2024-2025
Fall Semester

Course of Power System Analysis

Elimination of phase-to-ground short-circuits in distribution networks

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

Outline

Introduction

Maximum homopolar voltage relay in a system with isolated neutral

Shunt circuit-breaker in a system with isolated neutral

Directional earth relay in a system with isolated neutral

Networks with neutral grounded by the Petersen winding

Introduction

Single phase short-circuits to ground in the medium-voltage distribution network are caused by insulation faults between one phase of the system and earth.

These short-circuits can be grouped in **two categories:**

- ***Self-regenerating insulators:*** insulators which are capable of **resuming their insulating function without replacement**; typical examples are overhead line air insulators (glass/ceramic);

- ***Non-self-regenerating insulators:*** insulators which are **not capable of resuming their insulating function without replacement of certain parts**; typical examples are solid-state insulators, i.e. the insulating material of a cable.

Introduction

Possible cases:

- ***Self-regenerating insulator discharges to earth:*** to put the line back in service after the short-circuit, it is sufficient to make the electric arc to earth unstable. This effect can be attained by opening the circuit breaker of a line for a short time, or by using a shunt circuit-breaker;

- ***Non-self regenerating insulator discharges to earth**:* to put the line back in service, it is necessary to replace the damaged insulator; this involves a longer interruption of service for the line.

Introduction

To determine the nature of short-circuits, normally, medium-voltage circuit-breakers have an O-CO-CO open-close cycle. This cycle of operation, **following detection of a short-circuit by the protection system, consists of the following maneuvers:**

1. The circuit breaker opens for the first time (O-open) after the protection relay detects a short-circuit;
2. After a short interval of time (normally 0.3 seconds), the circuit-breaker automatically recloses (C-close); if the short-circuit is via a self-regenerating insulator, the opening operation will have extinguished the arc and the line may still be supplied;
3. The circuit-breaker immediately opens (O-open) because the insulation fault is still present;
4. The circuit breaker tries a subsequent closing attempt (C-close) after a longer time interval (for example, 3 minutes);
5. The circuit-breaker opens (O-open) and it will remain in this position if the insulation fault is still present.

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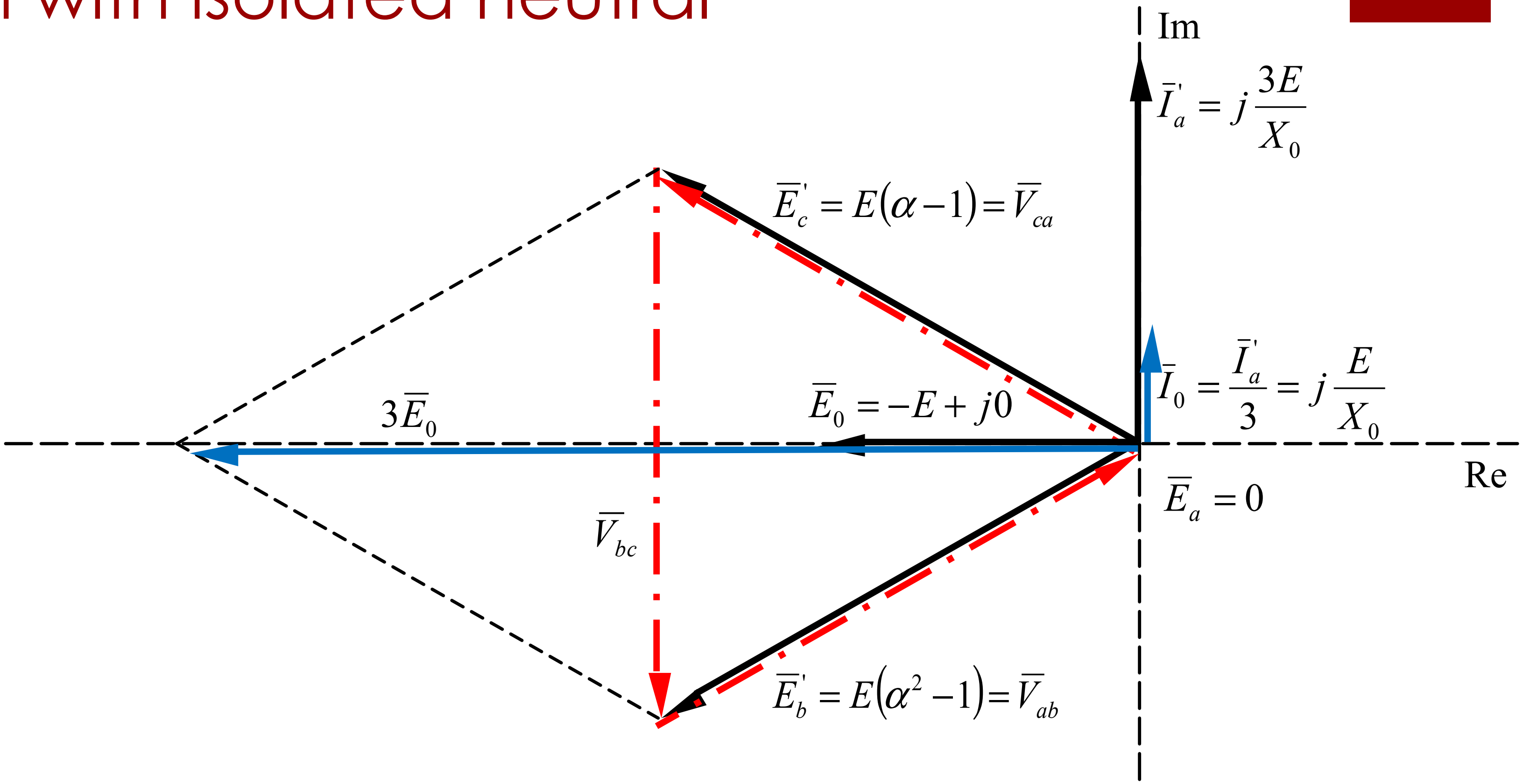
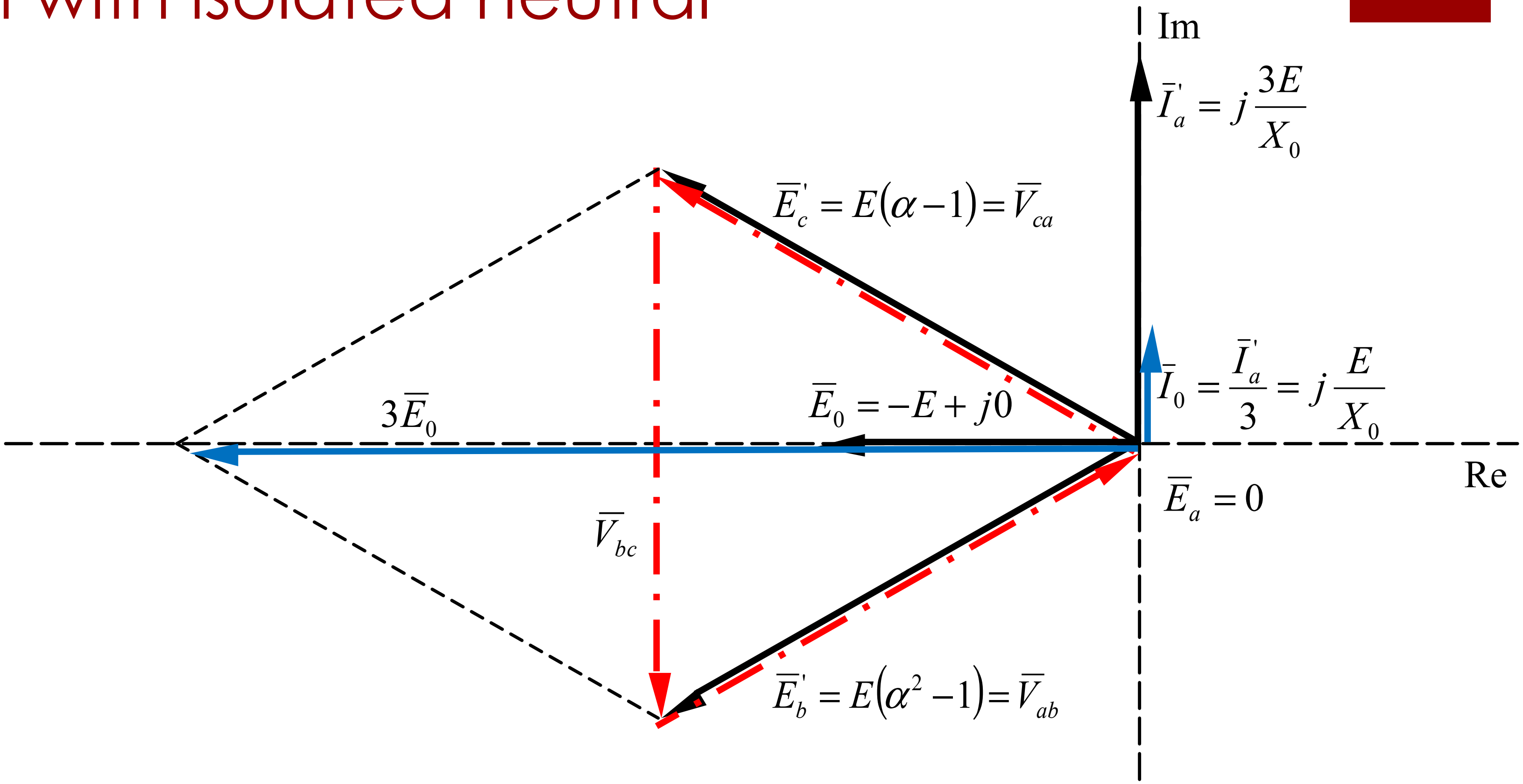
Maximum homopolar voltage relay in a system with isolated neutral



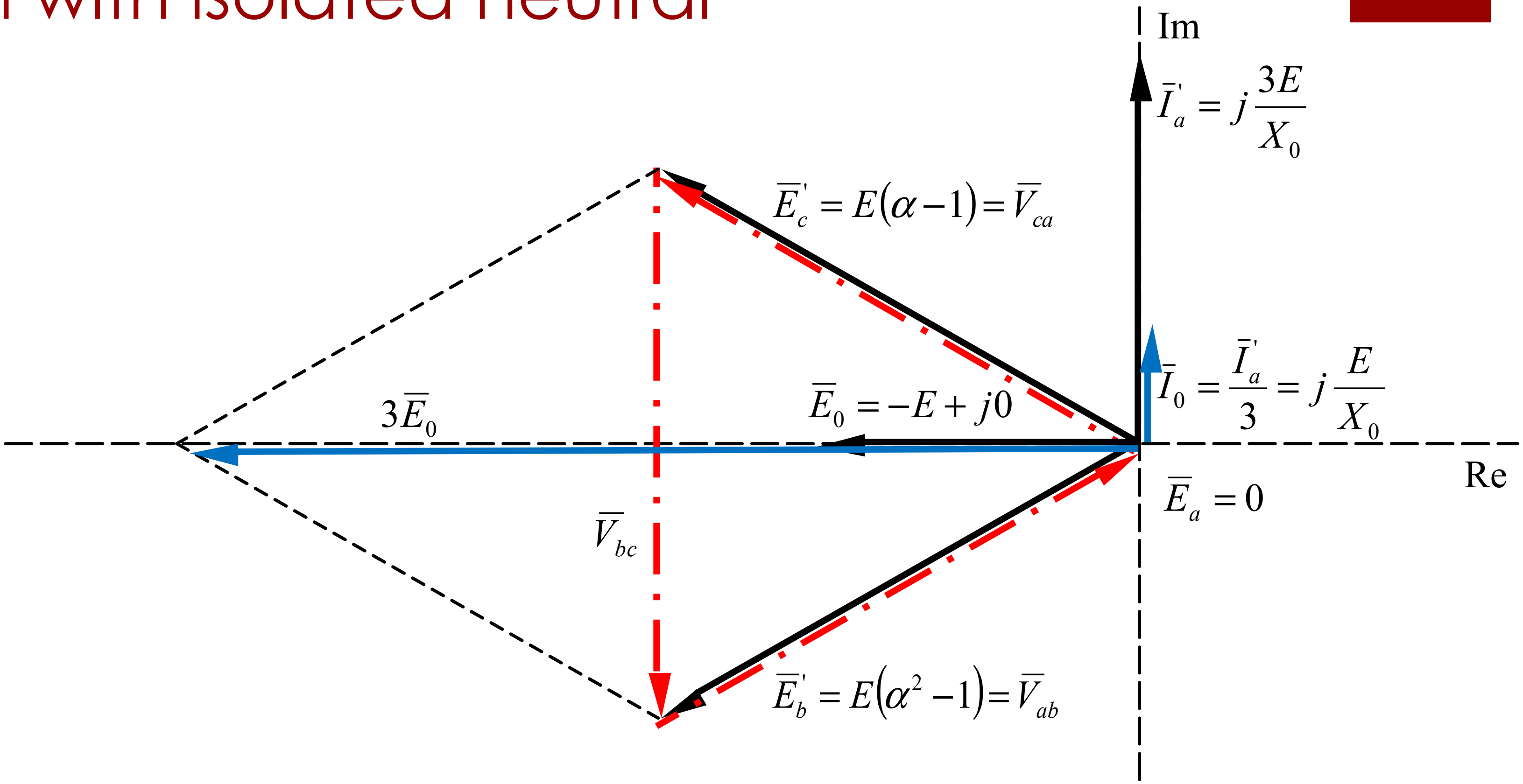
In medium-voltage distribution networks **with isolated neutral, the only electrical link between the system and the ground is given by the capacitances between phase and ground.**
These capacitances, even if of small value, are the homopolar impedance of the network, which is characterized in reality by a high but finite value.

