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EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education



THEORY OF TRANSMISSION AND DISTRIBUTION OF ELECTRIC ENERGY (KEE/TPDE)

1st lecture

Pavla Hejtmánková

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Content

- Organizational matters
- Course content
- Characteristics of the Czech electric power system (EPS CZE)
- Division of networks according to different aspects, i.e. according to:
  - function and voltage levels
  - construction (overhead lines X cables - material, properties, insulation)
  - wiring arrangement (constructional X operational)
  - connection of transformer node

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Organizational matters (1)

Contact: EK 306
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CZ Literature:

Mertlová, Hejtmánková, Tajtl: **Teorie přenosu a rozvodu elektrické energie**, ZČU v Plzni, 2008

http://portal.zcu.cz/ **(courseware)**

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Organizational matters (2)

- **Credit**
  - timely submission of correctly completed individual works
- **Exam**
  - mostly written
  - 2 parts
    - example
    - theoretical questions (from a predefined issue)

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Course content

- theoretical analysis of steady-state processes in symmetrical and asymmetrical networks of all voltage levels in normal operating and failure states
- the course extends the basic theoretical knowledge acquired in lower-year subjects to the real problems of electric networks of the Czech electrical power system (EPS)
- the subject matter will be supplemented by specific examples

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Characteristics of EPS CZE (1)

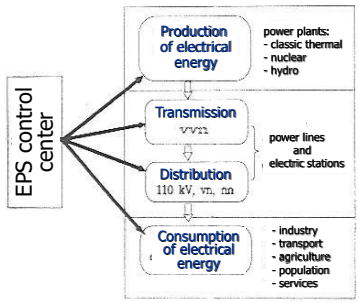
- three-phase AC (alternating) network
- 3 basic elements (schematically see Fig. 1.1)
  - production of electric energy
  - transmission and distribution of electricity
  - electricity consumption

EPS target:

- ensure the electricity supply at the required time at the required location in the required quantity while maintaining the quality and reliability of the supply, with regard to economy

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Characteristics of EPS CZE (2) – Fig. 1.1



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Characteristics of EPS CZE (3)

- The main parts of the EPS include:
  - power lines
  - electric stations (for transformation or distribution; configuration changes, data collection, troubleshooting)
- Power lines + electric stations of the same voltage ⇒ electrical network
  - Networks of different voltage levels – interconnected by transformers (optionally by rectifiers)

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Characteristics of EPS CZE (4) – Tab. 1.1

- **Normalized voltage level** (voltage levels of electrical network EPS CZE are given by the standard ČSN IEC 38 33 01 20, previously ČSN 33 01 20)

Low voltage	**nominal**	**0,4** (/023)			0,50	0,69
(lv) (nn) [kV]	operating max.	**0,42** (/0,241)			---	0,73
Medium Voltage	**nominal**	3	**6**	**10**	**22**	**35**
(mv) (vn) [kV]	operating max.	3,6	**7,2**	**12**	**25**	**37**
High voltage	**nominal**	**110**			**220**	
(hv) (vvn) [kV]	operating max.	**123**			**245**	
Extra high voltage	**nominal**	**400**	**750**			
(ehv) (zvn) [kV]	operating max.	**420**	787 (an increase to 800 is expected)			

- Normalized scale indicates **associated voltages !!!**

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Characteristics of EPS CZE (5) – Tab. 1.2

- **Range of networks of individual nominal voltages**

Nominal voltage [kV]	**Range of lines** [km]	
	overhead	cable
750	**0**	**0**
400	**3617**	**0**
220	**1 909**	**0**
110	**14 111**	**96**
35	**8 781**	**1 145**
22	**49 000**	**15 089**
10	**139**	**1 584**
6	**0**	**190**
0,4	**64 239**	**85 935**

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Characteristics of EPS CZE (6) – tab. 1.3

