real situation: residual current (small active)

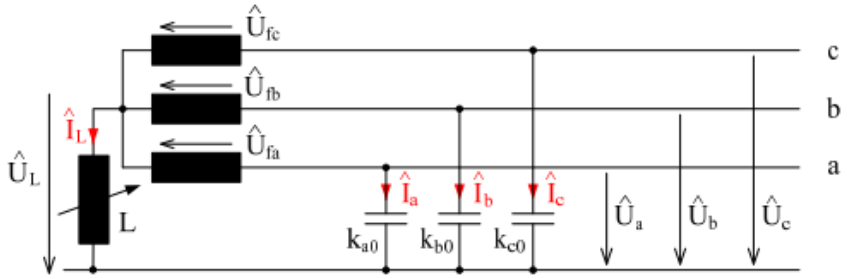
- inaccurate inductance setting (error or intention)
- uncompensatable active component (power line conductance, coil R)
- higher harmonics

$$\hat{I}_p = \left[\frac{1}{R_L} + 3G_0 + j\left(3\omega k_0 - \frac{1}{\omega L}\right)\right]\hat{U}_0$$



Arc-suppression coil tuning

L dimensioning by calculation, setting in the faultless state (for given system configuration).
Tuning is done by magnetic circuit change by means of motor (air gap).



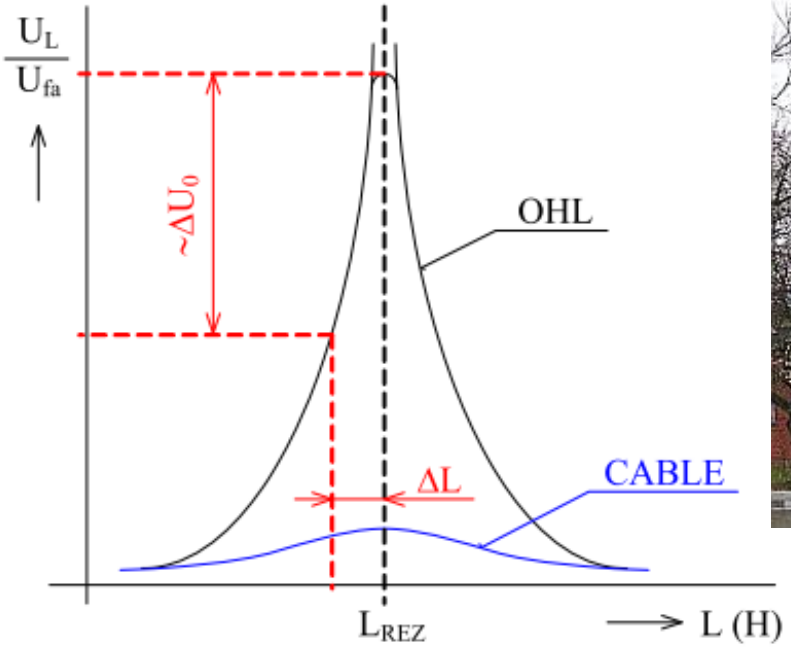
Coil voltage

$$\hat{U}_L = \frac{-\omega^2 L\left(k_{a0} + \hat{a}^2 k_{b0} + \hat{a} k_{c0}\right)}{\omega^2 L\left(k_{a0} + k_{b0} + k_{c0}\right) - 1}\hat{U}_{fa}$$

Resonance dependence

$$\left|\frac{U_L}{U_{fa}}\right| = f(L)$$

$$L_{REZ} = \frac{1}{\omega^2\left(k_{a0} + k_{b0} + k_{c0}\right)}$$









Overhead power lines

- higher capacitive unbalance
- maximum limited by resistances
- L_{REZ} compensates GF totally → resonance coil
- setting by U_L measurement
- with small R the transformer neutral point is strained too much in resonance → intended (small) detuning → dissonance coil

