2024-2025
Fall Semester

Course of Power System Analysis

Grounding regime

Prof. Mario Paolone
Distributed Electrical Systems Laboratory
École Polytechnique Fédérale de Lausanne (Switzerland)

Context

A fundamental element for the **choice of grounding regime** (i.e., the **connection of the star center of the three phase system**) in medium- and high-voltage networks is the **behaviour of the network itself in the case of a short-circuit to ground.**

This abnormal operating condition leads to **significant overvoltages at nominal frequency** (50 Hz), which must be managed in order to operate the system correctly.
Therefore, we must study the behavior of an electrical network after a single phase to ground short-circuit with a short-circuit impedance equal to $\bar{Z}$.

Outline

Single phase to ground short-circuit

Grounding regime in medium- and high-voltage distribution networks

Networks with earthed neutral

Networks with isolated neutral

Single phase to ground short-circuit

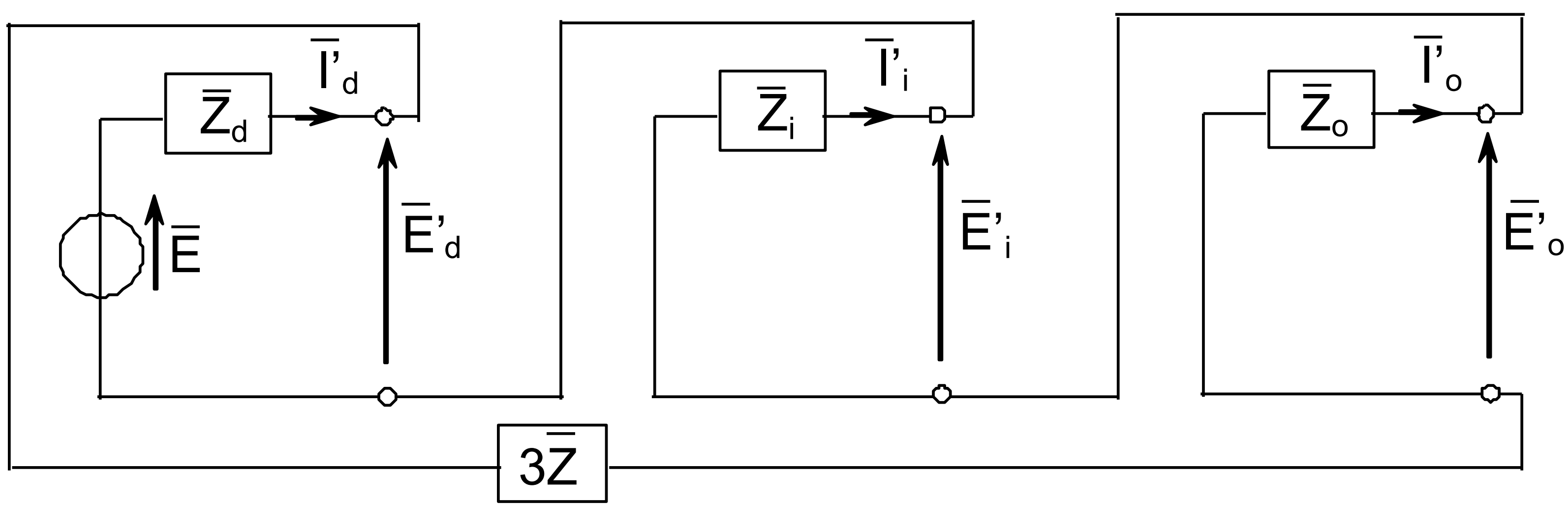
To recall, the following are the **three equations in the sequence domain**

$$\overline{I}_0' = \overline{I}_d'$$

$$\overline{I}_d' = \overline{I}_i'$$

$$\overline{E}_0' + \overline{E}_d' + \overline{E}_i' = 3\overline{Z}\overline{I}_0'$$

