Electromagnetic Energy Conversion ELEC0431

Exercise session 6: Synchronous machines

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Organisation point

Lab sessions

- Schedule is available on the course webpage.

- There are four different laboratories:

    - Lab 1 → Transformers
    - Lab 2 → Synchronous machines
    - Lab 3 → Asynchronous machines
    - Lab 4 → DC machines

- To prepare these laboratories, you can:

    - Check the corresponding theoretical material
    - Watch lab videos (available on course webpage)

- A lab manual will soon be available. In this manual, the lab components are presented and some questions are introduced. **You have to write a short lab report answering these questions and give it at the end of the lab session.**

Exercise 17: Constant air gap alternator

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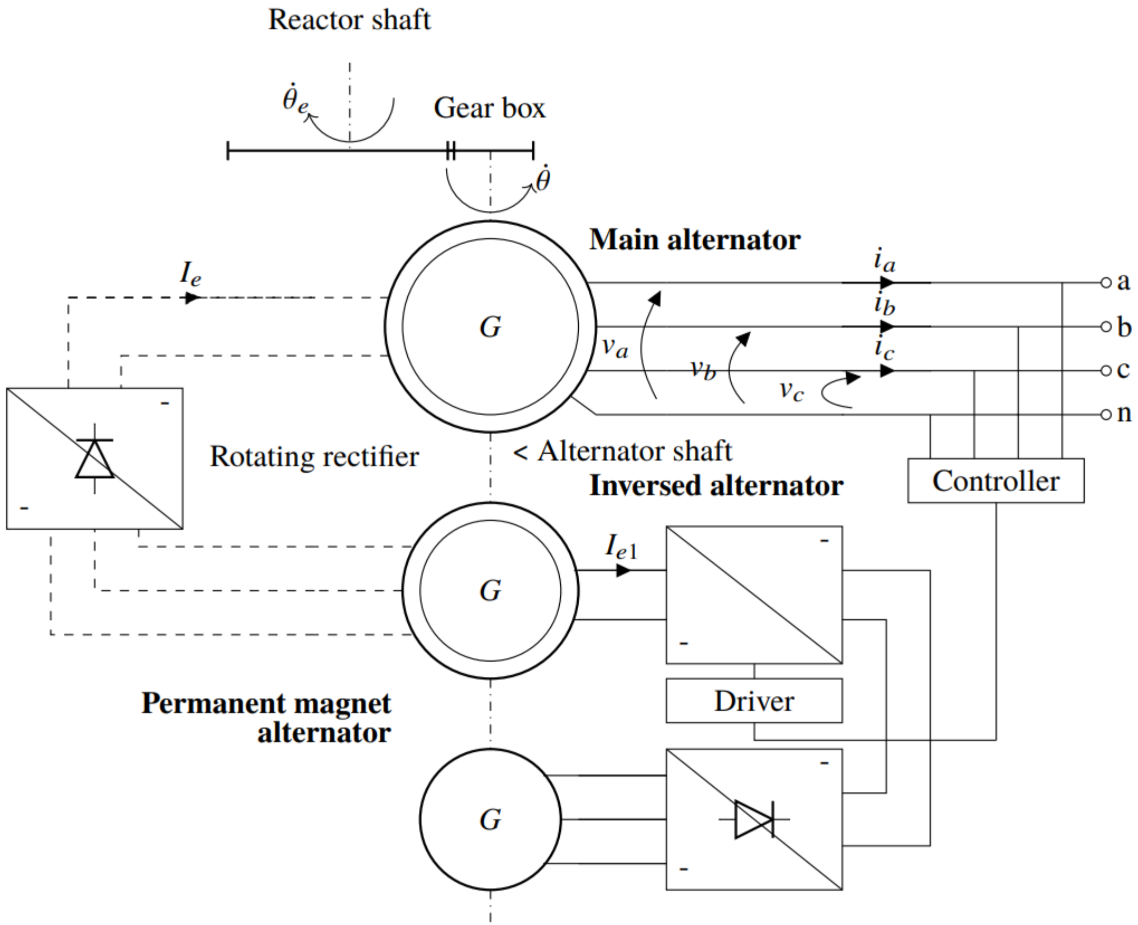
Several alternators are used on airplanes which, coupled to the reactors, feed all the necessary onboard electrical grids. Those alternators are characterized by a higher generated voltage and current frequency compared to alternators coupled to 50 Hz or 60 Hz electrical grids. Moreover, due the variable speed of the airplane reactors, the delivered frequency is not constant. The considered constant air gap three-phase alternator and its rotor winding are coupled following a star shape. Magnetic leakage, saturation, hysteresis and Eddy currents will be neglected. For a rotating speed of the alternator shaft of $\dot{\theta} = 11\,100\,RPM$, the frequency of the delivered voltages and currents is $f = 370\,Hz$ for a nominal apparent power $Sn = 150\,kVA$ and a direct voltage of RMS value $Vn = 115\,V$. The rotation speed of the reactor $\dot{\theta}_e$ varies from $4160\,RPM$ to $9000\,RPM$. The alternator is therefore coupled to the reactor through a gear box of ratio