Cable power lines

- small capacitive unbalance → flat curve → difficult tuning

Grounding the neutral through the Petersen coil is used for reducing the capacitive current in isolated networks. The adequate inductance in the neutral is selected for compensation of the capacitive current during a phase-to-ground fault; thus this method is also known as the ground-fault compensation method. The equivalent scheme for this arrangement is shown in Fig. 2.36. The coil reactance is adjustable in relatively coarse steps, to allow for changes in network zero-sequence capacitance resulting from the switching out of lines. If the coil inductance exactly matches the system capacitance, the fault current has resistive character and may be insufficient for selective relay operation. Frequently, the grounding equipment is completed with a resistor (resistor R_g in Fig. 2.36) that, with some delay, automatically paralleling the coil what permits fault current sufficient to correct relay operation.

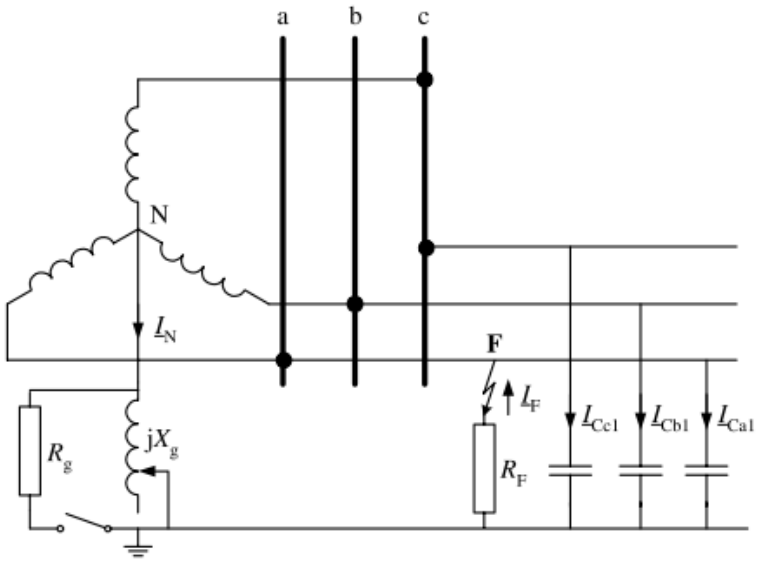


Fig. 2.36 Equivalent scheme of the network grounding through a Petersen coil





Example 1

Power line 22 kV has the partial capacity to the ground $k_0 = 4{,}3.\,10^{-9}$ F/km. Decide whether ground fault currents compensation is required if the line length is $l = 30$ km.

Solution:

We calculate the perfect ground fault current:

$$I_p = 3 \cdot \omega \cdot k_0 \cdot l \cdot U_f = 3 \cdot 314 \cdot 4{,}3 \cdot 10^{-9} \cdot 30 \cdot \frac{22 \cdot 10^3}{\sqrt{3}} = 1{,}54 \text{ A}$$

Necessary $I_p > 10\ A$

suitable $I_p \geq 5\ A$

without $I_p < 5\ A$

Example 2

Distribution grid has a 35 kV power line with the operational capacity $C = 9 \cdot 10^{-9}$ F/km and the partial mutual capacity $k' = 1{,}6.\,10^{-9}$ F/km.

Calculate:

a) Ground fault current
b) Power and induction of suppression coil

Situation is in Fig. 1.

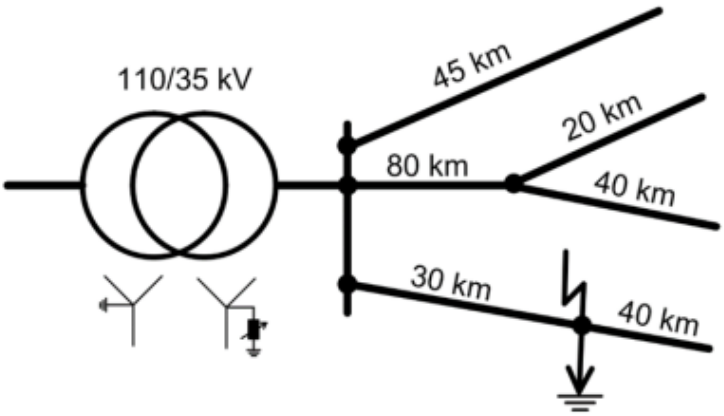


Fig. 1

Solution:

