Short-circuits in ES

Short-circuit:

- cross fault, quick emergency change in ES
- the most often fault in ES
- transient events occur during short-circuits

Short-circuit formation:

- fault connection between phases or between phase(s) and the ground in the system with the grounded neutral point

Main causes:

- insulation defect caused by overvoltage
- direct lightning strike
- insulation aging
- direct damage of overhead lines or cables

Short-circuit impacts:

- total impedance of the network affected part decreases
- currents are increasing => so called short-circuit currents I_k
- the voltage decreases near the short-circuit
- I_k impacts causes device heating and power strain
- problems with I_k disconnecting, electrical arc and overvoltage occurred during the short-circuit
- synchronism disruption of ES working in parallel
- communication line disturbing => induced voltages

Note: In short-circuit places transient resistances arise.

- transient resistance is a sum of electrical arc resistance and resistance of other I_k way parts (determination of exact resistances is difficult)
- current and electrical arc length is changing during short-circuit => resistance of electrical arc is also changing

- transient resistances are neglected for I_k calculation (dimensioning of electrical devices) → *perfect short-circuits*

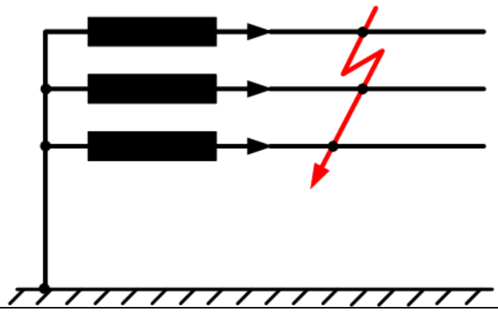
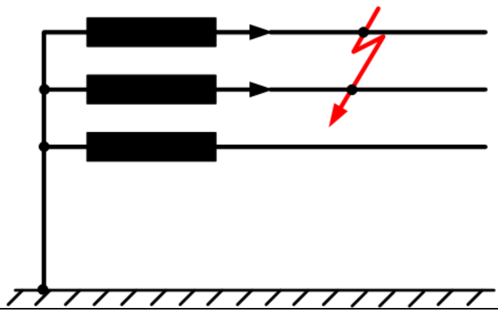
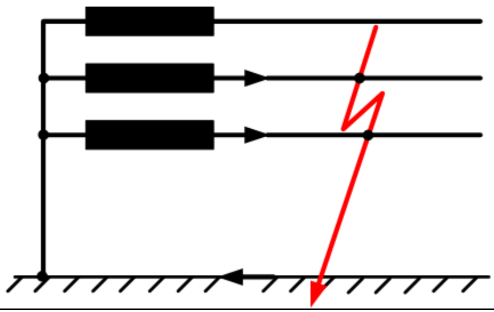
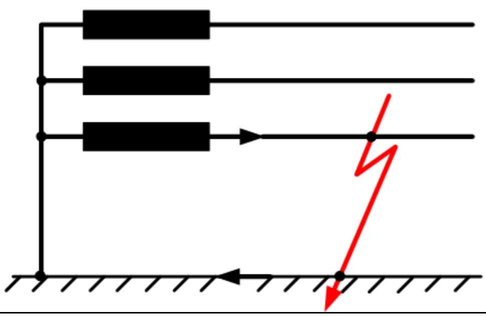
Short-circuits types

Symmetrical short-circuits:

- Three-phase short-circuit => all 3 phases are affected by short-circuit
  - little occurrence in the case of overhead lines
  - the most occurrences in the case of cable lines => other kinds of faults change to 3ph short-circuit due to electrical-arc impact

Unbalanced (asymmetrical) short-circuits:

- phase-to-phase short-circuit
- double-phase-to-ground short-circuit
- single-phase-to-ground short-circuit:
  - in MV a different kind of fault => so called *ground fault*
  - in case of ground fault in MV (insulated or indirectly grounded neutral point) => no change in LV (grounded neutral point)

Short-circuit type	Diagram	Occurrence probability (%)		
		MV	110 kV	220 kV
3ph		5	0,6	0,9
2ph		10	4,8	0,6
2ph to ground		20	3,8	5,4
1ph		*	91	93,1

Short-circuit current time behaviour

$$W_L = \frac{1}{2} L i^2$$

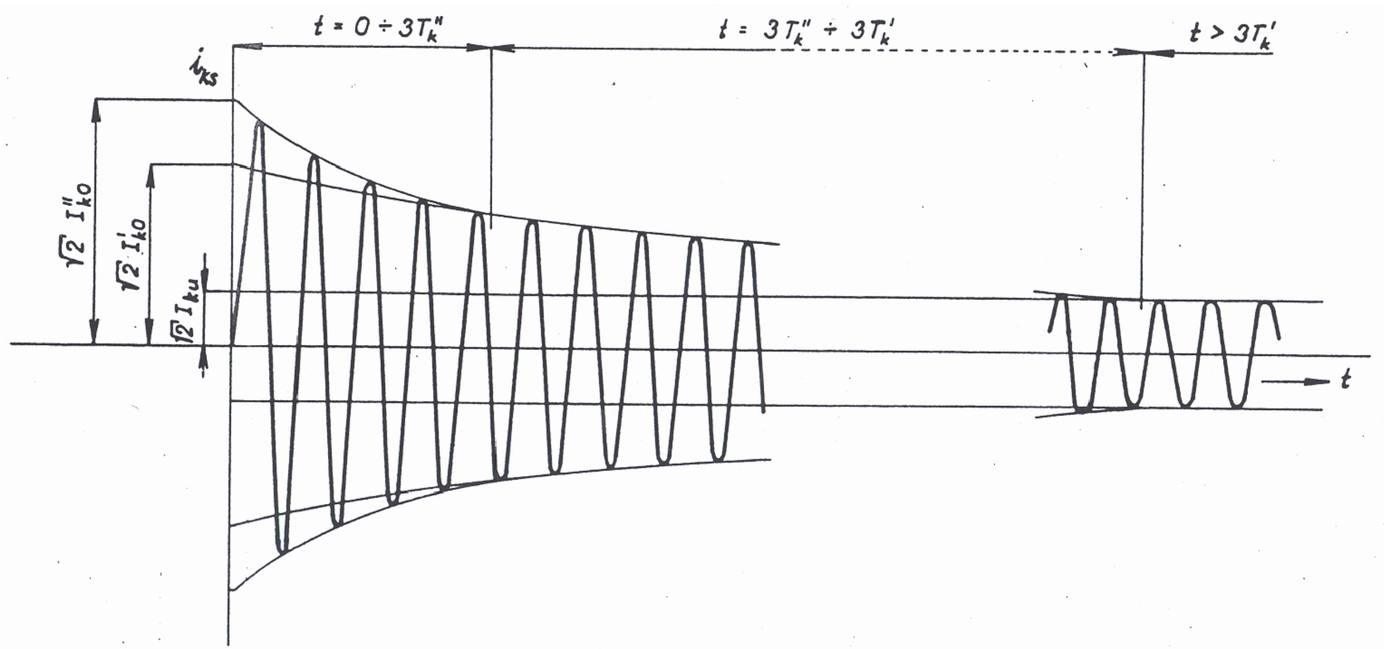
$$P = \frac{dW_L}{dt} < \infty$$ → transient event

Time behaviour: open-circuit, resistances neglected
→ reactance, current of inductive character, higher I_k values

Impact of R on I_k attributes:

- finite R values decrease short-circuit impacts
- R neglecting results in time constants prolongation $\tau = L/R$

$U = U_{max}$ in the short-circuit moment → I_k starts from zero (min. value)



Short-circuit components (f = 50 Hz):

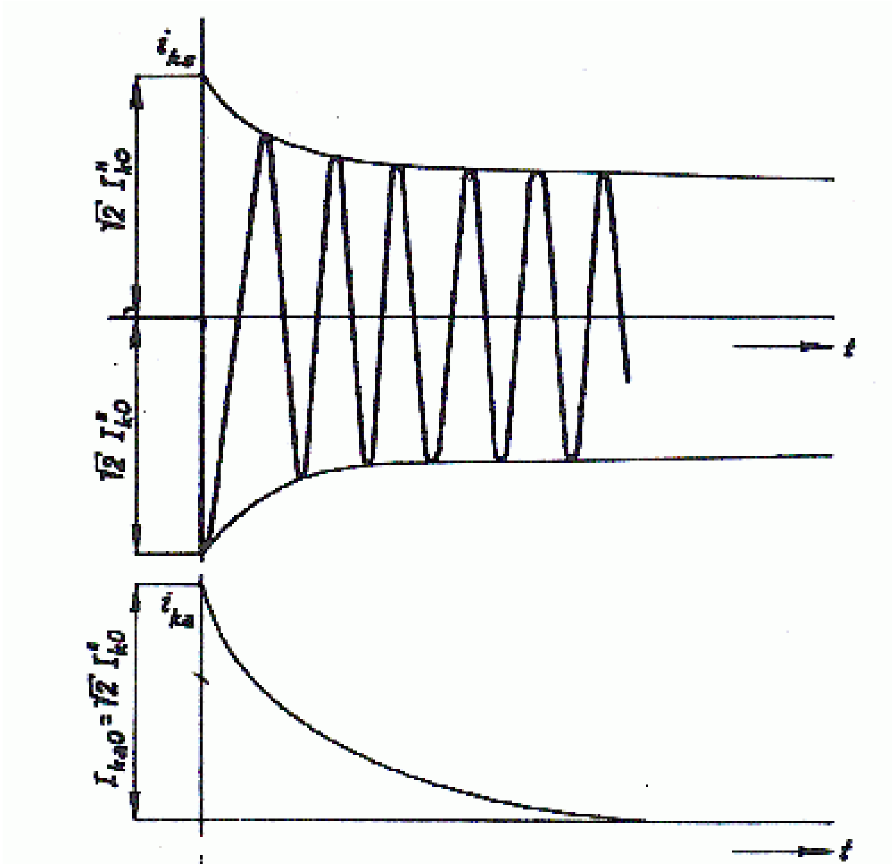
- sub-transient – exponential envelope, T_k''
- transient – exponential envelope, T_k'
- steady-state – constant magnitude

