NEUTRAL EARTHING IN MEDIUM VOLTAGE INDUSTRIAL APPLICATIONS

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Agenda

General introduction:

- Medium voltage system
- Type of earthing (definitions)

Criteria for selecting earthing (grounding) method:

- Step-by-step PROS / CONS of various earthing methods
- Limit overvoltages / Limit damage / Ensure reliable protection system

- **Conclusions, Takeaways**

Fault statistics

- Phase-to-ground (**80%** of faults)

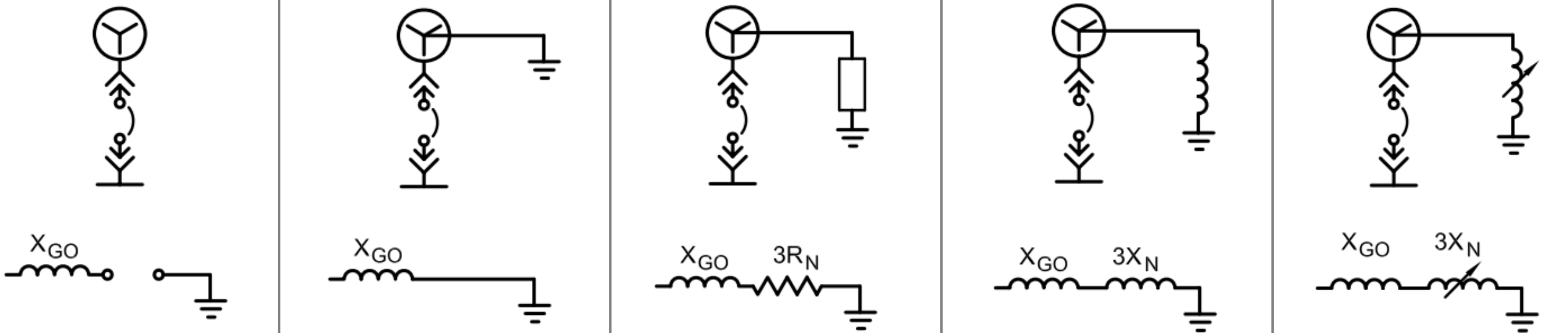
  This type of fault can degenerate into a phase fault.
- Phase-to-phase (**15%** of faults)

  This type of fault often degenerates into a three-phase fault.
- Three-phase (only **5%** of initial faults)

[Schneider Electric - Cahier technique no. 158]

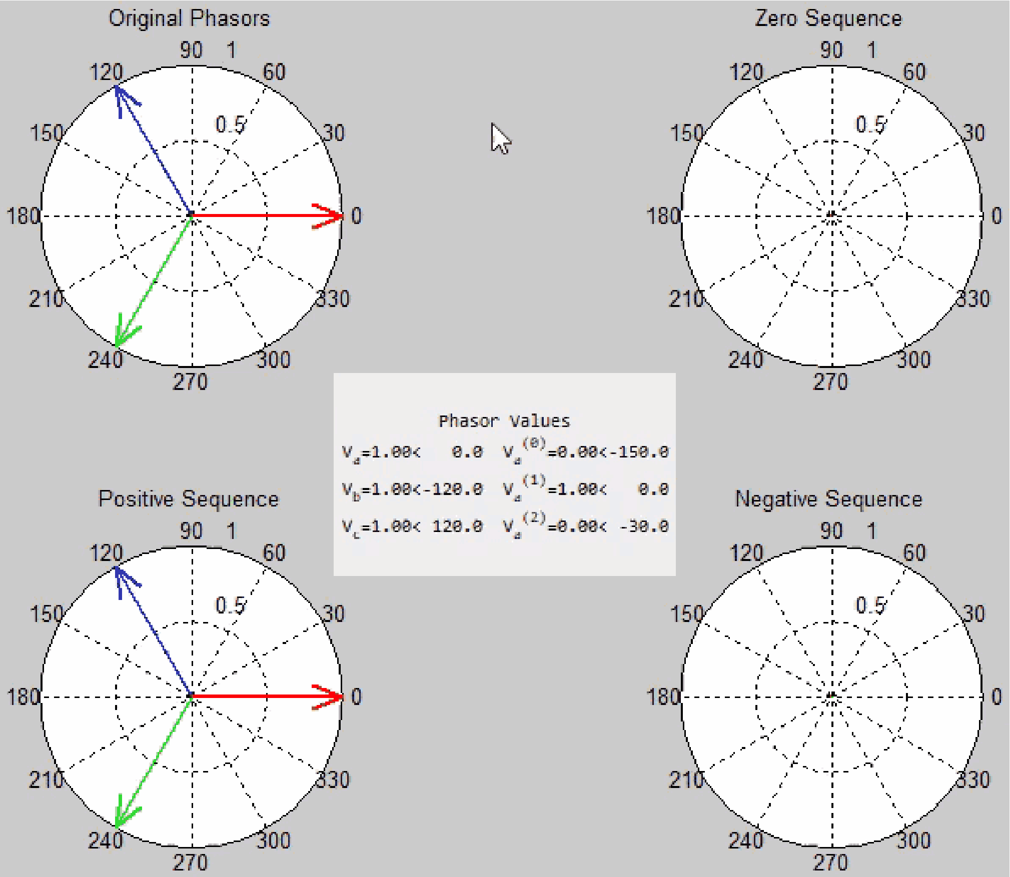
Type of earthing / grounding

Ungrounded (IEEE)	Solidly grounded	Resistance grounded	Inductance grounded	Resonant grounded
Isolated neutral (IEC)	Solidly earthed (neutral)	Impedance earthed (neutral)	Impedance earthed (neutral)	Resonant earthed (neutral)



[IEC 62271-100 High voltage switchgear and controlgear - Alternating current circuit breakers]
[IEEE 142 Grounding of Industrial and Commercial Power Systems]

Sequence components, background theory



from **phase values** to **sequence components**

$$I_1 = {}^1/_3 \cdot (I_a + a \cdot I_b + a^2 \cdot I_c)$$

$$I_2 = {}^1/_3 \cdot (I_a + a^2 \cdot I_b + a \cdot I_c)$$

$$I_0 = {}^1/_3 \cdot (I_a + I_b + I_c)$$

from **sequence components** to **phase values**

$$I_a = I_1 + I_2 + I_0$$

$$I_b = a^2 \cdot I_1 + a \cdot I_2 + I_0$$

$$I_c = a \cdot I_1 + a^2 \cdot I_2 + I_0$$

operators

$$a = -0.5 + j \cdot 0.866$$

$$a^2 = -0.5 - j \cdot 0.866$$

$$\cos 120° = -0.5$$

$$\sin 120° = 0.866$$

Factors in selecting a earthing scheme

Objectives:

- sufficiently damp overvoltages (many kA)
- limit damage and disturbances caused by an earth fault current (zero A)
- provide simple, reliable and selective protection system (enough A).

Best option / solution is an **Optimal Compromises**, case by case, between 3 contradictory requirements.

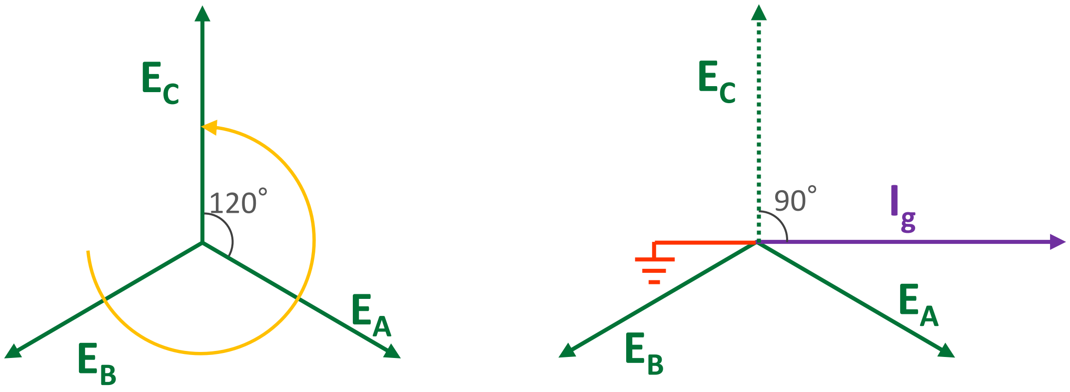
Sometimes, decisions are driven by Network supplier, Habitudes, Copy / Paste

Different Earthing Methods (PRO / CONS)

	Isolated neutral	Solidly earthed (neutral)	Resistance earthed (neutral)	Resonant earthed
Fault current (damage)				
Transient overvoltages / Arcing grounds faults				
Temporary overvoltages (TOV)				
Reliable protection				

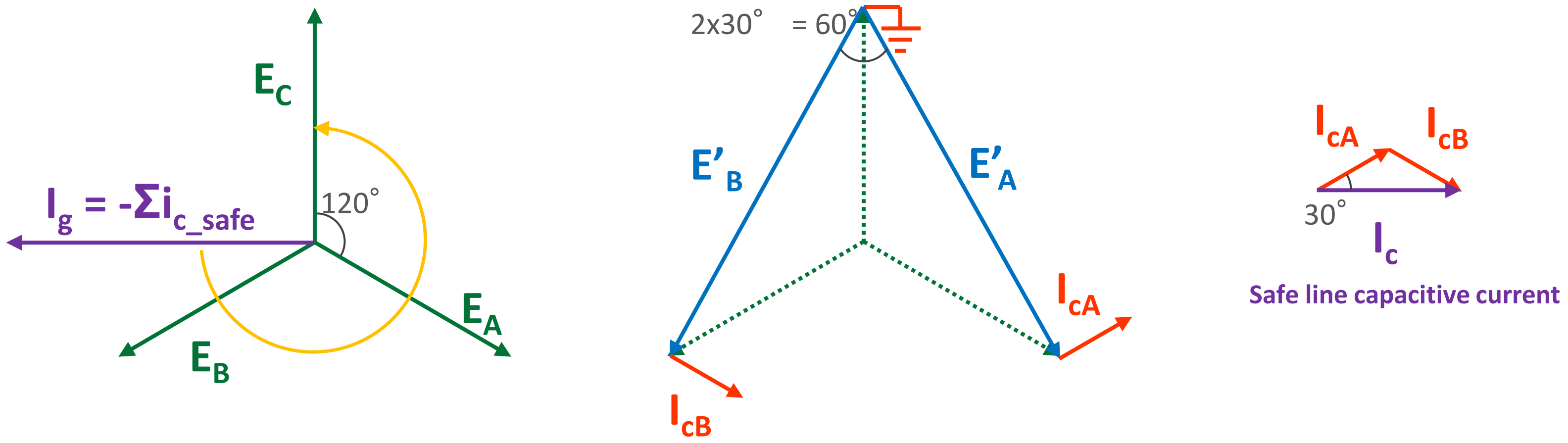
Temporary overvoltages

Damp overvoltages: TOV during LG fault - Solidly earthed



Inductive ground fault current (first approximation)