We need the partial capacity to the ground for ground fault calculation. From $C = k_0 + 3k'$, we get $k_0 = C - 3k' = (9 - 3 \cdot 1{,}6) \cdot 10^{-9} = 4{,}2 \cdot 10^{-9}$ F/km.

The ground fault current doesn't almost depend on the fault distance from the source. Therefore we calculate the total grid size as the sum of all lines lengths which are connected in MV substation:

$$l = 45 + 80 + 20 + 40 + 30 + 40 = 255 \text{ km}$$

a) Ground fault current

$$I_p = 3 \cdot \omega \cdot k_0 \cdot l \cdot U_f = 3 \cdot 314 \cdot 4{,}2 \cdot 10^{-9} \cdot 255 \cdot \frac{32 \cdot 10^3}{\sqrt{3}} = 20{,}4 \text{ A}$$

b) Resonance condition

$$I_L = I_p = 20{,}4 \text{ A}$$

$$X_L = X_C$$

$$\omega \cdot L = \frac{1}{3 \cdot \omega \cdot k_0 \cdot l}$$

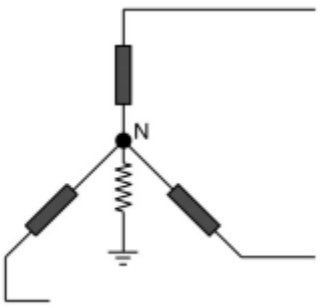
Suppression coil power: $S = U_f \cdot I_L = \frac{35}{\sqrt{3}} \cdot 20{,}4 = 414$ kVAr

Induction of suppression coil: $L = \frac{1}{3 \cdot \omega^2 \cdot k_0 \cdot l} = \frac{U_f}{\omega \cdot I_L} = \frac{35 \cdot 10^3}{\sqrt{3} \cdot 314 \cdot 20{,}4} = 3{,}16$ H

Grounding through resistor

A resistor is connected between the transformer neutral and earth (see Figure 6.2).

- Mainly used from 6.6 to 33 kV
- Value is such as to limit an earth fault current to between 1 and 2 times full load rating of the transformer, typically 400 A.



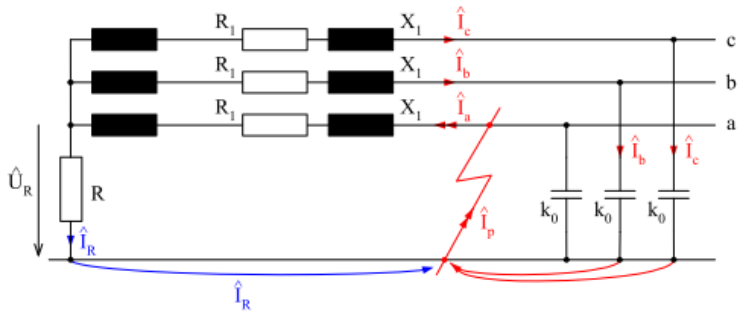


Advantages

Limits electrical and mechanical stresses on system when an earth fault occurs, but at the same time current is sufficient to operate normal protection equipment.

