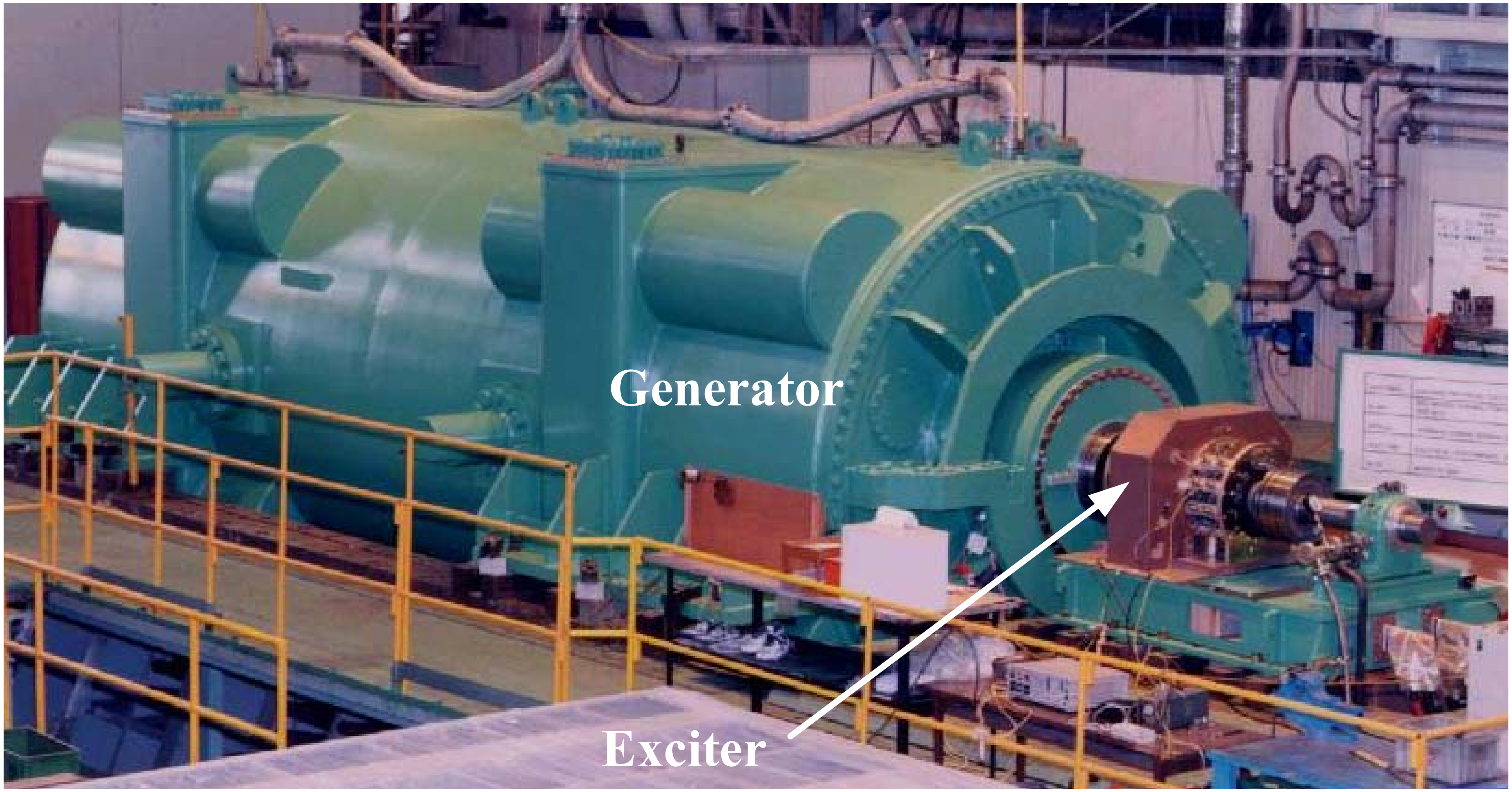
Synchronous machine

1. Construction

Synchronous Machines



View of a two-pole round rotor generator and exciter.

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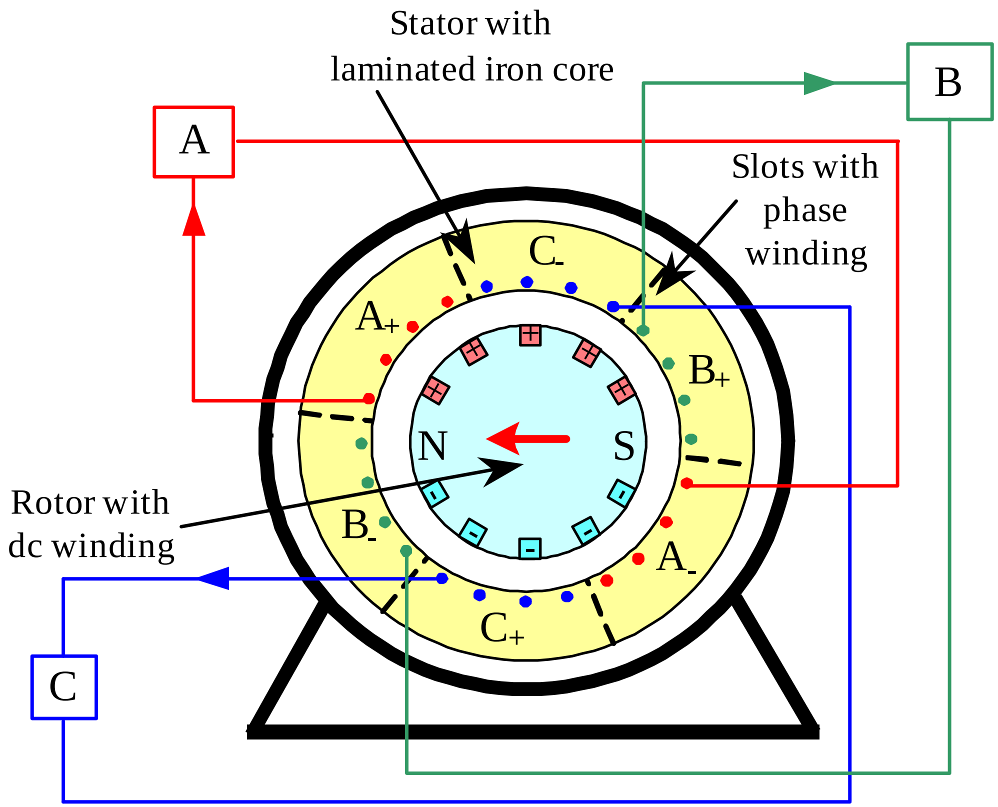

