

## Short-circuits in ES

### Short-circuit:

- transient events, quickly emergency change in ES
- the most often in ES
- transient events occurring during short circuit

### Short-circuit formation:

- failure connection between phases or between a phase and the ground in the system with the grounded neutral

### Causes:

- insulation defects because of overvoltage,
- lightning,
- insulation aging,
- mechanically

### Short-circuit impact:

- total impedance of affected part of network is decreasing

- currents are increasing => so called short-circuit currents  $I_k$
- the voltage is decreasing near the short circuit
- impact of  $I_k$  causes device heating and power strain
- problems with  $I_k$  disconnecting, electrical arc and overvoltage occurred during the short-circuit
- disruption of synchronism of parallel working ES
- communication line disturbing => induced voltages

Note: In places of short-circuit transitive resistances arises

- Transitive resistances are summation of electrical arc resistances and resistances of other parts  $I_k$  (determination of exact resistances is difficult)
- current and length of electrical arc is changing during short-circuit => resistance of electrical arc is also changing
- By  $I_k$  calculation (dimensioning of electrical devices) resistances are ignored → *absolute short-circuit*

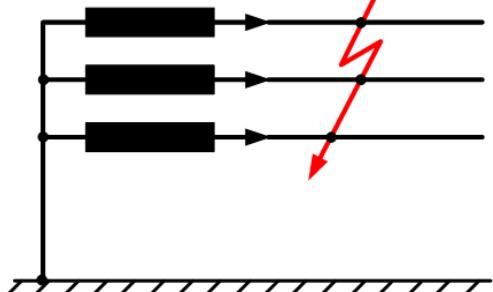
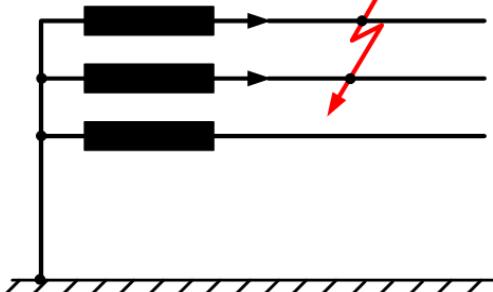
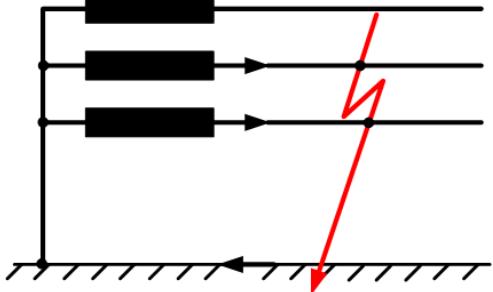
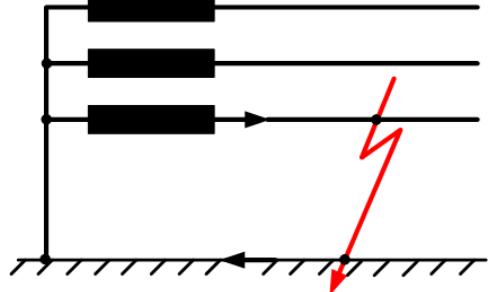
## Short-circuits types

### Symmetrical short-circuit:

- Three-phase short-circuit => all three-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 three-phase short-circuit due to electrical-arc impact.

### Unsymmetrical short-circuit:

- phase-to-phase short-circuit,
- double-phase-to-ground short-circuit,
- single-phase-to-ground short-circuit:
  - in MV it is not short-circuit => so called *ground fault*,
  - in case of ground fault in MV (insulated or indirectly grounded node) => no change in LV (grounded node).

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 course

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

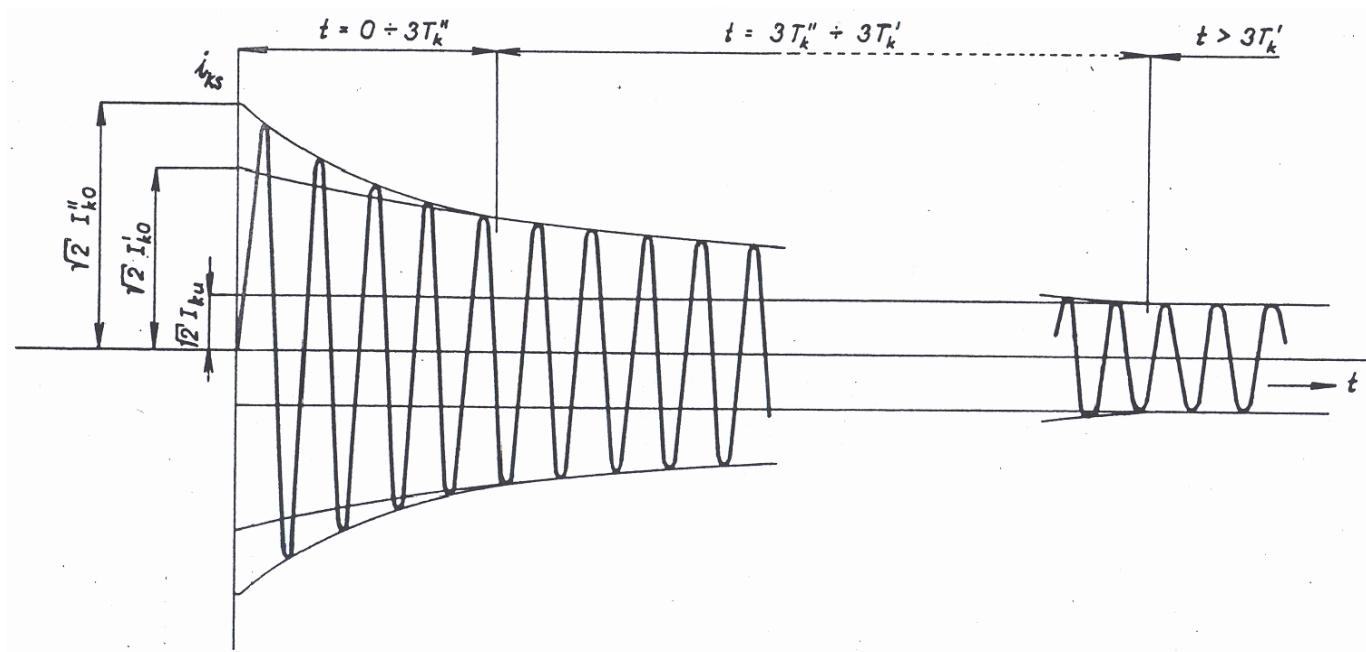
$$P = \frac{dW_L}{dt} < \infty \rightarrow \text{transient event}$$

Time course: open-circuit, resistances neglected  
→ reactance, current inductive character

Impact of R on attributes  $I_k$ :

- final value of R decreasing short-circuit impacts,
- neglecting of R leads to prolongation time constant  $\tau = L/R$ .

