

Analysis of Electric Machinery and Drive Systems | (2nd Edition)

Chapter 5, Problem 13P

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Step-by-step solution

Step 1 of 10

Consider the following equivalent circuit of a three phase synchronous machine with the reference frame fixed in a rotor:

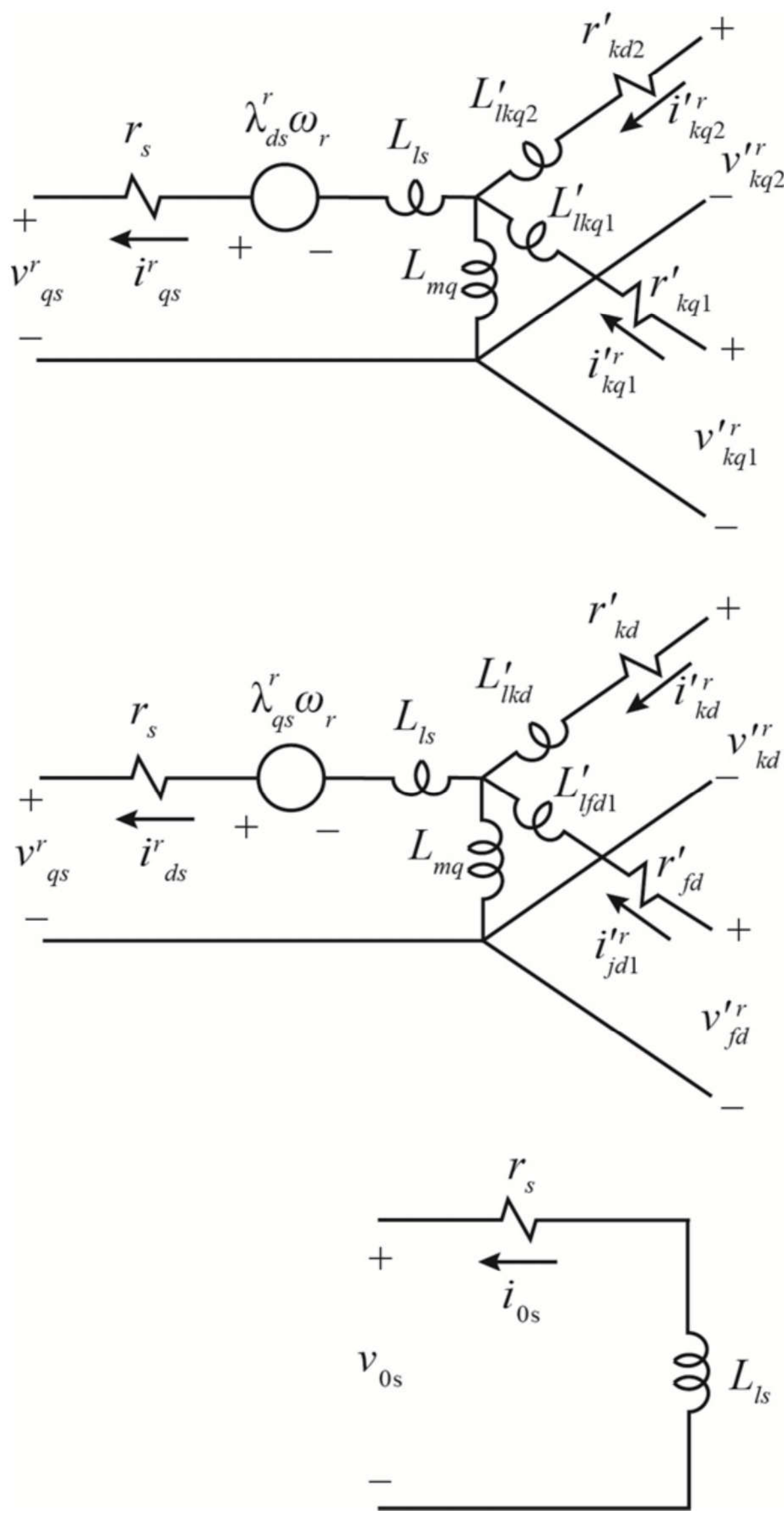


Figure 1

Comment

Step 2 of 10

Write the equation for the voltage (V'_q) .

$$V'_q = -r'_s i'_q + \frac{\partial}{\partial t} \psi'_q + \frac{P}{\omega_b} \psi'_q \dots \dots (1)$$

Write the equation for the voltage (V'_d) .

$$V'_d = -r'_s i'_d + \frac{\partial}{\partial t} \psi'_d + \frac{P}{\omega_b} \psi'_d \dots \dots (2)$$

Here,

The base electrical angular velocity is ω_b .

