EE-362 ELECTROMECHANICAL ENERGY CONVERSION-II

Real & Reactive Power, V-Curves of Synchronous Machines

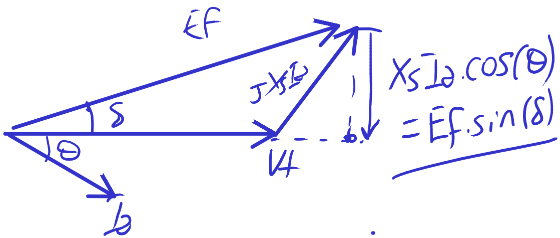
Ozan Keysan

ozan.keysan.me

Office: C-113 • Tel: 210 7586

Synchronous Machines Power:

$$P = 3V_t I_a cos(\theta) \text{ Watt}$$



Synchronous Machines Power:

$$P = 3V_t I_a cos(\theta)$$ Watt

or

$$P = \frac{3V_t E_f sin(\delta)}{X_s}$$

R_a is neglected

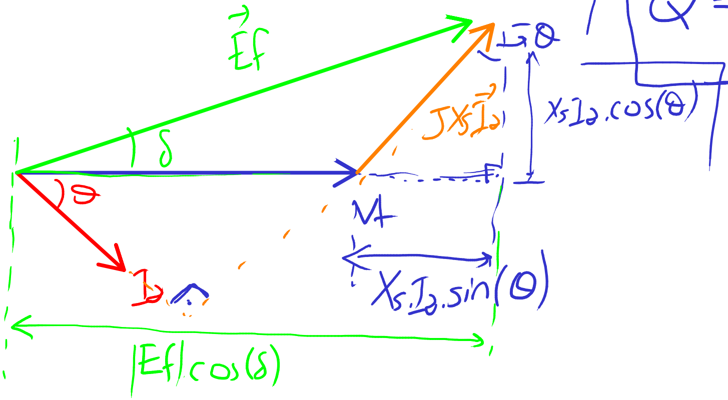
What about Q (Reactive power)?

$$Q = 3V_tI_a sin(\theta) \text{ VAR}$$

$|E_f| \cdot \cos(\delta) - |V_t| = X_s . I_a . \sin(\theta)$

$I_a \sin(\theta) = \frac{|E_f| . \cos(\delta) - |V_t|}{X_s}$

$$Q = 3 . V_t \left(\frac{E_f . \cos(\delta) - V_t}{X_s} \right)$$



What about Q (Reactive power)?

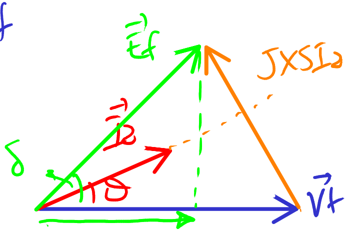
$$Q = 3V_t I_a sin(\theta) \text{ VAR}$$

$$Q = \frac{3V_t(E_f cos(\delta) - V_t)}{X_s}$$

If $|E_f| cos(\delta) > |V_t| \Rightarrow Q > 0$

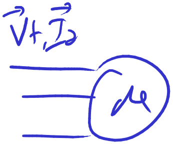
If $|E_f| cos(\delta) < |V_t| \Rightarrow Q < 0$

leading pf



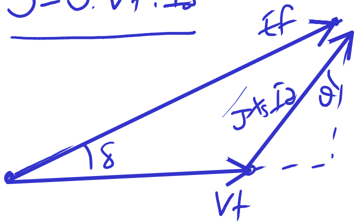
$\Rightarrow Q < 0$

What about Q (Reactive power)?



