EE 137A MT1 Review

Edison 60 Customers ⇒ Practical DC Motor ⇒ Westinghouse + Tesla int AC ⇒

AC induction Motor - Tesla ⇒ 3 phase First high(ish) voltage power line 2.3kV ⇒ AC lines pipe Hydro @ Niagra 20 miles ⇒

Natural Monopoly + States Step in ⇒ Large Companies control most of generation. ⇒ E utilities Est. vertical Monopolies ⇒

Congress breaks up large utilities. Repealed 2005 ⇒ Rural Electrification Act ⇒ Inflation, increased ff prices. Econ of Scale Exhausted

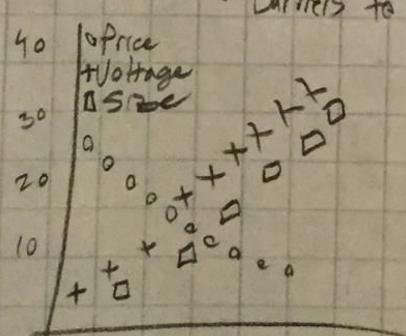
Rates Up

PURPA companies must purchase locally generated power. ⇒ NEPA ⇒ Inc. Competition ⇒

Natural Monopoly

Stems from
- High Cap. costs
- Econ of Scale
- Barriers to M. Entry

} more efficient for large company.



Vertical Monopoly

- Transmission
- Generation
- Distribution
- Customer Service.

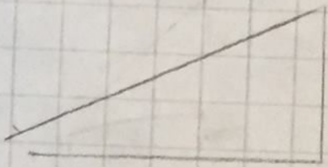
Legacy Grid

- One-way, Radial Power flow
- Redundancy
- Stability through Inertia

Smart Grid

Higher Spatiotemporal Resolution

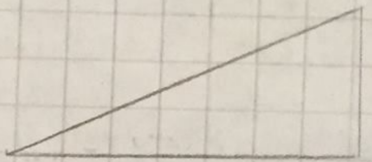
Complex Power



$Z = R + jX$

$R = Z\cos\theta$

$\cos\theta = p.f.$



$S = P + jQ$

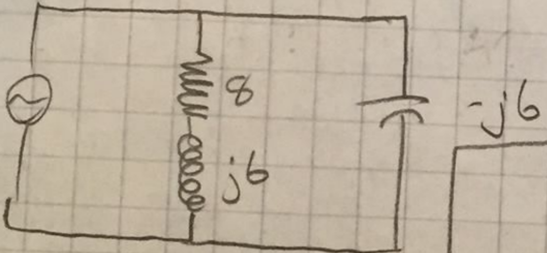
$P = S\cos\theta$

$V = |V|e^{j\theta}$

$\downarrow$

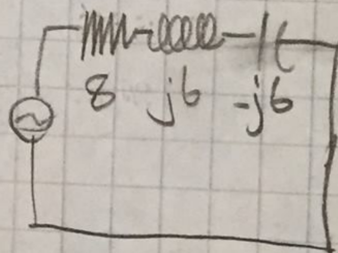
$e^{j\theta} = \cos\theta + j\sin\theta$

Parallel RC circuit



$V = 75\angle 0°$

$V(t) = 75\sqrt{2}\cos\omega t$



Power into Each Branch?

$S_1 = 450W + 337.5VAR$

$S_2 = 0W - 937.5VAR$

$S = S_1 + S_2 = 450W - 600VAR$

$pf_1 = .8$ lagging

$pf_2 = 0$

$pf_{tot} = .6$ leading

Why 50-60 Hz?

Too Low: Noticeable flicker

Too High: Reactive losses

Why 3 phases

- Steady Torque
- 1 wire can be neglected or minimized. Current sums to zero.

