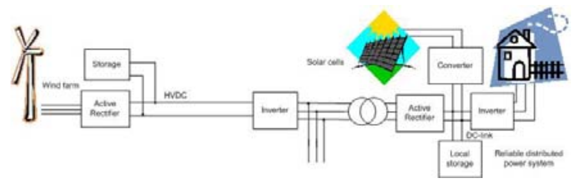
Marcelo Godoy Simões

Lecture #10

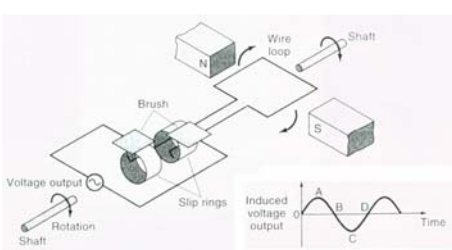
Wind Energy and HVDC

- Wind energy can be converted to dc, for HVDC transmission



Principles of Rotating Electrical Generators

- A wire loop rotating across a magnetic field produces a voltage.
- When the wire loop changes facing pole, the external circuit must be reconnected through brushes that swap the polarity



AC Electrical Generators

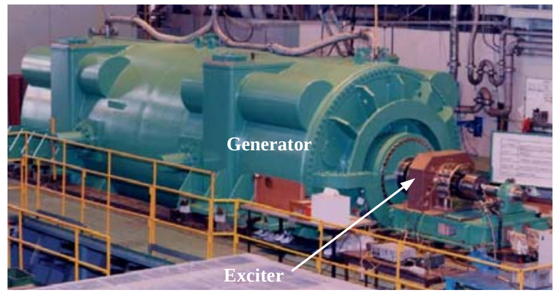
- **Major classes:**
  - Synchronous machines, large power.
  - Permanent magnet machines, small power.
  - Induction machines, small to medium power.
- **Two major parts of machines**
  - Stator, i.e. the STATIONARY part of machine
  - Rotor, i.e. the ROTATING part of the machine

How Field is Produced

- In a **synchronous generator**: DC currents create N-S poles in the rotor, which drive a rotating magnetic field flux through the stationary coils of the stator.
- In a **permanent magnet ac generator**: A permanent magnet generator is like the synchronous generator except that the rotor field is produced by permanent magnets on the rotor, rather than current in a coil of wire.
- In an **induction motor**: AC currents in the stator create a rotating magnetic flux which the internal rotor (with N-S poles) constantly chases.

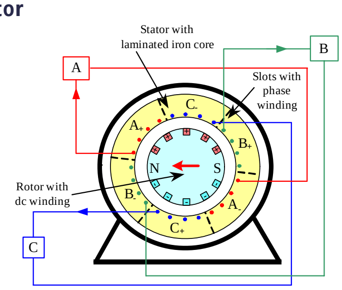
Synchronous Machines

- Two-pole round rotor generator and exciter



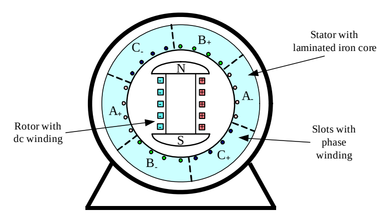
Synchronous Machines – Cont.

- Major components of a round rotor two-pole generator



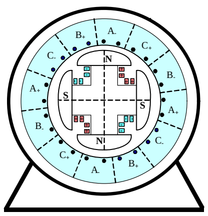
Synchronous Machines – Cont.

- Two-pole salient pole generator



Synchronous Machines – Cont.

- Four-pole salient pole generator



Synchronous Machines – Cont.

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

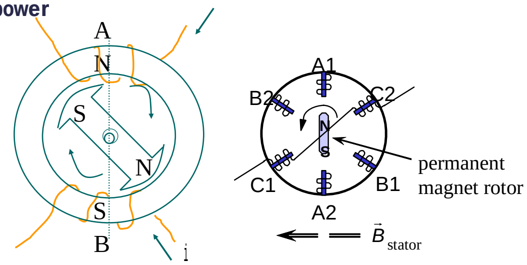
Reactive power regulation => when the excitation is:
- Increased, the generator reactive power also increases;
- Decreased, the generator reactive power also decreases

PM AC Generator

- No field supply is needed, which reduces costs. It also means that there is no I^2R power loss in the field, which helps to increase the efficiency.
- One disadvantage is that the reactive power flow can not be controlled if the PM generator is connected to the utility network. This is of little concern in an asynchronous mode, of course.
- The magnets can be cast in a cylindrical aluminum rotor, which is substantially less expensive and more rugged than the wound rotor of the conventional generator.
- No commutator is required, so the PM generator will less expensive than a dc generator.
- PM generator is of significant interest to designers of small asynchronous wind turbines.