Damp overvoltages: TOV during LG fault - Isolated neutral



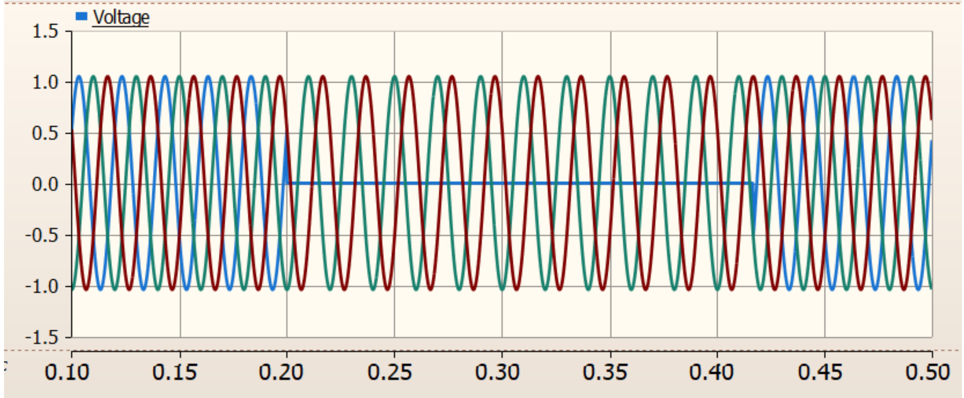
$$E'_A = V_{AC} \qquad I_{cA} = \omega \cdot C_o \cdot E'_A = \omega \cdot C_o \cdot V_{AC}$$

$$E'_B = V_{BC} \qquad I_{cB} = \omega \cdot C_o \cdot E'_B = \omega \cdot C_o \cdot V_{BC}$$

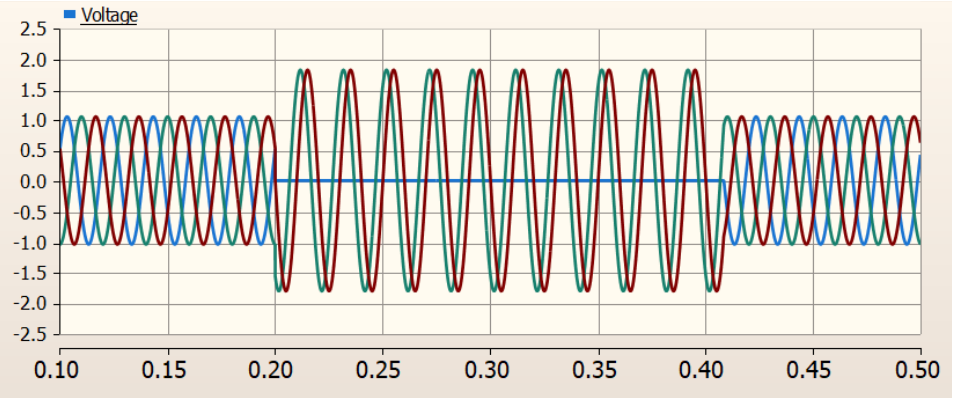
$$I_g = I_{cA} + I_{cB} = 2 \cdot \omega \cdot C_o \cdot \cos(30) \cdot V = 3 \cdot \omega \cdot C_o \cdot E = \mathbf{3} \cdot \boldsymbol{I_o}$$

Damp overvoltages: TOV during LG fault - Simulation set

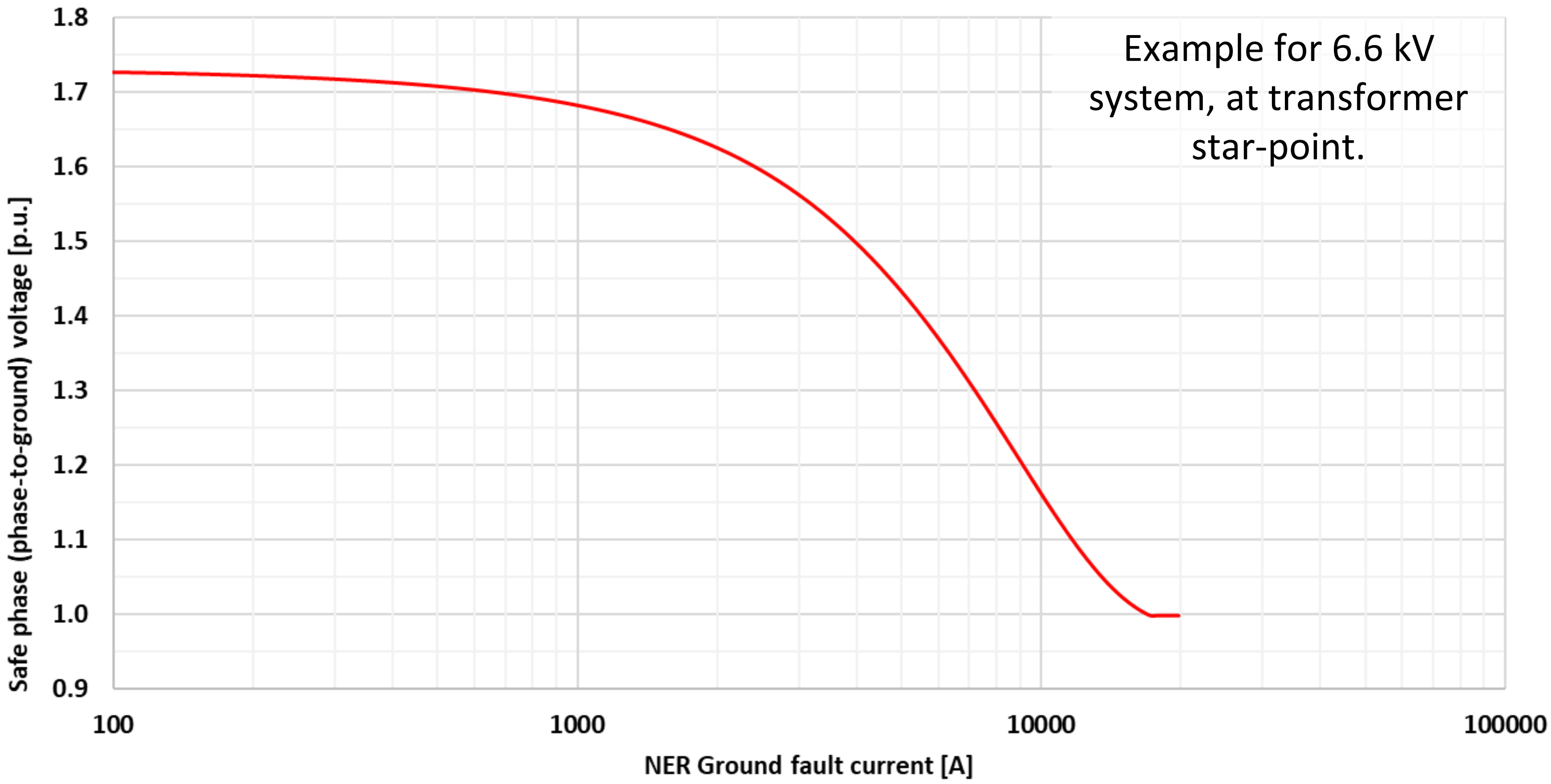
Solidly earthed



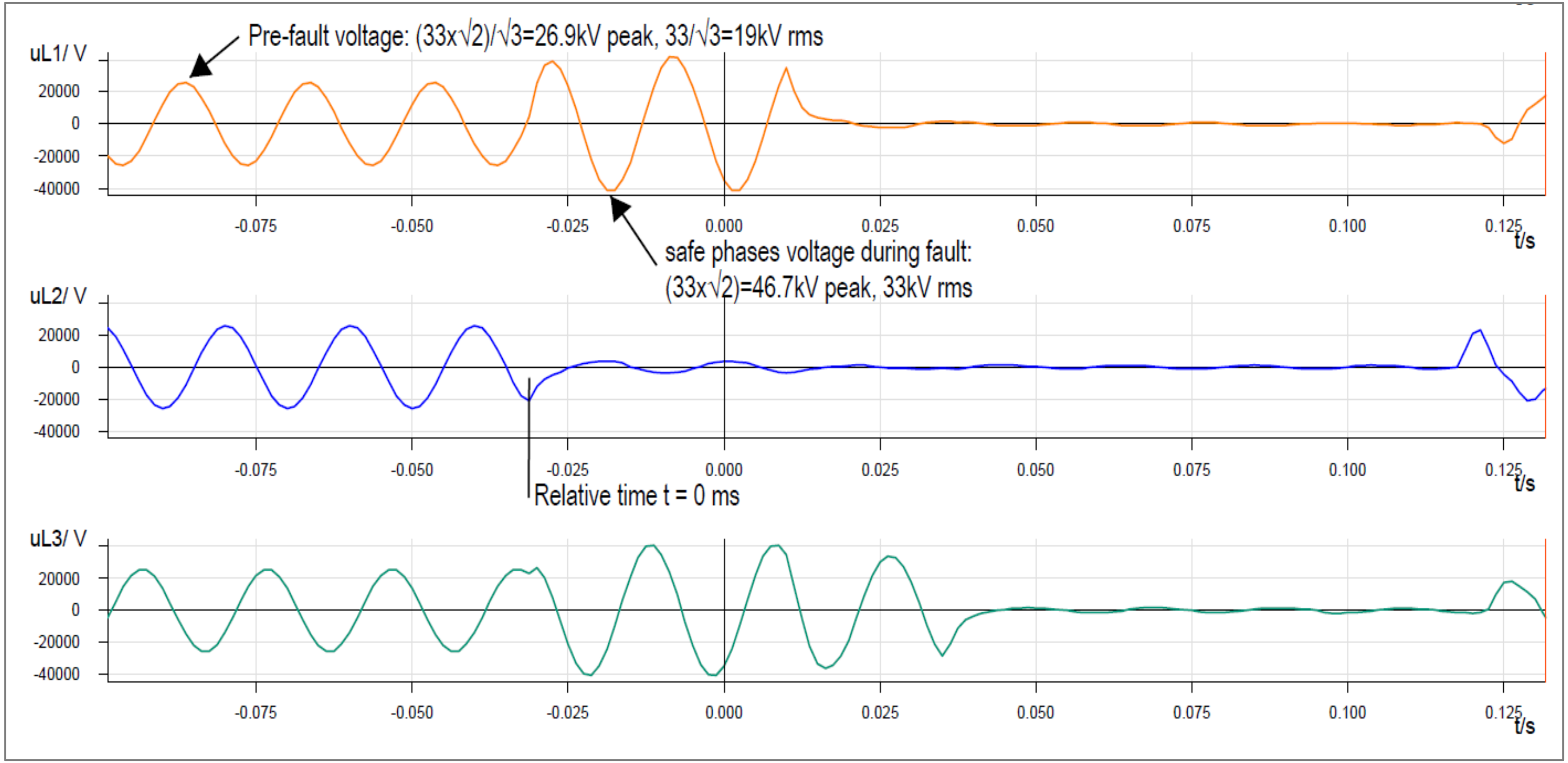
Isolated neutral



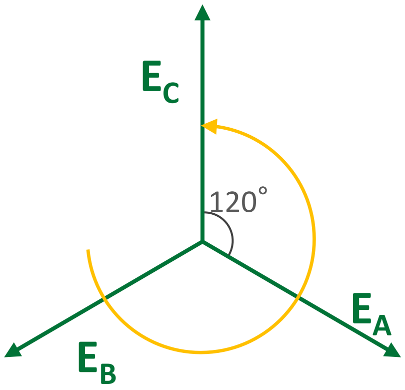
Damp overvoltages: TOV during LG fault - Simulation set

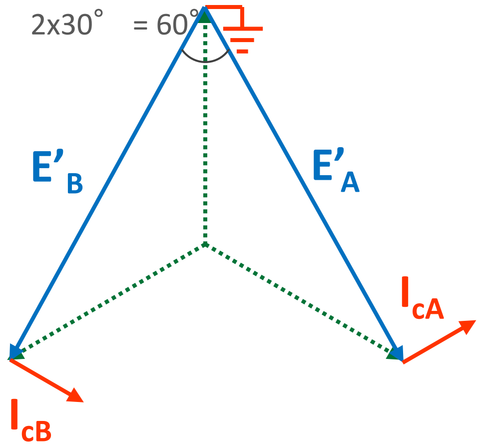


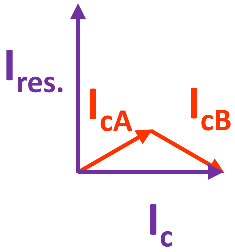
Damp overvoltages: TOV during LG fault - Recorded waveforms

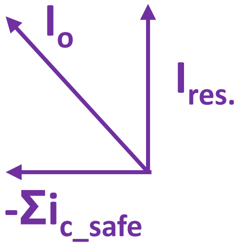


Damp overvoltages: TOV during LG fault - Resistance earthed









$$E'_A = V_{AC} \qquad I_{cA} = \omega \cdot C_o \cdot E'_A = \omega \cdot C_o \cdot V_{AC}$$

$$E'_B = V_{BC} \qquad I_{cB} = \omega \cdot C_o \cdot E'_B = \omega \cdot C_o \cdot V_{BC}$$

Damp overvoltages: TOV - Earthing definitions - @IEC

earth fault factor "k"	the **ratio** of the highest **RMS phase-to-earth** power-frequency voltage **on a healthy phase during a fault** to earth affecting one or more phases at any point on the system **to the RMS phase-to-earth** power-frequency voltage which would be obtained at the given location **in the absence of any such fault**.