Disadvantages

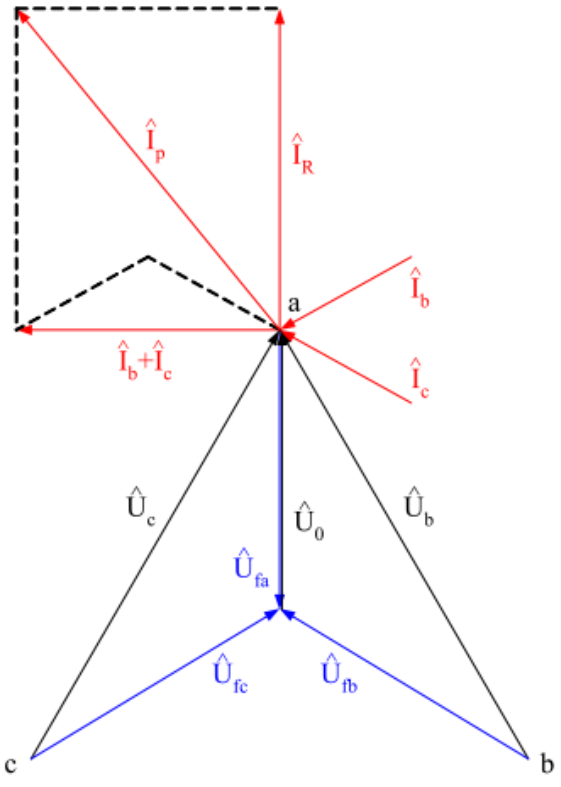
Full line-to-line insulation required between phase and earth.



During the fault

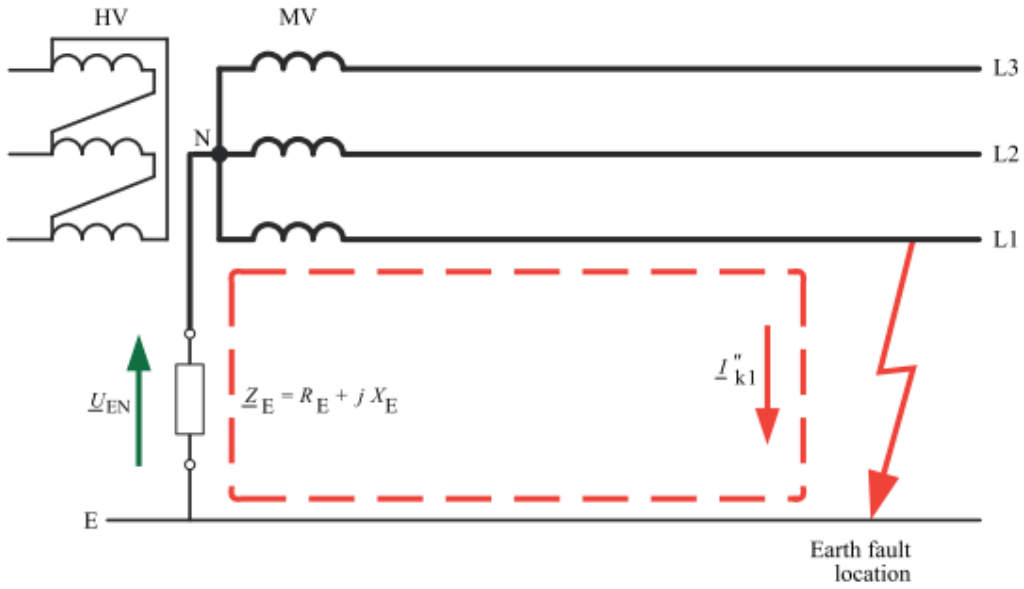
- neutral point voltage almost phase-to-ground value
- I_p uncompensated
- I_p depends on the system extent x decreases with the distance from the transformer (short-circuit character)
- R value choice can influence I_p size and character

$$\hat{I}_P = -\left(1/R + j3\omega k_0\right)U_f$$



Power system with low-impedance neutral earthing
[6.1 to 6.3, 6.5, 6.7, 6.47 to 6.59]

A power system with low-impedance neutral earthing (Fig. B6.13) is one in which the neutral point of one or more power transformers, neutral earthing transformers or generators is earthed through impedance $\underline{Z}_E$ that limits the line-to-earth short-circuit current. The purpose of earthing the transformer neutral point through an impedance $\underline{Z}_E$ is to clear any earth fault occurring in the system selectively and in the shortest possible time ($t_a < 3$ sec). To achieve this aim, the earthing impedance must be dimensioned in such a way that even a minimal line-to-earth short-circuit current in a cable feeder will reliably cause the power system protection equipment to trip. This minimum line-to-earth short-circuit current of a cable feeder can be calculated based on the equivalent circuit of the symmetrical component systems shown in Fig. B6.14.



