EE 6303: ELECTRIC MACHINES II

ASSIGNMENT 02

NAME :

REG No. : EG/ 2019/

SEMESTER: 06

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1. A 5.6 kV (line), Y connected cylindrical rotor synchronous generator is rated at 2 MVA, 0.5 power factor. The synchronous reactance of the machine is 4.321 Ω/phase. The generator is connected to a turbine capable of providing 1.9 MW of active power. The maximum value of the armature-induced voltage per phase is 3.9 kV.

   a) Draw the capability curve for this generator and indicate the operating region of the machine

Given Data,

Line to Line Voltage = 5.6 kV

Rated Apparent Power (S_{rated}) = 2 MVA

Power Factor = 0.5

Synchronous Reactance (X_s) = 4.321 Ω/phase

Active Power Output = 1.9 MW

Induced Voltage, (E_a) = 3.9 kV

Since this is star connected, the per phase voltage (V_Φ)

$$V_\Phi = \frac{V_{line}}{\sqrt{3}}$$

$$= \frac{5.6 \times 10^3}{\sqrt{3}}$$

$$V_\Phi = 3.233 \text{ kV}$$

Origin for field current circle,

$$-\frac{3V_\Phi^2}{X_s} = -\frac{3\times(3.233\times10^3)^2}{4.321}$$

$$= -7.257 \text{ MVAR}$$

Calculate Excitation limits ,

$$\frac{3V_\Phi E_{A,x}}{X_s} = \frac{3\times3.233\times10^3\times3.9\times10^3}{4.321}$$