[IEC 60071-2 Insulation coordination - Application guidelines]

Damp overvoltages: TOV - Earthing definitions - @IEC

Starting points:

$$Z_1 = R_1 + j \cdot X_1$$

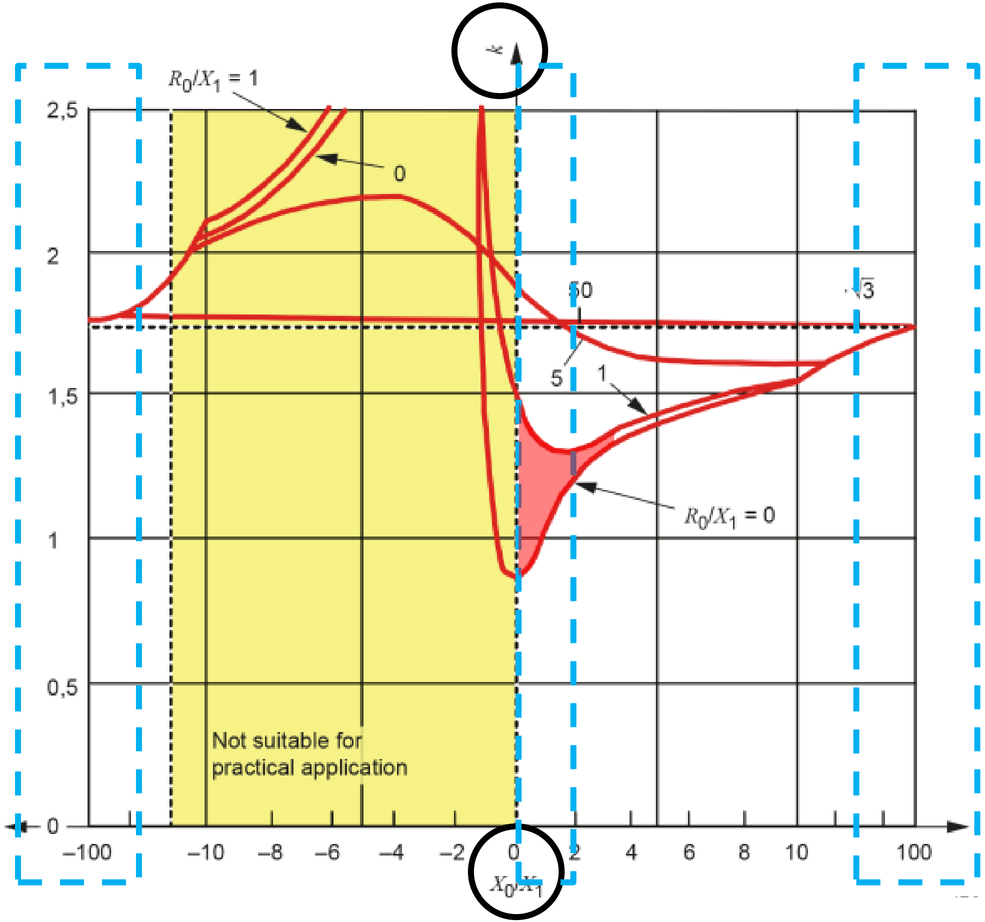
$$Z_0 = R_0 + j \cdot X_0$$

$$R_f$$

Figure basis:

$$R_1 = 0$$

$$R_f = 0$$



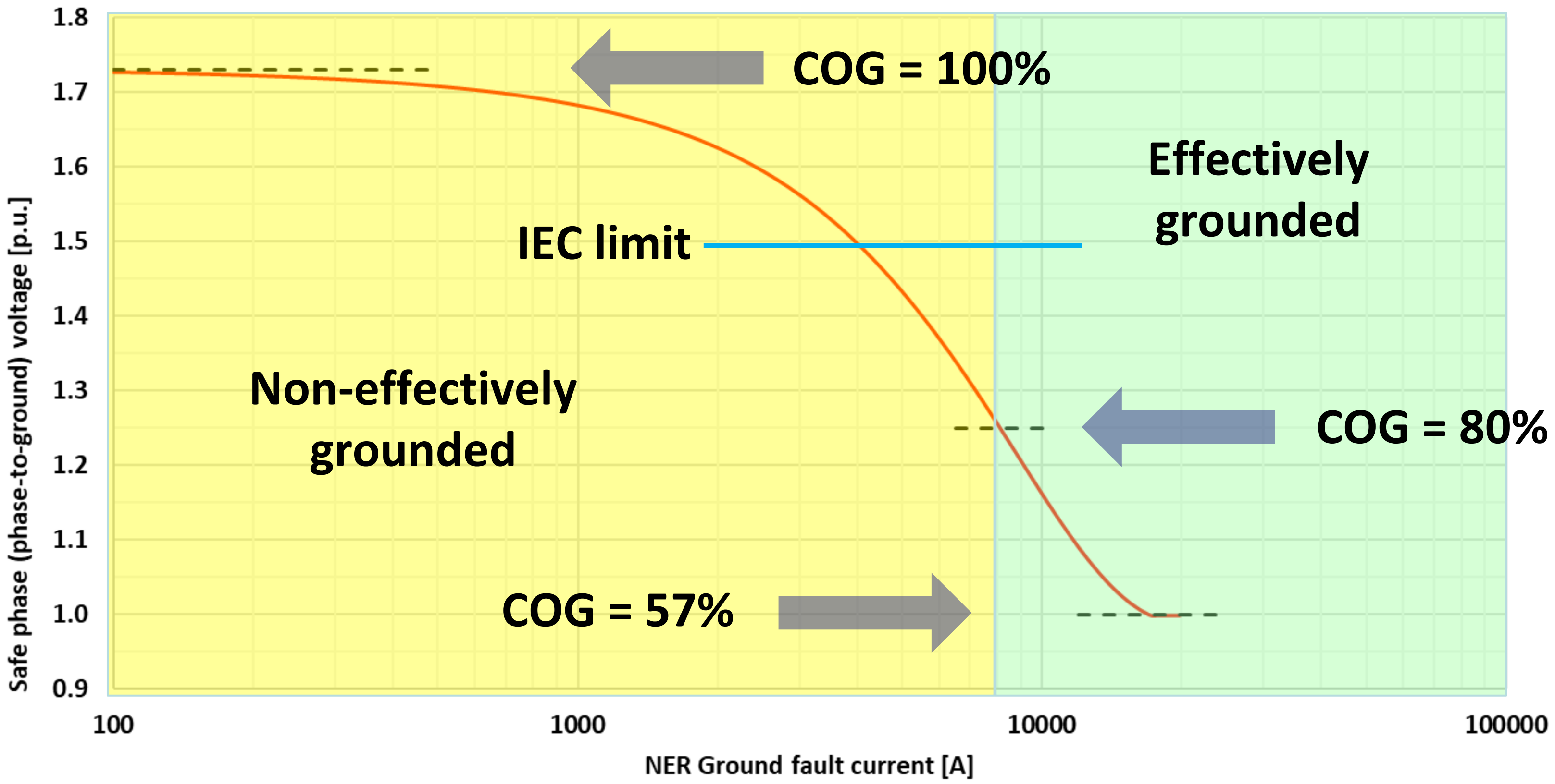
[IEC 60071-2 Insulation coordination - Application guidelines]

Damp overvoltages: TOV - Classes of grounding - @IEEE

Class of grounding	a specific range or **degree of grounding**, e.g., **effectively and non-effectively**.
Ground fault factor (GFF)	the **ratio** of the highest **phase-to-ground** power frequency voltage **on an unfault-ed phase** during a line-to-ground fault **to the phase-to-ground** power-frequency voltage **without the fault**.
Coefficient of grounding (COG)	the **ratio**, of the highest root-mean-square **(rms) line-to-ground** power-frequency voltage **on a sound phase**, at a selected location, during a fault to ground affecting one or more phases **to the line-to-line** power-frequency voltage that would be obtained at the selected location **with the fault removed**.

[IEEE C62-92.1-2016 Neutral Grounding in Electrical Utility System - Part I Introduction]

Damp overvoltages: TOV - Classes of grounding - @IEEE



Damp overvoltages: TOV during LG fault - sizing

Rated voltage factor: multiplying factor to be applied to the rated primary voltage

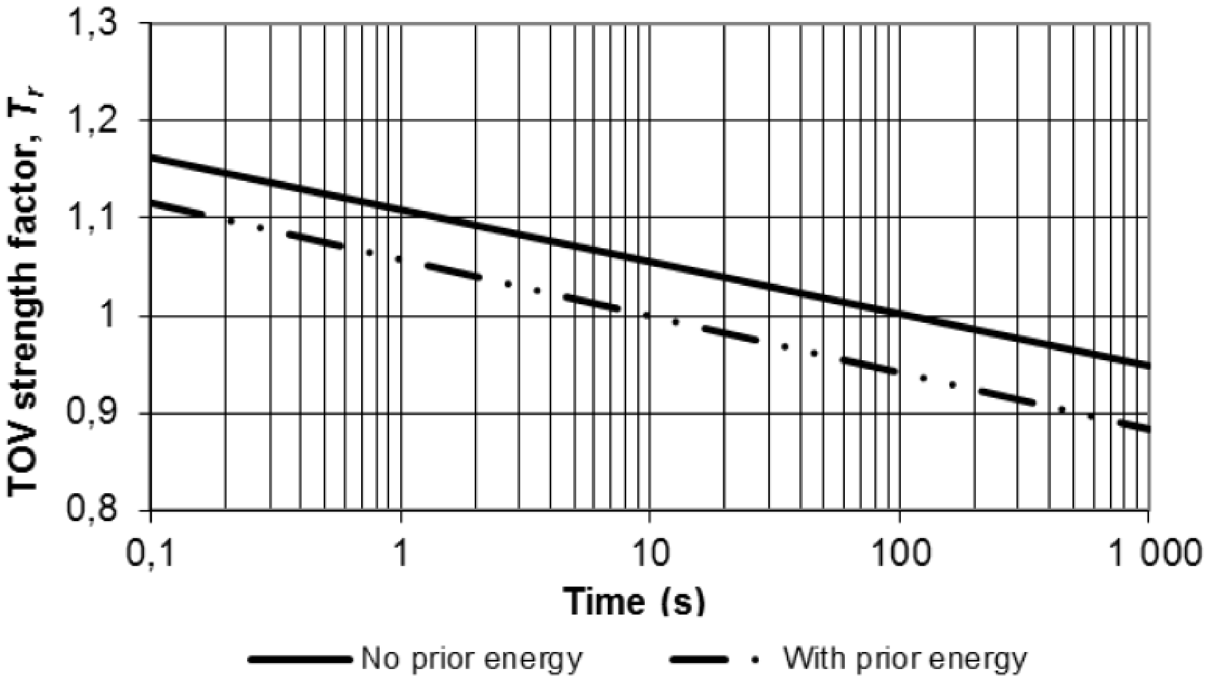
Table 304 – Standard values of rated voltage factors