Voltage level (kV)	Length of overhead routes (km)				
	ČEPS	ČEZ Distribuce	E.ON Distribuce	PREdistribuce	Total
Celkem	4 414	93 494	36 651	331	134 889
VVN	4 414	5 302	2 373	144	12 233
400	3 020	0	0	0	3 020
220	1 349	0	0	0	1 349
110	45	5 302	2 373	144	7 864
VN	0	40 203	18 107	107	58 417
35	0	9 781	0	0	9 781
22	0	30 283	18 107	107	48 497
10	0	139	0	0	139
6	0	0	0	0	0
5	0	0	0	0	0
3	0	1	0	0	1
NN 0,4	0	47 989	16 170	80	64 239

Voltage level (kV)	Length of overhead lines (km)				
	ČEPS	ČEZ Distribuce	E.ON Distribuce	PREdistribuce	Total
Total	5 610	98 003	38 678	505	142 796
VVN	5 610	9 811	3 914	301	19 637
400	3 617	0	0	0	3 617
220	1 909	0	0	0	1 909
110	84	9 811	3 914	301	14 111
VN	0	40 203	18 593	124	58 920
35	0	9 781	0	0	9 781
22	0	30 283	18 593	124	49 000
10	0	139	0	0	139
6	0	0	0	0	0
5	0	0	0	0	0
3	0	1	0	0	1
NN 0,4	0	47 989	16 170	80	64 239

zdroj dat: výkaz ERÚ-4

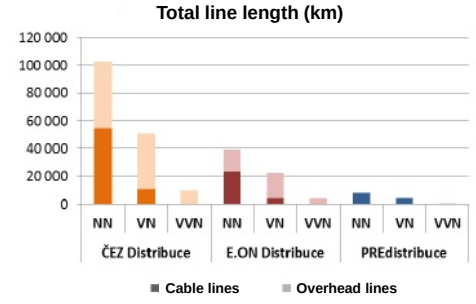
12

Characteristics of EPS CZE (7) – tab. 1.4

Voltage level (kV)		Length of cable lines (km) ČEPS	ČEZ Distribuce	E.ON Distribuce	PREdistribuce	Total
Total		0	65 208	27 175	11 682	104 065
VVN		0	23	10	63	96
	400	0	0	0	0	0
	220	0	0	0	0	0
	110	0	23	10	63	96
VN		0	10 448	3 827	3 759	18 034
	35	0	1 145	0	0	1 145
	22	0	7 504	3 827	3 758	15 089
	10	0	1 584	0	0	1 584
	6	0	189	0	1	190
	5	0	24	0	0	24
	3	0	1	0	0	1
NN	0,4	0	54 737	23 338	7 860	85 935

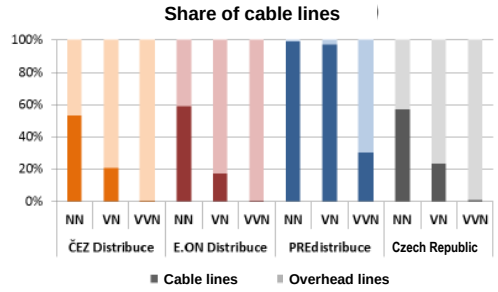
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Characteristics of EPS CZE (8) – Chart 1.1



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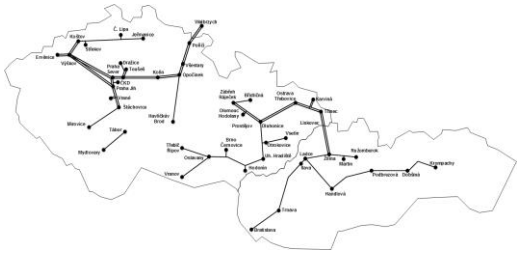
Characteristics of EPS CZE (9) – Chart 1.2



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EPS network development (1) – Fig. 1.2

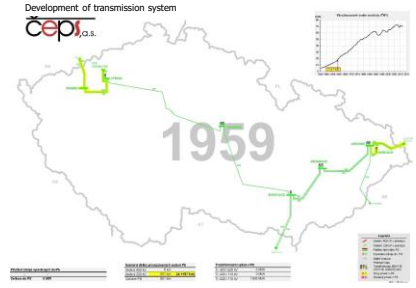
- 100 kV network in 1949



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EPS network development (2) – Fig. 1.3