Power factor angle, θ

$$= 8.754 \text{ kVAR}$$

$$\cos\theta = 0.5$$

$$\theta = \cos^{-1} 0.5\ \theta$$

$$= 60^\circ$$

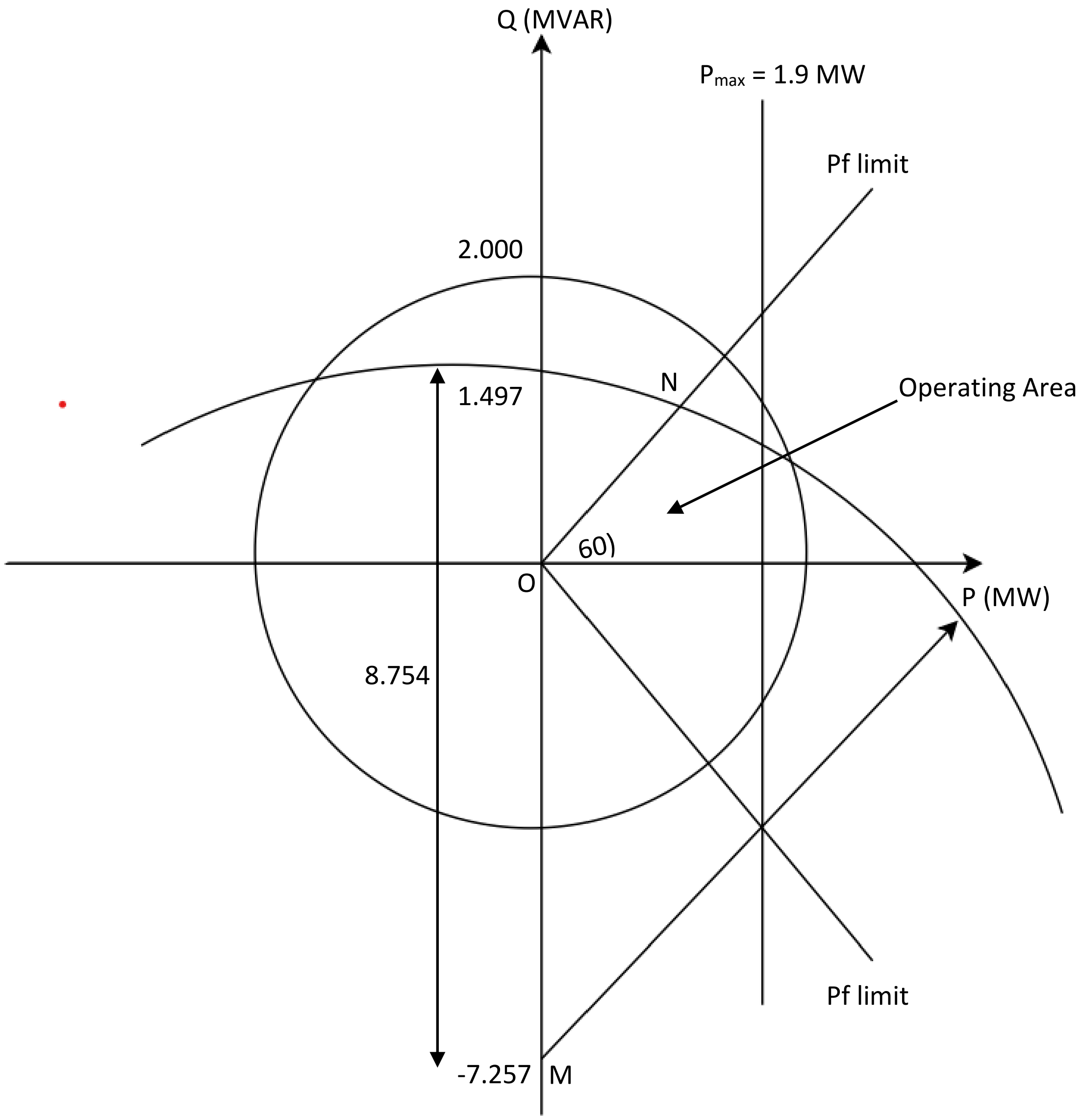


Figure 1: Capability Curve

b) Calculate the maximum amount of reactive power this machine can supply.

From cosine theory,

$$MN^2 = OM^2 + ON^2 - 2(OM)(ON)\,\text{Cos}\,(90 + 60)^\circ$$

$$8.754^2 = 7.257^2 + x^2 - 2(7.257)(x)\,\text{Cos}(150)^\circ$$

$$x^2 + 12.569x - 23.968 = 0$$

Solving the above equation,

$$x = 1.682$$

$$x = -14.251 \text{ (This is wrong)}$$

Therefore, ON = 1.682

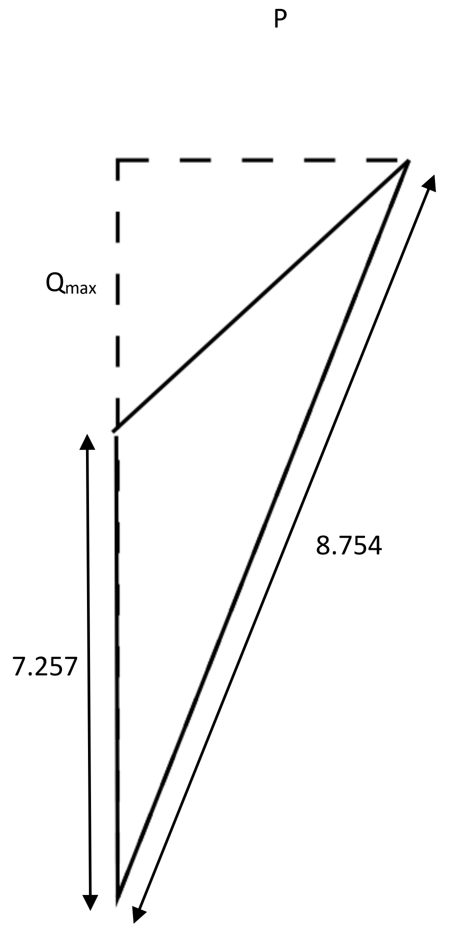
Therefore, the maximum reactive power can supply is,

$$Q_{max} = ON \sin 60^\circ$$

$$= 1.682 \times \sin 60^\circ$$

$$\underline{\underline{Q_{max} = 1.456 \text{ MVAR}}}$$

c) Calculate the maximum amount of reactive power this generator can supply when it is supplying the following active powers; 1.3 MW, 1.5 MW, 1.9 MW



According to the above figure,

$$8.754^2 = (7.257 + Q_{max})^2 + P^2$$

$$Q_{max} = \sqrt{8.7542 - P^2} - 7.257$$

When P = 1.3 MW

$$Q_{max} = \sqrt{8.754^2 - 1.3^2} - 7.257$$

$$\underline{\underline{Q_{max} = 1.400 \text{ MW}}}$$

When P = 1.5 MW

$$Q_{max} = \sqrt{8.754^2 - 1.5^2} - 7.257$$

$$\underline{\underline{Q_{max} = 1.368 \text{ MW}}}$$

When P = 1.9 MW

$$Q_{max} = \sqrt{8.754^2 - 1.9^2} - 7.257$$

$$\underline{\underline{Q_{max} = 1.288 \text{ MW}}}$$

d) Determine if this generator can deliver 155 A at a lagging power factor of 0.6.