Major components of a round rotor two-pole generator

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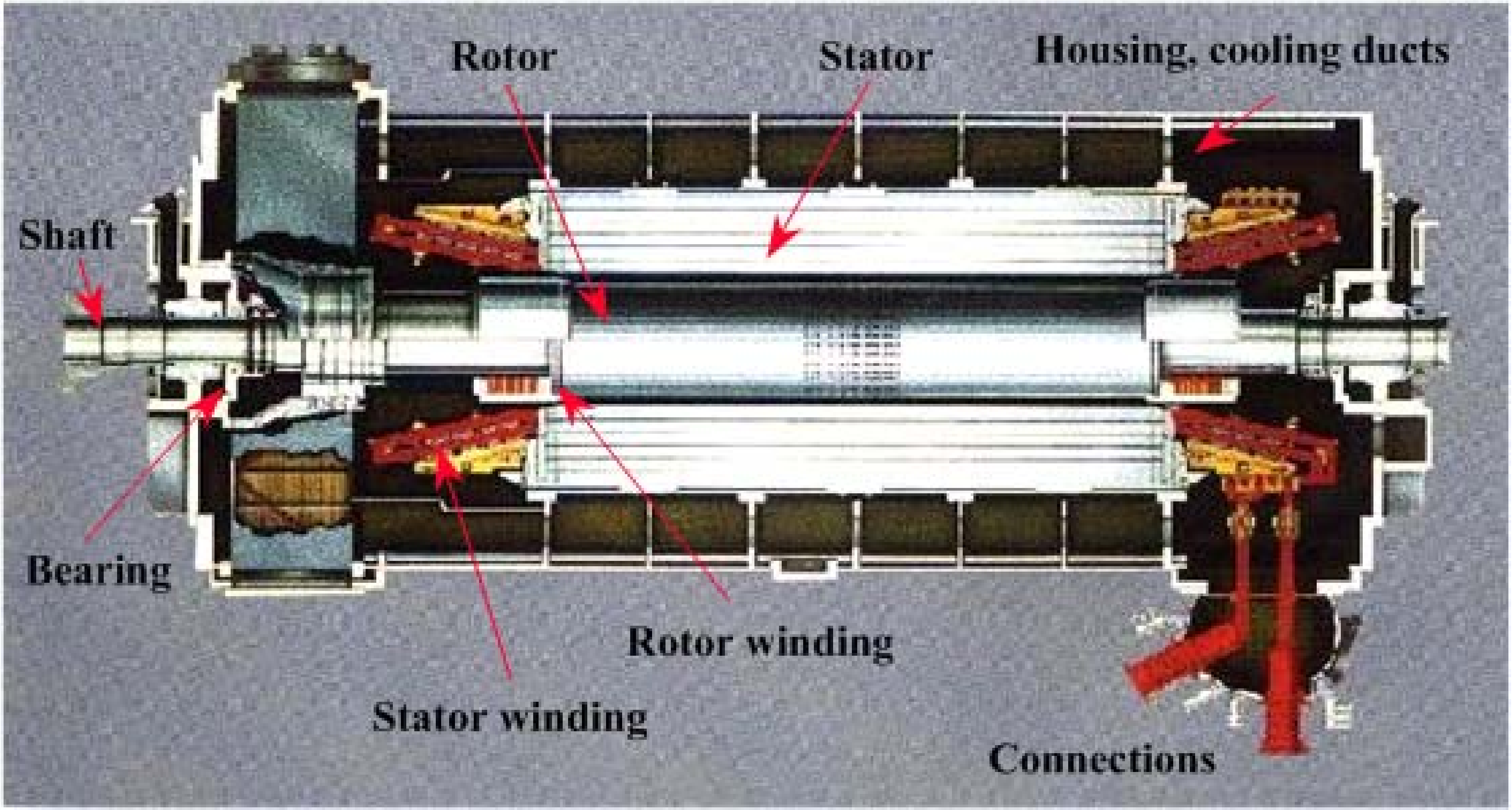

Cross-section of a large turbo generator. (Courtesy Westinghouse)

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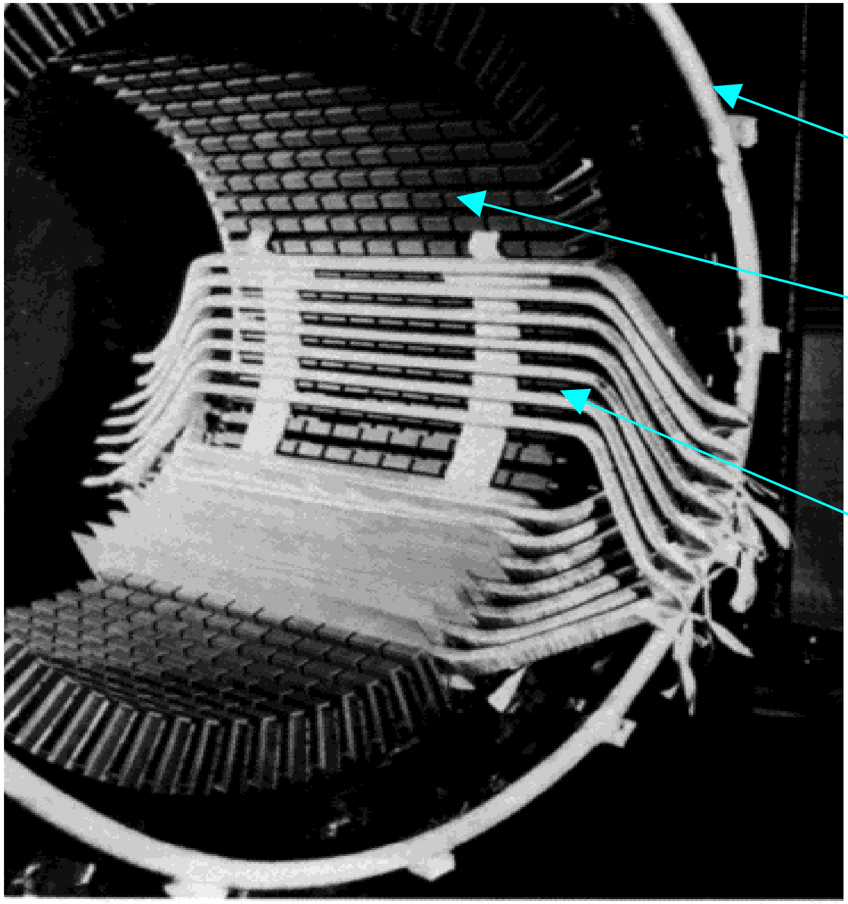

Details of a generator stator.

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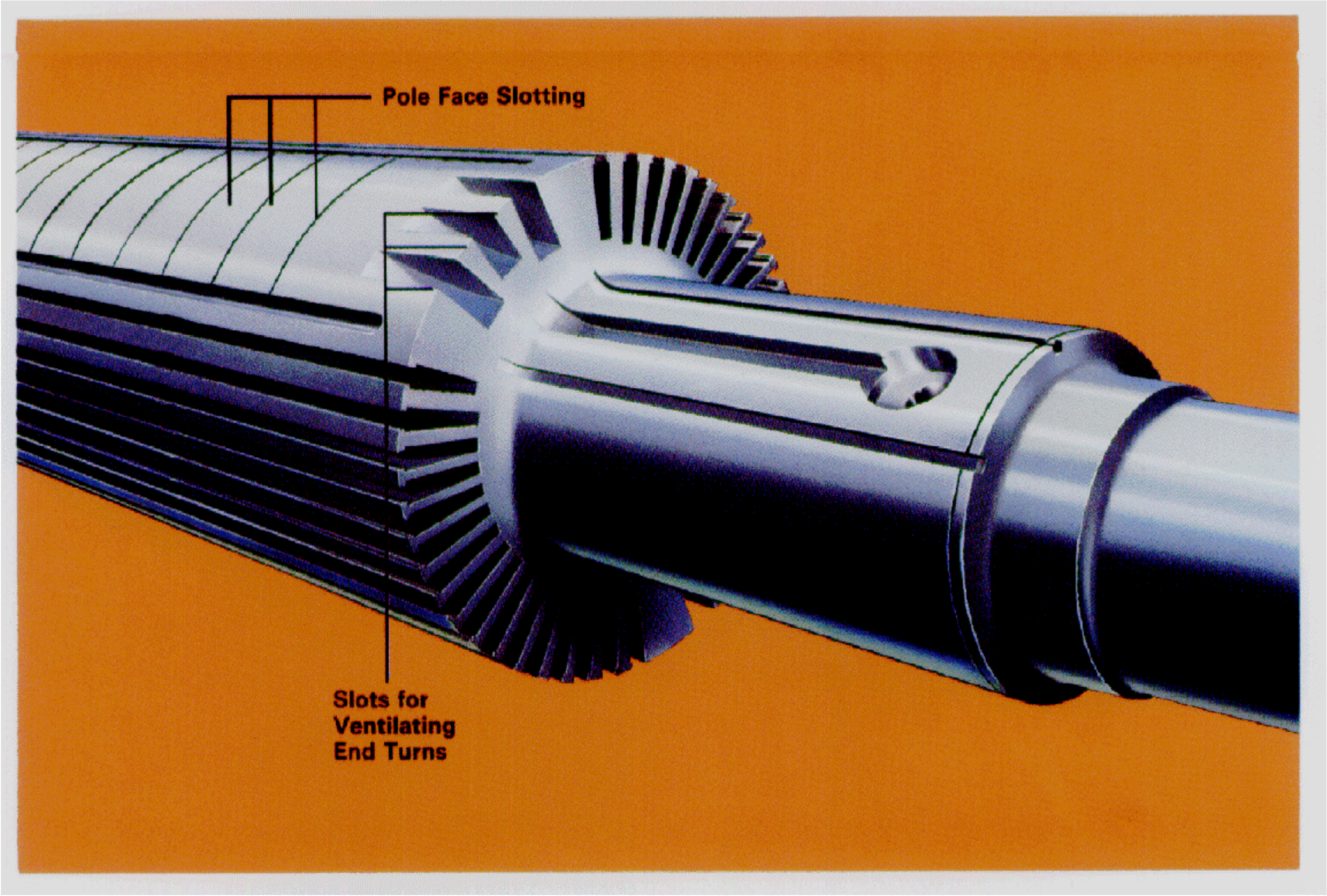

