LIÈGE université
Sciences Appliquées

Course ELEC0014 - Introduction to electric power and energy systems

Material for the examination on theory

December 2019

---

1. **Powers in balanced three-phase systems**

   Definition of the instantaneous, active, fluctuating, reactive and apparent powers entering a three-phase circuit.

   Relation with the power factor.

2. **Per-phase analysis**.

   Objectives.

   Per-phase equivalent of inductively coupled phases. Per-phase equivalent of capacitively coupled phases.

   Notion of cyclic impedance.

3. **Per unit system**

   Advantages, principle, choice of base values, reciprocal per unit system.

   Conversion in per unit of the following relations:

$$S = VI\cos(\theta - \psi) + jVI\sin(\theta - \psi) \qquad \psi_1 = L_{11}i_1 + L_{12}i_2 \quad \psi_2 = L_{21}i_1 + L_{22}i_2$$

$$v = Ri + L\frac{di}{dt} \qquad S = \bar{V}_a\bar{I}_a^\star + \bar{V}_b\bar{I}_b^\star + \bar{V}_c\bar{I}_c^\star \text{ (three-phase, balanced or not)}$$

4. **Voltage drop in an (R, L) link as function of active and reactive power flows**

   Respective effects of active and reactive power flows.

   Impossibility to transfer reactive power over long distances.

   Expressions of the active and reactive power flows as functions to the terminal voltage magnitudes and phase angles.

5. **QV characteristic of a network seen from one of its buses**

   Definition of QV curves.

   Linear approximation derived from Thévenin equivalent. Limits of validity. Impact of Thévenin reactance.

   Correction of voltage deviations by means of shunt inductors/capacitors.

6. **Short-circuit capacity**

   Definition.

   Relation with Thévenin equivalent.

   Drawbacks of a too high (respectively too small) short-circuit power.

   Be able to explain how it is influenced by some changes in the power system.

   Orders of magnitude.

7. **Maximum power transfer between two networks**

   Limits without and with voltage support at intermediate bus.

   Reactive power capability required for the compensator.

8. **Maximum power transfer from a generator to a load**

   Power flow equations. Condition of existence of a solution. Discussion.

   Maximum power under a given power factor.

   PV curves (under a given power factor). Interpretation of the solutions. Critical point. Influence of load compensation on critical voltage.

9. **Exponential load model**

   Definition, power factor, particular cases, choice of reference voltage, interpretation of exponents.

   Extension to take into account the sensitivity to frequency.

   Extension to loads including different components.

10. **Series inductance of a transmission line**

    Starting from :
    $$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \frac{\mu_0}{2\pi} \begin{bmatrix} \frac{\mu_r}{4} + \ln\frac{1}{r} & \ln\frac{1}{d_{ab}} & \ln\frac{1}{d_{ac}} \\ & \frac{\mu_r}{4} + \ln\frac{1}{r} & \ln\frac{1}{d_{bc}} \\ & & \frac{\mu_r}{4} + \ln\frac{1}{r} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

    derive the expression of the per length unit per phase series inductance of a line in the following cases: single conductor and bundle of two conductors per phase, untransposed and transposed.

    Influence of distance between phases.

    Motivation for using a bundle of conductors, and influence on the series inductance.

    Orders of magnitude.

11. **Shunt capacitance of a transmission line**

    Starting from :
    $$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{2\pi\epsilon_o\epsilon_r} \begin{bmatrix} \ln\frac{1}{r} & \ln\frac{1}{d_{ab}} & \ln\frac{1}{d_{ac}} & \ln\frac{1}{d_{aa'}} & \ln\frac{1}{d_{ab'}} & \ln\frac{1}{d_{ac'}} \\ \ln\frac{1}{d_{ab}} & \ln\frac{1}{r} & \ln\frac{1}{d_{bc}} & \ln\frac{1}{d_{ba'}} & \ln\frac{1}{d_{bb'}} & \ln\frac{1}{d_{bc'}} \\ \ln\frac{1}{d_{ac}} & \ln\frac{1}{d_{bc}} & \ln\frac{1}{r} & \ln\frac{1}{d_{ca'}} & \ln\frac{1}{d_{cb'}} & \ln\frac{1}{d_{cc'}} \end{bmatrix} \begin{bmatrix} q_a \\ q_b \\ q_c \\ -q_a \\ -q_b \\ -q_c \end{bmatrix}$$

    derive the expression of the per length unit per phase shunt capacitance of a line in the following cases: single conductor and bundle of two conductors per phase, untransposed and transposed.