Fault current: $I_F = I''_{k1}$ $I''_{k1} \leq 2$ kA

I''_{k1}	Initial line-to-earth short-circuit current at the earth-fault location
Z_E	Neutral earthing impedance
R_E	Neutral earthing resistance ($R_E = \frac{U_{nN}}{\sqrt{3} \cdot I_{thr\text{-}k1}}$ in the case of neutral earthing by resistance)
X_E	Neutral earthing reactance ($X_E = 0$ in the case of neutral earthing by resistance)
U_{nN}	Nominal system voltage
$I_{thr\text{-}k1}$	Rated line-to-earth short-time withstand current of the neutral earthing resistance

Fig. B6.13 MV power system with low-impedance neutral earthing (NOSPE)

For calculation of the line-to-earth short-circuit current $\underline{I}''_{k1}$ according to Fig. B6.14, the following applies:

$$\underline{I}''_{k1} = \frac{c \cdot \sqrt{3} \cdot \underline{U}_{nN}}{2 \cdot (\underline{Z}_{1N} + \underline{Z}_{1T} + \underline{Z}_{1C}) + \underline{Z}_{0T} + \underline{Z}_{0C} + 3 \cdot \underline{Z}_{E}} \tag{6.4}$$

In the case of resistance earthing ($\underline{Z}_E = R_E$), the modulus of the complex line-to-earth short-circuit current I_{k1} can be calculated as follows:

$$\left|\underline{I}''_{k1}\right| = \frac{c \cdot \sqrt{3} \cdot U_{nN}}{\sqrt{[2 \cdot (R_{1N} + R_{1T} + R_{1C}) + R_{0T} + R_{0C} + 3 \cdot R_E]^2 + [2 \cdot (X_{1N} + X_{1T} + X_{1C}) + X_{0T} + X_{0C}]^2}} \tag{6.5}$$

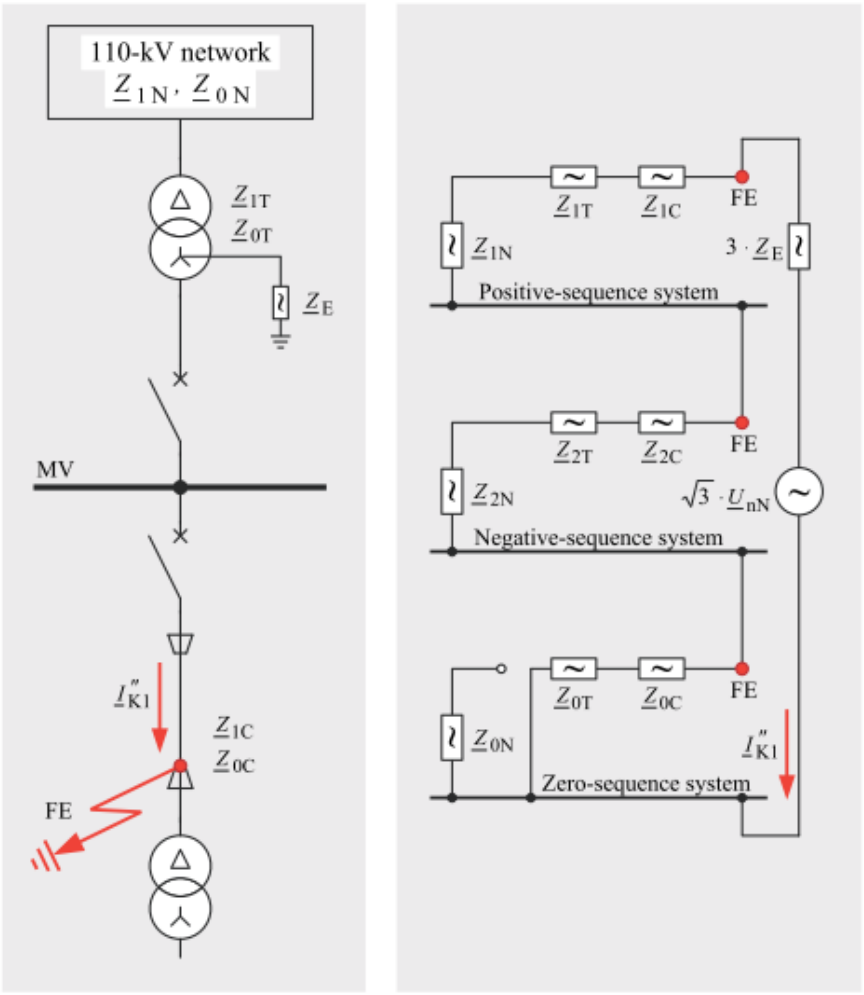
$$I''_{k1\text{-min}} = \frac{1}{f_D} \cdot \left|\underline{I}''_{k1}\right| \tag{6.5.1}$$