Load Types

Resistive: Lamps, Heaters

Inductive: Motors, power tools, Appliances

Capacitive: Arc Welder

Inductor V Capacitor

Inductor	Capacitor
E in Field (B)	· Stores E charge
Likes low Hz (DC)	· Likes high Hz also (AC)
Resists change in I	· Resists changes in V
Current lags Voltage	· AC lags voltage
Inductance L	Farads, C
$X_L = \omega L$	$X_C = \frac{1}{\omega C}$
$E_I = \frac{1}{2} L I^2$	$E_C = \frac{1}{2} C V^2$

Inductance

usually dominates so power factor is usually lagging.

Real Power:

$P_{ave} = I_{RMS} V_{RMS} \cos\theta$

. Reactive

$S_{Ave} = I_{RMS} V_{RMS} \sin\theta$

Complex:

$\underline{S} = \underline{I}^* \underline{V}$

$Z = R + jX$

Impedance = Resistance + Reactance

Admittance = Conductance + Susceptance

$Y = G + jB$

$$Y = \frac{1}{Z}$$

L3

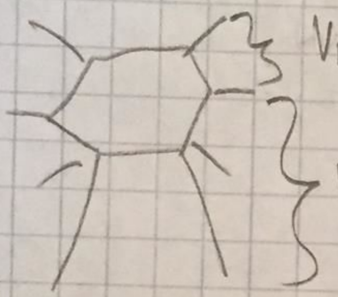
Why is Reactive Power A problem?

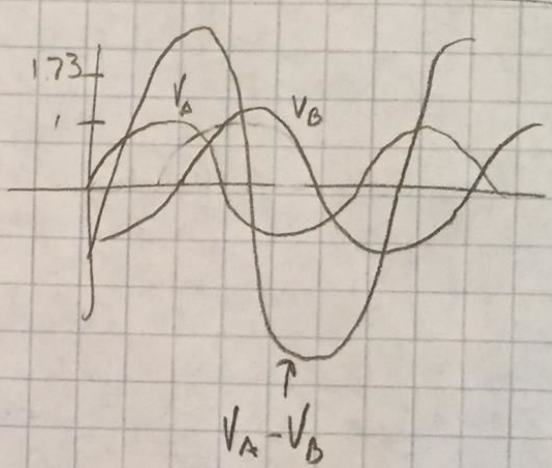
Line Losses associated with Circulating current.

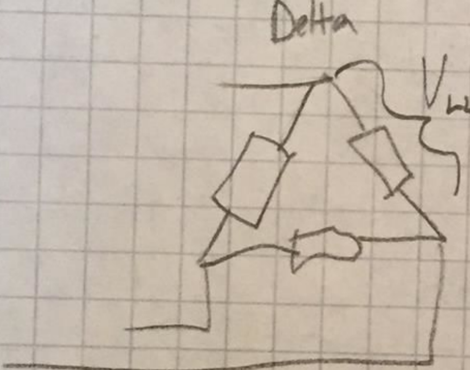
Capacity Limitations dictated ~~total~~ current.

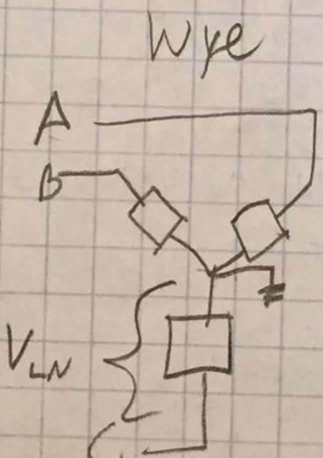
Why shunt and not series capacitors

- fault current
- Bypass switch/protection
- Vulnerability to Resonance









Also phase Angle is Shifted 30°

$V_{ab} = V_{an} - V_{bn} = \sqrt{3}\, V_{an} \angle 30°$

$V_{LL} = \sqrt{3}\, V_{LN}$ (magnitude)

$S_{3\phi} = |S_{3\phi}| = 3 V_{LN} I_L = \sqrt{3}\, V_{LL} I_L$ VA

V_{LL} higher, $\sqrt{3}\, V_{LN}$

Legacy Grid

- one-way, radial power flow
- Redundancy
- Stability through Inertia

Smart Grid

- Increased sensors allow for higher spatio-temporal resolution.