Maximum homopolar voltage relay in a system with isolated neutral



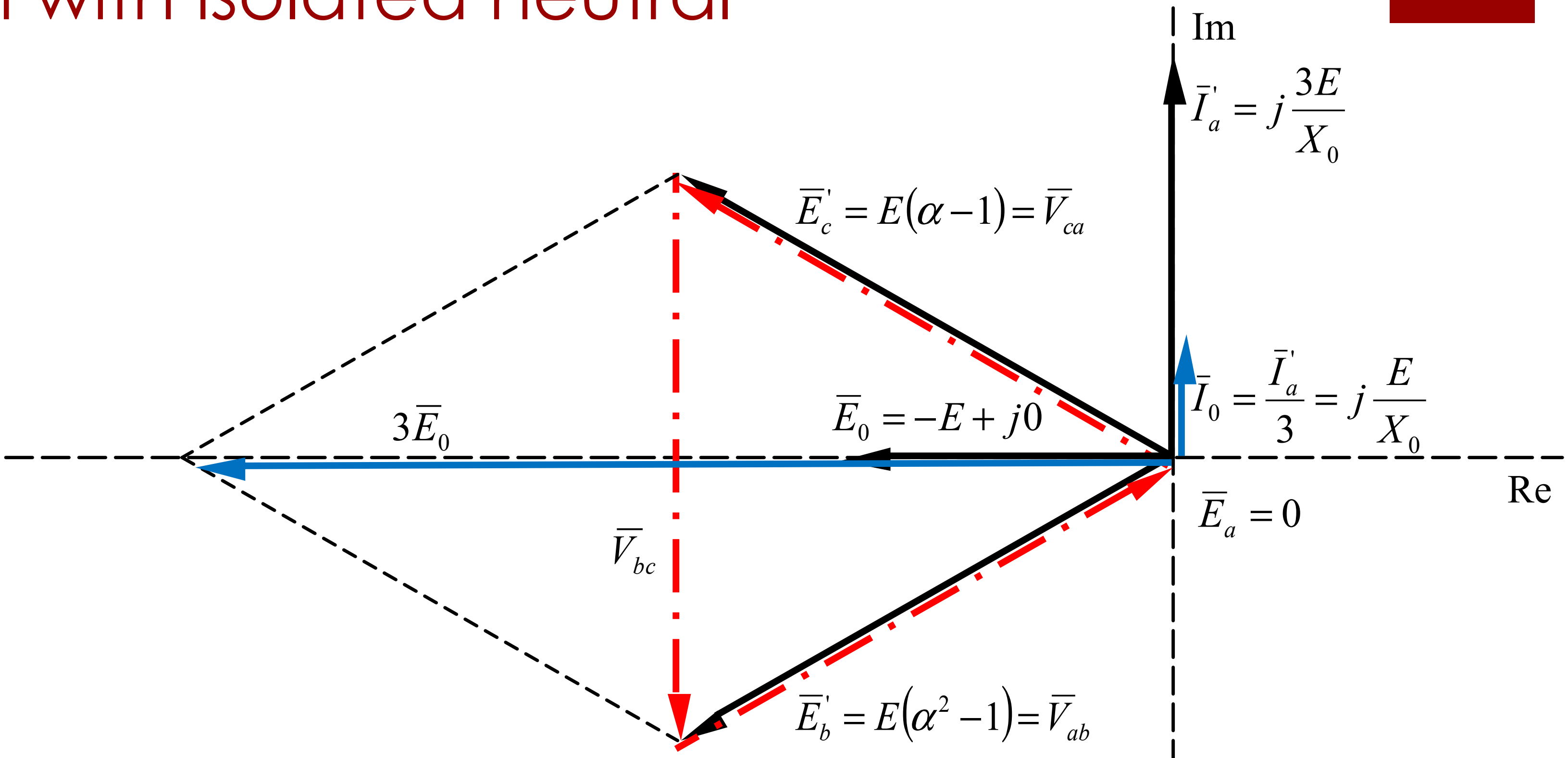
Under these conditions, a clean single-phase short to earth will cause the **voltage across the capacitor of the conductor where the fault occurred to be reduced to zero** or almost to zero (if the short is not clean). This will result in an **unbalanced** system of phase to ground voltages.

Maximum homopolar voltage relay in a system with isolated neutral



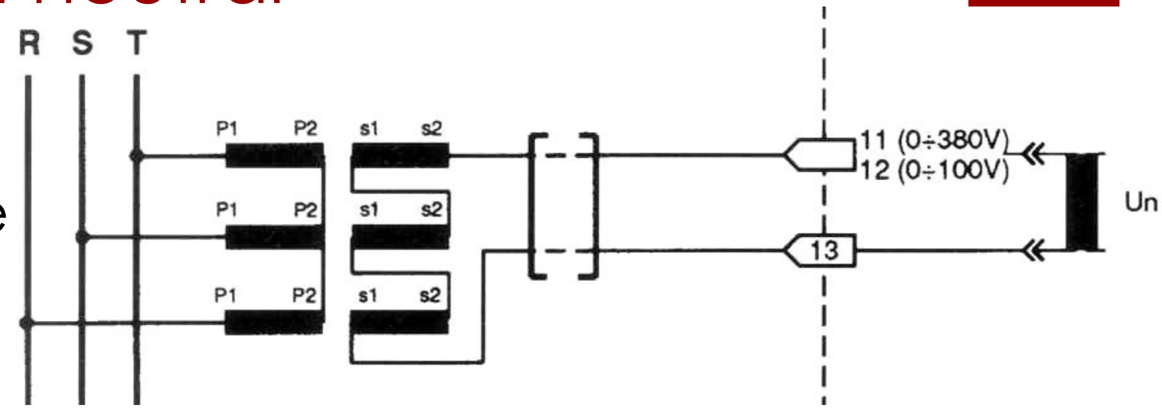
The figure shows the **homopolar voltage and current** positioned in the complex plane in the case of a clean single phase short-circuit to ground in a distribution network with isolated neutral. In this case, the phase voltage of the affected phase is zero and the other two healthy phases are subject to the value of the phase-to-phase voltage.

Maximum homopolar voltage relay in a system with isolated neutral



This imbalance is justified by the fact that, in networks with isolated neutral, **the constraints on the supply voltages concern the phase-to-phase voltages, and if the star center is connected to earth, the voltages can move according to the short-circuit impedance.** Thus, **the detection of a short-circuit can be achieved by a simple voltage imbalance relay capable of detecting the homopolar voltage E_0.**

Maximum homopolar voltage relay in a system with isolated neutral

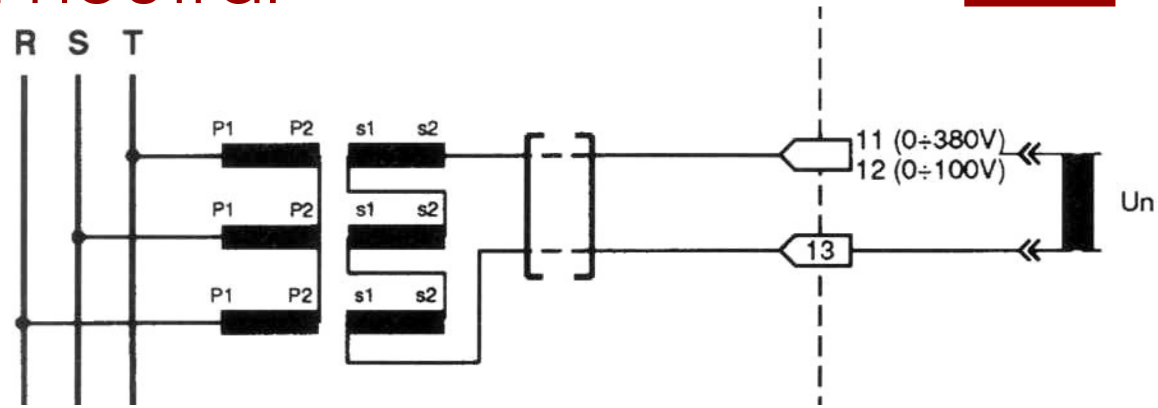


The **measurement of the homopolar voltage** is realized by measuring the voltage across the secondary windings of three **potential transformers (PT)** connected to an **open delta**.

The value of the measured voltage is **proportional to the homopolar voltage.** Specifically, $U_n = 3kE_0$, where k is the transformer ratio of the PT. It should be observed that in nominal operating conditions, U_n is zero, because the three phase voltages are balanced.

Problem: it is impossible to distinguish the faulty line (feeder) from other lines running from the primary substation. These protection devices, coded **59 N**, are capable of determining the **presence of a short-circuit in the network.**

Maximum homopolar voltage relay in a system with isolated neutral



Problem #1: this protection is **very sensitive to the value of the short-circuit resistance.**

Problem #2: the protection device for maximum homopolar voltage 59N is capable to determine the **presence** of a short-circuit in the network but **it is not able to determine the line with the fault.**

Maximum homopolar voltage relay in a system with isolated neutral

Problem #1: influence of the **short-circuit resistance** on the operation of prectiction device 59N.

In reality, short-circuits in electrical distribution networks (**and in particular single phase short-circuits to ground**) **are never perfectly clean,** but with a certain short-circuit impedance $Z_G \neq 0$.

In this case, the **homopolar voltage E_0 depends on the value of the short-circuit impedance.**

Recall the expression of the short-circuit current for phase *a* of the system with a **resistive short-circuit impedance R_G** (R_G is practically the arc resistance).

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

Maximum homopolar voltage relay in a system with isolated neutral

In the case of **networks with isolated neutral, the homopolar impedance of the network is**

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

where X_0 is the reactance linked to the capacitance of the lines:

$$X_0 = \frac{1}{\omega C_s}$$

(C_s is the equivalent homopolar capacitance of the entire network).