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



Short-circuit components ( $f = 50$  Hz):

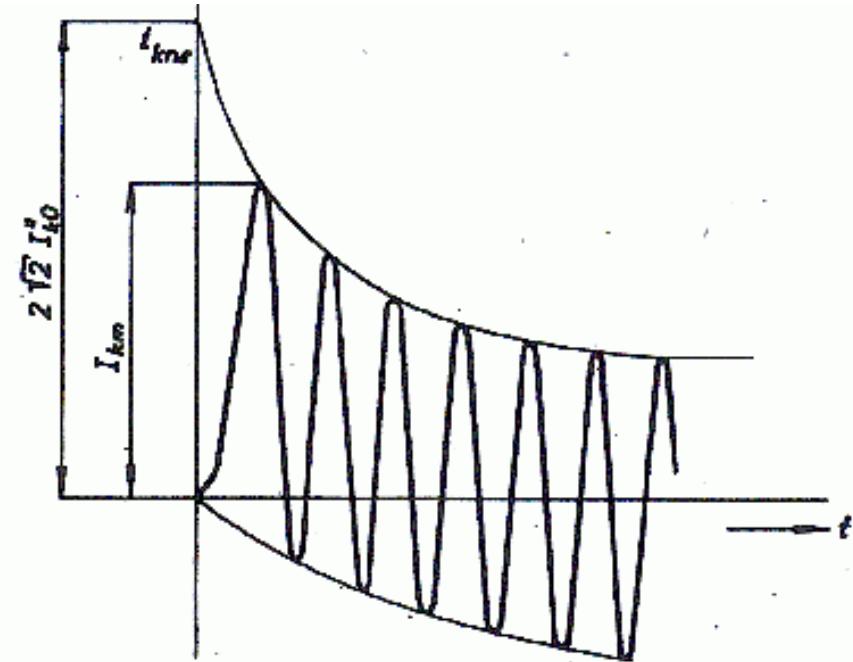
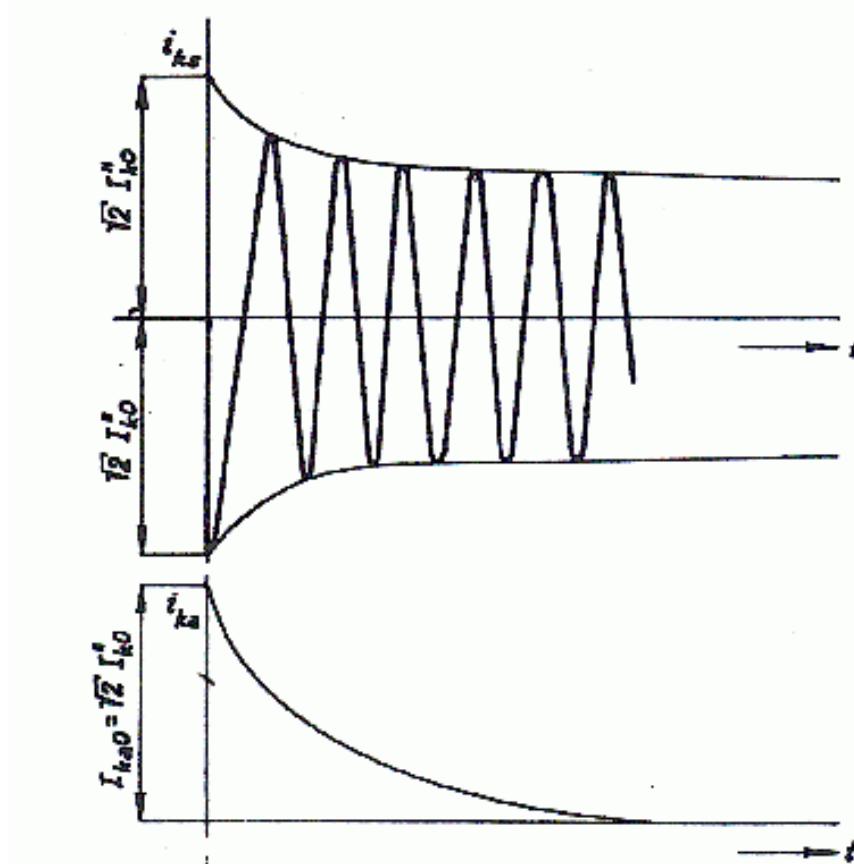
- sub-transient – exponential envelope,  $T_k''$
- transient – exponential envelope,  $T_k'$
- steady-state – constant magnitude

It is caused by synchronism machine behavior by short-circuit  $\rightarrow$  significantly by short-circuit 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  $t \doteq (0 \div 3T_k'')$
- 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  
 $t \doteq (3T_k'' \div 3T_k')$
- 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  $\rightarrow I_k$  starts from max. value



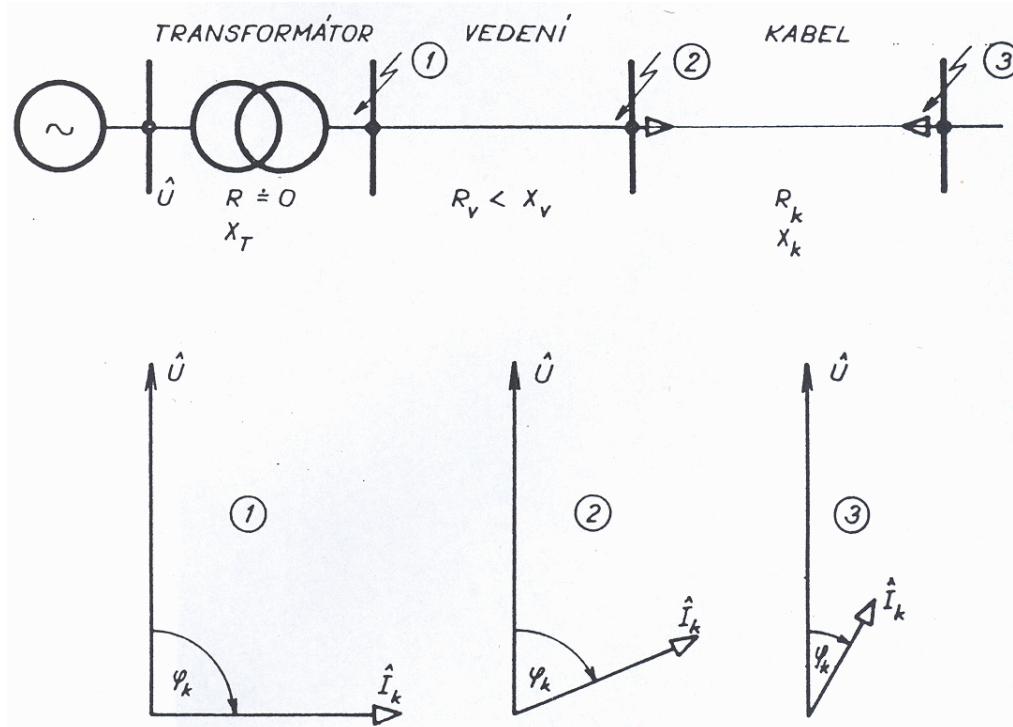
## Values

- 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 behavior
- unbalanced short-circuit current  $I_{kns}$  - steady-state, transient, sub-transient and DC component sum RMS value
- surge short-circuit current  $I_{km}$  - the first half-period magnitude during the maximal DC component

### Short-circuit current power factor

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

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
$\varphi_k$ ( $^\circ$ )	45	64	78,7	85,2	86,2	87,9	13	26	54