Formal derivation

$S = 3 V_t \cdot I_a^*$



$$\vec{I_a} = \frac{\vec{E_f} - \vec{V_t}}{jX_s}$$

$$\vec{I_a} = \frac{E_f(\cos(\delta) + j\sin(\delta)) - V_t}{jX_s}$$

$$S = 3V_t \cdot \left(\frac{E_f(\cos(\delta) + j\sin(\delta)) - V_t}{jX_s} \right)^*$$

$$= \underbrace{\frac{3V_t \cdot E_f \cdot \sin(\delta)}{X_s}}_{\text{Real Power (P)}} + j \cdot \underbrace{\frac{3V_t(E_f\cos(\delta) - V_t)}{X_s}}_{\text{Reactive Power (Q)}}$$

$|E_f|$ gets larger with I_f (field current)

Direction of P, Q?

Power (P) flows from leading side to lagging side

Reactive Power (Q) flows from over-excited to under-excited side.

I_f is large

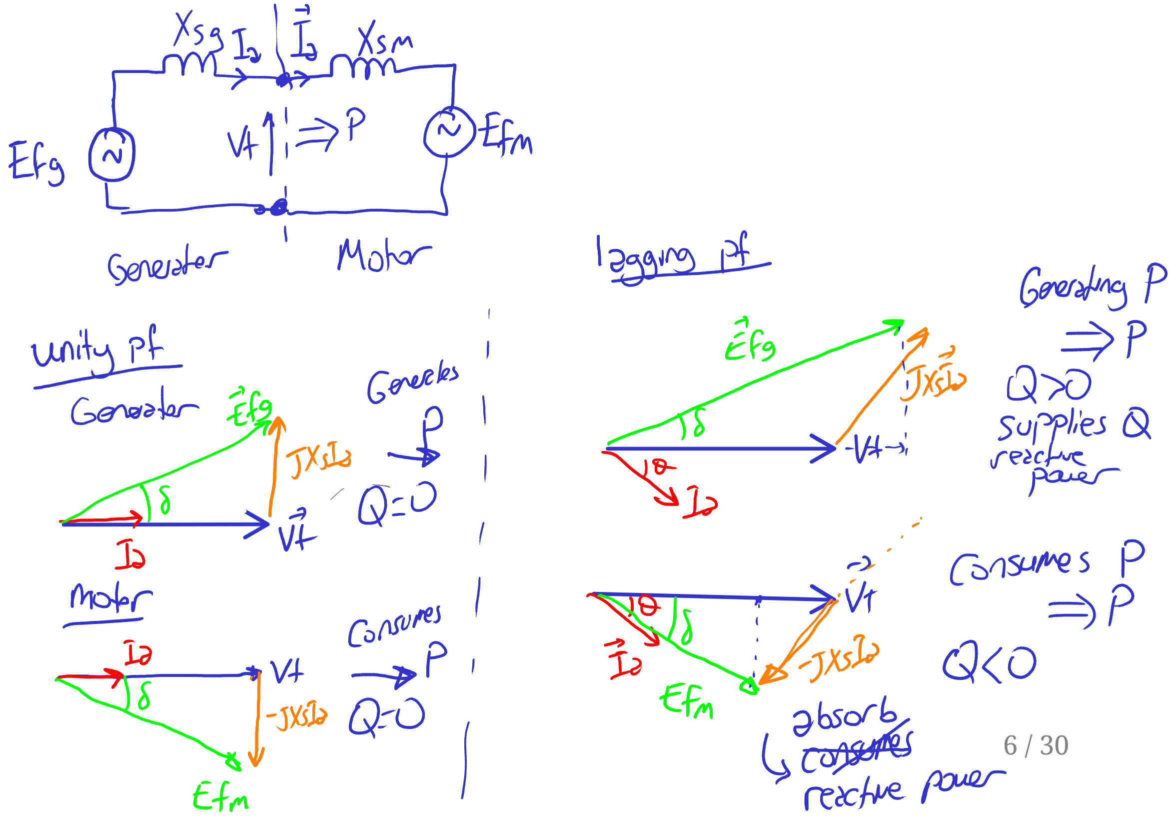
Direction of P, Q?