PM AC Generator

- The principles are same as a synchronous machine
- The field is impressed by magnets
- The machine is optimized for small and medium power



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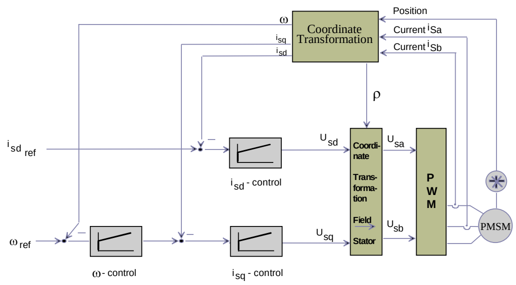
PM AC Generator – Cont.

- PM generators require advanced control

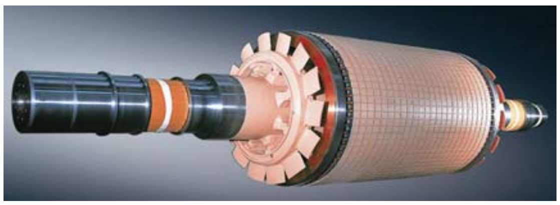


Induction Generators

- Large three-phase industrial induction motor

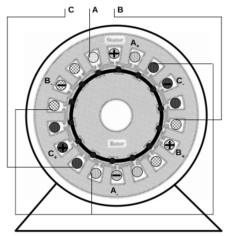
Induction Generators – Cont.

- Rotor of a large induction motor



Induction Generators – Cont.

- The rotating flux induces a voltage in the short-circuited bars of the rotor. This voltage drives current through the bars.
- The induced voltage is proportional with the difference of motor and synchronous speed. Consequently the motor speed is less than the synchronous speed
- The interaction of the rotating flux and the rotor current generates a force that drives the motor.
- The force is proportional with the flux density and the rotor bar current



Induction Generators – Cont.

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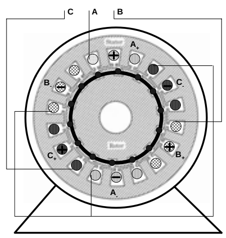
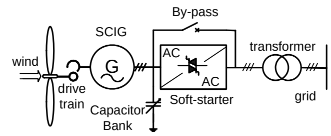
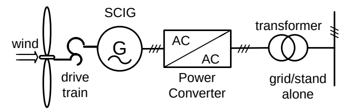


Induction Generator Grid Interconnection

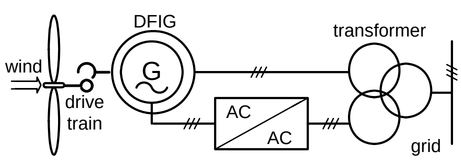
- Induction generators can be connected directly or through a power converter





Doubly Fed Induction Generators

- Used for large power wind or hydro turbines



The Induction Generator for Renewable Sources of Energy

- Historical milestones
- Steady state representation
- Fundamental concepts
- Mathematical relationships
- Measurement of the generator parameters
- Self-excited induction generator (SEIG)
- SEIG: mathematical relationships and general characteristics

Historical Milestones

- Principles: begun before 1900 (Nikola Tesla);
- Disappeared in the 60's shifted out by massive generators;
- Re-appeared in the 70's with the energy crisis;
- It was disseminated in the 80's;
- In the 90's became more popular by environmental concerns;
- In the 2000's, power electronics and digital controllers gave a technological boost for large asynchronous units.

Advantages of the Induction Generator

- robust and solid rotor;
- the machine does not feed large short circuit currents and it is free of oscillations;
- the rotor construction is suitable for high speeds;
- it does not need cares with synchronism;
- voltage and frequency are regulated automatically by the voltage and frequency of the distribution network in the case of parallel operation

Disadvantages of Induction Generators

- the power factor is determined by the slip factor and it has very little to do with the power factor of the load when they have to work in parallel with synchronous machines;

- the synchronous machines should supply with lagging reactive power as much the load as the induction generator and, consequently, they should work with a power factor higher than the one of the load.

IG : Exploded View

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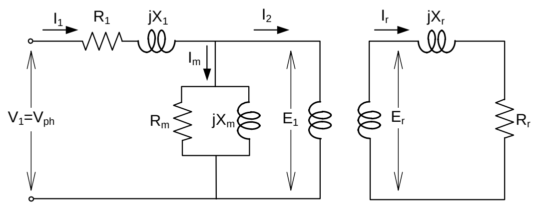
Classical Steady State Representation

- **Transformer model of the induction generator**



Fundamental Concepts

$$E_r = sE_{r0}$$

$$s = \frac{f_s - \frac{p}{2}\frac{n_r}{60}}{f_s} = \frac{n_s - n_r}{n_s}$$

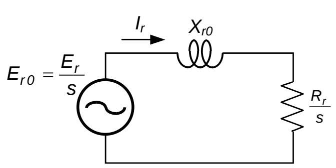
ns - nr is the relative speed between the stator and rotor magnetic fields.

$$f_r = \frac{p}{120}(n_s - n_r)\frac{n_s}{n_s} = sf_s$$

$$X_r = sX_{r0}$$

Fundamental Concepts – Cont.

- **Equivalent circuit of the rotor**



$$I_r = \frac{\vec{E_r}}{\vec{Z_r}} = \frac{sE_{r0}}{R_r + jsX_{r0}} = \frac{E_{r0}}{\frac{R_r}{s} + jX_{r0}}$$

Fundamental Concepts – Cont.