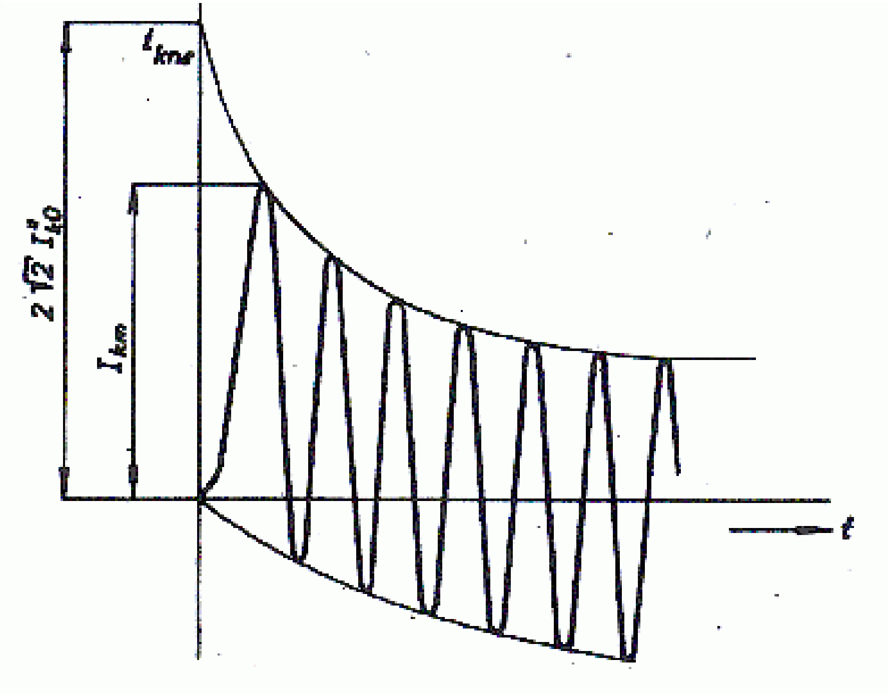
It is caused by synchronous machine behaviour during short-circuit → more significant during short-circuits near the machine.

Values

- symmetrical short-circuit current I_{ks} - steady-state, transient and sub-transient component sum, RMS value
- sub-transient short-circuit current I''_k - I_{ks} RMS value in the period of sub-transient component $t \doteq \left(0 \div 3T''_k\right)$
- initial sub-transient short-circuit current I''_{k0} - I''_k value in the moment of short-circuit origin t = 0
- transient short-circuit current I'_k - I_{ks} RMS value in the period from the sub-transient component end to the transient component end $t \doteq \left(3T''_k \div 3T'_k\right)$
- initial transient short-circuit current I'_{k0} - RMS value of the steady-state and transient component for t = 0
- steady-state short-circuit current I_{ku} - I_{ks} after transient components end $t > 3T'_k$

U = 0 in the short-circuit moment → I_k starts from max. value





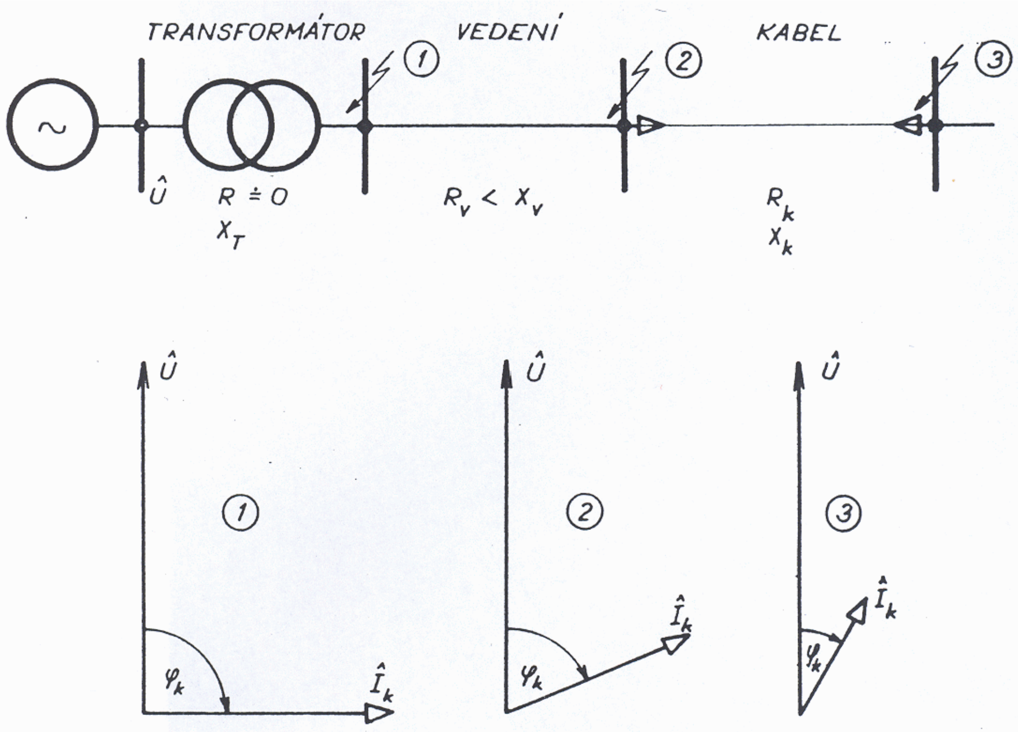
Values

- DC component I_{ka} - disappears exponentially, T_{ka}
- initial DC component I_{ka0} - I_{ka} in the moment t = 0, forced by the current continuous behaviour
- unbalanced short-circuit current I_{kns} - steady-state, transient, sub-transient and DC component sum, RMS value
- peak short-circuit current I_{km} - the first half-period magnitude during the maximal DC component

Short-circuit current power factor

$$\varphi_k = \operatorname{arctg} \frac{X_{tot}}{R_{tot}}$$

lines	overhead						cable		
U (kV)	22	110	220	400	750	1150	10	35	110
X : R	1/1	2/1	5/1	12/1	15/1	27/1	1/4	1/2	1/0,7
|Z| : X	1,41	1,12	1,02	1,01	1,005	1,00	4,1	2,24	1,22
φ_k (°)	45	64	78,7	85,2	86,2	87,9	13	26	54



Short-circuits in 3ph system

Conversion between phase values and symmetrical components

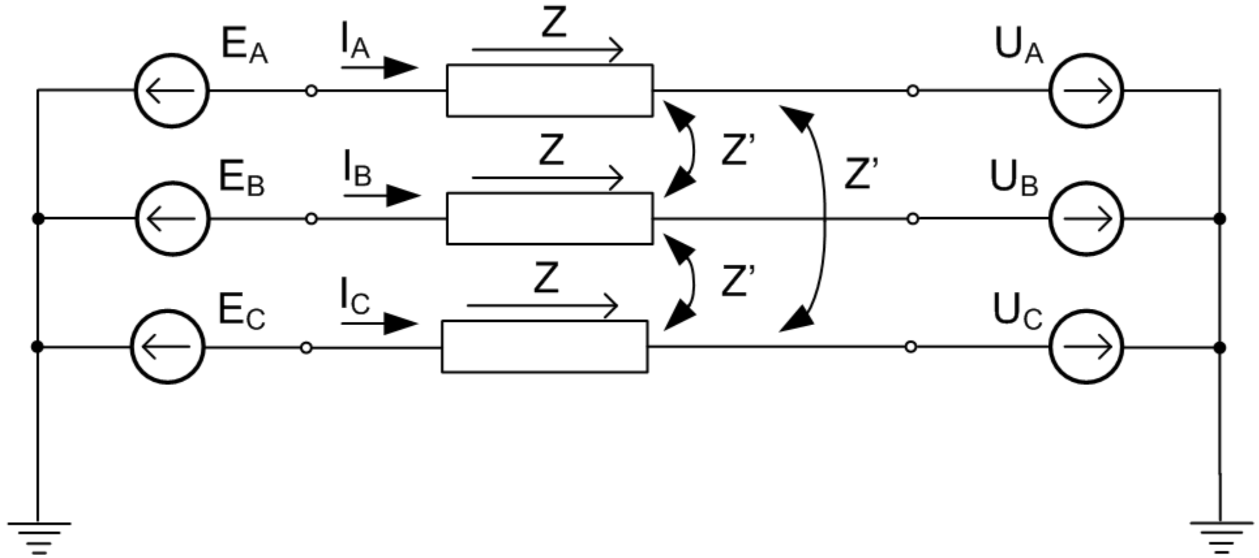
$$(U_{ABC}) = \begin{pmatrix} \hat{U}_A \\ \hat{U}_B \\ \hat{U}_C \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ \hat{a}^2 & \hat{a} & 1 \\ \hat{a} & \hat{a}^2 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix} = (T)(U_{120})$$

$$(U_{120}) = \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_A \\ \hat{U}_B \\ \hat{U}_C \end{pmatrix} = (T^{-1})(U_{ABC})$$