## Short-circuit in the 3ph system

Phase values conversion into symmetrical sequences

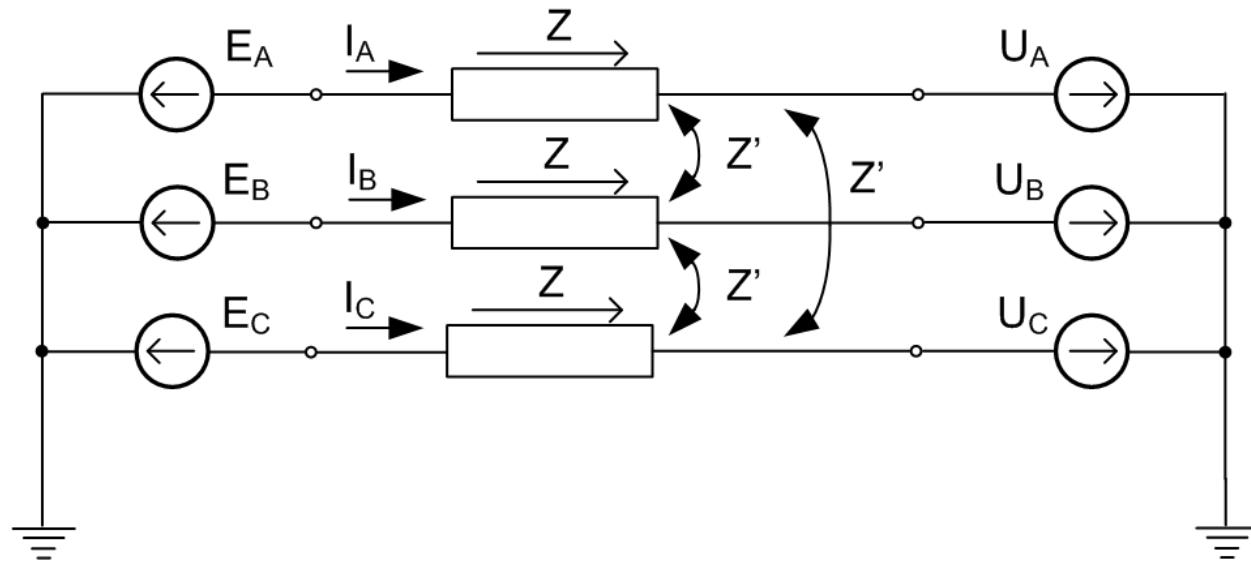
$$(U_{ABC}) = \begin{pmatrix} \hat{U}_A \\ \hat{U}_B \\ \hat{U}_C \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ \hat{a}^2 & \hat{a} & 1 \\ \hat{a} & \hat{a}^2 & 1 \end{pmatrix} \begin{pmatrix} \hat{U}_1 \\ \hat{U}_2 \\ \hat{U}_0 \end{pmatrix} = (T)(U_{120})$$

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

Impedance matrix in symmetrical sequences

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

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



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

Symmetrical system (independence system 1, 2, 0)

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

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

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

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

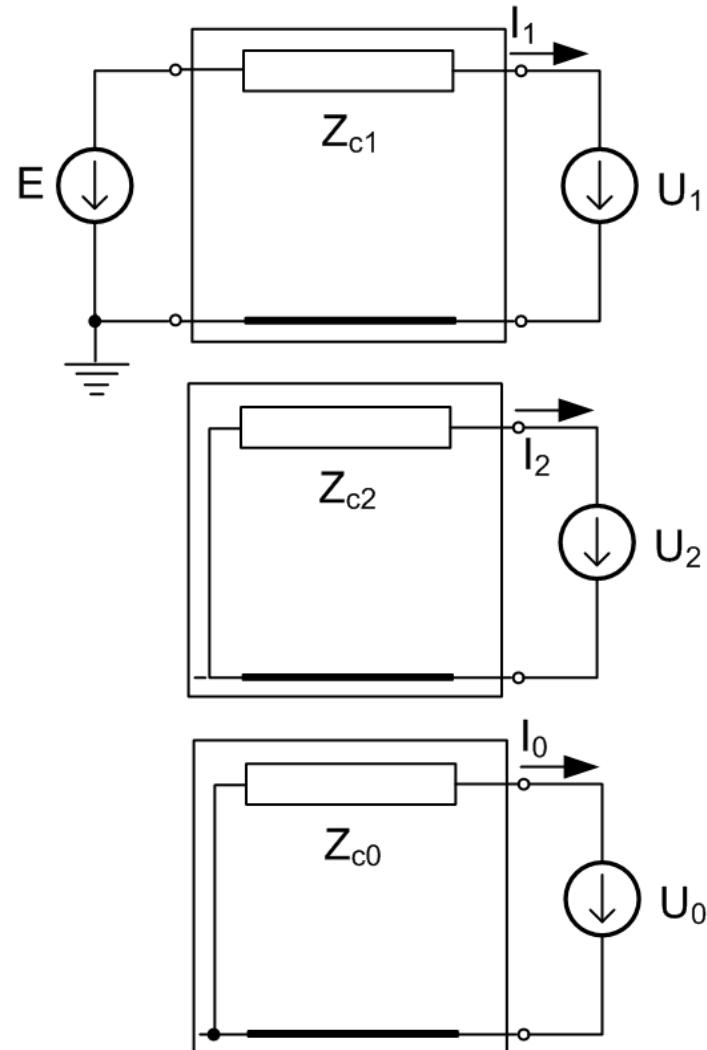
Generator symmetrical voltage → only positive sequence component  
 Reference phase A:

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

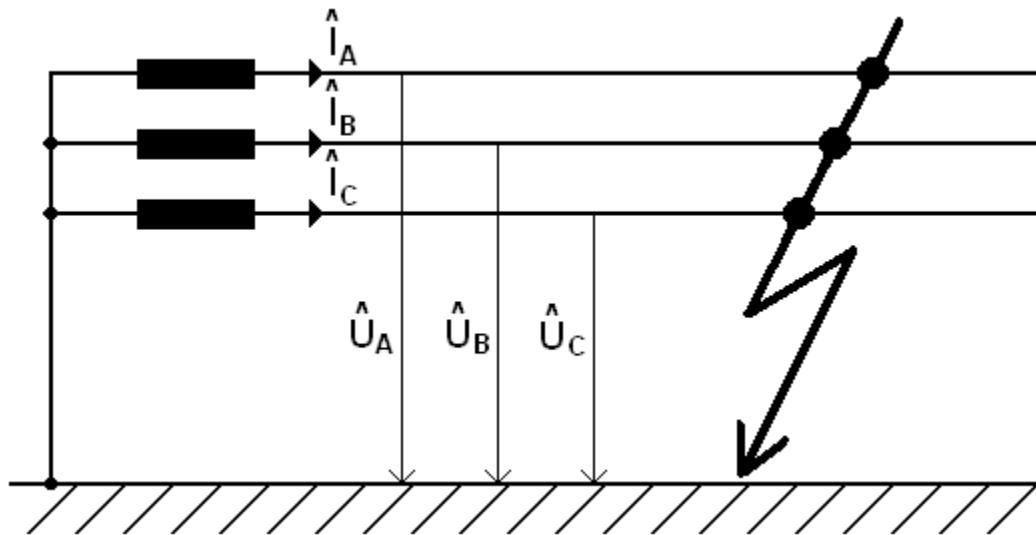
$$\begin{pmatrix} \hat{E}_1 \\ \hat{E}_2 \\ \hat{E}_0 \end{pmatrix} = \begin{pmatrix} \hat{E} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \hat{Z}_1 & 0 & 0 \\ 0 & \hat{Z}_2 & 0 \\ 0 & 0 & \hat{Z}_0 \end{pmatrix} \begin{pmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \hat{I}_0 \end{pmatrix} + \begin{pmatrix} \hat{U}_1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

Negative and zero sequence are done by unsymmetrical balance in faulted place.

In the failure point 6 quantities ( $U_{120}$ ,  $I_{120}$ )  $\rightarrow$  3 equations necessary to be added by other 3 equations according to the short-circuit type.