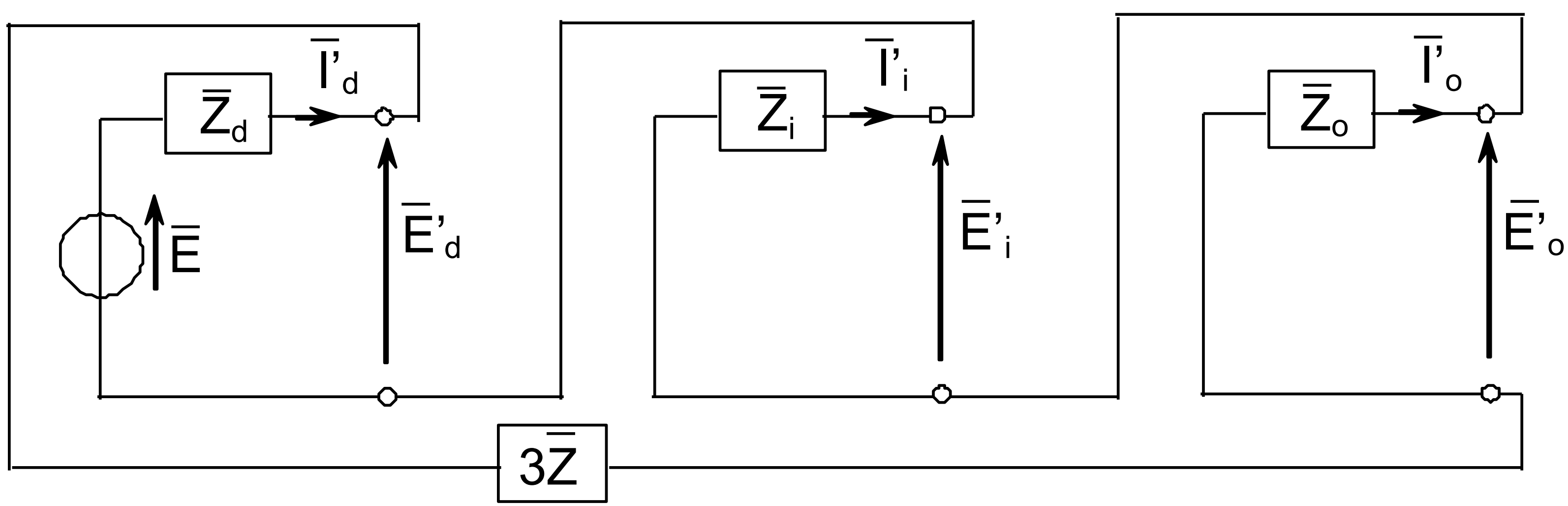
These three equations can be seen as a **coupling of the sequence equivalent circuits.**



Single phase to ground short-circuit

The solution of the circuit enables us to determine the **sequence currents:**

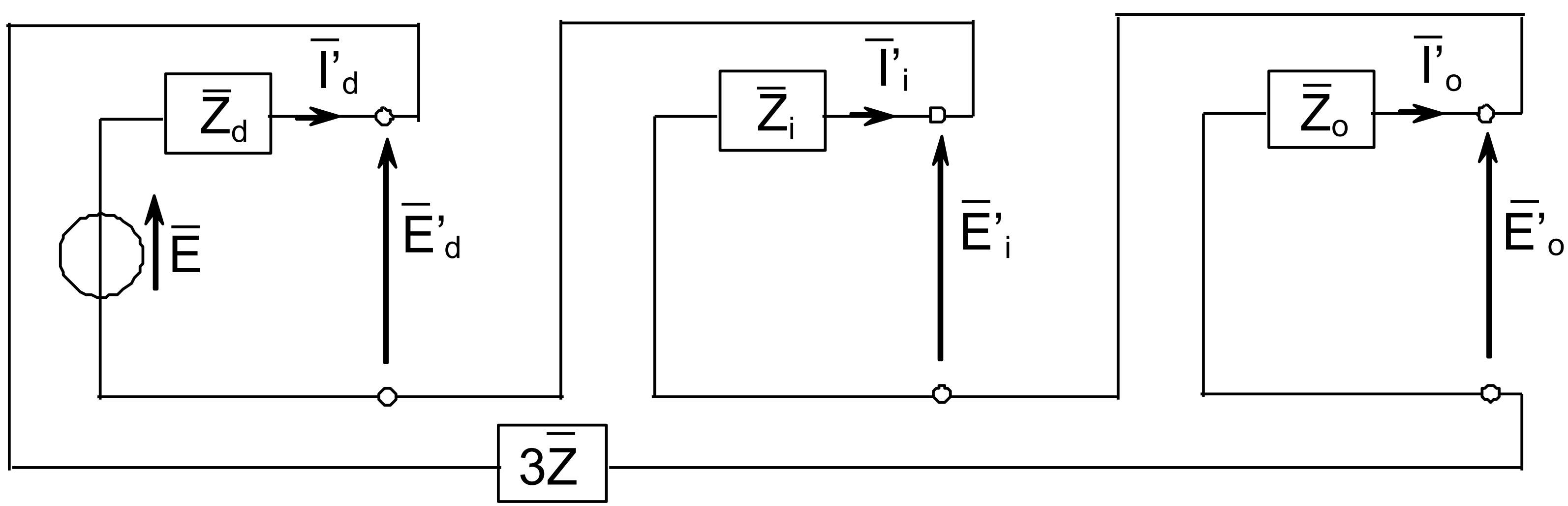
$$\overline{I}_0^{'} = \overline{I}_d^{'} = \overline{I}_i^{'} = \frac{\overline{E}}{\overline{\overline{Z}}_d + \overline{\overline{Z}}_i + \overline{\overline{Z}}_0 + 3\overline{Z}}$$