    Influence of distance between phases.

    Motivation for using a bundle of conductors, and influence on the shunt capacitance.

    Orders of magnitude.

12. **Design of overhead power lines**
    - Phase conductors: choice of material from electrical and mechanical viewpoints.
    - Thermal aspects. Reasons to limit the temperature rise. Factors influencing the temperature. Maximum admissible current and its estimation. HTLS conductors.
    - Thermal capacity of a line.
    - Orders of magnitude.
13. **Design of underground power cables**
    - Usage of cables (instead of overhead lines).
    - Conductor material. Insulating materials.
    - Three-core vs. single core cables.
    - Grounding of metallic shields.
    - Comment on the per length unit parameters: $\ell = \frac{\mu_0}{2\pi}\left(\frac{\mu_r}{4} + \ln\frac{\sqrt[3]{d_{ab}d_{ac}d_{bc}}}{r}\right) \qquad c = \frac{2\pi\epsilon_o\epsilon_r}{\ln\left(\frac{R}{r}\right)}$
    - Orders of magnitude.
14. **Distributed model of overhead power line**

    Derive the following relations for an overhead power line:

$$\bar{V} = \bar{V}_2 \text{ ch } \gamma x + Z_c\bar{I}_2 \text{ sh } \gamma x \qquad \bar{I} = \frac{\bar{V}_2}{Z_c} \text{ sh } \gamma x + \bar{I}_2 \text{ ch } \gamma x \qquad \text{where } Z_c = \sqrt{\frac{z}{y}} \tag{1}$$

    Interpretation in terms of electromagnetic waves. Speed of propagation and wavelength.

    Surge impedance.
15. **Operation and pi-equivalent of a transmission line**

    Starting from (1) derive the corresponding relations in the case of a lossless transmission line.

    Properties of operation of a lossless line feeding its surge impedance loading.

    Natural power: definition, order of magnitude for a line and a cable. Consequences for operation.

    Derive the pi-equivalent circuit of an overhead power line, in the general case where losses are not neglected. Case of a "short" line.
16. **Single-phase transformers**

    General equivalent circuit, variant used in practice.

    Adjustment of transformer ratio : purpose, load tap changer, simplified correction of equivalent circuit parameters.
17. **Three-phase transformers**

    Criteria for the choice of star vs. triangle mounting.

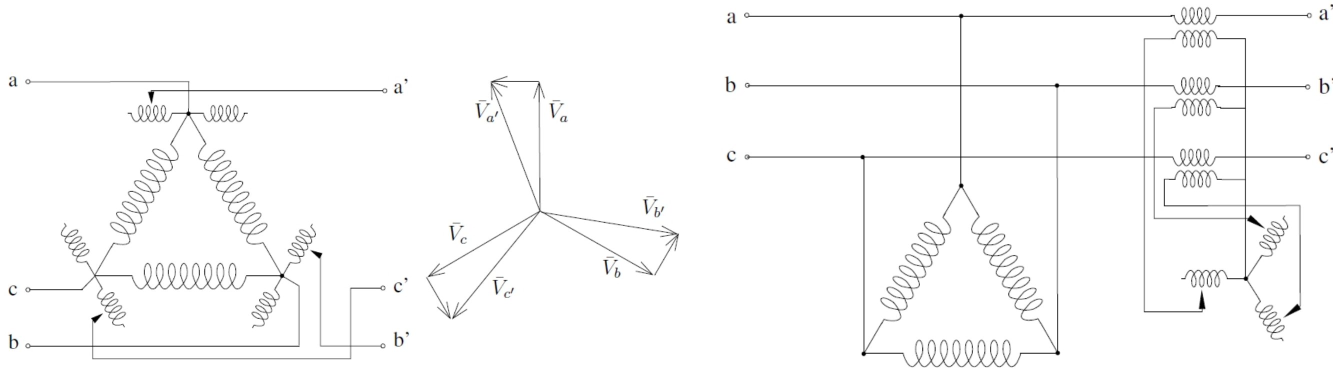
    Derive the per-phase equivalent of the star-triangle mounted transformer.

