Synchronous Motors & Sync Excitation Systems

Presented by Bill Horvath, TM GE Automation Systems

At Western Mining Electrical Association

Rapid City, North Dakota

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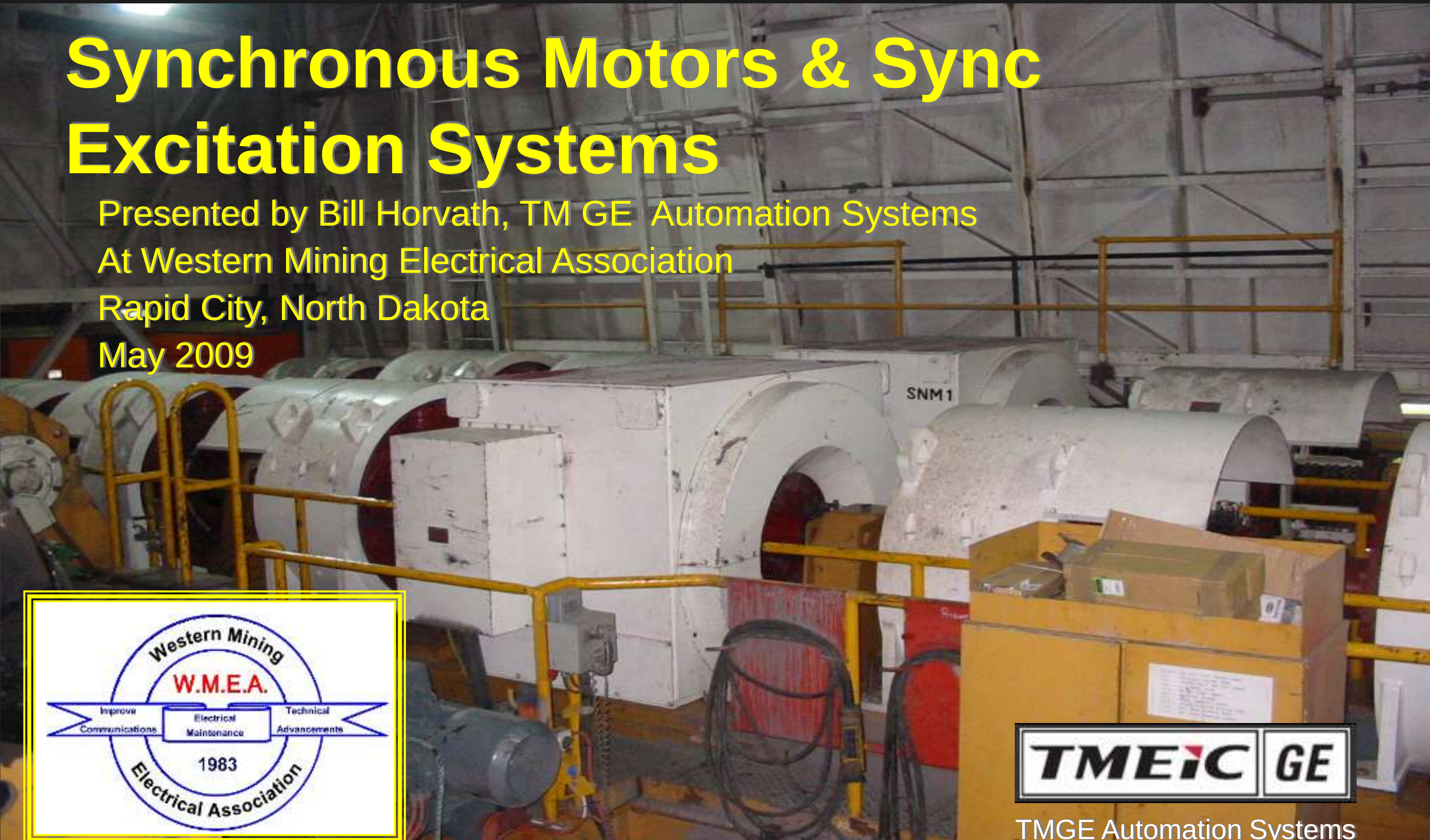
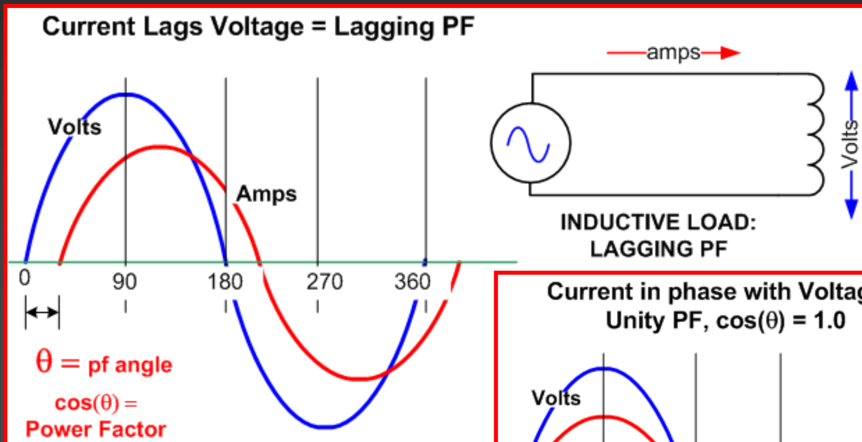


TMGE Automation Systems

Dragline Sync Motors and Excitation

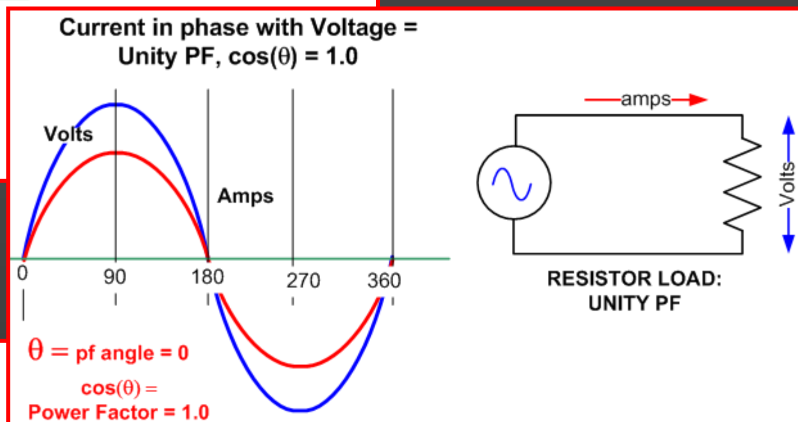
- Why use sync motors?
- Sync Motor & MG Set Basics
- Sync Motors for Excavators
- Sync field excitation & Issues
- Sync Motor Starting & Protection

Reactive Power Basics

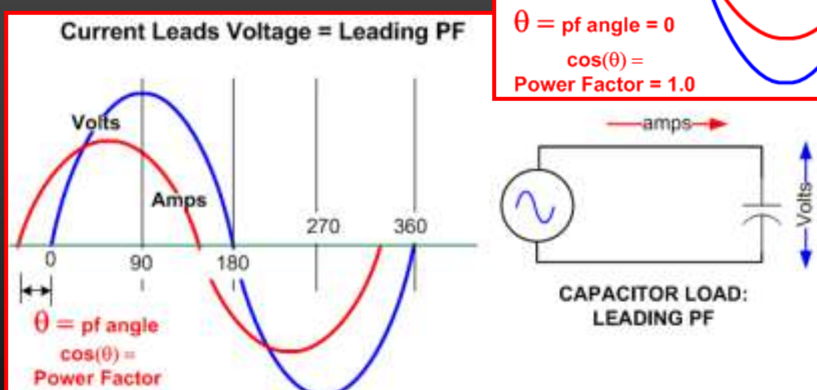


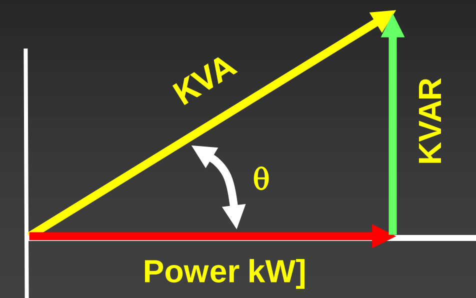
LAGGING

UNITY



LEADING



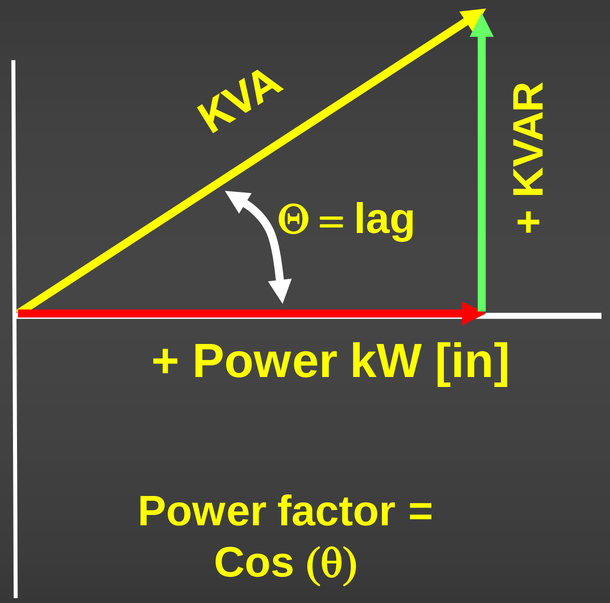


Power factor = Cos (θ)

- Circuit elements themselves are "pure" lead or lag
- Most loads are a mix, with a real [kW] and reactive [KVAR] part
- Real and reactive parts are at right angles

Reactive Power Basics - 2

- Circuit elements themselves are "pure" lead or lag
- Most loads are a mix, with a real [kW] and reactive [KVAR] part
- Real and reactive parts are at right angles
- + KVAR = flow is into load
- + kW = flow is in to load
- Leading PF = KVAR and kW are opposite in flow to or from load

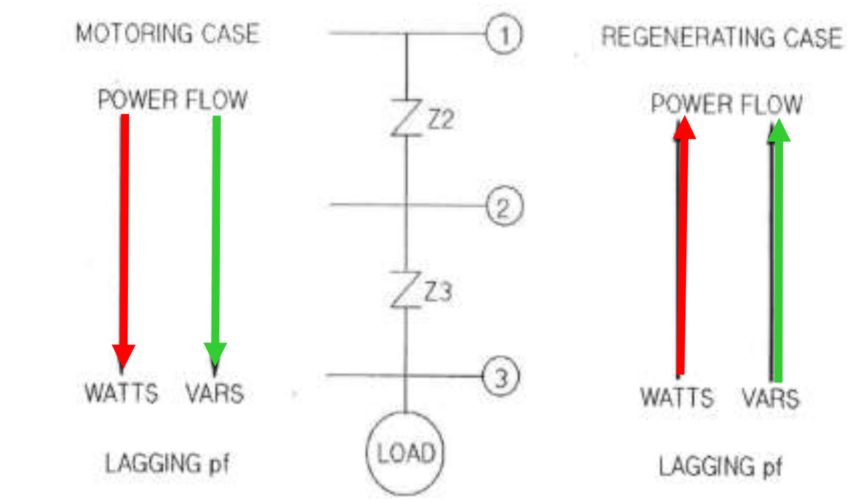


Power factor = Cos (θ)

Why Use Sync Motors?

REACTIVE POWER VOLTAGE CONTROL!

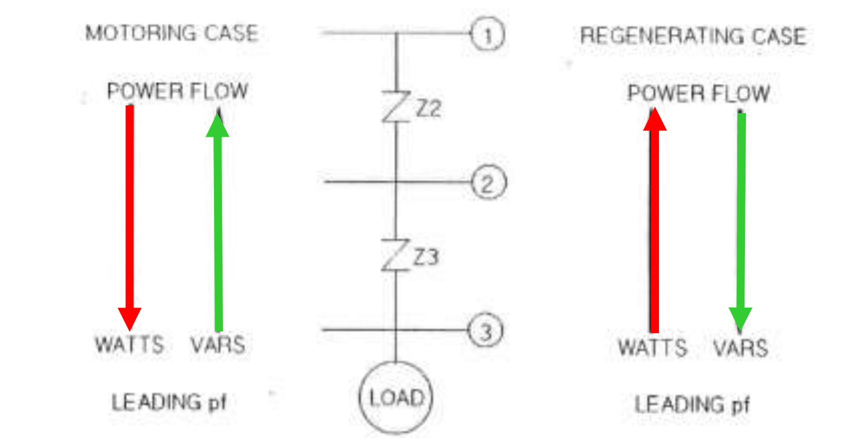
NO SYNCHRONOUS MOTOR



- MOTORING CASE: FLOW OF WATTS AND VARS TEND TO DECRESE VOLTAGE AT BUS 2 AND 3.
- REGENERATING CASE: FLOW OF WATTS AND VARS TEND TO INCREASE VOLTAGE AT BUS 2 AND 3.

RESULT: LARGE VOLTAGE SWINGS AT BUS 2 & 3

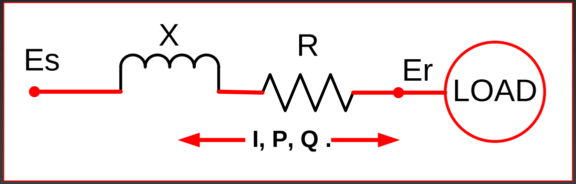
WITH SYNCHRONOUS MOTOR



- MOTORING CASE: FLOW OF WATTS TENDS TO DECRESE WHILE FLOW OF VARS TENDS TO INCREASE VOLTAGE AT BUS 2 AND 3.
- REGENERATING CASE: FLOW OF WATTS TENDS TO INCREASE WHILE FLOW OF VARS TENDS TO DECREASE VOLTAGE AT BUS 2 AND 3.