Rated voltage factor	Rated time	Method of connecting the primary winding and system earthing conditions
1,2	Continuous	Between phases in any network Between transformer star-point and earth in any network
1,2	Continuous	Between phase and earth in an effectively earthed neutral system (IEC 61869-1:2007, 3.2.7a)
1,5	30 s	
1,2	Continuous	Between phase and earth in a non-effectively earthed neutral system (IEC 61869-1:2007, 3.2.7b) with automatic earth-fault tripping
1,9	30 s	
1,2	Continuous	Between phase and earth in an isolated neutral system (IEC 61869-1:2007, 3.2.4) without automatic earth-fault tripping or in a resonant earthed system (IEC 61869-1:2007, 3.2.5) without automatic earth-fault tripping
1,9	8 h	

[IEC 61869-3 Instrument transformers - Additional requirements for voltage transformers]

Damp overvoltages: TOV during LG fault - sizing

Surge arresters selection are influenced by TOV during LG fault



[IEC 60099-5 Surge arresters - Selection and application recommendations]

Different Earthing Methods (PRO / CONS)

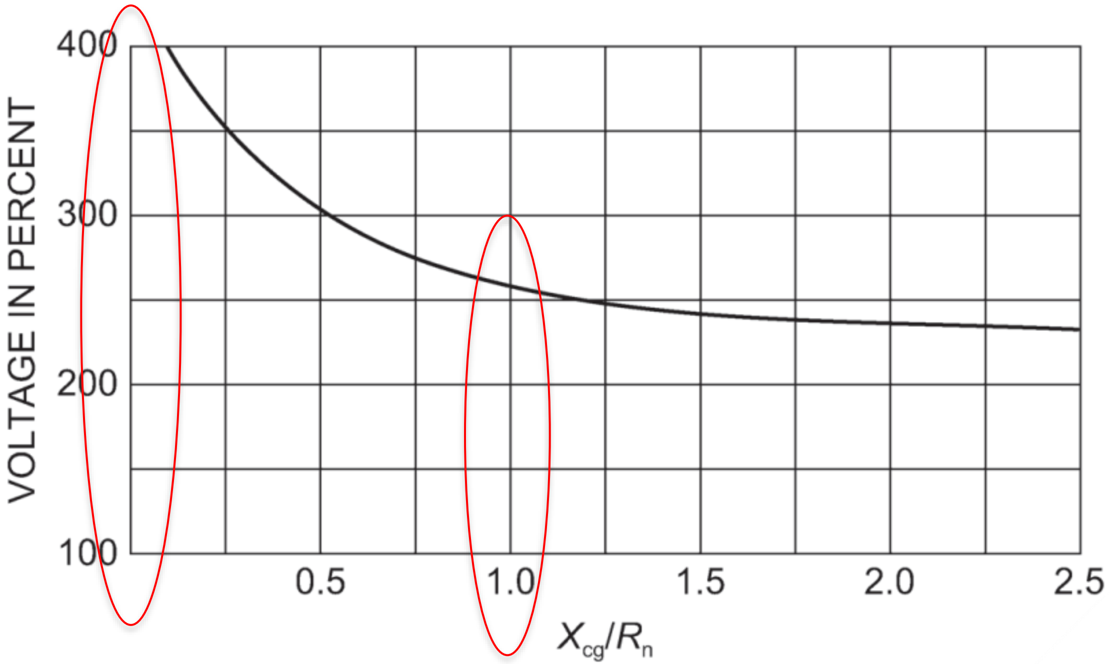
	Isolated neutral	Solidly earthed (neutral)	Resistance earthed (neutral)	Resonant earthed
Fault current (damage)				
Transient overvoltages / Arcing grounds faults				
Temporary overvoltages (TOV)	At phase-to-phase	At phase-to-ground	At phase-to-phase	At phase-to-phase
Reliable protection				

Transient overvoltages

Damp overvoltages: Transient Overvoltages

Transient line-to-ground voltage for any number of restrike

Ungrounded



C_g = capacitance of all three phases to ground (3 C_o)

X_{cg} = $1/2\pi fC_g$, f – operating frequency

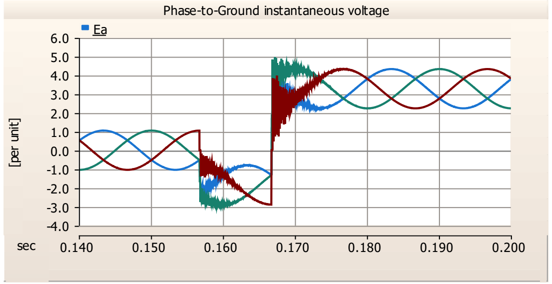
R_n = effective neutral resistance

[IEEE C62-92.2 Neutral Grounding in Electrical Utility System - Part II Grounding of synchronous generator systems]

Damp overvoltages: Transient Overvoltages

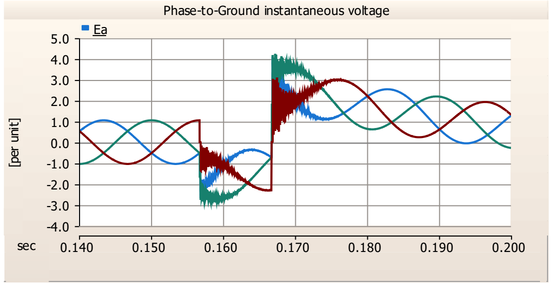
$I_R / I_c = 0$

$E_{peak} = 4.9$ p.u.



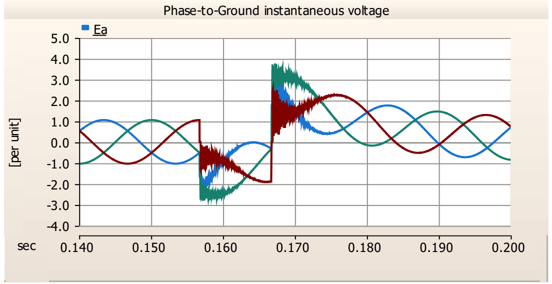
$I_R / I_c = 0.125$

$E_{peak} = 4.2$ p.u.



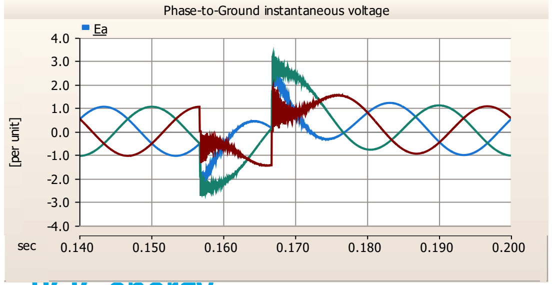
$I_R / I_c = 0.25$

$E_{peak} = 3.7$ p.u.



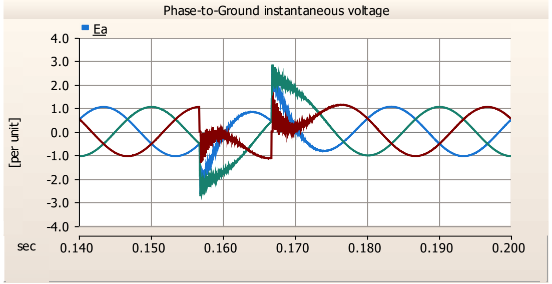
$I_R / I_c = 0.5$

$E_{peak} = 3.2$ p.u.



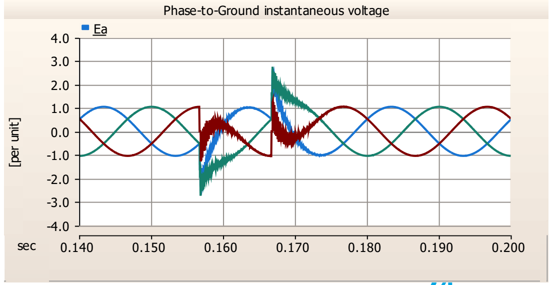
$I_R / I_c = 1$

$E_{peak} = 2.8$ p.u.

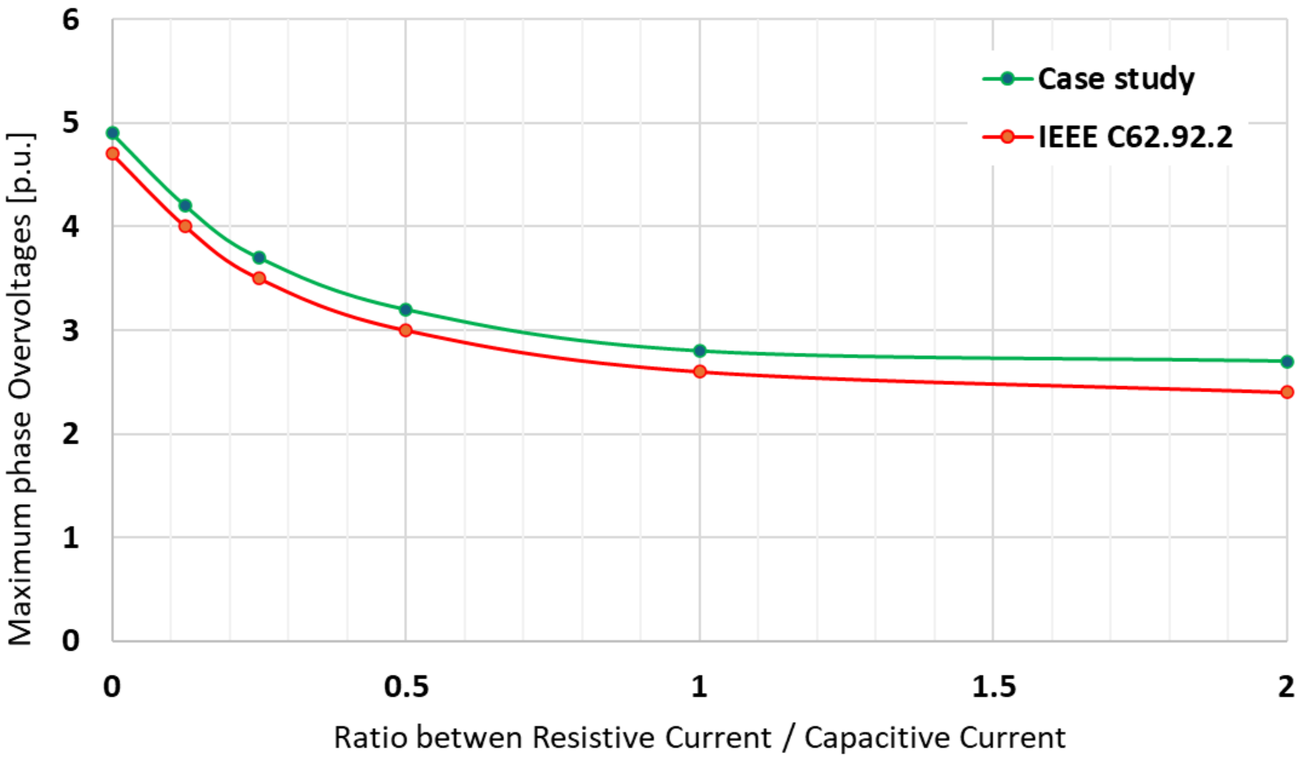


$I_R / I_c = 2$

$E_{peak} = 2.7$ p.u.



