राष्ट्रीय प्रौद्योगिकी संस्थान कालिकट
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# EE6303D Dynamics of Electrical Machines (DEM)

## Module 3

Dr. Gopakumar Pathirikkat
Asst Professor, EED

# Oscillations

Induction Machines

## Synchronous Machines

1. Isolated synchronous generator to a load
2. Synchronous generator connected to infinite bus
3. Synchronous Motor

The problem of small oscillations is encountered mainly with machines in which there is some form of feedback. This may consist of signals generated within the machine inherently, due to the configuration of windings, or externally in the form of a control system, or a voltage regulator on a d.c. generator.

Self-excited oscillations are fairly common in power systems. Usually two kinds of self-excited oscillations are encountered. One is a high-frequency electrical oscillation, to which the machine rotors, because of their high inertia, cannot respond. The analysis of the complete system using eigenvalue techniques will indicate whether or not such frequencies will be present. We are primarily concerned here with low-frequency oscillations (a few hertz) to which the rotors can respond. These are electromechanical in nature.

# Synchronous Machine Equation During Small Oscillations

$$Jp^2\Delta\theta + T_{de}p\Delta\theta + R_F p\Delta\theta + T_S\Delta\theta = \Delta T_i$$

where $T_S\Delta\theta$ = synchronising torque

$T_{de}p\Delta\theta$ = electrical damping torque

$R_F p\Delta\theta$ = mechanical damping torque

$Jp^2\Delta\theta$ = rotational torque due to the inertia of the rotor

$\Delta T_i$ = change in input/output torque

The damping and synchronising torque coefficients not only indicate whether or not a system is stable, they clearly indicate the extent of the stability /instability region and provide physical concepts which are not obtained by other methods.

When the oscillations are self-excited ΔTi= 0 and hence

$$Jp^2\Delta\theta + (T_{de} + R_F)p\Delta\theta + T_S\Delta\theta = 0$$

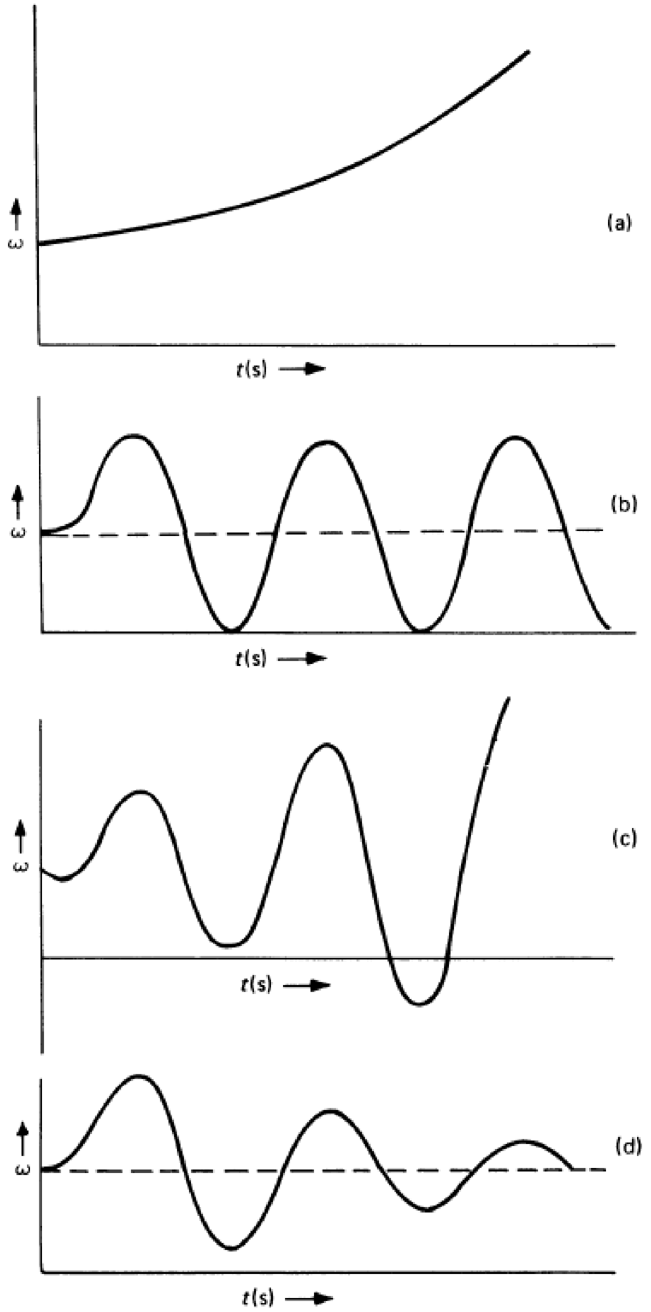
# Synchronous Machine Equation During Small Oscillations

$$Jp^2\Delta\theta + (T_{\mathrm{de}} + R_{\mathrm{F}})p\Delta\theta + T_{\mathrm{S}}\Delta\theta = 0$$