Impedance matrix in symmetrical components (for series sym. segment)

$$(Z_{120}) = \begin{pmatrix} \hat{Z}_1 & 0 & 0 \\ 0 & \hat{Z}_2 & 0 \\ 0 & 0 & \hat{Z}_0 \end{pmatrix} = \begin{pmatrix} \hat{Z} - \hat{Z}' & 0 & 0 \\ 0 & \hat{Z} - \hat{Z}' & 0 \\ 0 & 0 & \hat{Z} + 2\hat{Z}' \end{pmatrix}$$

3ph system during short-circuit – internal generator voltage E (or U_i)



$$(E_{ABC}) = (Z_{ABC})(I_{ABC}) + (U_{ABC})$$

Symmetrical system (independent systems 1, 2, 0)

$$\hat{E}_1 = \hat{Z}_1 \hat{I}_1 + \hat{U}_1$$

$$(E_{120}) = (Z_{120})(I_{120}) + (U_{120})$$

$$\hat{E}_2 = \hat{Z}_2 \hat{I}_2 + \hat{U}_2$$

$$\hat{E}_0 = \hat{Z}_0 \hat{I}_0 + \hat{U}_0$$

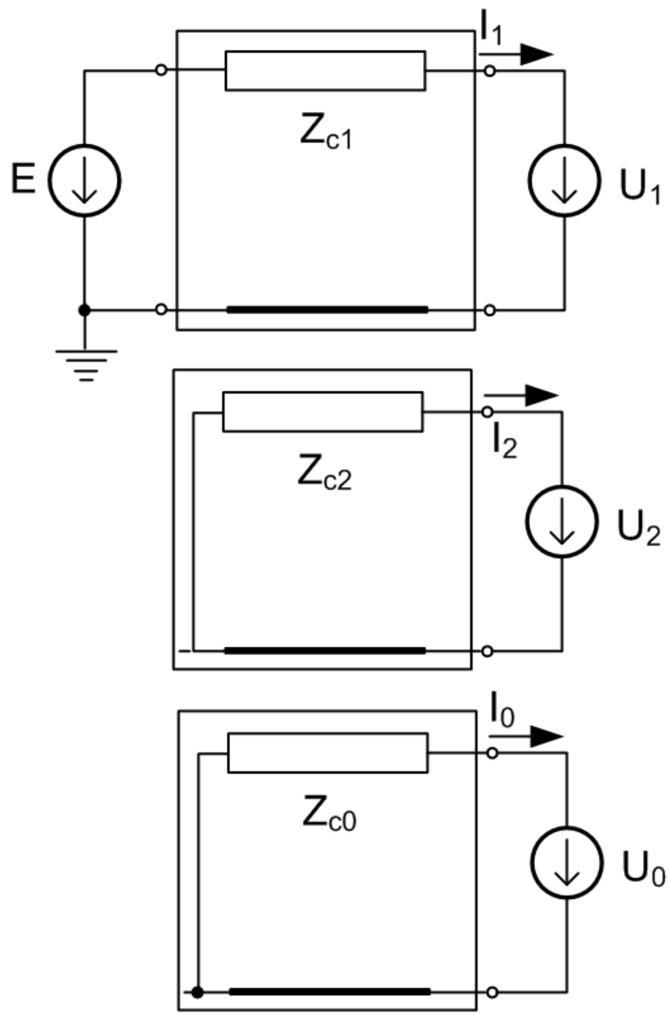
Generator symmetrical voltage → only positive sequence component
Reference phase A:

$$\left(E_{120}\right)=\left(T^{-1}\right)\left(E_{ABC}\right)=\frac{1}{3}\begin{pmatrix}1 & \hat{a} & \hat{a}^2\\ 1 & \hat{a}^2 & \hat{a}\\ 1 & 1 & 1\end{pmatrix}\begin{pmatrix}\hat{E}_A\\ \hat{a}^2\hat{E}_A\\ \hat{a}\hat{E}_A\end{pmatrix}=\begin{pmatrix}\hat{E}_A\\ 0\\ 0\end{pmatrix}=\begin{pmatrix}\hat{E}\\ 0\\ 0\end{pmatrix}$$

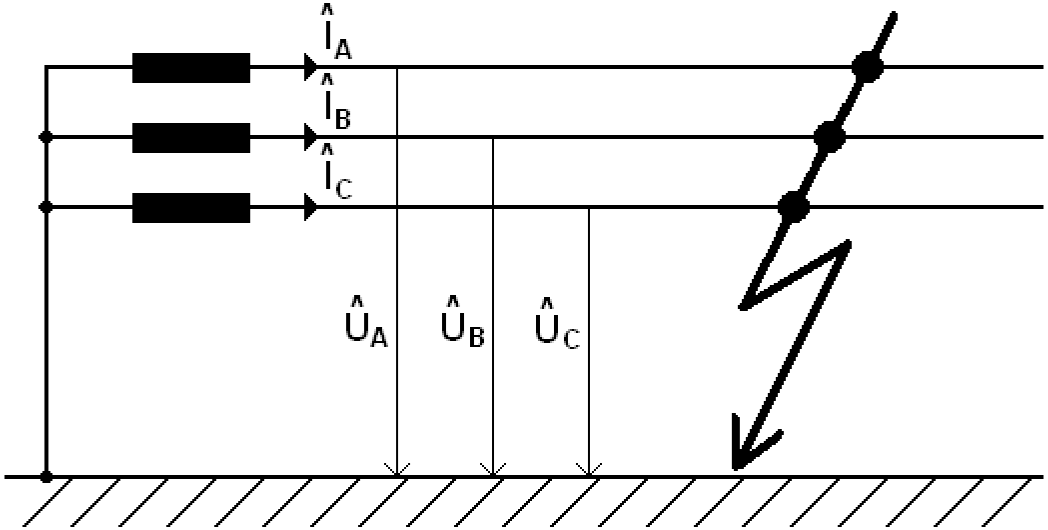
$$\begin{pmatrix}\hat{E}_1\\ \hat{E}_2\\ \hat{E}_0\end{pmatrix}=\begin{pmatrix}\hat{E}\\ 0\\ 0\end{pmatrix}=\begin{pmatrix}\hat{Z}_1 & 0 & 0\\ 0 & \hat{Z}_2 & 0\\ 0 & 0 & \hat{Z}_0\end{pmatrix}\begin{pmatrix}\hat{I}_1\\ \hat{I}_2\\ \hat{I}_0\end{pmatrix}+\begin{pmatrix}\hat{U}_1\\ \hat{U}_2\\ \hat{U}_0\end{pmatrix}$$

Negative and zero sequence are caused by voltage unbalance in the faulted place.

In the fault point 6 quantities (U_{120}, I_{120}) → 3 equations necessary to be added by other 3 equations according to the short-circuit type (local unbalance description).