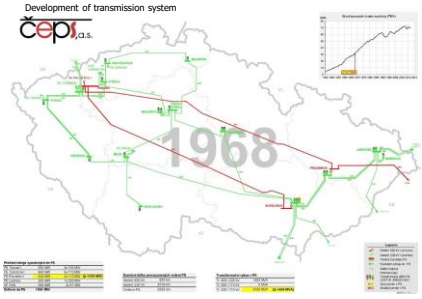
- TS 220 kV in 1959



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EPS network development (3) – Fig. 1.4

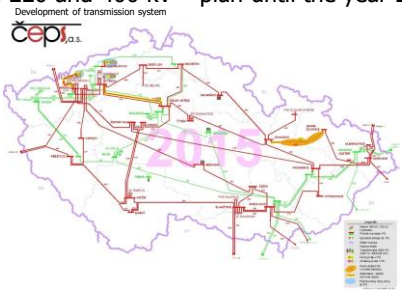
- TS 220 and 400 kV in 1968



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EPS network development (4) – Fig. 1.5

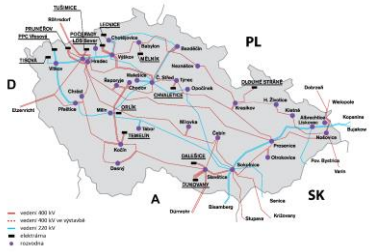
- TS 220 and 400 kV – plan until the year 2015



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EPS network development (5) – Fig. 1.6

- TS 220 and 400 kV – reality in the year 2015



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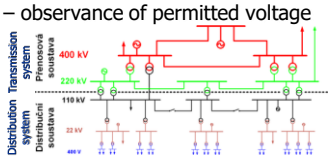
Division of networks according to function and voltage levels (1)

- **transmission networks** (400 kV and 220 kV) = superior system
  - interconnection of production and distribution nodes
  - connection of a large power plants
  - interconnected with foreign systems
- **distribution networks** (110 kV, mv (vn), lv (nn)) = distribution system
  - electricity supply to consumers
  - connected only small sources (industrial power plant, CHP unit = cogeneration, Renewable Energy using energy of water, wind, biomass, sun) mostly local character („distributed")

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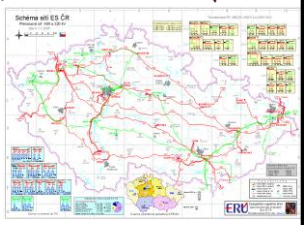
Division of networks according to function and voltage levels (2)

- For different voltage levels – **different importance of problem solving:**
  - **transmission system** – stability of el. energy (steady state reached during regulation), short-circuit currents
  - **mv (vn) networks** – short-circuit currents, restriction of loss
  - **lv (nn) networks** – observance of permitted voltage deviations
- **Fig. 1.7:** Block diagram



Division of net. according to function and vol. levels (3) – transmission system

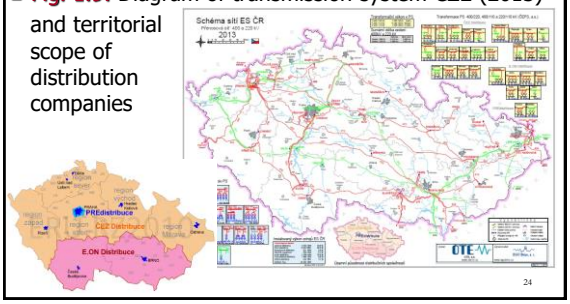
- **Basic task** – connection of mentioned nodes so that the distribution of power is in the area **optimal** in terms of production and transmission **costs**.
- **Fig. 1.8:** Diagram of transmission system CZE (2005)



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Division of net. according to function and vol. levels (4) – transmission system

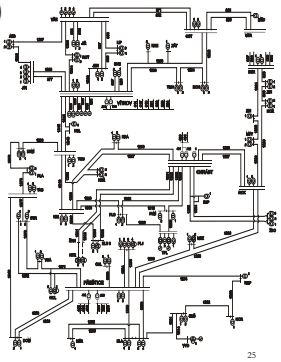
- **Fig. 1.9:** Diagram of transmission system CZE (2013) and territorial scope of distribution companies



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Division of net. according to function and volt. levels (5) – distribution system