Power (P) flows from leading side to lagging side

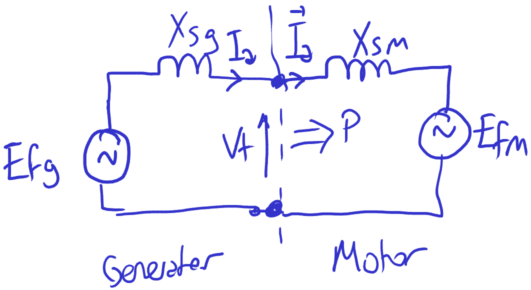
Reactive Power (Q) flows from over-excited to under-excited side.

Lagging pf generator supplies Q, lagging pf motor absorbs Q

Power-Reactive Power Directions



Power-Reactive Power Directions

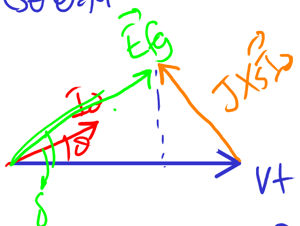


(P) Real power G ⇒ M

(Q) Reactive power G ⇐ M

leading pf

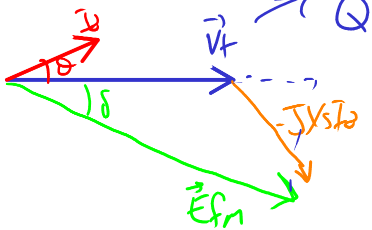
Generator



Supplies power ⇒ P

Q<0 (absorbs Q)