## 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

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

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

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

## Components

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

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

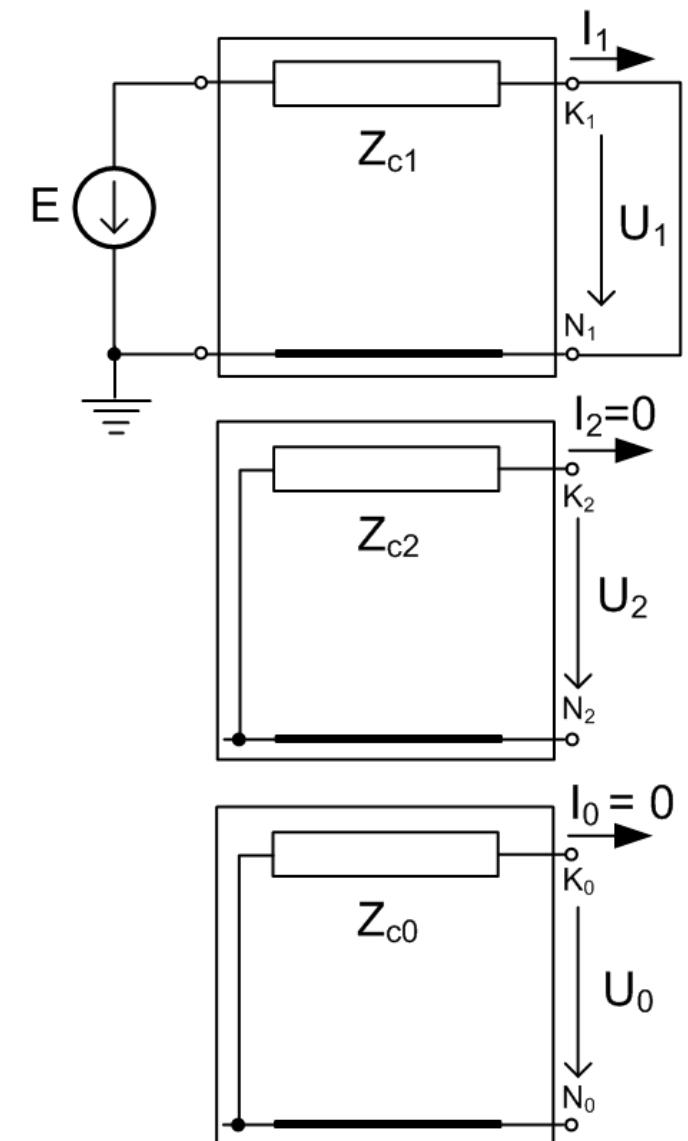
$$\hat{I}_1 = \frac{\hat{E}}{\hat{Z}_1}; \quad \hat{I}_2 = 0; \quad \hat{I}_0 = 0$$

## Short-circuit current

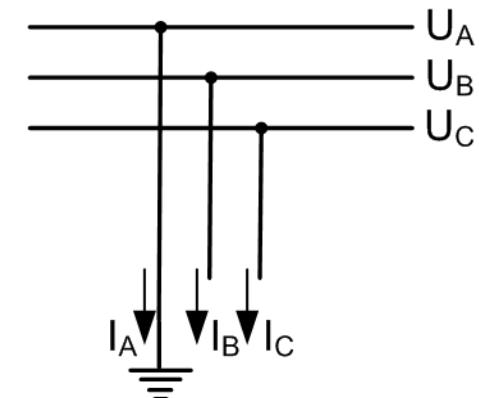
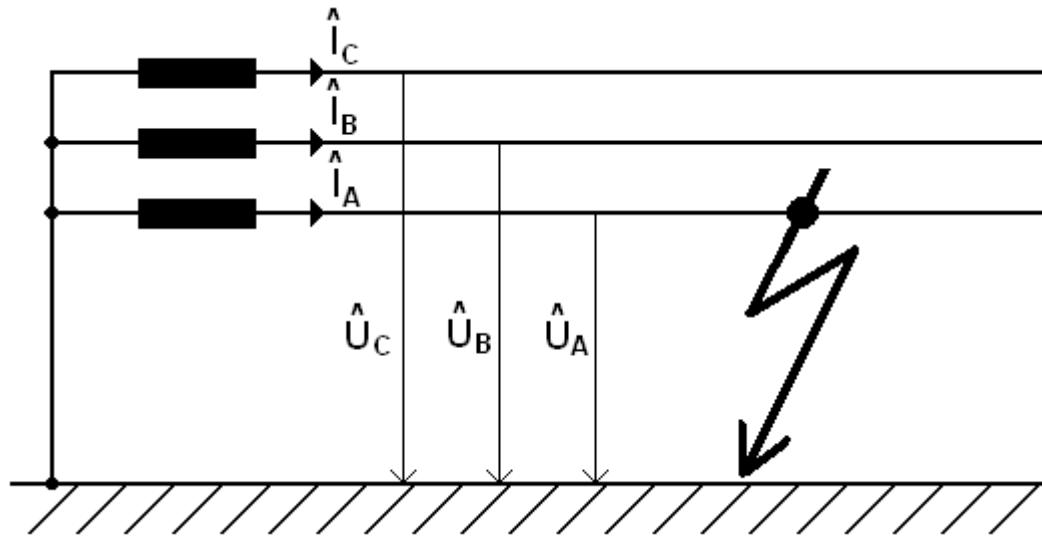
$$(I_{ABC}) = (T)(I_{120})$$

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

Only the positive-sequence component included.



## Single-phase-to-ground short-circuit



3 char. equations

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

Hence 6 equations for 6 unknowns

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

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

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

## Components

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

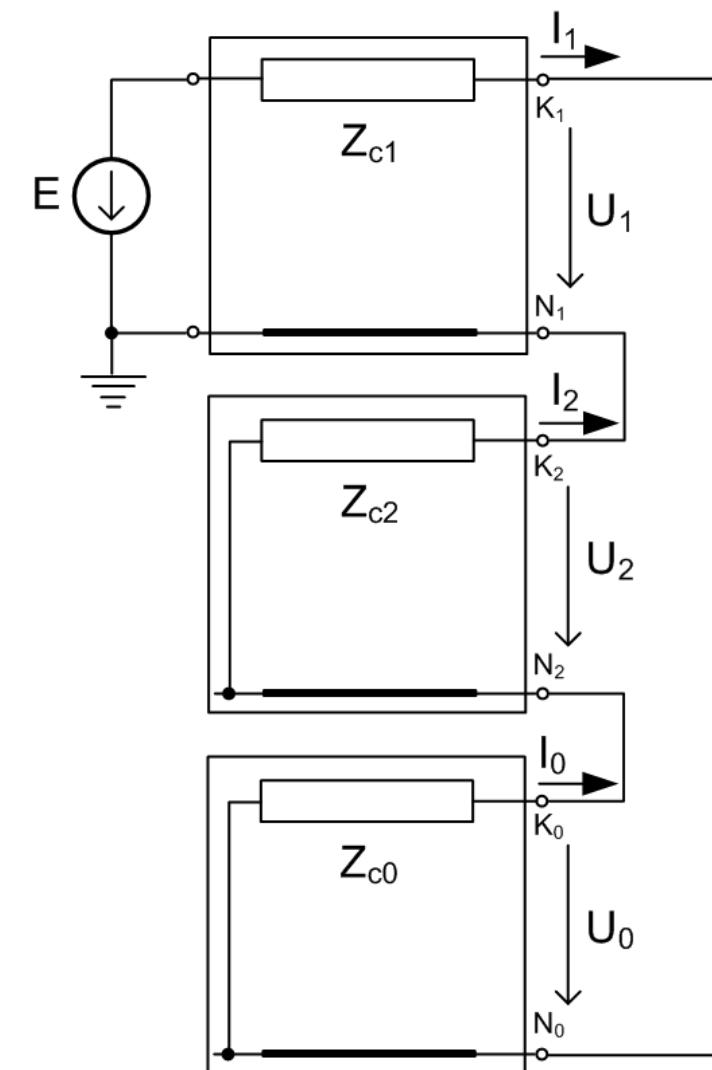
$$\hat{I}_1 = \hat{I}_2 = \hat{I}_0 = \frac{\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0}$$

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

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

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

All three components are in series.



