ESF II project of the University of West Bohemia in Pilsen
reg. number: CZ.02.2.69/0.0/0.0/18_056/0013239



THEORY OF TRANSMISSION AND DISTRIBUTION OF ELECTRIC ENERGY

11th lecture - theory

2

Content

- Failure states in electrical networks
  - Causes of origin, classification of failures
  - Decomposition of asymmetric system into symmetrical components
    - method of Fortescue (procedure, example)
- Short-circuits
  - Origin, types, effects
  - Running of short-circuit current
  - Effects of short-circuit currents (dynamic, thermal)
  - Calculation of short-circuit currents (solution procedure, examples)
    - Initial short-circuit current I_k''
    - Short-circuit current – 3ph, 2ph, 1ph (event. 1ph ground fault - repetition)

3

Failure states in electric networks – causes of origin

Origin where :

- on **overhead** or **cable** lines,
- even in **electric stations**

- Of the total number of failures, approximately:
  - overhead lines … 66 %,
  - cable lines … 21,5 %
  - electric station … 12,5 %

  } see tab. 9.1

The most common causes of long-term disorders - see also tab. 9.1.

4

Failure states in electric networks – causes of origin

Origin by influence:

- **extraordinary atmospheric conditions** (lightning, wind, icing, flood)
  - short-term disorder
  - equipment damage with long-term consequences
  - event. triggering another fault condition (network overload, short-circuits, voltage fluctuations, system breakdown)
- **human factor** (improper handling in the substation, incorrect dispatching decision, poor maintenance of equipment, deliberate destruction of equipment)

⇓

Consequence - change of quantities from **operating** on **disorder**.

5

Failure states in electric networks – causes of origin

Causes of origin	Object			
	overhead lines	cable lines	electric station	in sum
atm. overvoltage	38	1	7	46
ext. interventions	16	11	1	28
material defects	5	5	1	11
oper. and mainten. errors	4	0,5	2,5	7
others	3	4	1	8
total	66	21,5	12,5	100

Tab. 9.1: The approximate number of errors [%]

6

Failure states in electric networks – division

- **In terms of the change of basic quantities:**
  - faults leading to **increased current** (usually simultaneously **reduced voltage**)
    - **overload device**
    - **short-circuit**
  - faults leading to **voltage increases** (closer in **KEE/TVN**)
    - **atmospheric overvoltage**
    - **Overvoltage caused by switching** large inductances (transformers) and capacitances (long high-voltage lines)

7

Failure states in electric networks – division

- **By symmetry :**
  - **symmetrical** (they are the same in all phases):
    - **three-phase** failure
  - **asymmetrical** (they are different in different phases):
    - failure in **two** or **one** phase

8

Failure states in electric networks – division

- **We further divide the faults into:**
  - **transverse** (between node and ground, between phases)
    - phase **connection**, phase connection and earth
  - **lengthwise** (between 2 nodes)
    - **interruption** of one or more phases

9

Failure states in electric networks

- Origin of the disorder ⟹ transient storyline (closer in KEE/PJS)
- In TPR we solve ratios (sufficient for the design of the equipment):
  - in the first moment of failure
  - steady state after failure
- The most common serious disorder causing large overcurrents – **short-circuit** (= usually without impedance connection phases, event phase and ground).

Note: Arc short circuit - phases are connected through a certain Z.

10

Short-circuits – origin and types

- = the most widespread disorders in ES (transmission and distribution)
- they arise from unwanted connections
  - phases each other
  - phase with ground (in system with effectively grounded node)

Types of short-circuits :

- 3ph (symmetrical)
- 2ph, 2ph grounded, 1ph (asymmetric)

Note: In MV networks (with tansformer node isolated or inefficiently grounded) his is not a 1f short circuit, but a 1ph ground connection ← current is closed only through capacities (see introductory lecture)

11

Short-circuits – further division

We also distinguish short-circuits (see ČSN EN 60909-0):