(a) if $T_{\mathrm{S}} = 0$, the machine does not oscillate, but loses synchronism
(b) if $(T_{\mathrm{de}} + R_{\mathrm{F}}) = 0$ oscillations begin and are self-sustained

(c) $(T_{\mathrm{de}} + R_{\mathrm{F}}) < 0$ oscillations build up in magnitude and the machine loses synchronism
(d) $(T_{\mathrm{de}} + R_{\mathrm{F}}) > 0$ there may or may not be oscillations but in either case the system will be stable if $T_{\mathrm{S}} > 0$

# Synchronous Machine Equation During Small Oscillations




(a) Non-oscillatory increase of rotor angle (T, = 0)
(b) sustained oscillations (Tde + RF = 0)
(c) negatively damped oscillations (Tde + RF < 0)
(d) damped oscillations (Tde+RF > 0)

# Synchronous Machine Equation During Small Oscillations

Oscillations of small amplitude, the system equations may be linearised about the operating points. This makes it fairly easy to evolve criteria which will tell us whether the machines are dynamically stable or not, using methods such as the following:

(1) the Nyquist criterion

(2) Routh-Hurwitz criterion

(3) computation of the eigenvalues

(4) **computation of the synchronising and damping torque coefficients**

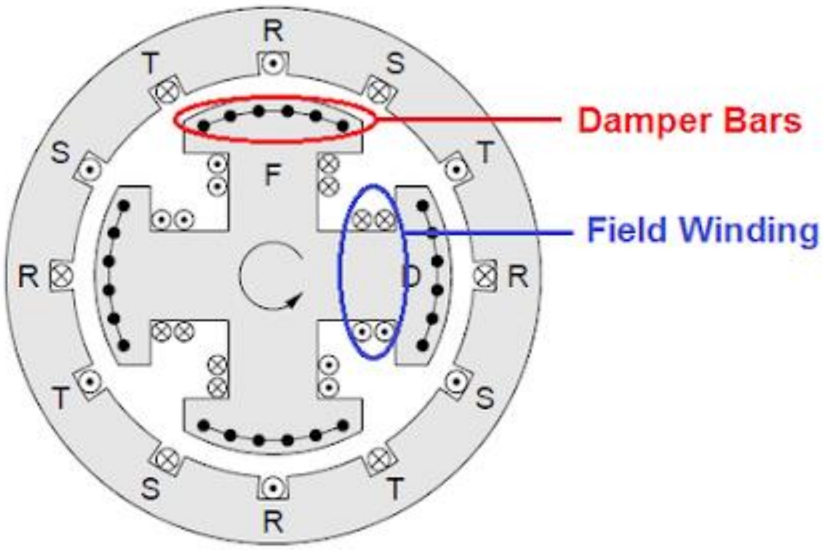
(5) D-partition techniques

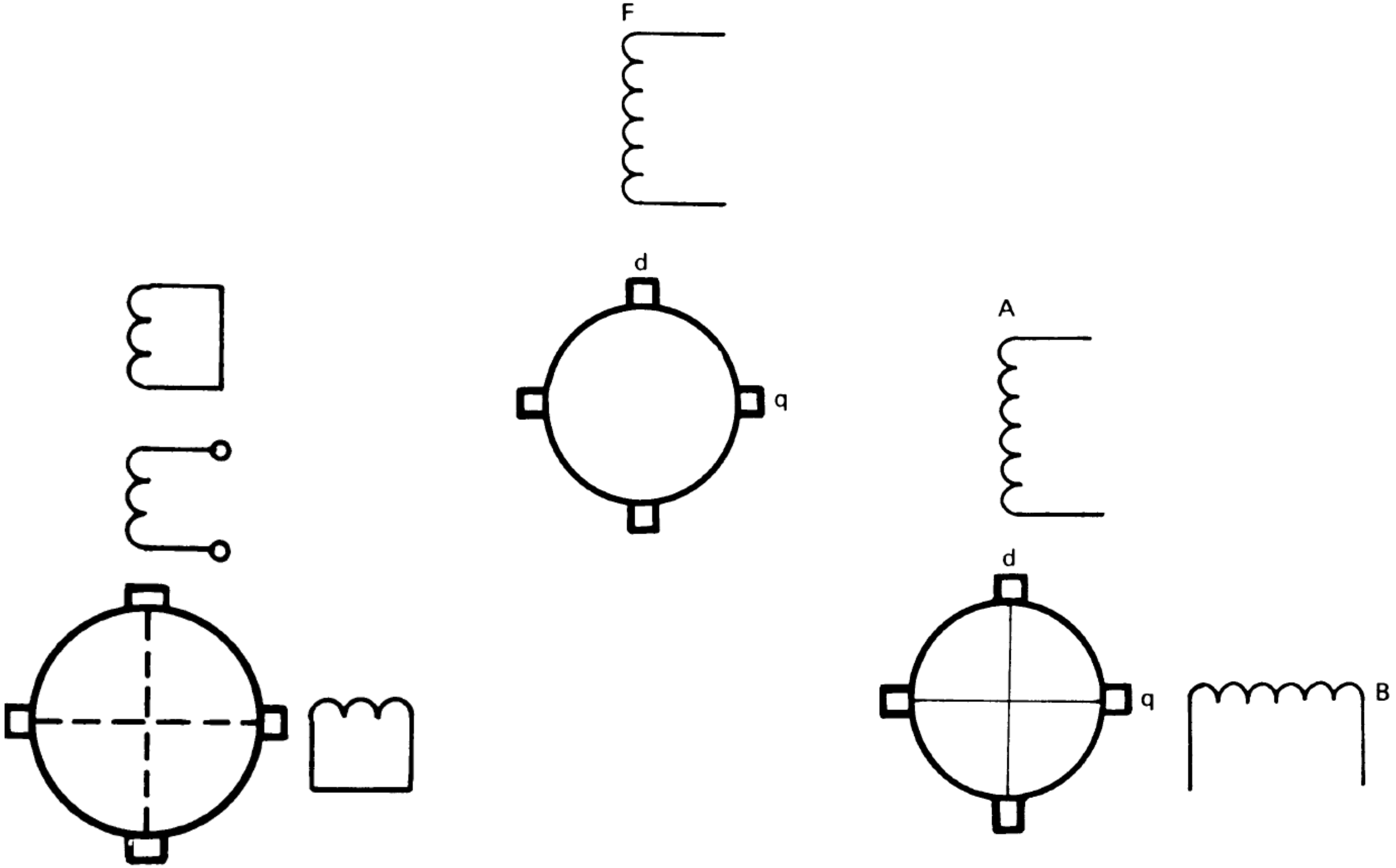
(6) computation of rotor swing with time-the so-called swing curves