When I = 155A and PF = 0.6

$$P = 3\ V_{\Phi} I cos\theta$$

$$= 3 \times 3.233 \times 10^3 \times 155 \times 0.6$$

$$P = 0.902 \text{ MW}$$

$$Q = 3\ V_{\Phi} I sin\theta$$

$$= 3 \times 3.233 \times 10^3 \times 155 \times s(\cos^{-1} 0.5)$$

$$Q = 1.302 \text{ MVAR}$$

Therefore,

$$P_{max} > P$$

$$Q_{max} > Q$$

Therefore, this can be supply by the generator.

2. Two generators are supplying a load of 13.5 MW at a lagging power factor of 0.8, as illustrated in the figure below. The system operates at a frequency of 50 Hz with a bus voltage of 32 kV.

Given Data,

$$P_L = 13.5\ MW$$
$$PF = 0.8\ lagging$$
$$f_{sys} = 50\ Hz$$
$$V_{sys} = 32\ kV$$

$$S_{P1} = 11.6$$
$$S_{P2} = 15$$
$$S_{V1} = 4$$
$$S_{V2} = 5.5$$

a) when no-load frequencies and no-load voltages are identical on both generator's

$$f_{nl,1} = f_{nl,2}$$
$$V_{nl,1} = V_{nl,2} \qquad \text{——— (01)}$$

Real powers supplied by generators,

$$P_1 = S_{P1}(f_{nl,1} - f_{sys}) \qquad \text{——— (02)}$$
$$P_2 = S_{P2}(f_{nl,2} - f_{sys}) \qquad \text{——— (03)}$$

From (01),

$$P_2 = S_{P2}(f_{nl,1} - f_{sys}) \qquad \text{——— (03)'}$$

From (02) & (03)',

$$\frac{P_1}{P_2} = \frac{S_{P1}}{S_{P2}}$$
$$\frac{P_1}{P_2} = \frac{11.6}{15} \qquad \text{——— (04)}$$

Considering the load,

$$P_L = P_1 + P_2$$
$$13.5 = P_1 + P_2 \qquad \text{——— (05)}$$

From (4),(5),

$$P_1 = 5.887\ MW$$
$$P_2 = 7.613\ MW$$

Considering real and reactive power of the load,

$$P = S\cos\theta$$
$$Q = S\sin\theta$$

Where,

$$cos\theta = 0.8$$

Therefore,

$$Q_L = P_L tan\theta \qquad \text{——— (A)}$$
$$Q_L = 13.5tan(36.87)$$
$$Q_L = 10.125\ MVAR$$

Considering Reactive powers of generators,

$$Q_1 = S_{V1}\left(V_{nl,1} - V_{sys}\right) \qquad \text{——— (06)}$$
$$Q_2 = S_{V2}\left(V_{nl,2} - V_{sys}\right) \qquad \text{——— (07)}$$

From (01),

$$Q_2 = S_{V2}\left(V_{nl,1} - V_{sys}\right) \qquad \text{——— (07)'}$$

From (06) & (07)',

$$\frac{Q_1}{Q_2} = \frac{S_{V1}}{S_{V2}}$$
$$\frac{Q_1}{Q_2} = \frac{4}{5.5} \qquad \text{——— (08)}$$

Also,

$$Q_L = Q_1 + Q_2$$
$$10.125 = Q_1 + Q_2 \qquad \text{——— (09)}$$

From (08) & (09),

$$Q_1 = 4.263\ MVAR$$
$$Q_2 = 5.862\ MVAR$$

Therefore Load Sharing,

$$P_1 = 5.887\ MW$$
$$P_2 = 7.613\ MW$$

$$\underline{\underline{Q_1 = 4.263\ MVAR}}$$

$$\underline{\underline{Q_2 = 5.862\ MVAR}}$$

b) Suddenly, the load changes to 18.6 MW at a lagging power factor of 0.92. Calculate the new system frequency and bus voltage after the load change.