Damp overvoltages: Transient Overvoltages



[IEEE C62-92.2 Neutral Grounding in Electrical Utility System - Part II Grounding of synchronous generator systems]

Damp overvoltages: Transient Overvoltages

In an ungrounded system, it is possible for destructive transient overvoltages to occur throughout the system during restriking ground faults. These overvoltages, which can be several times normal in magnitude, result from a resonant condition being established between the inductive reactance of the system and the distributed capacitance to ground. This phenomenon is discussed in detail by Beeman. Experience has proved that these overvoltages may cause failure of insulation at multiple locations in the system, particularly at motors. Transient overvoltages from restriking ground faults are the main reason why ungrounded systems are no longer recommended and grounded systems of some form are the predominant choice. To reduce transient overvoltages during restriking ground faults, one should ground the system using either solid or impedance grounding as indicated in Figure 1-4.

[IEEE 142 Grounding of Industrial and Commercial Power Systems 2007]

Damp overvoltages: Transient Overvoltages

For high impedance earthing, the zero-sequence earth fault current **should not be less than** the system capacitive charging current in order to maintain appropriate insulation coordination and limit transient over voltages.

[IEC 60076-25 Power transformers - Neutral grounding resistors]

Damp overvoltages: Transient Overvoltages

Sufficient damping to reduce transient overvoltages **to safe levels** can be achieved with a **properly sized resistor**.

This condition can be met by (equivalent terms):

- to make the resistive component of ground-fault **current equal to or greater** than the capacitive component $I_R \geq I_C$
- to make the **resistor ohms equal to or less** than the ohmic value of the three-phase capacitance-to-ground $R_{NER} \leq X_C$
- to shift the **phase angle of ground-fault current** to less than 45˚ $\phi_{fault} \leq 45^\circ$

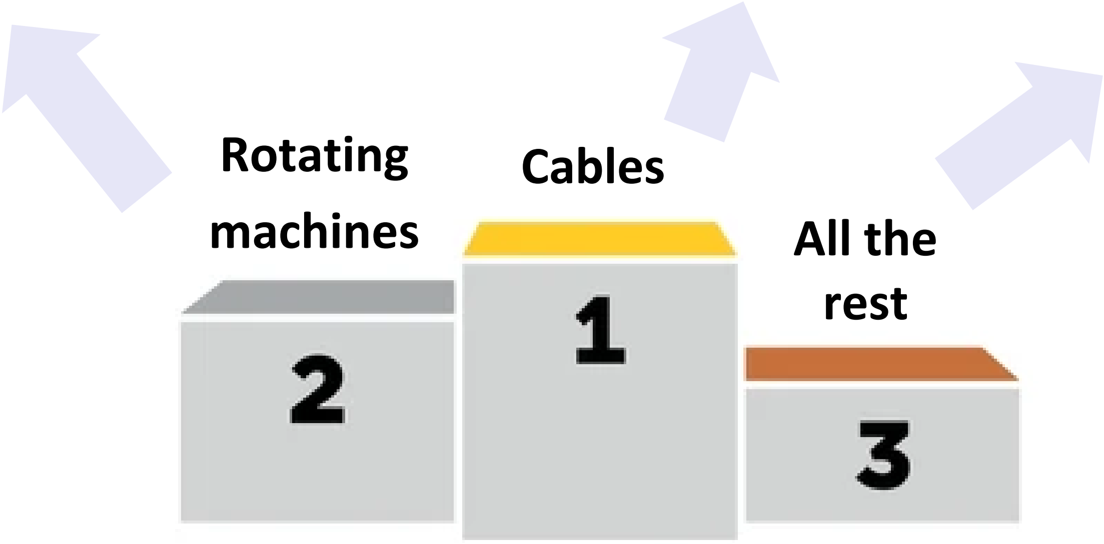
Damp overvoltages: Predict capacitive currents, @11kV, 50Hz

Synch. / Asynch.
avg. 1 A/each

Cable
avg. 2 A/km

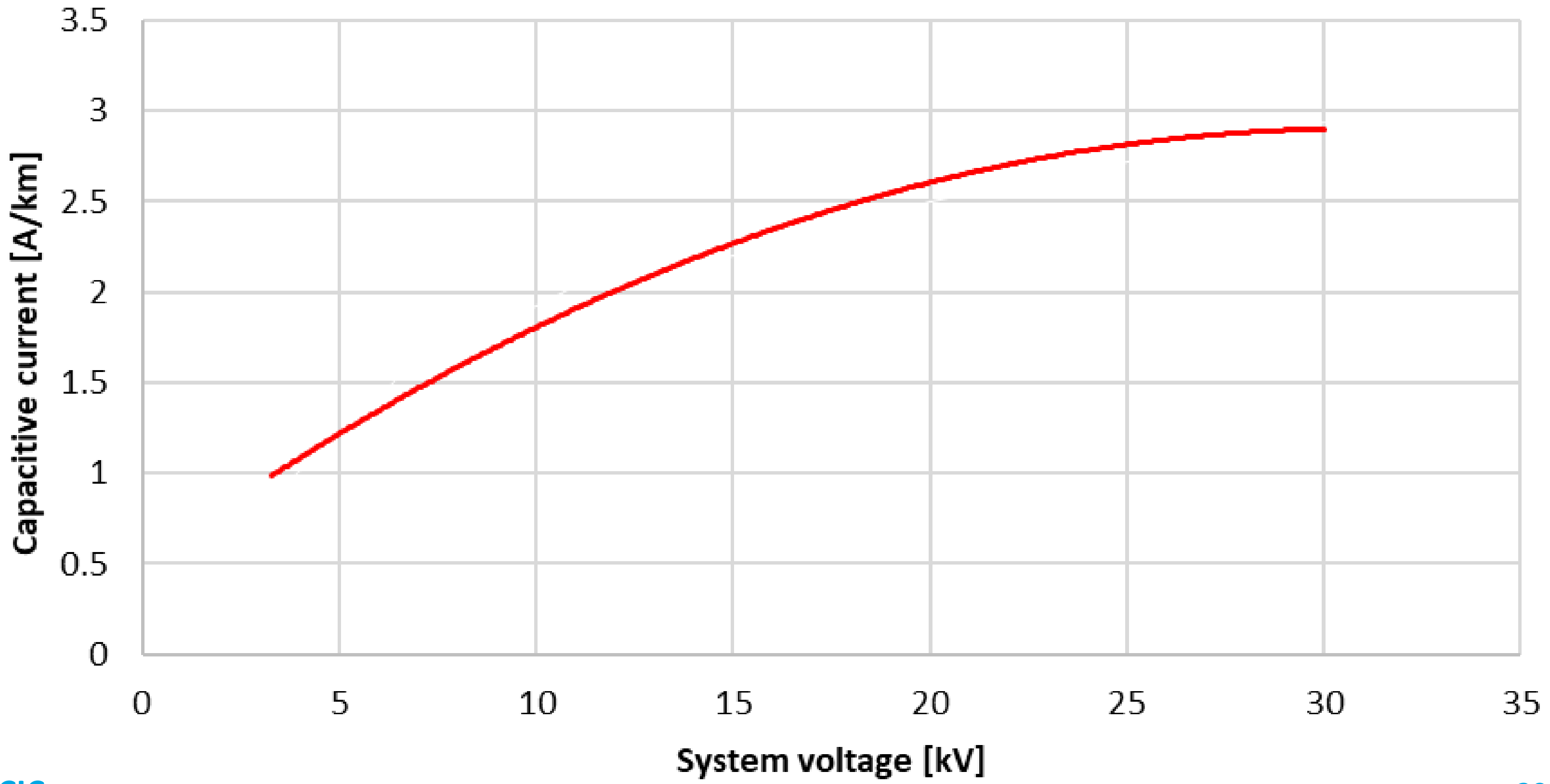
Transformers
avg. <0.1 A/each

Others
CB, CT, VT, DS, BB
avg. <n mA/each



$$I_C = \sqrt{3} \cdot \omega \cdot C \cdot V = 3 \cdot \omega \cdot C \cdot E$$

Damp overvoltages: Predict capacitive currents - Cables , @50Hz



Damp overvoltages: Predict capacitive currents - Cables

Simplified method (CEI 0-16) for 50 Hz

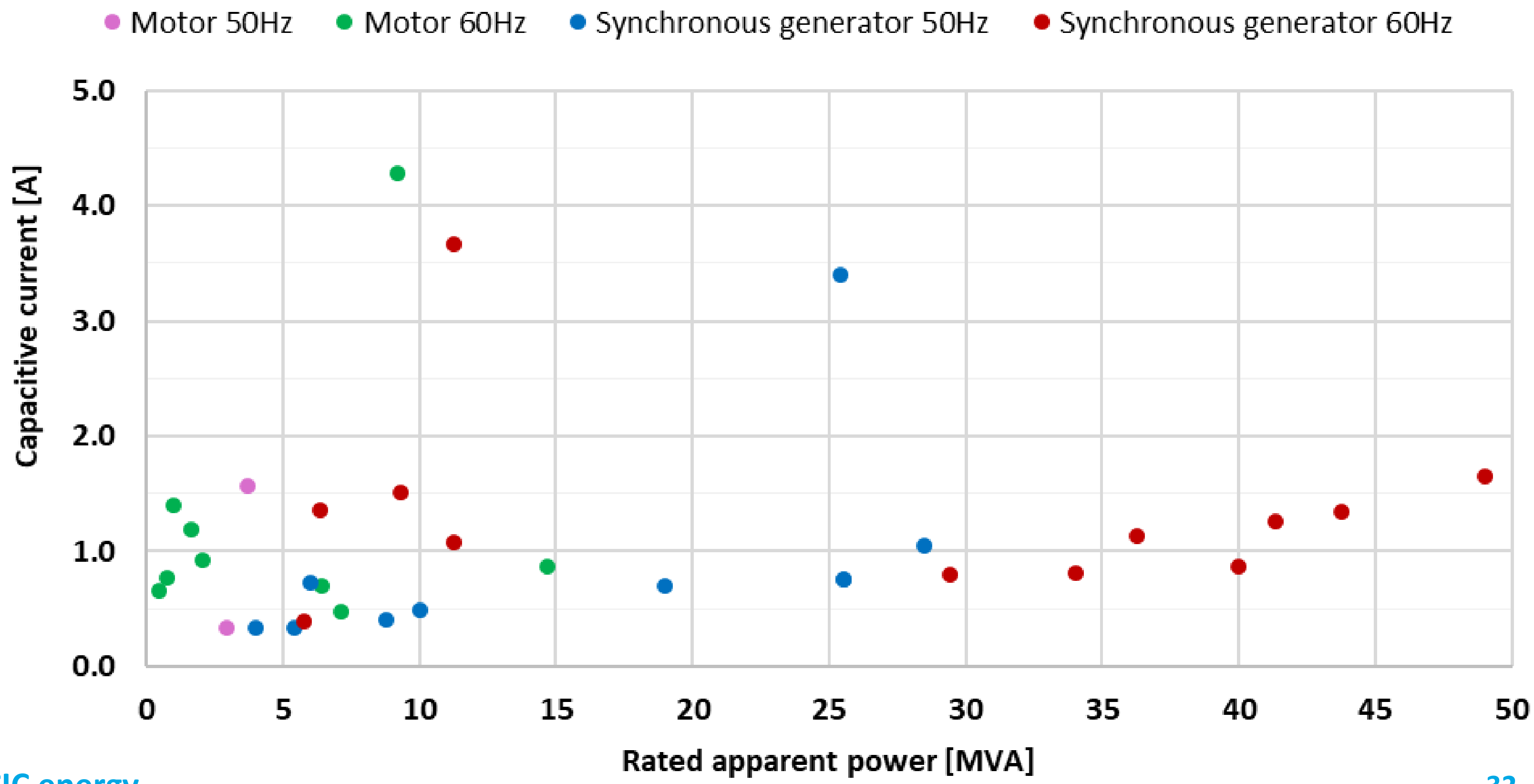
$$I_C = kV \cdot (0.003 \cdot km_{OHL} + 0.2 \cdot km_{cable})$$

where:

- I_C capacitive current in Amps
- kV voltage in kV
- km_{OHL} length in km of Overhead Lines
- km_{cable} length in km of Cables

[CEI 0-16 Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company]

Damp overvoltages: Predict capacitive currents - Rotating mac.



