Lecture 12
GENERATOR MODEL

Agenda

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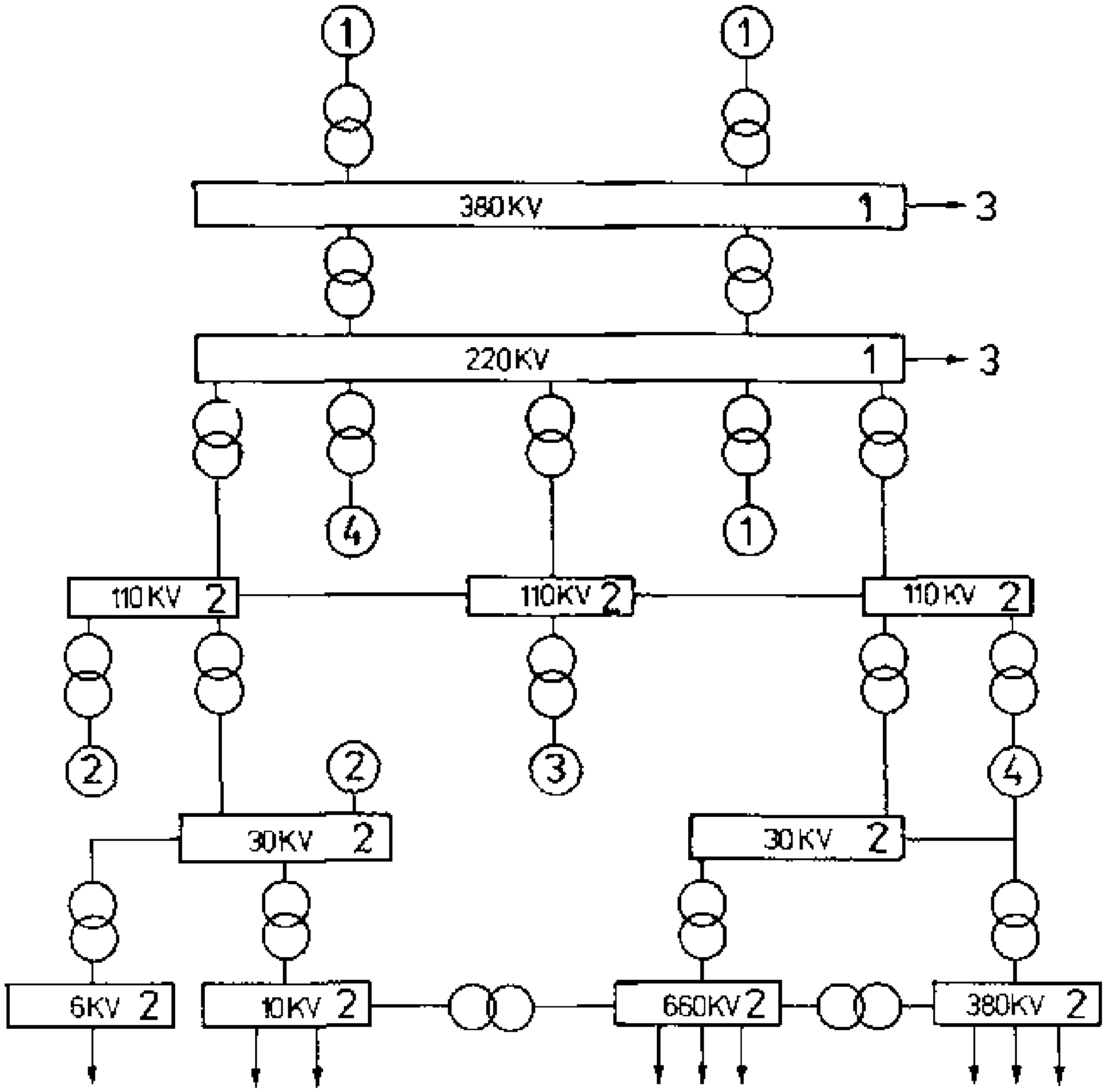
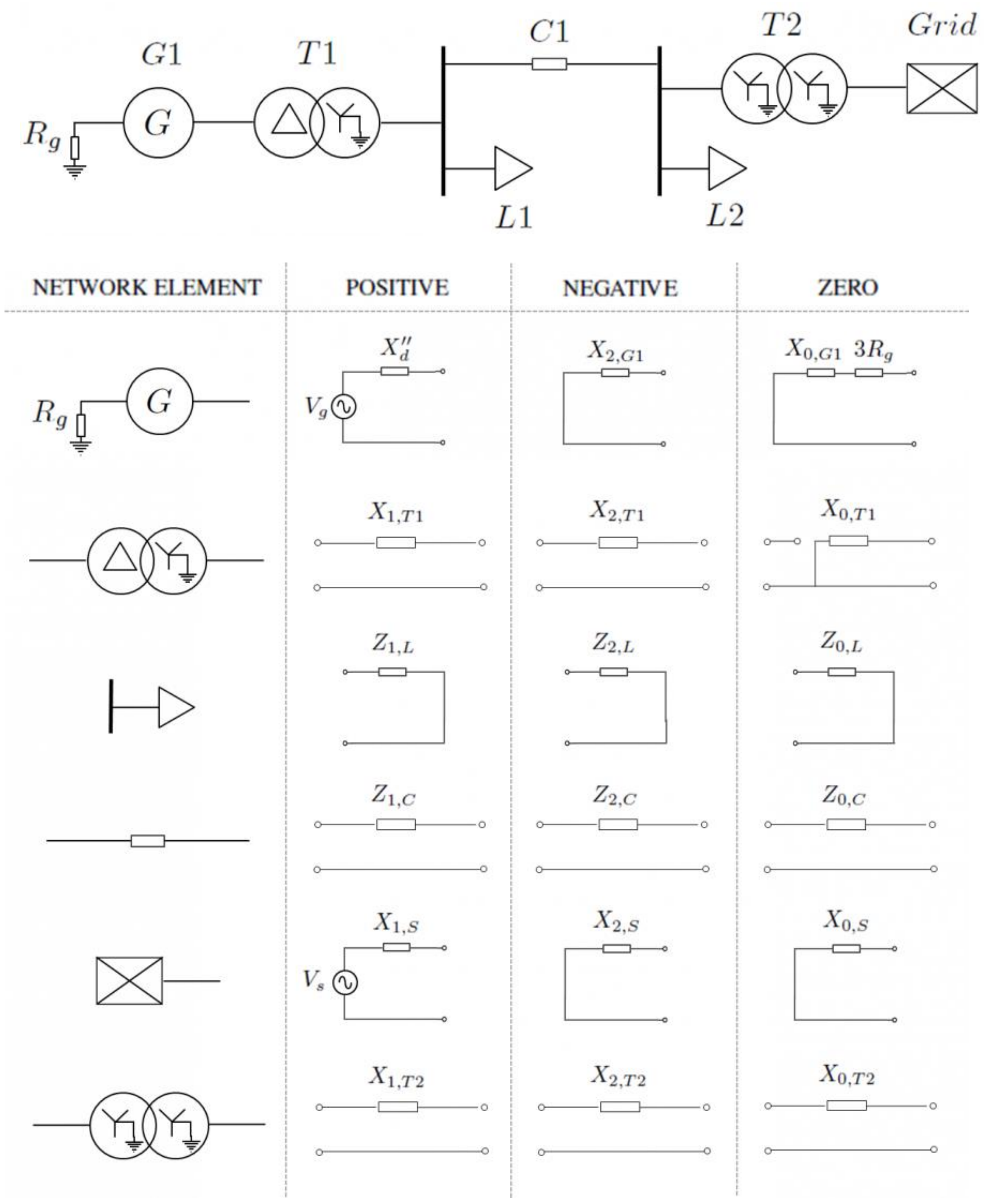