Now,

$$P_L = 18.6\ MW$$
$$PF = 0.92\ lagging$$

$$P_L = P_1 + P_2$$
$$P_L = S_{P1}(f_{nl,1} - f_{sys}) + S_{P2}(f_{nl,2} - f_{sys}) \qquad (10)$$

Calculating no load frequencies and voltage values,

From (02),

$$5.887 = 11.6(f_{nl,1} - 50)$$
$$f_{nl,1} = 50.508\ Hz$$

From (06),

$$4.263 = 4(V_{nl,1} - 32)$$
$$V_{nl,1} = 33.066\ kV$$

Therefore from (10),

$$P_L = 11.6(50.508 - f_{sys}) + 15(50.508 - f_{sys})$$
$$f_{sys} = 49.809\ Hz$$

so new system frequency is 49.809 Hz.

To find new reactive power, from (A)

$$Q_L = P_L tan\theta$$
$$Q_L = 18.6\tan(\cos^{-1} 0.92)$$
$$Q_L = 7.924\ MVAR$$

But,

$$Q_L = Q_1 + Q_2$$
$$Q_L = S_{V1}(V_{nl,1} - V_{sys}) + S_{V2}(V_{nl,2} - V_{sys})$$
$$7.924 = 4(33.066 - V_{sys}) + 5.5(33.066 - V_{sys})$$
$$V_{sys} = 32.232\ kV$$

So bus voltage after the load change is 32.232 kV.

c) It is necessary to maintain the system frequency at 50 Hz. Explain how the system frequency can be restored to 50 Hz. Calculate the necessary adjustments to the relevant set points.

Now the system frequency is decreased from 50Hz to 49.81Hz as the load is increased up to

18.6 MW. Therefore, to restore the system frequency to 50Hz, the governor no load set point should be increased.

The frequency should be increased from $= (50 - 49.81)$ Hz

$= 0.19$ Hz

d) The voltage of the buses should be maintained at 32±5% kV. Is the bus voltage within the acceptable limits after the load change? If not, explain how the system voltage can be brought back within the accepted range.

The acceptable lower limits $= (32 - 32 \times 0.05)$ kV

$= 30.400$ kV

The acceptable lower limits $= (32 + 32 \times 0.05)$ kV

$= 33.600$ kV

The bus voltage after increasing the load is 32.234 kV

$$30.400 < 32.234 < 33.600$$

The bus voltage is within the accepted limits.

3. A 3-phase, Y-connected salient pole synchronous generator with a line-line voltage of 2.0 kV supplies a load of 2 MVA at a 0.9 power factor lagging. The synchronous reactance of the machine are $X_{sd} = 1.4\ \Omega$ and $X_{sq} = 0.8\ \Omega$, while the armature resistance is $0.02\ \Omega$.
   Given data,

Let,

$$V_{LL} = 2\ kV$$
$$S_L = 2\ MVA$$
$$PF = 0.9\ lagging$$
$$X_{sd} = 1.4$$
$$X_{sq} = 0.8$$
$$R_a = 0.02$$

a) Draw the phasor diagram and calculate the load angle.