Single phase to ground short-circuit

Therefore, the **short-circuit current in the phase domain** is:

$$\overline{I}_a^{'} = \frac{3\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0 + 3\overline{Z}} = \left.\frac{3\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}\right|_{\overline{Z}=0}$$



Single phase to ground short-circuit

The **sequence voltages** are:

$$\overline{E}_d^{'} = \overline{E} - \overline{Z}_d \overline{I}_d^{'}$$
$$\overline{E}_i^{'} = -\overline{Z}_i \overline{I}_i^{'}$$
$$\overline{E}_0^{'} = -\overline{Z}_0 \overline{I}_0^{'}$$

Plugging in the current equations, we obtain:

$$\overline{E}_d^{'} = -\left(\overline{E}_0^{'} + \overline{E}_i^{'}\right)$$
$$\overline{E}_i^{'} = -\overline{Z}_i \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}$$
$$\overline{E}_0^{'} = -\overline{Z}_0 \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}$$

Outline

Single phase to ground short-circuit

Grounding regime in medium- and high-voltage distribution networks

Networks with earthed neutral

Networks with isolated neutral

Grounding regime in medium- and high-voltage distribution networks

Thanks to the transformation matrix for symmetrical components:

$$\begin{bmatrix} \bar{E}_a' \\ \bar{E}_b' \\ \bar{E}_c' \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} \bar{E}_0' \\ \bar{E}_d' \\ \bar{E}_i' \end{bmatrix}$$

It is possible to express the voltages in the phase domain.

Grounding regime in medium- and high-voltage distribution networks

$$\boxed{\overline{E}'_a = \overline{E}'_0 + \overline{E}'_d + \overline{E}'_i = 0}$$

$$\overline{E}'_b = \overline{E}'_0 + \alpha^2 \overline{E}'_d + \alpha \overline{E}'_i = -\overline{Z}_0 \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0} - \alpha^2 \left(\overline{E}'_0 + \overline{E}'_i \right) - \alpha \overline{Z}_i \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}$$

$$= \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0} \left[-\overline{Z}_0 - \alpha^2 \left(\overline{E}'_0 + \overline{E}'_i \right) \frac{\overbrace{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}^{1/\overline{I}_0}}{\overline{E}} - \alpha \overline{Z}_i \right] =$$

$$= \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0} \left[-\overline{Z}_0 - \alpha^2 \frac{\overbrace{\left(\overline{E}'_0 + \overline{E}'_i \right)}^{-\left(\overline{Z}_0 + \overline{Z}_i\right)}}{\overline{I}_0} - \alpha \overline{Z}_i \right] =$$

$$\frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0} \left[-\overline{Z}_0 + \alpha^2 \overline{Z}_0 + \alpha^2 \overline{Z}_i - \alpha \overline{Z}_i \right] = \Big|_{\overline{E} = E + j0} \boxed{E \frac{\left(\alpha^2 - 1 \right) \overline{Z}_0 + \left(\alpha^2 - \alpha \right) \overline{Z}_i}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0}}$$

Grounding regime in medium- and high-voltage distribution networks

$$\bar{E}_c^{'} = \bar{E}_0^{'} + \alpha \bar{E}_d^{'} + \alpha^2 \bar{E}_i^{'} = -\bar{Z}_0 \frac{\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0} - \alpha\left(\bar{E}_0^{'} + \bar{E}_i^{'}\right) - \alpha^2 \bar{Z}_i \frac{\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0} =$$

$$= \frac{\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}\left[-\bar{Z}_0 - \alpha\left(\bar{E}_0^{'} + \bar{E}_i^{'}\right)\frac{\overbrace{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}^{1/\bar{I}_0}}{\bar{E}} - \alpha^2 \bar{Z}_i\right] =$$

$$= \frac{\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}\left[-\bar{Z}_0 - \alpha \frac{\overbrace{\left(\bar{E}_0^{'} + \bar{E}_i^{'}\right)}^{-\left(\bar{Z}_0 + \bar{Z}_i\right)}}{\bar{I}_0} - \alpha^2 \bar{Z}_i\right] =$$

$$\frac{\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}\left[-\bar{Z}_0 + \alpha \bar{Z}_0 + \alpha \bar{Z}_i - \alpha^2 \bar{Z}_i\right] = \Big|_{\bar{E} = E + j0} \boxed{E \frac{\left(\alpha - 1\right)\bar{Z}_0 + \left(\alpha - \alpha^2\right)\bar{Z}_i}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}}$$

We can introduce the **ratios of the homopolar and inverse sequence impedances relative to the direct sequence impedance:**

$$\bar{m}_0 = \frac{\bar{Z}_0}{\bar{Z}_d}; \qquad \bar{m}_i = \frac{\bar{Z}_i}{\bar{Z}_d}$$