380KV 1
3
220KV 1
3
110KV 2
110KV 2
110KV 2
30KV 2
30KV 2
6KV 2
10KV 2
660KV 2
380KV 2


G1
T1
C1
T2
Grid
R_g
G
L1
L2
NETWORK ELEMENT
POSITIVE
NEGATIVE
ZERO
X''_d
V_g
$X_{2,G1}$
$X_{0,G1}$ $3R_g$
$X_{1,T1}$
$X_{2,T1}$
$X_{0,T1}$
$Z_{1,L}$
$Z_{2,L}$
$Z_{0,L}$
$Z_{1,C}$
$Z_{2,C}$
$Z_{0,C}$
$X_{1,S}$
V_s
$X_{2,S}$
$X_{0,S}$
$X_{1,T2}$
$X_{2,T2}$
$X_{0,T2}$

Lecture Outcomes

at the end of the lecture, the student must be able to …

- Draw the Generator Models used in Power System Analysis.
- Determine the difference in the sequence circuits of ground or ungrounded generators.

EEE 103
Introduction to Power Systems

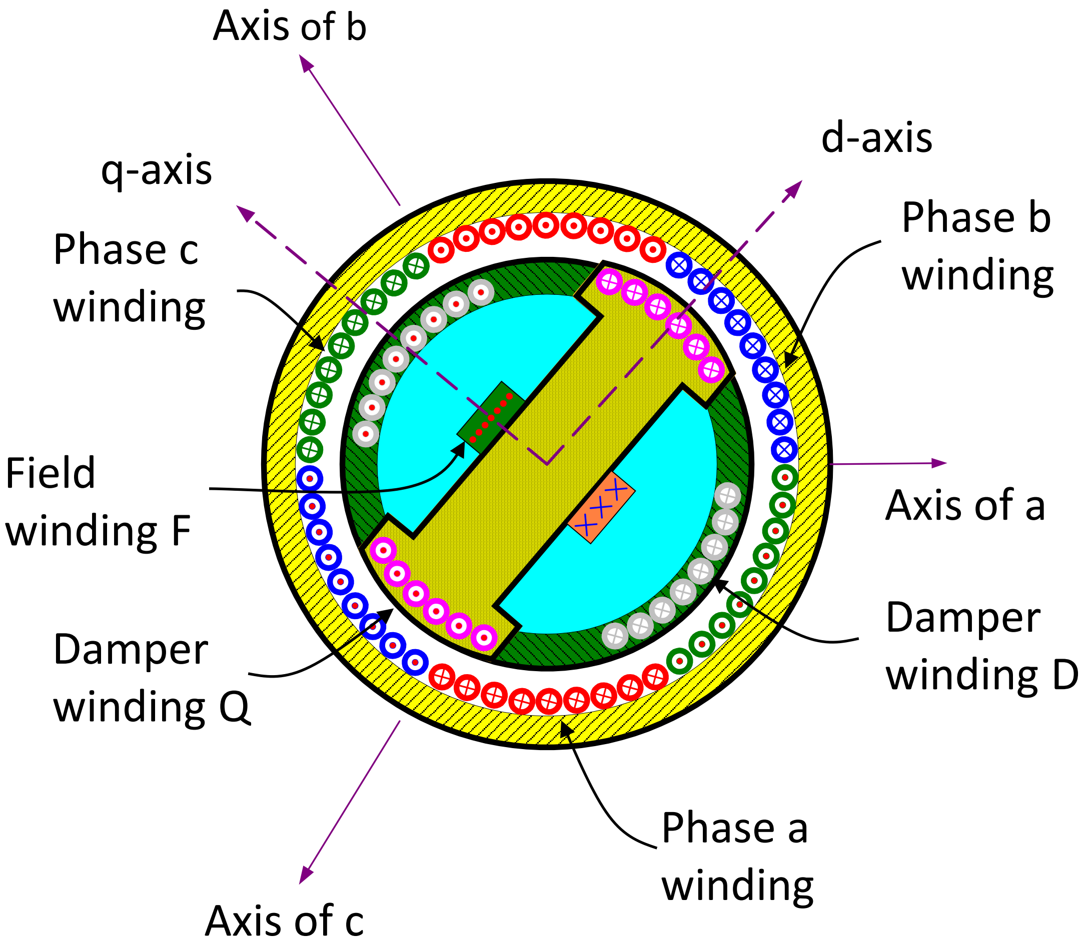
Power System Modeling
Part 2

Generator and Transformer Models

Generator Model

Generalized Machine Model

Constructional Details of Synchronous Machine



Stator:

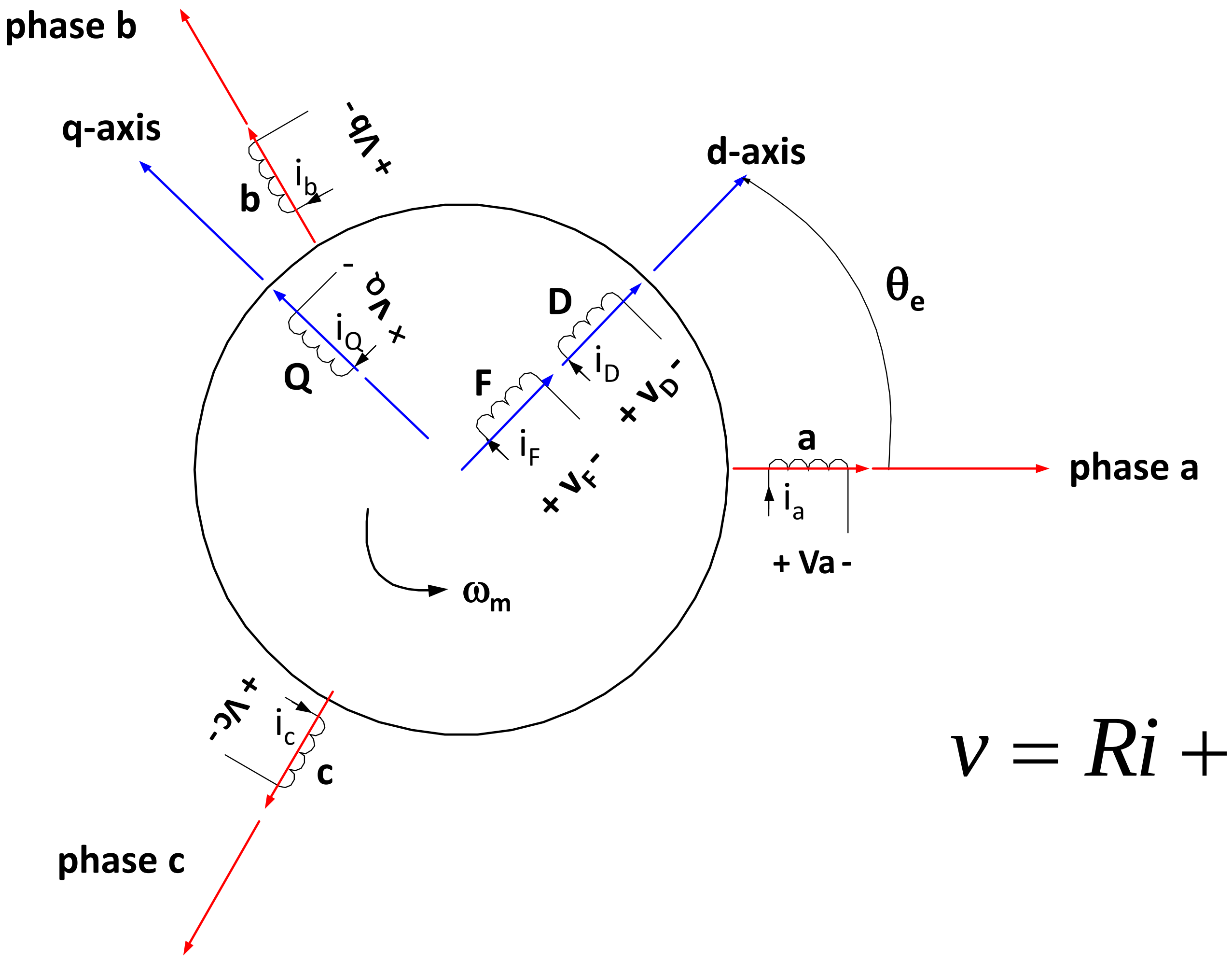
distributed three-phase winding (a, b, c)