Motor

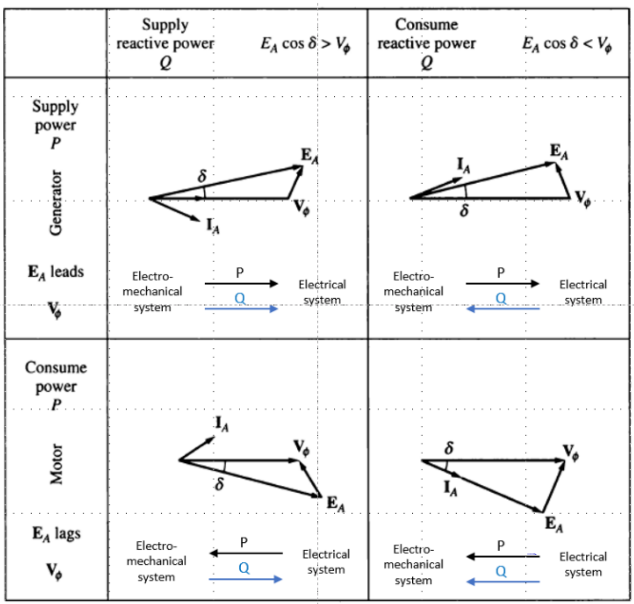


$\vec{E}f$ lags $\vec{V}t$ ⇒ consumes P

Q>0

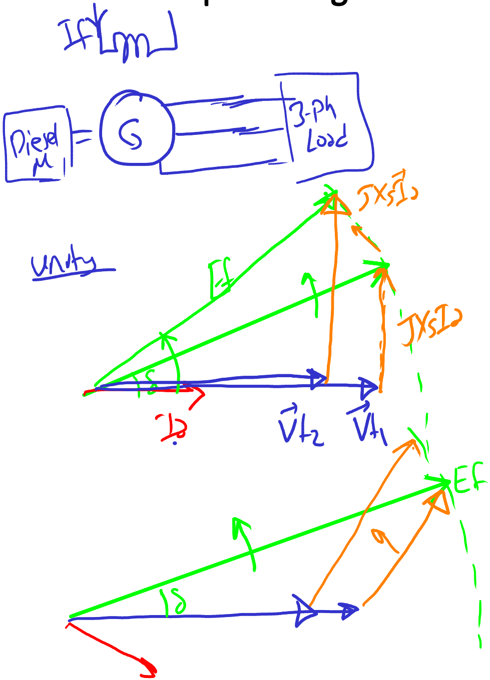
↳ supplies Q

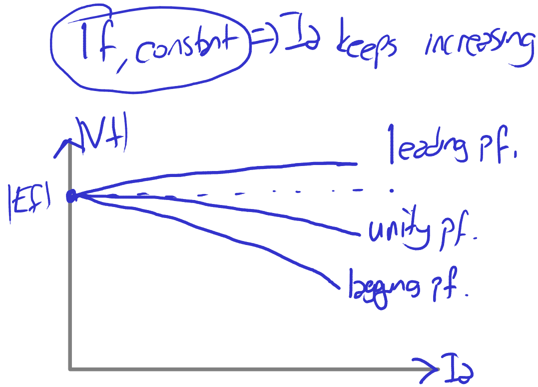
Direction of P, Q Summary

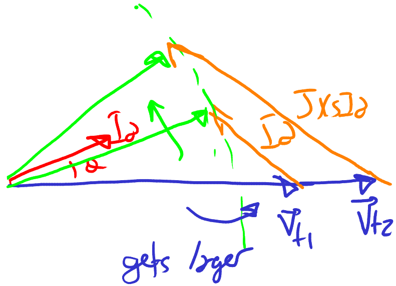


Standalone Operation:

Let's draw output voltage vs. load



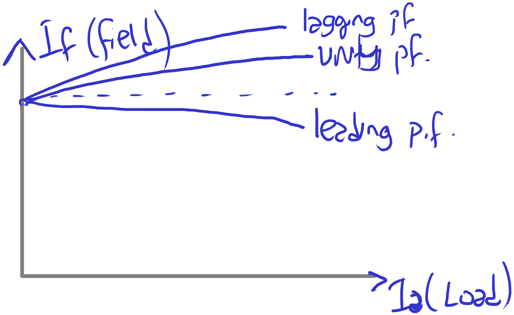




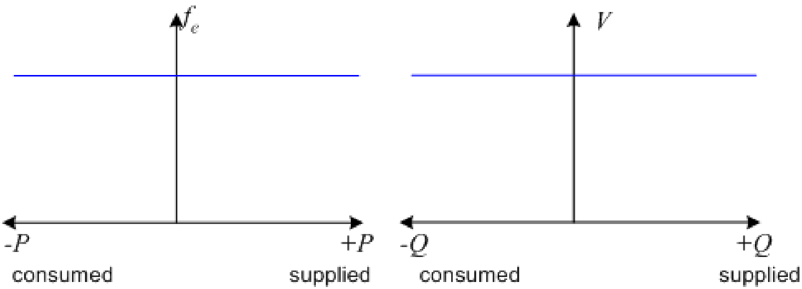
Standalone Operation:

P_{mech} and I_f must be controlled for constant V_t and f.

Automatically done by the AVR (Automatic Voltage Regulator)



Synchronous Generator Connected to Infinite Bus



Constant terminal voltage and speed

Synchronous Generator Connected to Infinite Bus

$$\overrightarrow{E_f} = \overrightarrow{V_t} \pm (R_a + jX_s)\overrightarrow{I_a}$$

$+$: Generating

$-$: Motoring

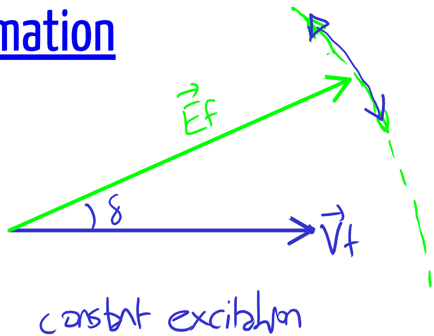
V_t : Constant (when connected to infinite bus)

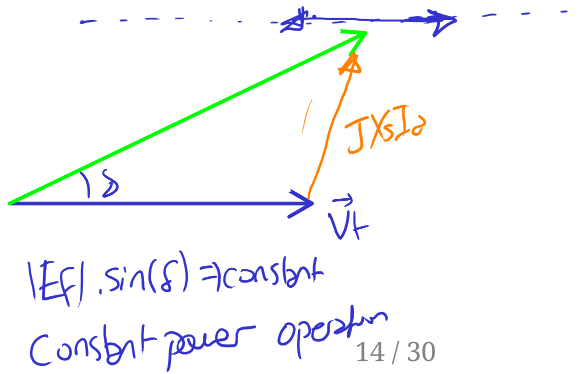
Synchronous Generator Connected to Infinite Bus