If we substitute these ratios in the previous equations where the phase voltages (b and c) are expressed relative to the voltage E, we obtain:

$$\bar{e}_b^{'} = \frac{\bar{E}_b^{'}}{E} = \frac{\left(\alpha^2 - 1\right)\bar{m}_0 + \left(\alpha^2 - \alpha\right)\bar{m}_i}{1 + \bar{m}_i + \bar{m}_0}$$

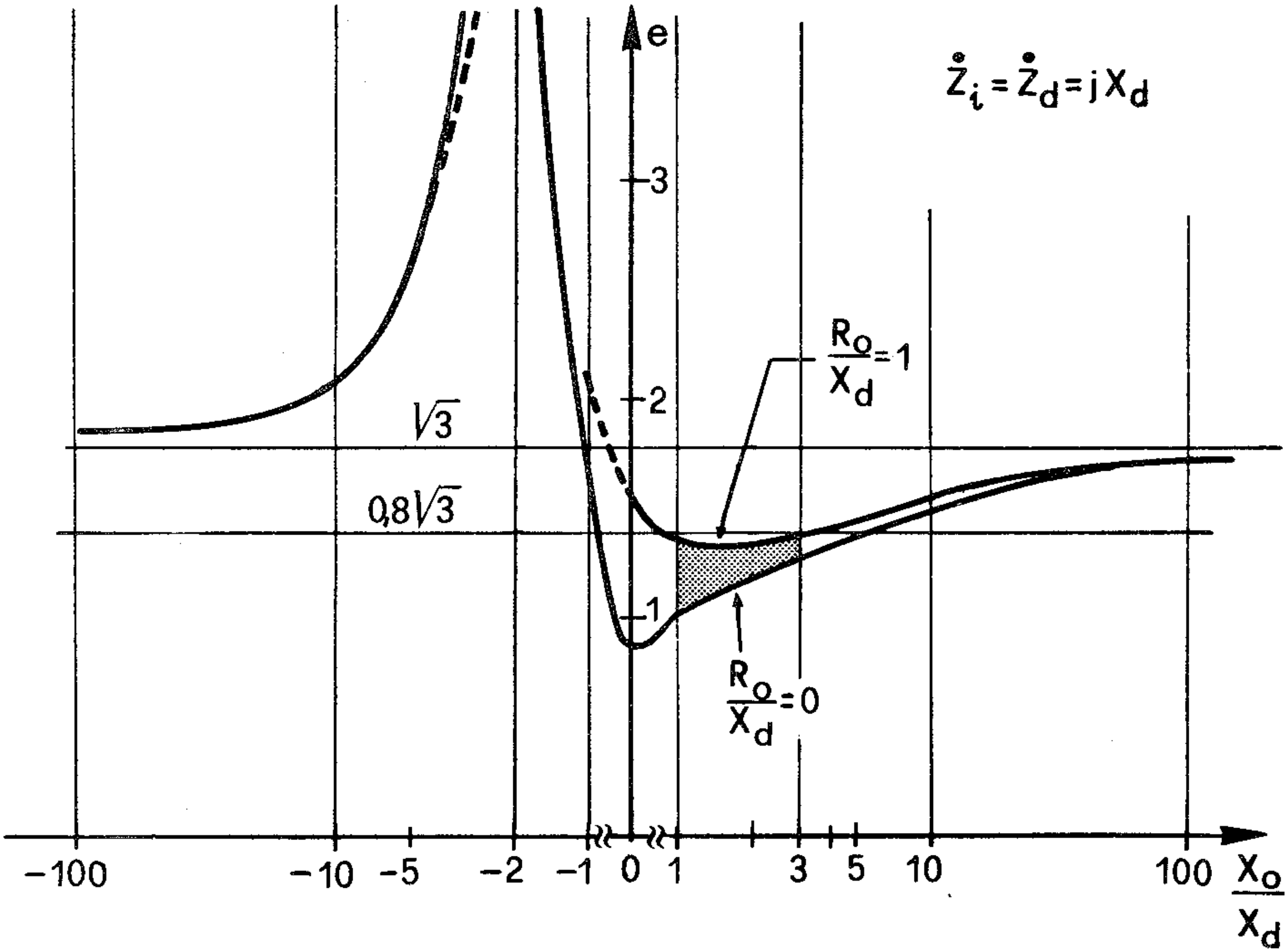
$$\bar{e}_c^{'} = \frac{\bar{E}_c^{'}}{E} = \frac{\left(\alpha - 1\right)\bar{m}_0 + \left(\alpha - \alpha^2\right)\bar{m}_i}{1 + \bar{m}_i + \bar{m}_0}$$

If we consider that **the inverse sequence impedance is almost the same as the direct sequence impedance**, we can say that $m_i=1$ and simplify the equations.