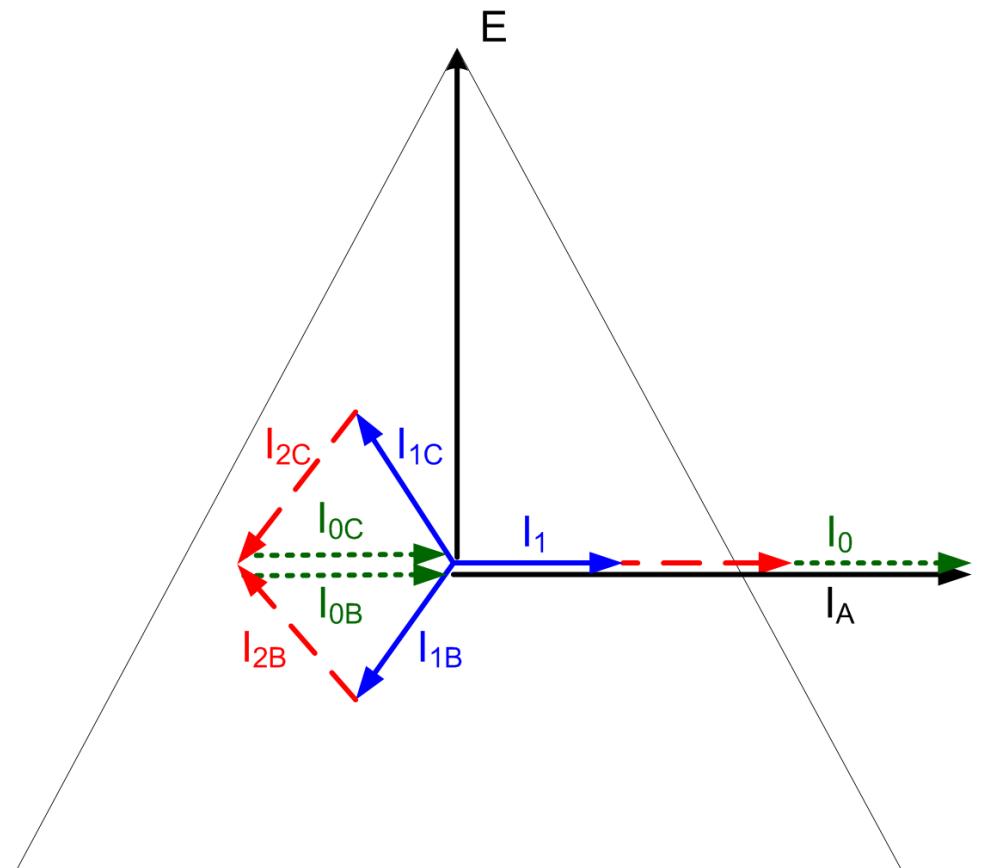
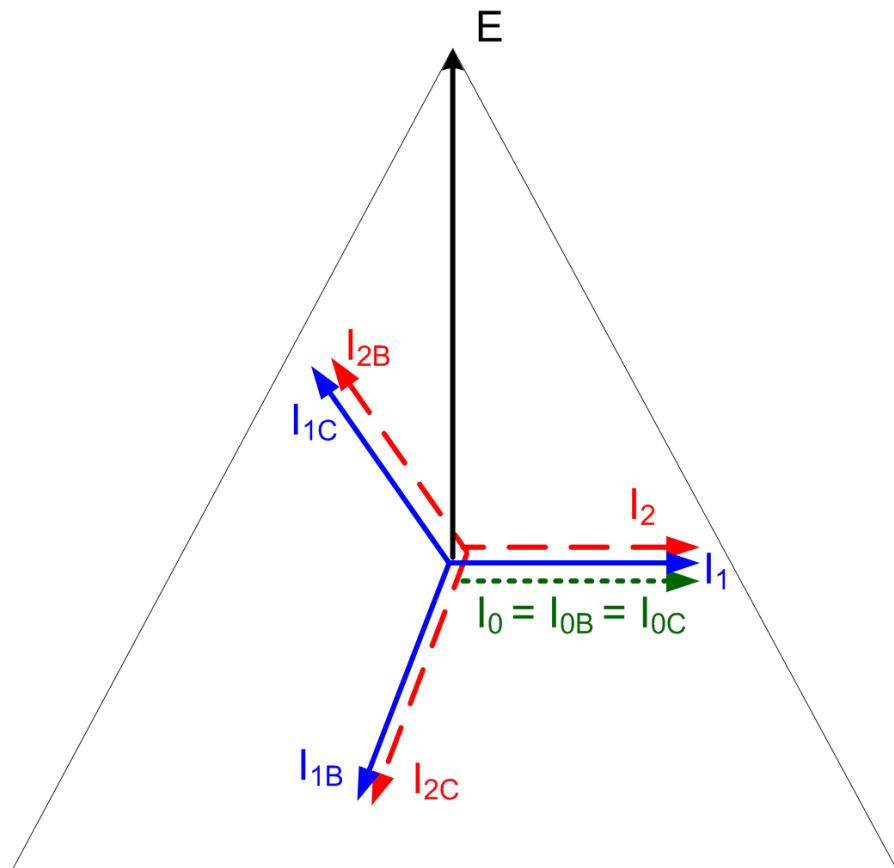
## Short-circuit current

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

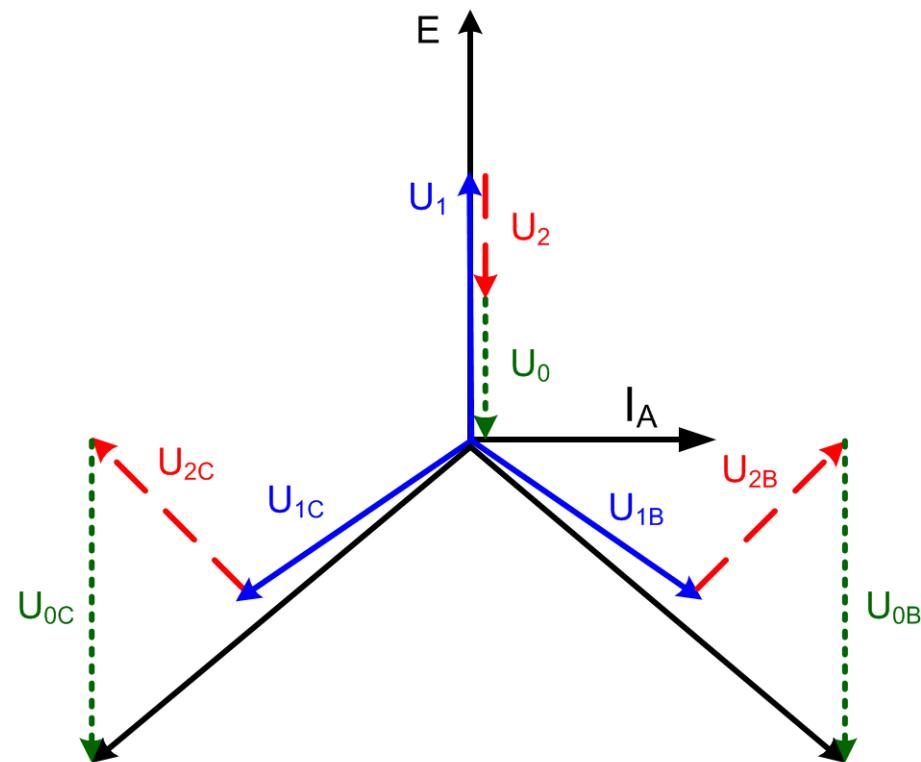
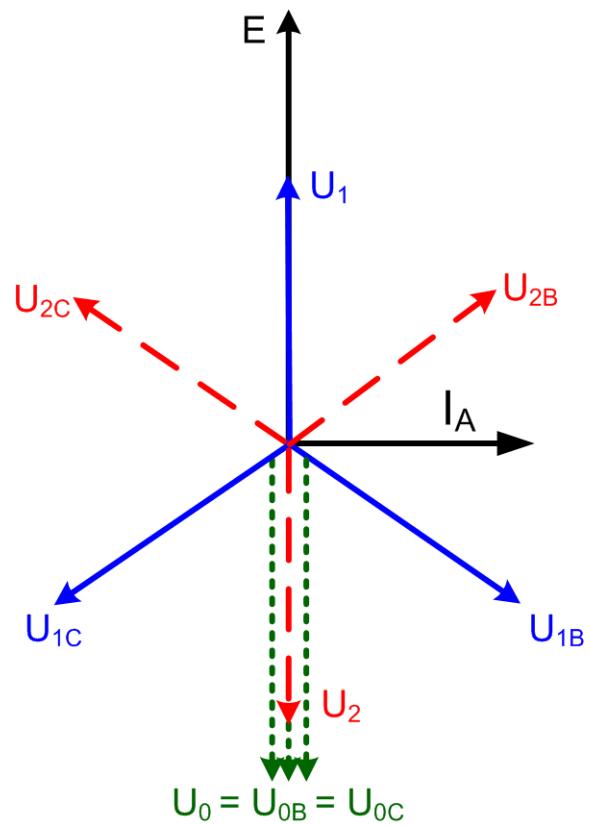
$$\hat{I}_A = \frac{3\hat{E}}{\hat{Z}_1 + \hat{Z}_2 + \hat{Z}_0}; \quad \hat{I}_B = 0; \quad \hat{I}_C = 0$$