There exists two main operating modes:

- Constant Excitation, Variable Load (Circle Diagram)
- Constant Power, Variable Excitation

[Animation]()





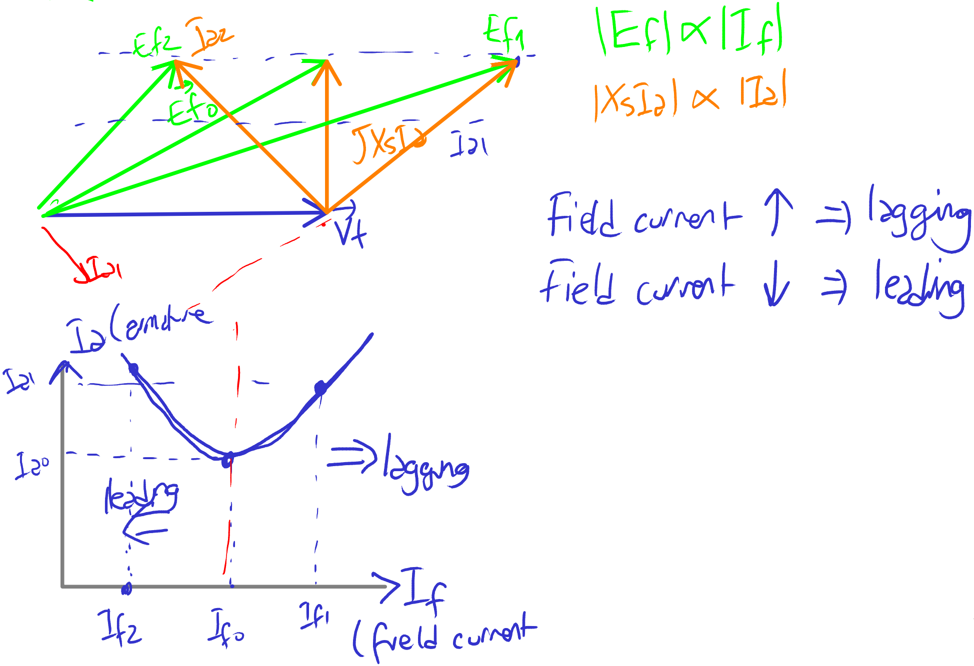
Constant Power, Variable Excitation

From geometry: $E_f sin(\delta) = X_s I_a cos(\theta)$ = Constant

E_f moves on horizontal line

For a generator connected to infinite bus:

Draw I_f vs I_a if the power kept constant (= constant $E_f\, sin(\delta)$.