Rotor:

DC field winding (F) and short-circuited damper windings (D, Q)

Generalized Machine Model

Primitive Coil Representation



$$v = Ri + \frac{d\lambda}{dt}$$

Generalized Machine Model

Voltage Equations for the Primitive Coils

For the stator windings

$$v_a = R_a i_a + \frac{d\lambda_a}{dt}$$

$$v_b = R_b i_b + \frac{d\lambda_b}{dt}$$

$$v_c = R_c i_c + \frac{d\lambda_c}{dt}$$

For the rotor windings

$$v_F = R_F i_F + \frac{d\lambda_F}{dt}$$

$$v_D = R_D i_D + \frac{d\lambda_D}{dt}$$

$$v_Q = R_Q i_Q + \frac{d\lambda_Q}{dt}$$

Note: The D and Q windings are shorted (i.e. $v_D = v_Q = 0$).

$$\left[\begin{array}{c} \underline{v}_{abc} \\ \hline \underline{v}_{FDQ} \end{array}\right] = \left[\begin{array}{c|c} R_{abc} & \\ \hline & R_{FDQ} \end{array}\right] \left[\begin{array}{c} \underline{i}_{abc} \\ \hline i_{FDQ} \end{array}\right] + p \left[\begin{array}{c} \underline{\lambda}_{abc} \\ \hline \underline{\lambda}_{FDQ} \end{array}\right] \qquad \lambda = Li$$

Generalized Machine Model

The flux linkage equations are:

$$\left[\begin{array}{c}\lambda_a\\ \lambda_b\\ \lambda_c\\ \hline \lambda_F\\ \lambda_D\\ \lambda_Q\end{array}\right]=\left[\begin{array}{ccc|ccc}L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ}\\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ}\\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ}\\ \hline L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & L_{FQ}\\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & L_{DQ}\\ L_{Qa} & L_{Qb} & L_{Qc} & L_{QF} & L_{QD} & L_{QQ}\end{array}\right]\left[\begin{array}{c}i_a\\ i_b\\ i_c\\ \hline i_F\\ i_D\\ i_Q\end{array}\right]$$

or

$$\left[\begin{array}{c}\underline{\lambda}_{abc}\\ \hline \underline{\lambda}_{FDQ}\end{array}\right]=\left[\begin{array}{c|c}[L_{SS}] & [L_{SR}]\\ \hline [L_{RS}] & [L_{RR}]\end{array}\right]\left[\begin{array}{c}\underline{i}_{abc}\\ \hline \underline{i}_{FDQ}\end{array}\right]$$