Natural Monopoly

Stems from:
- High Cap. costs
- Econ. of Scale
- Barriers to market Entry

more efficient for 1 large company

Vertical Monopoly

- Transmission
- Distribution
- Generation
- Customer Service

Why 50-60Hz

Too Low: Noticeable Flicker

Too High: Reactive Losses

Why 3 phases

- Steady Torque
- Sum of 3 phase current is zero, so neutral return can be neglected.

Load Types

Resistive: Lamps, Heaters

Inductive: Motors, power tools.

Capacitive: Arc Welders

$Z = R + jX$

Impedance

Resistance

Reactance

$Y = G + jB$

Admittance

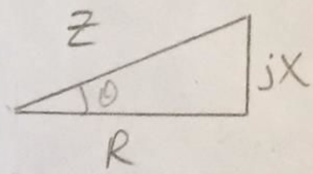
Conductance

Susceptance

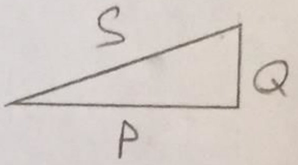
$Y = \frac{1}{Z}$

MT 1 EE 137A

Complex Power



$R = Z\cos\theta$ $\quad\cos\theta = \text{p.f.}$



$P = S\cos\theta$

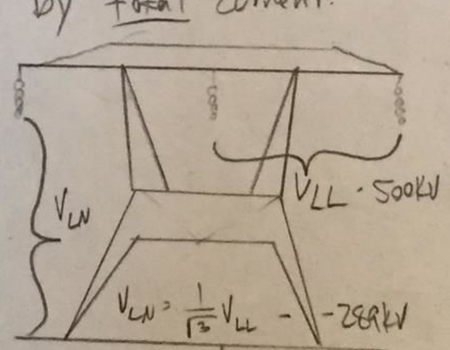
$V = |V|e^{j\theta}$

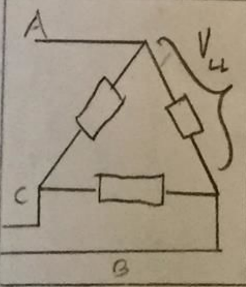
$e^{j\theta} = \cos\theta + j\sin\theta$

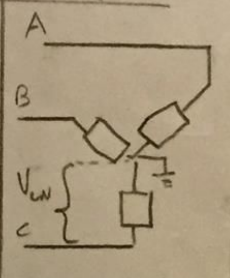
Reactive power is Bad, Why?

Line losses associated w/ circulating current

Capacity limitations dictated by total current.







$V_{ab} = V_{an} - V_{bn} = \sqrt{3}\, V_{an}\angle 30°$

phase angle shifted 30°

$|S_{3\phi}| = 3V_{LN}I_L = \sqrt{3}\,V_{LL}I_L$ VA

Symmetrical Components

Max Morrison

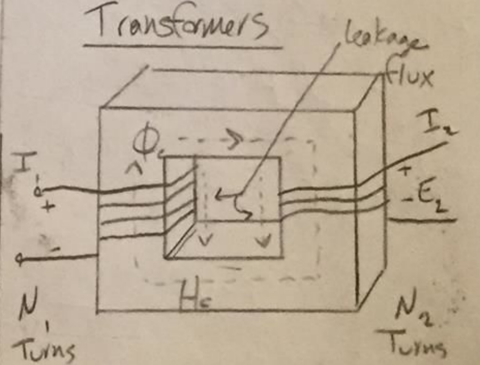
$$V_{ABC} = \begin{bmatrix} V_0 \\ V_0 \\ V_0 \end{bmatrix} + \begin{bmatrix} V_1 \\ \alpha^2 V_1 \\ \alpha V_1 \end{bmatrix} + \begin{bmatrix} V_2 \\ \alpha V_2 \\ \alpha^2 V_2 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$$

nonlinear loads cause current harmonics → cause voltage harmonics

Total p.f. = Displacement p.f. · Distortion p.f.