Additionally, recall that $|\bar{Z}_0| >> |\bar{Z}_d|$, and because $\bar{Z}_d = \bar{Z}_i$, we can also say that $|\bar{Z}_0| >> |\bar{Z}_i|$. Therefore, the fault and homopolar currents are as follows:

$$\bar{I}'_a \cong \frac{3\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}}; \quad \bar{I}_0 = \frac{\bar{I}'_a}{3} \cong \frac{\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}}$$

Maximum homopolar voltage relay in a system with isolated neutral

The homopolar voltage is therefore:

$$\bar{E}_0 = -\bar{Z}_0 \bar{I}_0 = j\frac{1}{\omega C_s}\frac{\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}} = j\frac{1}{\omega C_s}\frac{\bar{E}}{\dfrac{3R_G\omega C_s - j}{\omega C_s}} =$$

$$j\frac{\bar{E}}{3R_G\omega C_s - j} = -\frac{\bar{E}}{1 + j3R_G\omega C_s} = -\frac{\bar{E}}{1 + j\beta}$$

where: $\beta = 3R_G\omega C_s$

We can also derive the phase *a* voltage, $\bar{E}_a^{'}$, at the point of the fault as follows:

$$\bar{E}_a^{'} = R_G \bar{I}_a^{'} = R_G\frac{3\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}} = R_G\frac{3\bar{E}}{\dfrac{3R_G\omega C_s - j}{\omega C_s}} = \frac{3R_G\omega C_s\bar{E}}{3R_G\omega C_s - j} =$$

$$= \frac{\beta\bar{E}}{\beta - j} = \frac{\beta\bar{E}}{\beta - j}\frac{j}{j} = j\frac{\beta\bar{E}}{1 + j\beta}$$

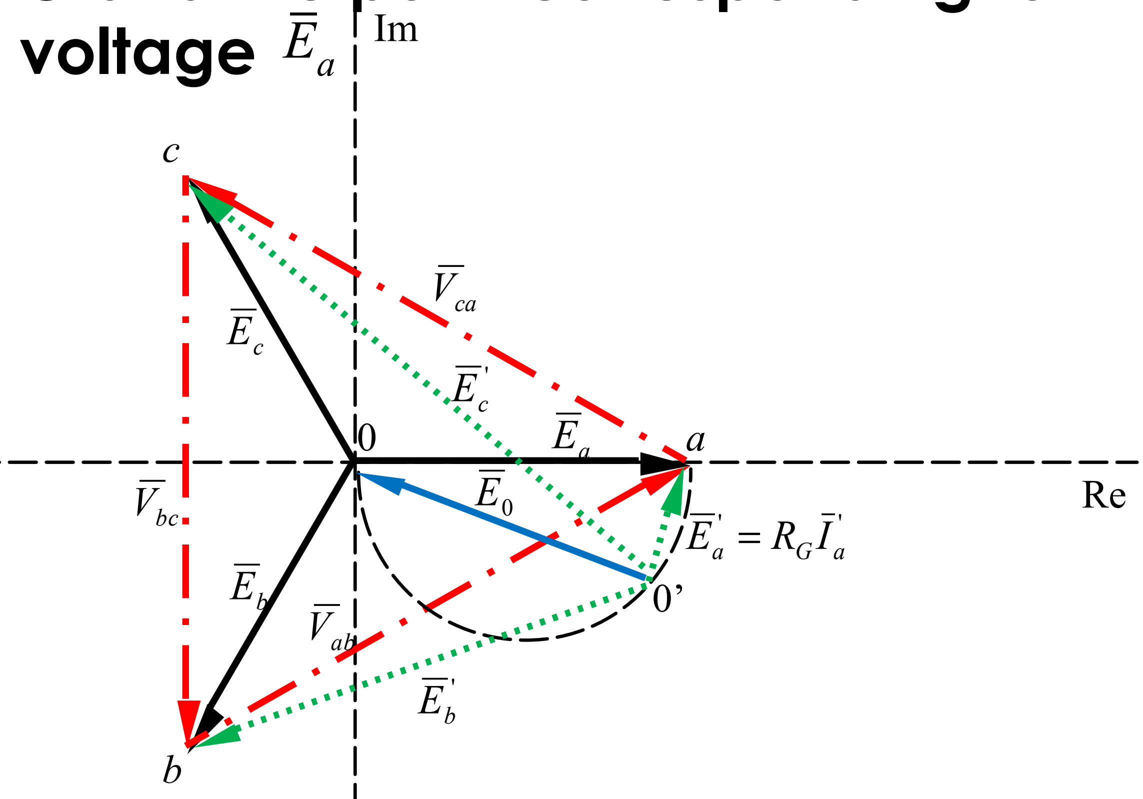
Maximum homopolar voltage relay in a system with isolated neutral

From the preceding equations, we can determine the ratio between the voltage of the faulted phase, $\overline{E}_a^{'}$, and the homopolar voltage, $\overline{E}_0$:

$$\frac{\overline{E}_a^{'}}{\overline{E}_0} = \frac{j\dfrac{\beta\overline{E}}{1+j\beta}}{-\dfrac{\overline{E}}{1+j\beta}} = -j\beta$$

Maximum homopolar voltage relay in a system with isolated neutral

This equation is represented in the figure: the voltages $\bar{E}'_a$ and $\bar{E}_0$ **are separated by an angle of $\pi/2$ and the star center is placed as a function of the value of β** (and therefore R_G and C_s), **in a point belonging to the half-circumference having as extremes the theoretical star center of the system O and the point corresponding to the no-load phase voltage** $\bar{E}_a$

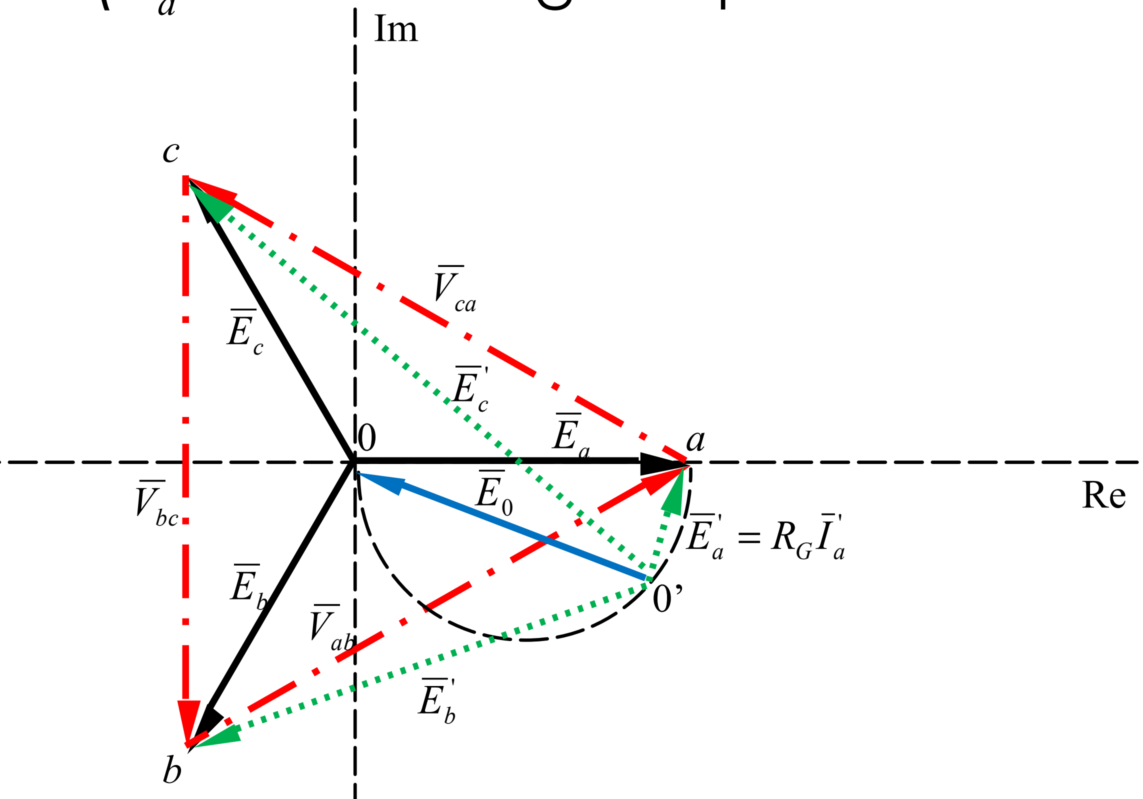


$$\frac{\bar{E}'_a}{\bar{E}_0} = \frac{j\dfrac{\beta\bar{E}}{1+j\beta}}{-\dfrac{\bar{E}}{1+j\beta}} = -j\beta$$

Maximum homopolar voltage relay in a system with isolated neutral

In the extreme cases:

- $\boldsymbol{R_G} = \infty$: the points 0 and $0'$ are coincident, and there is no short-circuit to ground.
- $\boldsymbol{R_G} = \mathbf{0}$: there is a **clean short-circuit to ground** where the point $0'$ is coincident with the peak *a* and $\overline{E}_0 = -\overline{E}_a$ ($\overline{E}_a$ is the voltage of phase *a* before the short-circuit).



$$\frac{\overline{E}_a'}{\overline{E}_0} = \frac{j\dfrac{\beta\overline{E}}{1+j\beta}}{-\dfrac{\overline{E}}{1+j\beta}} = -j\beta$$

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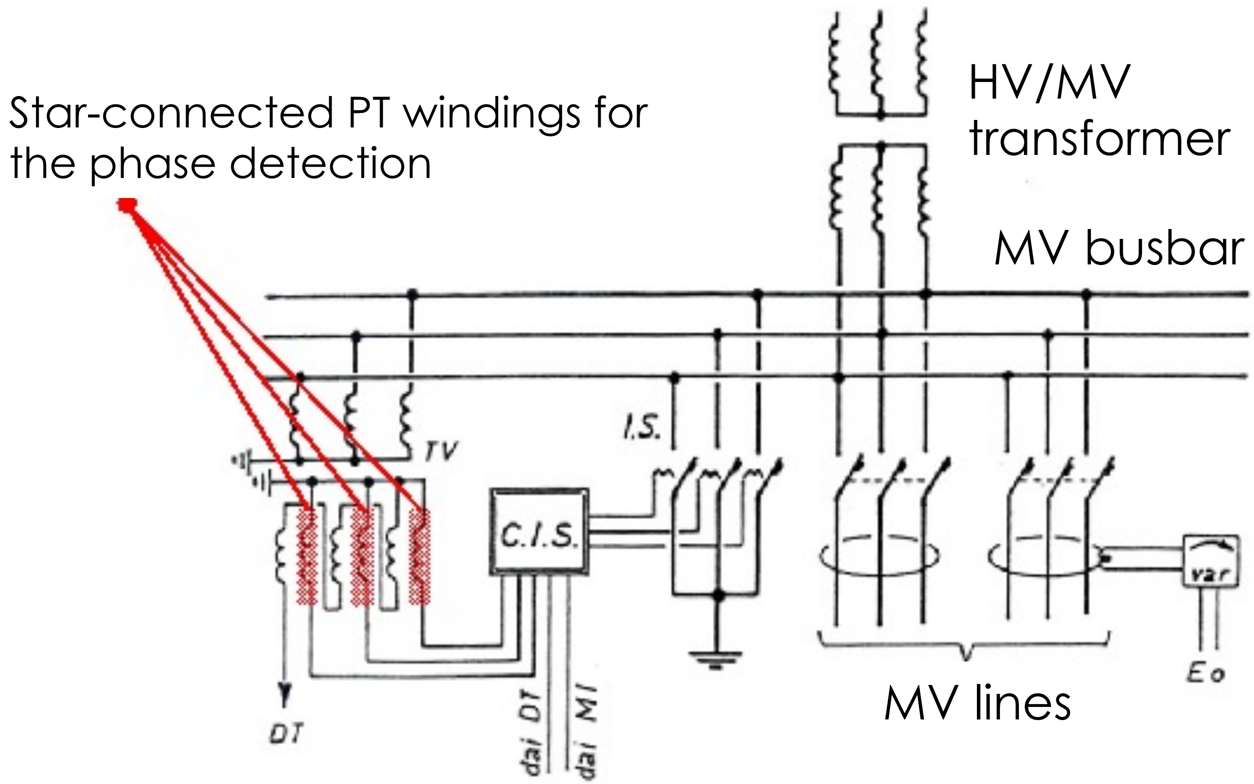
Shunt circuit-breaker in a system with isolated neutral