- The main source of electricity for distribution networks is the superior system
- Fig. 1.10: Part of the distribution network 110 kV (Pilsen region)



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Requirements for distribution networks (1)

1) Quality of electrical energy

- constant frequency 50 Hz
- constant voltage in permitted limits

2) Reliability of electricity supply

- minimizing supply outages to customers
  - Possible measures:
    - backup of transformers and lines
    - better equipment
    - substations with multiple busbar systems
    - power supply from multiple nodes of the transmission system hv (vvn)
    - automation for instantaneous voltage recovery (e.g. so-called reclosing = OZ)

EPS Goals : Ensure the supply of electricity to consumers at the required time, in the required quantity and at the required location quality and reliability delivery, respecting the economy.

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Requirements for distribution networks (2)

3) Possibility to easily extend and restore devices

- connection of other objects → sufficient reserve in transformers and line cross-section

4) Simplicity and clarity of the network

- simple operation and maintenance → no errors
- lower number of workers
- increased operator safety
- easier protection in case of malfunctions × reliability

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Requirements for distribution networks (3)

5) Economic operation of the network
- economy of operation in different operating states (different loads) → minimizing losses (appropriate configuration)

6) Economic network design
- minimum investment in reinsurance 1) – 5)
  → compromise between costs (investment, operation = maintenance, losses), reliability and safety
- selection of voltage levels, number of transformers stations, size and number of transformers, line cross sections etc.

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Interconnection of foreign systems (1)
(more details are in subject KEE/MR)

- Until 1990:
  - Our EPS works in a synchronously interconnected power system PES CDO-MIR (interconnected energy systems of European countries associated in The Council for Mutual Economic Assistance (RVHP), managed by the Central Dispatching Organization)
  - Next interconnection realized with Austria and SRN using DC couplings (locally, transmission of lower power), synchronous connection was not technically possible
  - After the disintegration RVHP new conditions for extending cooperation with Western states

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Interconnection of foreign systems (2)

- In 1992 an association was established CENTREL states Czechoslovakia, Hungary and Poland with a view to raising the technical standard of its EPS and connecting synchronously to the Western Europe system.
- In 1998 after a successful trial operation of the system CENTREL interconnected with the Western European system UCPTE (Union for the coordination of production and transmission of electricity), founded in 1951.
- In 1999 the power generation control was separated and the interconnected transmission system began to be labeled only UCTE (Union for the coordination of transmission of electricity).

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Interconnection of foreign systems (3)

- On 1. 7. 2009 UCTE ceased to exist, all her tasks transferred to ENTSO-E.
- 19. 12. 2008 was established ENTSO-E = European Network of Transmission System Operators for Electricity
  - A grouping of 42 European electricity transmission system operators from 35 countries
  - Divided into five regional groups, which are derived from former associations
  - see Fig. 1.11

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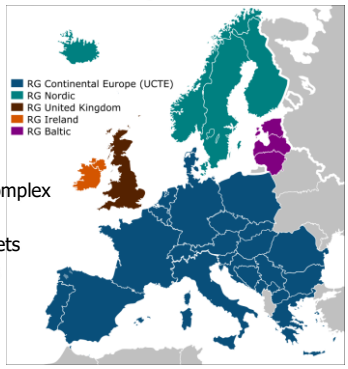
Interconnection of foreign systems (4)

- Fig. 1.11:

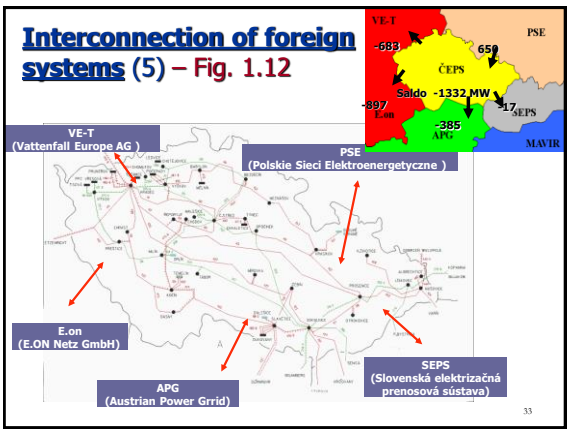
States associated in ENTSO-E

www.entsoe.eu

(it is possible to see complex illustration of whole transmission system nets operated by members)