Further, if we **neglegt the resistive components** of these impedances in the direct sequence impedance of the network, we have $\bar{e}_b^{'}$ and $\bar{e}_c^{'}$ depending only on the coefficient m_0, which is equal to

$$\bar{m}_0 = \frac{\bar{Z}_0}{jX_d}$$

Grounding regime in medium- and high-voltage distribution networks



Grounding regime in medium- and high-voltage distribution networks

Two possible cases:

1. Network with isolated neutral: in these networks, the **only possibility for short-circuit current to circulate is provided by the shunt capacitances of the conductors to ground**; therefore

$$\bar{Z}_0 = -jX_0$$

where X_0 is a purely capacitive reactance linked to the capacity of the lines in service

$$X_0 = \frac{1}{\omega C_{serv,linee}}$$

Therefore, the larger the network, the smaller the value of X_0.

Grounding regime in medium- and high-voltage distribution networks

Two possible cases:

2. Network with grounded neutral: in these networks, the **star center of the system is grounded in the primary substation by an ohmic-inductive impedance**, and therefore:

$$\bar{Z}_0 = R_0 + jX_0$$

It is important to observe that the value of Z_0 strongly depends on the **presence of inductances connected between the ground and the star center (Petersen winding)**, and on the behavior of the transformers and lines in the homopolar sequence.

Outline

Single phase to ground short-circuit

Grounding regime in medium- and high-voltage distribution networks

Networks with earthed neutral

Networks with isolated neutral

Networks with earthed neutral

A network is defined with **neutral effectively grounded** if, **in the case of a single phase to ground short-circuit**, the ratio k, at any point in the network, **between the largest voltage to earth of healthy phases and the phase-to-phase voltage without the short-circuit is no greater than 0.8:**

$$e \leq 0.8\sqrt{3} = 1.37$$

This ratio k is called the **grounding coefficient** and is one of the parameters for **insulation coordination**. In fact, **short-circuit to ground overvoltages are generally the most important**, and only sometimes can they be exceeded by **overvoltages due to sudden tripping of load.**

Networks with earthed neutral

The determination of the coefficient k, and therefore the **prediction of the most important overvoltages**, is used to **establish whether the 50 Hz test voltage set point for machines and devices is properly chosen.**

The dotted area in the previous figure means that $k < 0.8$ (neutral effectively grounded) if:

$$R_0 / X_d \leq 1 \qquad\qquad 1 \leq X_0 / X_d \leq 3$$

To understand these conditions, we should consider two cases:

- **Transmission networks**
- **Distribution networks**

Networks with earthed neutral

Transmission networks: to obtain a sufficiently low impedance Z_0 in any section of the network, the **star centers of transformers in substations should be connected to ground.**

Distribution networks: as soon as the **neutral is connected to ground at a single point** (medium-voltage side of the primary substation transformer), a **neutral to ground connection impedance must be provided by means of an inductance** (since the network impedance of the direct sequence X_d will surely be inductive and the ratio X_0/X_d must be **positive**).

Outline

Single phase to ground short-circuit

Grounding regime in medium- and high-voltage distribution networks

Networks with earthed neutral

Networks with isolated neutral

Networks with isolated neutral

Medium-voltage networks with isolated neutral exhibit, in general, a ratio X_0/X_d = -20 because the homopolar sequence reactance X_0, represented by the shunt capacitances of the line conductors, is **much larger than the direct sequence reactance of the system.** For these networks, the previously shown figure shows how the phase voltage of the healthy phases increases by a factor $\sqrt{3}$.

Therefore, in a distribution system with isolated neutral, in a case of short-circuit to ground, **the single-phase voltage of the healthy phases becomes equal to the phase-to-phase voltage and the short-circuit current has a small value.** In effect, **the only link between the electrical system and ground is given by the shunt capacitances of each phase.**

Networks with isolated neutral

The shunt capacitances, which have a small value, are the **homopolar impedance of the network, which has a high value**. Therefore, we can say that

$$\left|\bar{Z}_0\right| >> \left|\bar{Z}_d\right|$$

And, due to the following relations:

$$\bar{Z}_d = \bar{Z}_i \qquad\qquad \left|\bar{Z}_0\right| >> \left|\bar{Z}_i\right|$$

The voltages of the healthy phases are:

$$\bar{E}_b' = E\frac{\left(\alpha^2 - 1\right)\bar{Z}_0 + \left(\alpha^2 - \alpha\right)\bar{Z}_i}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0} \cong E\frac{\left(\alpha^2 - 1\right)\bar{Z}_0}{\bar{Z}_0} = \boxed{E\left(\alpha^2 - 1\right)}$$