In a network with **isolated neutral**, it is possible to **eliminate the short-circuit to ground automatically without interrupting the supply of the system** thanks to a **shunt circuit-breaker.**

Principle of operation: in the case of a short-circuit with self-regenerating insulators, for example **an electric arc in the air following a defect in the insulation of an overhead line, if we connect a branch with a lower impedance parallel to the arc, the short-circuit current will circulate in this branch. Therefore, the arc will become unstable and will be extinguished without interrupting the supply of the network.**

Shunt circuit-breaker in a system with isolated neutral

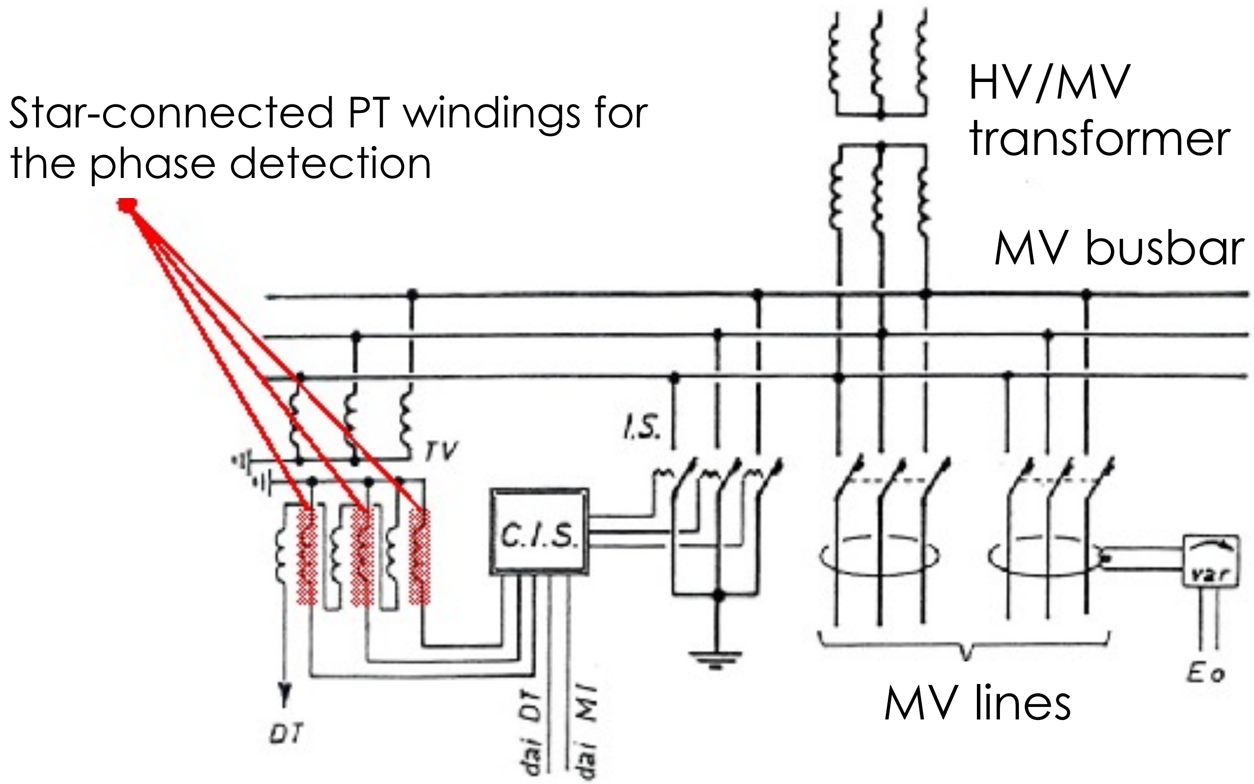
The **shunt circuit-breaker** is based on this principle, composed of **three single-phase circuit breakers in the primary substation and connected between the phases and the grounding network of the substation.** In case of a short-circuit to ground on one phase of the line, the system will give **the order to temporarily close the circuit-breaker for the faulted phase, identified by the voltage measurements in the system.**



Shunt circuit-breaker in a system with isolated neutral

If the affected area has self-regenerating insulators, the arc will extinguish, and the system regains nominal operating conditions when the circuit-breaker is opened.

Observation: the connection to ground of a single phase by a shunt circuit-breaker **does not mean that power to the entire system must be disconnected.** Further, if the MV/LV transformers are delta-connected on the MV side, they will not be affected by the fault because the supply voltages of the transformers are phase-to-phase voltages.



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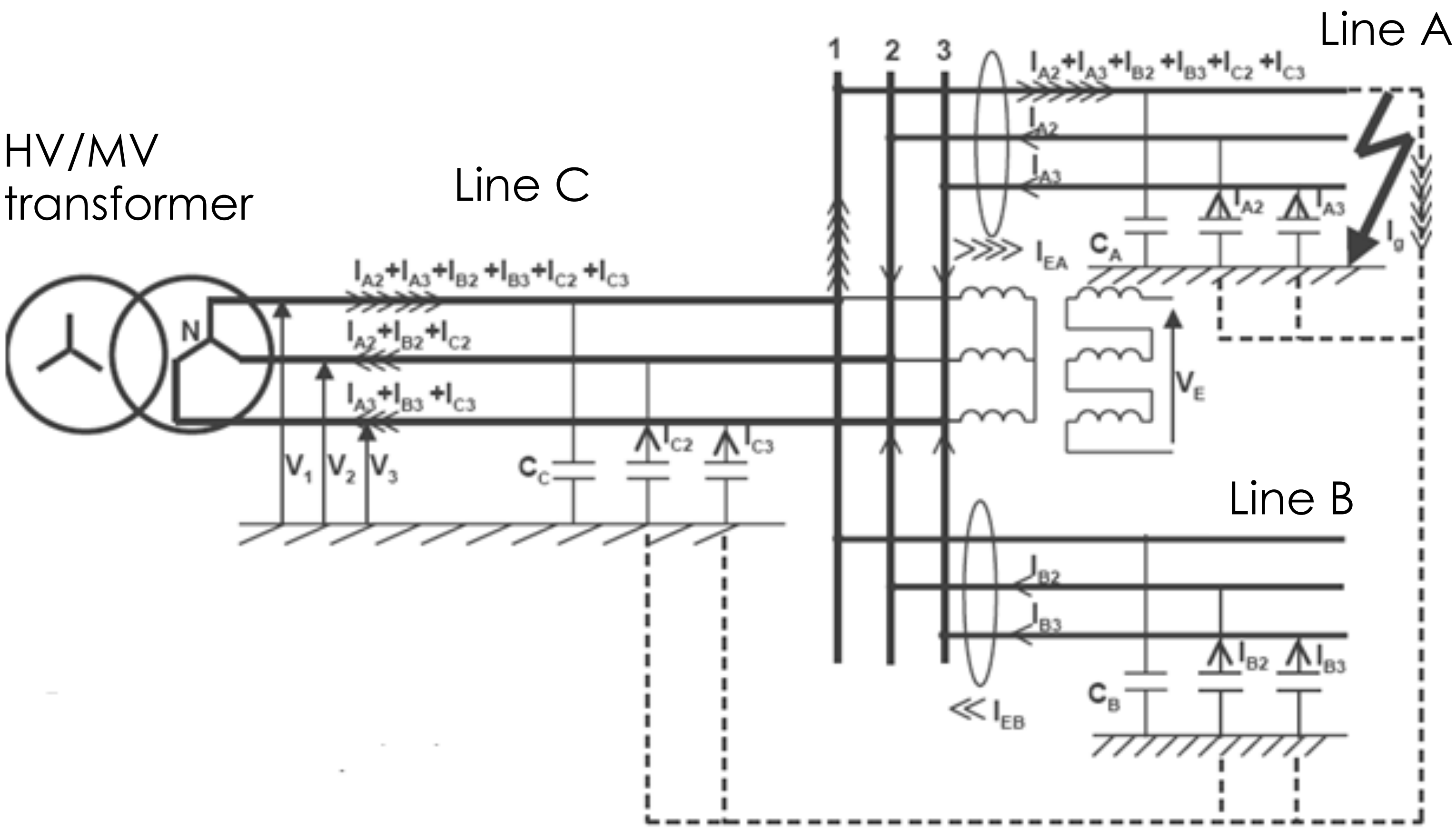
Directional earth relay in a system with isolated neutral

Problem #2: the protection device for maximum homopolar voltage 59N is capable to determine the **presence** of a short-circuit in the network but **it is not able to determine the line with the fault.**

The solution to this problem is the **directional earth relay.**

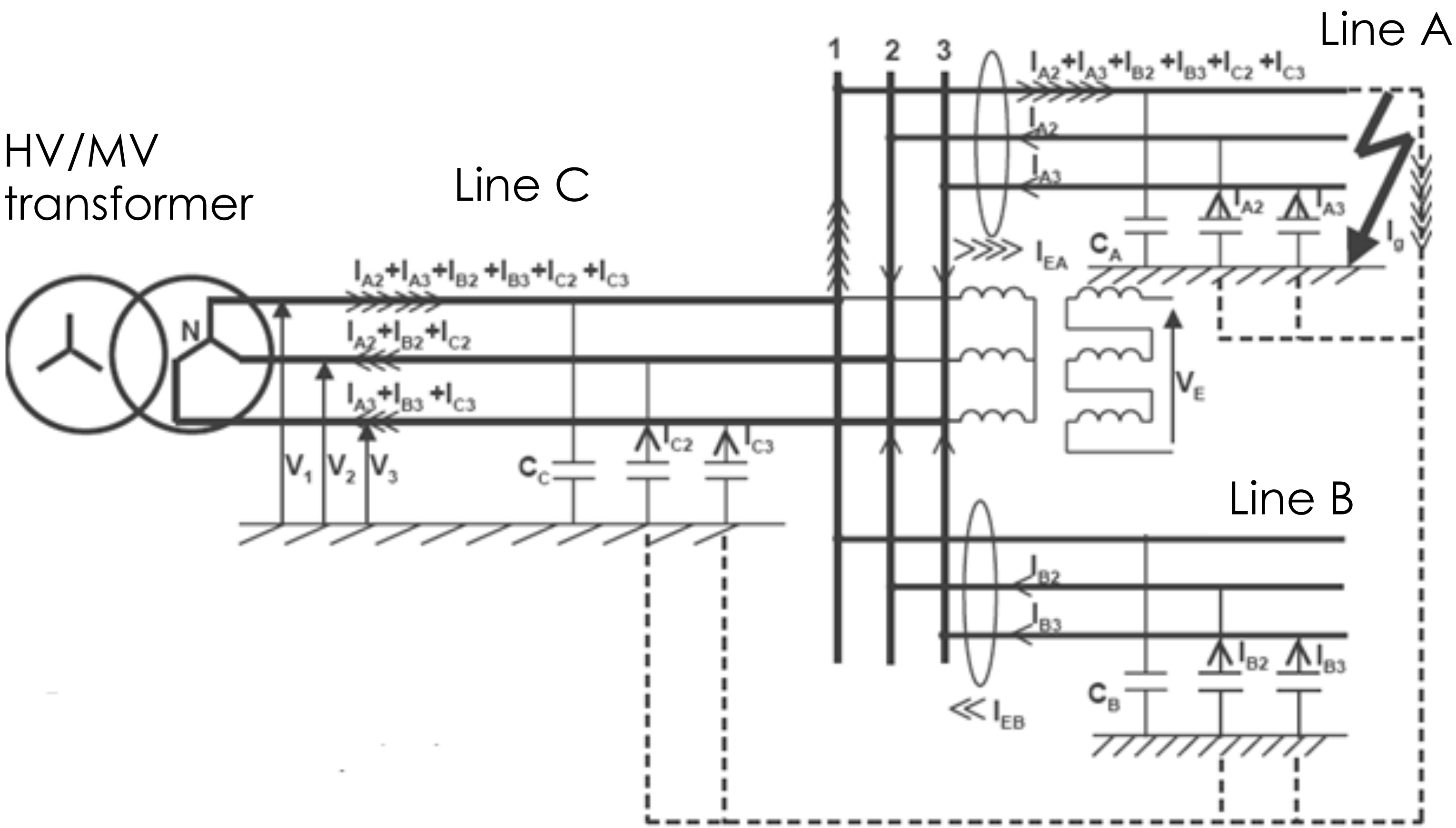
Directional earth relay in a system with isolated neutral

We will consider a generic MV distrivution system with **isolated neutral** (see figure) where the transformer in the primary substation supplies **three lines** (A,B,C) and there is a single phase short-circuit to ground on the line A.