Generalized Machine Model

COIL INDUCTANCES

Stator Self Inductances

$$L_{aa} = L_s + L_m \cos 2\theta_e$$

$$L_{bb} = L_s + L_m \cos(2\theta_e + 120^\circ)$$

$$L_{cc} = L_s + L_m \cos(2\theta_e - 120^\circ)$$

Stator-to-Stator Mutual Inductances

$$L_{ab} = L_{ba} = -M_s + L_m \cos(2\theta_e - 120^\circ)$$

$$L_{bc} = L_{cb} = -M_s + L_m \cos 2\theta_e$$

$$L_{ca} = L_{ac} = -M_s + L_m \cos(2\theta_e + 120^\circ)$$

Generalized Machine Model

COIL INDUCTANCES

Stator-to-Rotor Mutual Inductances

$$L_{aF} = L_{Fa} = L_{aF}\cos\theta_e$$

$$L_{bF} = L_{Fb} = L_{aF}\cos(\theta_e - 120^\circ)$$

$$L_{cF} = L_{Fc} = L_{aF}\cos(\theta_e + 120^\circ)$$

$$L_{aD} = L_{Da} = L_{aD}\cos\theta_e$$

$$L_{bD} = L_{Db} = L_{aD}\cos(\theta_e - 120^\circ)$$

$$L_{cD} = L_{Dc} = L_{aD}\cos(\theta_e + 120^\circ)$$

$$L_{aQ} = L_{Qa} = -L_{aQ}\sin\theta_e$$

$$L_{bQ} = L_{Qb} = -L_{aQ}\sin(\theta_e - 120^\circ)$$

$$L_{cQ} = L_{Qc} = -L_{aQ}\sin(\theta_e + 120^\circ)$$

Generalized Machine Model

COIL INDUCTANCES

Rotor Self Inductances

$$L_{FF} = L_{FF}$$
$$L_{DD} = L_{DD}$$
$$L_{QQ} = L_{QQ}$$

Rotor-to-Rotor Mutual Inductances

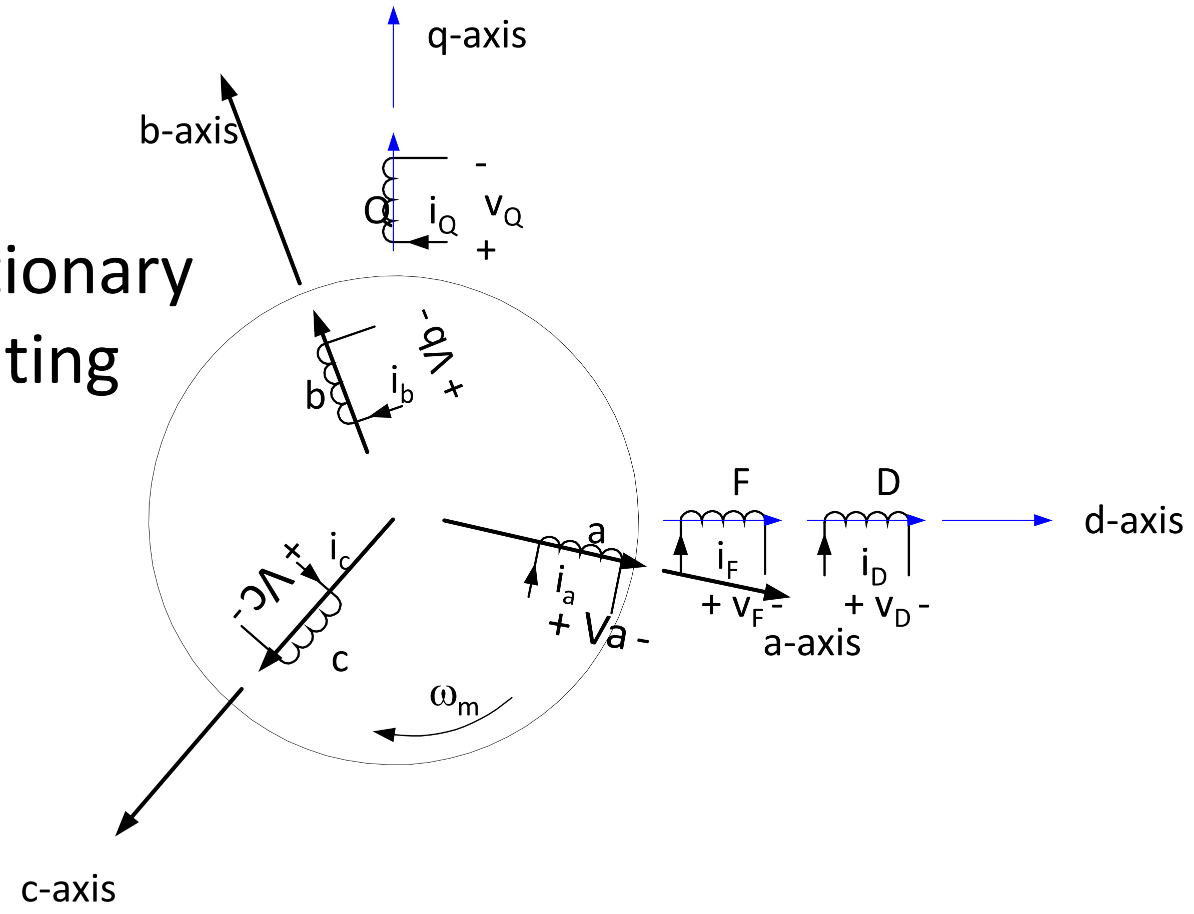
$$L_{FD} = L_{DF} = L_{FD}$$
$$L_{FQ} = L_{QF} = 0$$
$$L_{DQ} = L_{QD} = 0$$