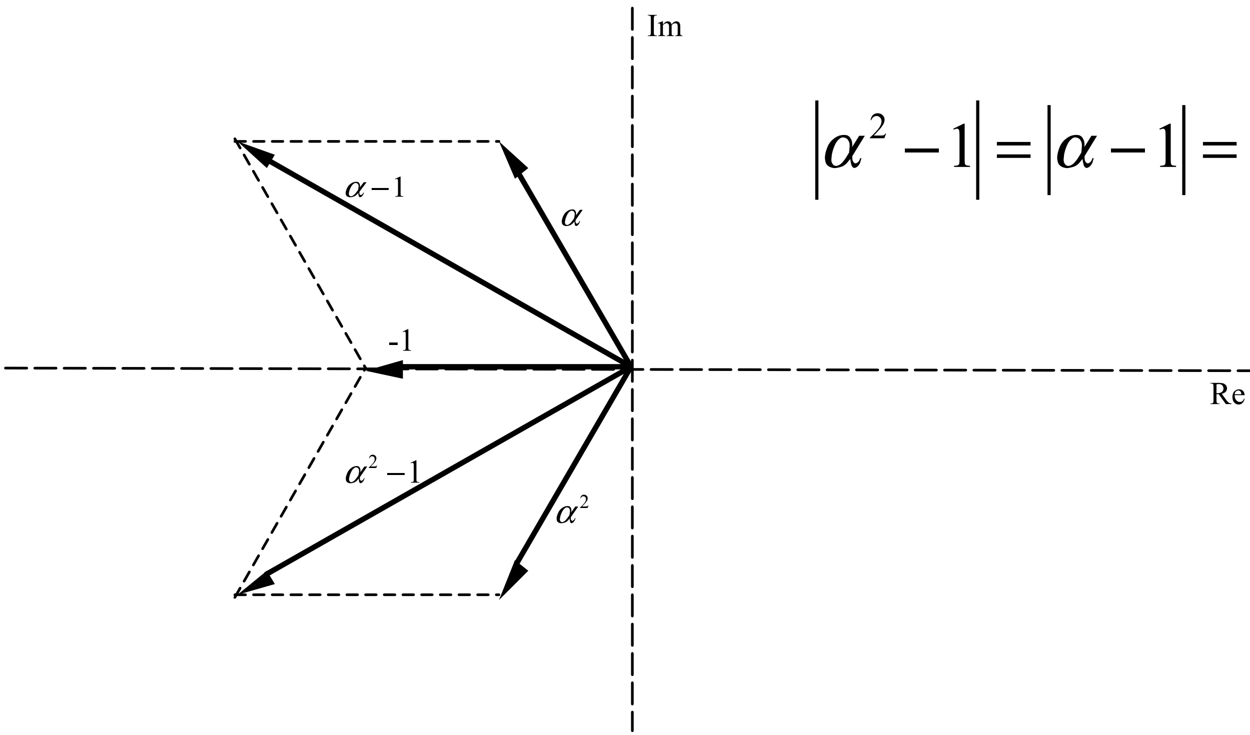
$$\bar{E}_c' = E\frac{\left(\alpha - 1\right)\bar{Z}_0 + \left(\alpha - \alpha^2\right)\bar{Z}_i}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0} \cong E\frac{\left(\alpha - 1\right)\bar{Z}_0}{\bar{Z}_0} = \boxed{E\left(\alpha - 1\right)}$$