RESULT: GREATLY REDUCED VOLTAGE SWINGS AT BUS 2 & 3

Controlling Voltage with Reactive Power



- Power delivery Equation:
  $Es^2 = Er^2 + I^2\{R^2 + X^2\} + 2\{PR + QX\}$
- Q / P is set by the load power factor
- R / X is set by the power system
- If we Ignore the very small term
  $I^2\{R^2 + X^2\}$ & set -Q / P = X / R
  then PR = - QX, and 3rd term
  becomes {-QX + QX} = 0
- Result: voltage swing at load is minimized

Es = Per-unit sending voltage

Er = Per-unit receiving Voltage

I = per-unit amps

P = Per Unit real power

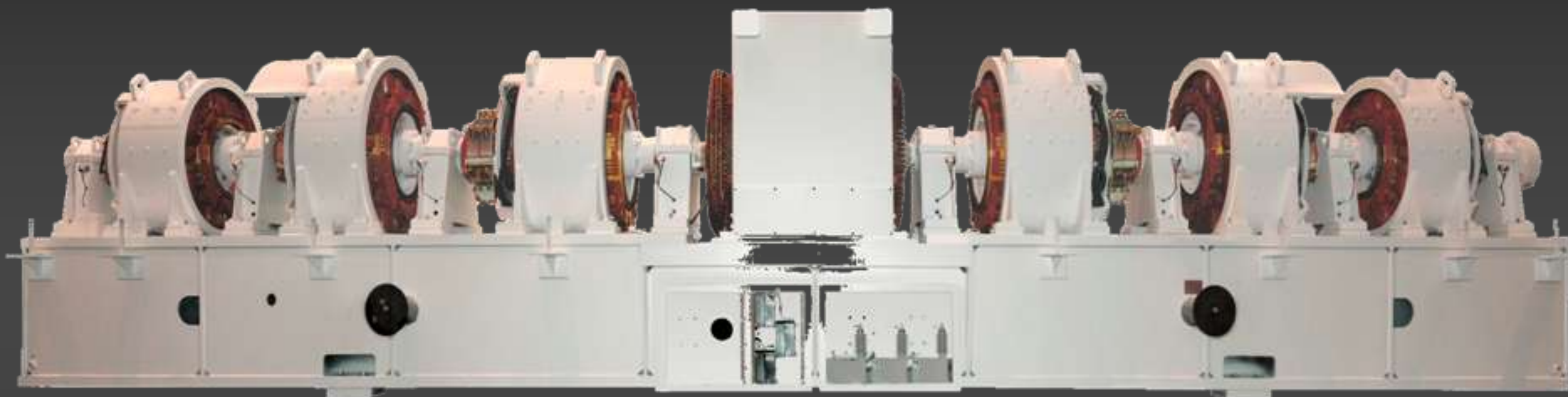
Q = per unit reactive power

R = per unit resistance

X = Per Unit Reactance

Modern 7 Unit Dragline MG Set

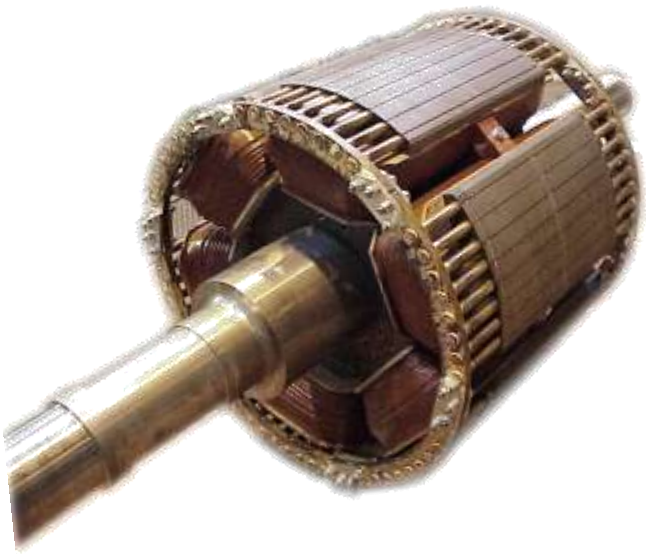
Overall 7 Unit Dragline MG Set



Swing Drag Hoist **Sync Motor** Hoist Drag Swing

- Motion generators share common shaft.
- Sync Motor provides or absorbs net power.

DL Sync Motor Rotors & Stator

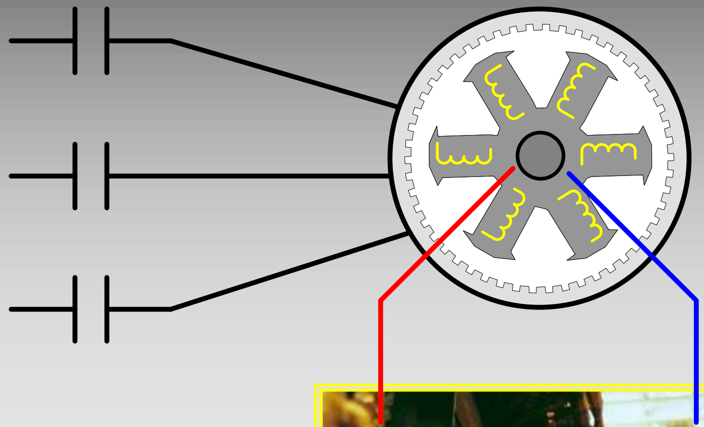


Rotor Drive End

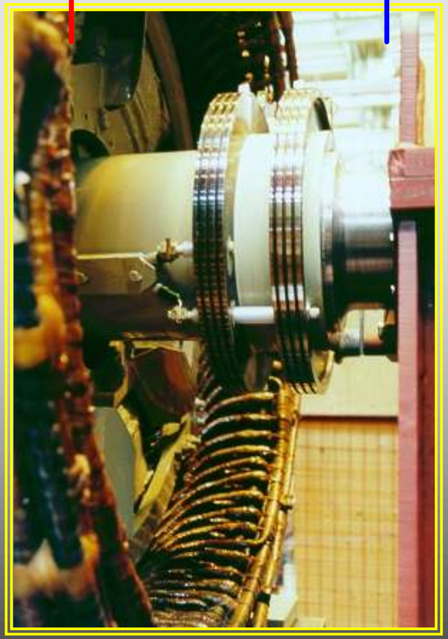
Slip Ring End [before slip-ring installation]

Three-Phase Stator

AC Stator & Rotor Field Connections

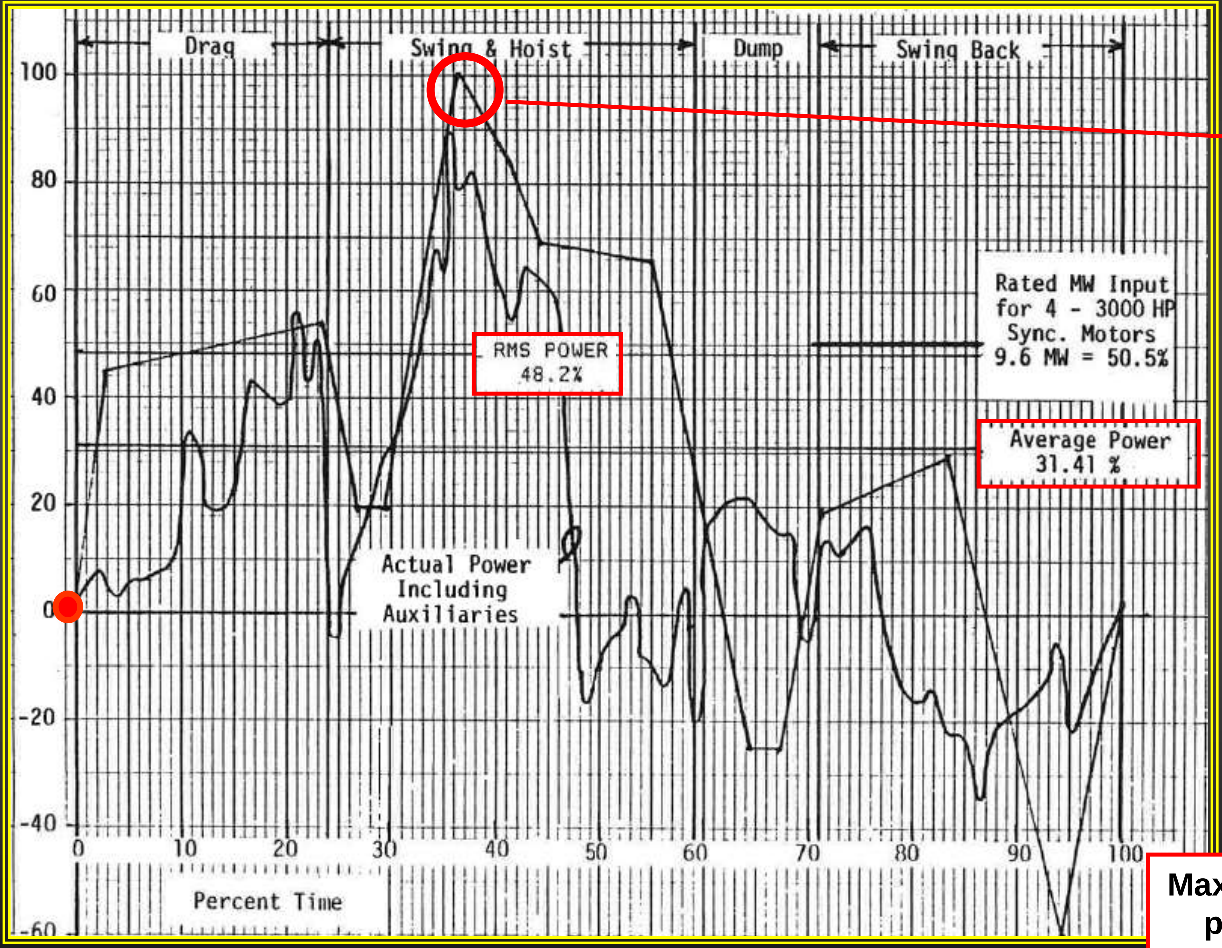


HV Junction Box
With Surge Caps &
Arrestors



Rotor DC
Slip Rings

Dragline Real & Idealized Power Cycle



Sync Motor Loading

Peak Hoist DC kw
+
Peak Swing DC kW
/ effic.
/ 2.5 pull out margin

@95% volts

Max Regen 60% x peak motoring

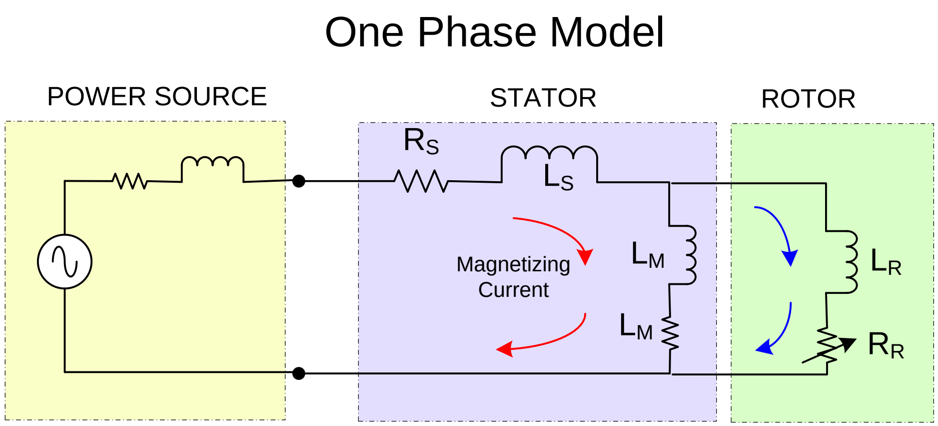
Sync Motor Basics

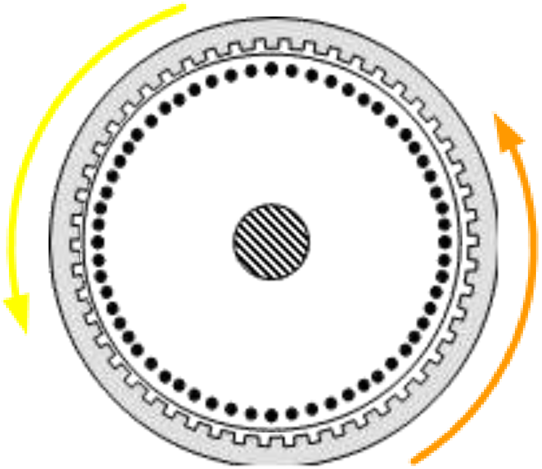
- Compare to induction Motors
- Electrical Characteristics
  - ✓Starting
  - ✓V Curves & Circle Diagrams
  - ✓Reactive Power Control
- Field Excitation –
  - ✓Power factor control
  - ✓Peak Torque requirements
- Sync motor construction

Sync Motors vs Induction Motors

- Motor Models
- Field – separate vs induced
- Starting
- Running
- Torque production

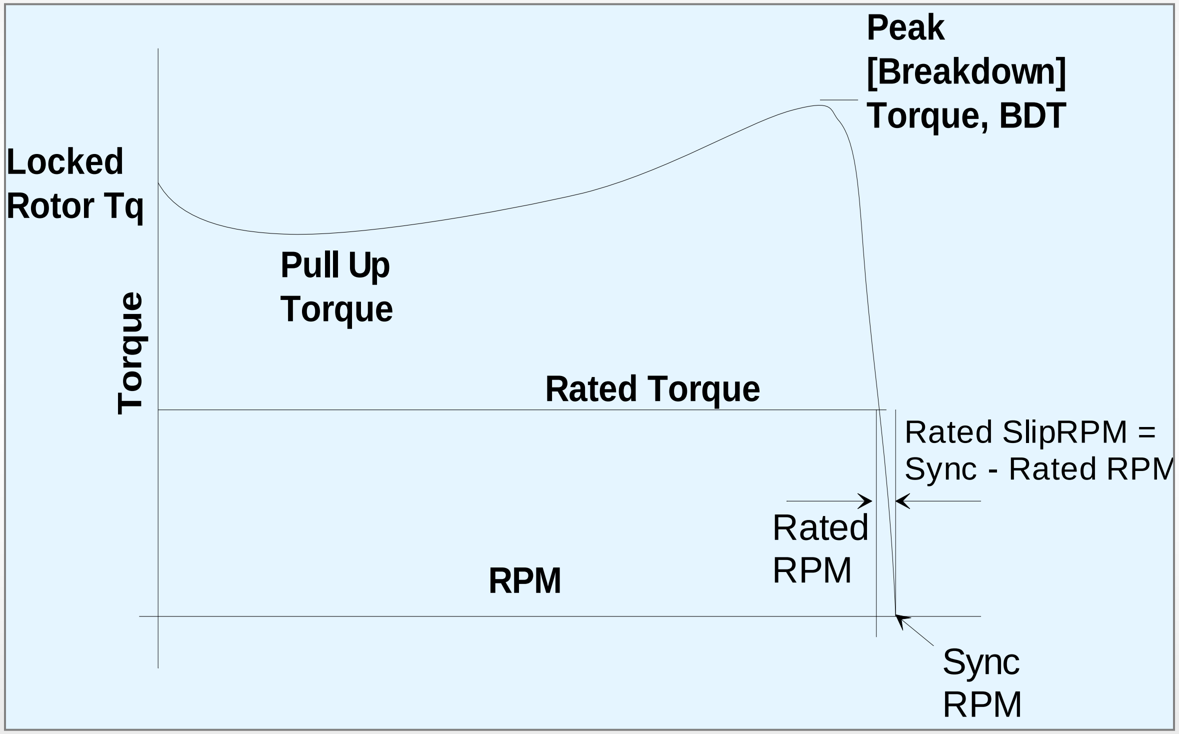
Induction Motor Model



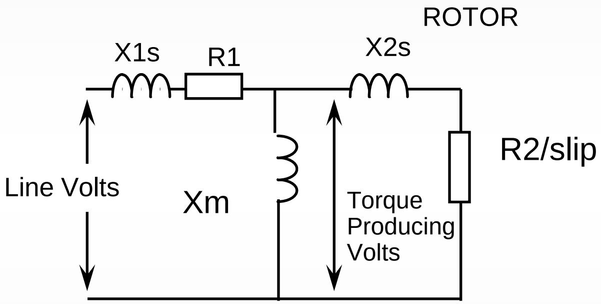


- AC Power on stator sets up rotating field magnetic flux
- Rotor acts as shorted transformer secondary, current produces rotor flux, torque results
- Rotor voltage dependent on difference between stator wave & rotor rpm = slip ***NO SLIP= NO POWER!***
- Power Factor is **always lagging**