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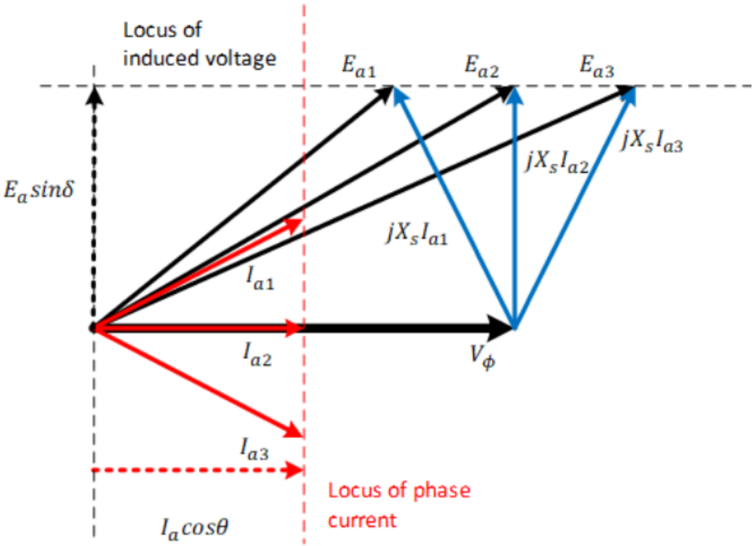
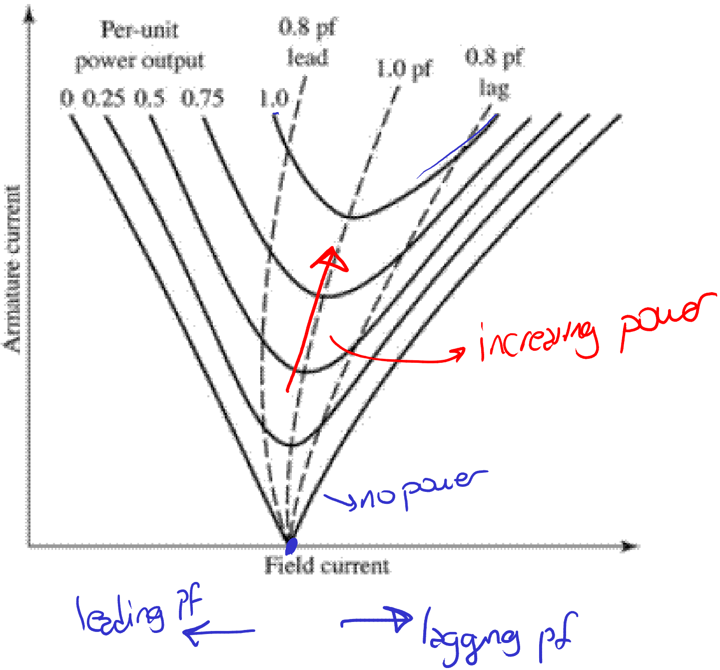
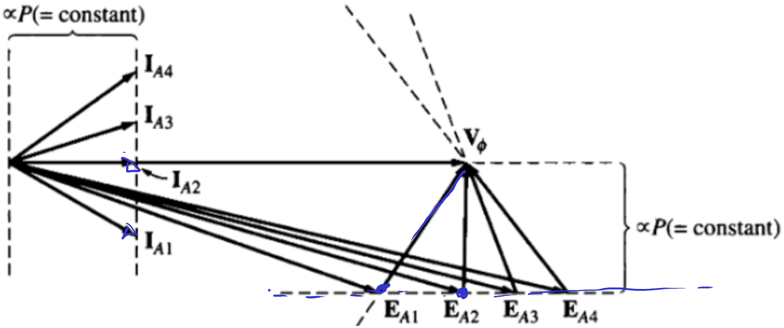


V-Curves: Generating Mode



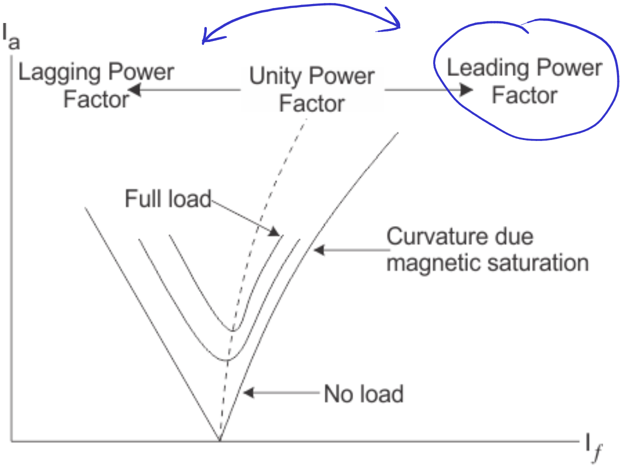
V-Curves: Motoring Mode

Phasor under constant power for the motoring mode



V-Curves: Motoring Mode

Different characteristics for motoring and generating modes



V curves for a synchronous motor with variable excitation

In motoring mode, excess I_{field} makes pf. leading.