Rotor block of a large generator. (Courtesy Westinghouse)

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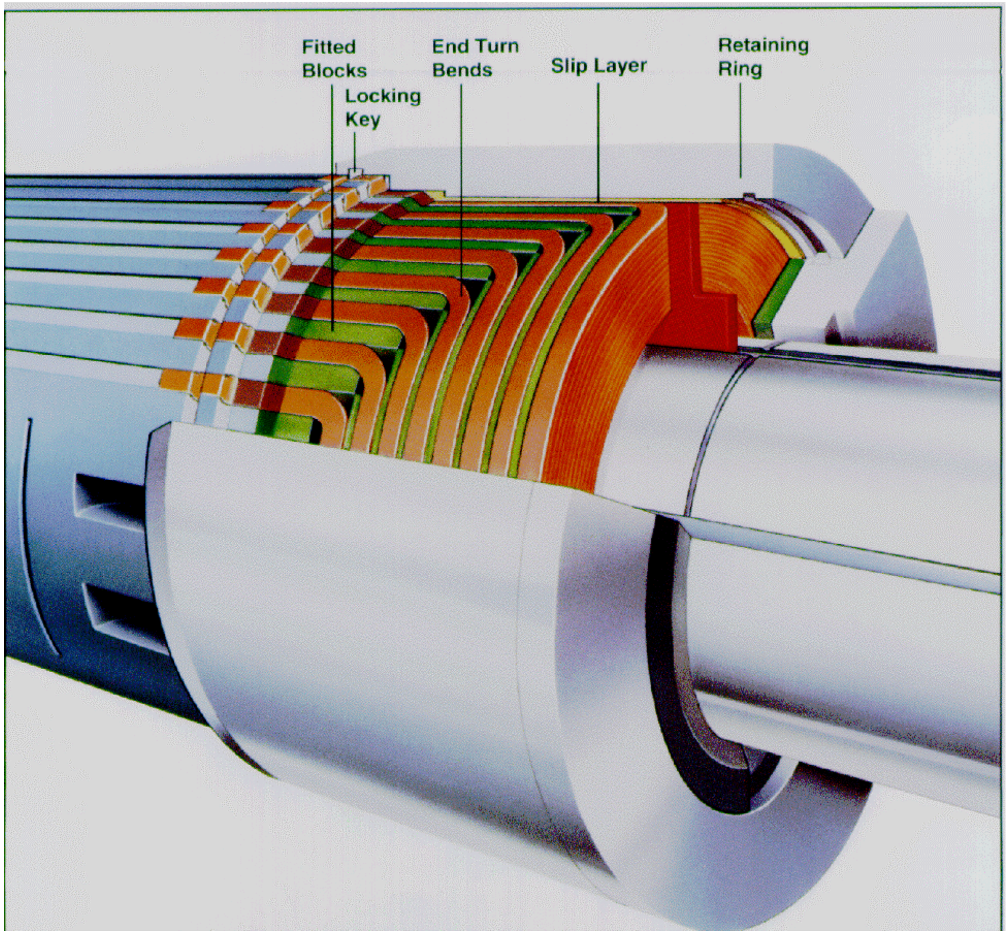

Generator rotor with conductors placed in the slots.

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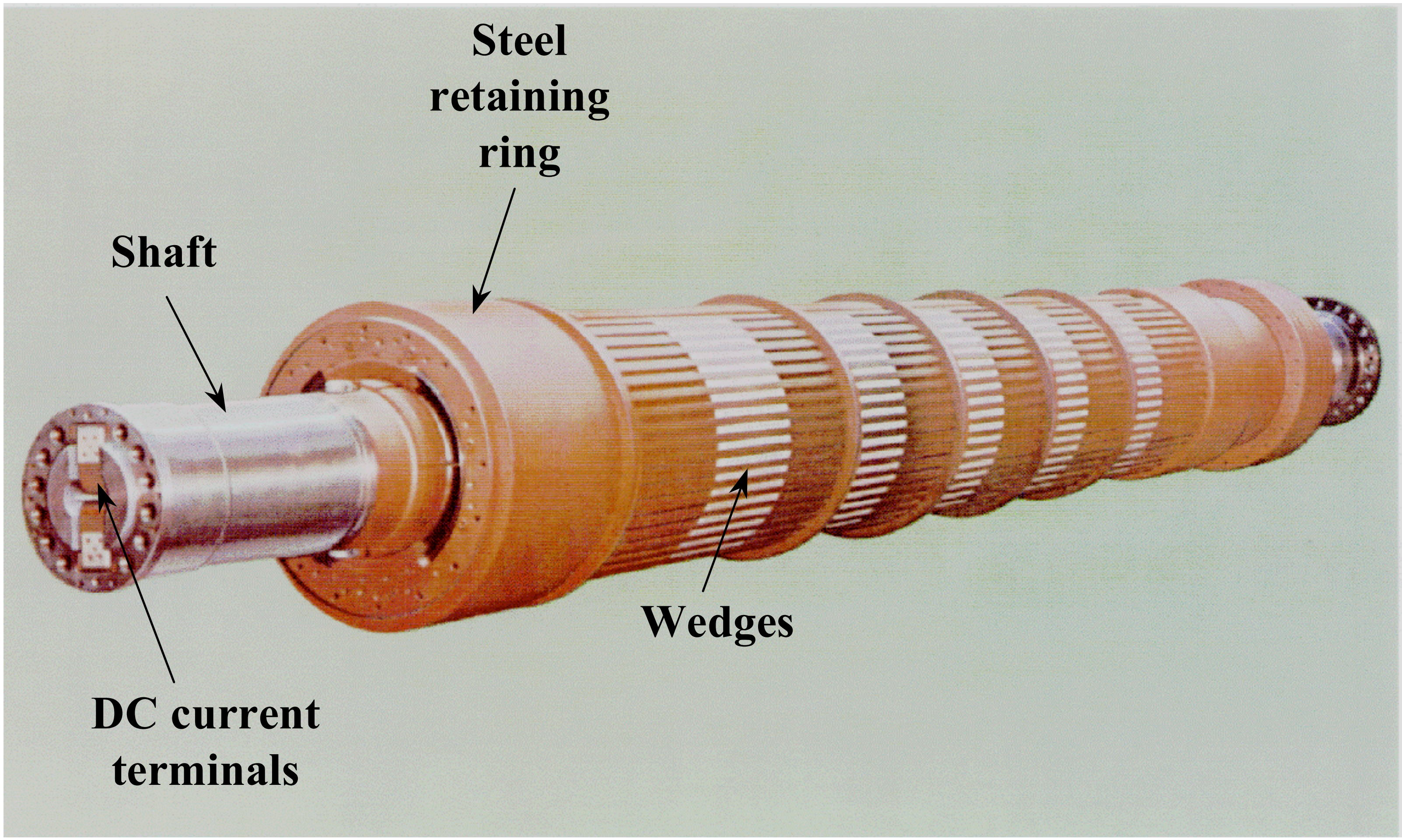

Large generator rotor completely assembled. (Courtesy Westinghouse)