Three-phase (to-ground) short-circuit



3 char. equations

$$\hat{U}_A = \hat{U}_B = \hat{U}_C = 0$$

Hence 6 equations for 6 unknowns

$$\hat{E} = \hat{Z}_1\hat{I}_1 + \hat{U}_1 \qquad 0 = \hat{U}_1 + \hat{U}_2 + \hat{U}_0$$

$$0 = \hat{Z}_2\hat{I}_2 + \hat{U}_2 \qquad 0 = \hat{a}^2\hat{U}_1 + \hat{a}\hat{U}_2 + \hat{U}_0$$

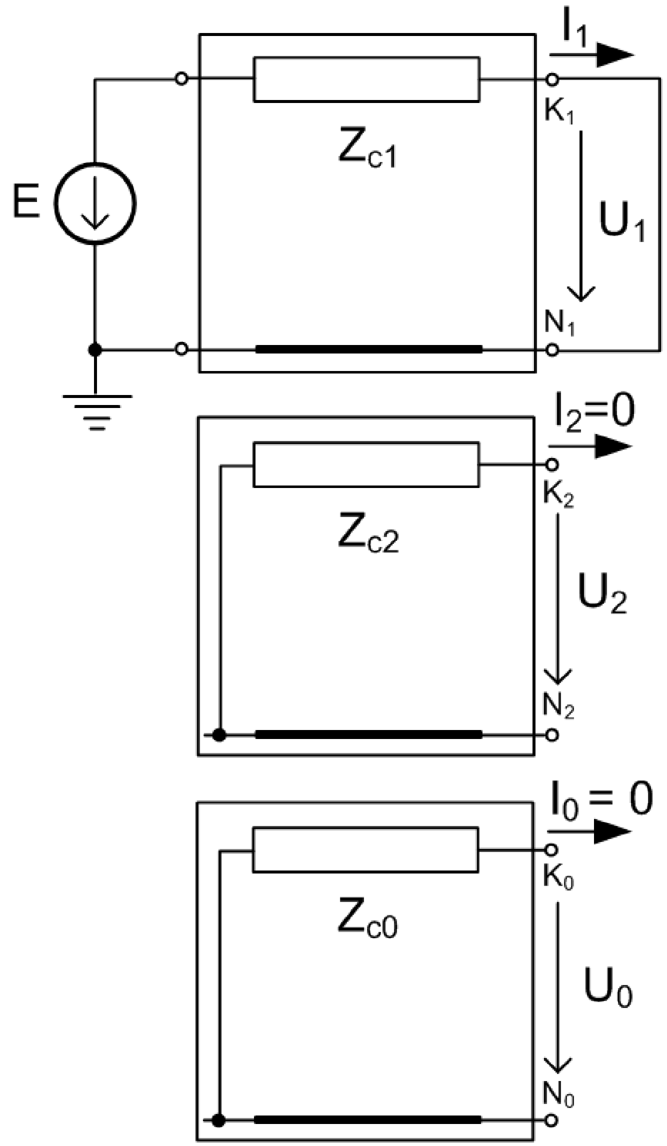
$$0 = \hat{Z}_0\hat{I}_0 + \hat{U}_0 \qquad 0 = \hat{a}\hat{U}_1 + \hat{a}^2\hat{U}_2 + \hat{U}_0$$

Components

$$(U_{120}) = (T^{-1})(U_{ABC}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\hat{U}_1 = \hat{U}_2 = \hat{U}_0 = 0$$

$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1};\ \hat{I}_2 = 0;\ \hat{I}_0 = 0$$



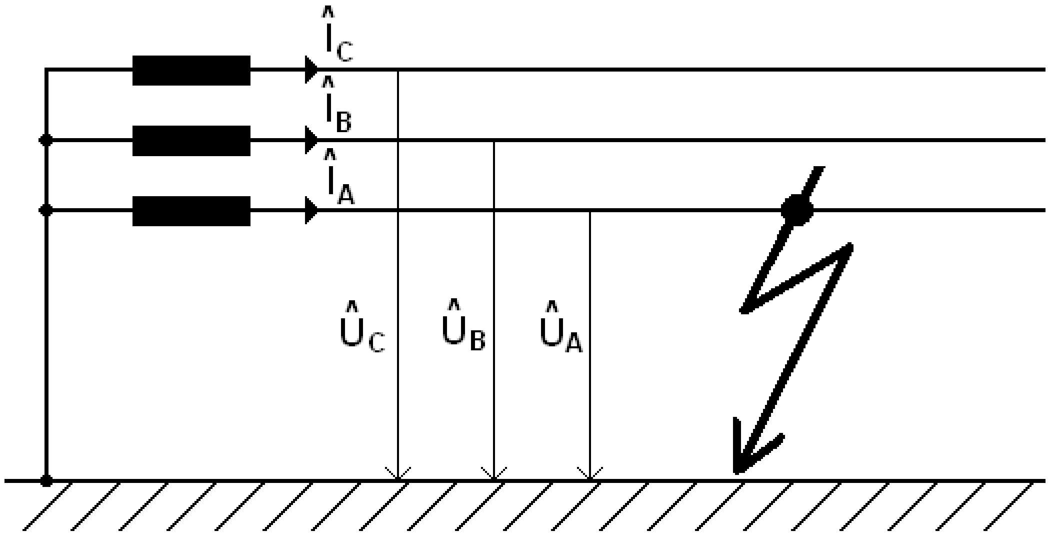
Phases

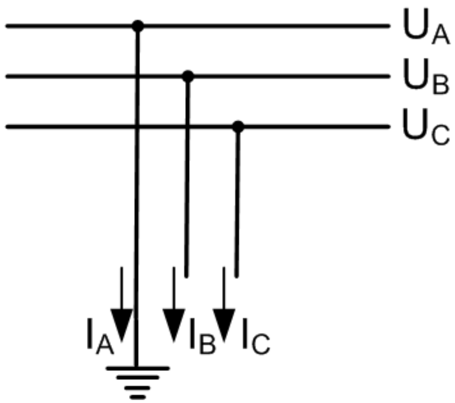
$$(I_{ABC}) = (T)(I_{120})$$

$$\hat{I}_A = \frac{\hat{E}}{\hat{Z}_1};\ \hat{I}_B = \hat{a}^2\frac{\hat{E}}{\hat{Z}_1};\ \hat{I}_C = \hat{a}\frac{\hat{E}}{\hat{Z}_1}$$

Only the positive-sequence component included.

Single-phase-to-ground short-circuit





3 char. equations

$$\hat{U}_A = 0; \ \hat{I}_B = \hat{I}_C = 0$$

Hence 6 equations for 6 unknowns

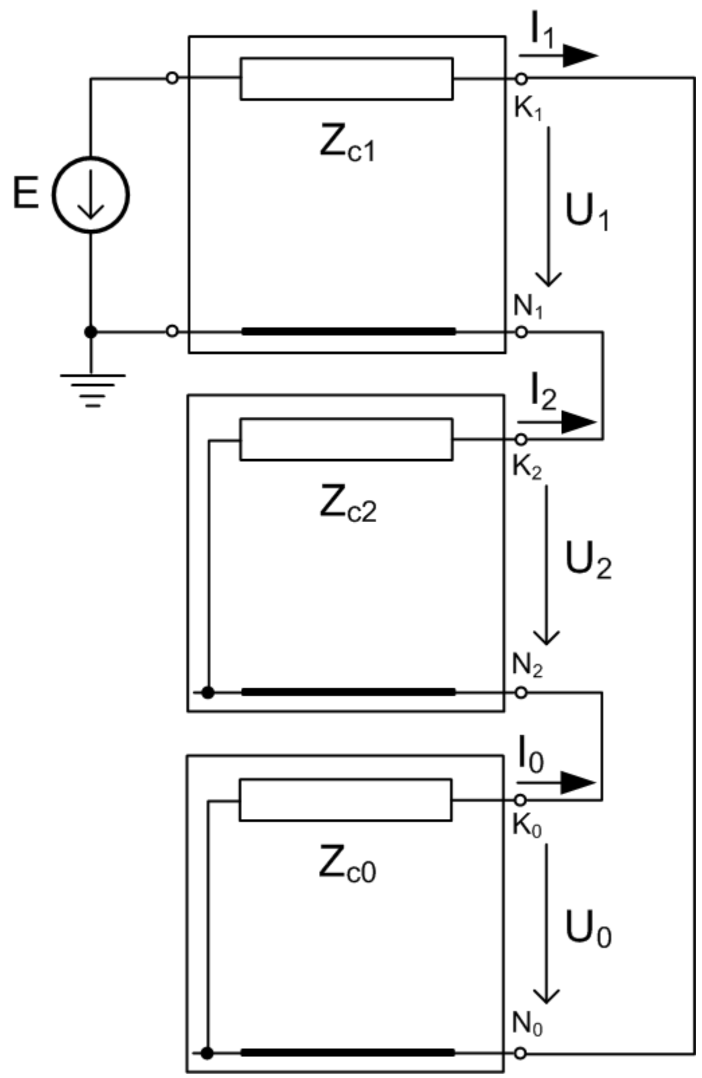
$$\hat{E} = \hat{Z}_1\hat{I}_1 + \hat{U}_1 \qquad 0 = \hat{U}_1 + \hat{U}_2 + \hat{U}_0$$

$$0 = \hat{Z}_2\hat{I}_2 + \hat{U}_2 \qquad 0 = \hat{a}^2\hat{I}_1 + \hat{a}\hat{I}_2 + \hat{I}_0$$

$$0 = \hat{Z}_0\hat{I}_0 + \hat{U}_0 \qquad 0 = \hat{a}\hat{I}_1 + \hat{a}^2\hat{I}_2 + \hat{I}_0$$

Components

$$(I_{120}) = (T^{-1})(I_{ABC}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} \hat{I}_A \\ 0 \\ 0 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} \hat{I}_A \\ \hat{I}_A \\ \hat{I}_A \end{pmatrix}$$



$$\hat{I}_1 = \hat{I}_2 = \hat{I}_0 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0}$$

$$\hat{U}_1 = (\hat{Z}_0 + \hat{Z}_2)\hat{I}_1$$

$$\hat{U}_2 = -\hat{Z}_2\hat{I}_1$$

$$\hat{U}_0 = -\hat{Z}_0\hat{I}_1$$

All three components are in series.