Generalized Machine Model

Equivalent Coil Representation

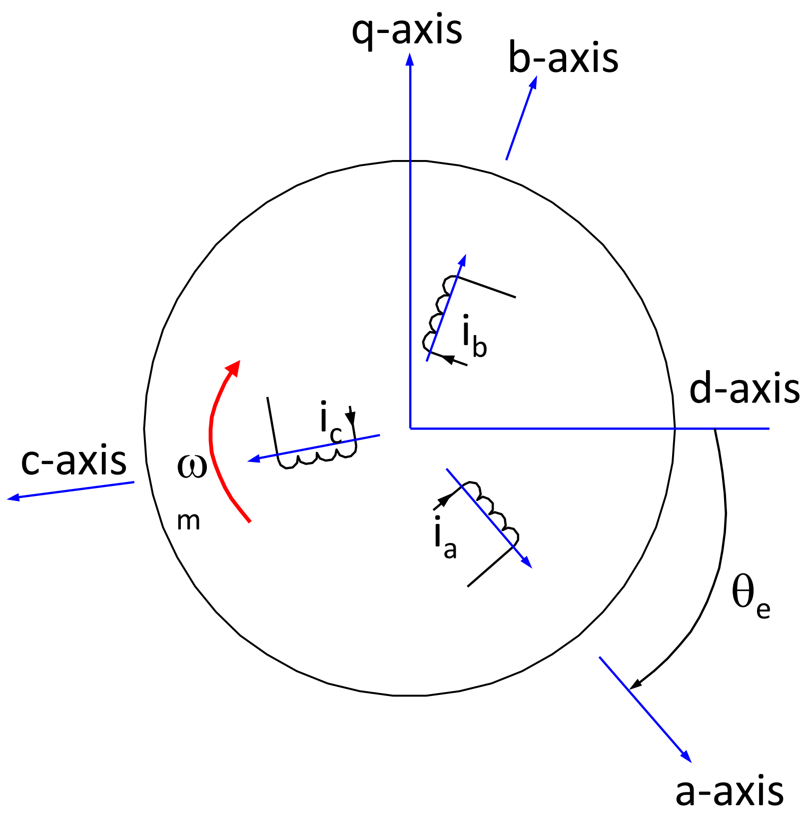
Rotor coils FDQ stationary

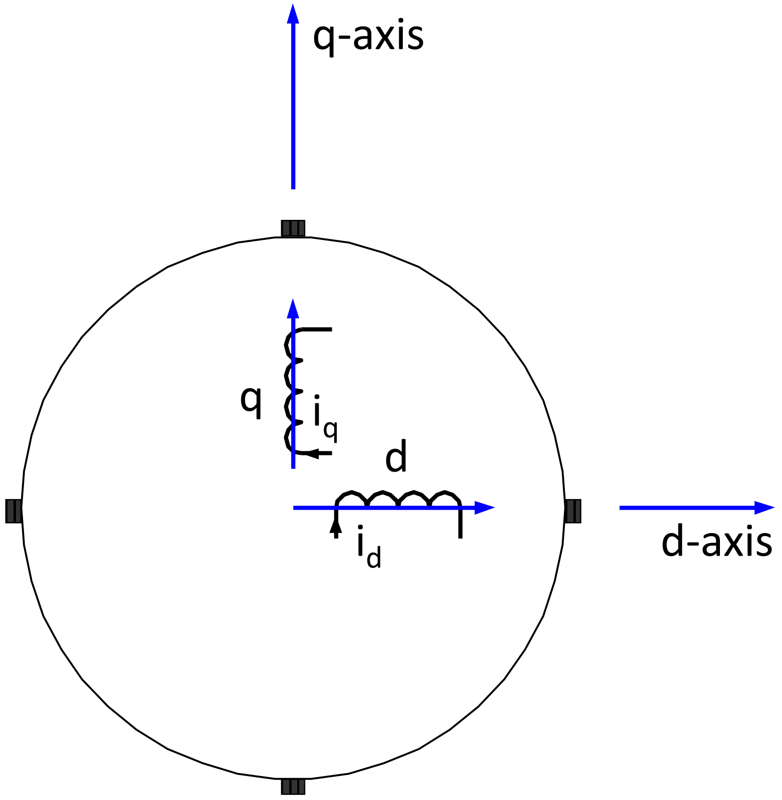
Stator coils abc rotating



Generalized Machine Model

Transformation from abc to Odq





Note: The d and q windings are pseudo-stationary. The O axis is perpendicular to the d and q axes.

Generalized Machine Model

Park's Transformation Matrix

$$[P] = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta_e & \cos(\theta_e - 120) & \cos(\theta_e + 120) \\ -\sin\theta_e & -\sin(\theta_e - 120) & -\sin(\theta_e + 120) \end{bmatrix}$$

$$[P]^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \cos\theta & -\sin\theta_e \\ \frac{1}{\sqrt{2}} & \cos(\theta_e - 120) & -\sin(\theta_e - 120) \\ \frac{1}{\sqrt{2}} & \cos(\theta_e + 120) & -\sin(\theta_e + 120) \end{bmatrix}$$