Typical Induction Motor Torque Profiles



AC Induction Motor



Relationships

Rated Slip ~ r2

Peak Torque ~ V^2 /[2(X1 + X2)ωb]

Slip At BDT ~ r2/(X1 + X2)

Starting Amps ~ V/(X1 + X2)

Starting Tq ~ (r2/ωb)*[V/(X1 + X2)]^2

VnL Amps ~ V/Xm

Sync Motor Construction

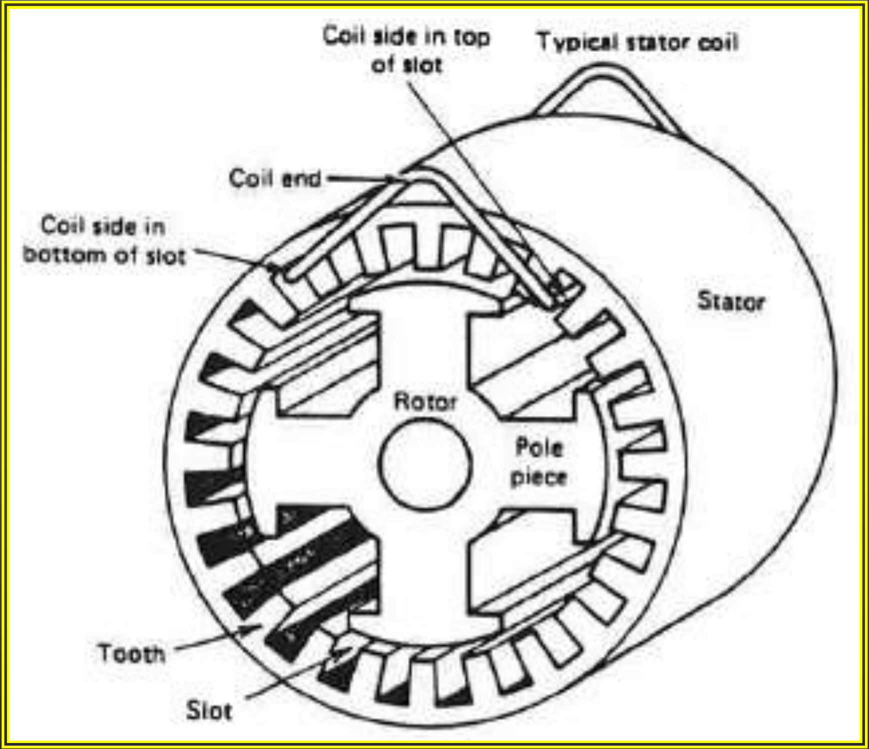
4-Pole Example

- Three phase stator field
- DC field on rotor poles
- DC Fields fed from brushes through sliprings
- Sync RPM =

120xFreq / #Poles

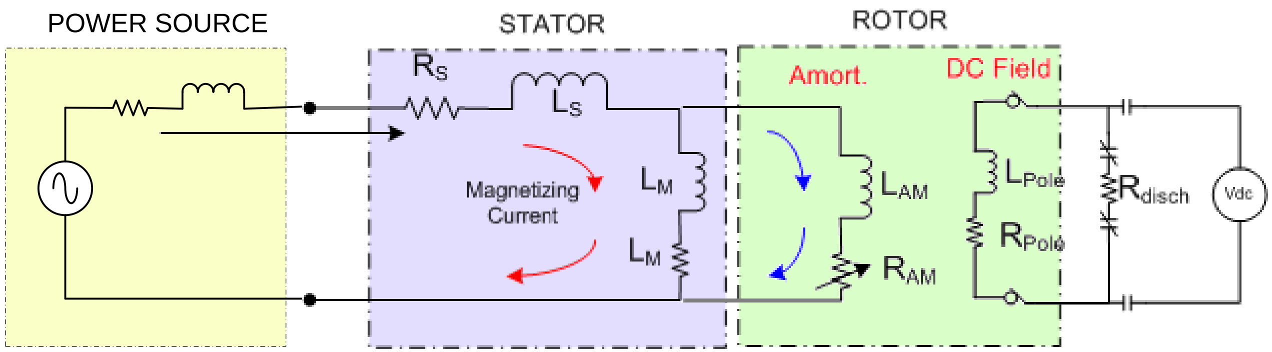
for 60 Hz Systems, 6-pole DL MG Sets

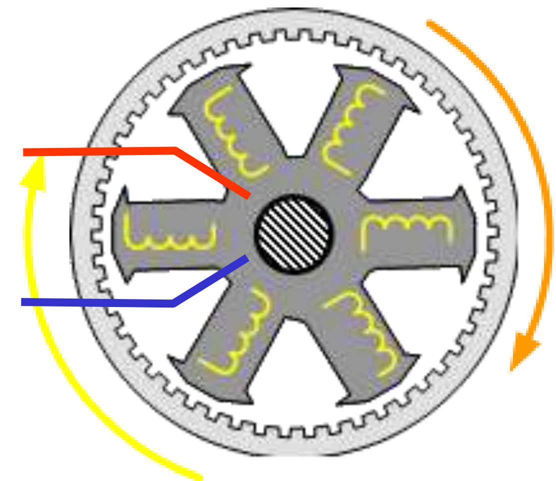
120 x 60 / 6 = 1200



Synchronous Motor Model - Starting

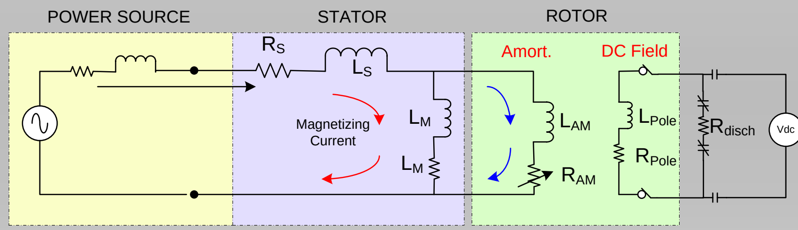
One Phase Model

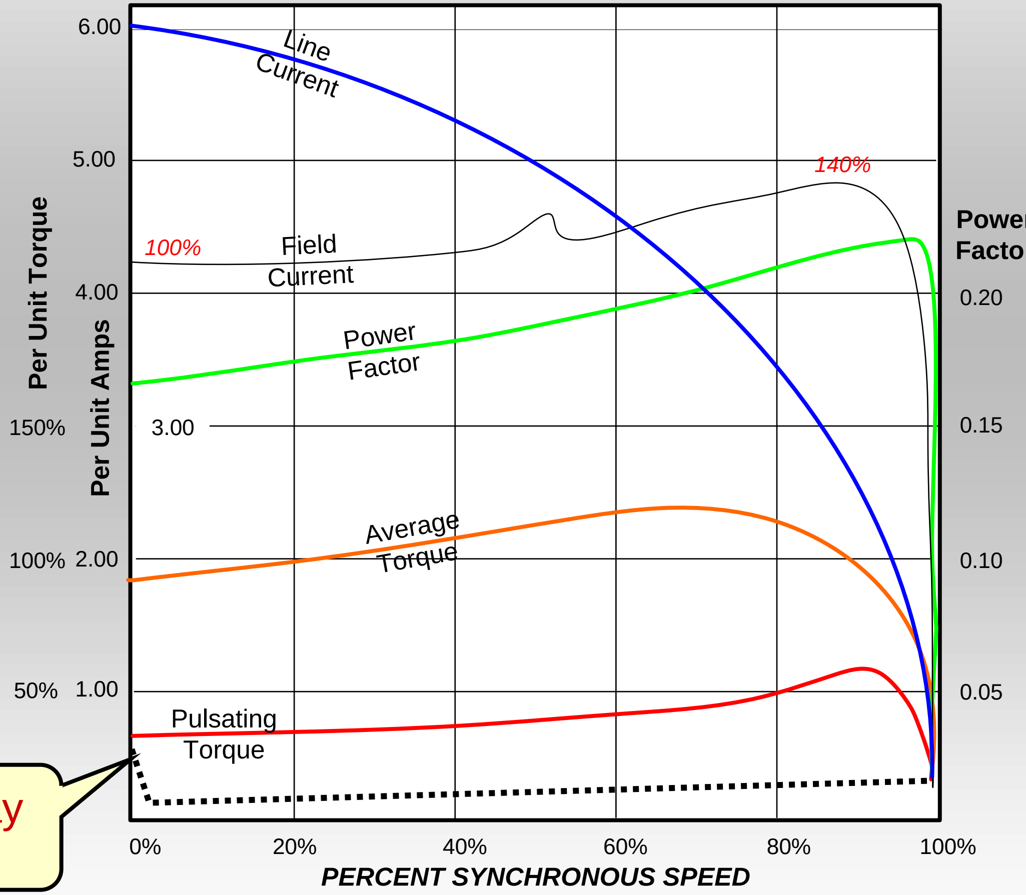




- AC Power on stator sets up rotating field magnetic flux
- For starting, rotor amortiseur acts as shorted transformer secondary, current produces rotor flux like induction motor
- Torque produced accelerates load to near sync speed
- DC field poles shorted by “discharge resistor during start
- Near sync speed, DC field is applied, rotor syncs to line

Typical Sync Motor Starting Curves





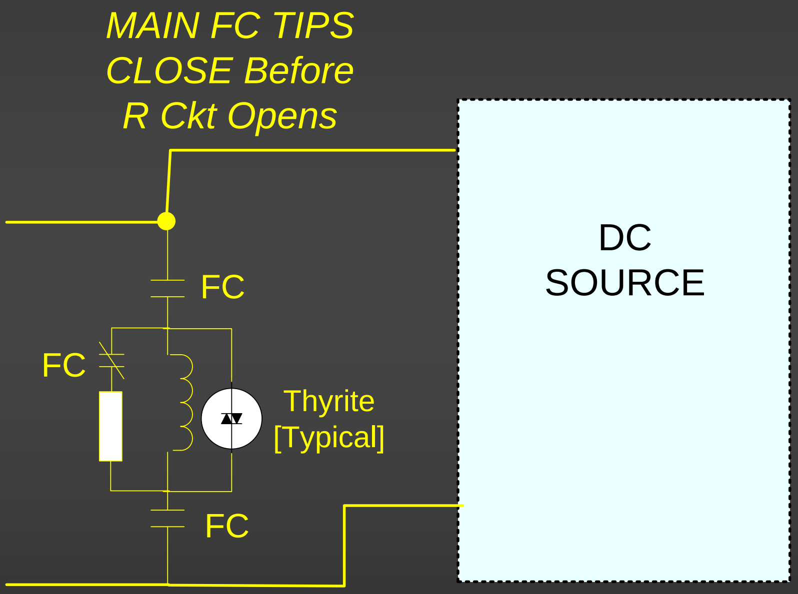
MG Set Breakaway
~10-20%

Notes on Sync Motor Starting - 1

- **Speed of 95-97% is typical field application point**
- **"Best Angle" field application is not needed for Dragline MG sets – timed application is effective & simpler**
- **Turning on the fields too soon can create excessive torques at "lock in" to synchronous speed**
- **Open circuit fields during start creates high voltages [10,000 volts or more] – damage to fields, slip rings!**
  - ✓ **Either a short circuit or a resistor should be used during start.**
  - ✓ **Using an optimal resistor can give 30-50% more start torque**
- **"Thyrite" voltage surge protectors act as backup to resistors and contactors across the fields**

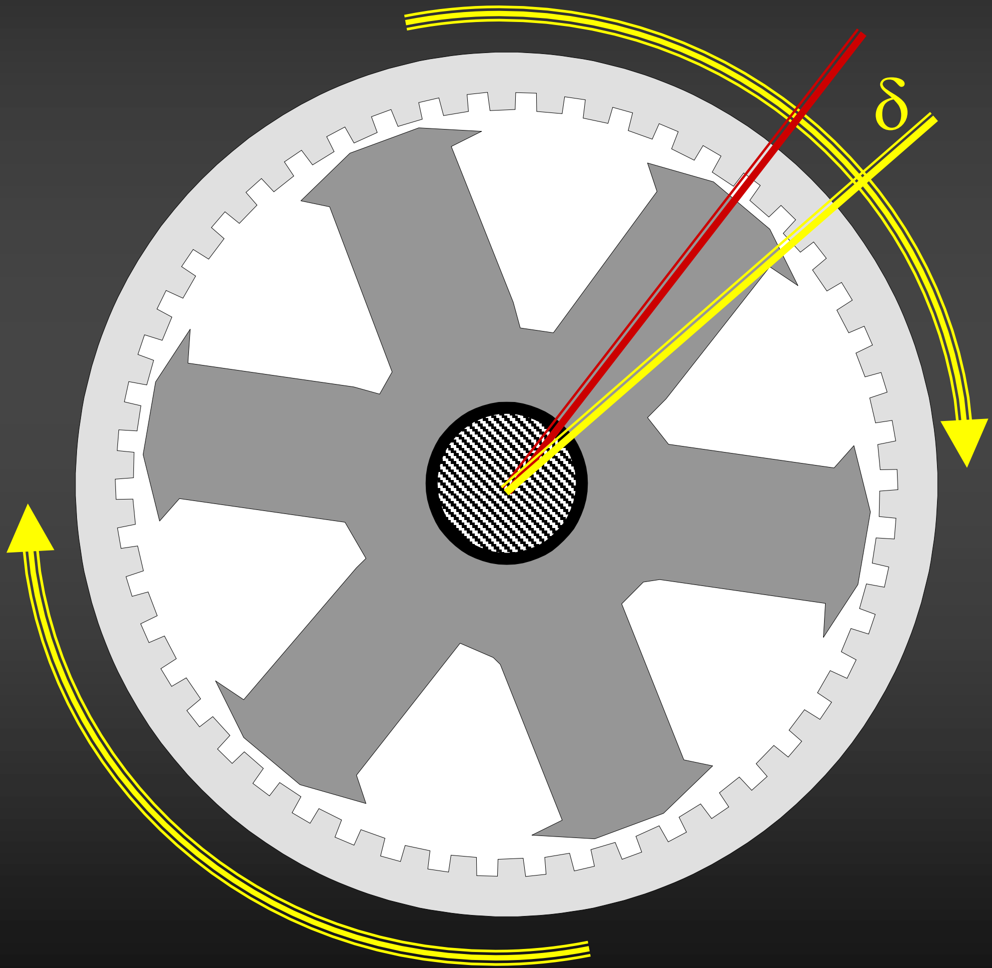
Notes on Sync Motor Starting - 2

- **Field application Contactors connect DC before discharge path breaks**
- **"Reluctance torque" is produced by attraction of rotor iron to rotating stator field near synchronizing – aids synch process**
- **Sync Motors are stressed by starting – design limit is 2 cold starts per hour**
- **600% inrush, @15-20% pf is typical**