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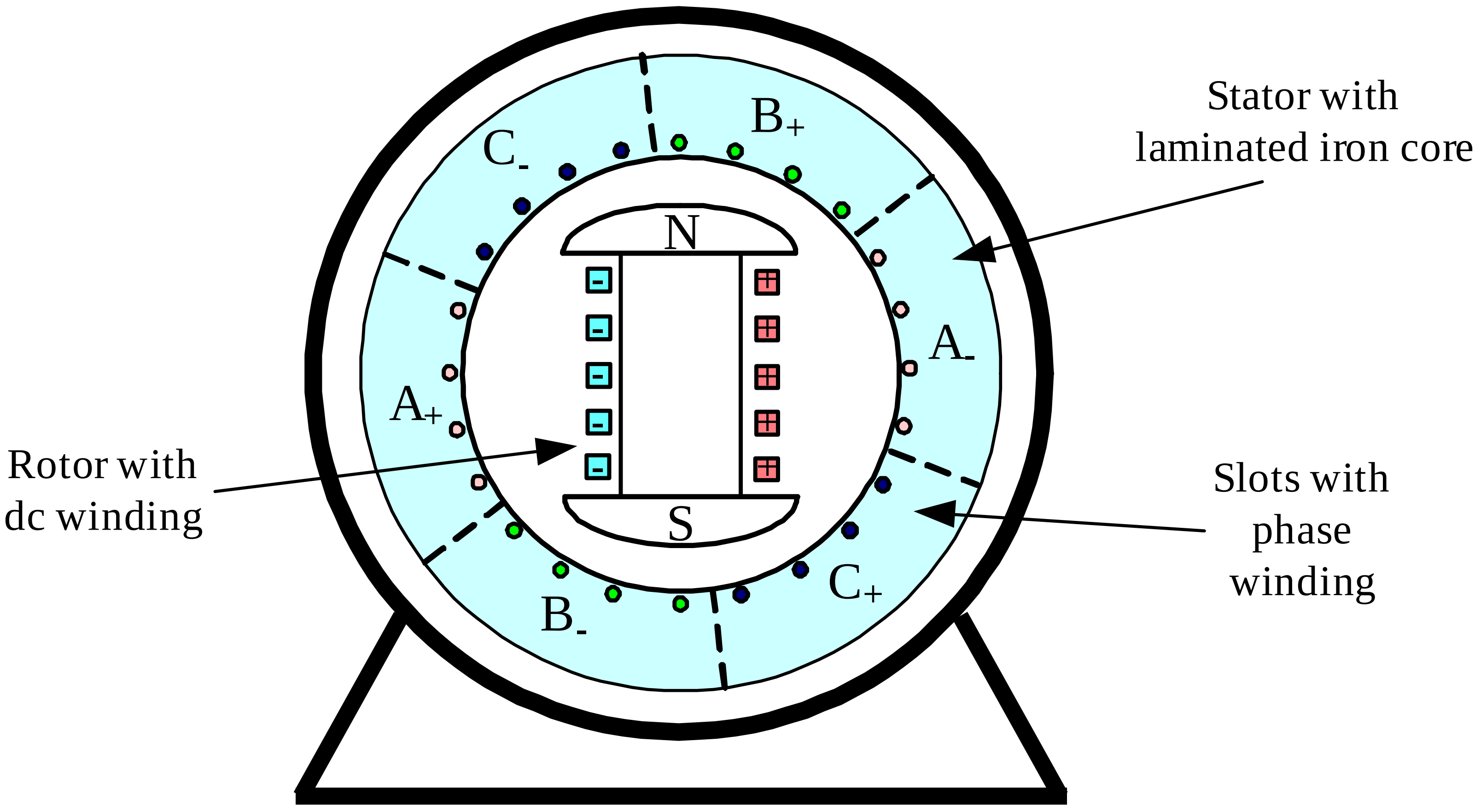

Two-pole salient pole generator concept.

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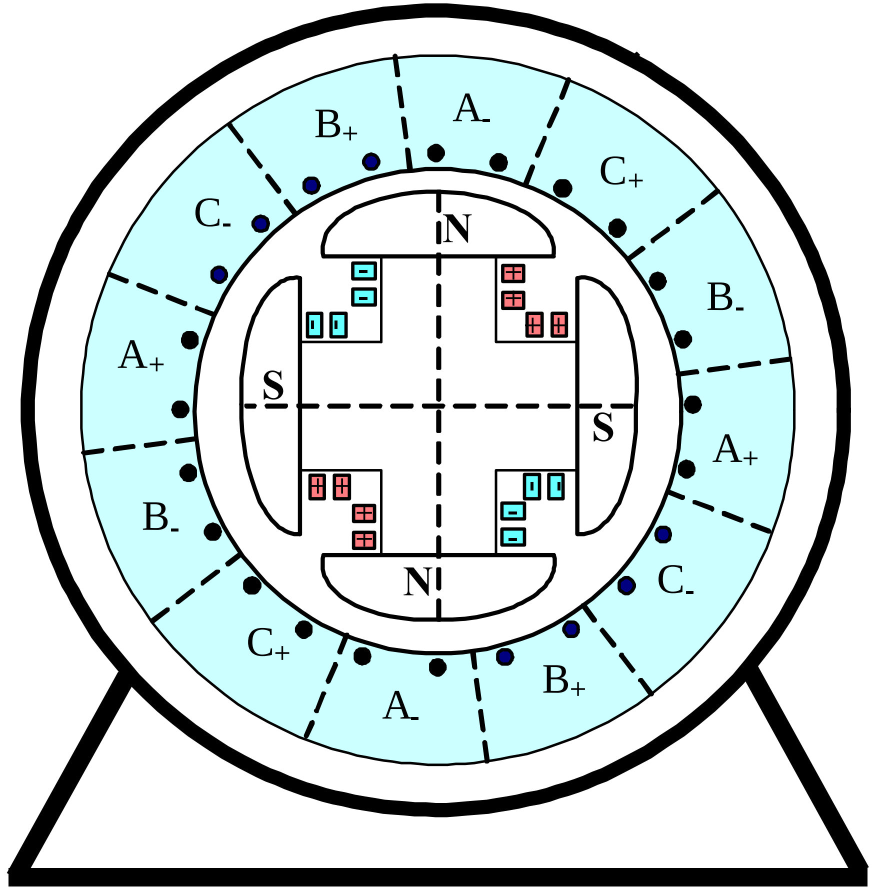

Four-pole salient pole generator concept.

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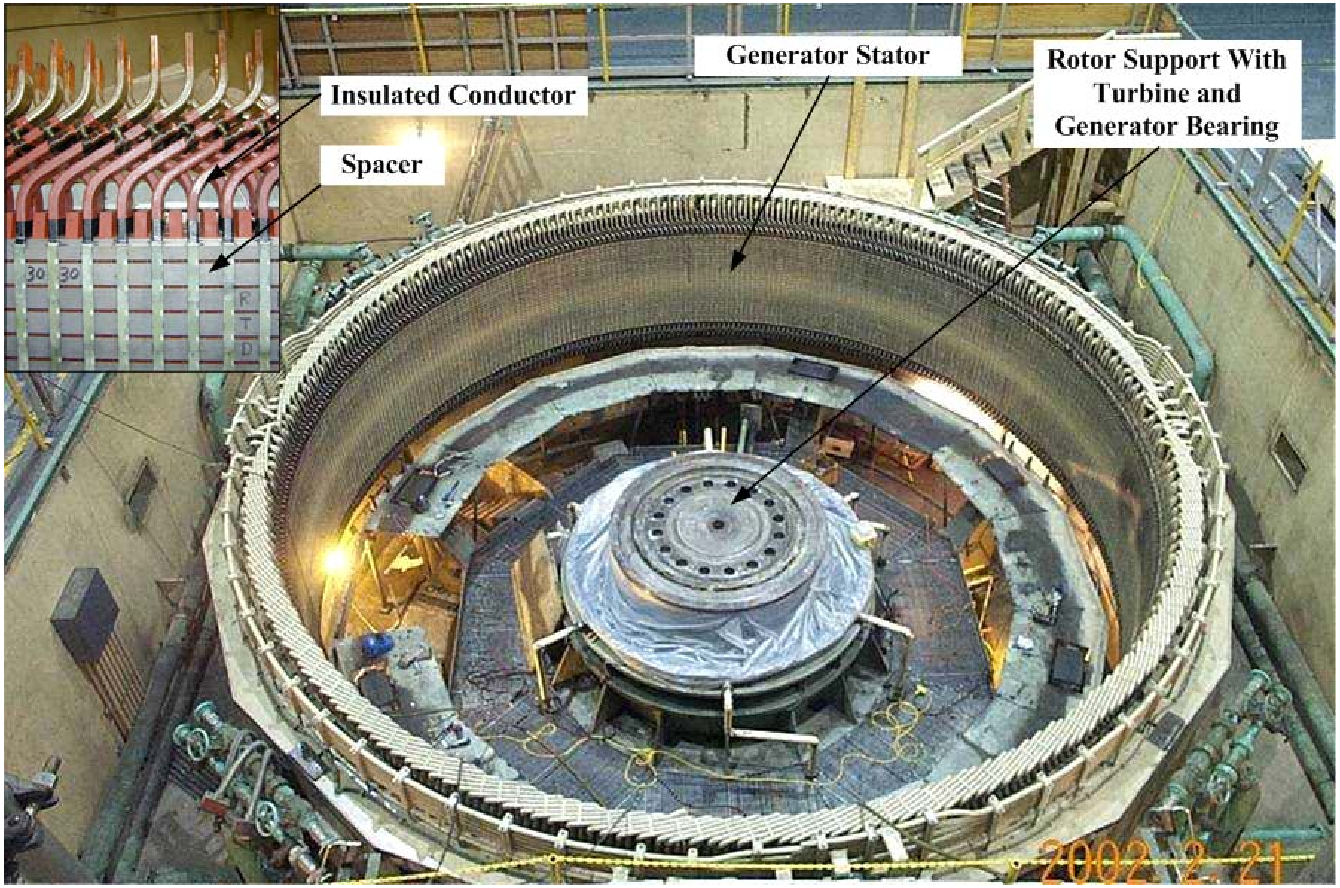

Stator of a large salient pole hydro generator; inset shows the insulated conductors and spacers.