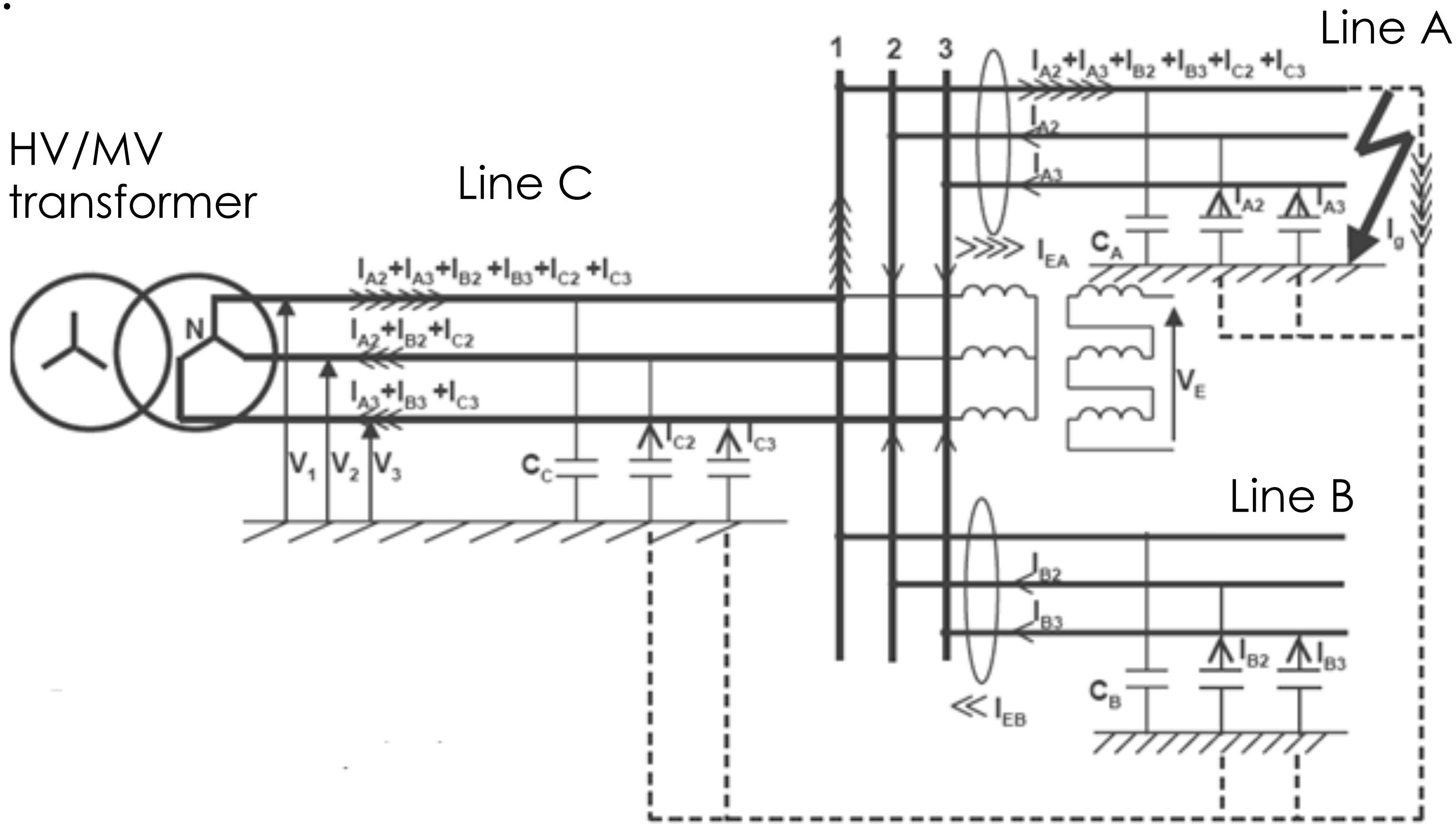
Directional earth relay in a system with isolated neutral

The short-circuit of phase 1, line A, causes currents to flow, closing **through the parasitic capacitances of the healthy phases of all lines.**



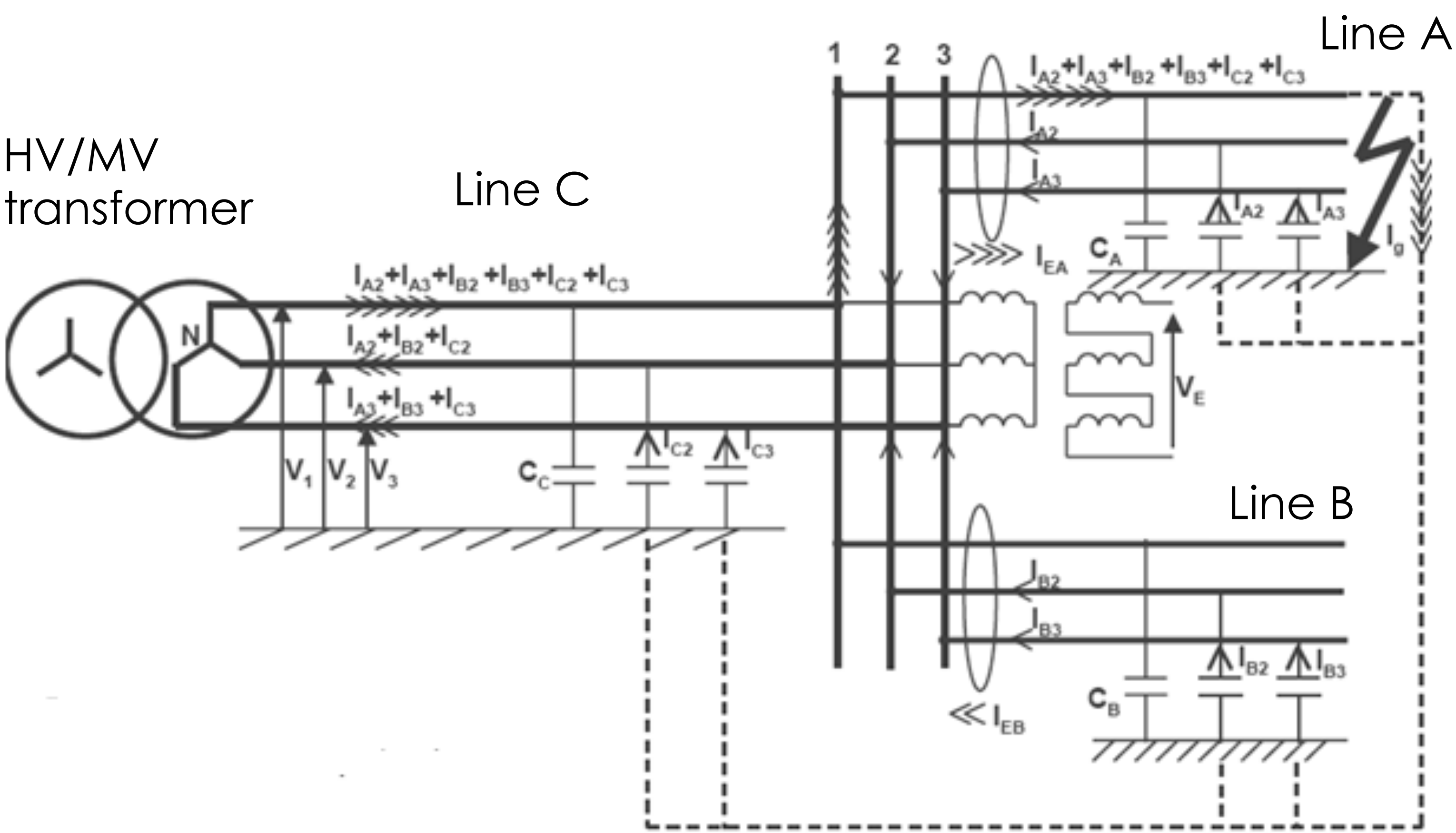
Directional earth relay in a system with isolated neutral

Observation: if the system short-circuit protections were composed of **homopolar current/voltage relays**, the current/voltage sensors would be able to detect a current on the faulted line A, and would open the line using the grounding relays. Similarly, the sensor placed on line B would have given the command to open healthy line B.



Directional earth relay in a system with isolated neutral

Therefore, the simple homopolar current relays are not appropriate for distinguishing healthy and faulted lines. We use the **directional earth relay** instead.