Interconnection of foreign systems (5) – Fig. 1.12



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Network design (more in KEE/ELS, PIR, RS)

overhead lines X cables (1)

- Tasks of wires – create a well-defined path for electric current
  - Depending on the shape of the core (the core is usually made of Cu, Al, Fe)
    - wires
    - ropes
    - Shaped conductors (strips, rods, tubes, …)
  - Wire isolated from surroundings
    - insulating substrate (insulators)
    - full length insulating cover
  - The conductor may have several cores (1 core = conductive core + insulation)

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Network design (2) - overhead lines

- Brief characteristics
  - usually mv (vn) and above, in networks lv (nn) less often (in the village)
  - they consist of bare conductors (wires, ropes), poles and insulators
  - cheaper then cables
  - higher L a smaller C then cables
  - at the same distances and at the same cross section they have large voltage drop ΔU and greater reactive losses ΔQ
  - they are more defective, but many failures are of transient nature, troubleshooting is easier

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Network design (3) – cables

- Brief characteristics
  - prevail in networks lv (nn)
  - they are of different design
    - Al or Cu, wires or ropes, circular or sector cross-section
    - single core, multi core (3÷5 cores)
    - with different core insulation
    - with various shielding material, packaging, etc.
    - with different shielding arrangements
  - more expensive
  - smaller L, larger C than overhead lines, smaller ΔU and ΔQ
  - Fewer disturbances than overhead lines, but usually permanent

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Network division in terms of wiring arrangement (1)

2 basic species:

a) open network – electrical energy is supplied to the consumer in one way

b) closed network – power can always be provided from two or more sides

- Choosing a suitable network wiring arrangement - more aspects:
  - economy
  - safety
  - reliability etc.

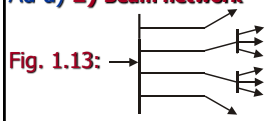
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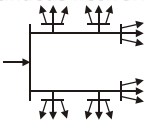
Network division in terms of wiring arrangement (2)

Ad a) 1) Beam network

2) Continuous network

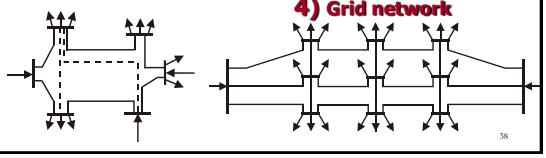
Fig. 1.13:





Ad b) 3) Circular network

4) Grid network



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Network division in terms of wiring arrangement (3)

Ad 1) **Beam networks**

- individual offtakes are supplied from one supply point (transformer station, switching station)
- each outlet (beam) separates, they cannot be connected
- easiest, cheapest
- lowest reliability of supply (failure lasting even several hours)

Ad 2) **Continuous networks**

- similar properties as 1)
- e.g. light distribution in villages

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Network division in terms of wiring arrangement (4)

Ad 3) **Circular networks** (looped)

- they are operated according to the main voltage level
  - unbuttoned – the rays (semi-loops) can be switched on
    - in the event of a failure, the affected part can be switched to the adjacent outlet
    - possibility of relieving overloaded outlets → even load distribution
  - pin together (even power distribution for both economy and reliability)
- more expensive to build, transparent and unpretentious operation

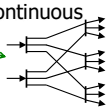
Ad 4) **Grid networks**

- wired, used in large cities
- expensive, reliable

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Network division in terms of wiring arrangement (5)

- Parent system 400 kV and 220 kV
  - structurally and operationally designed as circular
- Distribution system 110 kV and mv (vn)
  - structurally designed like beam, it allows a number of interconnections in two-beam and circular way, which allows backup in case of failure
  - operated beams, event. in the form of continuous divorce



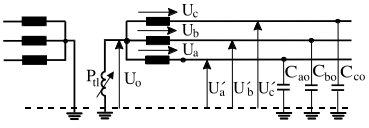
- Distribution networks (lv) nn
  - dense nets constructed as grid
  - operated mainly by radial and continuous distribution

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Network classification in terms of transformer node connection (1)