Some Useful Animations

Infinite Bus Operation Animation

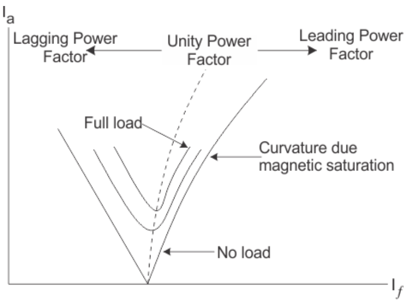
V-curves of a synchronous motor

Synchronous generator capability curves

Other Animations

Synchronous Condenser

A Synchronous motor operating at no-load



V curves for a synchronous motor with variable excitation

Used to deliver or to absorb VAR by controlling I_f

Can behave as a capacitor or an inductor!

Synchronous Condenser

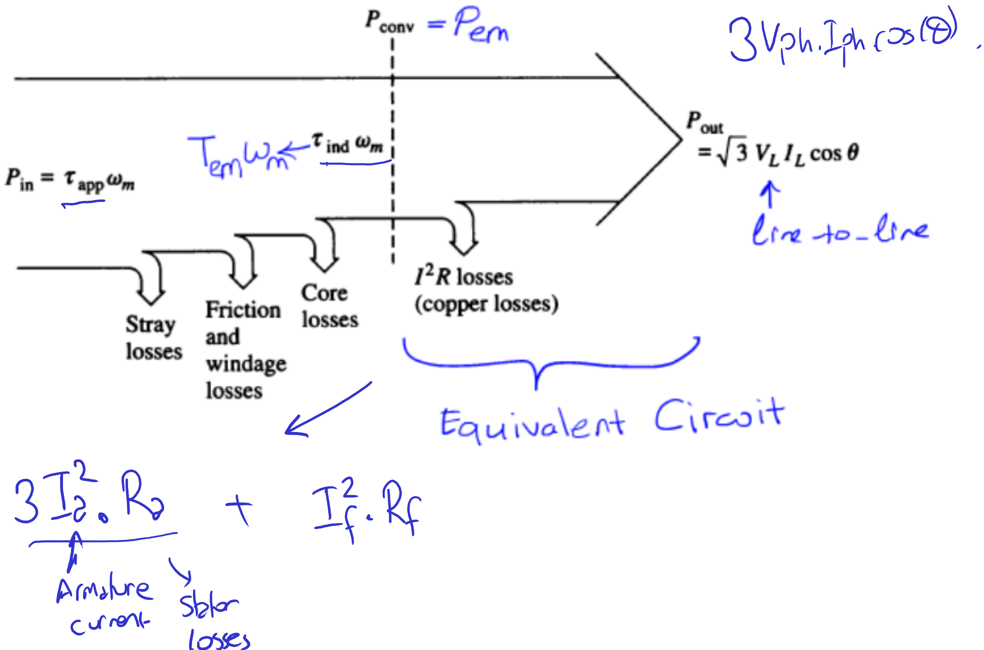
Any difference compared to a motor?

Largest Synchronous Condenser

100 MVAr, 300 tons, built in 2014 by WEG for the Brasil Grid.
Manufacturing Video

For curious students: Rise of renewables leads to synchronous condenser revival, An old tool rediscovered to address new grid challenges