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

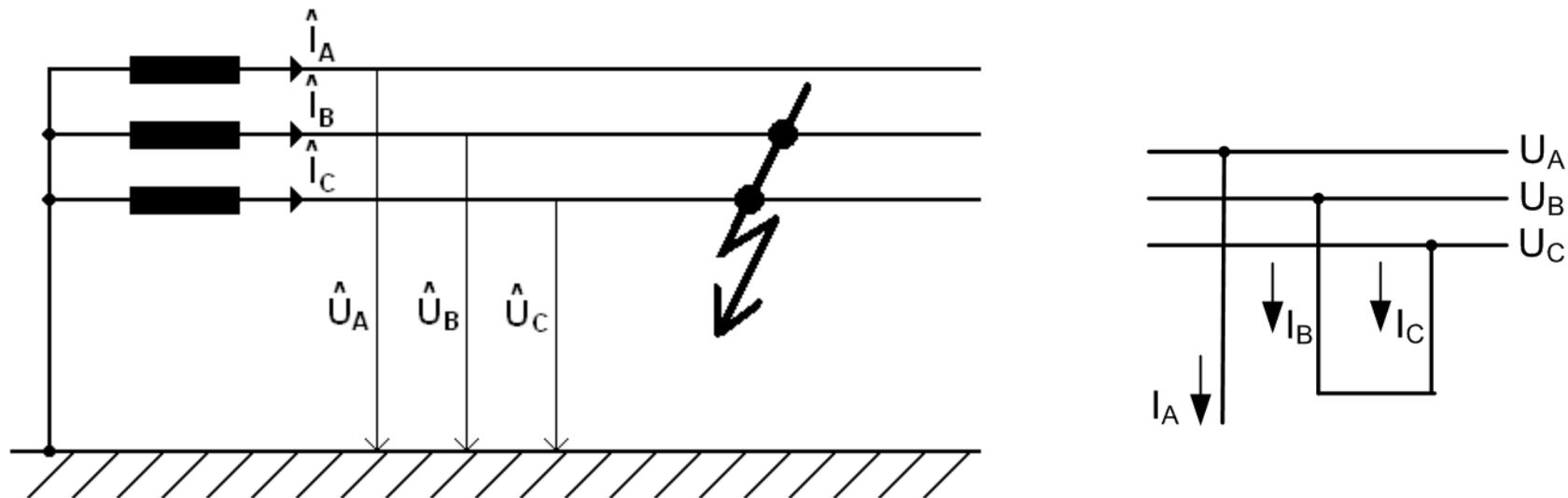
## Current phase diagram



## Voltage phase diagram



## Phase-to-phase short-circuit



3 char. equations

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

Hence 6 equations for 6 unknowns

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

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

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

## Components

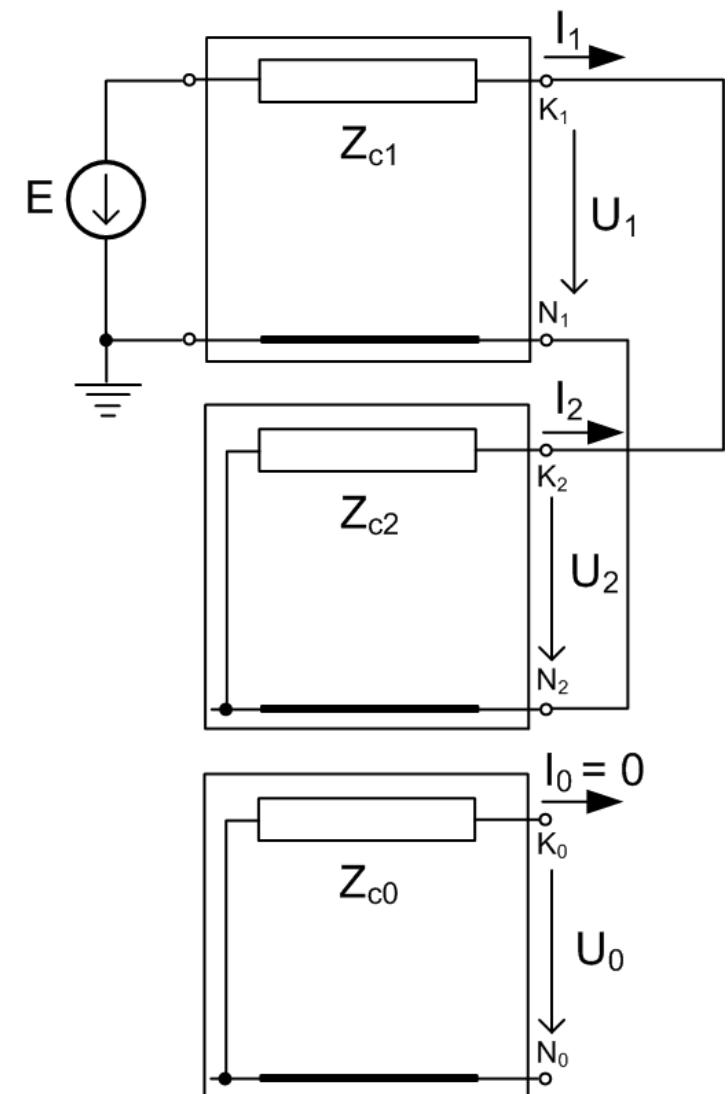
$$(I_{120}) = \frac{1}{3} \begin{pmatrix} 1 & \hat{a} & \hat{a}^2 \\ 1 & \hat{a}^2 & \hat{a} \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ \hat{I}_B \\ -\hat{I}_B \end{pmatrix} = \frac{1}{3} \begin{pmatrix} j\sqrt{3}\hat{I}_B \\ -j\sqrt{3}\hat{I}_B \\ 0 \end{pmatrix}$$

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

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

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

Positive and negative components are parallel.