Generalized Machine Model

After Park's Transformation

Voltage Equations

$$(1)\quad v_o = R_a i_o + p\lambda_o$$

$$(2)\quad v_d = R_a i_d + p\lambda_d - \omega_m \lambda_q$$

$$(3)\quad v_q = R_a i_q + p\lambda_q + \omega_m \lambda_d$$

$$(4)\quad v_F = R_F i_F + p\lambda_F$$

$$(5)\quad v_D = R_d i_D + p\lambda_D = 0$$

$$(6)\quad v_Q = R_Q i_Q + p\lambda_Q = 0$$

Flux Linkages

$$(1)\quad \lambda_o = L_{oo} i_o$$

$$(2)\quad \lambda_d = L_{dd} i_d + L_{dF} i_F + L_{dD} i_D$$

$$(3)\quad \lambda_q = L_{qq} i_q + L_{qQ} i_Q$$

$$(4)\quad \lambda_F = L_{Fd} i_d + L_{FF} i_F + L_{FD} i_D$$

$$(5)\quad \lambda_D = L_{Dd} i_d + L_{DF} i_F + L_{DD} i_D$$

$$(6)\quad \lambda_Q = L_{Qq} i_q + L_{QQ} i_Q$$

Generalized Machine Model

$$L_{oo} = L_S - 2M_S$$

$$L_{dd} = L_S + M_S + \frac{3}{2}L_m$$

$$L_{qq} = L_S + M_S - \frac{3}{2}L_m$$

$$L_{dF} = \sqrt{\frac{3}{2}}L_{aF} \qquad L_{dD} = \sqrt{\frac{3}{2}}L_{aD} \qquad L_{qQ} = \sqrt{\frac{3}{2}}L_{aQ}$$

$$L_{Fd} = \sqrt{\frac{3}{2}}L_{aF} \qquad L_{Dd} = \sqrt{\frac{3}{2}}L_{aD} \qquad L_{Qq} = \sqrt{\frac{3}{2}}L_{aQ}$$

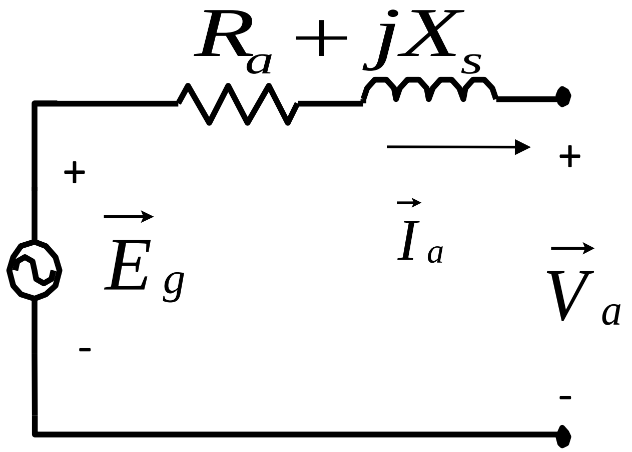
Note: All inductances are constant.

Steady–State Analysis

Using Park's transformation of balance 3-phase voltage and currents of generators

$$\vec{V}_a = R_a\left(-\vec{I}_a\right) + jX_s\left(-\vec{I}_a\right) + \vec{E}_g$$

$$\vec{E}_g = R_a\vec{I}_a + jX_s\vec{I}_a + \vec{V}_a$$



Equivalent Circuit of Cylindrical Rotor Synchronous Generator

Equivalent Circuit of Generators

Positive-Sequence Impedance:

X_d''=Direct-Axis Subtransient Reactance

X_d'=Direct-Axis Transient Reactance

X_d=Direct-Axis Synchronous Reactance

Negative-Sequence Impedance:

$X_2 = \frac{1}{2}(X_d'' + X_q'')$ for a salient-pole machine

$X_2 = X_d''$ for a cylindrical-rotor machine

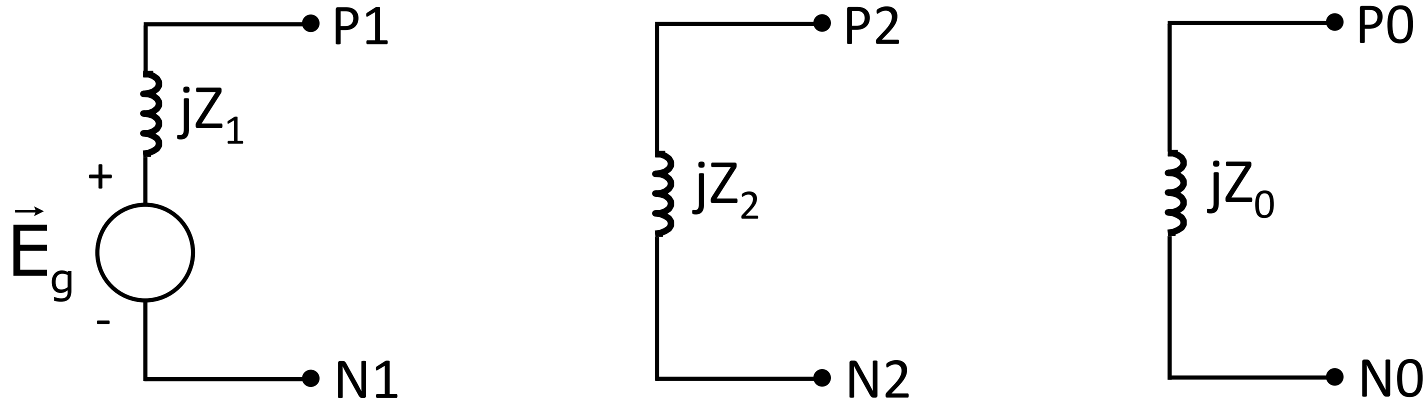
Zero-Sequence Impedance:

$$0.15X_d'' \leq X_0 \leq 0.6X_d''$$

Equivalent Circuit of Generators

Grounded-Wye Generator

The sequence networks for the grounded-wye generator are shown below.