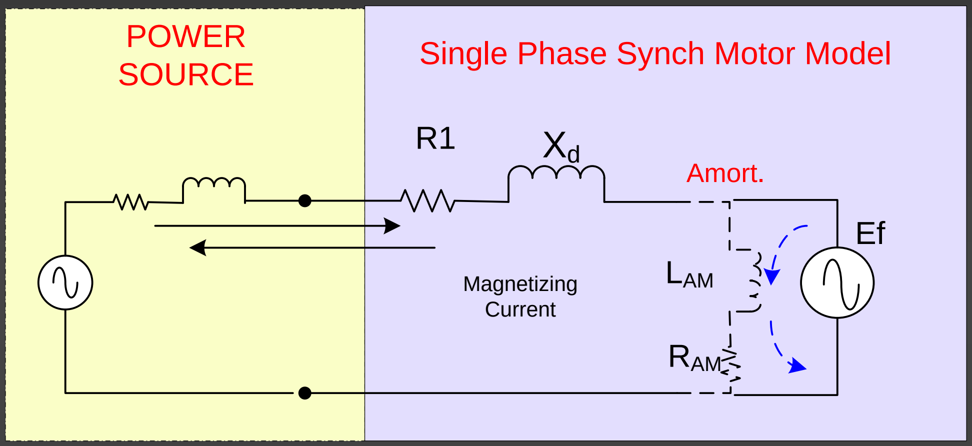
After Synchronizing – With DC Field

- Rotor follows stator magnetic wave at sync RPM
- Magnetic Coupling between Stator & Rotor:
  - ✓ Like an elastic band
  - ✓ Torque "stretches" band and rotor trails stator by an angle called the torque angle δ



Sync Motor Model

Fully Running

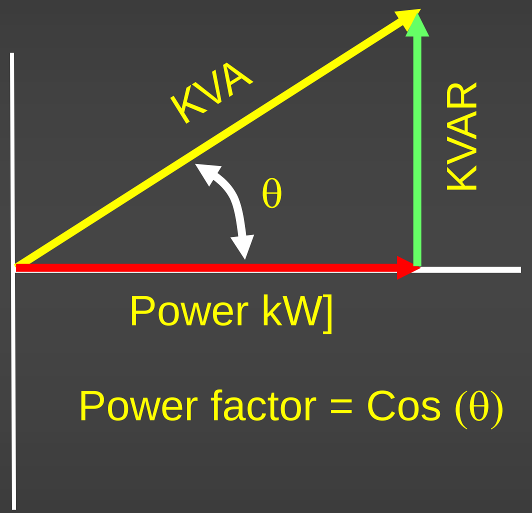


Effect of DC Field

- Sync Motor KVAR
  - ✓Exported with strong DC field [leading pf]
  - ✓Imported with weaker field [lagging pf]
- Increases torque capability [power output]

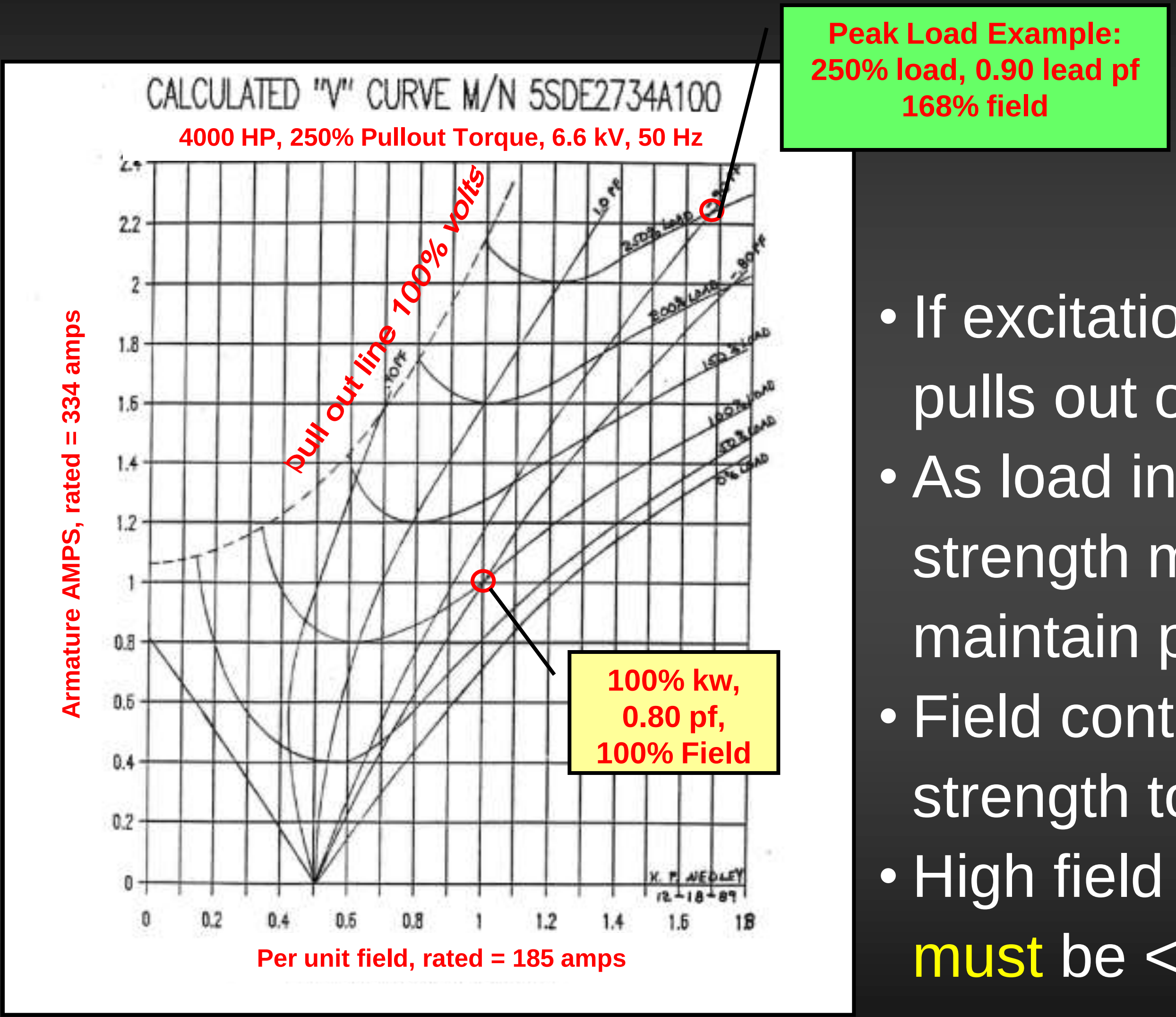
Sync Motor Reactive Power

- Motors are rated both in kVA and HP [or kW] and PF
- Typically 1.0 PF or 0.8 lead PF
- Excavator MG sync motors:
  - ✓ NNNN HP, 0.8 pf
  - ✓ 250% pullout torque at 0.95 volts
  - ✓ 6-pole, 1200 RPM [1000 RPM on 50 Hz]



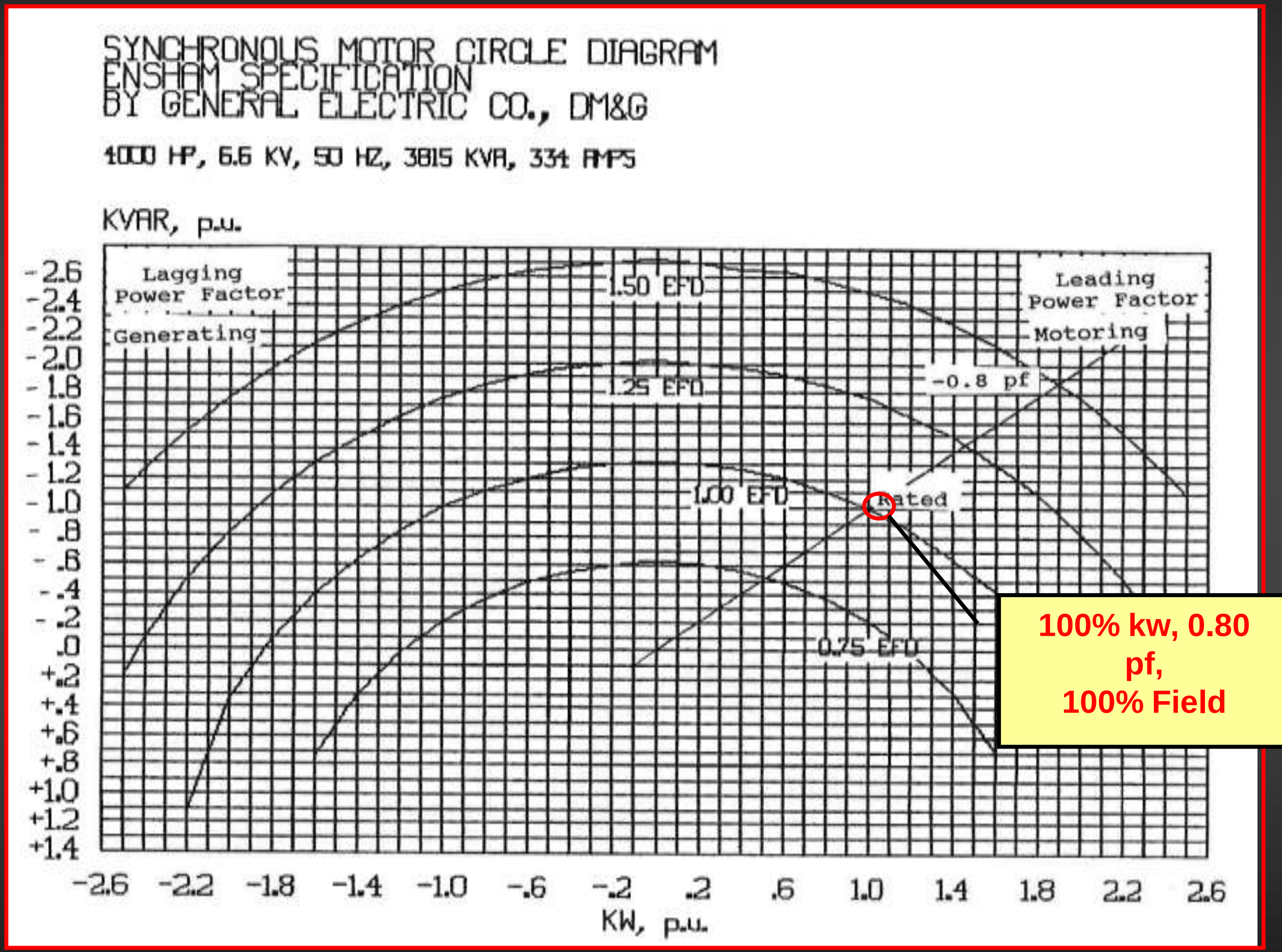
Power factor = Cos (θ)

Sync Motor Capability "Vee" Curves



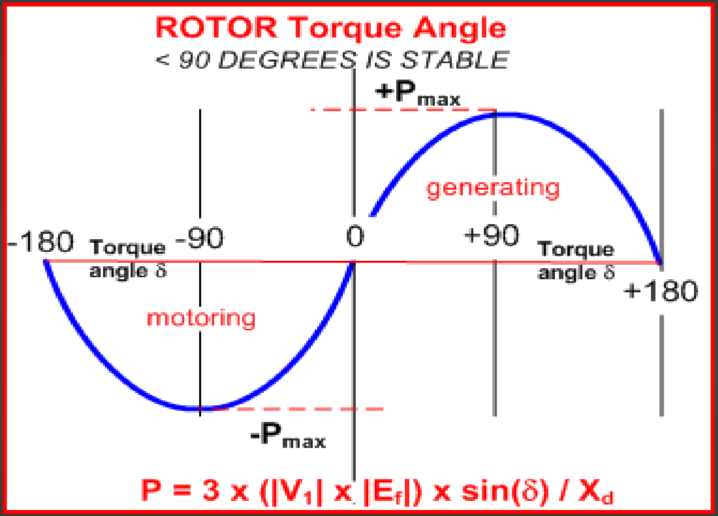
- If excitation too low, motor pulls out or pushes out of sync
- As load increases field strength must increase to maintain power factor
- Field control MUST move field strength to follow load
- High field amps is OK but RMS must be < 1.0 pu

Sync Motor Capability Curves



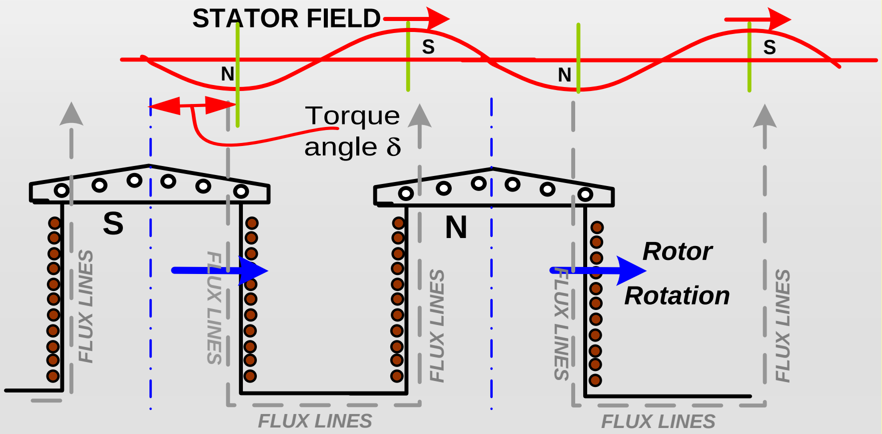
- Another way of showing sync capability.
- Same notes as shown on VEE curve

Sync Rotor Power Curve



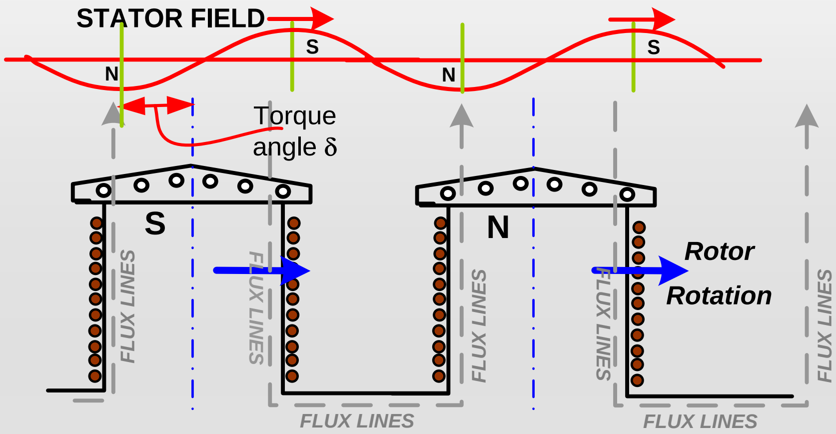
- Curve applies to a particular level of field generated volts [E_f] and Terminal Volts [V_1]
- Stronger E_f or changing V_1 affects max power
- Power [torque] past 90 deg will result in de-sync