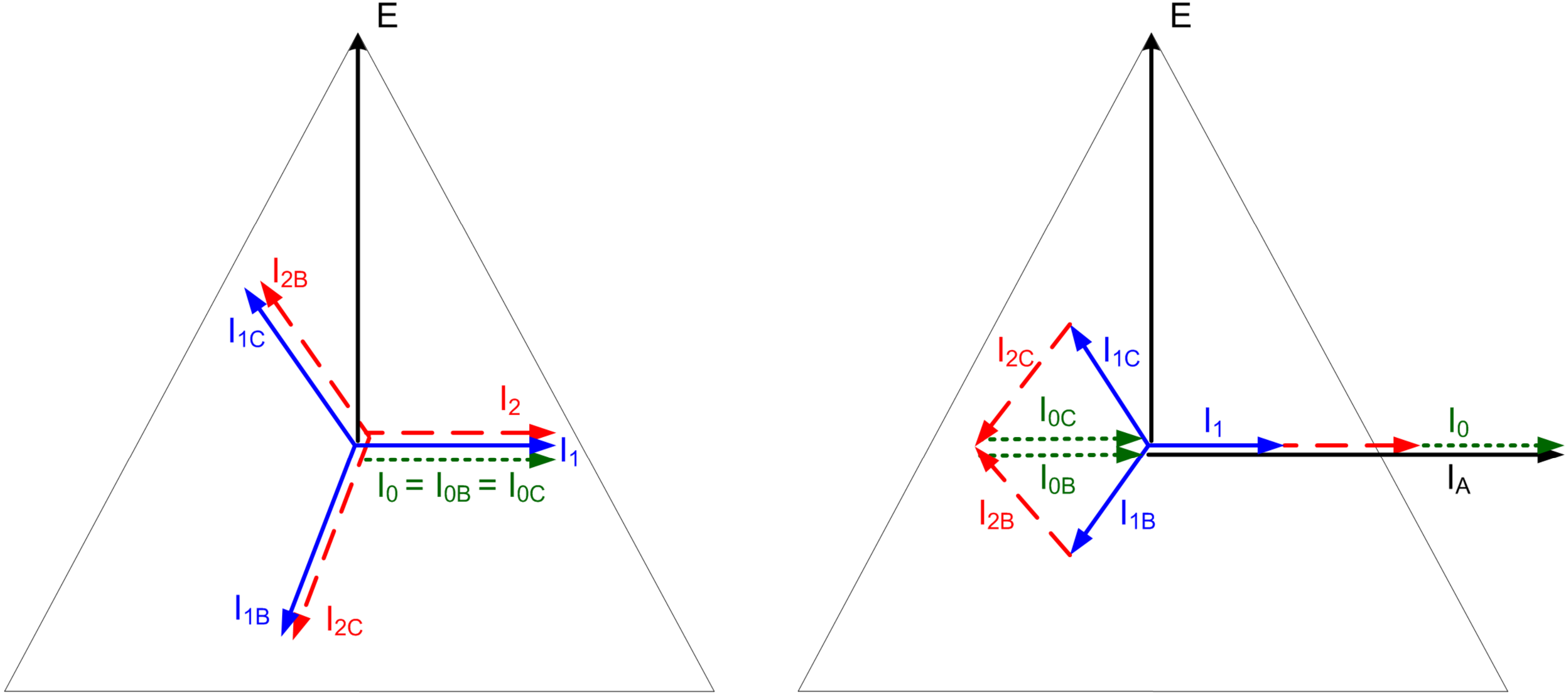
Phases

$$\left(I_{ABC}\right)=\left(T\right)\left(I_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{I}_1\\ \hat{I}_1\\ \hat{I}_1\end{pmatrix}=\begin{pmatrix}3\hat{I}_1\\ 0\\ 0\end{pmatrix}$$

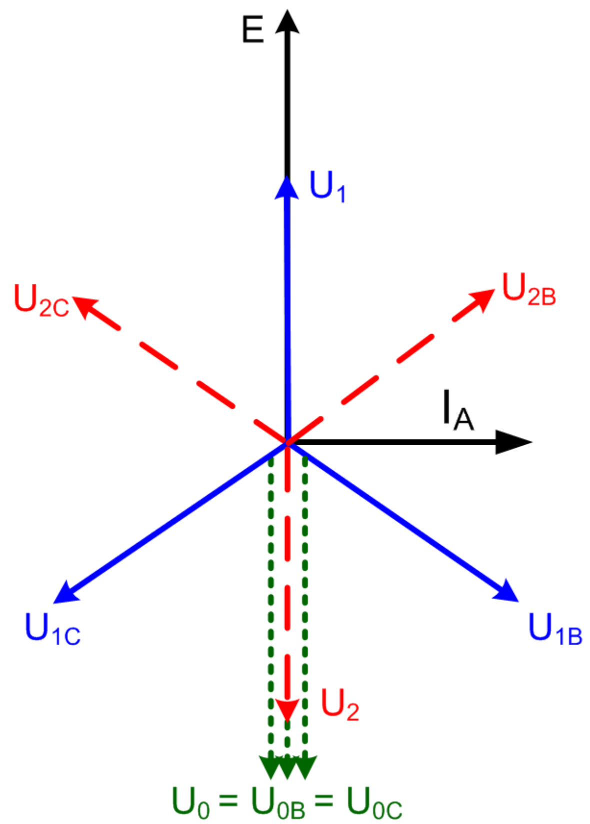
$$\hat{I}_A=\frac{3\hat{E}}{\hat{Z}_1+\hat{Z}_2+\hat{Z}_0};\ \ \hat{I}_B=0;\ \ \hat{I}_C=0$$

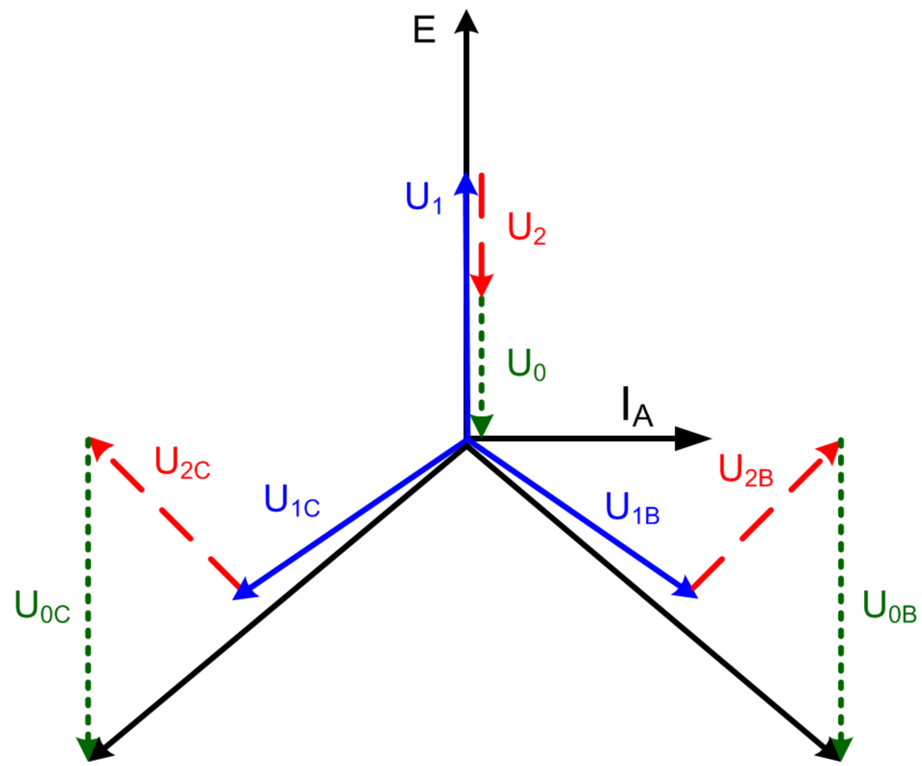
$$\left(U_{ABC}\right)=\left(T\right)\left(U_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\left(\hat{Z}_0+\hat{Z}_2\right)\hat{I}_1\\ -\hat{Z}_2\hat{I}_1\\ -\hat{Z}_0\hat{I}_1\end{pmatrix}=\begin{pmatrix}0\\ \left(\hat{a}^2-\hat{a}\right)\hat{Z}_2+\left(\hat{a}^2-1\right)\hat{Z}_0\\ \left(\hat{a}-\hat{a}^2\right)\hat{Z}_2+\left(\hat{a}-1\right)\hat{Z}_0\end{pmatrix}\hat{I}_1$$