Let I_a is the armature current,

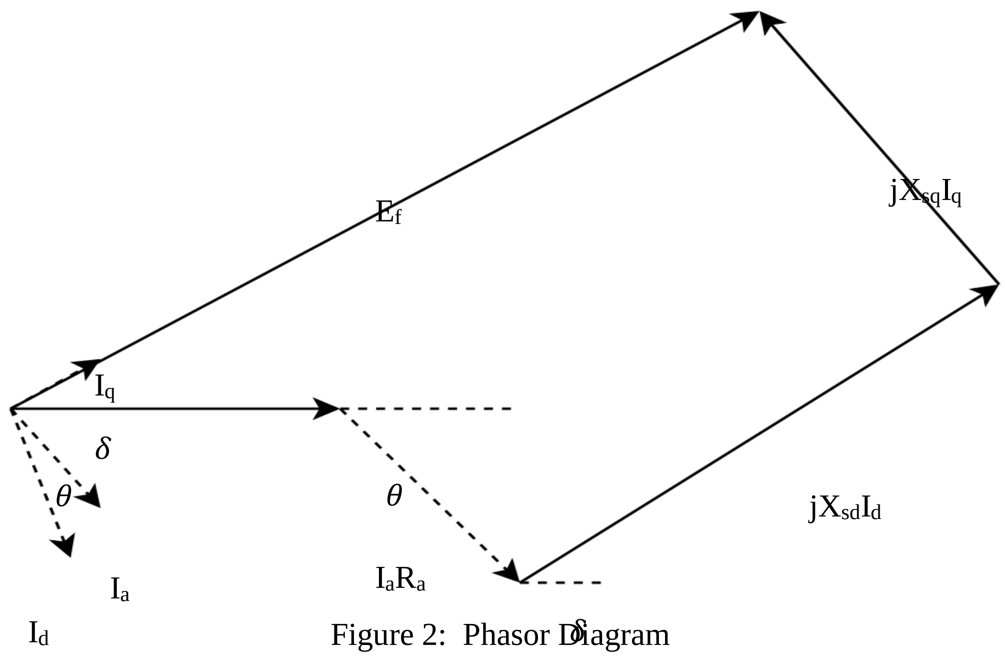


Figure 2: Phasor Diagram

$$V_\phi = \frac{2\ kV}{\sqrt{3}} \qquad \text{——— (01)}$$
$$V_\phi = 1154.7\ V$$

$$S = 3V_{\phi}I_a$$

$$I_a = \frac{S}{3V_{\phi}}$$

$$I_a = \frac{2 \times 10^6}{3 \ \times 1.155 \times 10^3}$$

$$I_a = 577.2 \ A$$

$$\cos\theta = 0.9$$
$$\theta = 25.842$$

Load angle,

$$\tan\delta = \frac{I_a X_{sq}\cos\theta - I_a R_a \sin\theta}{V_{\phi} + I_a X_{sq}\sin\theta + I_a R_a\cos\theta}$$

$$\tan\delta = \frac{577.35 \times 0.8 \times 0.9 - 577.35 \times 0.02 \times Sin(25.842)}{1154.7 + 577.35 \times 0.8 \times Sin(25.842) + 577.35 \times 0.02 \times 0.9}$$

$$\tan\delta = 0.3004$$

$$\underline{\underline{\delta = 16.720}}$$

b) Calculate the direct-axis and quadrature-axis components of the load current.

From the phasor diagram,

Direct-axis current, $I_d = I_a \sin(\delta + \theta)$

$I_d = 577.2 \times \sin(16.720 + 25.842)$

$\underline{\underline{I_d = 390.411 \text{ A}}}$

Quadrature-axis current, $I_q = I_a \cos(\delta + \theta)$

$I_q = 577.2 \times \cos(16.720 + 25.842)$

$\underline{\underline{I_q = 425.134 \text{ A}}}$

c) Calculate the no-load voltage of the generator. When consider the effect of armature resistance,

No load voltage, $E_f = V\cos\delta + I_a R_a \cos(\delta + \theta) + I_d X_{sd}$

$= (1.155 \times 10^3 \times \cos 16.720^\circ) + \{577.2 \times 0.02 \times \cos(16.720 + 25.842)^\circ\} + (390.411 \times 1.4)$

$\underline{\underline{E_f = 1.661 \text{ kV}}}$

d) Neglect the armature resistance and calculate the power due to field excitation and the power due to saliency when this machine supplies the above load.

Power output of the Generator can be written as shown in below.

$$P_{out} = \frac{3VE_f Sin\ \delta}{X_{sd}} + \frac{3V^2(X_{sd} - X_{sq})Sin\ 2\delta}{2\ X_{sd}X_{sq}}$$

$$P_{out} = P_{excitation} + P_{saliency}$$

Where,

$$P_{excitation} = \frac{3VE_f Sin\ \delta}{X_{sd}} \quad \text{———————} \quad (01)$$

$$P_{excitation} = \frac{3V^2\ (X_{sd} - X_{SQ})Sin\ \delta}{2\ X_{sd}\ X_{sq}} \quad \text{————} \quad (02)$$

From the equation (01), the power due to field excitation is,

$$P_{excitation} = \frac{3 \times 1.155 \times 10^3\ \times 1.661\ \times\ 10^3\ Sin\ 16.720}{1.4}$$

$$\underline{\underline{P_{excitation} = 1.183\ MW}}$$

From the equation (02), the power due to saliency is,

$$P_{excitation} = \frac{3 \times (1.155 \times 10^3)^2\ \times (1.4 - 0.8\ ) \times Sin\ 2 \times 16.720}{2 \times 1.4 \times 0.8}$$

$$\underline{\underline{P_{excitation} = 0.591\ MW}}$$