Positive Sequence

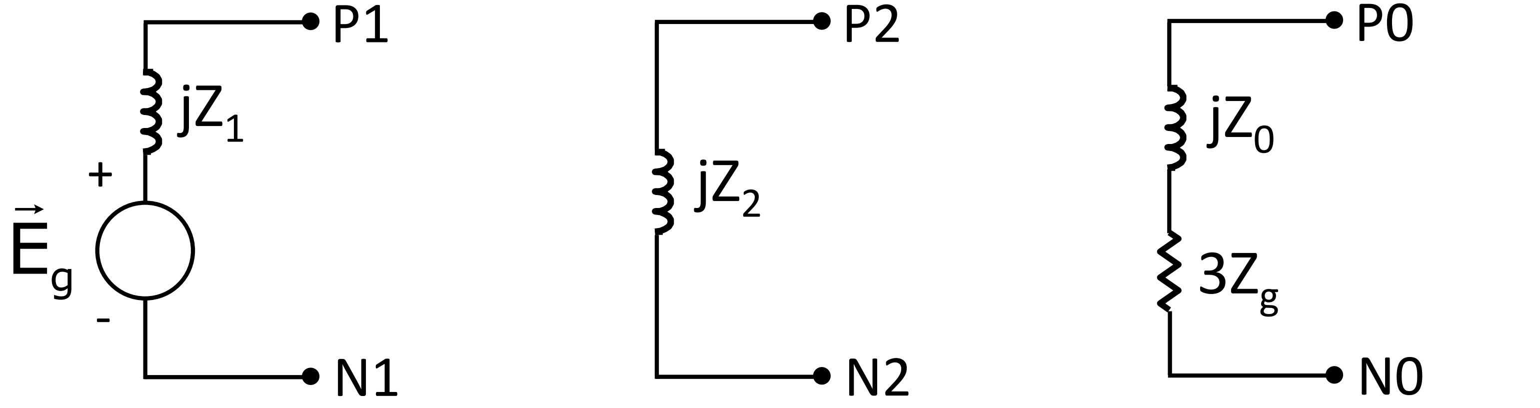
Negative Sequence

Zero Sequence

Equivalent Circuit of Generators

Grounded-Wye through an Impedance

If the generator neutral is grounded through an impedance Z_g, the zero-sequence impedance is modified as shown below.



Positive Sequence

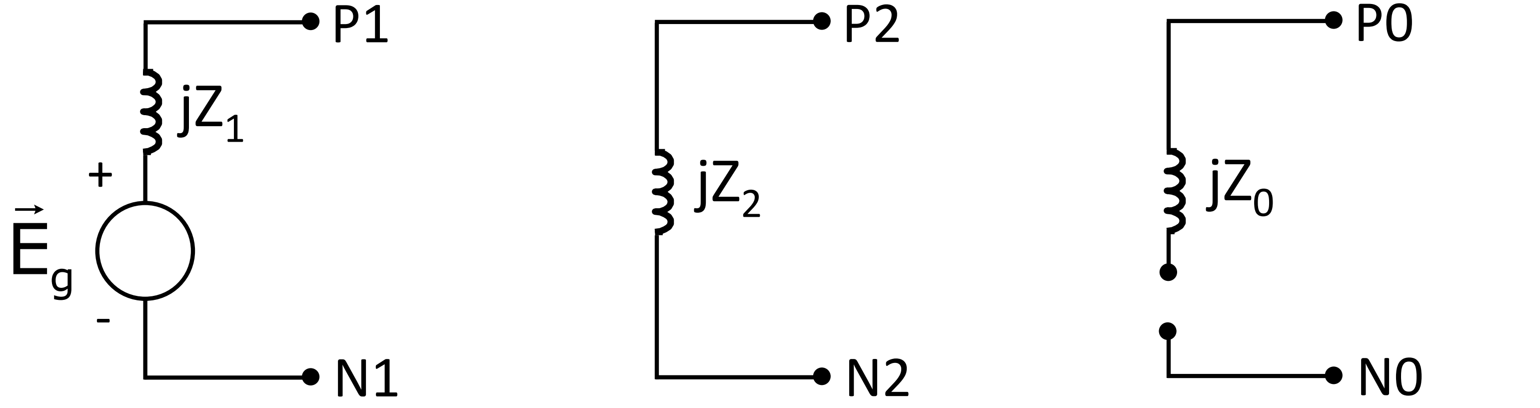
Negative Sequence

Zero Sequence

Equivalent Circuit of Generators

Ungrounded-Wye Generator

If the generator is connected ungrounded-wye or delta, no zero-sequence current can flow. The sequence networks for the generator are shown below.



Positive Sequence

Negative Sequence

Zero Sequence