- **a_{rms} = secondary parameters per phase to primary parameters per phase by using the transformation ratio**

$$E_1 = a_{rms}E_{r0}$$

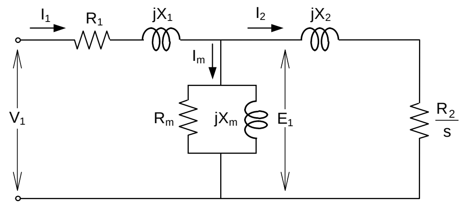
$$I_2 = \frac{I_r}{a_{rms}}$$

$$Z_2 = a_{rms}^2\left(\frac{R_r}{s} + jX_{r0}\right)$$

$$Z_2 = \frac{R_2}{s} + jX_2$$

Fundamental Concepts – Cont.

- **Equivalent circuit per phase of the induction generator**



$$Z = R_1 + jX_1 + \cfrac{1}{\cfrac{1}{jX_m} + \cfrac{1}{R_m} + \cfrac{1}{\cfrac{R_2}{s} + jX_2}}$$

Generated Power

$$P_{out} = P_{in} - P_{losses}$$

$$P_{out} = \sqrt{3} V_\ell I_\ell \cos\varphi$$

$$P_{losses} = P_{statorCu} + P_{iron} + P_{rotorCu} + P_{frict+air} + P_{stray}$$

$P_{statorCu} = 3I_1^2 R_1$

R_m (iron losses with the other mechanical losses) $P_{iron} = \dfrac{3E_1^{\,2}}{R_m}$

$P_{rotorCu} = I_2^2 R_2$

High frequency losses

Generated Power – Cont.

$$P_{airgap} = 3I_2^2 \frac{R_2}{s}$$

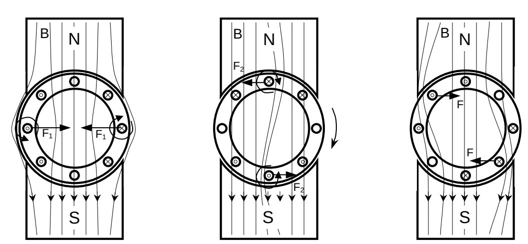
$$P_{rotorCu} = 3I_r^2 R_r$$

$$P_{rotorCu} = 3I_2^2 R_2 = sP_{airgap}$$

$$P_{converted} = 3I_2^2 \frac{R_2}{s} - 3I_2^2 R_2$$

$$P_{converted} = P_{mec} = 3I_2^2 R_2 \frac{1-s}{s} = (1-s)P_{airgap}$$

Magnetic Torques of the Induction Generator

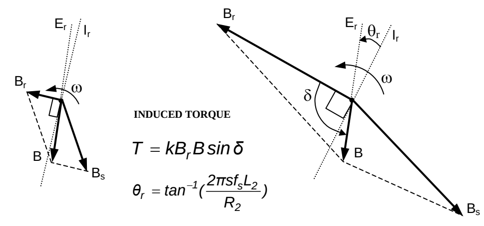


(a) Torque due to an increase of B

(b) Torque due to the rotor movement

(c) Resulting torque

Magnetic Fields of the Induction Generator



$$T = kB_r B \sin\delta$$

$$\theta_r = \tan^{-1}\left(\frac{2\pi s f_s L_2}{R_2}\right)$$

(a) – light loads (b) – heavy loads

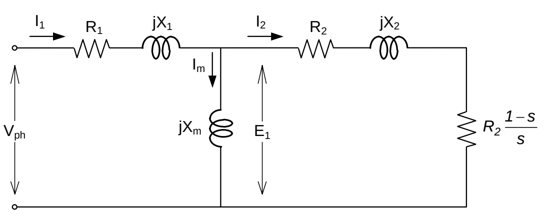
Induced Torques

$$P = T\omega \qquad \omega_r = (1-s)\omega_s$$

$$T_{converted} = \frac{P_{converted}}{\omega_r}$$

$$P_{airgap} = \omega_s T_{converted}$$

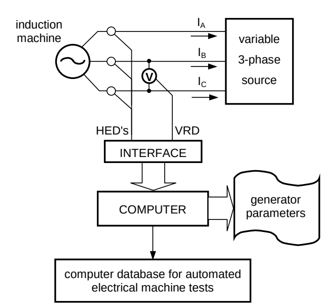
Separate Representation Of The Induction Generator Copper Losses



$$P_{out} = P_{mec} - P_{losses} = (-3I_2^2 R_2 \frac{1-s}{s}) - (3I_1^2 R_1 + 3I_2^2 R_2 + \frac{3E_1^2}{R_m} + P_{frict+air} + P_{stray})$$

$$P_{out} = P_{mec} - P_{losses} = -3I_2^2 R_2 \frac{1}{s} - 3I_1^2 R_1 - \frac{3E_1^2}{R_m} - P_{frict+air} - P_{stray}$$