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Large hydro generator rotor with view of the vertical poles.

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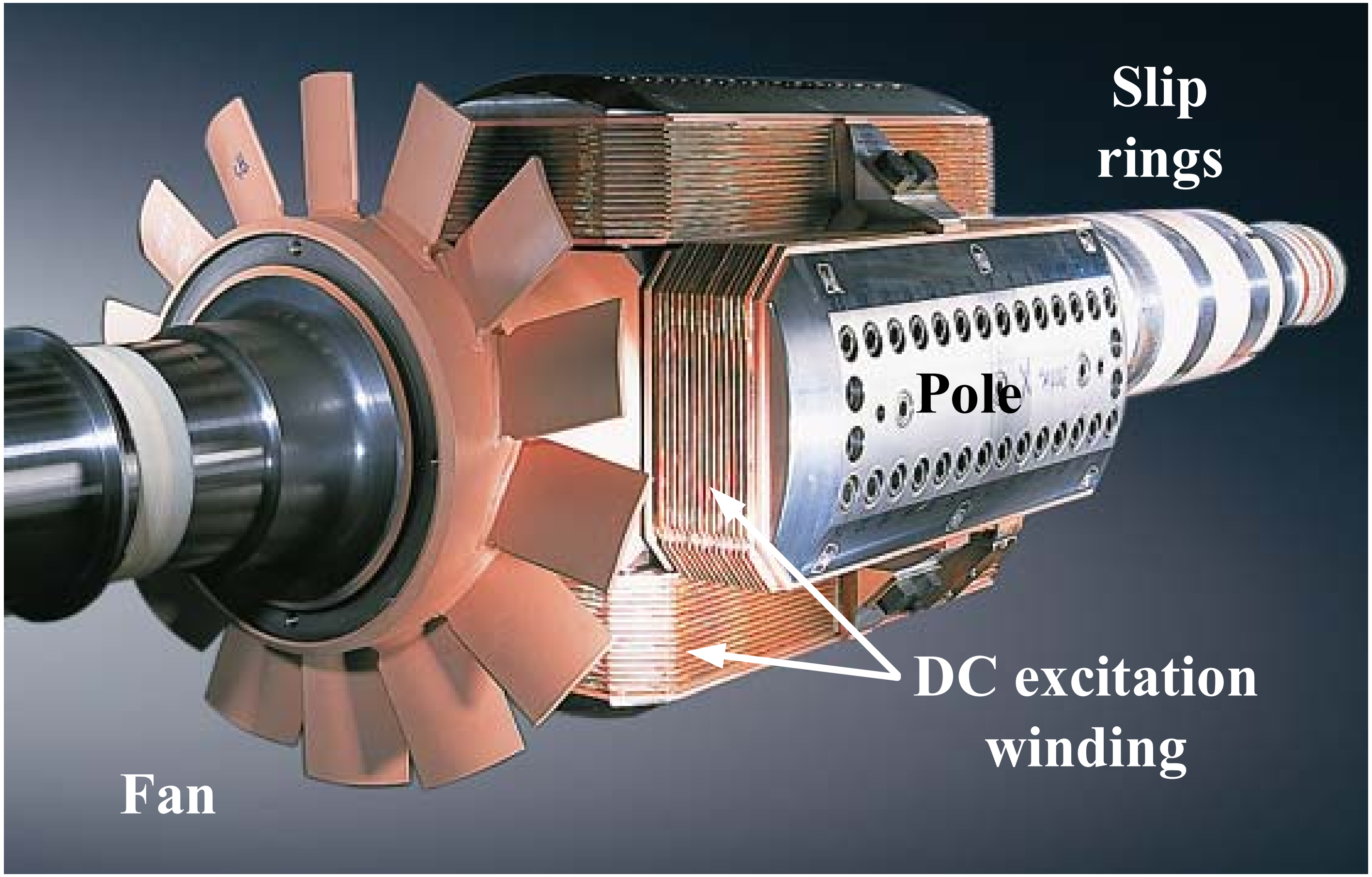

Rotor of a four-pole salient pole generator.

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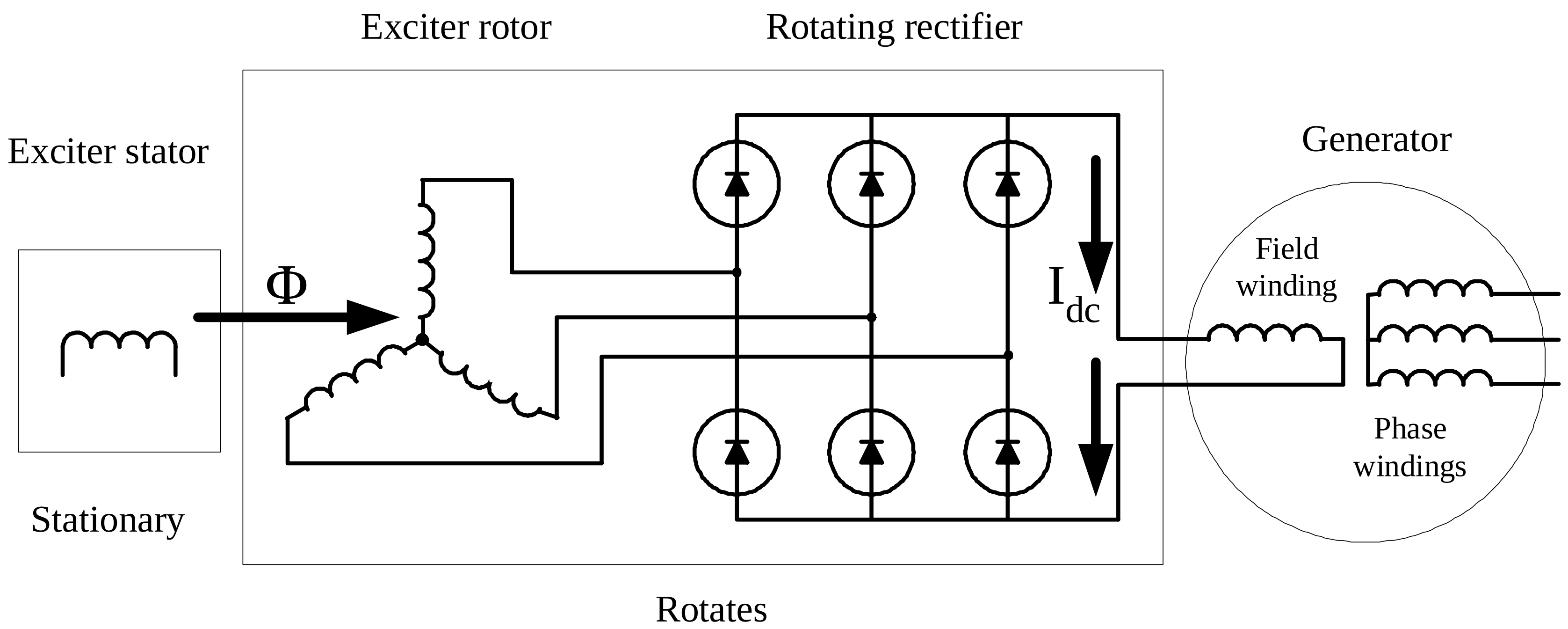
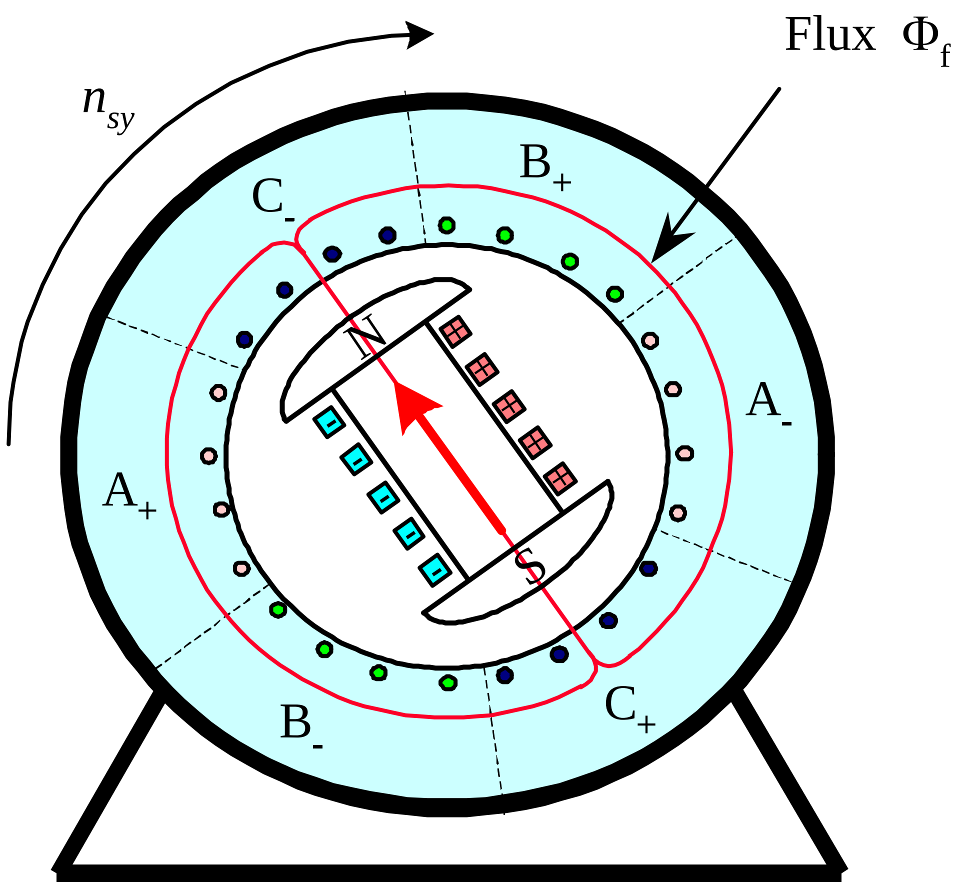