Sync Motors & Torque Production



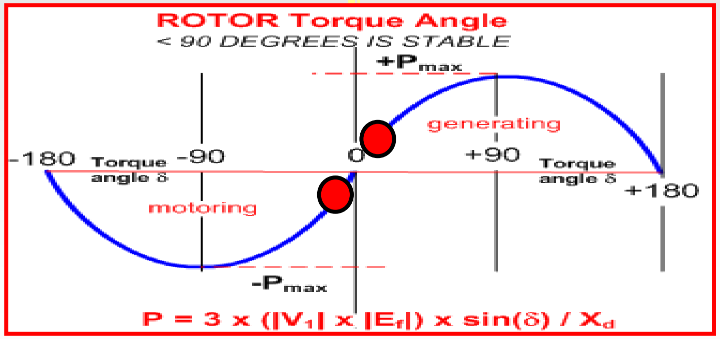
Motoring Torque

Rotor Trails Stator Wave

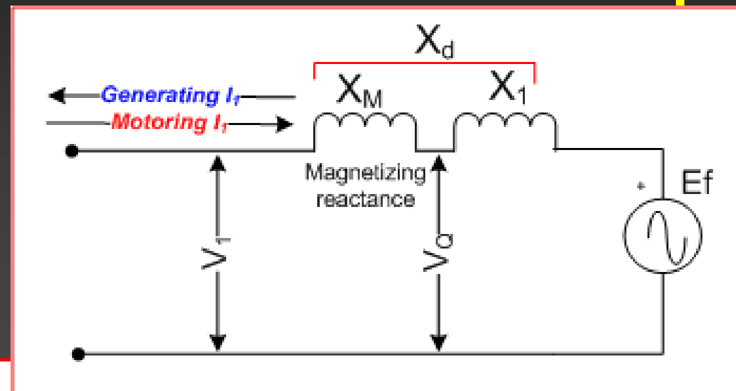


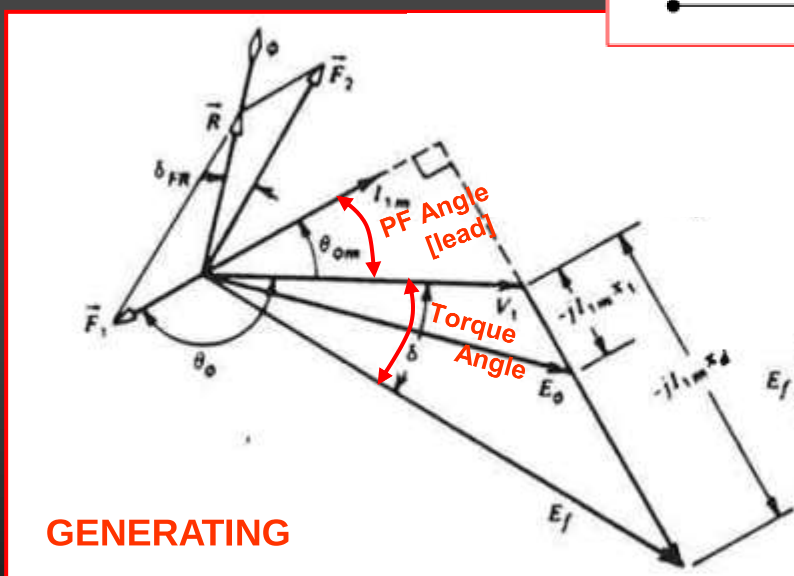
Regen Torque

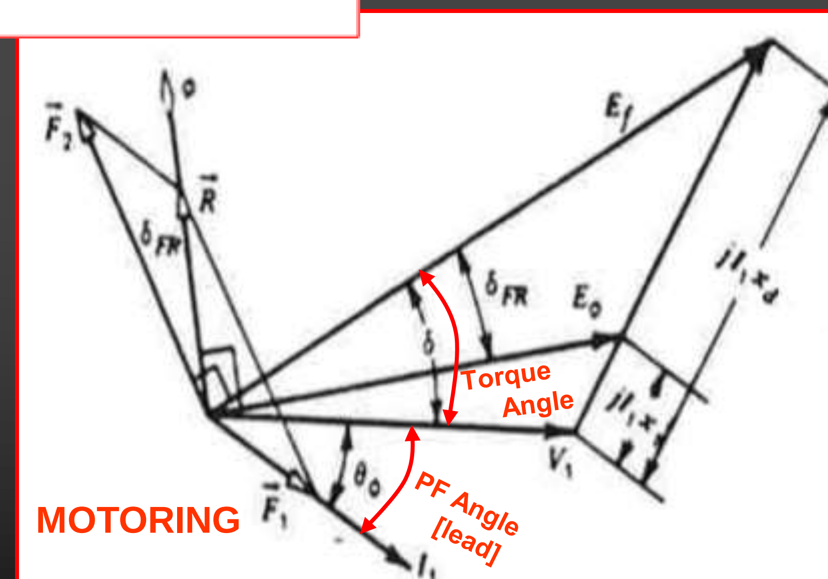
Rotor Leads Stator Wave



Vector Relationships







Summary

- Sync Motor provides kW to generators but can independently generate KVAR [reactive power]
- Reactive power flow opposite of kW helps hold voltage at DL steady.

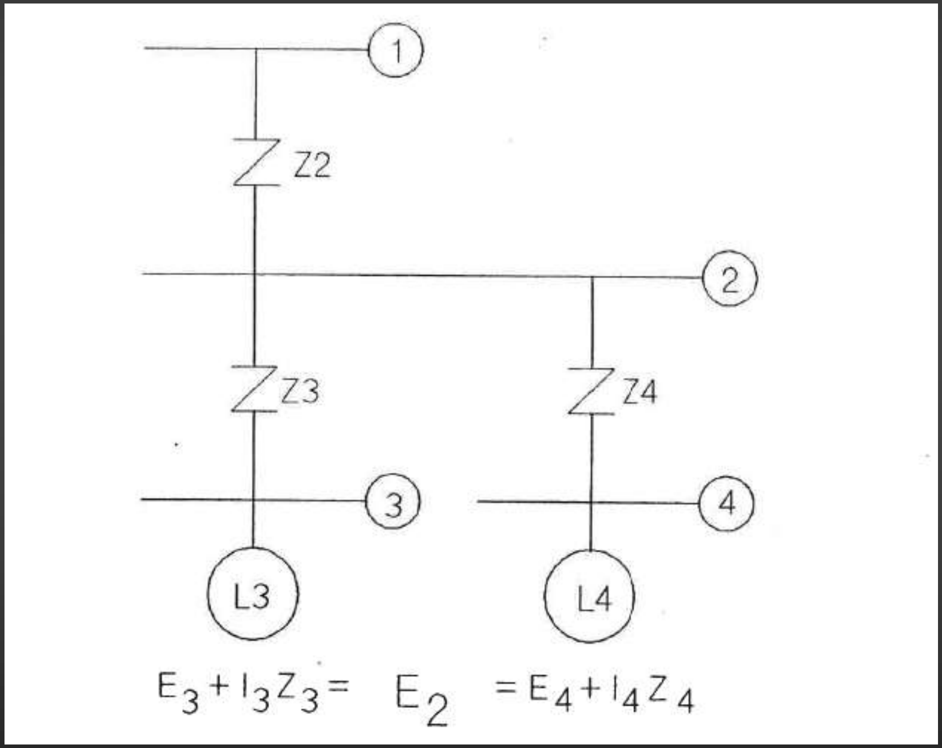
Sync Excitation Control Scheme Evolution

1. Fixed Field
2. Fixed Source with Stepped resistance in fields
3. Power Factor Regulators
   - ✓ Saturable Reactor
   - ✓ Solid State op-amp & thyristor
4. kW vs KVAR regulator
5. Field current vs kW regulator

Can't respond to digging cycle (items 1–2)

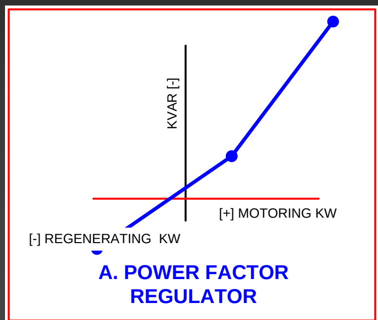
Each have strengths and weaknesses (items 3–5)

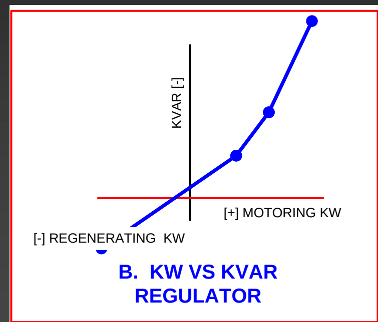
Why Not Simply Regulate Voltage?

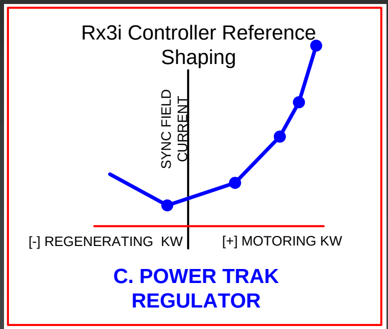


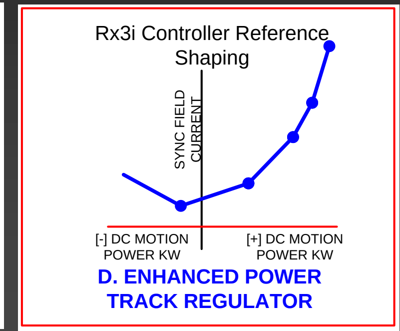
If Draglines L3 and L4 are both set to regulate voltage at same source [Bus 2] – they will likely be unstable and “fight” each other.

Sync Reactive Regulating Schemes









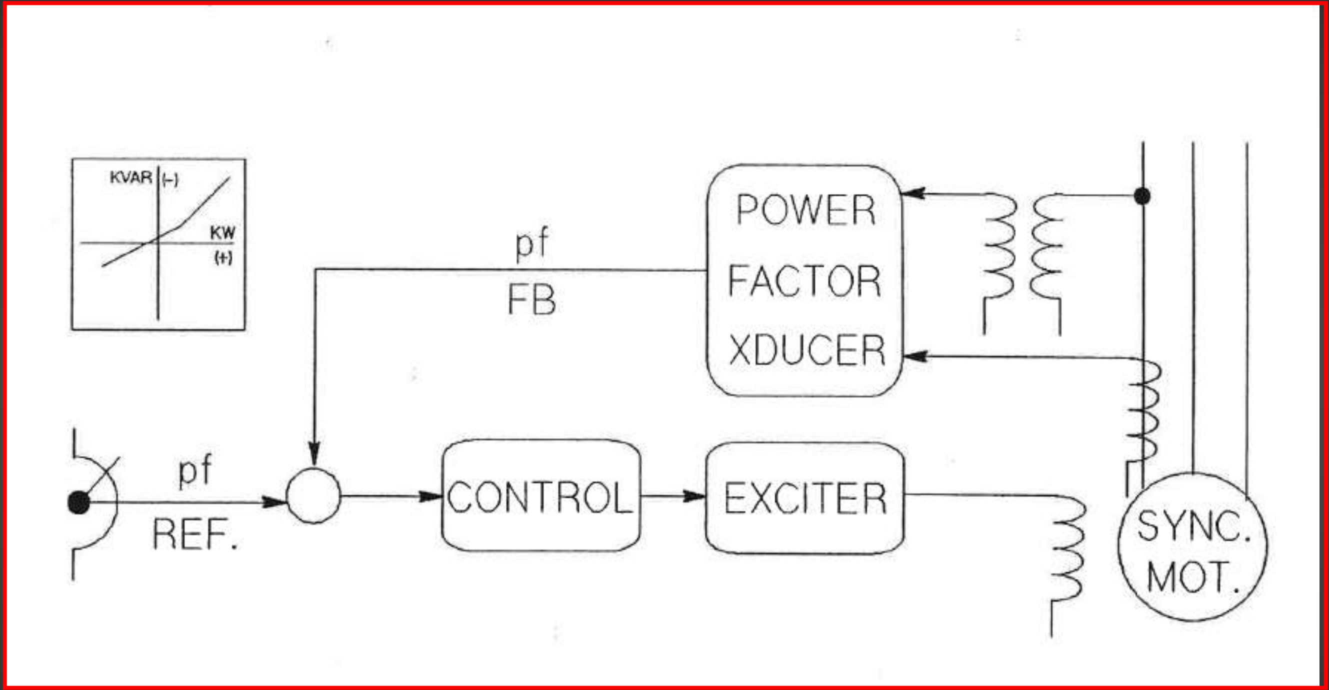
A. **POWER FACTOR REGULATOR**
Single PF setting with minimum field clamp.