$I''_{k1\text{-min}}$	minimum initial line-to-earth symmetrical short-circuit current of the cable feeder
U_{nN}	nominal system voltage
f_D	reduction factor for damping by the earth contact resistance and arc resistance (f_D = 1.25...1.5)
c	voltage factor ($1.0 \le c \le 1.1$ at $U_{nN} > 1$ kV)
R_{1N}, X_{1N}	resistance or reactance of the upstream network in the positive-sequence system
R_{1T}, X_{1T}	resistance or reactance of the transfer transformer in the positive-sequence system
R_{1C}, X_{1C}	resistance or reactance of the cable route in the positive-sequence system
R_{0T}, X_{0T}	resistance or reactance of the transfer transformer in the zero-sequence system
R_{0C}, X_{0C}	resistance or reactance of the cable route in the zero-sequence system
R_E	neutral-point resistance

The neutral earthing impedance must be implemented as a resistor to limit the line-to-earth short-circuit current. The evaluation criteria for safe and reliable low-impedance neutral earthing operation are better met with resistance than with reactance earthing (Table B6.15).

Table B6.15 Evaluation of resistance and reactance earthing

Evaluation criterion	Implementation of neutral-point earthing by means of									
	resistance					reactance				
	⊖⊖	⊖	0	⊕	⊕⊕	⊖⊖	⊖	0	⊕	⊕⊕
Low investment costs for the neutral earthing resistors										
Small space requirement										
Reliable current limitation effect										
High response reliability and selectivity due to undamped starting of the residual current protection										
Strict avoidance of transient earth-fault overvoltages										
Low electrical stress on the circuit-breakers on clearing earth faults										



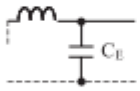
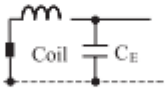
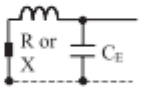
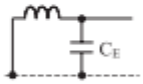
$\underline{Z}_{1N}$	Positive-sequence impedance of the upstream network ($\underline{Z}_{1N} = R_{1N} + j X_{1N}$)
$\underline{Z}_{0N}$	Zero-sequence impedance of the upstream network ($\underline{Z}_{0N} = R_{0N} + j X_{0N}$)
$\underline{Z}_{1T}$	Positive-sequence impedance of the transfer power transformer ($\underline{Z}_{1T} = R_{1T} + j X_{1T}$)
$\underline{Z}_{0T}$	Zero-sequence impedance of the transfer power transformer ($\underline{Z}_{0T} = R_{0T} + j X_{0T}$)
$\underline{Z}_{1C}$	Positive-sequence impedance of the cable ($\underline{Z}_{1C} = R_{1C} + j X_{1C}$)
$\underline{Z}_{0C}$	Zero-sequence impedance of the cable ($\underline{Z}_{0C} = R_{0C} + j X_{0C}$)
$\underline{Z}_E$	Neutral earthing impedance ($\underline{Z}_E = R_E + j X_E$, $X_E = 0$ in the case of neutral earthing by resistance)