In the case of transient (nonlinear) instability, the standard approach is to compute the swing curves.

# Primitive Machines

**Synchronous machines with amortisseur winding**



# Synchronous Machine Equation During Small Oscillations

transient equation for torque

$$Jp^2\theta + R_F p\theta - \mathbf{i}_t^* \mathbf{G}\mathbf{i} = T_{\text{input}}$$

For small oscillations, we take increments in θ, i, and Ti;

$$Jp^2\Delta\theta + R_F p\Delta\theta - \mathbf{i}_t^* \mathbf{G}\Delta\mathbf{i} - \Delta\mathbf{i}_t^* \mathbf{G}\mathbf{i} - \mathbf{i}_t^* \frac{\partial \mathbf{G}}{\partial \theta}\Delta\theta\, \mathbf{i} = \Delta T_i$$

$$\partial \mathbf{G}/\partial\theta = 0$$

$$Jp^2\Delta\theta + R_F p\Delta\theta - \mathbf{i}_t^* (\mathbf{G} + \mathbf{G}_t)\Delta\mathbf{i} = \Delta T_i$$

$$\Delta T_i = Jp^2\Delta\theta + R_F p\Delta\theta - \Delta\mathbf{i}_t^* (\mathbf{G} + \mathbf{G}_t)\mathbf{i}$$

$$\mathbf{V} = \mathbf{R}\mathbf{i} + \mathbf{L}p\mathbf{i} + \mathbf{G}\mathbf{i}p\theta$$

$$\mathbf{V} + \Delta\mathbf{V} = \mathbf{R}(\mathbf{i} + \Delta\mathbf{i}) + \mathbf{L}p(\mathbf{i} + \Delta\mathbf{i}) + \mathbf{G}(\mathbf{i} + \Delta\mathbf{i})p\theta + \mathbf{G}\mathbf{i}p(\Delta\theta)$$

$$\Delta\mathbf{V} = \mathbf{R}\Delta\mathbf{i} + \mathbf{L}p\Delta\mathbf{i} + \mathbf{G}p\theta\Delta\mathbf{i} + \mathbf{G}\mathbf{i}p(\Delta\theta)$$