Transformers



In core: $B_c = \mu_c H_c$

magnetic flux $\phi_c = B_c A_c$

Reluctance $R_c = \frac{\text{path length}}{\mu_c A_c}$ [kinda Resistance]

$N_1 I_1 - N_2 I_2 = R_c \phi_c$

Losses

Copper - coil; I^2R

Iron - Core

Hysteresis

Eddy Currents

Stray Losses

Transmission 1

Resistance depends on
- Specific conductivity
- cross section
- Temperature ~10%
- spiral ~1-2%
- Freq <~1%

$R = \rho \frac{l}{A}$, Area: 1 cmil = $5.067\times10^{-4}\ mm^2$

why bundled conductors?
More surface area → cooling
↳ less corona loss

Greater GMR → less inductance

Line Inductance $L_x = \frac{\lambda_x}{I} = 2\times10^{-7} \ln \frac{D}{r'_x} \left[\frac{H}{m}\right]$ per cond.

D: Distance

Equivalent Radius $r' = e^{-\frac{1}{4}} r = .7788r$

small r' = more inductance b/c flux density
Big D = more inductance b/c less cancellation

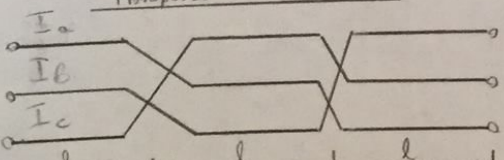
$D_{eq} = \sqrt[3]{D_{12} D_{23} D_{31}}$ = GMD for 3 conductors

r' can also be GMR for conductor Bundle

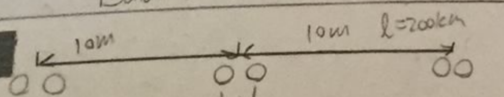
$D_{2\,cond.}: \sqrt[4]{(D_s \times d)^2}$ $D_{3\,cond.}: \sqrt[3]{(D_s \times d \times d)^3}$

$D_{4\,cond}: \sqrt[16]{(D_s \times d \times d \times \sqrt{2}d}$

Transposed Conductors



Balances Inductance



From table:
GMR = .0114 → $D_{sL} = \sqrt{(.0114)(.40)} = .0676$ for bundle

$D_{eq} = \sqrt[3]{(10)(10)(20)}$

$L_a = 2\times10^{-7} \ln\left(\frac{12.6}{.0676}\right)(200{,}000m) =$ .209H

$X_a = 2\pi f L_1 = 78.8\Omega$

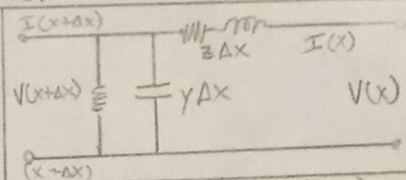
Capacitance

$C_{xy} = \frac{\pi\varepsilon}{\ln\left(\frac{D}{r}\right)}$

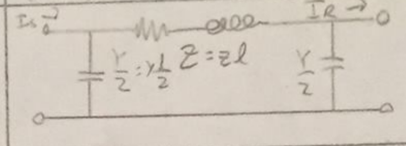
EE 137A Final Cheat Sheet

T Line:

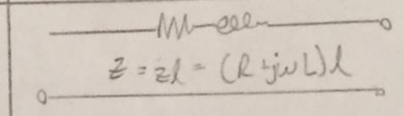
Long

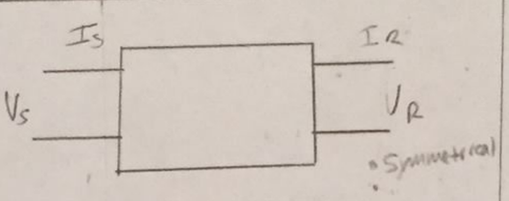


Medium "nominal π"