Fig. B6.14 Connection of the symmetrical component systems in the event of an earth fault in the cable feeder of an MV power system with low-impedance neutral earthing

Overview of neutral point arrangement

Table 7.2 gives an overview of neutral point arrangement on fault behavior in three-phase high-voltage networks.

Table 7.2: Arrangement of neutral point

Arrangement of neutral point (only one-phase shown)	Isolated 	With arc suppression coil 	Current limiting 	Low resistance ground 
Examples of use	Power plant auxiliaries	Overhead line	Cable network	High voltage
Fault current	$I_E < 40$ A	$I_{Rest} < 60$–120 A	e.g. $I''_{k1} = 2$ kA	high
Fault duration	$t > 2$ h	$t < 2$–3 h	$t \leq 1$–3 s	$t \leq 1$–3 s
Ground fault factor $\delta = U_{LE} / (U_{LL}/\sqrt{3})$	$\delta \sim \sqrt{3}$	$\delta \sim \sqrt{3}$	$\delta \sim 1.4$–1.8	$\delta \leq 1.4$
Over-voltage	$k \sim 2.5$	$k \sim 3.0$	$k < 2.5$	$k < 2.5$
Voltage rise	yes	yes	no	no
Ground fault arc	self-quenching up to several A	self-quenching	usually sustained	sustained
Detection of fault	location by disconnection	location by disconnection	selective disconnection	short circuit protection

Where

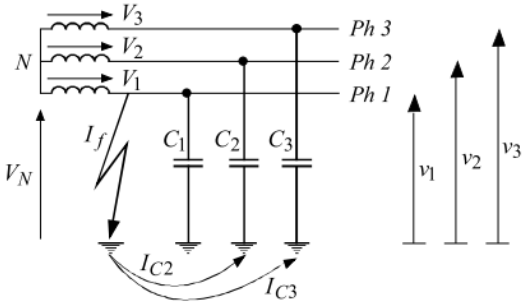
δ: Ground fault factor
U_{LE}: Conductor – ground voltage at fault occurrence
U_{LL}: Operating voltage before fault occurrence
I_E: Ground fault current
I_{Rest}: Residual current
C_E: Ground capacitance
I''_{kEE}: Double ground fault
I''_{kEE}: Two phase to ground fault
I''_{kEE}: Phase to ground fault

Table 7.3: Application of neutral point arrangements

Neutral point selection	*Ground fault factor δ*	*Application*	*Results*
Direct grounding	≤ 1.4	in low voltage power systems < 1 kV	short circuit protection selective disconnection
		in high voltage power systems > 110 kV	saving of insulation
Low resistance ground	0.87 to 1.4	medium voltage power systems for cable networks 10–30 kV	short circuit protection selective disconnection
With arc suppression coil	> 1.4	overhead and cable networks up to 110 kV	location by disconnection
Short circuited with suppression coil	first > 1.4 after short grounding < 1.4	cable network 10–110 kV	first location by disconnection then disconnection