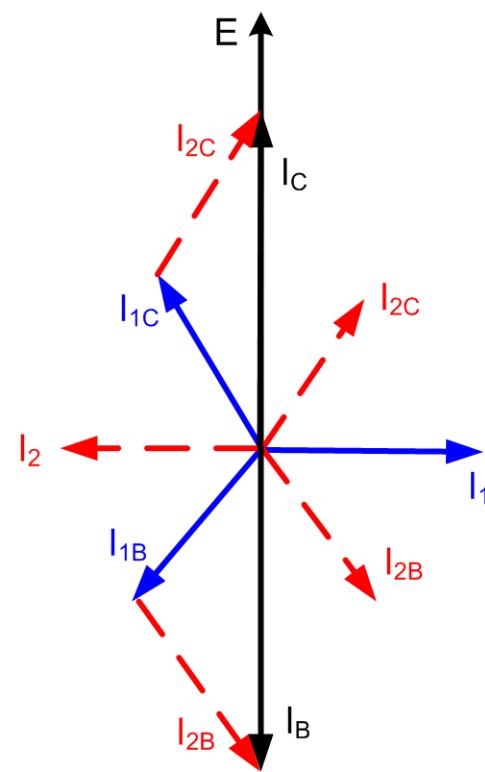
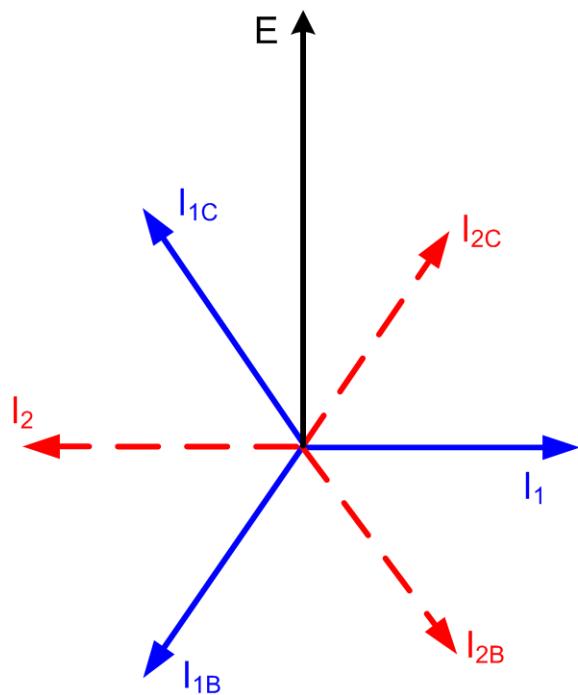
## Short-circuit current

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

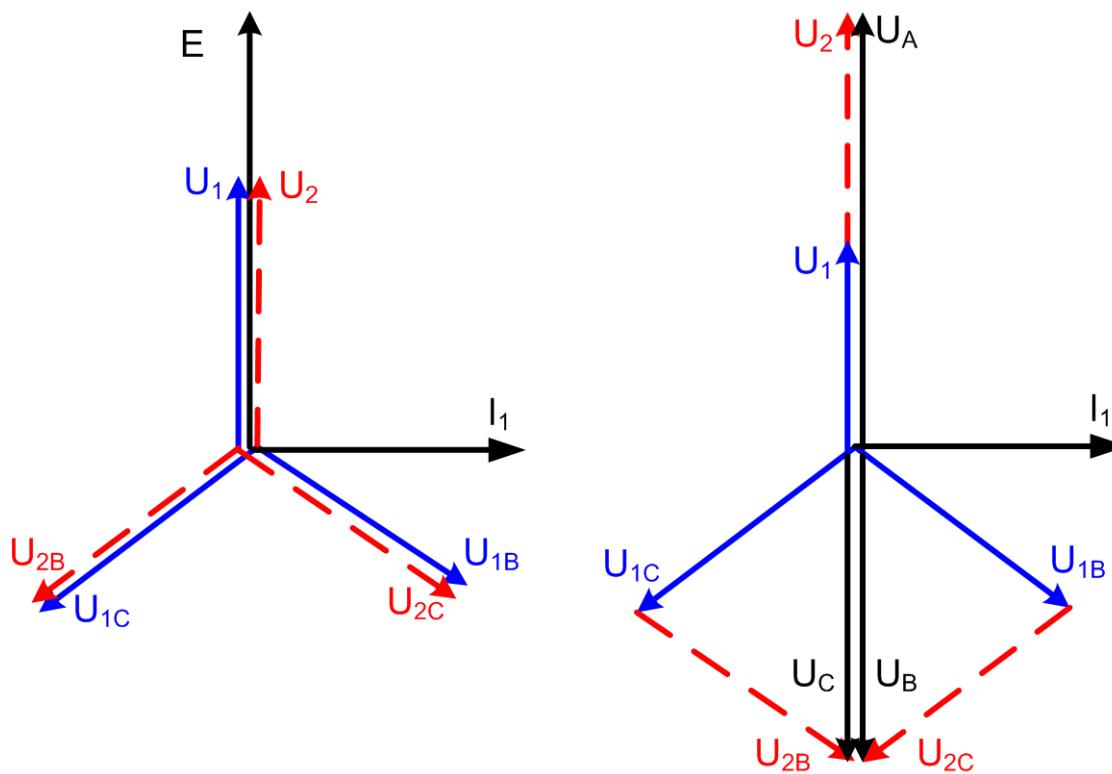
$$\hat{I}_A = 0; \quad \hat{I}_B = \frac{-j\sqrt{3}\hat{E}}{\hat{Z}_1 + \hat{Z}_2}; \quad \hat{I}_C = \frac{j\sqrt{3}\hat{E}}{\hat{Z}_1 + \hat{Z}_2}$$

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

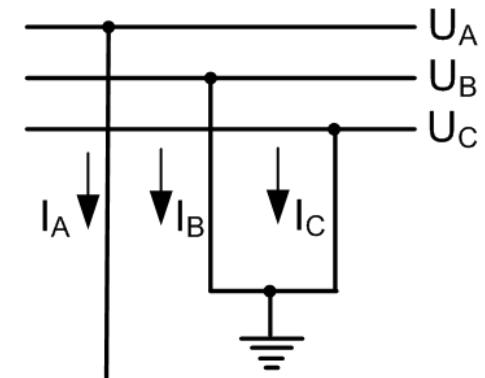
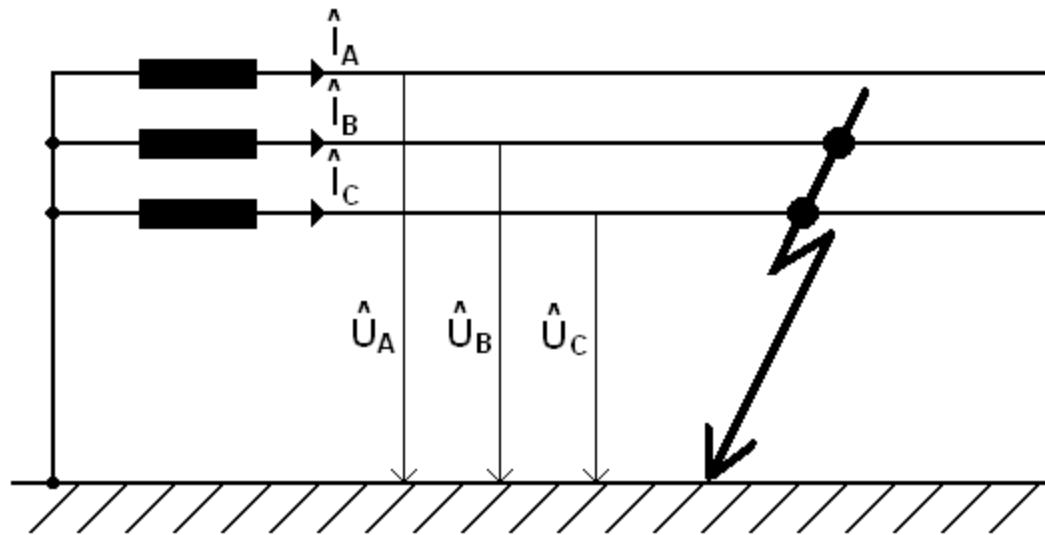
## Current phase diagram