- near current sources(important influence of the alternator)
  - ∃ 2 destination options :
    - contribution of one synchronous machine to the initial short-circuit current exceeds double I_n machine's motor
    - he motor contribution is greater than 5% of the initial short-circuit current without these motors
- remote from the power source (important influence of the system) – symmetrical component size short-circuit. current remains constant
  - short-circuit powered from the mains through the transformer = short-circuit electrically remote
- according to this division we evaluate the effects, of the short-circuit (for short-circuiting a simpler calculation)

12

Short-circuits – occurrence

- On overhead lines (see tab. 9.2)
  - most common 1ph fault (short-circuit, ground fault)
  - 3ph short-circuit – quite a few
  - the higher the mains voltage, the higher the 1ph short-circuit rate
- In cable networks
  - 3ph most short circuits (approx. 90% at MV)
  - small distances between phases - the arc will damage the insulation of all phases → the other types of short-circuit pass easily in 3ph

13

Short-circuits – occurrence

Network	Short-circuit			
	3ph	2ph	2ph gr.	1ph
HV	10	8	17	65 */
110 kV	0,5	5	3,5	91
220 kV	1	1	5	93

Tab. 9.2: Approximate frequency of occurrence of short-circuits in [%]

- Based on the total annual number of short-circuits of the respective voltage level

*/ in HV networks with transformer node grounded by arc suppression coil or isolated ground fault

14

Short-circuits – why we solve?

We need to know the short-circuit conditions in networks :

a/ for

- dimensioning of power lines on the effects of short-circuit currents
- the choice of electrical devices and the design of the distribution equipment (eg busbars) in power stations

b/ for

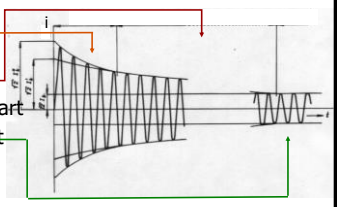
- selection and setting of protections, that switch off short circuits
- choice of fuses, circuit breakers etc.

15

Progress of short-circuit current

Progress of short-circuit current is a transient process!!!

- We watch:
  - It´s beginning
  - The transitional part
  - steady-state short circuit (transient events dampend)



- The following is a characteristic course of two extreme cases – the most favorable and the least favorable

16

Progress of short-circuit current

The most favorable case

- only the symmetrical AC component of the short-circuit current is generated the DC component does not develop (see Fig. 9-1)
- the initial conditions for emergence 13/5000
- this short-circuit:
  - before the short circuit the system is idling (i.e. a short-circuit in the unloaded branch)
  - R in a negligible circuit, we only consider X
  - → short-circuit current - inductive character, delayed with voltage about π/2, the sinusoidal voltage passes at the moment of a short circuit MAXIM → the short-circuit starts at ZERO

17

Progress of short-circuit current – the most favorable case

- **Folders:**
  - impact:
    - sine wave about frequency of the system, exponentially decreasing
  - transition:
    - sine wave at the system frequency, decreasing exponentially
  - steady:
    - sine wave with constant amplitude and frequency of the system

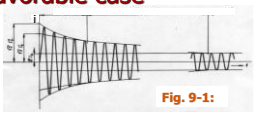


Fig. 9-1:

18

Progress of short-circuit current

Least favorable case

- the DC component also develops $I_{d.c.}$ (see Fig. 9-3)
- initial conditions:
  - again occurs on an unloaded branch
  - we neglect R
  - the sinusoidal voltage passes ZERO when the short circuit occurs → the short-circuit current starts with MAXIM

19

Progress of short-circuit current – in general

- Resulting short-circuit current (Fig. 9-4) = sum of alternating (Fig. 9-2) and dc components (Fig. 9-3)
- In every phase - the short-circuit currents are different → we consider the worst condition (with the most developed DC component)
- Determining the exact course of the DC component is almost impossible → when solving short-circuit conditions we use the value of short-circuit current for symmetrical AC, tzv. so called shock component at the moment of short-circuit

20

Progress of short-circuit current – Fig.