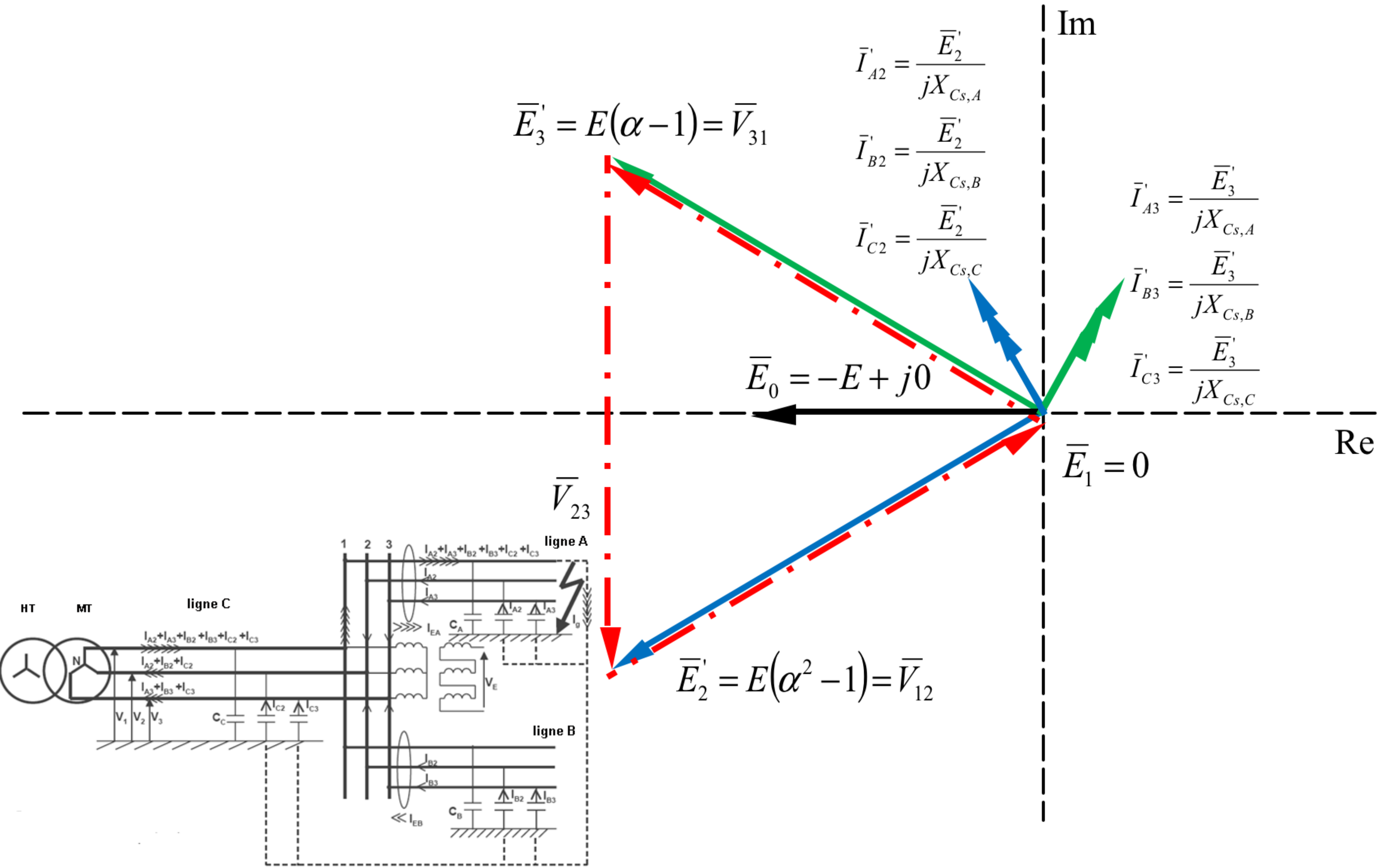
Directional earth relay in a system with isolated neutral

Assumptions

1. In the network, there has been a clean single phase short-circuit, and the network has **reached steady-state conditions**. Therefore, the quantities can be represented by **phasors**, and we consider the transients to have ended.

2. The **lines are transposed**, and we can express the currents on the healthy phases of lines A, B, and C by the post-fault voltages and line capacities.

Directional earth relay in a system with isolated neutral



Directional earth relay in a system with isolated neutral

Each current $\bar{I}_{A2}, \bar{I}_{A3}, \bar{I}_{B2}, \bar{I}_{B3}, \bar{I}_{C2}, \bar{I}_{C3}$ **is linked to the post-fault phase voltage and the line capacity** according to the following relations:

$$\bar{I}'_{A2} = \frac{\bar{E}'_2}{jX_{Cs,A}} \qquad \bar{I}'_{A3} = \frac{\bar{E}'_3}{jX_{Cs,A}}$$

$$\bar{I}'_{B2} = \frac{\bar{E}'_2}{jX_{Cs,B}} \qquad \bar{I}'_{B3} = \frac{\bar{E}'_3}{jX_{Cs,B}}$$

$$\bar{I}'_{C2} = \frac{\bar{E}'_2}{jX_{Cs,C}} \qquad \bar{I}'_{C3} = \frac{\bar{E}'_3}{jX_{Cs,C}}$$

Observation: the currents $\bar{I}_{A2}$ and $\bar{I}_{A3}$ will be lagging relative to the post-fault phase voltages $\bar{E}'_2$ and $\bar{E}'_3$ (and similarly for the other phases, $\bar{I}_{B2}, \bar{I}_{B3}$ and $\bar{I}_{C2}, \bar{I}_{C3}$).

Directional earth relay in a system with isolated neutral

If we apply Kirchoff's current law **at the homopolar current relay installed on line** $\mathbf{A}$ we obtain the current measured by the relay $\overline{I}_{EA}$

$$\overline{I}_{EA} = \overline{I}_{A2} + \overline{I}_{A3} + \overline{I}_{B2} + \overline{I}_{B3} + \overline{I}_{C2} + \overline{I}_{C3} - \overline{I}_{A2} - \overline{I}_{A3} = \overline{I}_{B2} + \overline{I}_{B3} + \overline{I}_{C2} + \overline{I}_{C3}$$

The current measured by the relay on line B is

$$\overline{I}_{EB} = -\overline{I}_{B2} - \overline{I}_{B3}$$

We can then place the currents in the complex plane.
Observation: the current measured by the homopolar current relay on the faulted line A, $\overline{I}_{EA}$, is **lagging relative to the homopolar voltage.**
The current measured by the homopolar current relay on the line B, $\overline{I}_{EB}$, is **leading relative to the homopolar voltage.**

Directional earth relay in a system with isolated neutral

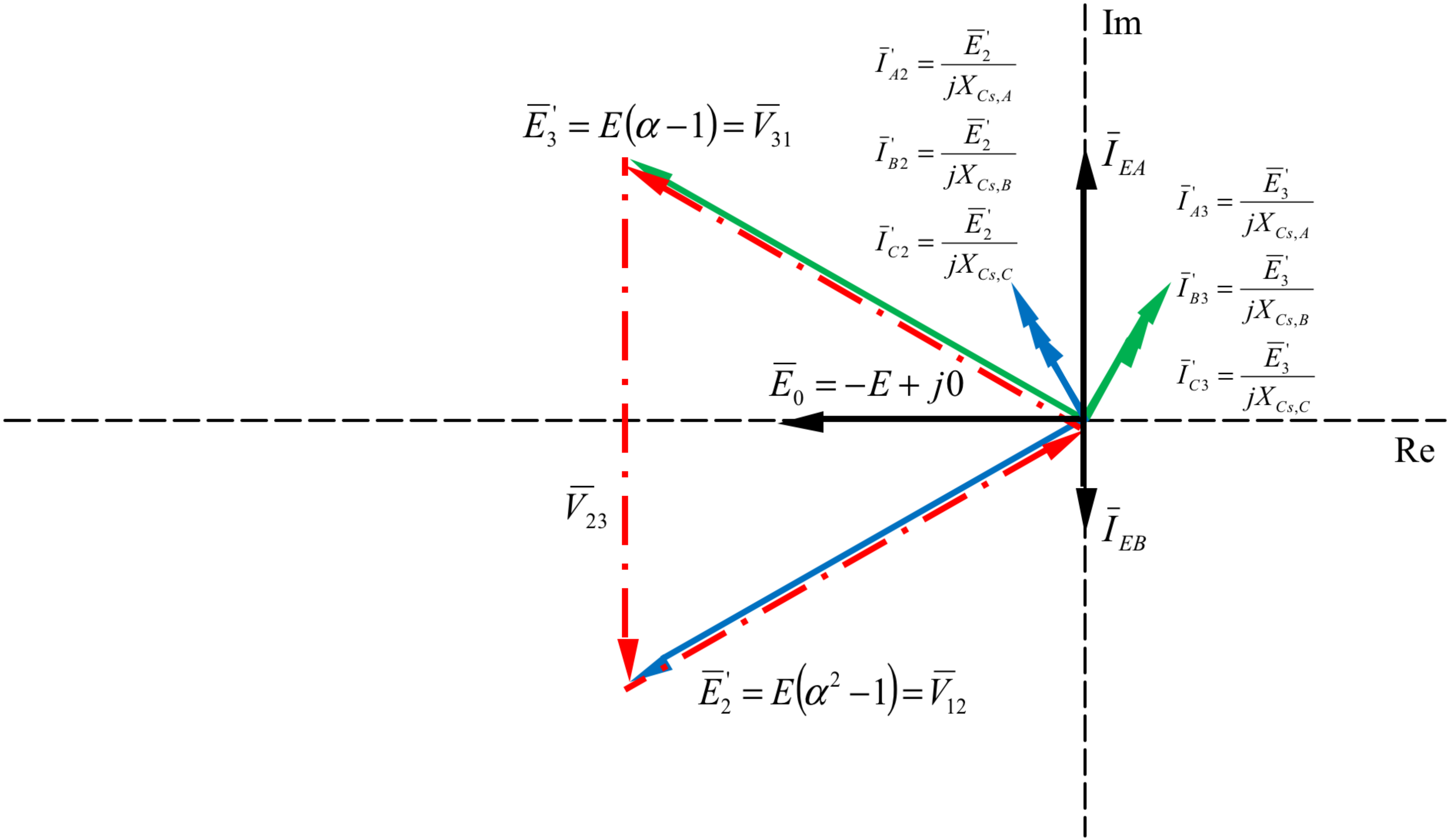
This observation is at the basis of the operation of the directional earth relay, which will **simply measure the virtual reactive power associated with the homopolar voltage and the current measured at the beginning of each line.**
The two protections will measure the reactive power as follows:

$$Q_A = E_0 I_{EA} \sin\left(\frac{\pi}{2}\right) > 0$$

$$Q_B = E_0 I_{EB} \sin\left(-\frac{\pi}{2}\right) < 0;$$

The reactive power associated with the **faulted line will have a positive sign** while the reactive power measured in the **healthy lines will have a negative sign.** In this way, we can detect which line is faulted.
Directional earth protection relays are called **varmetric protection.**

Directional earth relay in a system with isolated neutral



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Networks with neutral grounded by the Petersen winding

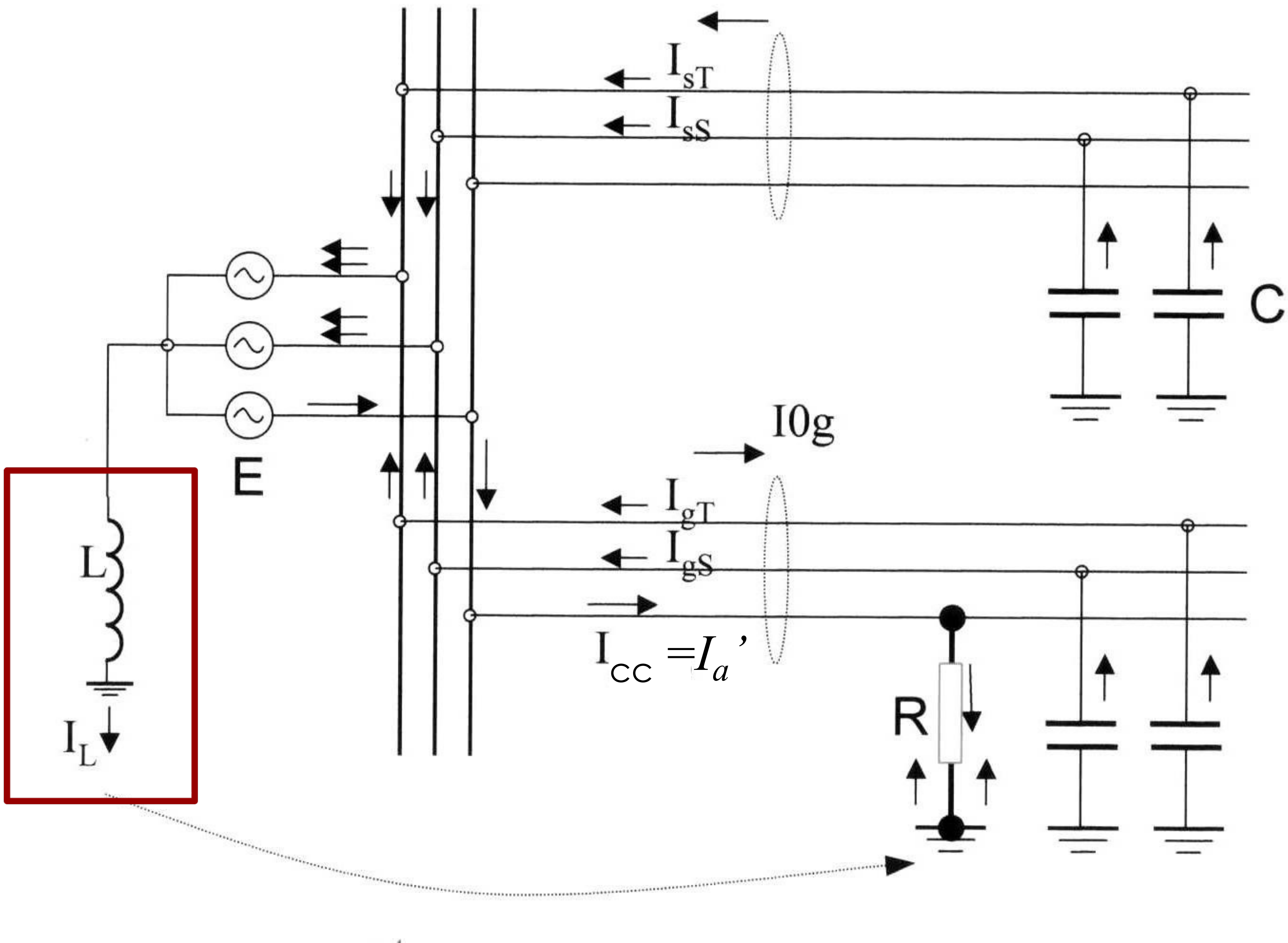
Networks with neutral grounded by the Petersen winding

In the operation of medium-voltage distribution networks, there are two primary requirements:

- The **reduction of short-circuit current to ground** (to improve safety of personnel in case of indirect contact);
- **Improvement to the service quality** and avoid interruption of supply in the case of short-circuits in the presence of self-regenerating insulators.