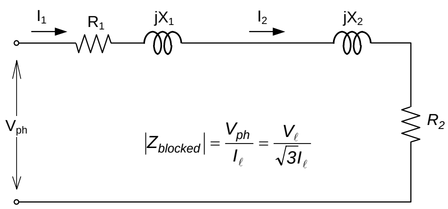
Measurement of the Induction Generator Parameters



HED = Hall effect device for current
RVD = Voltage resistive divider

Measurement of the Induction Generator Parameters

Blocked Rotor Test (s = 1)



$$|Z_{blocked}| = \frac{V_{ph}}{I_\ell} = \frac{V_\ell}{\sqrt{3}I_\ell}$$

$$R_1 + R_2 = |Z_{blocked}|\cos\varphi$$

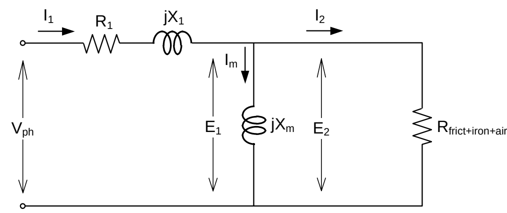
$$X_1 + X_2 = |Z_{blocked}|\sin\varphi$$

$$R_1 \approx \frac{V_{cc}}{2I_{cc}}$$

X_1 contributes with something between 30% and 50% and X_2 between 50% and 70%.

Measurement of the Induction Generator Parameters – Cont.

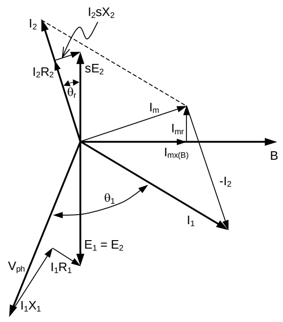
No Load Test (s = 0)



$$P_{in} = 3I_1^2R_1 + P_{iron} + P_{frict+air} + P_{stray}$$

$$\frac{V_{ph}}{I_{10}} \cong (X_1 + X_m)$$

IG Interconnected to the Utility Grid



$$E_1 = V_{ph} + I_1R_1 + jI_1X_1$$

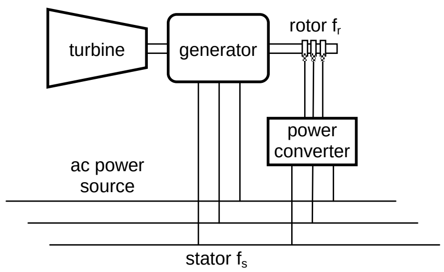
$$E_2 = I_2\frac{R_2}{s} + jI_2X_2$$

$$E_1 = E_2 = I_mZ_m = (I_1 - I_2)Z_m$$

The High Efficiency Induction Generator

- **efficiency more than about 10% for small powers (up to 50 kW);**
- **high efficiency generators are more suitable to better stand the harmful effects of the harmonic generated by non-linear loads (power converters) for they have higher thermal margin and smaller losses;**
- **about 2% for higher powers (above 100 kW);**
- **investment return time (payback) for these high efficiency generators will be smaller in a inversely proportional way to the local tariff values;**
- **payback time: 0.9 to 3 or 4 years for micro power plants.**

The Doubly Fed Induction Generator

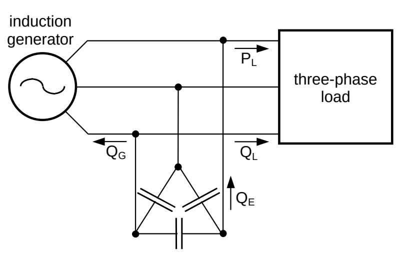


- speed usually limited to a 2:1 range
- up to several hundreds of kW ratings

The Self Excited Induction Generator

- **The induction generator needs an external source of reactive power from:**
  - the mains network (nr > ns);
  - a bank of capacitors.

SEIG : Fundamental Concepts



P_L – Active power to the load
Q_L - Reactive power to the load
Q_G - Reactive power to the generator
Q_E – Excitation reactive power

Capacitor self-excited induction generator

Parameters of the Induction Machine

- **operating voltage**
- **rated power**
- **rated frequency of the parameter measurements**
- **power factor of the machine**
- **rotor speed**
- **capacity of acceleration**
- **isolation class**
- **operating temperature**
- **carcass type**
- **ventilation system**
- **service factor**
- **noise**

Parameters of the Load

- power factor of the load
- starting torque
- maximum torque
- starting current
- generated harmonics
- form of connection to the load: directly to the distribution network or through converters.
- load type:
  - resistive, inductive or capacitive
  - constant or variable, passive or active
- evolution of the load along the time.

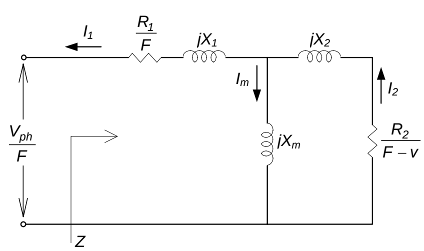
Performance of the Self-Excited Induction Generator

- self-exciting process:
  - degree of the iron saturation of the generator caused by the choice of the capacitor;
  - fixed or controlled self-excitation capacitor.
- type of primary source:
  - hydro
  - wind
  - biomass/biogas
  - other combinations.