Short

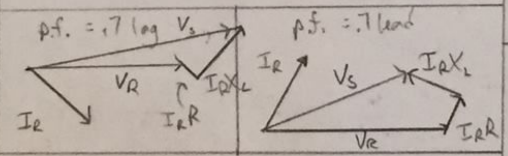




• Symmetrical

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

P	A = D	B	C
Units	P.U.	Ω	S
Short	1	Z	0
Med	$1 + \frac{YZ}{2}$	Z	$Y\left(1+\frac{YZ}{4}\right)$
Long	$\cosh(\gamma l) = 1 + \frac{Y'Z'}{2}$	$Z_c \sinh(\gamma l) = Z'$	$\frac{1}{Z_c}\sinh(\gamma l) = Y'\left(1+\frac{YZ}{4}\right)$
Lossless	$\cos(\beta l)$,	$jZ_c \sin(\beta l)$	$j\frac{\sin(\beta l)}{Z_c}$



Long Line Voltage Eq'n

$V(x) = k_1 e^{\gamma x} + k_2 e^{-\gamma x}$

$V_x = (k_1 + k_2)\left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) + (k_1 - k_2)\left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right)$

$V_x = K_1(\cosh(\gamma x)) + k_2 \sinh(\gamma x)$

Gamma γ. $\gamma = \sqrt{zy} = \alpha + j\beta$ — α: attenuation, β: phase

Power Transfer

$P_R = \frac{|V_s||V_R|}{|B|}\cos(\beta - \delta) - \frac{|A||V_R|^2}{|B|}\cos(\beta - \delta)$

angles of A, B

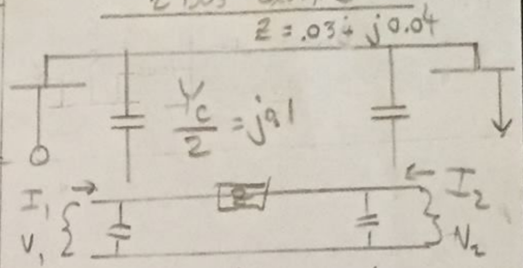
$Q_R = \frac{|V_s||V_R|}{|B|}\sin(\alpha - \delta) - \frac{|A||V_R|^2}{|B|}\sin(\alpha - \delta)$

T-Line Loading Limits:
Thermal - Expansion → Sag (short)
Angle - max P @ $\delta_1 - \delta_2 = 90°$, Practice ($\delta < 35°$) (long lines)
Voltage - can be addressed w/ reactive comp. (increase w/ l^2)

Power Flow

- P, Q given. Find |V|, θ
- Steady state tool, nonlinear
- Admittance matrix, (ie not Resistance)
  - ↳ off diag. branches × (-1)

2 Bus Example



$I_1 = \frac{(V_1 - V_2)}{Z} + V_1\frac{Y_c}{2} = \frac{1}{.03 + j.04} = 12 - j16$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 12 - j15.9 & -12 + j16 \\ -12 + j16 & 12 - j15.9 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

Power:
$S_1 = V_1 I_1^*$
$S_2 = V_2 I_2^*$

plug in V_1, get I

Usual knowns: Load Bus: P, Q
Gen Bus: P, V
Slack Bus; Unknown: P, Q

* Power Balance Eqn *

$S_i = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^*$ $\langle e^{j\theta} = \cos\theta + j\sin\theta \rangle$

$S_i = \sum_{k=1}^{n} |V_i||V_k| e^{j\theta_{ik}} (G_{ik} - jB_{ik})$

$P_i = \sum_{k=1}^{n} |V_i||V_k| (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})$

$Q_i = \sum_{k=1}^{n} |V_i||V_k| (G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik})$

P depends on Voltage Angle b/c $\sin(0^+) = 0^+$ and G is small (R is large)
Q depends on Voltage Magnitude b/c and $\cos(\sim90°) \approx 1$

Decoupled Power Flow.

$\frac{\partial P}{\partial \delta}, \cancel{\frac{\partial P}{\partial V}}, \cancel{\frac{\partial Q}{\partial \delta}}, \frac{\partial Q}{\partial \theta}$

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}$$

Dishonest N-R - don't update J
Fast Decoupled - Simple J, no updates
"DC" - no reactive power, V = p.u.
Gauss Seidel - Gauss Elimination. Small numerous iterations.

