1 DC MOTOR

The separately excited dc machine having the magnetization curve shown in Figure 1 is operating as a motor at a speed of 1500 rpm with a developed (shaft) power of 10 hp (1hp=735 Watt) and I_F = 2.5 A. The armature resistance is R_A=0.3 Ω and the field resistance is R_F = 50 Ω.

a) Explain shortly why the magnetization curve in Figure 1 is curved at high field current. You can disregard this phenomenon in your subsequent calculations.
b) Find the machine speed in radians per second
c) In this operating condition, find the developed torque, the armature current I_A and the voltage V_T applied to the armature circuit.
d) The field current is still I_F = 2.5 A. Assume the terminal voltage is V_T =127.5 V and the power supplied to the motor terminals is 3.2 kW. What is the speed of the machine?

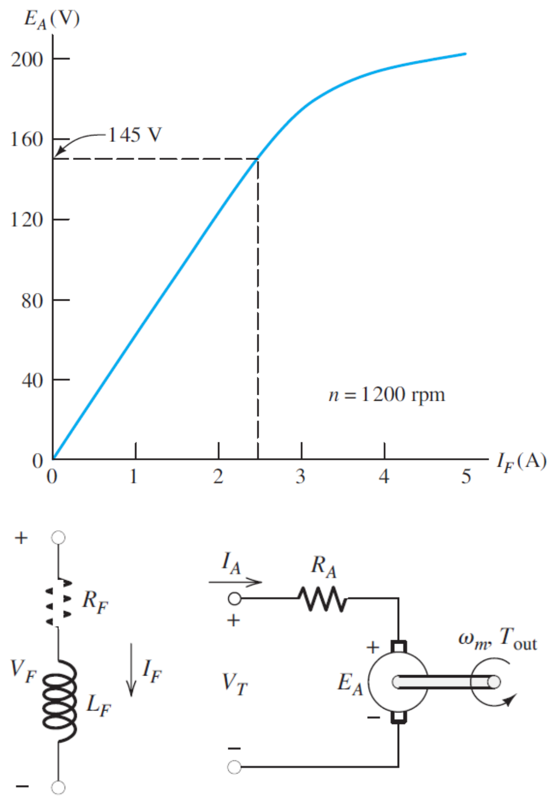

Figure 1: Magnetization curve for 200 V-10 hp dc motor and equivalent circuit of the dc machine

2 MAGNETIC CIRCUIT

For the core shown in Figure 2, the reluctances of all three paths between points *a* and *b* are equal. $\Re 1 = \Re 2 = \Re 3 = 106$ (A·turns)/Wb Assume that all of the flux is confined to the core.

a) Do the fluxes produced by i_1 and i_2 aid or oppose one another in path 1? In path 2? In path 3? Explain why.
b) If a dot is placed on the top end of coil 1, which end of coil 2 should carry a dot? Explain why . Make a simple sketch showing the dots.
c) Should the mutual term for the voltages in the following equations carry a plus sign or a minus sign? Explain why

$$e_1 = \frac{d\lambda_1}{dt} = L_1\frac{di_1}{dt} \pm M\frac{di_2}{dt}$$

$$e_2 = \frac{d\lambda_2}{dt} = \pm M\frac{di_1}{dt} + L_2\frac{di_2}{dt}$$

d) Determine the values of L_1, L_2, and M.