Fundamental Concepts (p.u)

$$F = \frac{f_{exc}}{f_b} = \frac{\omega_{exc}}{\omega_b}$$

$$\frac{R_2}{Fs} = \frac{R_2}{F(1-\frac{n_r}{n_s})} = \frac{R_2}{F-v}$$



Voltage Regulation

$$Z = R_1 + jX_1 + \frac{1}{\frac{1}{jX_m} + \frac{1}{\frac{R_2}{s} + jX_2}}$$

$$Z = (R_1 + \frac{a}{a^2+b^2}) + j(X_1 + \frac{b}{a^2+b^2})$$

$$a = \frac{\cos(\theta_2)}{|Z_2|} \qquad b = \frac{1}{X_m} + \frac{\sin(\theta_2)}{|Z_2|}$$

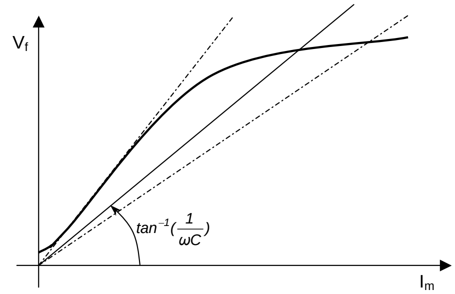
Voltage Regulation – Cont.

$$|Z_2| = \sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2} \qquad \theta_2 = \tan^{-1}\left(\frac{sX_2}{R_2}\right)$$

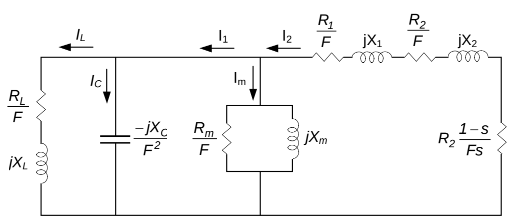
$$|Z| = \sqrt{\left(R_1 + \frac{a}{a^2 + b^2}\right)^2 + \left(X_1 + \frac{b}{a^2 + b^2}\right)^2}$$

$$\theta = \tan^{-1}\left[\frac{(a^2 + b^2)X_1 + b}{(a^2 + b^2)R_1 + a}\right]$$

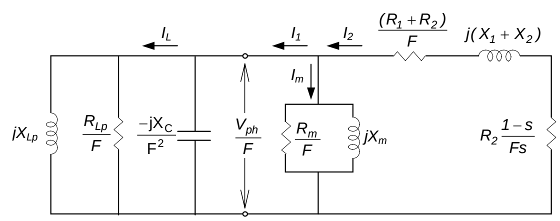
Magnetizing Curves and Self-excitation



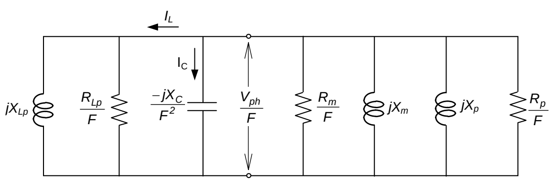
Mathematical Description of the Self-Excitation Process



Mathematical Description of the Self-Excitation Process – Cont.



Doxey Simplified Model for the Induction Generator



$$R_p = \frac{(\frac{R_1}{F} + \frac{R_2}{Fs})^2 + (X_1 + X_2)^2}{R_1 + \frac{R_2}{s}} \qquad X_p = \frac{(\frac{R_1}{F} + \frac{R_2}{Fs})^2 + (X_1 + X_2)^2}{X_1 + X_2}$$

Balance of Active and Reactive Power

$$\frac{V_f^2}{X_p} + \frac{V_f^2}{X_m} - \frac{V_f^2}{X_c} + \frac{V_f^2}{X_{Lp}} = \sum Q = 0$$

$$I_2^2 R_2 \frac{1-s}{s} + I_2^2 (R_1 + R_2) + \frac{V_f^2}{R_m} + \frac{V_f^2}{R_{Lp}} = \sum P = 0$$

$$s = \frac{2R_2}{-2R_1 - R_{mL} \pm \sqrt{R_{mL}^2 - 4F^2 (X_1 + X_2)^2}}$$

$$s \cong -\frac{R_2}{R_1 + R_{mL}} \qquad X_m = \frac{1}{F^2 \omega_s C - \frac{1}{X_p} - \frac{1}{X_{Lp}}}$$