1/effectively grounded 3/inefficiently grounded

Fig. 1.14 a)



2/isolated

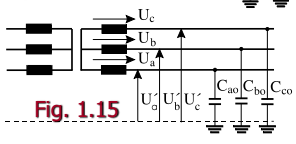


Fig. 1.14 b)

Fig. 1.15

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Network classification in terms of transformer node connection (2)

Ad 1) System effectively grounded – Fig. 1.14 a)

- In our country - network **hv, lv – 0,4 kV**
- the network has all transformer **zero points** connected **directly to the ground** (or via a small impedance × in our country - directly)
- when **connecting one phase** to ground we consider pure **inductive current** (neglect R) – **a single-phase short-circuit (1p) occurs**

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Network classification in terms of transformer node connection (3)

System effectively grounded – 1p short circuit

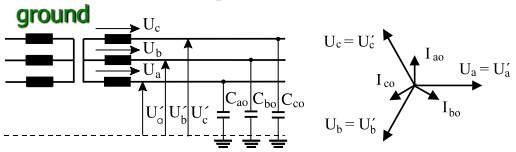
- Advantages:
  - the voltage of the healthy phases to ground remains at the phase value → **It is possible to dimension** the lines for **phase voltage** (cheaper)
  - the voltage at the transformer node is zero
- Disadvantages:
  - there is a significant ground (short-circuit) current→ **the cable must be disconnected quickly**

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Network classification in terms of transformer node connection (4)

Ad 2) System isolated - Fig. 1.15

- In our country - network **mv** (from 6 to 35 kV) and **lv** with voltage 0,5 kV (event. 0,69 kV), excep. 0,4 kV (large industrial plants)
- **transformer winding nodes** are **not connected to ground**

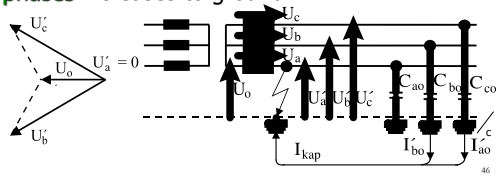


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Network classification in terms of transformer node connection (5)

Ad 2) System isolated

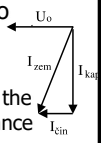
- when one phase is connected to ground, the voltage in the transformer winding node is grounded to ground, the voltage of healthy phases increases to ground

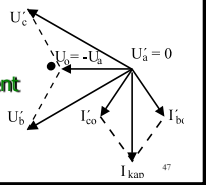


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Network classification in terms of transformer node connection - isolated system (ground connection) (6)

- the connection point of the conductor to the ground running through current predominantly capacitance character
  - given by capacitances of healthy phases of the whole network to ground and active resistance (R) circuit, through which the current is closed
  - R is often neglected, then we consider purely capacitive current and determine its magnitude from the phasor diagram





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Network classification in terms of transformer node connection - isolated system (ground connection) (7)

- Size of capacitive current is determined from a phasor diagram

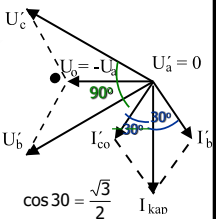
$$I_{kap} = |I'_{b0}|\cos 30 + |I'_{c0}|\cos 30$$

  - we assume symmetrical passive line parameters, then

$$C_{b0} = C_{c0} = C_0$$

$$|I'_{b0}| = |I'_{c0}| = U_{sdr} \cdot B_0$$

$$I_{kap} = 2 \cdot |I'_{c0}| \cos 30 = 2 \cdot |I'_{c0}| \cdot \frac{\sqrt{3}}{2} = \sqrt{3} \cdot U_{sdr} \cdot B_0$$



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Network classification in terms of transformer node connection (8)

- isolated system (ground connection)

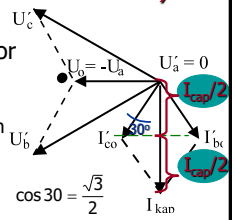
- **Size of capacitive current** is determined from a phasor diagram
  - we assume symmetrical passive line parameters, then

$$C_{b0} = C_{c0} = C_0$$

$$|I'_{b0}| = |I'_{c0}| = U_{sdr} \cdot B_0$$

$$\frac{I_{kap}}{2} = |I'_{c0}| \cos 30$$

$$I_{kap} = 2 \cdot |I'_{c0}| \cos 30 = 2 \cdot |I'_{c0}| \cdot \frac{\sqrt{3}}{2} = \sqrt{3} \cdot U_{sdr} \cdot B_0$$