Current phasor diagram

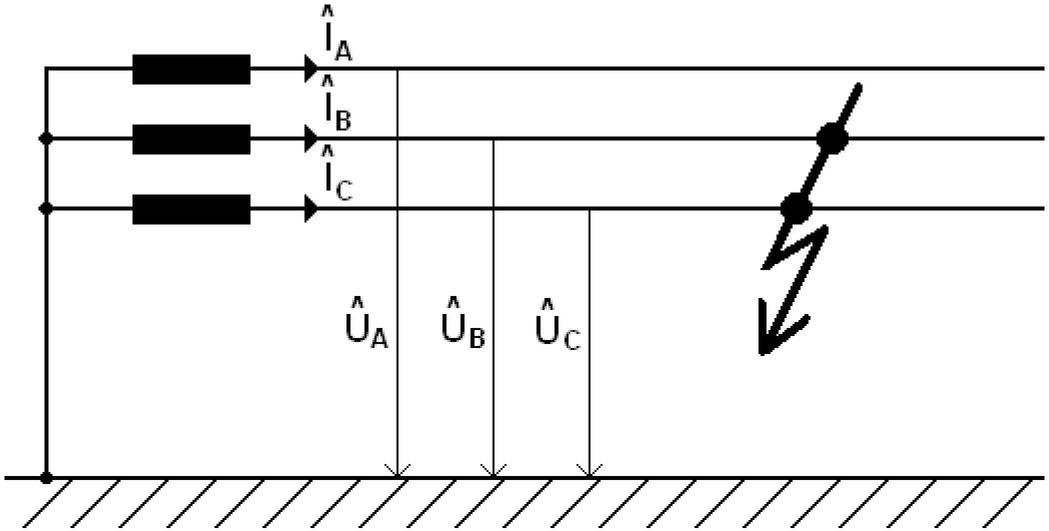


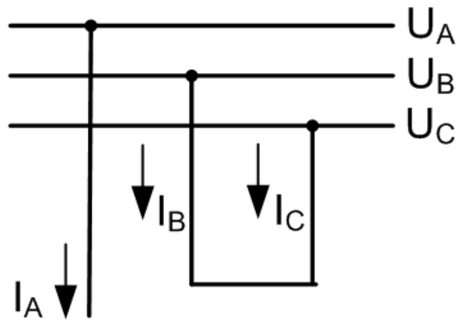
Voltage phasor diagram





Phase-to-phase short-circuit





3 char. equations

$$\hat{U}_B = \hat{U}_C;\ \ \hat{I}_B = -\hat{I}_C;\ \ \hat{I}_A = 0$$

Hence 6 equations for 6 unknowns

$$\hat{E} = \hat{Z}_1\hat{I}_1 + \hat{U}_1 \qquad \hat{a}^2\hat{U}_1 + \hat{a}\hat{U}_2 + \hat{U}_0 = \hat{a}\hat{U}_1 + \hat{a}^2\hat{U}_2 + \hat{U}_0$$

$$0 = \hat{Z}_2\hat{I}_2 + \hat{U}_2 \qquad \hat{a}^2\hat{I}_1 + \hat{a}\hat{I}_2 + \hat{I}_0 = -\left(\hat{a}\hat{I}_1 + \hat{a}^2\hat{I}_2 + \hat{I}_0\right)$$

$$0 = \hat{Z}_0\hat{I}_0 + \hat{U}_0 \qquad \hat{I}_1 + \hat{I}_2 + \hat{I}_0 = 0$$

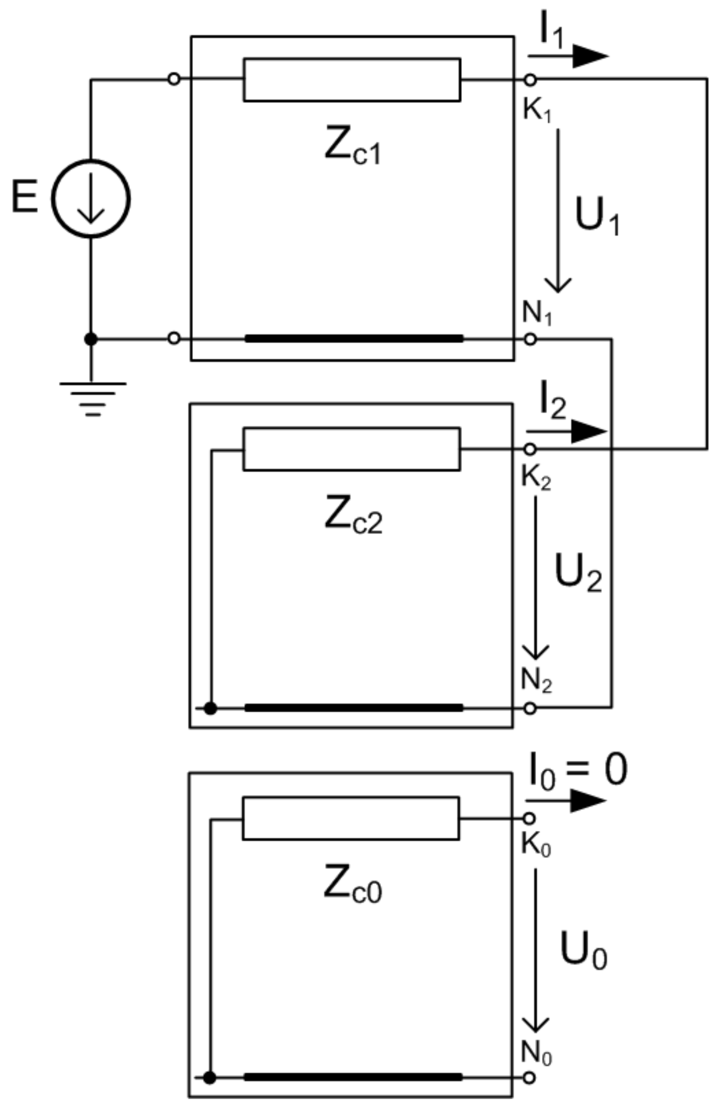
Components

$$(I_{120}) = \frac{1}{3}\begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ \hat{I}_B \\ -\hat{I}_B \end{pmatrix} = \frac{1}{3}\begin{pmatrix} j\sqrt{3}\hat{I}_B \\ -j\sqrt{3}\hat{I}_B \\ 0 \end{pmatrix}$$

$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2}; \quad \hat{I}_2 = -\hat{I}_1; \quad \hat{I}_0 = 0$$

$$\hat{U}_1 = \hat{U}_2 = \frac{\hat{Z}_2 \cdot \hat{E}}{\hat{Z}_1 + \hat{Z}_2} = \hat{Z}_2 \cdot \hat{I}_1$$

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



Positive and negative components in parallel.

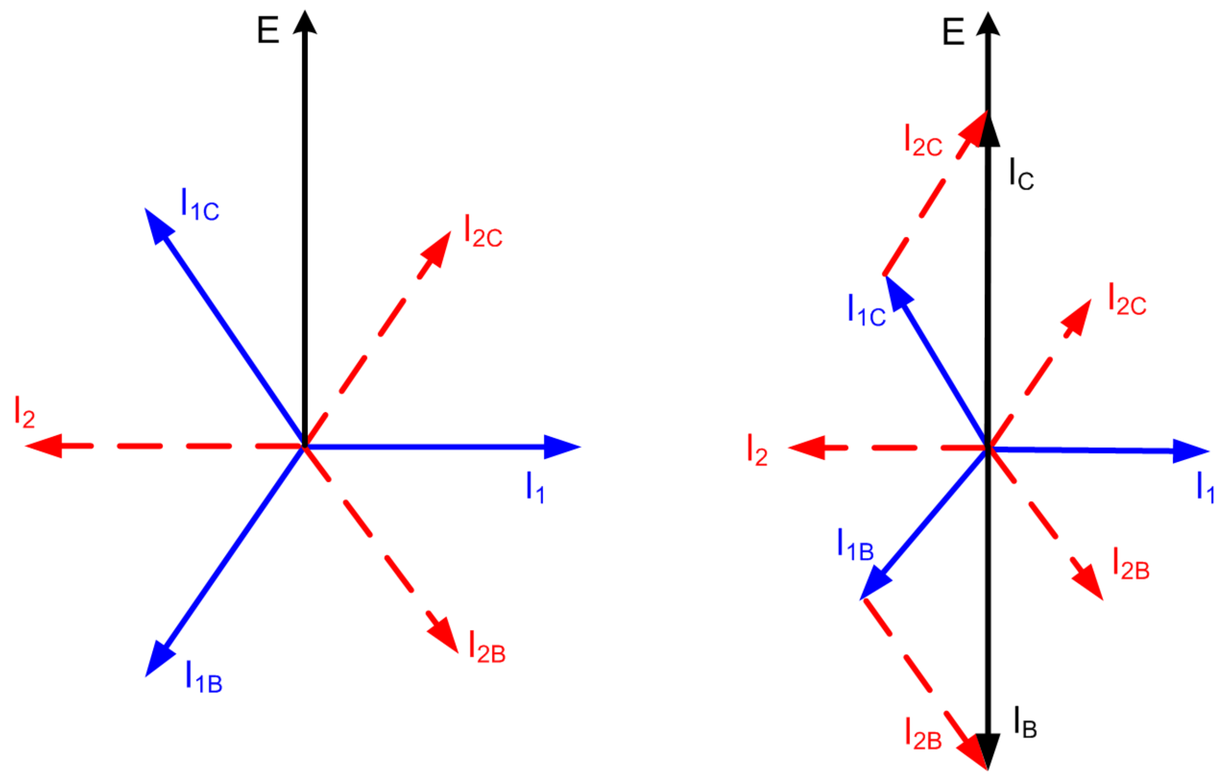
Phases

$$\left(I_{ABC}\right)=\left(T\right)\left(I_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{I}_1\\ -\hat{I}_1\\ 0\end{pmatrix}=\begin{pmatrix}0\\ -j\sqrt{3}\hat{I}_1\\ j\sqrt{3}\hat{I}_1\end{pmatrix}$$