Comment

Step 3 of 10

Write the expression for flux linkage (ψ'_q) .

$$\psi'_q = -X'_q i'_q + X_{mq} (-i'_q + i'_{q1} + i'_{q2})$$

Write the expression for flux linkage (ψ'_d) .

$$\psi'_d = -X'_d i'_d + X_{md} (-i'_d + i'_{d1} + i'_{d2})$$

Substitute the corresponding values in equation (1).

$$V'_q = \left\{ -r'_s i'_q + \frac{\partial}{\partial t} \left(-X'_q i'_q + X_{mq} (-i'_q + i'_{q1} + i'_{q2}) \right) + \frac{P}{\omega_b} \left(-X'_q i'_q + X_{mq} (-i'_q + i'_{q1} + i'_{q2}) \right) \right\} \dots \dots (3)$$

Substitute the corresponding values in equation (2).

$$V'_d = \left\{ -r'_s i'_d + \frac{\partial}{\partial t} \left(-X'_d i'_d + X_{md} (-i'_d + i'_{d1} + i'_{d2}) \right) + \frac{P}{\omega_b} \left(-X'_d i'_d + X_{md} (-i'_d + i'_{d1} + i'_{d2}) \right) \right\} \dots \dots (4)$$

Comment

Step 4 of 10

The reactances X'_q and X'_d are generally referred as the q and d axis reactances.

Write the expression for reactance (X'_q) .

$$X'_q = X_s + X_{mq}$$

Write the expression for reactance (X'_d) .

$$X'_d = X_s + X_{md}$$

Comment

Step 5 of 10

For the balanced state conditions the electrical angular velocity of the rotor is constant and is denoted by ω_b . Thereafter, the electrical angular velocity of the rotor reference frame becomes the electrical angular velocity of the synchronously rotating reference frame. For the specified mode of operation, the rotor winding do not experience a change of flux linkages. So, the current is not flowing in the short circuited damper winding. So, with (ω_r) set equal to (ω_b) and the time rate of change of all flux linkages avoided to obtain the steady state version of the specified equations as follows:

The expression for voltage (V'_q) in terms of reactances (X'_q) , (X'_d) , and ratio $\left(\frac{\partial}{\partial t}\right)$ can be obtained as follows:

$$V'_q = -r'_s i'_q + \frac{\partial}{\partial t} X'_q i'_q + \frac{P}{\omega_b} X_{mq} i'_{q1} \dots \dots (5)$$

Therefore, the expression for voltage, (V'_d) is $\left[-r'_s i'_d + \frac{\partial}{\partial t} X'_d i'_d + \frac{P}{\omega_b} X_{md} i'_{d1} \right]$.

Comment

Step 6 of 10

The expression for voltage (V'_d) in terms of reactances (X'_q) and $\left(\frac{\partial}{\partial t}\right)$ can be obtained as follows:

$$V'_d = -r'_s i'_d + \frac{\partial}{\partial t} X'_d i'_d \dots \dots (6)$$

Therefore, the expression for voltage, (V'_q) is $\left[-r'_s i'_q + \frac{\partial}{\partial t} X'_q i'_q \right]$.

Comment

Step 7 of 10

The expression for the electromagnetic torque in terms of rotor reference frame variables.

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) \left[\frac{1}{\omega_b} \left(\psi'_d i'_q - \psi'_q i'_d \right) \right]$$

With reference to the torque equation in the machine variables, the energy stored in the coupling field of a synchronous machine can be obtained by an expression as follows:

$$W_f = \frac{1}{2} (i'_{d1})^2 (L_s - L_s') i'_{d1} - (i'_{d1})^2 L_s' i'_{d1} + \frac{1}{2} \left(\frac{3}{2} \right) (i'_{q1})^2 (L_s' - L_s) i'_{q1}$$

The total energy transferred to the coupling field (W_f) is given by an expression as follows:

$$W_f = W_f + W_g$$

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The stored energy and co-energy in a magnetic field of a singly excited electromagnetic device is shown by the graphical representation given below:

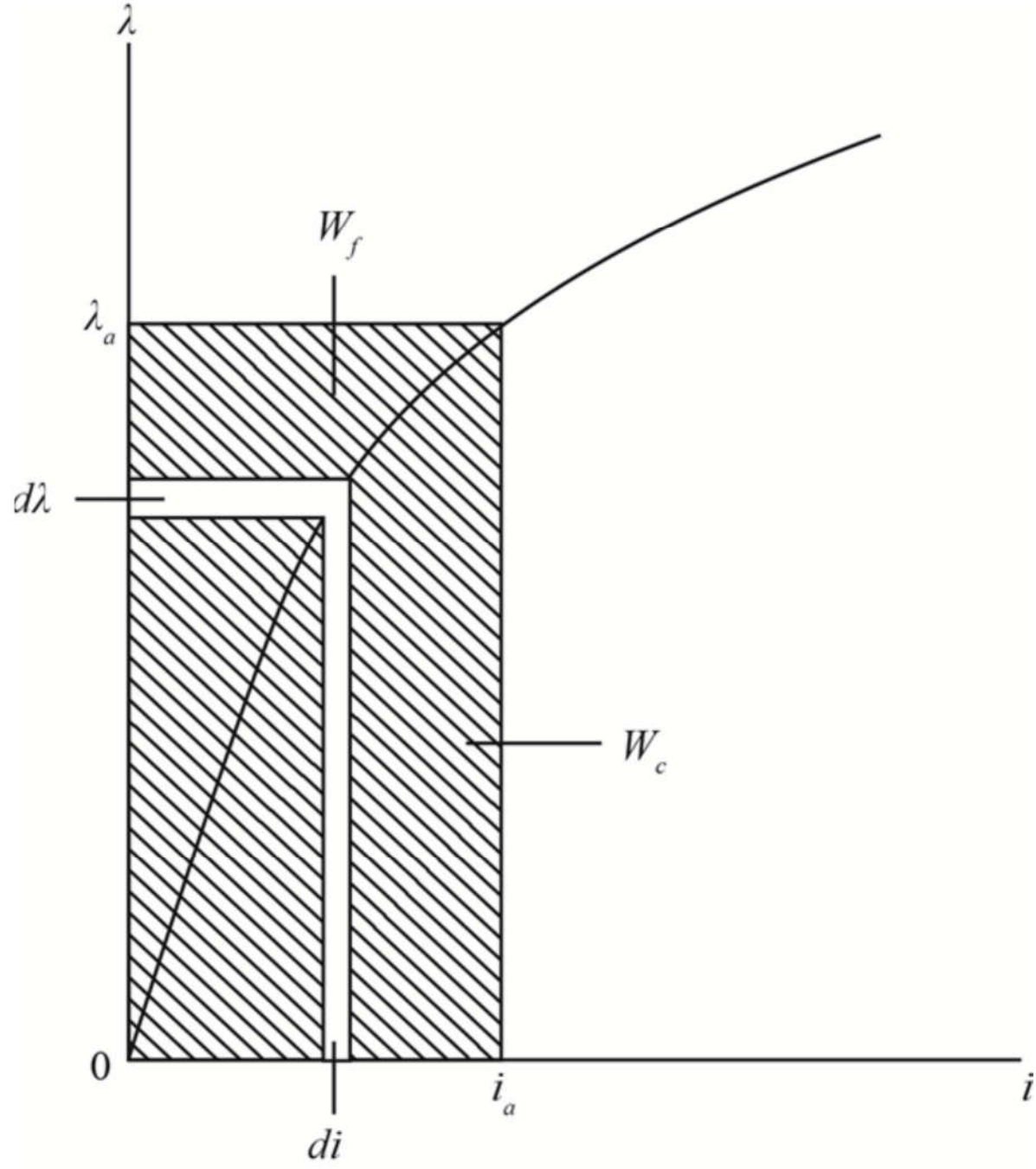


Figure 2

Comment

Step 8 of 10

The matrix representation of the inductance $(\mathbf{L}_s)$ can be obtained as follows:

$$\mathbf{L}_s = \text{diag} \left[L_{s11}, L_{s22}, L_{s33}, L_{s44} \right]$$

The magnetic flux is assumed to be linear with $W_f = W_c$ and an expression for the $(f_{is}(i_s, x_s))$ can be obtained as follows:

$$f_{is}(i_s, x_s) = \frac{\partial W_c(x_s, i_s)}{\partial x_s}$$

Comment

Step 9 of 10

The above equation can be employed with a factor of $\left(\frac{P}{2}\right)$ included to account for a P-pole machine and a negative sign to make torque positive for the generator action.