Generators

60sec/min   2 poles mag.

$$n = \frac{120 f}{P}$$

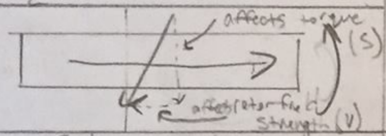
mech, elec

Increase P_{gen}: More fuel → angle pulls ahead until $\tau_{mag} = \tau_{prime\ mover}$ → more power

How to?

Q changes → θ_{stator} changes w.r.t. θ_{stator}. Field changes str. Voltage changes

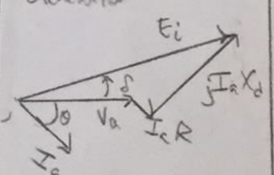
When serving { inductive [lag] → increase excitation
capacitive [lead] → decrease



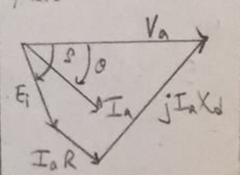
Induction Machines

- Slip causes torque through induced AC currents in rotor.
- Can't start w/o External AC power.
- Rotor lags stator, consumes reactive power

Generator



Motor



$E_i = V_a + I_aR + jI_aX_d$ $V_a = E_i + I_aR + jI_aX_d$

overexcited - supplying Q

under - absorbing Q

Power To Phase A

$$S = V_t I_a^*$$

$$I_a = \frac{|E_i|\angle\delta - |V_t|}{jX_d} \quad I_a^* = \frac{|E_i|\angle -\delta - |V_t|}{-jX_d}$$

$$S = P + jQ = V_t I_a^* = \frac{|V_t||E_i|\angle -\delta - |V_t|^2}{-jX_d} = \frac{|V_t||E_i|(\cos\delta - j\sin\delta) - |V_t|^2}{-jX_d}$$

$$P = \frac{|V_t||E_i|}{X_d}\sin\delta \quad Q = \frac{|V_t|}{X_d}(|E_i|\cos\delta - |V_t|)$$

Stability

Steady State
- δ_{12} w/in limits?
- Voltages close to nominal?
- What happens w/ displacement

Transient
- Return to Eq. after contingency.

Dynamic
- Response to continuous Disturb.

Gen. Mech. Model $\boxed{\delta \text{ (in rad)}}$

$$P_m - P_e(\delta) = J\alpha_m\omega_s = J\omega_s\ddot{\delta}$$

$$\frac{P_m - P_e(\delta)}{S_B} = \frac{J\omega_s^2}{2S_B}\frac{1}{\pi f_s}\ddot{\delta}$$

Define $H = \frac{J\omega_s^2}{2S_B}$ (sec or $\frac{MJ}{MVA}$)

$$P_m - P_e(\delta) = \frac{H}{\pi f_s}\ddot{\delta}, \quad M = \frac{H}{\pi f_s}$$

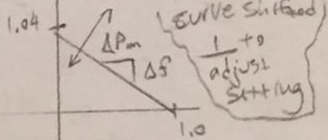
$$P_m - P_e(\delta) = M\ddot{\delta}$$

Damping

Swing Eqn.

$$P_m - P_e(\delta) = M\ddot{\delta} + D\dot{\delta}$$

Droop Curve



$$\text{Slope} = -R = \frac{\Delta f}{\Delta P_m} = -0.04 \text{ p.u.}$$

Droop Setting

Area freq. Response characteristic $\beta = \frac{1}{R_1} + \dots + \frac{1}{R_n}$

Droop curves stabilize grid freq., but do not return it to nominal 60Hz.

AGC { Load Freq. Control [Droop]
Economic Dispatch.

$$ACE = \Delta P_{tie} + B_f \Delta f.$$

should be zero; Freq Bias Const may be = β but not always.