# Synchronous Machine Equation During Small Oscillations

$$
\begin{bmatrix} \Delta V_{ds} \\ \Delta V_{dr} \\ \Delta V_{qr} \\ \Delta V_{qs} \\ \Delta T_{i} \end{bmatrix}
=
\begin{array}{c|ccccc|}
 & ds & dr & qr & qs & s \\ \hline
ds & R_{ds}+L_{ds}p & M_{d}p & & & \\
dr & M_{d}p & R_{r}+L_{dr}p & L_{qr}p\theta & M_{q}p\theta & L_{qr}i_{qr}+M_{q}i_{qs} \\
qr & -M_{d}p\theta & -L_{dr}p\theta & R_{r}+L_{qr}p & M_{q}p & -M_{d}i_{ds}-L_{dr}i_{dr} \\
qs & & & M_{q}p & R_{qs}+L_{qs}p & \\
s & -i_{qr}^{*}M_{d} & -i_{qs}^{*}M_{q}-(L_{qr}-L_{dr})i_{qr}^{*} & -i_{ds}^{*}M_{d}-i_{dr}^{*}(L_{qr}-L_{dr}) & -i_{dr}^{*}M_{q} & Jp+R_{F} \\ \hline
\end{array}
\cdot
\begin{bmatrix} \Delta i_{ds} \\ \Delta i_{dr} \\ \Delta i_{qr} \\ \Delta i_{qs} \\ p\Delta\theta \end{bmatrix}
$$

# Synchronous Machine Equation During Small Oscillations

$$\begin{bmatrix} \Delta \mathbf{V} \\ \Delta T_{\mathrm{i}} \end{bmatrix} = \begin{bmatrix} \overline{\mathbf{L}} & \\ & J \end{bmatrix} p \begin{bmatrix} \Delta \mathbf{i} \\ \Delta \omega \end{bmatrix} + \begin{bmatrix} \mathbf{R} + \mathbf{G} p \theta_0 & \mathbf{G} \mathbf{i}_0 \\ -\mathbf{i}_0^*(\mathbf{G} + \mathbf{G}_{\mathrm{t}}) & R_{\mathrm{F}} \end{bmatrix} \cdot \begin{bmatrix} \Delta \mathbf{i} \\ \Delta \omega \end{bmatrix}$$

$$\Delta \mathbf{x} = \begin{bmatrix} \Delta \mathbf{i} \\ \Delta \omega \end{bmatrix}$$

$$\Delta \mathbf{f} = \begin{bmatrix} \Delta \mathbf{V} \\ \Delta T_{\mathrm{i}} \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} \overline{\mathbf{L}} & \\ & J \end{bmatrix}$$

$$p \Delta \mathbf{x} = -\mathbf{L}^{-1} (\overline{\mathbf{A}}) \Delta \mathbf{x} + (\mathbf{L})^{-1} \Delta \mathbf{f}$$

$$\overline{\mathbf{A}} = \begin{bmatrix} \mathbf{R} + \mathbf{G} p \theta_0 & \mathbf{G} \mathbf{i}_0 \\ -\mathbf{i}_0^*(\mathbf{G} + \mathbf{G}_{\mathrm{t}}) & R_{\mathrm{F}} \end{bmatrix}$$

$$\Delta \dot{\mathbf{x}} = \mathbf{A} \Delta \mathbf{x} + \mathbf{B} \Delta \mathbf{u}$$

The characteristic equation is

$$\det \ (s\mathbf{I} - \mathbf{A}) = 0$$

# Synchronous Machine Equation During Small Oscillations

Having obtained the characteristic equation of a machine, the roots, or eigenvalues, can be computed by standard procedures. If the roots have no positive real parts, the system is stable. However, when the roots are obtained it may be found that one of the roots has a small negative real part and a low value of imaginary part. This root will predominantly influence the rotor dynamics. This will indicate that the machine will oscillate at an angular frequency determined by the imaginary part of the root and the rate of decay of the oscillations will depend on the magnitude of the real part. If a voltage regulator is present, roots with relatively small imaginary parts will be present which will also affect the dynamics of the rotor. The effect of the other roots, with faster decay rates (higher negative real values) will be apparent only at the initial stage and these will not affect the small oscillation behavior over the longer period given by the dominant root. Roots with large values of imaginary part will not affect the rotor dynamics because the rotor, due to its inertia, will not respond to high frequency oscillations. Hence we can often assume that there will be virtually one dominant root which will determine the machine kinetics during small oscillation