$$km = \frac{\dot{\theta}}{\dot{\theta}_e} = 2.67.$$

The excitation of the alternator is controlled such that the output voltage of the alternator is 115 V (direct voltage or 200 V for the composed voltage). This excitation consists of an inversed alternator coupled with a permanent magnet alternator



Exercise 17: Constant air gap alternator

1. Explain how the excitation system works. What are the main advantages of such a system?
2. Express the frequency of the generated voltages and currents f with respect to the rotation speed of the reactor $\dot{\theta}$, the gear box ratio k_m and the number of pairs of poles of the alternator p;
3. Deduce the number of pair of poles, as well as the minimal and maximal values $f_{\min}$, $f_{\max}$ of the generated voltages and currents;
4. For an airplane, justify the relevance of a system working at a variable frequency in the targeted range;
5. Calculate the nominal RMS current I_{sn} of the line currents of the alternator;
6. The flux generated by a pole is:

   $$\phi(t) = \Phi_m \cos\left(p\left(\dot{\theta}t - \theta_0\right)\right),$$

   where Φ_m is the flux amplitude, p the number of pairs of poles, $\dot{\theta}$ the speed of rotation, t the time variable and θ_0 the initial angular position of the rotor. Express the electromotive force e_s induced in a single turn of the rotor with respect to Φ_m, f, t and θ_0. Deduce the RMS value E_s of $e_s(t)$ with respect to Φ_m and f;
7. The RMS value E of the induced electromotive force in a phase is $E = k_b N_s E_s$ where $k_b = 0.850$ is the coil factor and $N_s = 16$ is the number of turn per phase. The magnetic circuit is built using laminations allowing to reach a maximal magnetic field corresponding to a flux amplitude $\Phi_{m0} = 6.84$ mWb and a current $I_{e0} = 2.95$ A. Express the RMS value E of the electromotive force induced in each phase with respect to k_b, N_s, Φ_{m0}, I_{e0}, I_e and f. Plot E with respect to I_e in the range between $f_{\min}$ and $f_{\max}$ and conclude.

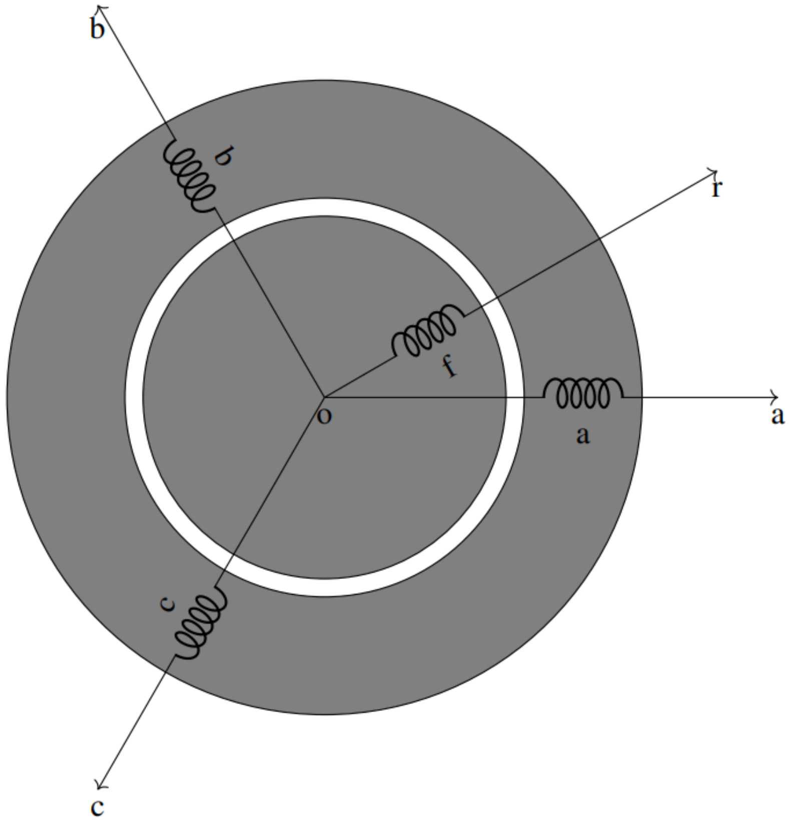
Exercise 17: Constant air gap alternator