B. **WATT-VAR REGULATOR**
Multiple break slope VAR vs Input KW

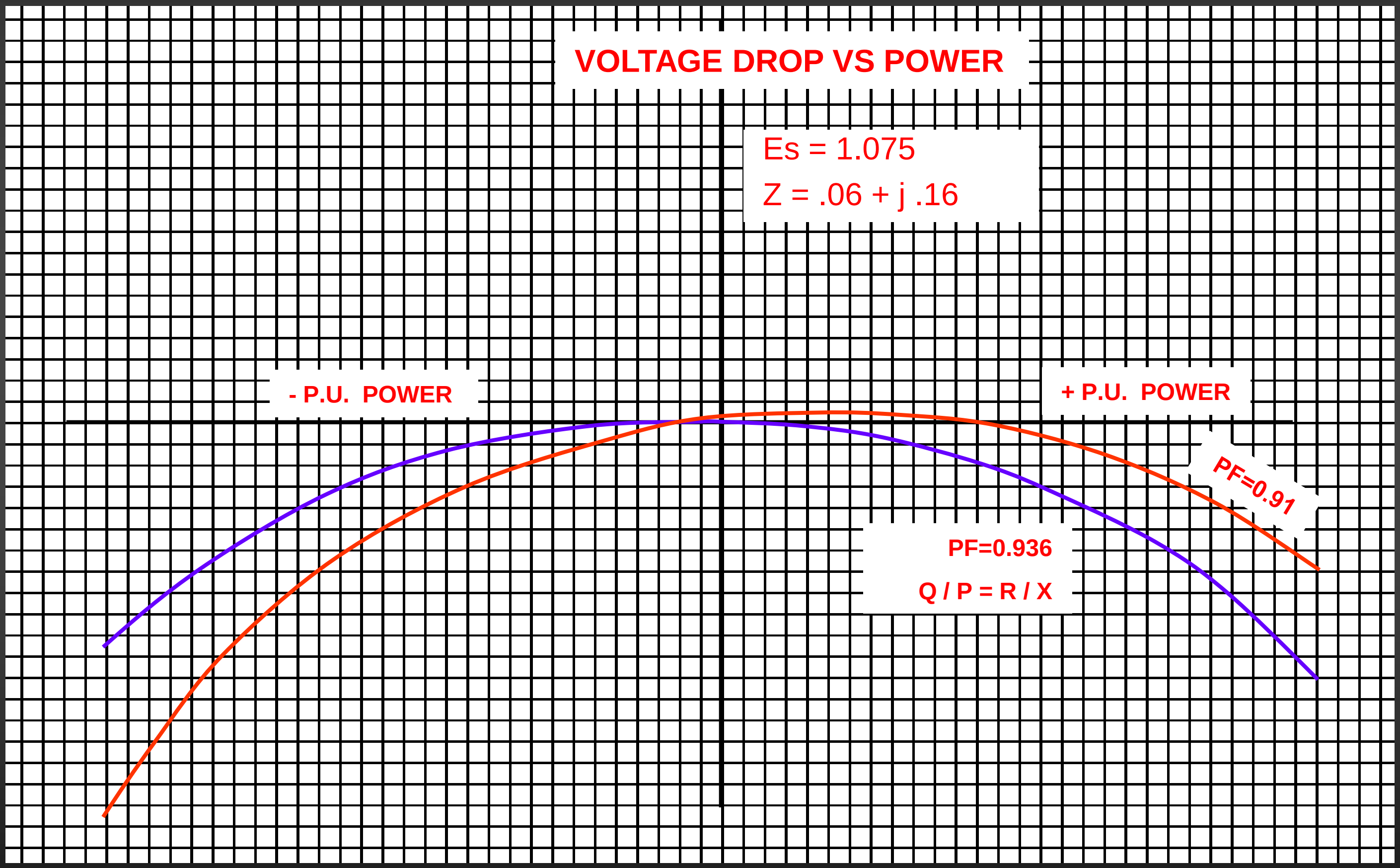
C. **FIELD CURRENT VS KW [POWER TRAK] REGULATOR**
Multiple break slope Sync Field Amps vs AC kW

D. **ENHANCED POWER TRAK REGULATOR**
Multiple break slope Sync Field Amps vs DC kW with AC kW fixed offset

Power Factor Regulator
Simplified Representation



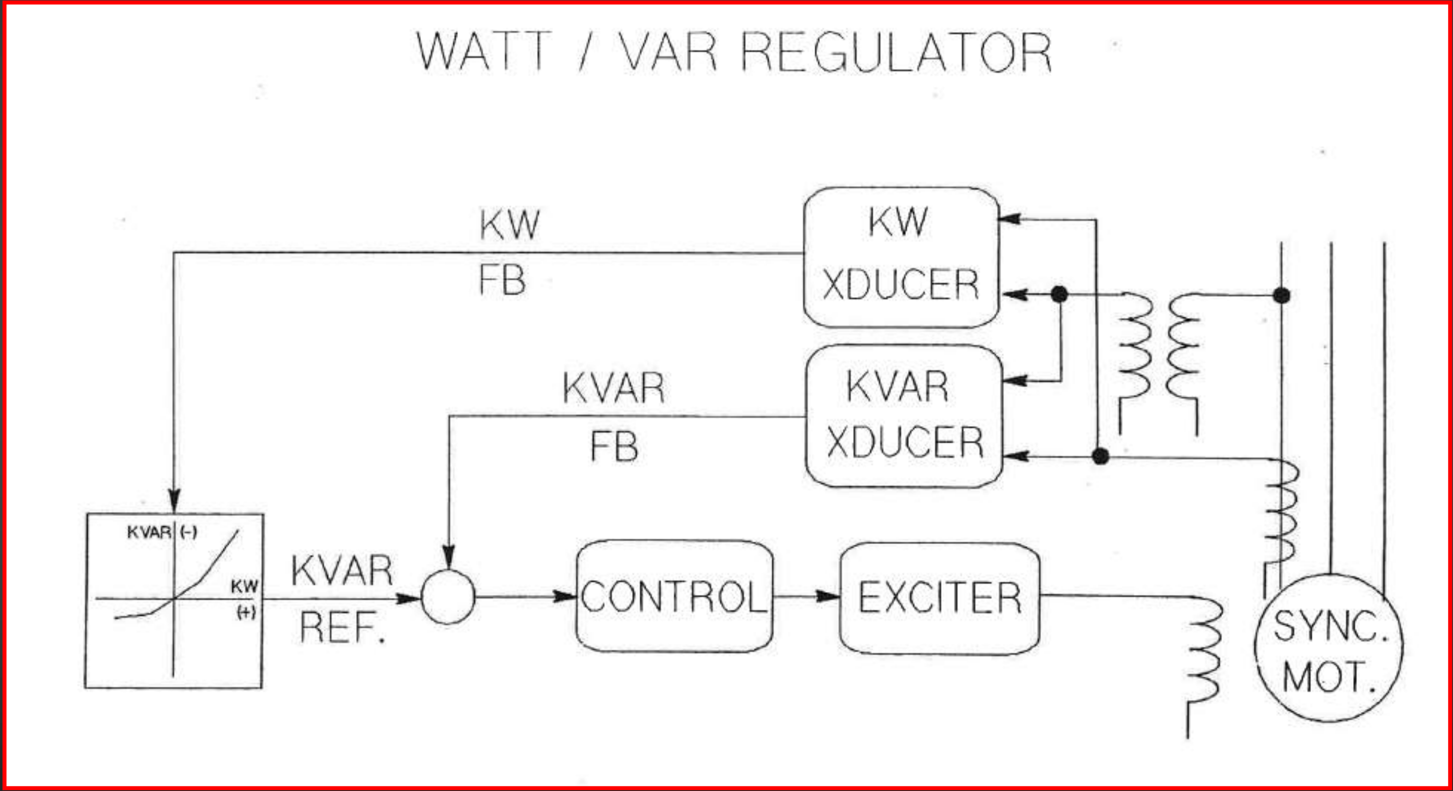
Pure "Power-Factor" Regulator Calculated Performance



CONSTANT REGULATED POWER FACTOR ONLY CREATES SYMETRICAL VOLTAGE DROP OR RISE!

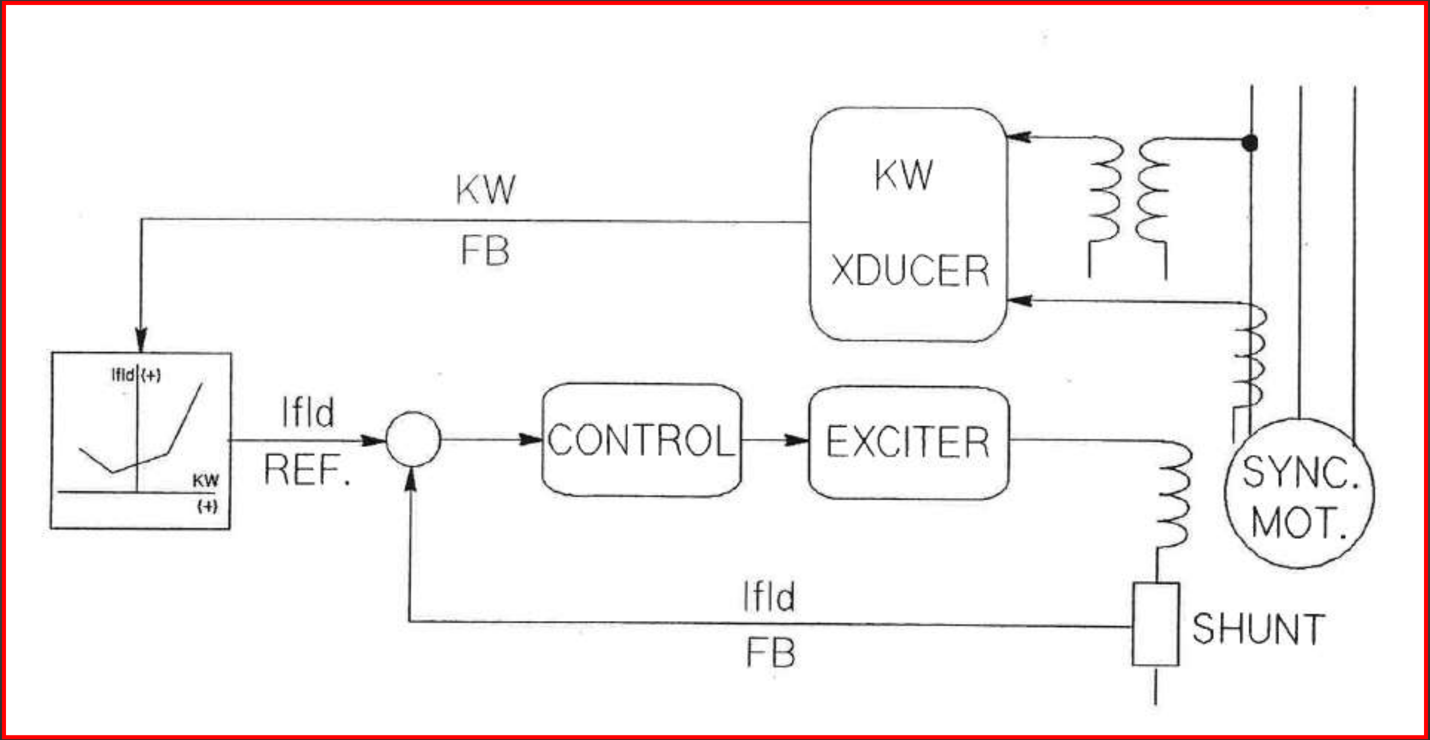
Watt-VAR [KVAR vs Kw] Regulator

Simplified Representation



kW vs Field Current [Power-Trak] Regulator

Simplified Representation – Any technology



Sync Field Current vs Kw Regulator [Power-Trak]

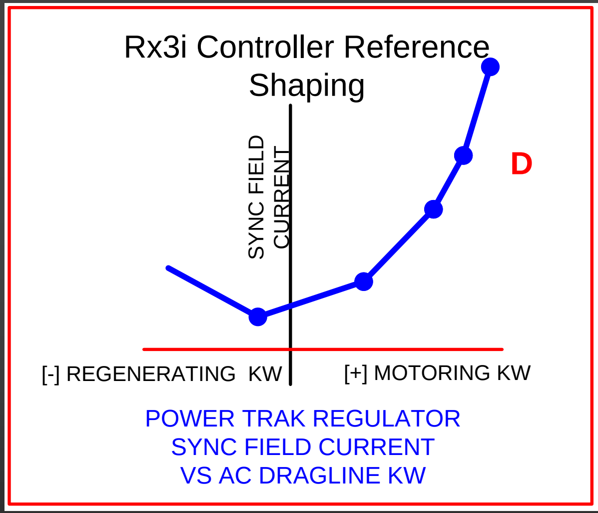
Advantages vs PF or WATT-VAR Regulators

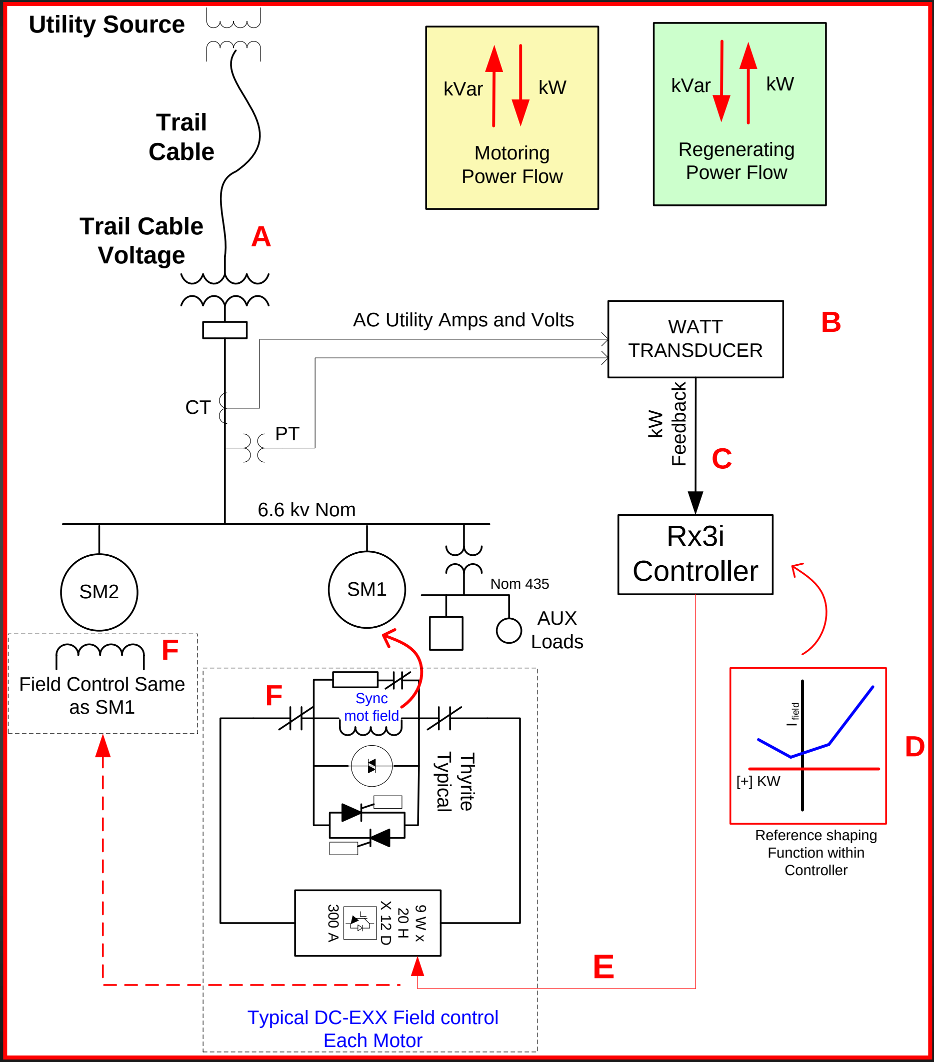
- Lower Overall Cost
- Easier to understand, easier to adjust
- Better voltage regulation from:
  - ✓Independent regulation of motoring and regen allows lower field amps at light load
  - ✓As line voltage from utility side drops, sync motor automatically produces more compensating kVARs to hold voltage.