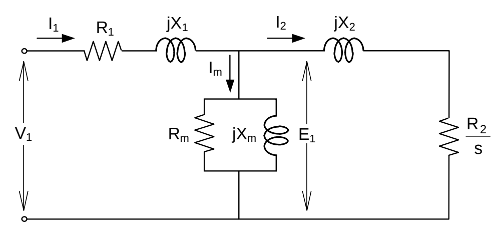
Efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{losses}}{P_{in}} \qquad \frac{V_f^2}{F^2 I_2^2} = (\frac{R_2}{Fs} + \frac{R_1}{F})^2 + (X_1 + X_2)^2$$

$$P_{out} = P_{in} - P_{losses} = 3I_2^2 R_2 \frac{1-s}{s} + 3I_2^2 (R_1 + R_2) + \frac{3V_{ph}^2}{R_m} = -\frac{3V_{ph}^2}{R_{Lp}}$$

$$\eta = \frac{(\frac{R_2}{s} + R_1) + \frac{1}{R_m}[(\frac{R_2}{s} + R_1)^2 + F^2 (X_1 + X_2)^2]}{R_2 \frac{1-s}{s}}$$

Torque and Speed Characteristics



$$P_{airgap} = \frac{3I_2^2 R_2}{s} = \frac{3V_{ph}^2 R_2 / s}{(R_1 + R_2 / s)^2 + (X_1 + X_2)^2}$$

$$P_{converted} = (1 - s) P_{airgap}$$

$$T_{converted} = \frac{P_{airgap}}{\omega_s}$$

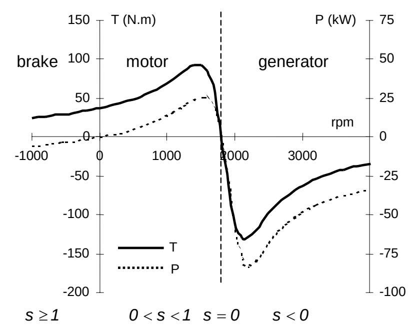
Torque and Speed Characteristics – Cont.

$$P_{out} = P_{mec} - P_{losses} = -3I_2^2 R_2 \frac{1-s}{s} - 3I_1^2 R_1 - \frac{3E_1^2}{R_m} - 3I_2^2 R_2 - P_{frict+air} - P_{stray}$$

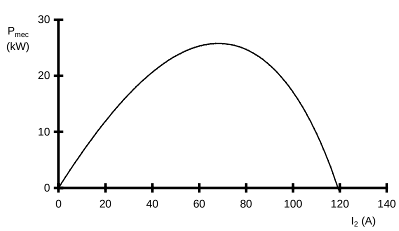
$$P_{out} = P_{airgap} - P_{losses} = -3I_2^2 R_2 \frac{1}{s} - 3I_1^2 R_1 - \frac{3E_1^2}{R_m} - P_{frict+air} - P_{stray}$$

$$T_{converted} = \frac{3V_{ph}^2 R_2 / s}{\omega_s [(R_1 + R_2 / s)^2 + (X_1 + X_2)^2]}$$

Torque and Speed Characteristics – Cont.



Mechanical Power versus Output Current



$$P_{mec} = 3I_2^2 \left(\frac{R_2}{s} - R_2\right)$$

$$I_2 = \frac{V_{ph}}{\sqrt{(R_1 + R_2 / s)^2 + (X_1 + X_2)^2}}$$

$$\frac{R_2}{s} = \sqrt{\left(\frac{V_{ph}}{I_2}\right)^2 - (X_1 + X_2)^2} - R_1$$

$$P_{mec} = 3I_2^2 \left[\sqrt{\left(\frac{V_{ph}}{I_2}\right)^2 - (X_1 + X_2)^2} - (R_1 + R_2)\right]$$

Vg versus Im Relationship

a) Table of values

b) Polynomial

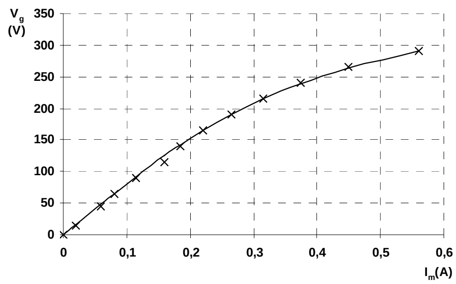
$$L_m = a_0 + a_1 V_{ph} + a_2 V_{ph}^2 + a_3 V_{ph}^3 + a_4 V_{ph}^4$$

c) Exponential

$$V_g = FI_m (K_1 e^{K_2 I_m^2} + K_3)$$

$$X_m = \omega L_m = \frac{V_g}{I_m} = F(K_1 e^{K_2 I_m^2} + K_3)$$

Magnetizing Curve



Characteristics of Rotation

$$P_{conv} = (1-s)P_{airgap} = \frac{3V_{ph}^2 R_2 \frac{1-s}{s}}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2}$$

$$V_{ph} = \sqrt{\frac{P_{conv}[(R_1 + \frac{R_2}{s})^2 + (X_1 + X_2)^2]}{3R_2 \frac{1-s}{s}}}$$

$$V_{ph} = \sqrt{\frac{P_{conv}(\frac{n_s}{n_r} - 1)[(R_1 + \frac{R_2}{1 - \frac{n_r}{n_s}})^2 + (X_1 + X_2)^2]}{3R_2}}$$

Flowchart for Performance

n_r (or n_s), R_1, R_2, X_1, X_2, R_m, R_L, X_L, X_C, no. of poles, K_1, K_2, K_3 (or a table)