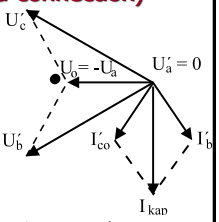
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Network classification in terms of transformer node connection - (9)

isolated system (ground connection)

- **Size of capacitive current** is determined from a phasor diagram

$$I_{kap} = \sqrt{3} \cdot U_{sdr} \cdot B_0 = \\ = \sqrt{3} \cdot U_{sdr} \cdot \omega \cdot C_0 \cdot l$$



- where:
  - C_0 [F/km] - capacity 1 km of line (non-rotating component)
  - B_0 [S] - susceptance of the entire leadership (non-rotating component)
    $B_0 = \omega \cdot C_0 \cdot l$ (about **1,2 – 1,5.10⁻⁶ S/km**)
  - l [km] - length of all lines connected to the ground connection

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Network classification in terms of transformer node connection (10)

- isolated system (ground connection)

- **Example**
- **Task:** Calculate the earth-fault current in the 22 kV grid if the length of all connected lines is 250 km and the capacitance susceptance for 1 km is $B_0 = \omega.C_0 = 1.5.10^{-6}$ S / km.

Solution:

$$I_{kap} = \sqrt{3} \cdot U_{sdr} \cdot \omega \cdot C_0 \cdot l = \\ = \sqrt{3} \cdot 22 \cdot 10^3 \cdot 1{,}5 \cdot 10^{-6} \cdot 250 = 14{,}29 \text{ A}$$

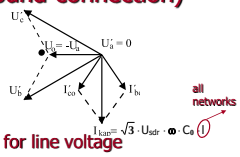
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Network classification in terms of transformer node connection (11)

- isolated system (ground connection)

Great advantage:

- the network **can be** further **operated**



Disadvantages:

- the line must be **dimensioned for line voltage**
- instead of ground contact, capacitive current (R-neglect) flows due to capacities of healthy phases to ground, **if it exceeds 10 A**, there may be a break in the conductor by the thermal effect of the current → **disconnecting the line**
- **Significant overvoltages** can occur (on healthy phases) → 2p ground can occur. short circuit → **disconnecting the line**

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Network classification in terms of transformer node connection (12)

Ad 3) System inefficiently grounded

- in our country also networks **mv** (as compensated)
- transformer nodes are connected via high impedance

  a/ connected through resistance

  b/ compensated - Fig. 1.14 b) – via a quench choke (adjustable), the so-called Petersen choke - an inductive current source for compensating the capacitive current flowing through the earth at ground fault **(Fig. 1.16 – further)**

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Network classification in terms of transformer node connection

- System inefficiently grounded (13)

ad b/ Networks compensated

- quench choke must be adjustable, her current $\mathbf{I_{tl}}$ must correspond to earth current $\mathbf{I_{cap}}$ (given by the total length of all connected lines that vary ← off or on individual lines, event. network expansion)

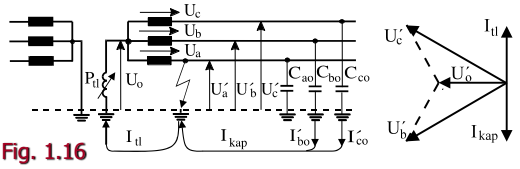


Fig. 1.16

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Network classification in terms of transformer node connection – according to voltage levels (Tab. 1.3) (14)

400 kV	effectively grounded system	ehv (zvn)
220 kV		hv (vvn)
110 kV		
35 kV	isolated system or inefficiently grounded system	mv (vn)
22 kV		
10 kV		
6 kV		
0,69 kV	isolated system	lv (nn)
0,5 kV		
0,4 kV	effectively grounded system (exceptionally isolated)	

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Next time

- Defining of the electrical network
- Calculation of overhead line passive parameters

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