Enhanced Power Trak Regulator

- DC kw used as reference
- Eliminates delay associated with sync field to AC power quantities
- Reduces stimulation of 2 – 3 Hz Sync-MG oscillations
- Includes long term [10 minute time constant] integration of actual variations in system – to compensate for changes

Details on Power Trak [with DC-EXX Implementation]

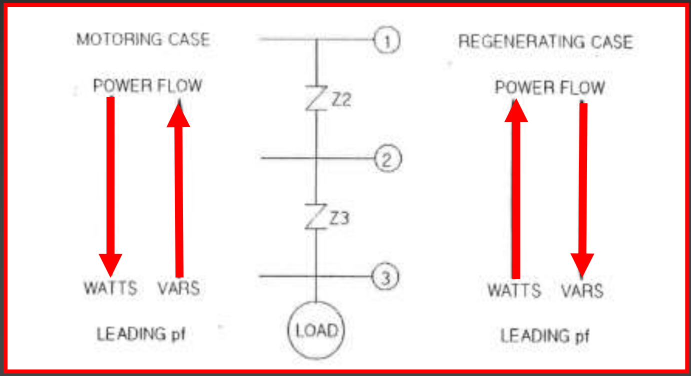




Gotchas In Sync Motor Excitation

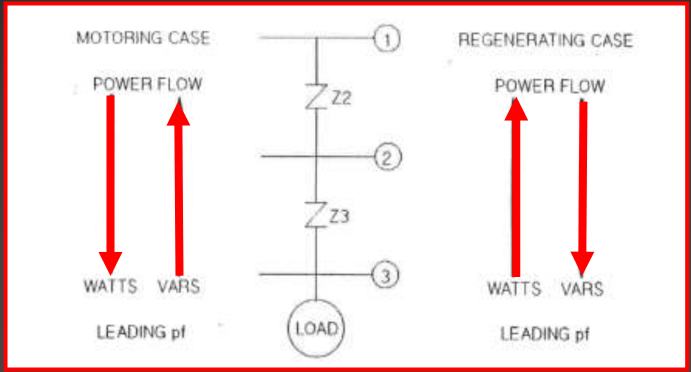
- Weak power systems
- Customer or utility specs
- Pit configurations that change
- Oscillations / instability

DL Sync Motors – on Weak Power Systems



- For weak systems, either supply [Z2] or mine & pit distribution [Z3] impedances are high
- Sync motors at DL have limit on reactive power available
- If voltage swing at DL bus 3 exceeds -5% + 10% of motor rating, trip or damage can result
- Excitation Control is usually set up for best voltage control at Bus 3.

Pit Conditions Changing



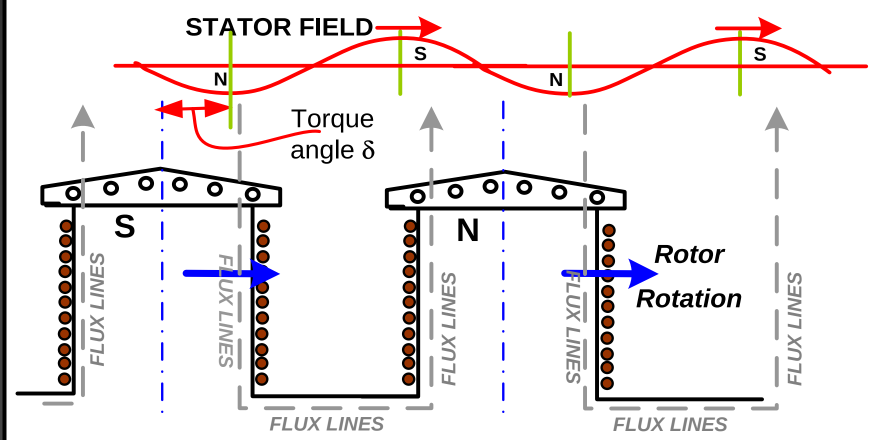
- When Draglines are moved to new digging areas, Z3 [pit distribution impedance changes.
- Field Excitation Control set up for best voltage control at Bus 3 may have to change to keep Bus 3 volts within -5% + 10% motor limits.

Sync Motor MG Set Natural Frequency

- Sync Motors **all** have a natural frequency – like a spring and mass
- Natural frequency $\mathbf{f_n}$ of a connected motor is approximately:

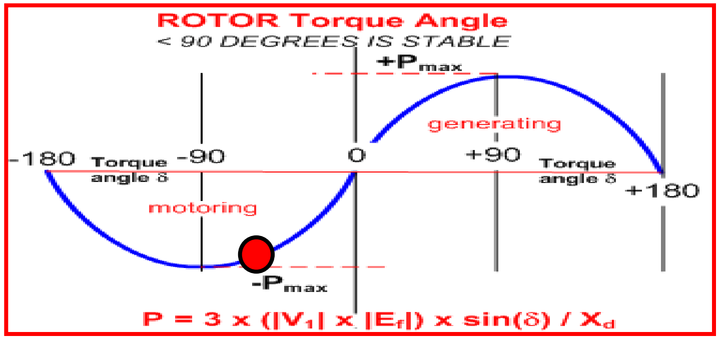
$$f_n = \frac{35200}{RPM}\sqrt{\frac{Pr \times f}{WK^2}}$$

- For Dragline MG sets [sync motor plus DC gens] this natural frequency calculates to 2-3 Hz
- Increasing field strength “stiffens” the spring, but does not change the natural $\mathbf{f_n}$.
- Impact loading on motor can “bounce the spring”.

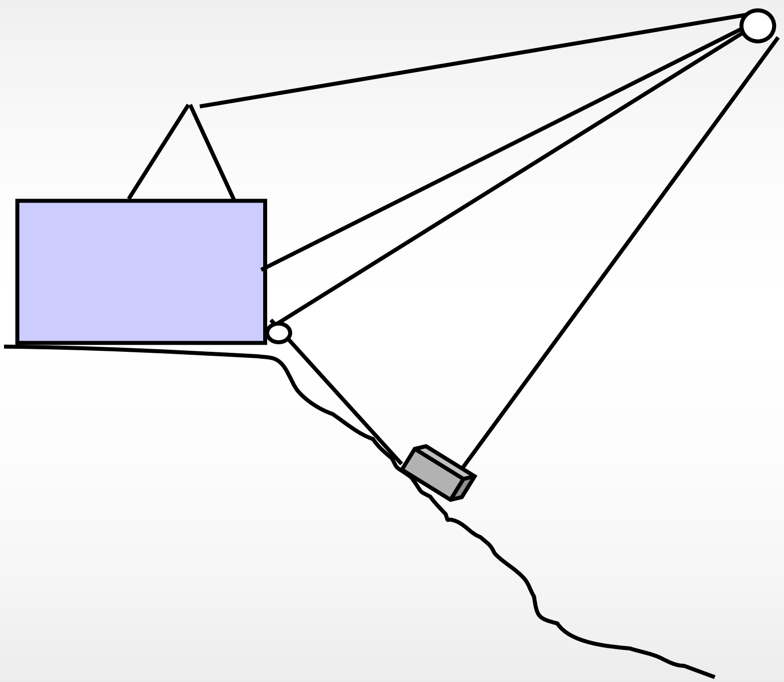


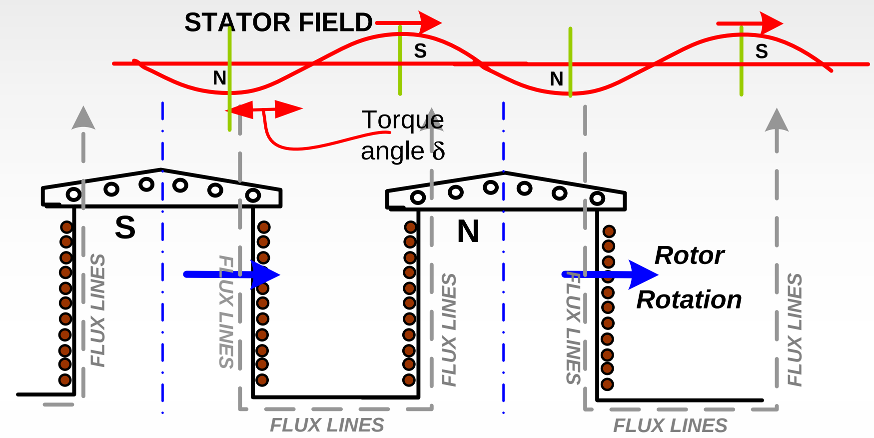
Swing from Motor to Regen Power

Stimulated 2 Hz with Low Damping



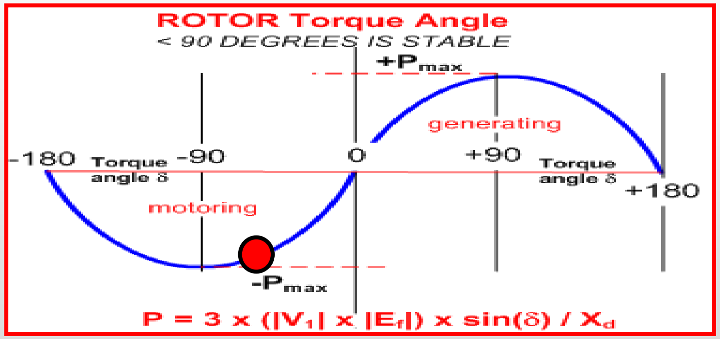
Sync Motors 2 Hz Example





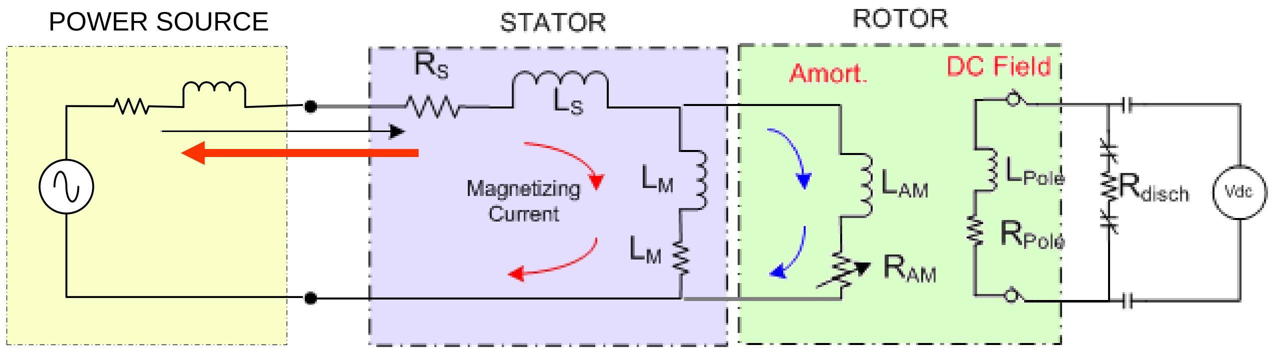
Swing from Motor to Regen Power

Stimulated 2 Hz with Low Damping



2 Hz Rotor Power – Where Can It Go?

One Phase Model



- Disturbance power flows into power system!
- Amortiseur winding provides damping torque.

2 Hz MG Set Resonance Effects

- Sudden load impacts shift sync motor power [torque] angle
- Rotor overshoots, swings back and forth.
- Rotor angle pushes watts and vars in and out of dragline sometimes in huge swings
- Voltage swings can trip off dragline and nearby equipment

Example Traces of 2 Hz Phenomenon

[before regulator modifications]

Large power swings show up at trail cable as measured by PTs

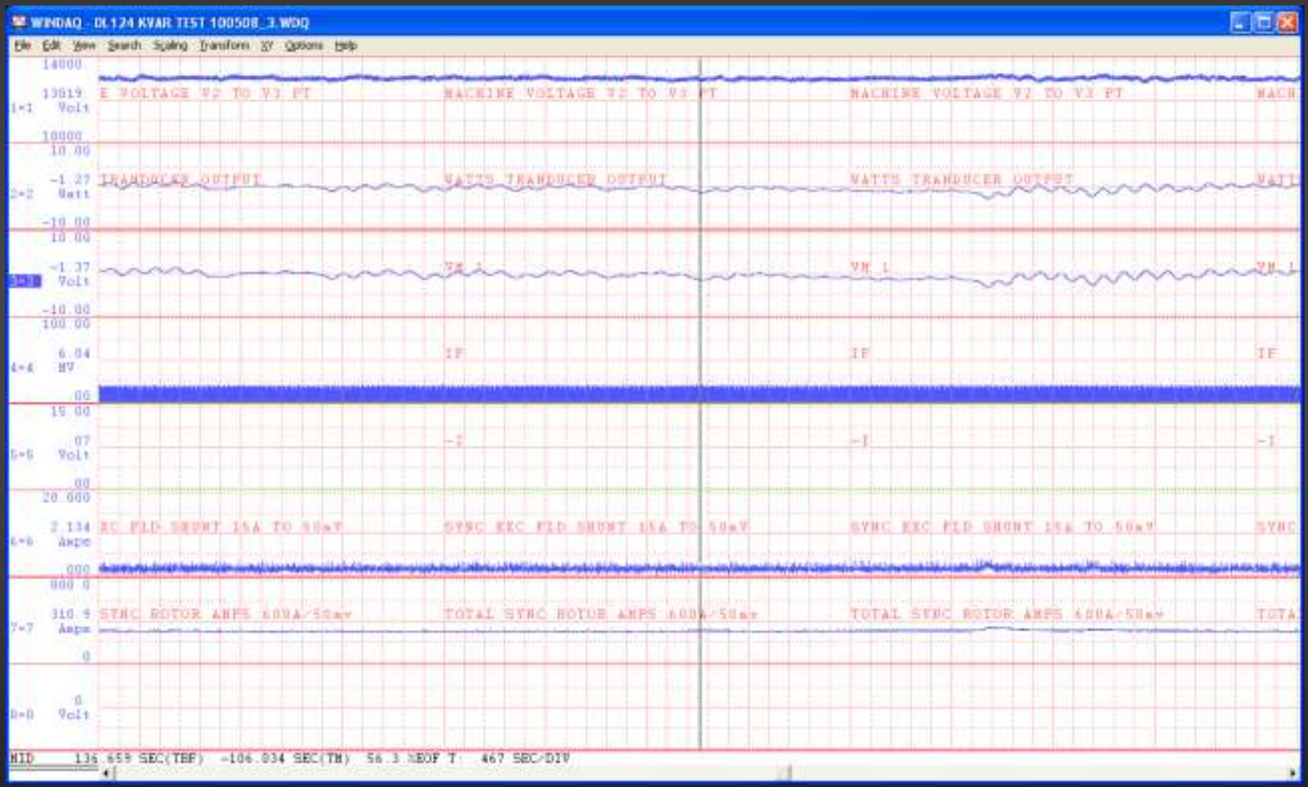
1. Freq = 1/0.467 = 2.14 Hz
2. kW Transducer is not lying! Rotor oscillations are really causing wild power swings

Rotor amps follow kW feedbback with 2 hz

Western Energy Co
Coalstrip, MT DL3124

Example Traces of 2 Hz Phenomenon

[after regulator modifications]



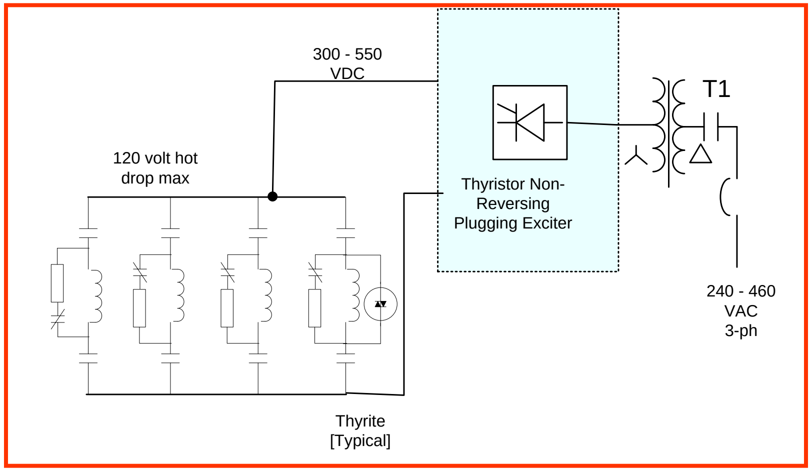
Notes & Experience with 2 Hz Problems

- All sync MG sets have 2-3 Hz resonance!
- Amortiseur windings of low starting current motors [400-450% vs standard 600%] have low damping and prone to worse 2 Hz problems.
- Weak pit feeder gives low damping – worsens 2Hz.
- Using DC kW as field amps reference has shown to be best in 2 Hz performance and voltage stability
- High forcing [ratio of exciter max volts to sync field hot drop] helps.