Different Earthing Methods (PRO / CONS)

	Isolated neutral	Solidly earthed (neutral)	Resistance earthed (neutral)	Resonant earthed
Fault current (damage)				
Transient overvoltages / Arcing grounds faults	High / Likely	Not excessive / Unlikely	Not excessive / Unlikely	Not excessive / Unlikely
Temporary overvoltages (TOV)	At phase-to-phase	At phase-to-ground	At phase-to-phase	At phase-to-phase
Reliable protection				

Limit damages

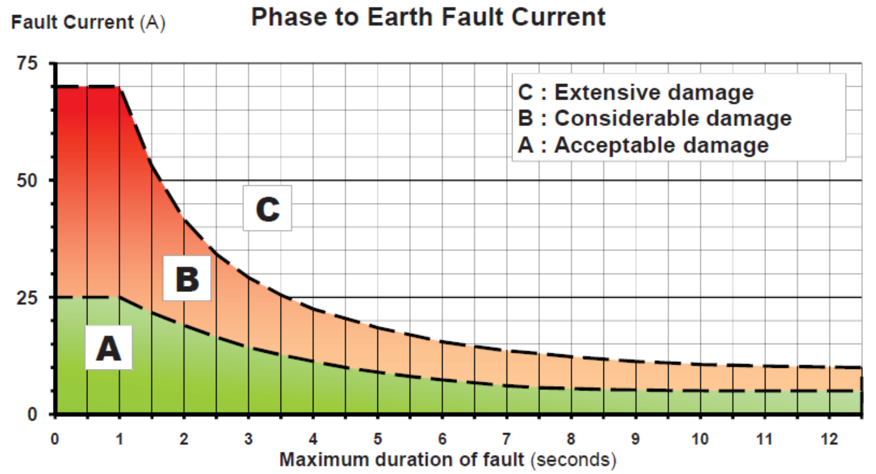
Limit damages and disturbances: Withstand limits

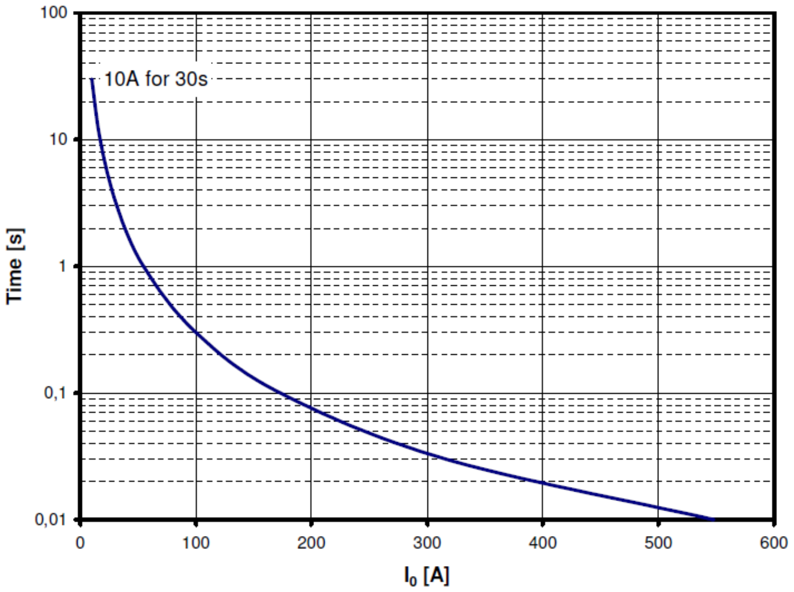
Key points:

- Rotating machines have **limited withstand capability** for internal ground fault
- Depends on fault **current** and fault **duration**
- Generated **energy** is proportional to I^2R (R = fault resistance neither constant nor linear)
- Limiting damages enable repairs rather than replace

Limit damages and disturbances: Withstand limits

Synchronous generator examples:





I_0 [A] Ground fault current over neutral point to earth

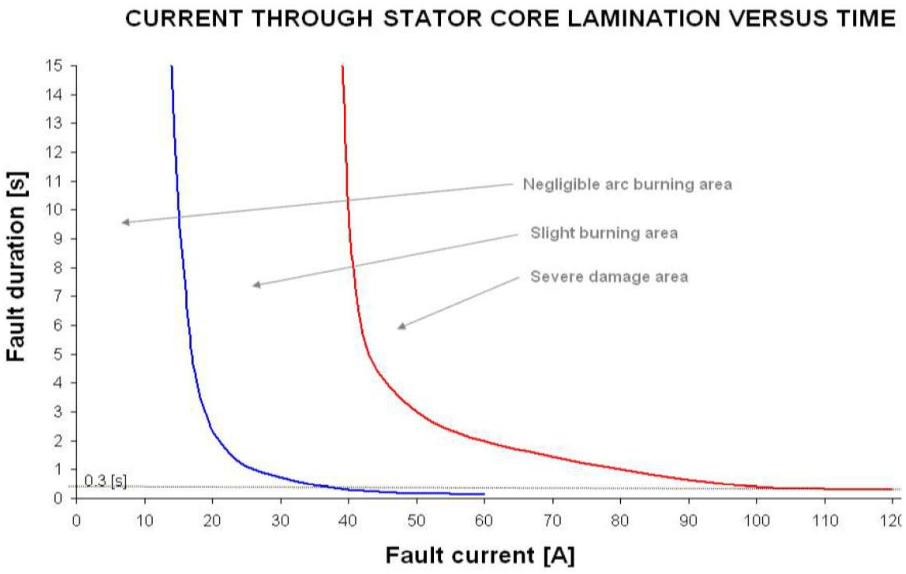
Time [s] Limitation time for I_0 to prevent damage from stator iron core

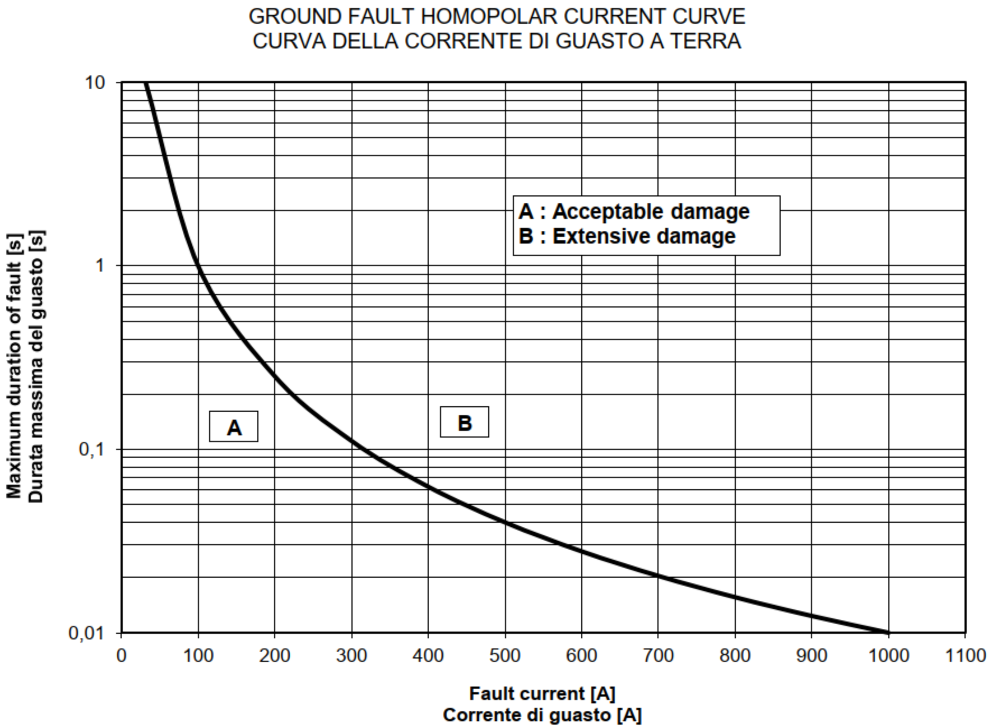
Diagram basis is $I^2 * t$ = const.; 10 A for 30 s is Siemens standard for dimensioning earthing.

When exceeding limitation curve, stator iron is endangered melting in the fault region.

Limit damages and disturbances: Withstand limits

Induction motor examples:



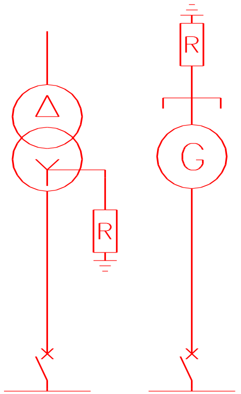


Different Earthing Methods (PRO / CONS)

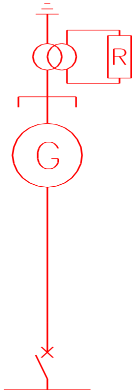
	Isolated neutral	Solidly earthed (neutral)	Resistance earthed (neutral)	Resonant earthed
Fault current (damage)	**Usually very low**	**~ 3phase fault**	**Limited**	**~ zero / Limited**
Transient overvoltages / Arcing grounds faults	High / Likely	Not excessive / Unlikely	Not excessive / Unlikely	Not excessive / Unlikely
Temporary overvoltages (TOV)	At phase-to-phase	At phase-to-ground	At phase-to-phase	At phase-to-phase
Reliable protection				