The stator of the machine is composed of three-phase windings whose phases are noted a, b and c, while the rotor is composed of a inductor winding f (Fig. 45). Each phase has an impedance composed of a resistance R_s, a self inductance λ (also noted L_s) and a mutual inductance λ_m (also noted M_s) with respect to each other phase. The mutual inductances between each phase and the inductor phase have a sinusoidal pulsation with respect to the rotation angle θ:

$$\lambda_{m,af} = \lambda_{m,sf} \cos(p\theta)$$

$$\lambda_{m,bf} = \lambda_{m,sf} \cos\left(p\left(\theta - \frac{2\pi}{3}\right)\right)$$

$$\lambda_{m,cf} = \lambda_{m,sf} \cos\left(p\left(\theta + \frac{2\pi}{3}\right)\right)$$



Exercise 17: Constant air gap alternator

8. Express the total fluxes Ψ_a, Ψ_b and Ψ_c crossing the phase windings a, b and c with respect to the flowing current intensities i_a, i_b and i_c, the excitation current intensity I_e, the self inductance λ, the stator mutual inductance λ_m, the mutual inductance between the stator and the rotor $\lambda_{m,sf}$ and the angle $p\theta$;

9. Express the voltages v_a, v_b and v_c across the phase windings a, b, c with respect to i_a, i_b and i_c, the total flux derivatives Ψ_a, Ψ_b and Ψ_c and R_s;

10. Show that the direct voltages of the stator can be written:

$$v_a = e_a - R_s i_a - \lambda_f \frac{di_a}{dt}$$
$$v_b = e_b - R_s i_b - \lambda_f \frac{di_b}{dt}$$
$$v_c = e_c - R_s i_c - \lambda_f \frac{di_c}{dt}$$

Express the electromotive forces e_a, e_b and e_c with respect to $\lambda_{m,sf}$, I_e, ω, t, p and θ_0, and their common RMS value E with respect to $\lambda_{m,sf}$, I_e and ω. Explain the significance of λ_f and reexpress it in terms of λ and λ_m.

Exercise 17: Constant air gap alternator

The single-phase equivalent model of Behn-Eschenburg is now considered with $R_s = 0.4\,\mathrm{m}\Omega$. To characterize the alternator two tests have been performed:

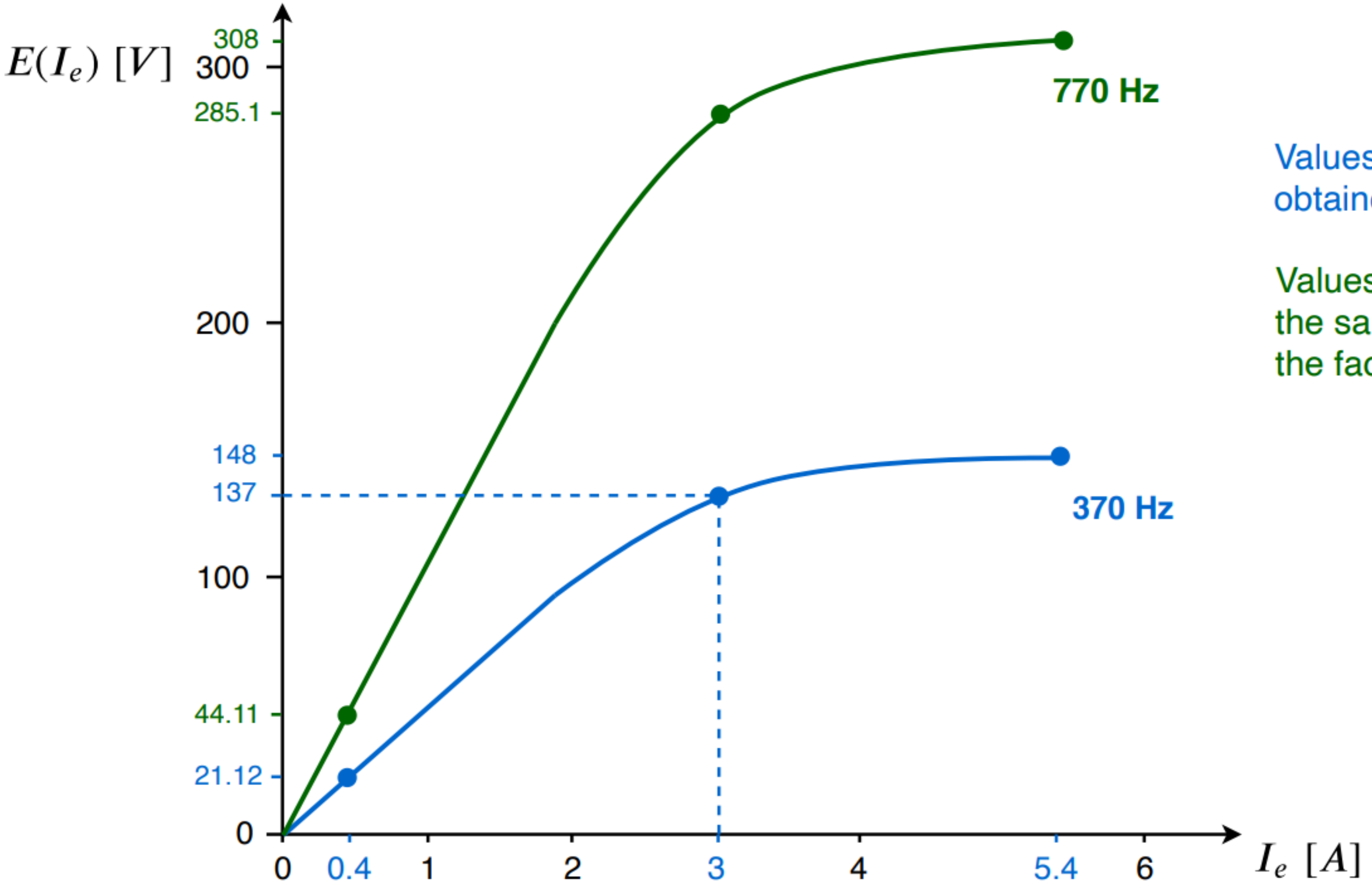
- Using open stator windings, at the speed of rotation $\dot{\theta} = 11\,100\,\mathrm{RPM}$, the RMS direct voltage values have been measured with respect to the RMS current intensity I_e flowing through the inductor
- Using short-circuited stator windings, at the speed of rotation $\dot{\theta} = 11\,100\,\mathrm{RPM}$, the RMS current intensity I_c have been measured with respect to the RMS current intensity I_e flowing through the inductor

I_e [A]	E [V]	I_s [A]
0.4	21.2	94.8
0.8	42.2	190
1.2	63.6	284
1.6	84.8	379
2	106	474
2.4	122	569
3	137	670
3.6	143	770
4.2	145	860
4.8	147	948
5.4	148	1040

Exercise 17: Constant air gap alternator

11. Knowing that $E = \alpha\,\omega I_e$, compute the value of the coefficient α for $I_e = 0.4, 3.0, 5.4$ A;
12. Plot the open stator windings curve, E with respect to I_e, for $f_{\text{min}} = 370$ Hz and $f_{\text{max}} = 770$ Hz;
13. Calculate the synchronous reactance X_s for the linear part of the curve;
14. Plot the short-circuited stator windings curve, I_s with respect to I_e, for $f_{\text{min}} = 370$ Hz and $f_{\text{max}} = 770$ Hz;
15. The alternator is connected to a star-shaped load composed of 3 resistors of value $R_L = 0.5\,\Omega$ working at a frequency $f = 500$ Hz for an excitation current $I_e = 2$ A.
    (a) Calculate the stator RMS current and voltage values I_s and V_s;
    (b) Sketch the Behn-Eschenburg diagram;
    (c) Explain how I_s and V_s vary when the frequency increases;
16. Working at constant I_e, a balanced inductive load is now considered with a corresponding impedance $Z_c = R_c + \jmath\omega L_c$ for each phase.
    (a) Sketch the Behn-Eschenburg diagram for a power factor $\cos\phi = 0.75$;
    (b) Express the stator RMS voltage V_s with respect to α, ω, R_c, L_c, L_s and I_e;
    (c) Express the resistive torque C_r with respect to p, α, ω, R_c, L_c, L_s and I_e;
    (d) How does the frequency variation influence the load power factor?

Exercise 17: Constant air gap alternator 12)



Values for 370 Hz are obtained from Table 1

Values for 770 Hz are the same multiplied by the factor $\frac{770}{370}$

Exercise 17: Constant air gap alternator 14)