↓

$$s = \frac{2R_2}{-2R_1 - R_{mL} - \sqrt{R_{mL}^2 - 4F^2(X_1 + X_2)^2}} \approx -\frac{R_2}{R_1 + R_{mL}}$$

↓

$$\omega_r = \frac{P}{2}(2\pi \frac{n_r}{60}) \;;\; \omega_s = \frac{\omega_r}{1-s} \text{ and } F = \frac{\omega_s}{377}$$

↓

$$X_p = \frac{(\frac{R_1}{F} + \frac{R_2}{Fs})^2 + (X_1 + X_2)^2}{X_1 + X_2}$$

↓

$$X_m = \frac{1}{F^2 \omega_s C - \frac{1}{X_p} - \frac{1}{X_{Lp}}}$$

↓

$$I_m = \sqrt{\frac{1}{K_2} \ell n(\frac{X_m - K_3}{K_1})}$$

↓

$$V_f = F I_m X_m$$

↓

$$I_1 = I_C + I_L \qquad I_L = \frac{V_{ph}}{Z_L \angle \theta_L} \qquad I_C = jF\omega C V_{ph}$$

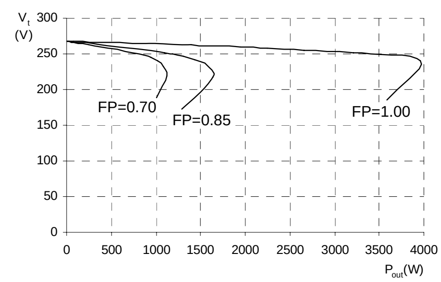
$$S = \frac{V_{ph}^2}{F^2 Z_L \angle \theta_L} \qquad P_L = \frac{V_{ph}^2}{FR_{Lp}} = \frac{V_{ph}^2}{F^2 Z_L^2} R_L$$

$$\eta = \frac{(\frac{R_2}{s} + R_1) + \frac{1}{R_m}[(\frac{R_2}{s} + R_1)^2 + F^2(X_1 + X_2)^2]}{R_2 \frac{1-s}{s}}$$

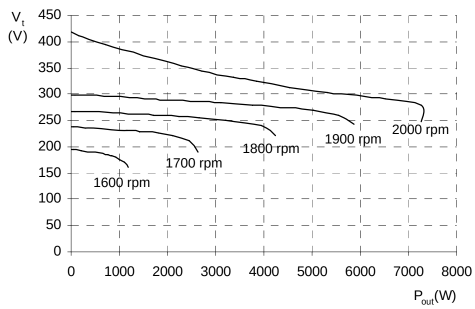
$$\frac{1}{R_{mL}} = \frac{1}{R_m} + \frac{1}{R_{Lp}}$$

$$R_{Lp} = \frac{Z_L^2}{FR_L}$$

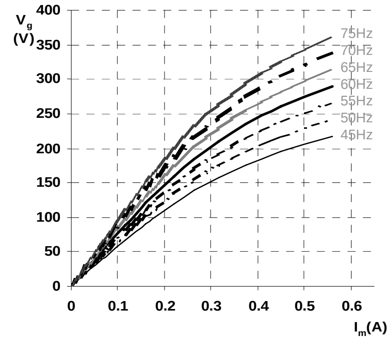
Influence of Power Factor



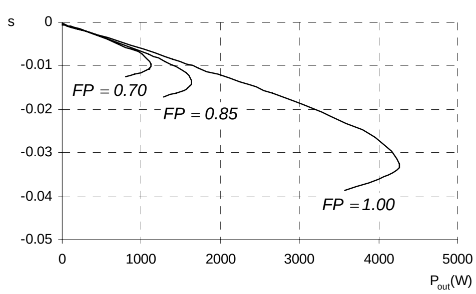
Voltage versus Rotation



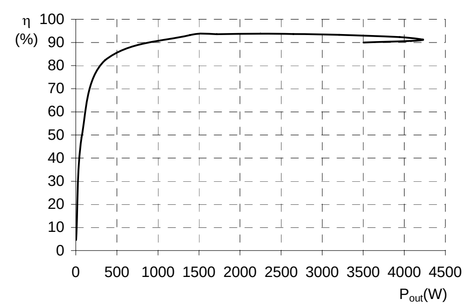
Influence of the Exciting Frequency on the Air Gap Voltage