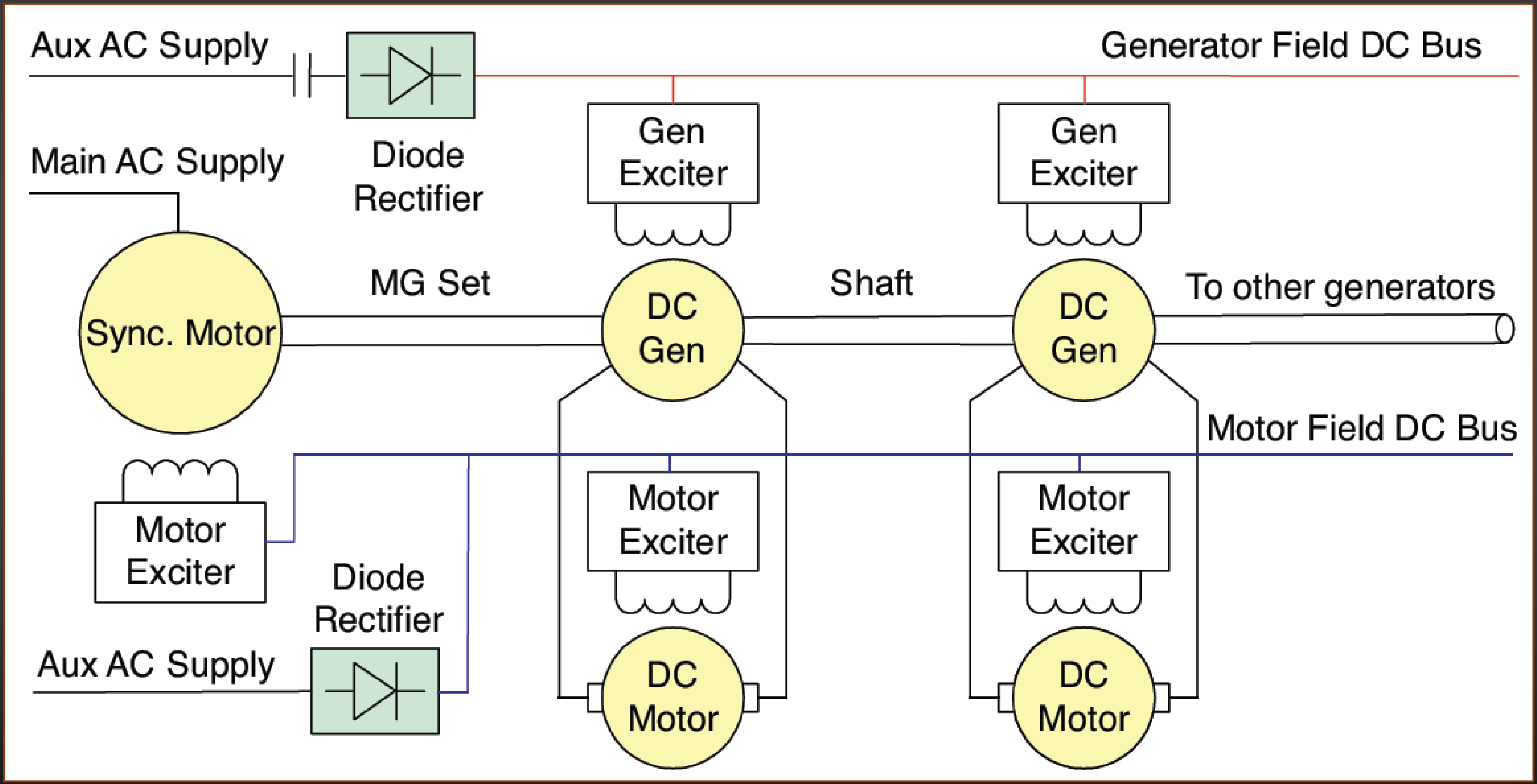
Sync Excitation Control Hardware Evolution

- Rotating Exciters with
  - ✓ Fixed Field - resistor off 120 volt house exciter
  - ✓ Multi-step Contactors & Resistors off 120 volt house exciter
  - ✓ Dedicated 230 volt sync exciter with Saturable Reactor field control
- Solid State op-amp & direct analog thyristor exciter
- Digital thyristor exciter with reactive power control in firmware.
- PLC based field excitation reference control
- IGBT based exciters

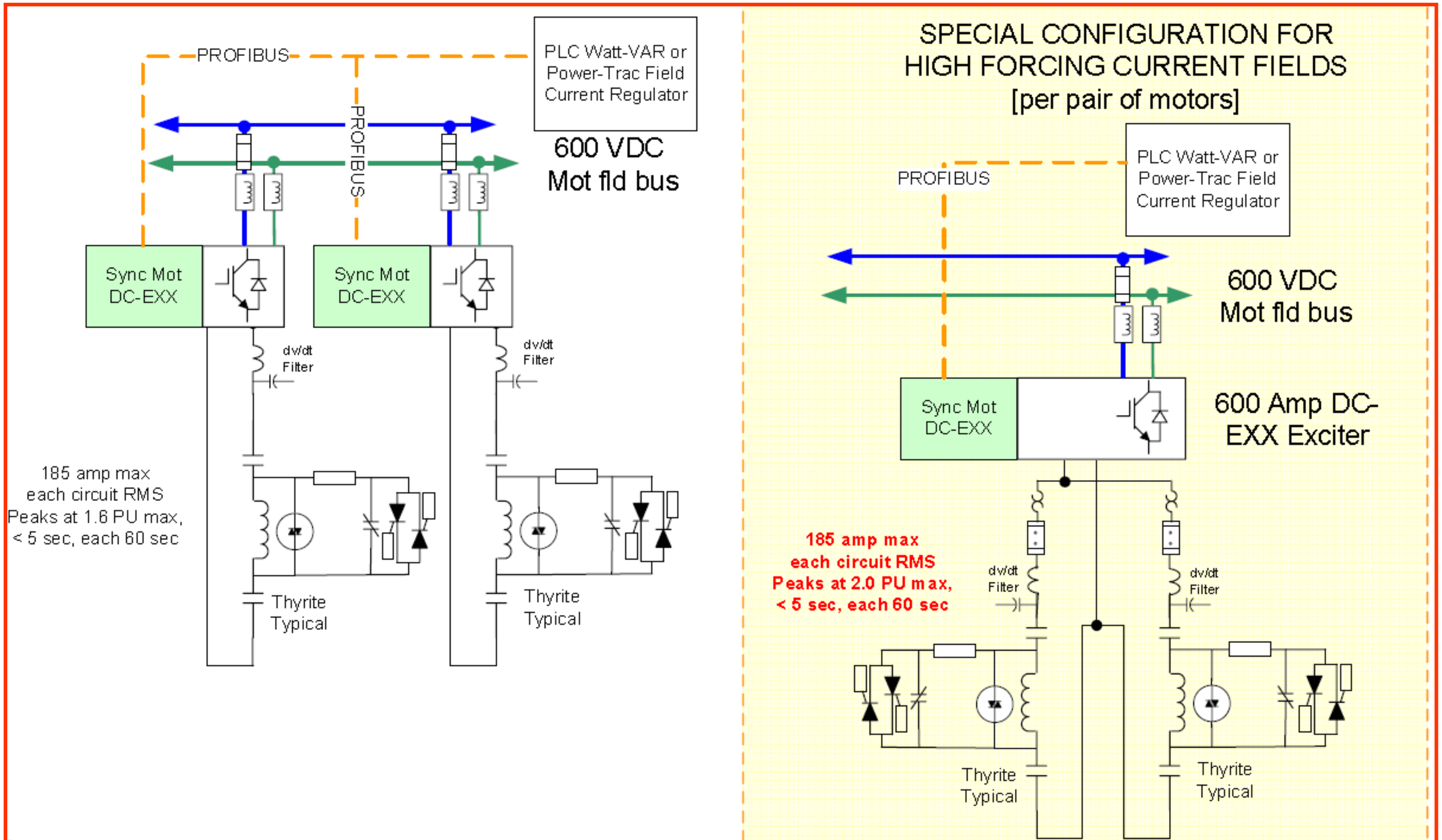
Thyristor Sync Exciter



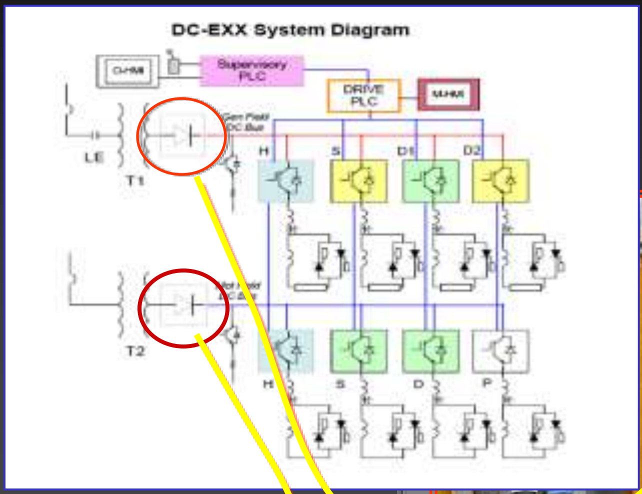
Dragline MG Set DC-EXX IGBT System Block Diagram

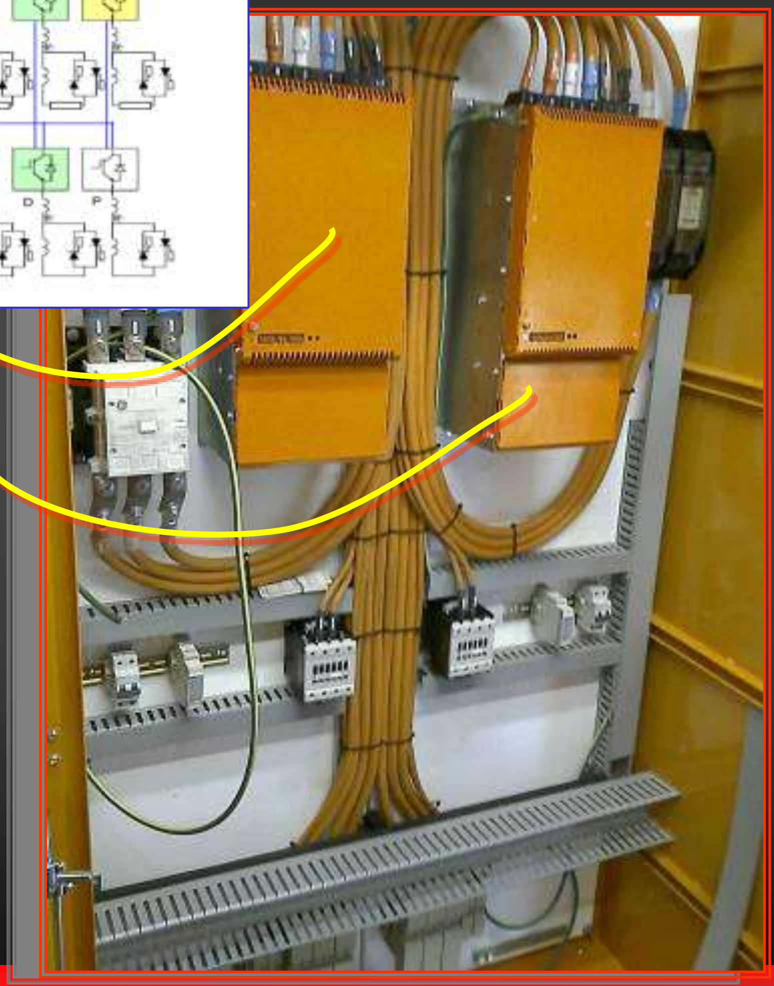


IGBT Based Sync Exciter



Motor & Gen AC / DC Converter





- 435 VAC 3 Phase in 600 VDC out
- 350 amp 6-pulse diode
- 3 thyristor legs for soft on, overcurrent protection.
- Includes energy absorbing chopper
- Feeds two overhead buses at cabinet top

Sync Motor Cabinet

- 300 Amp Exciter [with same control as 150 amp]
- Fed from 600 volt DC source for high forcing
- Traditional three-pole application contactor
- Fed from DC bus above cabinet

Overhead DC Bus

- 600 VDC, two busses
- Independent feed for motor and gen exciters
- Feed for each exciter is dropped by cable into enclosure
- Excess energy absorbed by converter braking chopper.
- Safety Provisions:
  - Disconnects
  - Discharge contactor
  - Voltage presence lights
- Voltage held to 725 volts even when AC feed is lost

Sync Cabinet Details

DC Decoupling Reactors

Isolation Switches

dv/dt Filter Reactors

300 Amp Exciters

Field Application Contactors

Sync Motor Protection

Examples From Recent Systems

Stator overcurrent & over RMS	369 Motor Protector
Out of Step Pull-Out, Push Out	369 Motor Protector – power factor trip
Field Voltage Surges	Discharge resistor, crowbar [IGBT Exciter], Thyrite
Stator voltage surges	Surge Capacitors, Arrestors
Winding & Bearing Over Temp	RTDs into 369 Motor Protector
Field Overcurrent – single and multiple fields per source	Exciter overcurrent Thermal OL relay per field

Thanks!

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