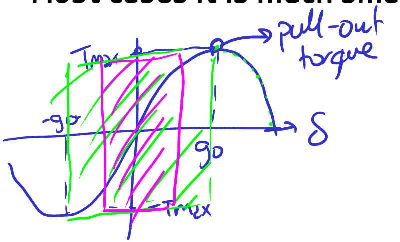
Losses in Synchronous Machines



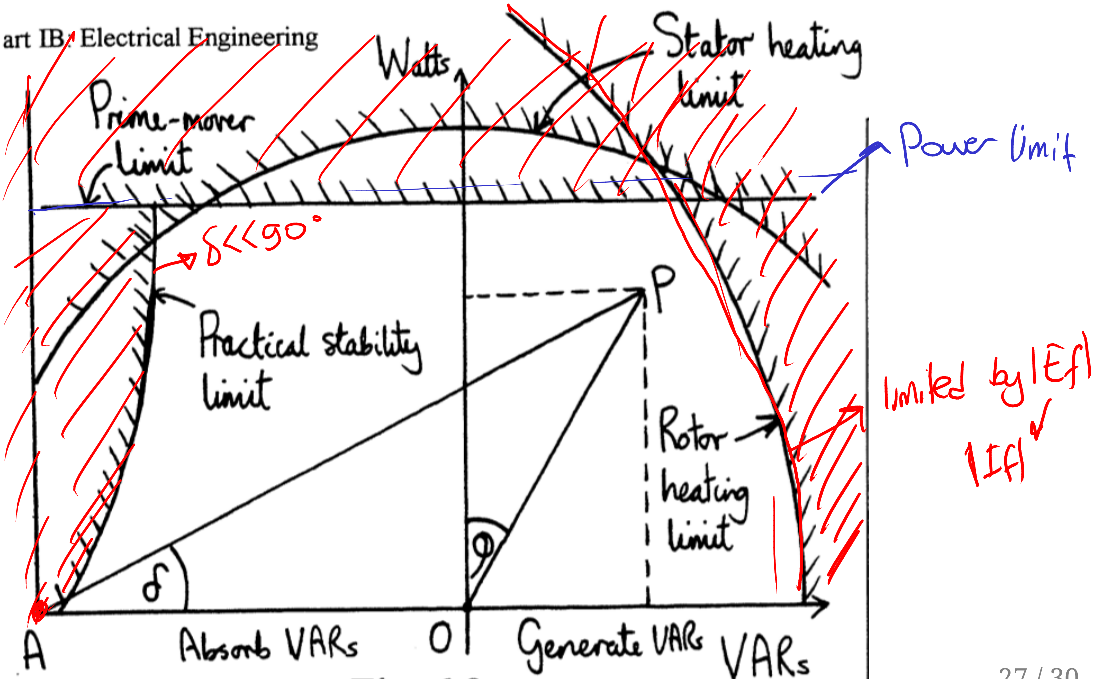
Operating Limits of Synchronous Machines

- Stator Heating: $\propto \; I_a^2$
- Rotor Heating: Limited I_f = Limited E_f
- Mechanical Power Input Limit
- Stability Limit $\delta \; < \; 90$

Most cases it is much smaller for extra safety



Operating Limits of Synchronous Machines



Real Data

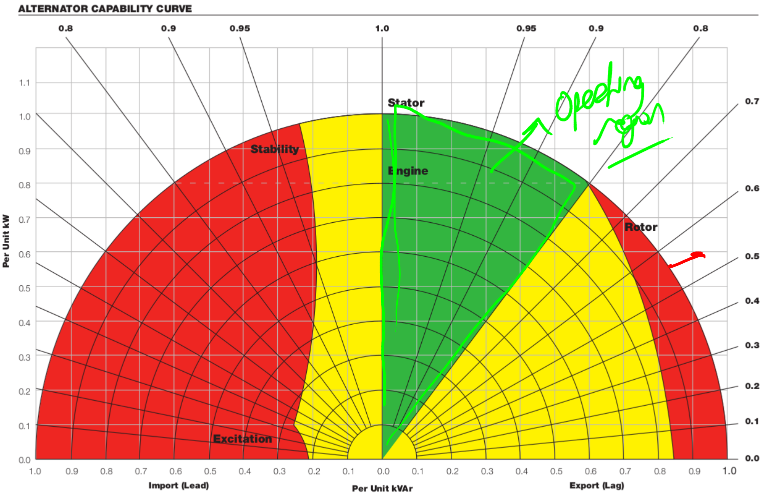


FIGURE 2 – Green area is normal operating range of a typical synchronous machine, yellow is abnormal but not damaging, and operating in red regional will cause damage or misoperation.

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