We can complete both requirements by grounding the star center of the electrical system with an inductance whose value is matched to that of the system's grounded capacitance.

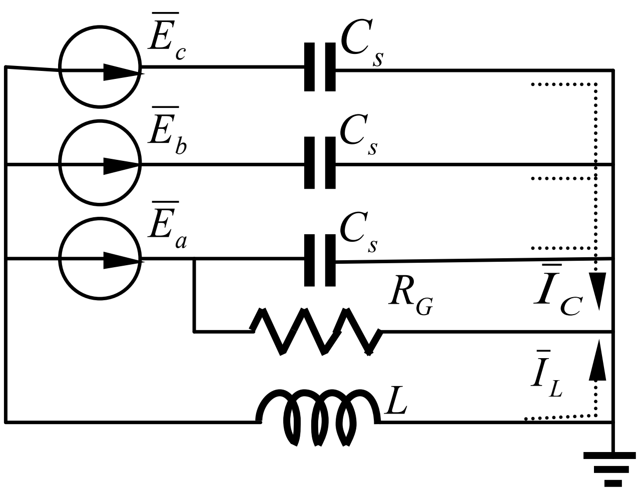
Networks with neutral grounded by the Petersen winding

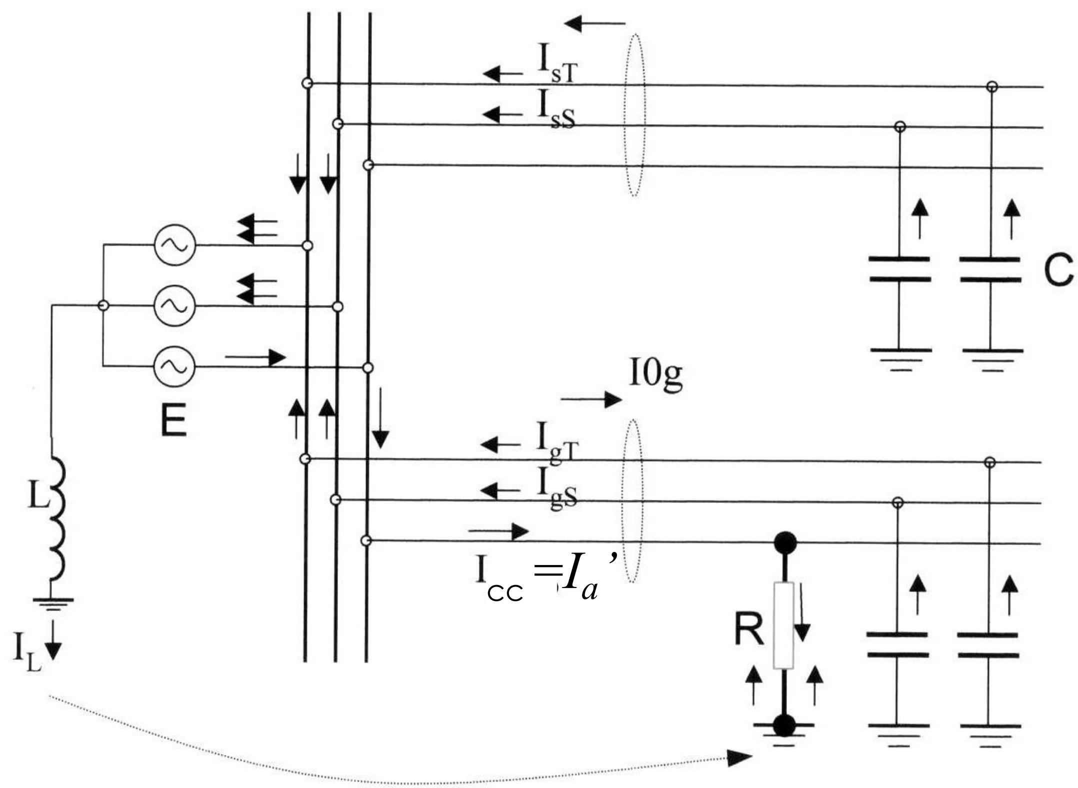


Networks with neutral grounded by the Petersen winding

When a short-circuit occurs, the following currents will flow:

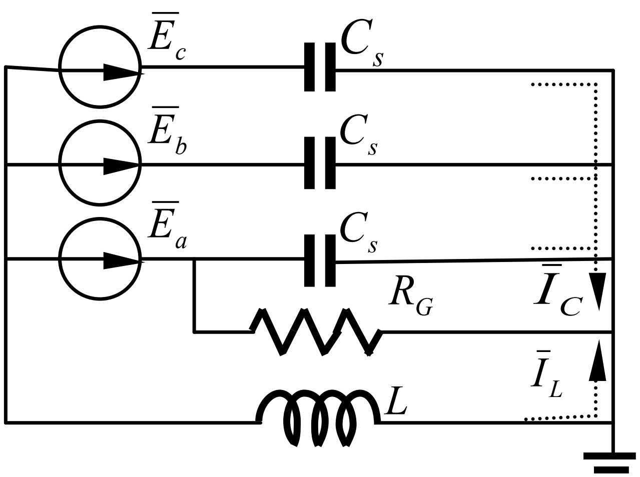
- The part of the short-circuit current which passes through the inductance (I_L);
- The part of the short-circuit current which passes through the line capacitance (I_C).

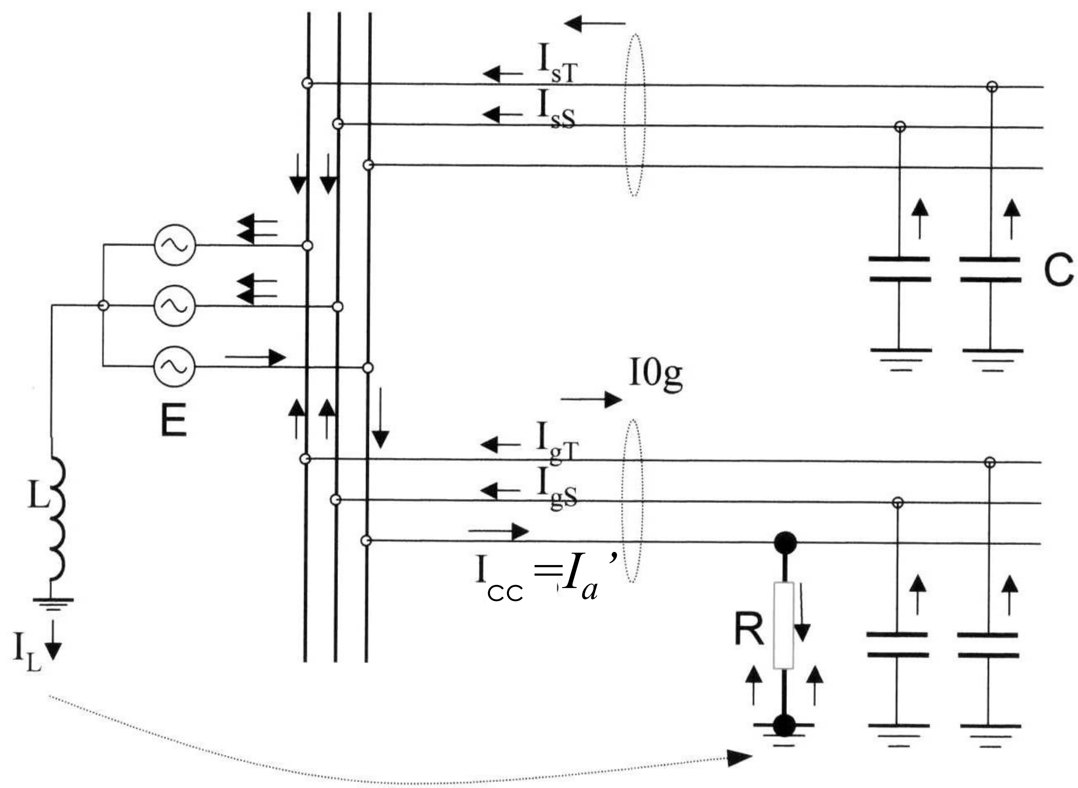




Networks with neutral grounded by the Petersen winding

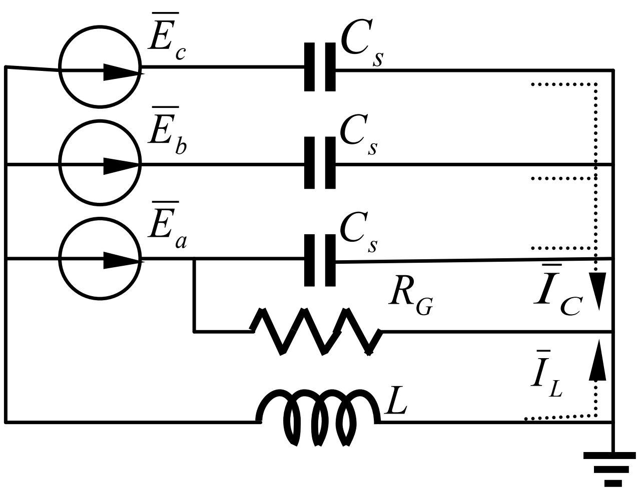
Since the currents I_L and I_C are separated by a phase angle of π, if the current flowing through the inductance is equal in amplitude to the sum of the currents passing through the line capacitances, we will have a zero short-circuit current (**anti-resonance condition of the homopolar sequence**).