Networks with isolated neutral

It is interesting to note that the coefficients

$$\left(\alpha^2 - 1\right) \qquad \left(\alpha - 1\right)$$

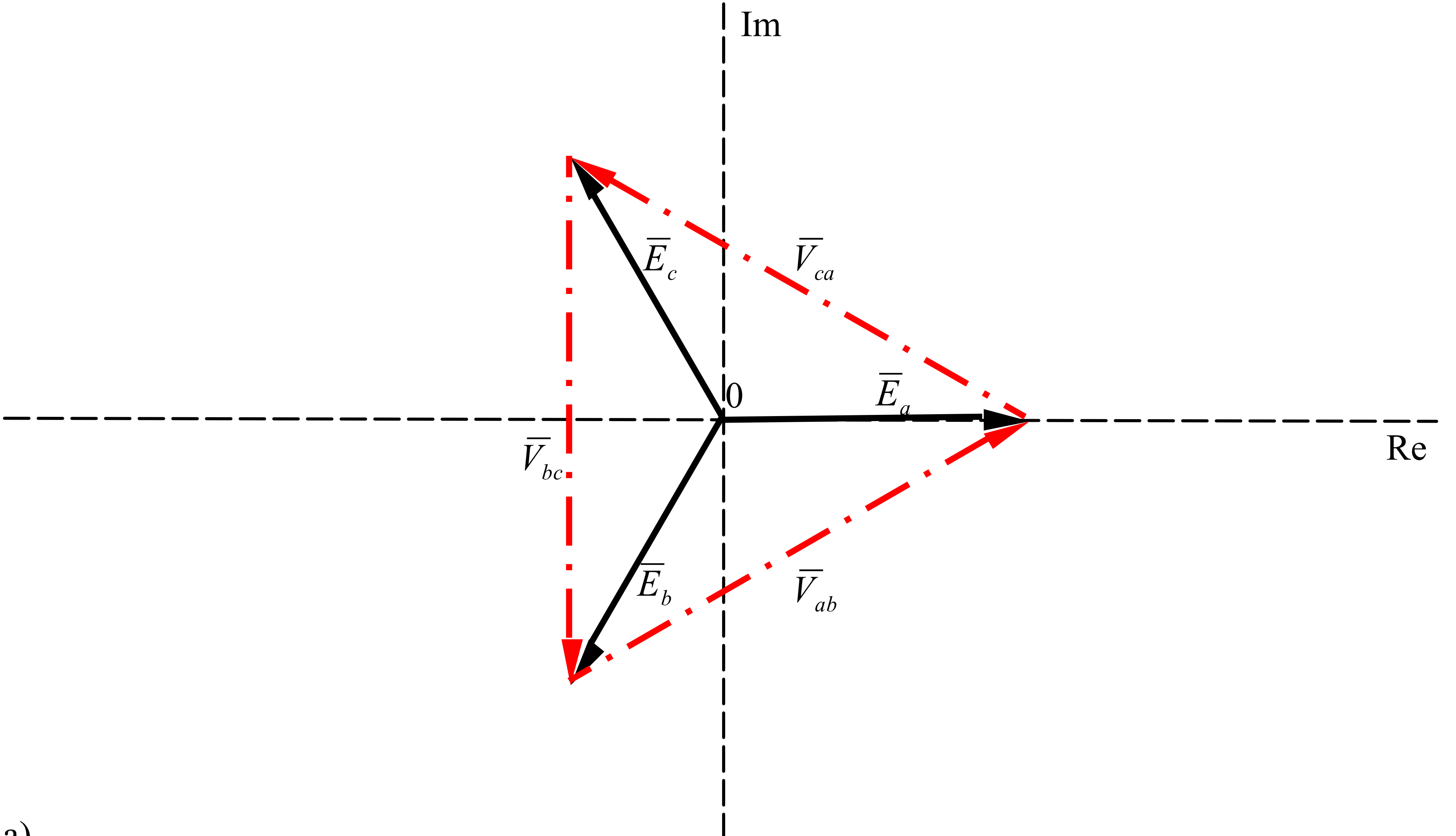
Are two well-defined complex numbers in the Gaussian plane (see below) and their magnitude is equal to:



$$\left|\alpha^2 - 1\right| = \left|\alpha - 1\right| = \sqrt{3}$$

Networks with isolated neutral

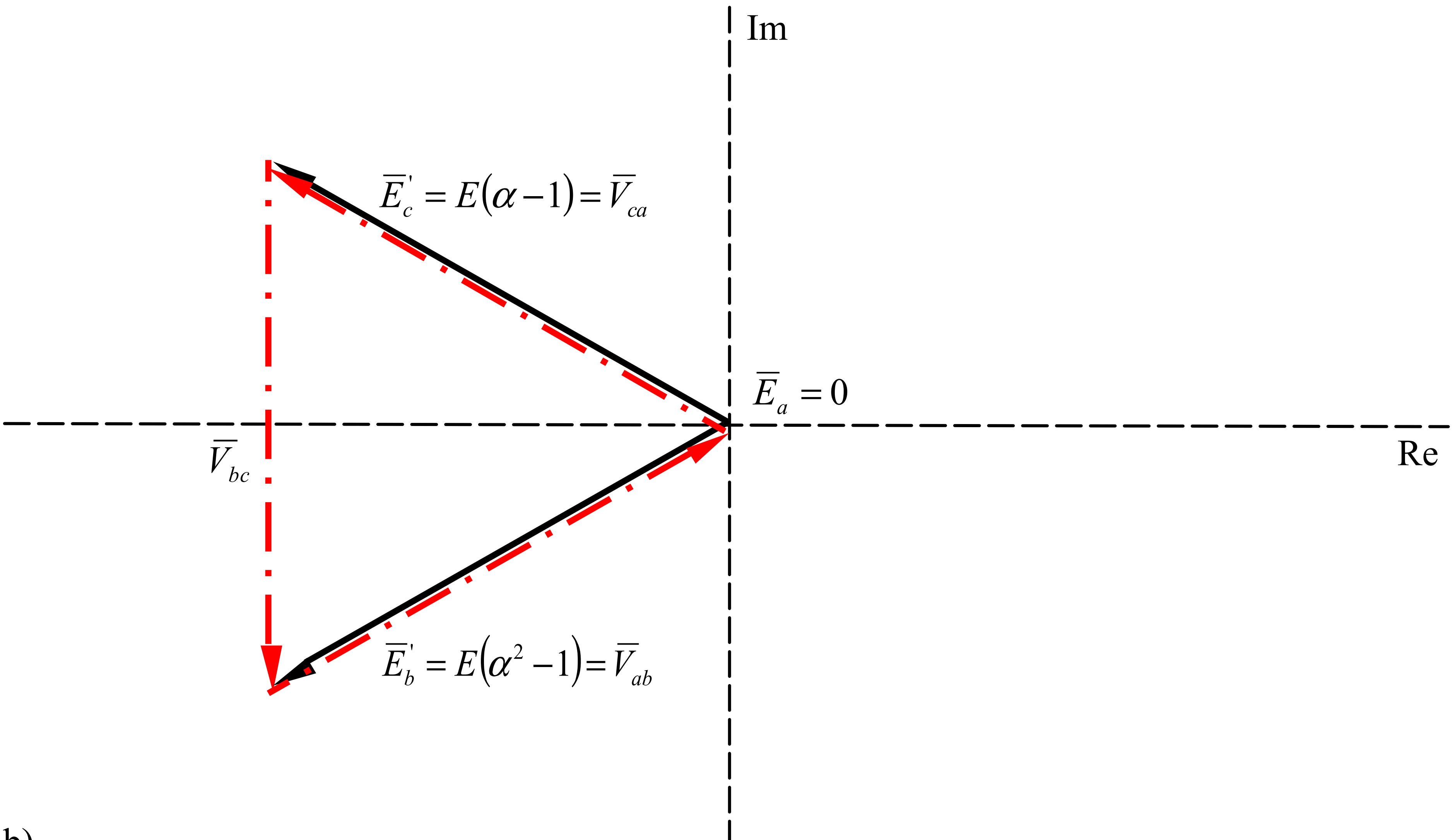
Before the short circuit:



a)

Networks with isolated neutral

After the short circuit:



b)

Networks with isolated neutral

Observation:

$$\bar{E}_b' = E\left(\alpha^2 - 1\right)$$
$$\bar{E}_c' = E\left(\alpha - 1\right)$$

Figure a) shows the single phase and phase-to-phase voltages in a network with an isolated neutral before a single phase short-circuit to ground. Figure b) shows the single phase and phase-to-phase voltages after the short-circuit. Looking at Figure b), we can note that:

i) The phase voltages are as given by the above equations

ii) The phase-to-phase voltages have not changed in value.

This last remark is coherent with the fact that in a system with isolated neutral, the voltages imposed by the system are phase-to-phase voltages.

Networks with isolated neutral

It is interesting to note that **in systems with isolated neutral**, the short-circuit current for a single phase to ground short-circuit is generally **low** (on the order of tens or hundreds of amps). Using the equation

$$\bar{I}_a^{'} = \frac{3\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0 + 3\bar{Z}} = \left.\frac{3\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0}\right|_{\bar{Z}=0}$$

we can see that the **short-circuit current is inversely proportional to the sum of the sequence impedances of the network.**

Networks with isolated neutral

Given that

$$\bar{Z}_0 = -jX_0 = \frac{1}{\omega C_{serv,linee}}$$

And that the capacitances of the network are on the order of **10 ·10^{-12} F/km** for overhead lines and on the order of **300 ·10^{-12} F/km** for cables, we can deduce that $\boldsymbol{X_0}$ **is on the order of hundreds or millions of Ohms** (and is a function of the line length).

Networks with isolated neutral

It is equally important to remark that **the short-circuit current and the homopolar voltage can be easily placed in the Gaussian plane.**

The **homopolar voltage** is:

$$\overline{E}_0 = \frac{1}{3}\left(\overline{E}_a^{'} + \overline{E}_b^{'} + \overline{E}_c^{'}\right) =$$

$$= \frac{1}{3}\left(\overbrace{E\left(\alpha^2 - 1\right)}^{\overline{E}_b^{'}} + \overbrace{E\left(\alpha - 1\right)}^{\overline{E}_c^{'}}\right) = \frac{1}{3}E\left(\alpha^2 + \alpha - 2\right) = -E + j0$$

Networks with isolated neutral

The **homopolar current** is:

$$I_0^{'} = \overline{I}_d^{'} = \overline{I}_i^{'} = \frac{\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0 + 3\overline{Z}}$$

Given that

$$\left|\overline{Z}_0\right| >> \left|\overline{Z}_d\right| \qquad \left|\overline{Z}_0\right| >> \left|\overline{Z}_i\right| \qquad \overline{Z}_0 = -jX_0$$

And that the voltage E is the voltage that supplies the short-circuited phase a on the real axis, we can write that

$$\overline{E} = E + j0$$

and therefore:

$$\overline{I}_a^{'} = 3\overline{I}_0^{'} = 3\overline{I}_d^{'} = 3\overline{I}_i^{'} = \frac{3\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0} \cong \frac{3E}{-jX_0} = j\frac{3E}{X_0}$$

Networks with isolated neutral