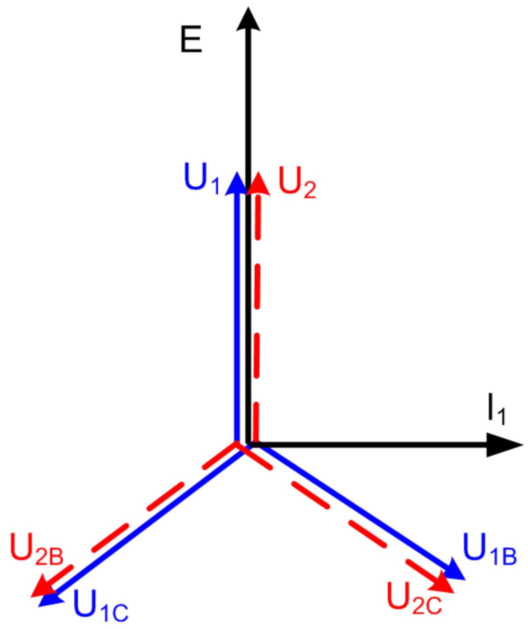
$$\hat{I}_A=0;\quad \hat{I}_B=\frac{-j\sqrt{3}\hat{E}}{\hat{Z}_1+\hat{Z}_2};\quad \hat{I}_C=\frac{j\sqrt{3}\hat{E}}{\hat{Z}_1+\hat{Z}_2}$$

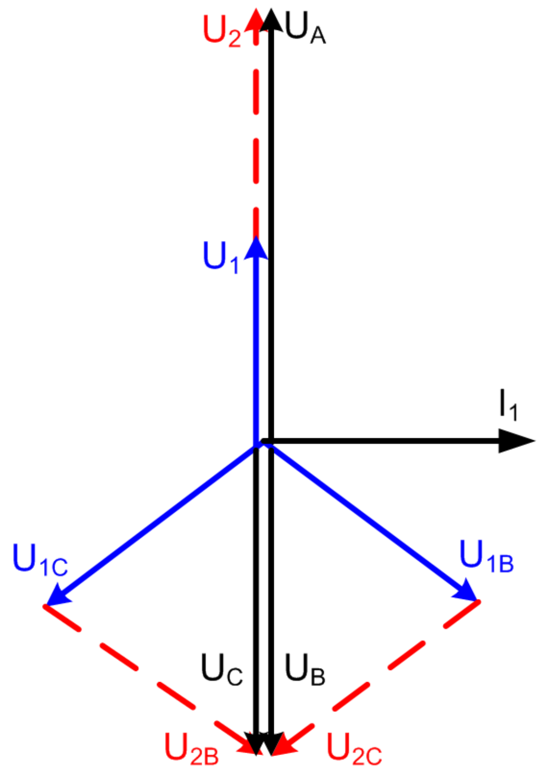
$$\left(U_{ABC}\right)=\left(T\right)\left(U_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{U}_1\\ \hat{U}_1\\ 0\end{pmatrix}=\begin{pmatrix}2\hat{U}_1\\ -\hat{U}_1\\ -\hat{U}_1\end{pmatrix}=\begin{pmatrix}2\hat{Z}_2\cdot\hat{I}_1\\ -\hat{Z}_2\cdot\hat{I}_1\\ -\hat{Z}_2\cdot\hat{I}_1\end{pmatrix}$$

Current phasor diagram

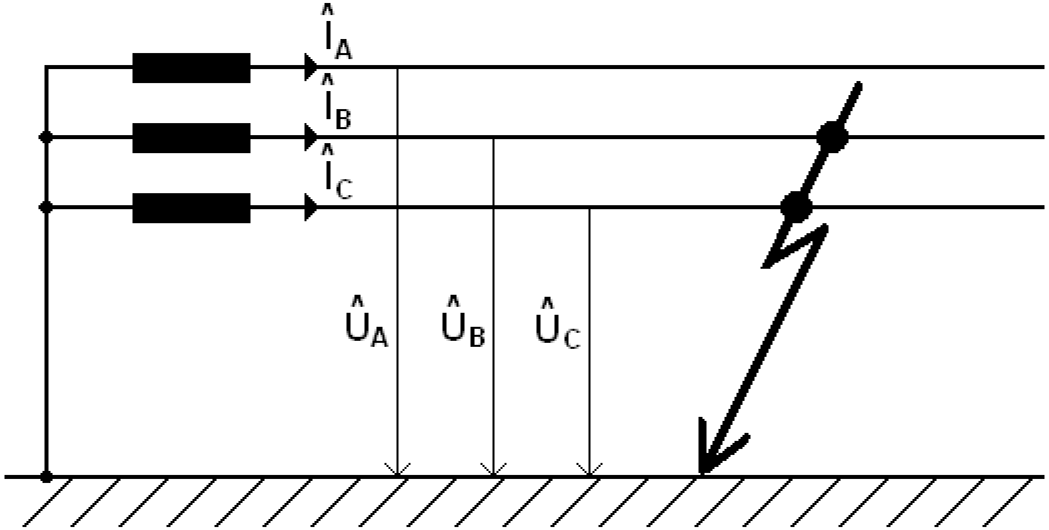


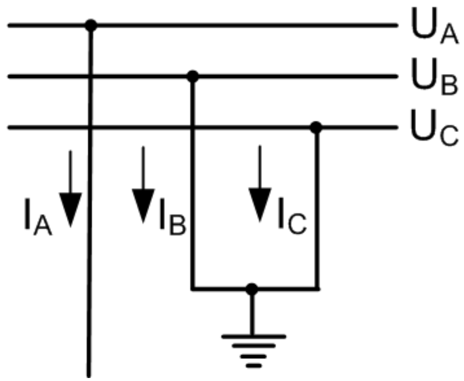
Voltage phasor diagram





Double-phase-to-ground short-circuit





3 char. equations

$$\hat{U}_B = \hat{U}_C = 0; \quad \hat{I}_A = 0$$

Hence 6 equations for 6 unknowns

$$\hat{E} = \hat{Z}_1\hat{I}_1 + \hat{U}_1 \qquad \hat{a}^2\hat{U}_1 + \hat{a}\hat{U}_2 + \hat{U}_0 = 0$$

$$0 = \hat{Z}_2\hat{I}_2 + \hat{U}_2 \qquad \hat{a}\hat{U}_1 + \hat{a}^2\hat{U}_2 + \hat{U}_0 = 0$$

$$0 = \hat{Z}_0\hat{I}_0 + \hat{U}_0 \qquad \hat{I}_1 + \hat{I}_2 + \hat{I}_0 = 0$$

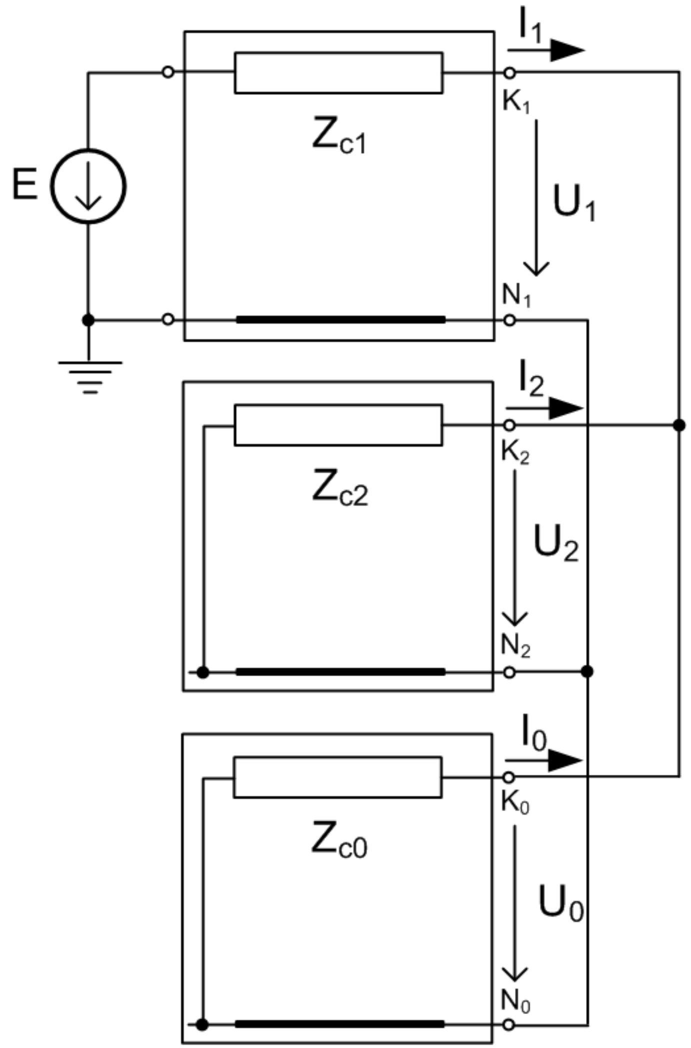
Components

$$\left(U_{120}\right)=\frac{1}{3}\begin{pmatrix}1 & \hat{a} & \hat{a}^2\\ 1 & \hat{a}^2 & \hat{a}\\ 1 & 1 & 1\end{pmatrix}\begin{pmatrix}\hat{U}_A\\ 0\\ 0\end{pmatrix}=\frac{1}{3}\begin{pmatrix}\hat{U}_A\\ \hat{U}_A\\ \hat{U}_A\end{pmatrix}$$