Economic Dispatch

$$C_i(P_{Gi}) = \alpha_i + \beta P_{Gi} + \gamma P_{Gi}^2 \ [\tfrac{\$}{hr}]$$

$$IC_i(P_{Gi}) = \frac{dC_i(P_{Gi})}{dP_{Gi}} = \beta + 2\gamma P_{Gi} \ [\tfrac{\$}{MWh}]$$

Minimize $G = \sum_{i=1}^{m} C_i(P_{Gi})$ such that $\sum_{i=1}^{m} P_{Gi} = P_D + P_{losses}$

Econ. Disp Lagrange

$$P_D = P_{G1} + P_{G2} = 500MW$$

$$C_1(P_{G1}) = 1000 + 20P_{G1} + .01P_{G1}^2$$

$$C_2(P_{G2}) = 400 + 15P_{G2} + .03P_{G2}^2$$

$$\frac{dC_1(P_{G1})}{dP_{G1}} - \lambda = 20 + .02P_{G1} - \lambda = 0$$

$$\frac{dC_2(P_{G2})}{dP_{G2}} - \lambda = 15 + .06P_{G2} - \lambda = 0$$

$$500 - P_{G1} - P_{G2} = 0$$

$$\begin{bmatrix} .02 & 0 & -1 \\ 0 & .06 & -1 \\ -1 & -1 & 0 \end{bmatrix}\begin{bmatrix} P_{G1} \\ P_{G2} \\ \lambda \end{bmatrix} = \begin{bmatrix} -20 \\ -15 \\ -500 \end{bmatrix}$$

$$\begin{bmatrix} P_{G1} \\ P_{G2} \\ \lambda \end{bmatrix} = \begin{bmatrix} 312.5\,MW \\ 187.5\,MW \\ 26.2\,\$/MW \end{bmatrix}$$

Penalty factors

$$L_i = \left(\frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}}\right)$$

losses; gen (approx w/ small Δ)

Econ. Dispatch

- Does not turn on/off. [unit commitment]
- Ignores T system Limit.

OPF - Optimal Power Flow takes into account Transmission sys θ.
- Gen Voltage setpoints
- Real and Reactive Power
  - Generator Limits
  - Conservation of Energy.

Controls
- Gen MW outputs
- Transformer taps + Phase θ

Locational Marginal Price

- Sys. marginal cost (λ) same all over, unless congestion
- w/ congestion price varies along network, LMP = nodal price.

Ancillary Services

- f regulation
- Supplemental Reserve
- Spinning Reserve
- Replacement Reserve
- Voltage cont.

Grid Quality

Stability - return to equilibrium

Security - (n-1) sudden loss.

Reliability - Actual interruption.

Resiliency -

IROL - Contingencies outside area.

$$\frac{V_2}{V_1} = \frac{n_2}{n_1}$$

Energy Conserved $\Rightarrow P_1 = P_2$

$$I_2 V_2 = I_1 V_1$$

Transformer - 20kVA
- 480/120V
- 60Hz

Leakage Impedance $Z_{eq2} = .0525\angle 78 \boxed{\Omega}$
@ winding 2

$S_b = 20kVA \quad V_{b1} = 480V \quad V_{b2} = 120V$

$$Z_{base2} = \frac{V_{b2}^2}{S_{base}} = \frac{120^2}{20{,}000} = .72\Omega$$

$$Z_{eq2pu} = \frac{Z_{eq2}}{Z_{base2}} = \frac{.0525\angle 78.13}{.72}$$

$$= .0729\angle 78.13pu.$$

$$Z_{eq1} = a_t^2 Z_{eq2} = \left(\frac{480}{120}\right)^2(.0525\angle 78.13)$$

$$= .84\angle 78.13\Omega$$

$$Z_{base1} = \frac{V_{base1}^2}{S_{base}} = \frac{480^2}{20{,}000} = 11.52\Omega$$

$$Z_{eq1pu} = \frac{Z_{eq1}}{Z_{base1}} = \frac{.84\angle 78.13}{11.52}$$

$$= .0729\angle 78pu$$

Z_{eq2pu}

Transformer Simplification