Unearthed neutral

$I_f = I_C = I_{C2} + I_{C3}$



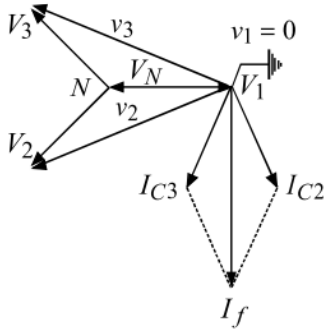
$I_f = I_C = I_{C2} + I_{C3}$

$I_{C2} = j\,C\omega\,v_2$

$I_{C3} = j\,C\omega\,v_3$

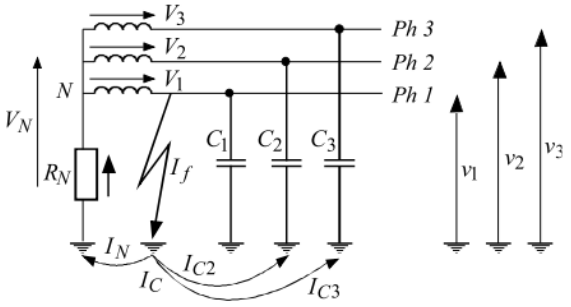
$I_C = 3\,j\,C\omega V_1$

$|I_f| = 3C\omega|V_1|$



Resistance earthing

$I_C = I_{C2} + I_{C3}$



$I_C = I_{C2} + I_{C3}$

$I_f = I_N + I_{C2} + I_{C3}$

$I_N = -\dfrac{V_1}{R_N}$

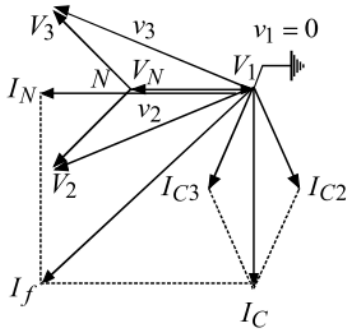
$I_{C2} = j\,C\omega\,v_2$

$I_{C3} = j\,C\omega\,v_3$

$I_C = 3\,j\,C\omega V_1$

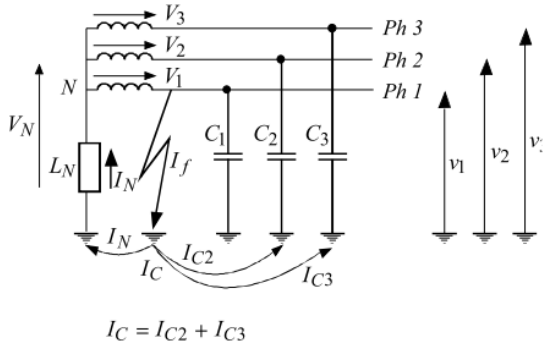
$I_f = -\dfrac{V_1}{R_N} + 3\,j\,C\omega V_1$

$|I_f| = |V_1|\sqrt{\left(\dfrac{1}{R_N}\right)^2 + 9\,C^2\,\omega^2}$



Reactance earthing

$$I_C = I_{C2} + I_{C3}$$



$$I_C = I_{C2} + I_{C3}$$

$$I_f = I_N + I_{C2} + I_{C3}$$

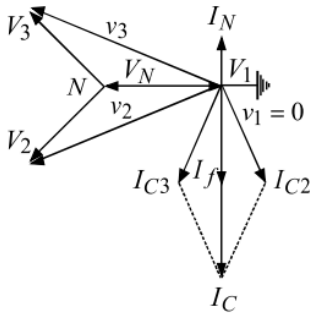
$$I_N = -\,j\,\frac{V_1}{L_N\,\omega}$$

$$I_{C2} = j\,C\omega\,v_2$$

$$I_{C3} = j\,C\omega\,v_3$$

$$I_C = 3\,j\,C\omega\,V_1$$

$$I_f = -\,j\,\frac{V_1}{L_N\,\omega} + 3\,j\,C\omega\,V_1$$



$$\left|I_f\right| = \left|V_1\right| \sqrt{9\,C^2\,\omega^2 - \frac{1}{L_N^2\,\omega^2}}$$

Petersen coil earthing

This is the previous case, for which:

$$3\,C\omega = \frac{1}{L_N\,\omega}$$

where: $3\,L_N\,C\omega^2 = 1$

The current in the fault is zero, when tuning is perfect.

Source: Schneider Electric