Fig. 9-1: The course of symmetrical short-circuit current

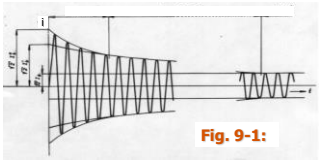
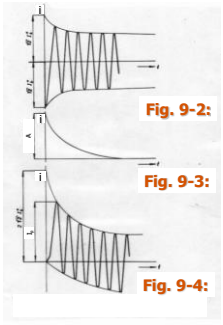


Fig. 9-4: The course of asymmetric short-circuit current



21

Short-circuit – initial phenomena

- the impedance of the affected part of the network decreases
- currents increase (current increase above nominal value = overcurrent, extreme value of overcurrent = short-circuit current)
- the voltage at the places of the short-circuit decreases
  - we usually consider a perfect short-circuit (= without impedance connection) → the short-circuit voltage in the damaged phases is zero

22

Short-circuit – effects

- Immediate
  - dynamic, thermal (breaking of supporting insulators, deformation of busbars, winding damage, wire remelting, contact sintering)
- Malfunctions of equipment operation
  - voltage drop (affect the performance of connected appliances)
  - Short-circuit disconnection(power outage)
- Danger to persons and surroundings
  - step voltage at ground at short-circuit
  - the effect of short-circuit currents on parallel lines

23

Short-circuit – immediate effects

- Most endangered instead of short-circuit – flowes here many times the operating current → the occurrence of a more serious disorder → it is necessary to determine in advance what thermal and mechanical a correctly design the equipment (it will not be damaged)
- The dimensioning and design of mesh elements is based on the calculation called Initial short-circuit surge current I_k''

24

Calculation of short-circuit currents

- The purpose of short-circuit calculations is to determine:
  - least favorable short-circuit conditions (for **sizing** the device)
  - short-circuit conditions under the most favorable conditions (for **protection settings**, tability calculations etc.)
- They are usually determined :
  - initial surge short-circuit current I_k'' [A]
    - we perform so-called short-circuit calculation
  - surge short-circuit current I_p [A]
  - equivalent warming short-circuit current I_{th} [A]
  - switching off short-circuit current I_b [A]

25

Calculation of short-circuit currents - assumptions

- the parameters of the power system elements do not change during the short-circuit
- the system before the short-circuit is symmetrical or symmetrized
- short-circuits affecting more than one phase occur at the same site and simultaneously
- impedance is neglected sequential and reverse component systems connected between phase and ground (capacitors, chokes, line capacities, magnetization branches of transformers, etc.)
- non-motor loads are not considered connected in the network section where the short circuit occurred (e.i. consumption)

26

Initial short-circuit current I_k''

= effective value alternating symmetrical components short-circuit current when the short circuit occurs

- Calculate:

$$I_k'' = \frac{U_{výp}}{Z_k} = \frac{c \cdot U_n}{\sqrt{3} Z_k} = \frac{c \cdot S_v}{z_k \cdot \sqrt{3} \cdot U_v} = \frac{c \cdot I_v}{z_k} \qquad S_v = \sqrt{3} U_v I_v \quad (*)$$

kde:

- $U_{výp}$ ... so-called computational stress $U_{výp} = \frac{c \cdot U_n}{\sqrt{3}}$ (phase value)
- U_n ... the rated voltage at the short-circuit point
- Z_k [Ω] ... short-circuit impedance $Z_k = z_k \frac{U_v^2}{S_v}$
- z_k [p.j.] ... short-circuit impedance
- c ... multiple constant see tab. 9.3

27

Initial short-circuit current I_k''

Zdroj	Součinitel c pro výpočet zkratových proudů	
	maximální	minimální
turboalternátory	1,13	1
hydroalternátory	1,16	1
synchronní kompenzátory	1,2	1
synchronní motory	1,2	1
soustava nn	1	0,95
soustava vn, 110, 220 a 400 kV	1,1 (1,05)	1
asynchronní motory	0,9	-

Tab. 9.3:

28

Initial short-circuit current I_k''

Calculation procedure:

- from the wiring diagram (in the most unfavorable configuration) we create a **substitute diagram** with impedances either v [Ω], or in relative units (relative to the selected reference power S_v and related voltage $U_v = U_n$ at the place of the short-circuit), these impedances must be recalculated to 1 voltage level
- from the substitution scheme we determine **the total impedance** of the short circuit, ie the impedance between the place of the short circuit and ground
- according to that relationship **(*) we calculate I_k''**