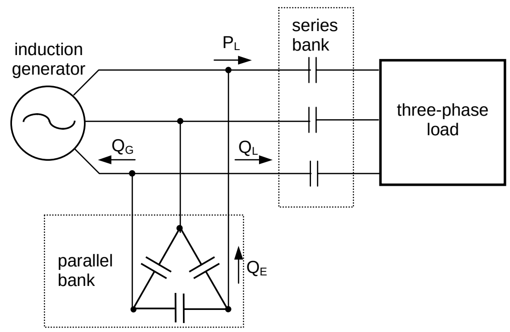
Slip Factor x Power Factor



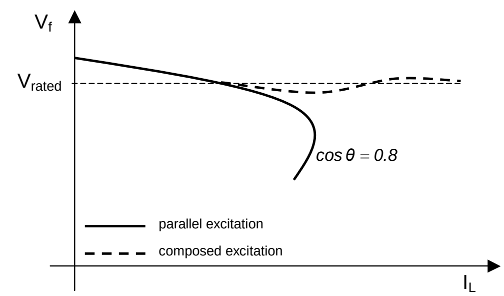
Efficiency and Load for ns = 1,700 rpm



Series Capacitors and Composed Excitation

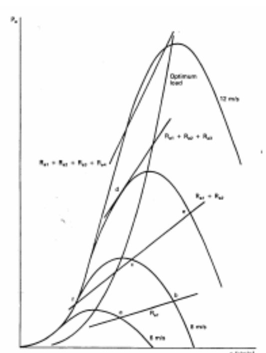


Voltage x Current Characteristic for Composed Excitation



Load Following

- A generator with a fixed resistive load is not an optimum load for a wind turbine
- Blade pitching mechanism is a technically good solution, but rather available only for larger turbines.
- One alternative is a variable resistance load. One way of varying the load resistance seen by the generator is to insert a variable autotransformer between the generator and the load resistors.
- The voltage seen by the load can be varied from zero to some value above the generator voltage in this system. The power can therefore be adjusted from zero to rated in a smooth fashion.

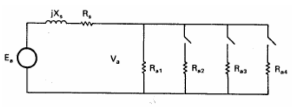


Load Following – Cont.

- A microcomputer is required to sense the wind speed, the turbine speed, and perhaps the rate of change of turbine speed. It would then signal the electrical actuator on the autotransformer to change the setting as necessary to properly load the turbine. A good control system could anticipate changes in turbine power from changes in wind speed and keep the load near the optimum value over a wide range of wind speeds.
- One problem with this concept is that the motor driven three-phase variable autotransformer probably costs as much as a small generator. Another problem would be mechanical reliability of the autotransformer sliding contacts. These would certainly require regular maintenance.

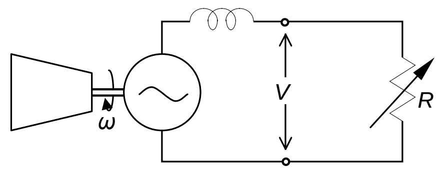
Load Following – Cont.

- Another way of controlling the load, which eliminates the variable autotransformer, is to use a microcomputer to switch in additional resistors as the wind speed and turbine speed
- The switches can be solid state (triacs) which are easily controlled by microcomputer logic levels and which can withstand millions of operating cycles. Costs and reliability of this load control system are within acceptable limits.



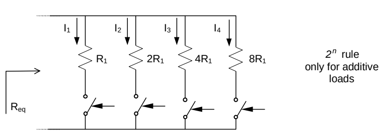
Electronic Control by the Load

- Electronic controls may exert their action by the load, and so changes in the load may be used to control speed, frequency and voltage.
- The load represented by a variable resistor could represent the energy transferred to the utility grid.
- It can also be a battery charger, back pumping of water, irrigation, hydrogen production, heating, or fluid tank freezing.



Electronic Control by the Load – Cont.

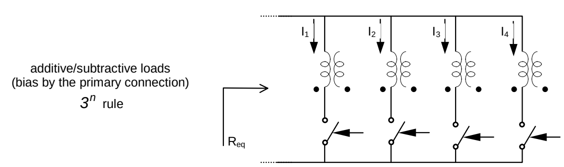
- For essentially additive loads, like resistors, it is possible to optimize their rated values to obtain a smoother variation of load with a minimum number of resistors by using the 2^n rule, as depicted below for current control by discrete modulation of load.



- One practical example : irrigation, using water pumps with different sizes, 1 kW, 2 kW, 4 kW and 8 kW

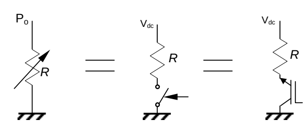
Electronic Control by the Load – Cont.

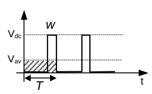
- For additive/subtractive loads like power transformers, the optimization may be obtained even with a fewer number of elements by using the 3^n rule, for a series connection of the secondary windings.



Electronic Control by the Load – Cont.

- **Using IGBTs with PWM control**
  - The advantages of this type of control are the good speed/voltage regulation within certain ranges, use of a single power resistor/IGBT set, ease in modular manufacturing, suitability for ac and dc loads through power electronic ac switches and an absence of switching surges.





$$V_{av}T = V_{dc}w$$

$$D = \frac{V_{av}}{V_{dc}} = \frac{I_{av}}{I_{dc}} = \frac{w}{T}$$

$$\frac{V_{dc}}{R_{eff}} = I_{eff}$$

$$\frac{V_{dc}}{R} = I_{dc}$$

$$R_{eff} = \frac{R}{D}$$

Electronic Control by the Load – Cont.

- **Electronic control by the load (ECL) for random generation and random load**