Concept of the brushless exciter system

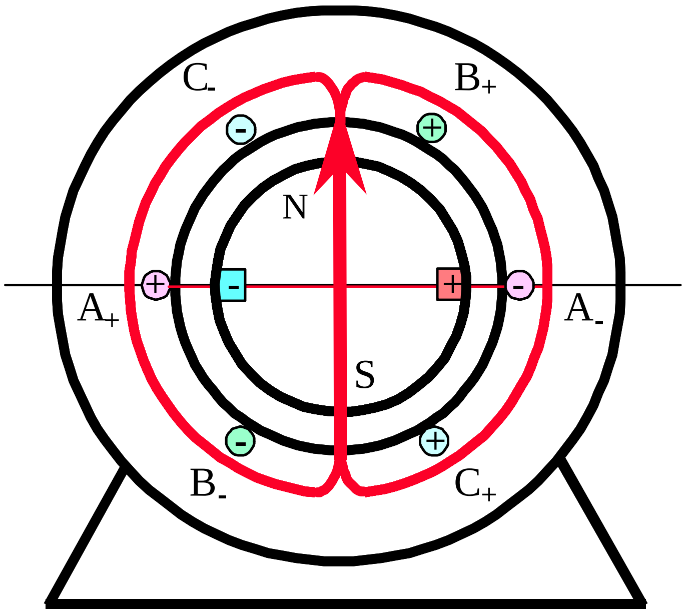
Operating Concept

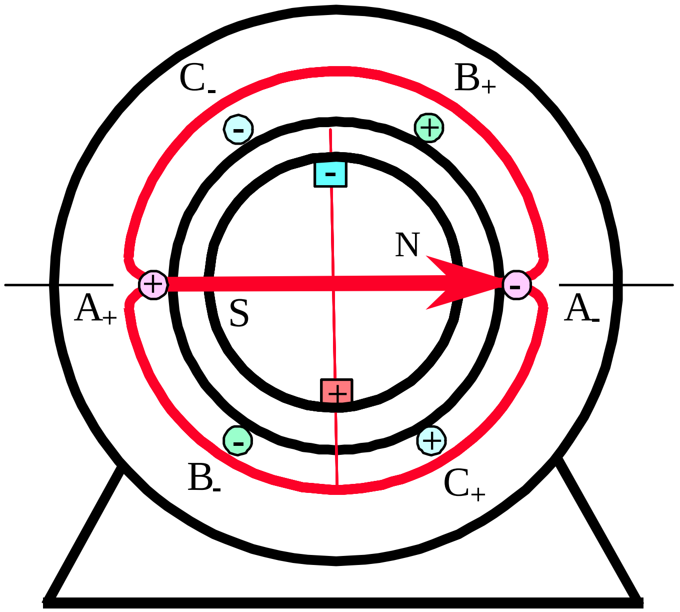
Synchronous Machines



Operating concept of a synchronous generator

Synchronous Machines





(a) Flux is perpendicular to phase A

(b) Flux is parallel to phase A

Rotation produced flux linkage variation.

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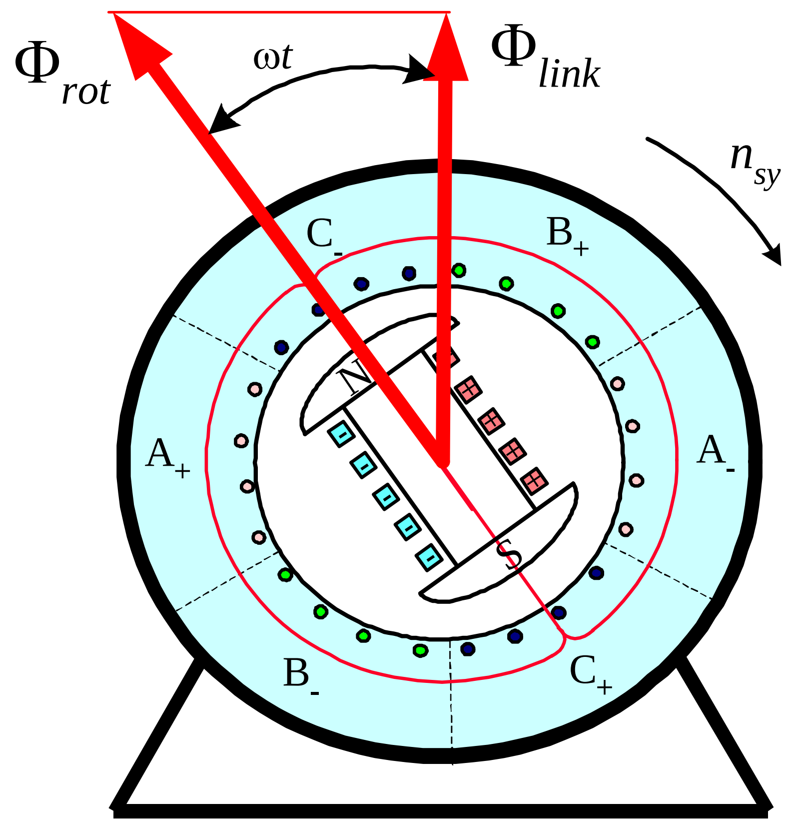

Rotating flux linkage to phase A.