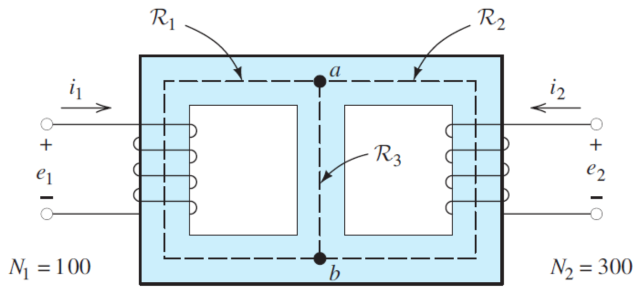

Figure 2: Magnetic circuit for problem 2

3 WIND TURBINE CONTROL AND GRID CONNECTION

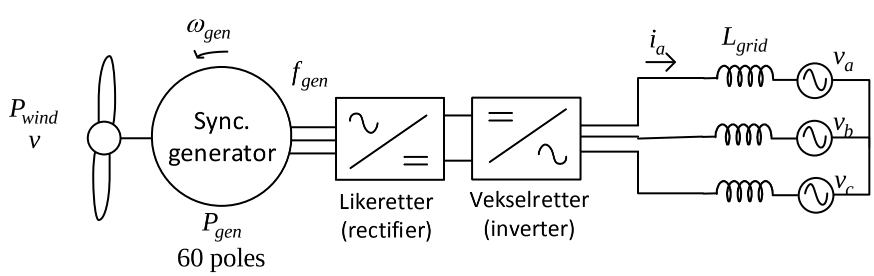

Figure 3: Overview of wind turbine with frequency converter

The wind turbine in Figure is connected to the grid by a generator, rectifier and inverter. The mechanical rotational speed of the generator is ω_{gen}, while the electrical frequency of the generator voltages is f_{gen}. The maximum available power from the wind is P_{wind}, while the actually produced power is P_{gen}. The generator is a synchronous generator with 60 poles.

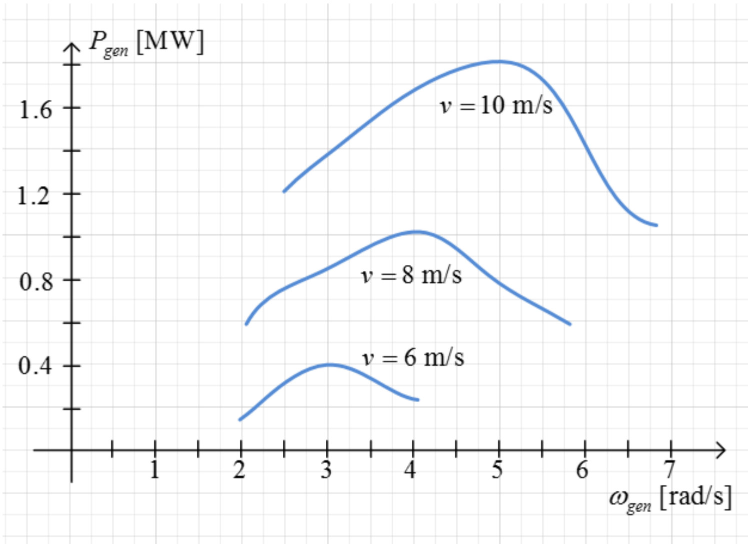

Figure 4: Wind power production curve as a function of generator speed (for three different wind speeds v)

The curves in Figure shows the wind power production P_{gen} as a function of generator mechanical speed ω_{gen}.

a) If the wind speed is 10 m/s, what is the produced power if the generator electrical frequency is $f_{gen} = 18\text{ Hz}$?

b) Use Figure to discuss the best strategy to control ω_{gen}. Also, explain the concept of Maximum Power-Point Tracking (MPPT).

The maximum available power from the wind can be expressed by the formula $P_{wind} = kv^3$, where k is a constant and v is the wind speed. Assume $k = 3480$.

c) Assume the turbine is controlled based on MPPT. What is the efficiency of the wind turbine for the three wind speeds in Figure ? Efficiency is expressed as (produced power)/(available power).

d) The turbine produces $P_{gen} = 1.5\,MW$. Neglect all losses in the generator, rectifier and inverter. The maximum allowed line current i_a is 350 A (RMS). Phase-to-phase grid voltage is $3000\,V$ (RMS). What is the maximum possible reactive power that the inverter can supply to the grid? You can assume a symmetrical three-phase system, hence the per phase equivalent can be used.

4 PHASOR TRANSFORM

a) Write the corresponding differential equations that models the RLC circuit in Figure 5. The source voltage is $v(t) = V_o cos(\omega t + \alpha_v)$

b) Transform the differential equations into phasor domain, keep in mind that $\cos(\omega t + \theta) = \mathrm{Re}\left(e^{j\theta} \cdot e^{j\omega t}\right)$, $\cos(\theta) = \mathrm{Re}\left(e^{j\theta}\right)$

Based on the analysis of the expression obtained in b) demonstrate the following:

c) Demonstrate that the impedance of the series RLC circuit is $Z = R + j(\omega L - \frac{1}{\omega C})$ and that the current phasor is $I = \frac{V}{\left(R + j\left(\omega L - \frac{1}{\omega C}\right)\right)}$

d) Write the expression of the current in time domain, $i(t)$, as a function of the current phasor parameters found in part c)