Resistive earthing methods

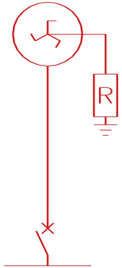
Methods to achieve Resistance earthing



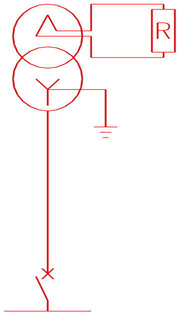
Direct connection to the **star-point**



Connection to the star-point through a **single-phase power transformer**

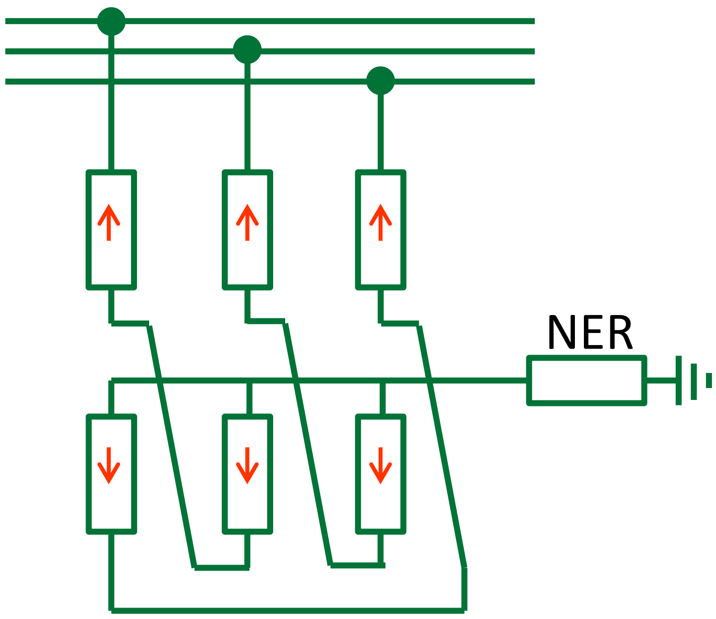


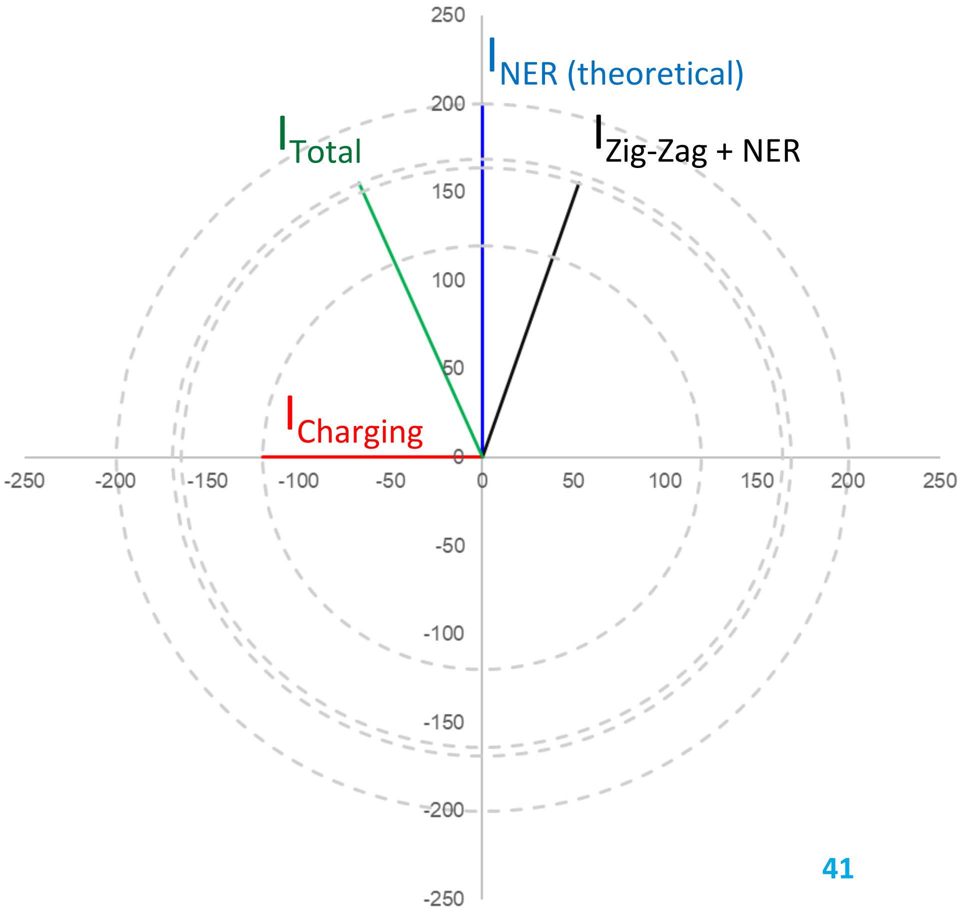
Direct connection of a **zig-zag reactance** to the artificial star-center



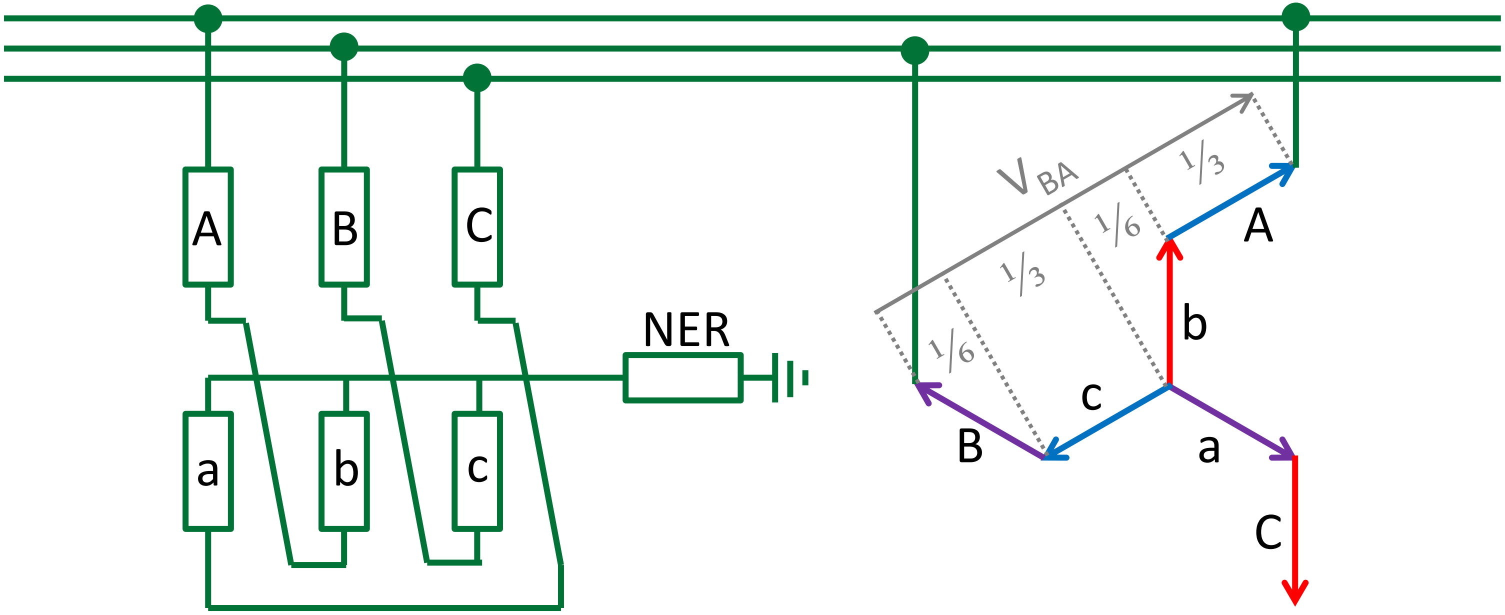
Indirect connection with primary three-phase transformer in star connected to earth and secondary in open delta loaded with a resistor

Homopolar generator impedance





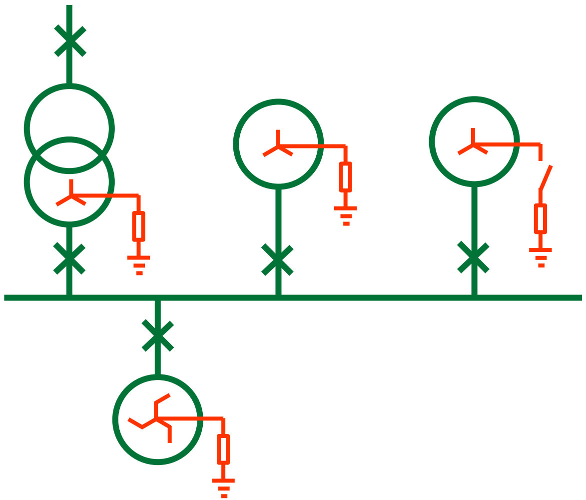
Sizing of zig-zag transformers, 1.73 benefits



Methods to achieve Resistance earthing, multiple sources

Key aspects:

- variable / fixed ground fault current based on the configuration
- Suitable for each configuration:
  - adequate I_R / I_C ratio
  - maintain current within the withstand capabilities
  - allows reliable protection (detection & coordination)



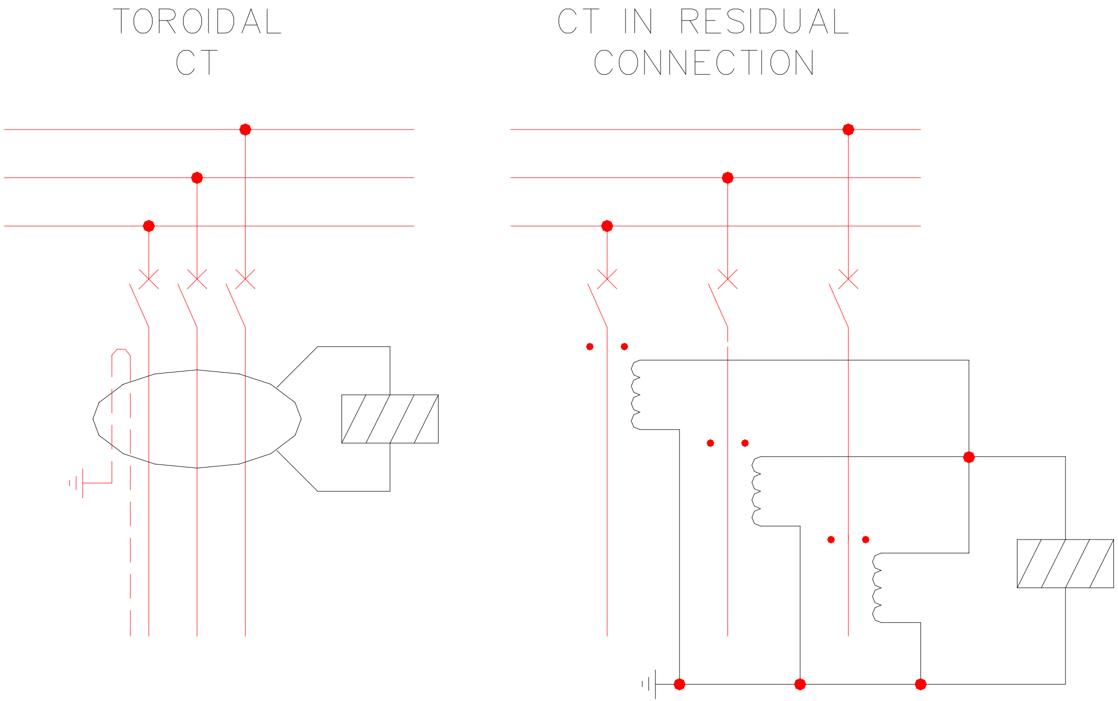
Simple, reliable and selective protection system