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Main rotating flux

$$n_{sy} = \frac{f}{p/2}$$

$$\omega = 2\pi\, n_{sy}$$

$$\Phi_{link}(t) = \Phi_{rot}\ \cos(\omega t)$$

$$E_s(t) = N_{sta}\,\frac{d\,\Phi_{link}(t)}{dt}$$

$$E_s(t) = -N_{sta}\ \Phi_{rot}\ \omega \sin(\omega t)$$
$$= N_{sta}\ \Phi_{rot}\ \omega \cos(\omega t + 90°)$$

$$E_{sta} = \frac{N_{sta}\ \Phi_{rot}\ \omega}{\sqrt{2}}$$

The rotating flux generates the induced voltage

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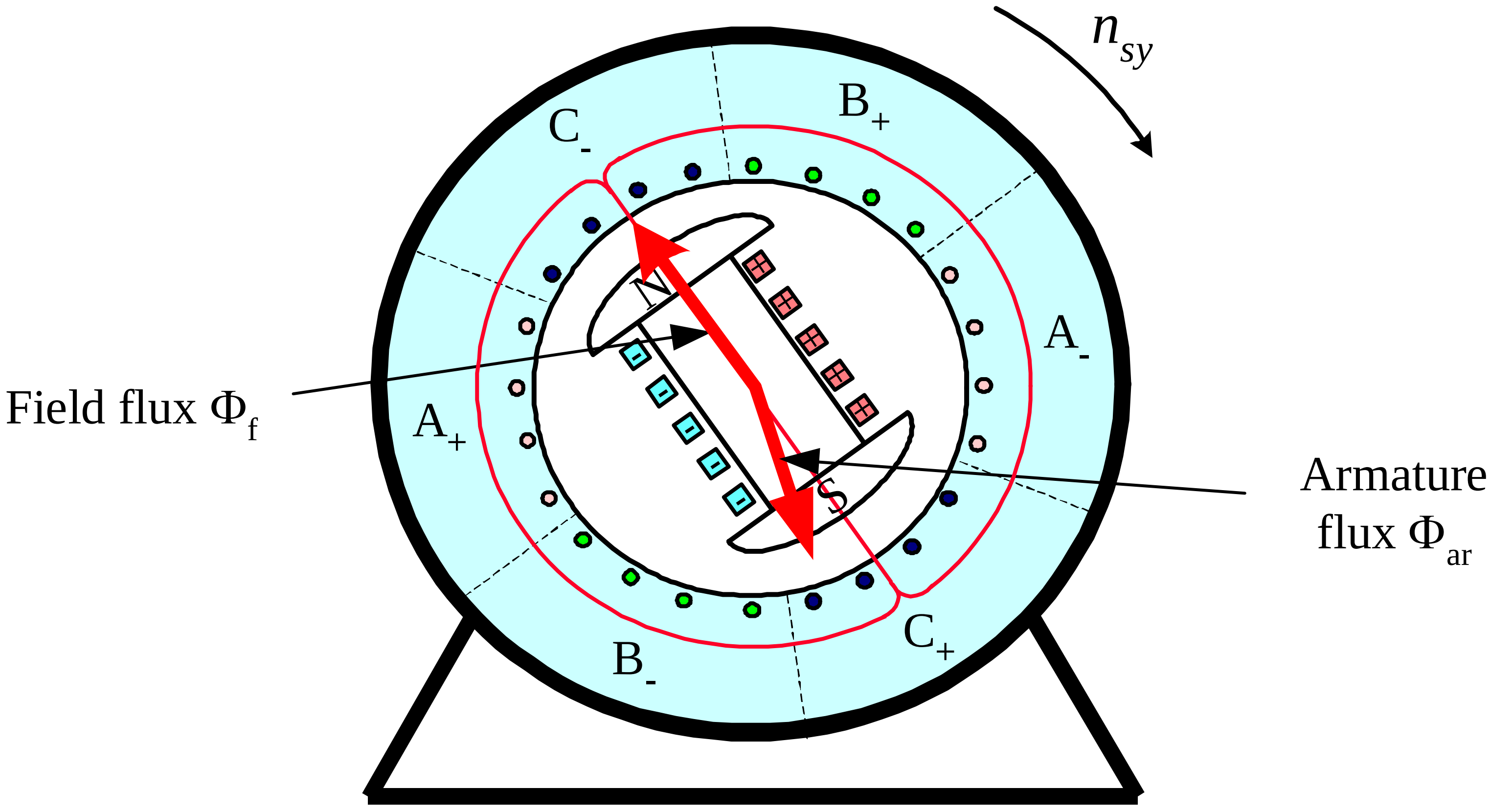

Field (Φ_f) and load generated (Φ_{ar}) rotating fluxes.

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Armature flux

Load current generates a rotating flux reducing the main flux and induced voltage

$$I_{arm}(t) = \sqrt{2}\, I_{sta}\, \cos(\omega t)$$

$$\Phi_{arm}(t) = \Phi_{ar}\, \cos(\omega t)$$

$$E_{ar}(t) = N_{sta}\, \frac{d\Phi_{arm}(t)}{dt} = -N_{sta}\, \Phi_{ar}\, \omega \sin(\omega t)$$

$$E_{arm} = \frac{N_{sta}\, \Phi_{ar}\, \omega}{\sqrt{2}}$$

$$\mathbf{V}_t = \mathbf{E}_{sta} - \mathbf{E}_{arm}$$

Synchronous Machines

Armature flux

$$E_{ar}(t) = L_{arm} \frac{dI_{arm}(t)}{dt} = L_{arm} \frac{d}{dt} \sqrt{2}\, I_{sta} \cos(\omega t)$$

$$= -L_{arm}\omega \sqrt{2}\, I_{sta} \sin(\omega t)$$

$$= -X_{arm} \sqrt{2}\, I_{sta} \sin(\omega t)$$

$$X_{arm} = \frac{N_{sta}\, \Phi_{ar}\, \omega}{\sqrt{2}\, I_{sta}}$$

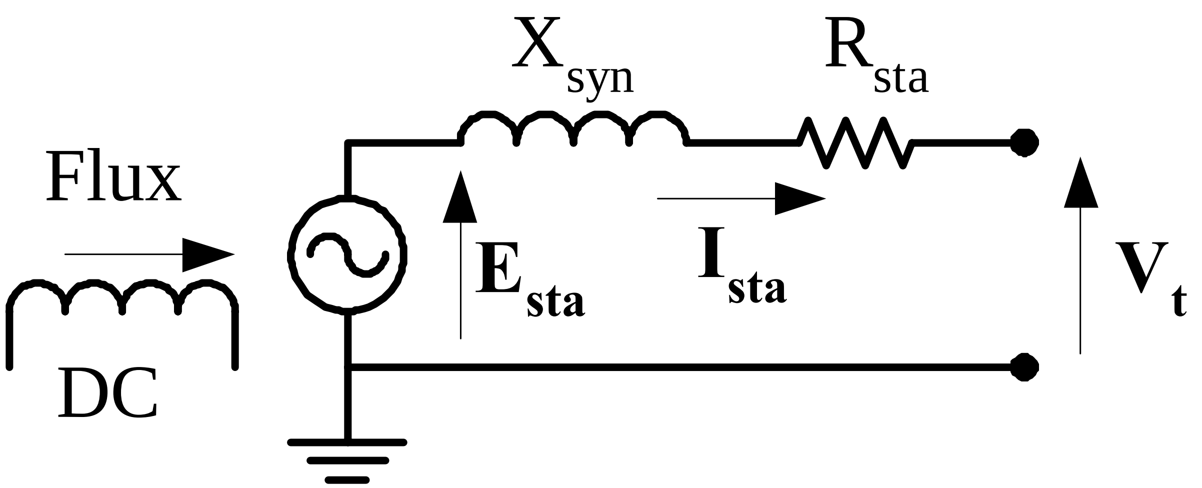
$$X_{syn} = X_{arm} + X_{leakage}$$

Synchronous Machines

Single phase equivalent circuit

$$\mathbf{E}_{arm-syn} = \mathbf{I}_{sta}\,(j\,X_{syn})$$

$$\mathbf{V}_t = \mathbf{E}_{sta} - \mathbf{E}_{arm-syn} = \mathbf{E}_{sta} - \mathbf{I}_{sta}\,j\,X_{syn}$$



Single-phase equivalent circuit of a synchronous generator.