$$\hat{I}_1=\frac{\hat{E}}{\hat{Z}_1+\dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0+\hat{Z}_2}}$$

$$\hat{I}_2=-\frac{\hat{Z}_0}{\hat{Z}_0+\hat{Z}_2}\hat{I}_1;\quad \hat{I}_0=-\frac{\hat{Z}_2}{\hat{Z}_0+\hat{Z}_2}\hat{I}_1$$

$$\hat{U}_1=\hat{U}_2=\hat{U}_0=\frac{\hat{E}\dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0+\hat{Z}_2}}{\hat{Z}_1+\dfrac{\hat{Z}_0\hat{Z}_2}{\hat{Z}_0+\hat{Z}_2}}$$



All three components are in parallel.

Phases

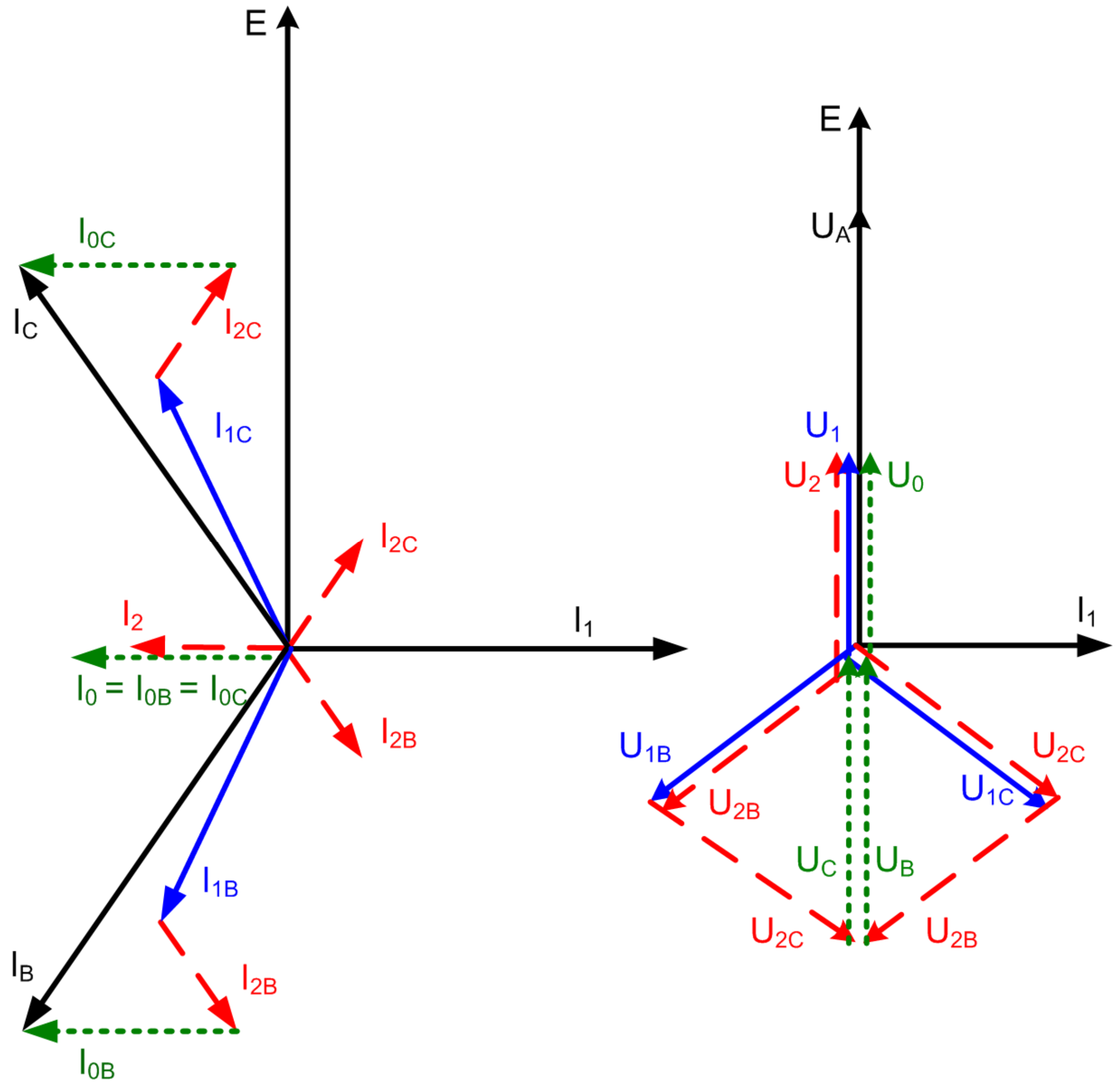
$$\left(I_{ABC}\right)=\left(T\right)\left(I_{120}\right)$$

$$\hat{I}_B=\frac{\hat{E}\left(\hat{Z}_0(\hat{a}^2-\hat{a})+\hat{Z}_2(\hat{a}^2-1)\right)}{\hat{Z}_1\hat{Z}_2+\hat{Z}_0\hat{Z}_1+\hat{Z}_0\hat{Z}_2}$$

$$\hat{I}_C=\frac{\hat{E}\left(\hat{Z}_0(\hat{a}-\hat{a}^2)+\hat{Z}_2(\hat{a}-1)\right)}{\hat{Z}_1\hat{Z}_2+\hat{Z}_0\hat{Z}_1+\hat{Z}_0\hat{Z}_2}$$

$$\left(U_{ABC}\right)=\left(T\right)\left(U_{120}\right)=\begin{pmatrix}1 & 1 & 1\\ \hat{a}^2 & \hat{a} & 1\\ \hat{a} & \hat{a}^2 & 1\end{pmatrix}\begin{pmatrix}\hat{U}_1\\ \hat{U}_1\\ \hat{U}_1\end{pmatrix}=\begin{pmatrix}3\hat{U}_1\\ 0\\ 0\end{pmatrix}$$

Phasor diagrams



Components during short-circuit:

3ph	positive
2ph	positive, negative
2ph ground	positive, negative, zero
1ph	positive, negative, zero

Short-circuits calculation by means of relative values

Relative values – related to a defined base.

base power (3ph)	S_v (VA)
base voltage (phase-to-phase)	U_v (V)
base current	I_v (A)
base impedance	Z_v (Ω)

$$S_v = \sqrt{3} U_v I_v$$

$$Z_v = \frac{U_{vf}}{I_v}$$

Relative impedance

$$z = \frac{Z}{Z_v} = \frac{Z}{\frac{U_{vf}}{I_v}} = Z \frac{I_v}{U_{vf}} \frac{3U_{vf}}{3U_{vf}} = Z \frac{S_v}{3U_{vf}^2} = Z \frac{S_v}{U_v^2}$$

Initial sub-transient short-circuit current (3ph short-circuit)

$$I''_{k0} = \left|\hat{I}_A\right| = \frac{\left|\hat{U}_f\right|}{\left|\hat{Z}_1\right|}$$

$$Z_1 = z_1 \frac{U_v^2}{S_v}$$

$$I''_{k0} = \frac{\frac{U_v}{\sqrt{3}}}{z_1 \frac{U_v^2}{S_v}} = \frac{1}{z_1} \frac{S_v}{\sqrt{3}U_v} = \frac{1}{z_1} I_v$$

Initial sub-transient short-circuit power

$$S''_{k0} = \sqrt{3} U_v I''_{k0} = \sqrt{3} U_v \frac{I_v}{z_1} = \frac{1}{z_1} S_v$$

Similarly for

1ph short-circuit

$$I''^{(1)}_{k0} = \frac{3}{z_1 + z_2 + z_0} I_v$$

2ph short-circuit

$$I''^{(2)}_{k0} = \frac{\sqrt{3}}{z_1 + z_2} I_v$$

Note: Sometimes it is respected generator loading, more precisely higher internal generator voltage than nominal one.

$$I''_{k0} = k \frac{1}{z_1} I_v$$

$$k > 1$$