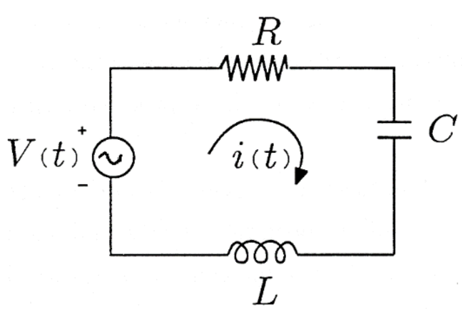

Figure 5: Series RLC circuit with $v(t) = V_o cos(\omega t + \alpha_v)$

APPENDIX: FORMULAS

Inductance and capacitance

$$v_L = L\frac{di_L}{dt} \;,\; i_C = C\frac{dv_C}{dt} \;,\; X_L = \omega L \;,\; X_C = \frac{1}{\omega C}$$

Phasors and complex power

$$e^{j\theta} = \cos\theta + j\sin\theta$$

$$X\cos(\omega t + \theta) = \mathrm{Re}\left(Xe^{j\theta}\cdot e^{j\omega t}\right)$$

$$X\cos(\omega t + \theta) \xleftrightarrow{\text{PhasorTransform}} Xe^{j\theta} \quad , \quad S = VI^* = P + jQ$$

Electromagnetism:

$$\varepsilon = N\frac{d\varphi}{dt} \;,\; NI = \Re\varphi \,,\; \Re = \frac{l}{\mu A} \;,\; \varphi = BA$$

$$\lambda_1 = \lambda_{11} \pm \lambda_{12}$$

$$\lambda_2 = \pm\lambda_{21} + \lambda_{22}$$

$$L = \frac{N^2}{\Re}$$

$$L_1 = \frac{N_1\varphi_1}{i_1};\; L_2 = \frac{N_2\varphi_2}{i_2}$$

$$M = \frac{\lambda_{21}}{i_1} = \frac{\lambda_{12}}{i_2}$$

$$\lambda_1 = N_1\varphi_1$$

$$\lambda_2 = N_2\varphi_2$$

Trigonometrics

$$\cos(2x) = 1 - 2\sin^2(x)$$

$$\sin(2x) = 2\sin(x)\cos(x)$$

Three-phase

$$|V_{LL}| = \sqrt{3}|V_{ph}|$$

$$|S| = \sqrt{3}|V_{LL}||I_L| = 3|V_{ph}||I_L|$$

$$|S| = \sqrt{P^2 + Q^2}$$

Electrical machines

$$f_{el} = \frac{p}{2} f_{mech}$$

DC-machine

$$E_A = K\varphi\omega_m \qquad T_{out} = K\varphi I_A$$

$$\frac{E_{A1}}{E_{A2}} = \frac{n_1}{n_2} = \frac{\omega_1}{\omega_2}$$

Inverters

Single-phase: $m = \frac{\sqrt{2}|V_{ac}|}{V_{dc}}$

Three-phase: $m = \frac{2\sqrt{2}|V_{LL}|}{\sqrt{3}V_{dc}}$

Mechanics

$$P = T\omega \quad P = F\cdot v \quad v = \omega r \quad E_k = \frac{1}{2}mv^2$$

$$T_{mot} - T_{load} = J\frac{d\omega}{dt}$$

Laplace transforms

Constant: $\mathcal{L}(K\cdot f(t)) = K\cdot F(s)$

Step response: $\mathcal{L}(u(t)) = \frac{1}{s}$

Exponential: $\mathcal{L}\left(e^{at}\right) = \frac{1}{s-a}$

s-shift: $\mathcal{L}\left\{e^{-at}\cdot f(t)\right\} = F(s+a)$

Sine: $\mathcal{L}\left\{\sin(\omega t)\right\} = \frac{\omega}{s^2+\omega^2}$

Cosine: $\mathcal{L}\left\{\cos(\omega t)\right\} = \frac{s}{s^2+\omega^2}$

Damped cosine: $\mathcal{L}\left\{e^{-at}\cos(\omega t)\right\} = \frac{s+a}{(s+a)^2+\omega^2}$