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- The generator is loaded
- The load current produces a rotating flux
- This rotating flux induces a ac three phase voltage in the stator winding.
- This voltage is
  - subtracted from the induced voltage.
  - represented by a voltage drop on the synchronous reactance
- The equivalent circuit of a synchronous generator is a voltage source and a reactance connected in series

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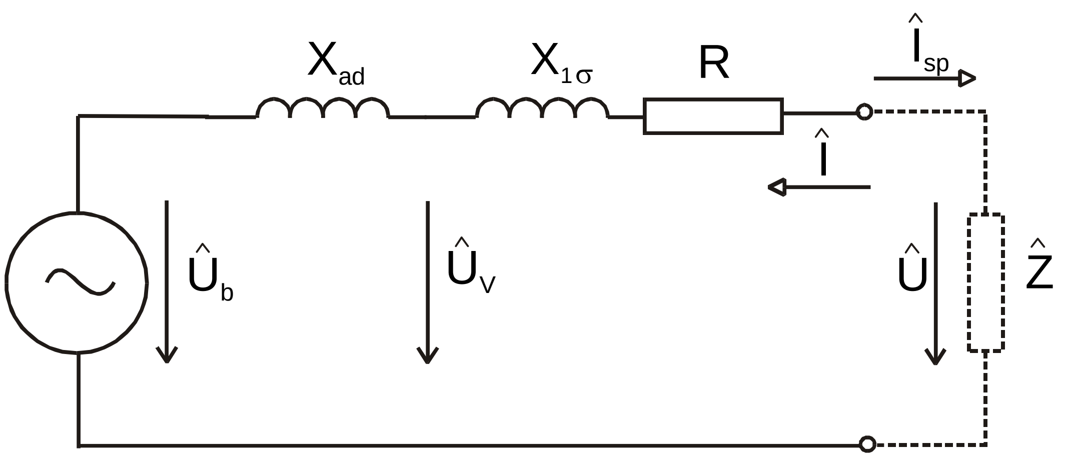
Generator Application

- **Power angle:** Angle between the dc excitation current generated induced voltage and the terminal voltage

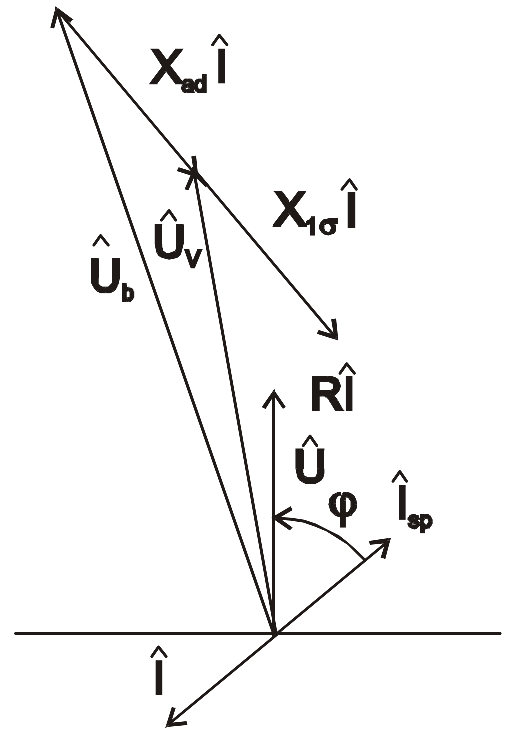


$$\hat{U} = \hat{U}_b + j\,X_{ad}\,\hat{I} + j\,X_{1\sigma}\,\hat{I} + R\,\hat{I}$$

Synchronous Machines

- Phasor diagram of synchronous machine

$$\hat{U} = \hat{U}_b + j\,X_{ad}\,\hat{I} + j\,X_{1\sigma}\,\hat{I} + R\,\hat{I}$$



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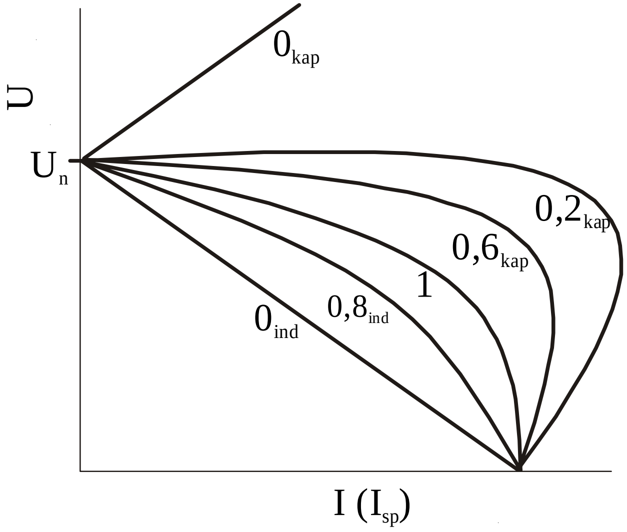
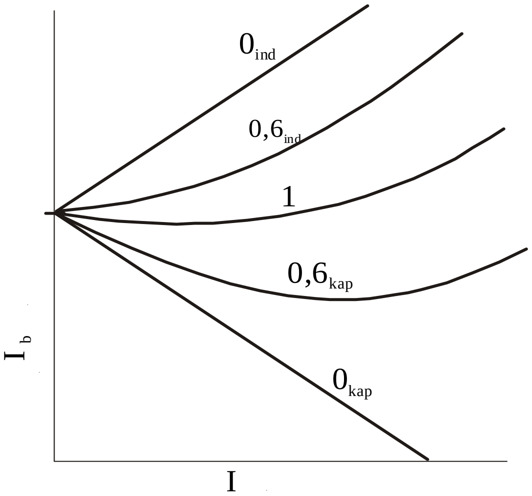
Generator Application

- **Loading: power is less than angle 90 deg**
  - **All generators in the system are connected in parallel**
  - **All generators rotates with the synchronous speed**
  - **The load can be increased by increasing the input mechanical power by regulating the turbine impute power**
  - **The speed does not change, the power angle increases**
  - **Maximum power angle is 90 degree, beyond that operation is unstable**

- **Reactive power regulation**
- **When the excitation is:**
  - **Increased, the generator reactive power also increases;**
  - **Decreased, the generator reactive power also decreases**

- Load and excitation dependence





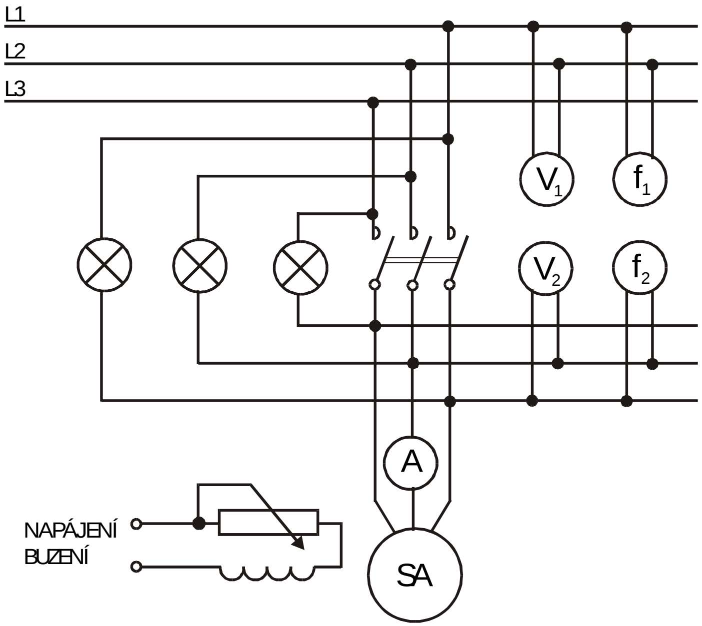
Synchronous Machines

Synchronization

- **Verify that the phase sequences of the two systems are the same.**
- **Adjust the machine speed with the turbine that drives the generator until the generator voltage frequency is nearly the same as the frequency of the network voltage.**
- Adjust the terminal voltage of the generator by changing the dc field (rotor) current until the generator terminal voltage is almost equal to the network voltage. Acceptable limit is 5%.
- **Adjust the phase angle of the generator terminal voltage by regulating the input power until it is nearly equal with the phase angle of the network voltage. Acceptable limits are about 15°.**

Synchronous Machines

- Synchronization



The generator and network power vs power angle

$\delta := 0\text{deg}, 1\text{deg}..\ 180\text{deg}$