    IEC designation of transformers.

    Caution as regards using transformers with different phase shifts. Simplification of computations.

18. **"Special" transformers used in power systems**

    - Autotransformer : principle and applications
    - Three-winding transformer : principle and equivalent circuit
    - Phase shifting transformer : purpose. Explain its operation from the following schemes:



19. **Modelling of synchronous machine with magnetically coupled circuits**

    Modelling assumptions.

    Justify the expression of the inductance matrix in:

$$
\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_f \end{bmatrix} = \underbrace{\begin{bmatrix} L_o & -L_m & -L_m & L_{af}\cos\theta_r \\ -L_m & L_o & -L_m & L_{af}\cos(\theta_r - \frac{2\pi}{3}) \\ -L_m & -L_m & L_o & L_{af}\cos(\theta_r - \frac{4\pi}{3}) \\ L_{af}\cos\theta_r & L_{af}\cos(\theta_r - \frac{2\pi}{3}) & L_{af}\cos(\theta_r - \frac{4\pi}{3}) & L_{ff} \end{bmatrix}}_{\mathbf{L}(\theta_r)} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix}
$$

    Steady-state operation : derive and comment the expressions of the magnetic fluxes in a stator winding, and in the field winding. Corresponding phasor diagram.

20. **Electrical behaviour of the synchronous machine in steady state**

    Modelling assumptions.

    Steady-state operation : starting from the following expression of the flux linkage:

$$
\psi_a = \sqrt{2}(L_o + L_m) I \cos(\omega_N t + \psi) + L_{af} I_f \cos(\omega_N t + \theta_r^o)
$$

    derive the relation between the voltage and the current in one phase of the stator. Establish the corresponding equation involving phasors, the phasor diagram and the equivalent per-phase circuit.

    Per unit system. Orders of magnitude.

    Expression of active and reactive powers as function of terminal voltage, internal emf and internal angle (neglecting the stator resistance).

21. **Powers in the synchronous machine**

    Power balance of stator and rotor in the general case.

    Power balance of stator and rotor in steady-state operation, using the following expressions of the magnetic fluxes:

$$
\begin{aligned}
\psi_a &= \sqrt{2}(L_o + L_m) I \cos(\omega_N t + \psi) + L_{af} I_f \cos(\omega_N t + \theta_r^o) \\
\psi_f &= L_{ff} I_f + \frac{3\sqrt{2} L_{af}}{2} I \cos(\theta_r^o - \psi)
\end{aligned}
$$

22. **Capability curves of the synchronous machine**

    Definition.

    Derivation of the limits relative to stator and rotor.

    Derivation of the limit relative to the underexcitation limiter: undesired operation with large reactive power absorption, capability curve corresponding to a limit on the internal angle.

23. **Speed governors of turbines for frequency control**

    Relationship between frequency and active power balance. Frequency evolution after an event.

    Principle of speed governors. Isochronous and with speed droop. Block diagrams.

    Steady-state characteristics of a turbine-governor set. Speed droop. Interpretation.

24. **Primary frequency control**

    Modelling assumptions.

    Share of a load power variation among the generators.

    Composite frequency response characteristic.

    Notion of primary reserve.

25. **Secondary frequency control**

    Motivation for interconnecting AC networks.

    Primary and secondary frequency control of two interconnected networks after a disturbance in one of them.

    Secondary frequency control: objectives, principle, implementation.

    Comment on the choice of the bias factors λ_i, taking into account the following relations from primary frequency control:

    $$\text{network 1:} \quad -\beta_1 \Delta f = \Delta P_{c1} + \Delta P_{12} \qquad \text{network 2:} \quad -\beta_2 \Delta f = -\Delta P_{12}$$

    Comment on the choice of the PI controller gains and the participation factors ρ_i.