Provide simple, reliable and selective protection system

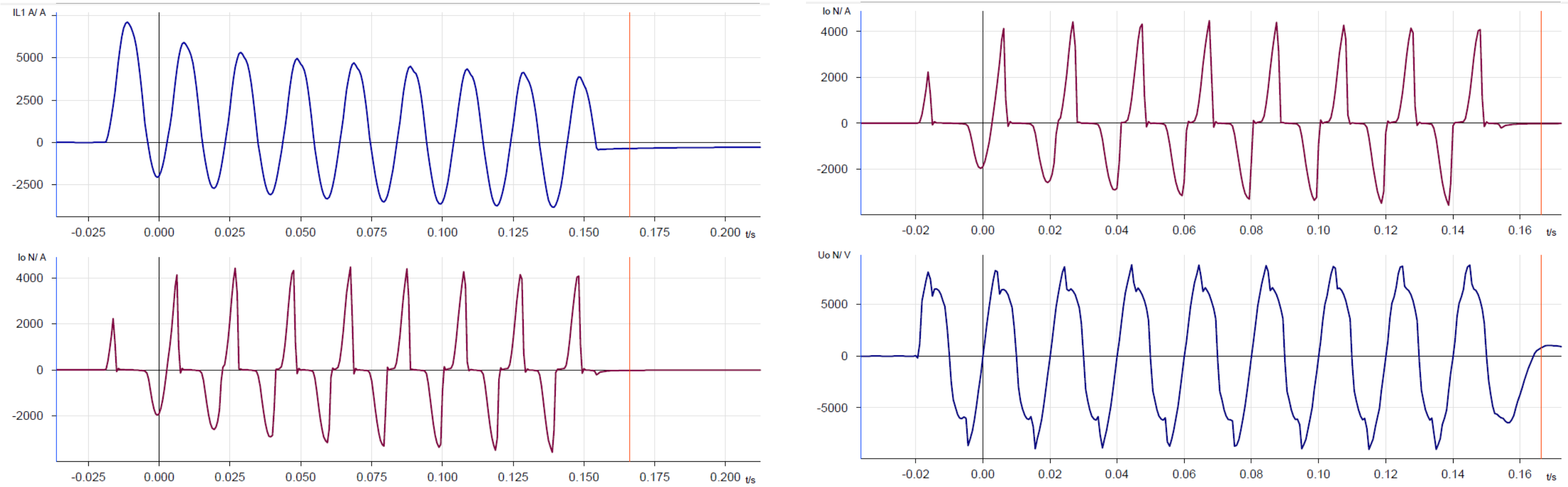
Key aspects:

- the protection system is the **combination** of CT, VT, wiring, relay, breaker, fuse, contactor, …
- protections depends on **CT** and VT **position.**
- adequate **protective functions** and **proper settings**.
- **interoperability** across the configurations, with a single setting group (optimized solution).

Ground fault current detection



Unproper use of Ring CT, not sized for solidly earthed

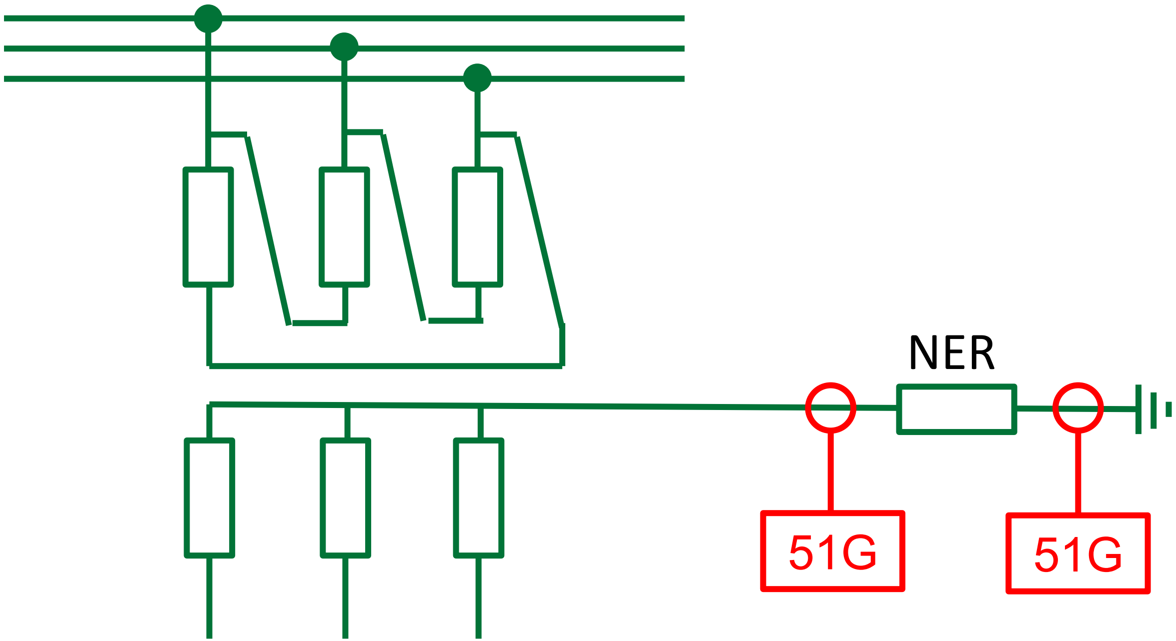


Compromise of grounding current vs protection system

Compromises for high-impedance earthing system (low earthing current):

- requirement of Ring CT:
  - uncovered zone, feeder fault "as busbar fault"
  - not possible to install everywhere (Incomer bus-duct / Bus-tie) *remotization*
  - n. of zero sequence current input in the relays (star-point plus feeder)
  - adequate windings / installation concerns *good installation*
- discriminate between safe feeder and faulted feeder *directional protection*
- enable protection below NER continuous current

NER CT position



Protective ANSI C37-2 codes, definitions

Overcurrent ANSI codes:

- 50 overcurrent of instantaneous type
- 50TD overcurrent of definite time (with a time delay)
- 51 overcurrent of inverse (dependent) time type
- 67 directional overcurrent
- 59 overvoltage

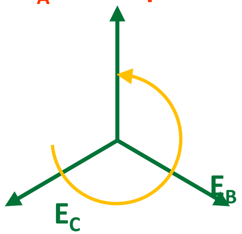
Ground fault protection suffix:

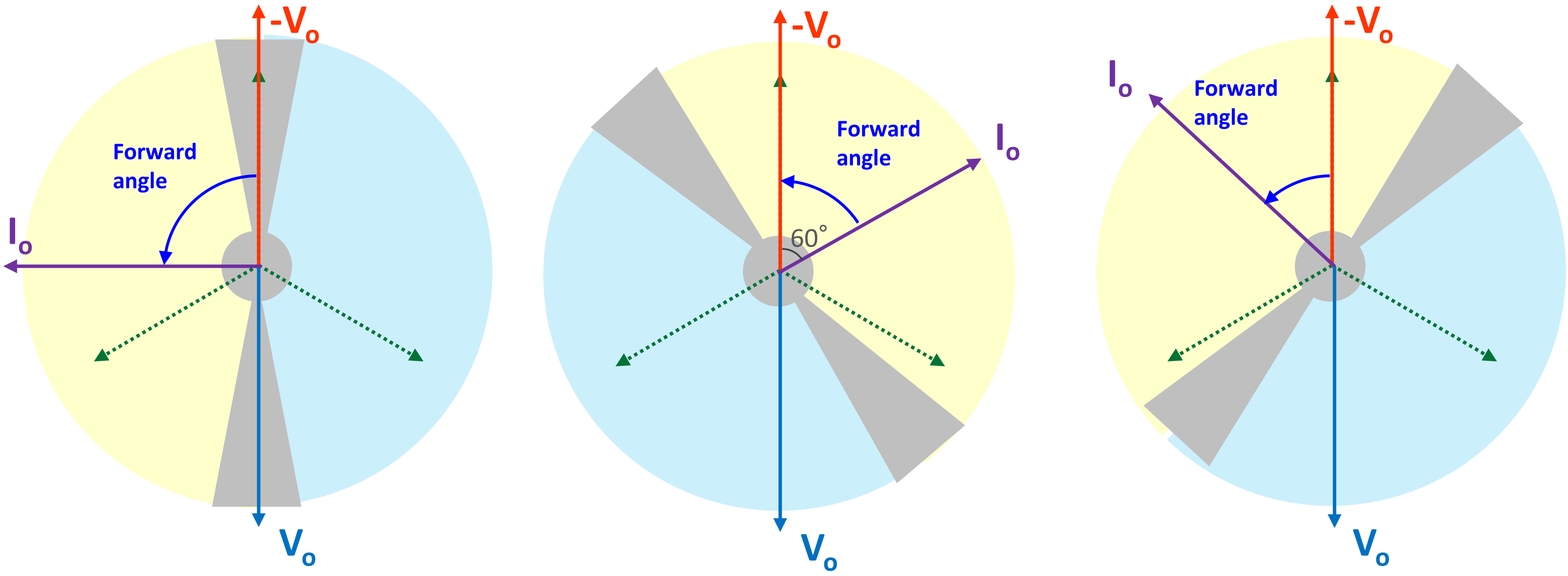
- N connected in residual into the line CT's (Neutral)
- G connected in a Ground (zero sequence) circuit (star point, ring CT, etc.)

[IEEE C37-2 Standard Electrical Power System Device Function Numbers]

67G / 67N

Directional ground overcurrent angles





Feeder protection, 50G or 67G

Specific situations that requires 67G:

- 67G allows to not pick-up for **charging current**
  - with 67G it is possible to lower the settings, independently from cable charging capacity, increasing protection sensibility (allows coordination with DSO setting)
  - it is important where downstream there are long cables, otherwise 50G can properly fit
  - it make sense where grounding current is limited (vs charging current).
- in case of **multiple ground fault sources**, 67G may become essential
- Require **VT and voltage measurement**:
  - stabilize protection
  - is dependent from VT suitability and proper check of polarities (CT and VT)

Provide simple, reliable and selective protection system

It is necessary:

- Select **earthing method and current** considering possibility to detect ground fault condition
- Provide adequate CT / Ring CT - accept compromise situations
- Select carefully protective functions and detection (and of course AFTER calculate right settings):
  - 50G or 51G
  - N or G
  - 50G or 67G
- Enable coordination (grading time, 59N)

Different Earthing Methods (PRO / CONS)

	Isolated neutral	Solidly earthed (neutral)	Resistance earthed (neutral)	Resonant earthed
Fault current (damage)	Usually very low	~ 3phase fault	Limited	Nearly zero / or Limited
Transient overvoltages / Arcing grounds faults	High / Likely	Not excessive / Unlikely	Not excessive / Unlikely	Not excessive / Unlikely
Temporary overvoltages (TOV)	At phase-to-phase	At phase-to-ground	At phase-to-phase	At phase-to-phase
Reliable protection	**Complex**	**Satisfactory**	**Satisfactory**	**Satisfactory with special provisions**

Takeaways & Conclusions

Takeaways - Overall summary conclusions

- Limit TOV (for medium voltage generally is not the driving factor) I_{NER} ~ kAs
- Limit Transient overvoltages and Arcing grounds faults $I_{NER} > I_c$
- Limit rotating machines damages (only in such case apply) $I_{NER} <$ ...A *
- Limit Ground Grid current (where a concern) $I_{NER} <$ ...
- Detectable by Phase CT (no Ring CT) $I_{NER\ Permanent} > I_{set} \geq 10\%$ Phase CT
- Require 67G function $I_{NER} > (1.5\ min\ *) \times I_{set} \geq (1.5\ min\ *) \times I_{c\ @feeder}$ *

** case-by-case*

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Q&A

Thanks for your attention

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SELECTY
selectivity art in protection setting calculation