The expression for torque in accordance with the above specified conditions can be obtained as follows:

$$T_e = -\left(\frac{P}{2}\right) \left[\left(L_{s11} - L_{s22} \right) \left(i_{s1}^2 + \frac{1}{2} i_{s2}^2 + \frac{1}{2} i_{s3}^2 \right) \sin 2\theta_s \right. \\ \left. - L_{s22} \left(i_{s1} + i_{s2} \right) \left[\left(L_{s1} - \frac{1}{2} L_{s2} - \frac{1}{2} L_{s3} \right) \sin \theta_s - \frac{\sqrt{3}}{2} \left(i_{s1}^2 + i_{s2}^2 + 2 i_{s1} i_{s2} \right) \cos 2\theta_s \right] \right. \\ \left. + L_{s22} \left(i_{s1} + i_{s2} \right) \left[\left(L_{s1} - \frac{1}{2} L_{s2} - \frac{1}{2} L_{s3} \right) \cos \theta_s + \frac{\sqrt{3}}{2} \left(i_{s1} - i_{s2} \right) \sin \theta_s \right] \right] \dots (7)$$

Comment

Step 10 of 10

The voltage equation in the machine variable waveform can be expressed in the matrix representation as follows:

$$\mathbf{v}_{abs} = -\mathbf{r}_s \mathbf{i}_{abs} + p \lambda_{abs} \dots (8)$$

The voltage $(\mathbf{v}_{abs})$ can be obtained as follows:

$$\mathbf{v}_{abs} = \mathbf{r}_s \mathbf{i}_{abs} + p \lambda_{abs} \dots (9)$$

Substitute the corresponding values from equations (2) and (3) in equation (1) and matrix representation of the inductances to obtain an expression as follows:

$$T_e = \left(\frac{P}{2}\right) \left[-\frac{1}{2} \left(i_{abs} \right)^T \frac{\partial}{\partial \theta} \left[\mathbf{L}_s - L_{s2} \right] i_{abs} + \left(i_{abs} \right)^T \frac{\partial}{\partial \theta} \left[\mathbf{L}_{s2} \right] i_{abs} \right] \dots (10)$$

The above equation can be rewritten as follows:

$$T_e = \left(\frac{P}{2}\right) \left(i_{abs} \right)^T \left[-\frac{1}{2} \frac{\partial}{\partial \theta} \left[\mathbf{L}_s - L_{s2} \right] i_{abs} + \frac{\partial}{\partial \theta} \left[\mathbf{L}_{s2} \right] i_{abs} \right]$$

The expression for the current (i_{abs}) can be obtained as follows:

$$i_{abs} = \left(\mathbf{K}^* \right)^{-1} i_{mtr} \dots (11)$$

Substitute the value from equation (5) in equation (6) to obtain an expression as follows:

$$T_e = \left(\frac{P}{2}\right) \left(\left(\mathbf{K}^* \right)^{-1} i_{mtr} \right)^T \left[-\frac{1}{2} \frac{\partial}{\partial \theta} \left[\mathbf{L}_s - L_{s2} \right] \left(\mathbf{K}^* \right)^{-1} i_{mtr} + \frac{\partial}{\partial \theta} \left[\mathbf{L}_{s2} \right] i_{mtr} \right]$$

Simplify the above equation further to obtain an expression as follows:

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) \left[L_{s22} \left(-i_{s1}^2 + i_{s2}^2 + i_{s3}^2 \right) i_{s1}^2 - L_{s22} \left(-i_{s1}^2 + i_{s2}^2 + i_{s3}^2 \right) i_{s2}^2 \right]$$

The above equation can be written in terms of an expression given as follows:

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) \left(i_{s1}^2 i_{s2}^2 - i_{s2}^2 i_{s1}^2 \right)$$

Hence, the above equation in terms of the flux linkages per second can be obtained as follows:

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) \left(\frac{1}{\omega_b} \right) \left(\psi_{s1} i_{s2}^2 - \psi_{s2} i_{s1}^2 \right)$$

Hence, the required expression for torque, T_e is $\left[\left(\frac{3}{2}\right) \left(\frac{P}{2}\right) \left(\frac{1}{\omega_b} \right) \left(\psi_{s1} i_{s2}^2 - \psi_{s2} i_{s1}^2 \right) \right]$.

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