26. **Automatic voltage regulation of a synchronous machine**

    Overall description of the excitation system and its limiters.

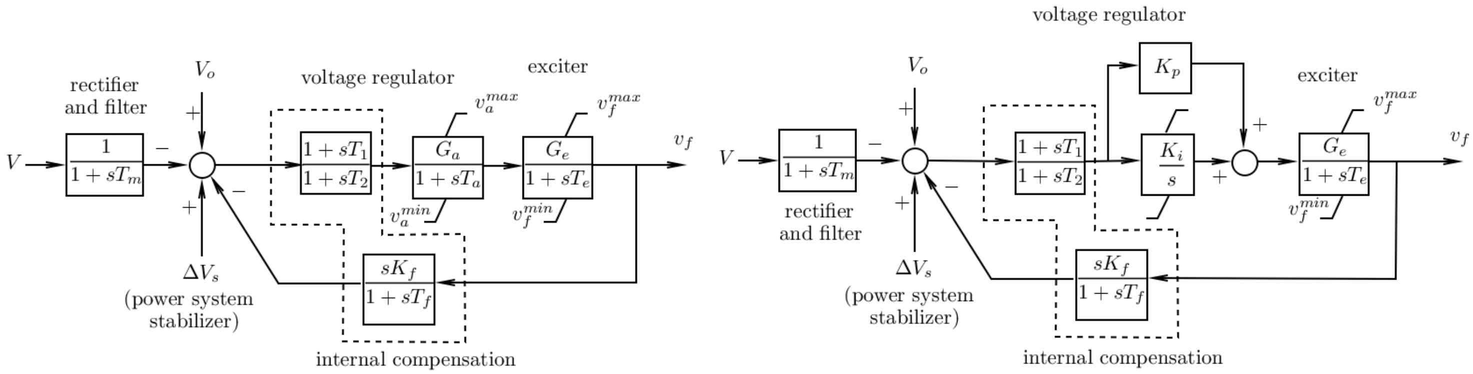
    Response of a voltage-controlled machine to a disturbance in the network.

    Over- and under-excited modes of operation.

    Synchronous condenser: principle, phasor diagram.

27. **QV curves of a synchronous machine**

   - under control of its automatic voltage regulator, considering the following two simplified generic models of excitation system:



   - under rotor or stator current limit

28. **Static var compensators**

   Principle of the TSC and of the TCR.

   Block diagram and nominal power of a TCR (in steady-state).

   QV characteristics and principle of voltage regulation.

   Comparison with synchronous condensers and with mechanically switched shunt capacitors/inductors

29. **Voltage control by load tap changers**

   Load tap changer: principle, choice of voltage setpoint, deadband, time delay between tap changes.

   Behaviour of a distribution network controlled by a load tap changer. Evolution of powers after a step decrease of the (sub-)transmission voltage.

30. **Balanced fault analysis**

   Clearing of faults by protections and circuit breakers. Types of faults.

   Behaviour of a synchronous machine during a three-phase fault. Comment on the expression of the stator current:

$$i_a(t) = -\sqrt{2}E_q^o\left[\frac{1}{X} + \left(\frac{1}{X'} - \frac{1}{X}\right)e^{-t/T_d'} + \left(\frac{1}{X''} - \frac{1}{X'}\right)e^{-t/T_d''}\right]\cos(\omega_N t + \theta_r^o) + \sqrt{2}E_q^o\frac{1}{X''}e^{-t/T_\alpha}\cos\theta_r^o$$

   Comparison with short-circuit of an AC voltage source in series with an (R, L) circuit :

$$i(t) = -\left[\frac{\sqrt{2}E}{\sqrt{R^2+\omega^2L^2}}\cos(\theta-\phi)\right]e^{-\frac{R}{L}t} + \frac{\sqrt{2}E}{\sqrt{R^2+\omega^2L^2}}\cos(\omega t + \theta - \phi)$$

   Usual simplifications for the computation of fault currents.

   Equivalent circuit of a synchronous machine in short-circuit calculations.