29

Calculation of short-circuit currents
– create a substitute schema

- Differences from surrogate schema for operating states in EPS:
  - there is no lateral admittance at both the line and the transformer
  - no consumption– except for motors that are also a source of short-circuit current (see below - note /*)
  - we replace the system and alternator with passive elements and we ground them
  - put the voltage source into the short-circuit $U_{výp}$ (phase) → current flows from this point only in branches to short-circuit current sources (system, alternator, motor)

30

Calculation of short-circuit currents – create a substitute schema

- Differences from surrogate scheme for operating states in EC – contin.:

/* note: The AM contribution need not be considered, if :

- contribution of engines to I_k'' set without these engines < 5%
- the voltage at the place of the short-circuit does not drop at its origin under 90% U_n
- 2 transformers in series are inserted between the short circuit and the motor
- it is a short-circuit calculation in the public LV distribution network

- The calculation of short-circuit conditions in the network is described in detail in the standard ČSN EN 60 909-0 (previously ČSN 33 30 20) and "Calculation of the effect of short-circuit conditions" is given in the standard ČSN EN 60 865-1 (previously ČSN 33 30 40)

31

Calculation of short-circuit currents – create a substitute schema

Note:

- Any short circuit element can be neglected:
  - R ... if it is $R \leq 0{,}3.X$ (VHV, HV)
  - X ... if it is $X \leq 0{,}3.R$ (LV)
- In the surrogate scheme of the network solution, we represent the machines with longitudinal impact reactance x_d''
  - for turbo-alternator $x_d'' = 12\ \%$
  - for hydro-alternator $x_d'' = 18\ \%$
- The transfers:
  - with p_s we do not know which branch will be set when a short circuit occurs
  - p_f It is convenient to use → The calculation will be simplified, the error will not be great (short circuit → only slightly oversized)

32

Effects of short-circuit currents

- **Dynamic (mechanical) effects**
  - Generation by electromagnetic effects of currents in adjacent conductors (they are directly proportional to them)
  - The greatest amplitude of the shock is caused by the first amplitude of the short-circuit current, the so-called. surge short-circuit current (dynamic) I_p
    - = max. value of unbalanced short-circuit current (see Fig. 9-5), has both components (DC and AC)
    - generates forces which, if sizing incorrectly, can cause mechanical damage to the equipment

33

Effects of short-circuit currents - dynamic

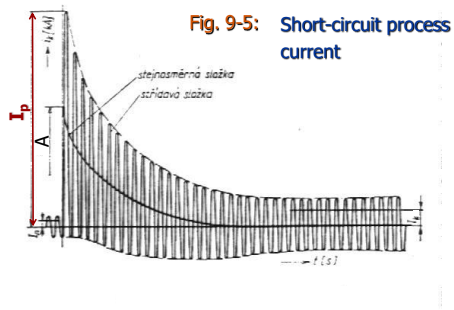


Fig. 9-5: Short-circuit process current

34

Effects of short-circuit currents - dynamic

- A multiple constant **K** is introduced to calculate the **impact short-circuit current** I_p (see **tab. 9.4**), which represents the **DC component** of the short-circuit current and which can be used I_p simply calculate by relation:

$$I_p = K \cdot \sqrt{2} \cdot I_k''$$

- where:
  - I_k'' ... initial shock short-circuit current
  - **K** ... constant dependent **distance from the place of the short circuit**

Místo zkratu	K
Na svorkách alternátoru > 55 MW	1,97
Na svorkách alternátoru < 55 MW	1,94
Soustava vvn, zvn	1,7
vn	1,6
nn	1,4
nn (kabelové sítě)	1,3

Tab. 9.4:

Effects of short-circuit currents

- **Thermal effects**
  - Given by the time-varying short-circuit current for the duration of the short-circuit T_k on the conductor

$$I_{th} = \sqrt{\frac{\int_0^{T_k} i_k^2(t)dt}{T_k}}$$

  - They are expressed by means of so-called. **equivalent warming short-circuit current I_{th}**
    - **= constant current**, which causes **at the same time the same conductor warming** as the variable short-circuit current (fictitious RMS value of constant current) - see **Fig. 9-6**

$$I_{th} = k_e \cdot I_k''$$

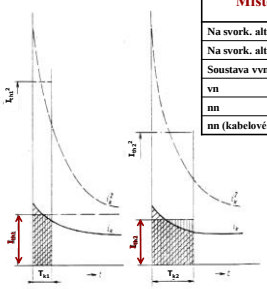
kde: k_e ... constant dependent **at the time of the short circuit** (see **tab. 9.5**)

36

Effects of short-circuit currents - thermal

Místo zkratu	k_e				
	T_k = 0,05 s	0,1	0,5	1	3
Na svork. alternátoru>55 MW	2,76	2,07	1,29	1,15	1,05
Na svork. alternátoru<55 MW	2,05	1,61	1,15	1,08	1,03
Soustava vvn, zvn	1,25	1,13	1,03	1,01	1
vn	1,18	1,09	1,02	1,01	1
nn	1,1	1,05	1,01	1	1
nn (kabelové sítě)	1,08	1,04	1,01	1	1

Tab. 9.5:



Obr. 9-6: Equivalent warming current for different duration short circuit

37

Effects of short-circuit currents - thermal

- Check for wire warming caused by a short circuit. we provide the currents:
  - for **cables** and **insulated conductors** (exceptionally bare) MV
  - for low-voltage lines where protection is a ballast fuse or circuit breaker, it is not made
- The duration of the short-circuit is so short, that **the heat generated is not sufficient to dissipate** into the environment → it accumulates in wires → the wire increases its temperature from ϑ_1 before shorting to ϑ_2 after short-circuit.

  ⇓
- Insufficient dimensioning → **destructive effects** (insulation damage, at bare conductors reduce mechanical strength)

38

Unsymmetrical failure conditions - in general

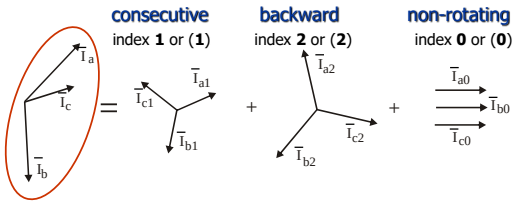
- Any asymmetries n the system are not limited to the place of origin, but spread throughout the network.
- So that EC calculations can only be performed for one phase - **the network must be symmetrical**
  - passive parameters (R, L, C, G) - the same for each phase
  - active parameters ($\bar{U}, \bar{I}$) - equally large, shifted by 120°, 240°
- Symmetrization of passive parameters - structures
  - E.g. for lines - transposition of conductors
- In case of asymmetries of active parameters symmetry is performed by decomposing asymmetries into symmetrical components
  - Use the Fortescue method

39

Unsymmetrical failure conditions - decomposition of asymmetric system into symmetrical components

Fortescue method:

- Unsymmetrical system (phasor star $\bar{I}$ or $\bar{U}_f$) is divided into symmetrical systems (see Fig.):



40

Unsymmetrical fault conditions – decomposition of asymmetric system into symmetrical components (Fortescue)

- The conversion of the phase quantities of the asymmetric system to the quantities of the individual component systems and back is done by means of a matrix
- Applies $\bar{I} = \underline{F} \cdot \bar{I}_{(s)}$, where: (for phase a)

$$\bar{I} = \begin{bmatrix} \bar{I}_a \\ \bar{I}_b \\ \bar{I}_c \end{bmatrix} \quad \bar{I}_{(s)} = \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ \bar{I}_0 \end{bmatrix} \quad \underline{F} = \begin{bmatrix} 1 & 1 & 1 \\ \bar{a}^2 & \bar{a} & 1 \\ \bar{a} & \bar{a}^2 & 1 \end{bmatrix}$$

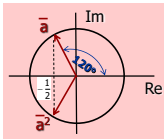
Unit phasor expressing:

- turn o 120 °

$$\bar{a} = e^{j120^\circ} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

- turn o 240 °

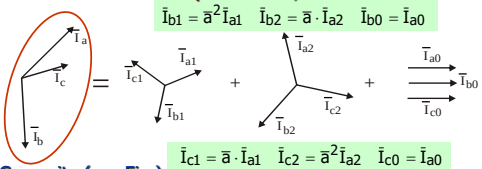
$$\bar{a}^2 = e^{j240^\circ} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$



41

Unsymmetrical fault conditions - decomposition of asymmetric system into symmetrical components (Fortescue)

$$\bar{I}_{b1} = \bar{a}^2\bar{I}_{a1} \quad \bar{I}_{b2} = \bar{a}\cdot\bar{I}_{a2} \quad \bar{I}_{b0} = \bar{I}_{a0}$$



$$\bar{I}_{c1} = \bar{a}\cdot\bar{I}_{a1} \quad \bar{I}_{c2} = \bar{a}^2\bar{I}_{a2} \quad \bar{I}_{c0} = \bar{I}_{a0}$$

Can write (see Fig.):

$$\bar{I}_a = \bar{I}_{a1} + \bar{I}_{a2} + \bar{I}_{a0} = \bar{I}_1 + \bar{I}_2 + \bar{I}_0$$

$$\bar{I}_b = \bar{I}_{b1} + \bar{I}_{b2} + \bar{I}_{b0} = \bar{a}^2\bar{I}_{a1} + \bar{a}\cdot\bar{I}_{a2} + \bar{I}_{a0} = \bar{a}^2\bar{I}_1 + \bar{a}\cdot\bar{I}_2 + \bar{I}_0$$

$$\bar{I}_c = \bar{I}_{c1} + \bar{I}_{c2} + \bar{I}_{c0} = \bar{a}\cdot\bar{I}_{a1} + \bar{a}^2\bar{I}_{a2} + \bar{I}_{a0} = \bar{a}\cdot\bar{I}_1 + \bar{a}^2\bar{I}_2 + \bar{I}_0$$

Everything is phase-related a => index a we can omit

42

Unsymmetrical fault conditions – decomposition of asymmetric system into symmetrical components (Fortescue)

- When solving asymmetric failures more often we need to decompose the asymmetric system into symmetrical components, ie we use the relation (matrix notation):
- Inverse matrix : $\underline{\bar{F}}^{-1} = \frac{1}{3}\begin{bmatrix} 1 & \bar{a} & \bar{a}^2 \\ 1 & \bar{a}^2 & \bar{a} \\ 1 & 1 & 1 \end{bmatrix}$

$$\underline{\bar{I}}_{(s)} = \underline{\bar{F}}^{-1} \cdot \underline{\bar{I}}$$

- itemized:

$$\bar{I}_1 = \frac{1}{3}(\bar{I}_a + \bar{a}\cdot\bar{I}_b + \bar{a}^2\bar{I}_c)$$
$$\bar{I}_2 = \frac{1}{3}(\bar{I}_a + \bar{a}^2\bar{I}_b + \bar{a}\cdot\bar{I}_c)$$
$$\bar{I}_0 = \frac{1}{3}(\bar{I}_a + \bar{I}_b + \bar{I}_c)$$

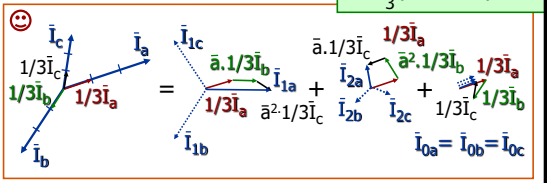
we will use for numeric i graphic decomposition

43

Unsymmetrical fault conditions - decomposition of asymmetric system into symmetrical components (Fortescue)

- Numerical decomposition
  – dosadíme do vztahů:
- Graphic decomposition
  – rovněž dle vztahů:

$$\bar{I}_1 = \frac{1}{3}(\bar{I}_a + \bar{a}\cdot\bar{I}_b + \bar{a}^2\bar{I}_c)$$
$$\bar{I}_2 = \frac{1}{3}(\bar{I}_a + \bar{a}^2\bar{I}_b + \bar{a}\cdot\bar{I}_c)$$
$$\bar{I}_0 = \frac{1}{3}(\bar{I}_a + \bar{I}_b + \bar{I}_c)$$



44