## Voltage phase 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

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

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

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

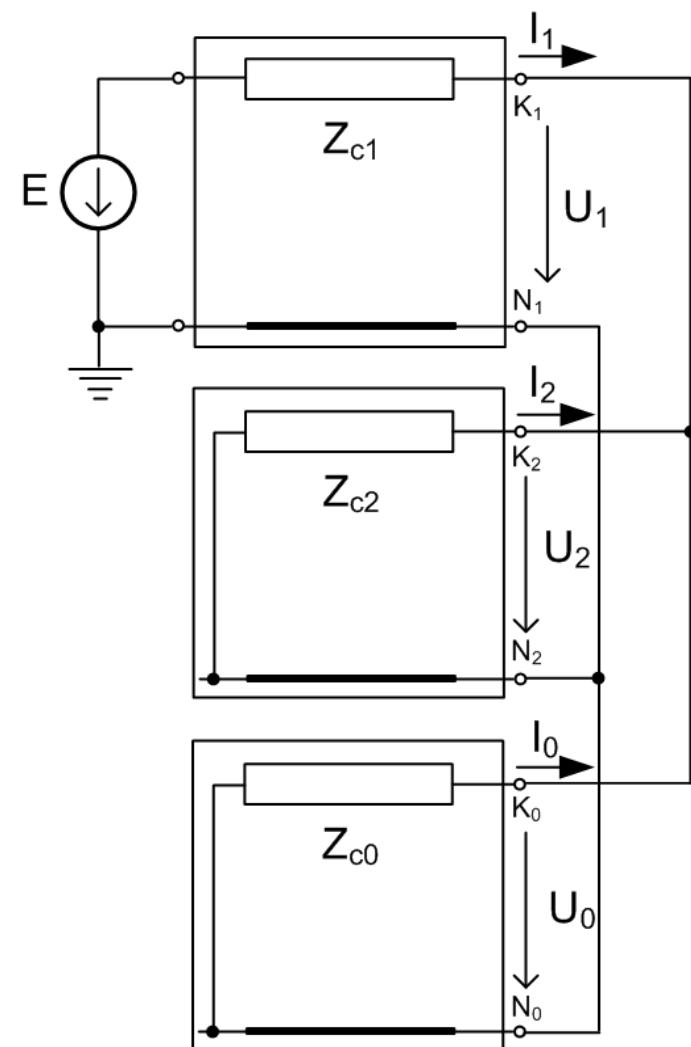
## Components

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

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

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

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



All three components are parallel.

Short-circuit current

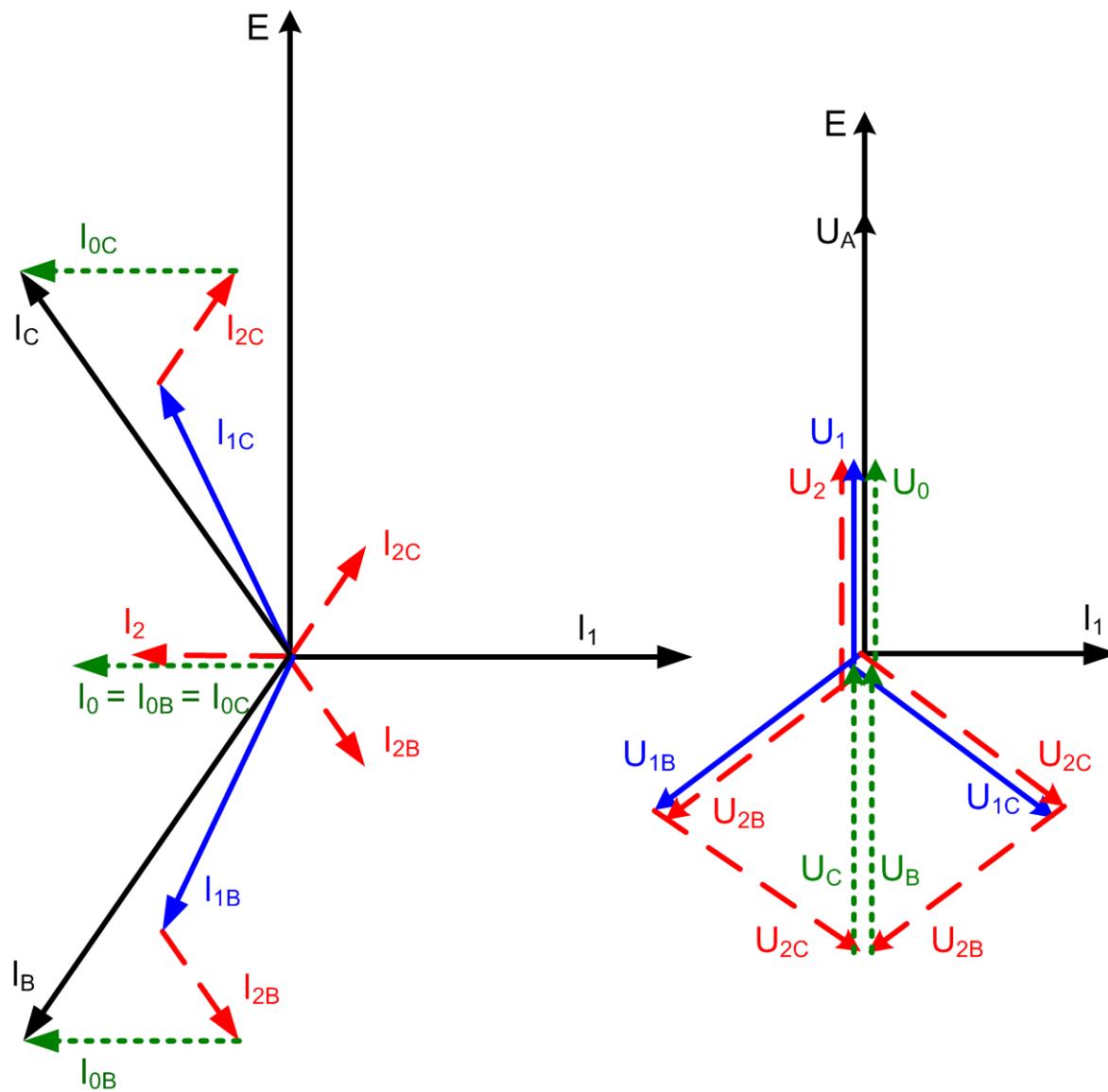
$$(I_{ABC}) = (T)(I_{120})$$

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

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

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

## Phase diagram



## Components in 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 (line-to-line)	$U_v$ (V)
base current	$I_v$ (A)
base impedance	$Z_v$ ( $\Omega$ )

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

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

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

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

2ph short-circuit

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

Note: Sometime is respected load of generator, more precisely generators higher voltage than nominal.

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

$$k > 1$$