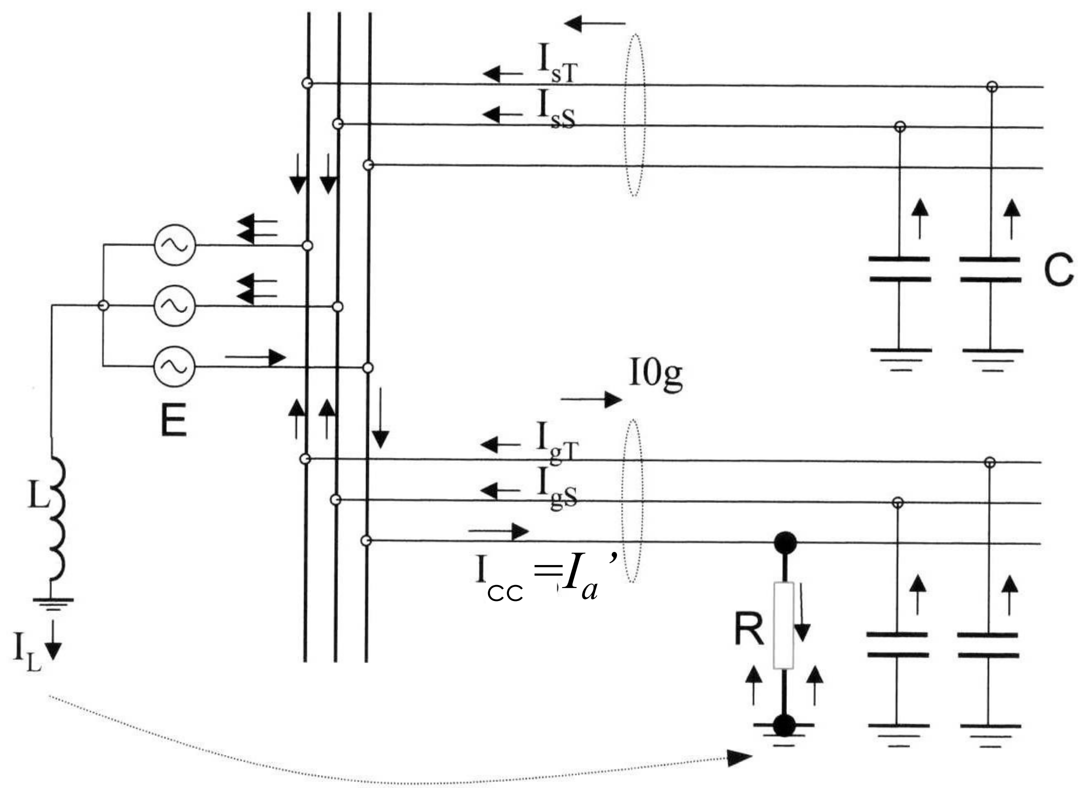




Networks with neutral grounded by the Petersen winding

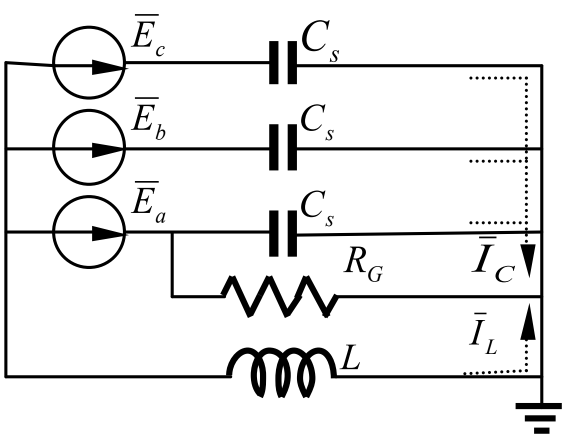
Distribution networks have **daily topological variations** as controlled by the system operator. Therefore, the **capacitances of the network are not constant.** Therefore, we use a value of the **inductance L which varies as a function of the capacitance of the network.** This inductance is called the **Petersen winding.**





Networks with neutral grounded by the Petersen winding

The Petersen winding is an **anti-resonant circuit to the homopolar sequence.** If we **neglect the impedances of the direct and inverse sequences**, the homopolar impedance of a network with neutral grounded by an inductance is given by the parallel of the inductance with the parasitic capacitance of the system:



$$\frac{1}{\overline{Z}_0} = \frac{1}{3j\omega L} + j\omega C_s = \frac{1-3\omega^2 LC_s}{3j\omega L} \rightarrow \overline{Z}_0 = \frac{3j\omega L}{1-3\omega^2 LC_s}$$

Networks with neutral grounded by the Petersen winding

The short-circuit current is given by

$$\bar{I}_a' = \frac{3\bar{E}}{\bar{Z}_d + \bar{Z}_i + \bar{Z}_0 + 3R_G} \cong \frac{3\bar{E}}{\bar{Z}_0 + 3R_G} = \frac{3\bar{E}}{\dfrac{3j\omega L}{1-3\omega^2 LC_s} + 3R_G} =$$

$$= \frac{\bar{E}\left(1-3\omega^2 LC_s\right)}{j\omega L + R_G\left(1-3\omega^2 LC_s\right)} = \frac{\bar{E}\left(\dfrac{1}{\omega L} - 3\omega C_s\right)}{R_G\left(\dfrac{1}{\omega L} - 3\omega C_s\right) + j}$$

Observation: in this equation, note that for $\omega L \rightarrow \infty$ (i.e., for **networks with isolated neutral**) the short-circuit current is as previously given:

$$\bar{I}_a' = \frac{\bar{E}\left(-3\omega C_s\right)}{R_G\left(-3\omega C_s\right) + j} = \frac{3\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}} = \frac{3\bar{E}}{3R_G - j\dfrac{1}{\omega C_s}}$$

Networks with neutral grounded by the Petersen winding

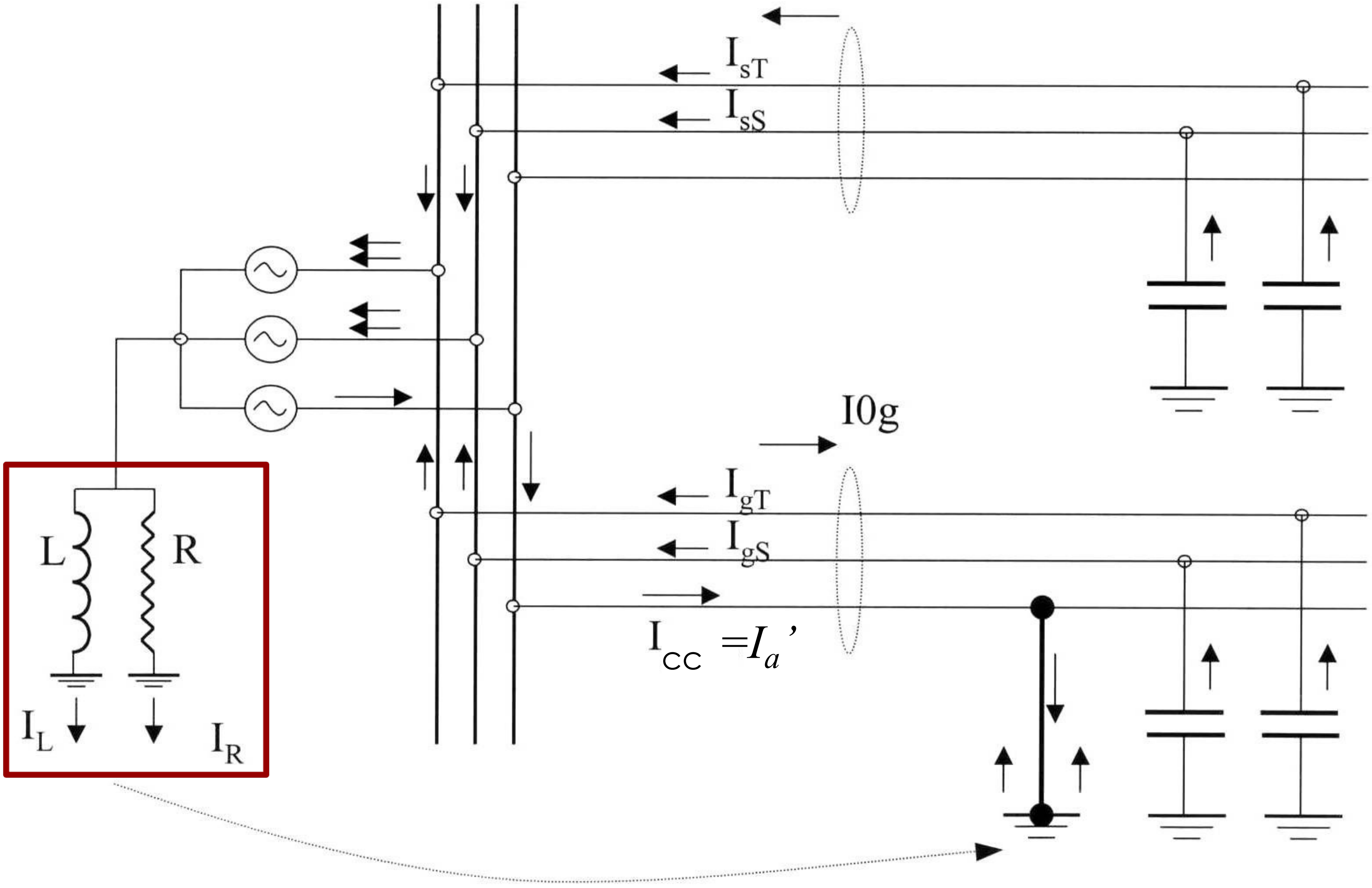
For a perfect anti-resonance condition:

$$\frac{1}{\omega L} = 3\omega C_s \rightarrow \overline{I}_a' = 0$$

In reality, we have very small currents because we still need to guarantee the functionality of the directional earth relays.

If the compensation is perfect, the short-circuit current is zero even with a short-circuit still present.
To guarantee the functioning of the directional earth relays, it is necessary to connect a resistance in parallel to the inductance.

Networks with neutral grounded by the Petersen winding



Networks with neutral grounded by the Petersen winding

In this case, the homopolar impedance is:

$$\frac{1}{\overline{Z}_0} = \frac{1}{3R} + \frac{1}{3j\omega L} + j\omega C_s = \frac{R - 3\omega^2 LC_s R + j\omega L}{3j\omega LR}$$

$$\overline{Z}_0 = \frac{3j\omega LR}{R\left(1 - 3\omega^2 LC_s\right) + j\omega L}$$

And the short-circuit current is:

$$\overline{I}_a^{'} = \frac{3\overline{E}}{\overline{Z}_d + \overline{Z}_i + \overline{Z}_0 + 3R_G} \cong \frac{3\overline{E}}{\overline{Z}_0 + 3R_G} = \frac{3\overline{E}}{\dfrac{3j\omega LR}{R\left(1 - 3\omega^2 LC_s\right) + j\omega L} + 3R_G}$$

Networks with neutral grounded by the Petersen winding

If the short-circuit resistance is $R_G=0$:

$$\bar{I}_a' = \frac{3\bar{E}}{\dfrac{3j\omega LR}{R\left(1-3\omega^2 LC_s\right)+j\omega L}} = \frac{\bar{E}\left[R\left(1-3\omega^2 LC_s\right)+j\omega L\right]}{j\omega LR} =$$

$$= \frac{\bar{E}\left[R\left(\dfrac{1}{\omega L}-3\omega C_s\right)+j\right]}{jR}$$

In the case of **perfect anti-resonance between the Petersen winding and the network capacitance**, the short-circuit current is:

$$\bar{I}_a' = \frac{\bar{E}\left[R\left(\dfrac{1}{\omega L}-3\omega C_s\right)+j\right]}{jR} = \frac{j\bar{E}}{jR} = \frac{\bar{E}}{R}$$

Networks with neutral grounded by the Petersen winding

The homopolar current which circulates in the **healthy line** will be capacitive and it will therefore be possible to detect the faulted line.

The insertion of the Petersen winding (with the grounding resistance) can be applied **at the star center of the HV/MV transformer in the primary substation**, or by creating an artificial star center.

Networks with neutral grounded by the Petersen winding

The Petersen winding is dimensioned by a regime of **under-compensation** $I_L = 0.95 \cdot I_C$. Therefore, the short-circuit current and elimination time of the short-circuit are:

$I_{fault} = 50$ A;
$t_{elim} > 10$ s.

These values are supplied by the MV network operator.

With the Petersen winding, the elimination time of the fault is longer because more time is needed for auto-extinction of the fault.