Synchronous Generators Suggested Problems

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4-2. A 13.8-kV, 50-MVA, 0.9-power-factor-lagging, 60-Hz, four-pole Y-connected synchronous generator has a synchronous reactance of 2.5 Ω and an armature resistance of 0.2 Ω. At 60 Hz, its friction and windage losses are 1 MW, and its core losses are 1.5 MW. The field circuit has a dc voltage of 120 V, and the maximum I_F is 10 A. The current of the field circuit is adjustable over the range from 0 to 10 A. The OCC of this generator is shown in Figure P4-1.

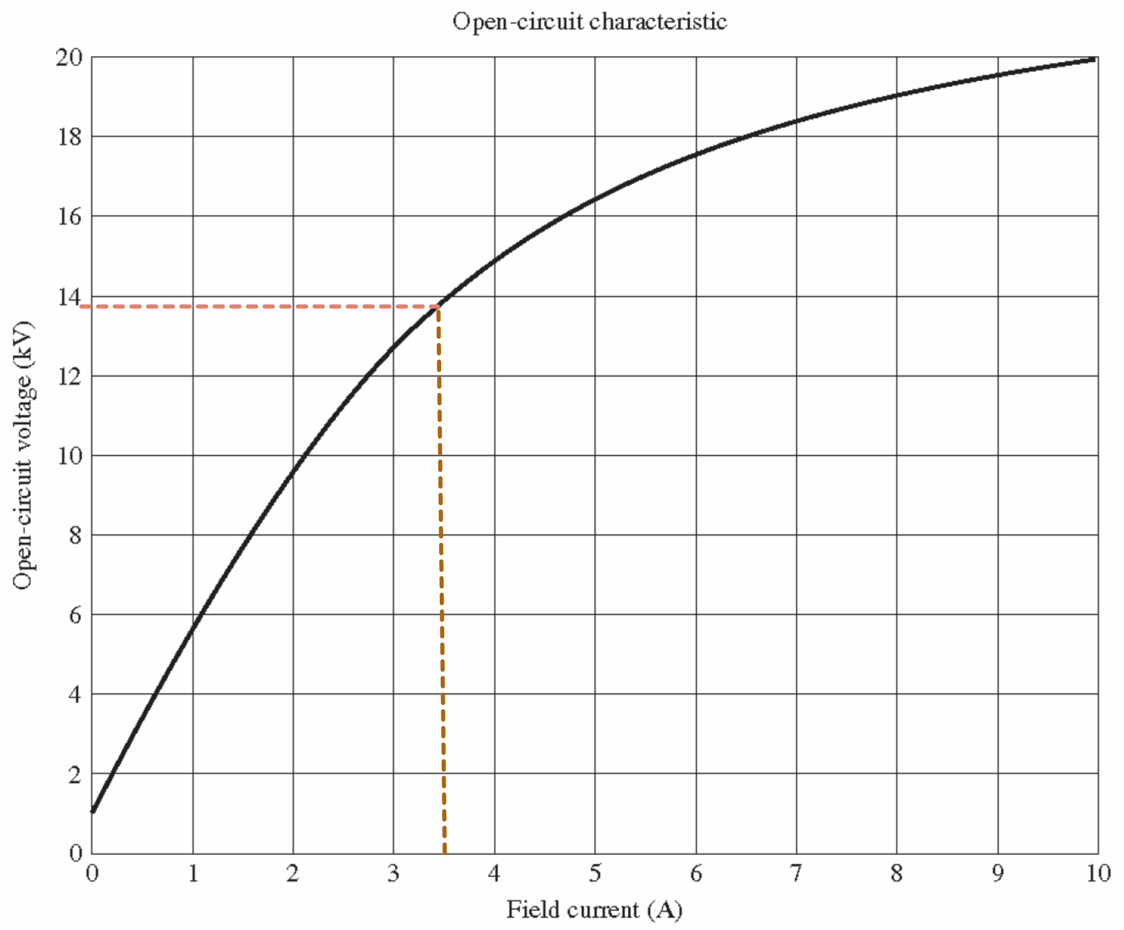

FIGURE P4–1

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(a) How much field current is required to make the terminal voltage V_T (or line voltage V_L) equal to 13.8 kV when the generator is running at no load?

(b) What is the internal generated voltage E_A of this machine at rated conditions?

(c) What is the phase voltage V_ϕ of this generator at rated conditions?

(d) How much field current is required to make the terminal voltage V_T equal to 13.8 kV when the generator is running at rated conditions?

(e) Suppose that this generator is running at rated conditions, and then the load is removed without changing the field current. What would the terminal voltage of the generator be?

(f) How much steady-state power and torque must the generator's prime mover be capable of supplying to handle the rated conditions?

(g) Construct a capability curve for this generator.

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Solution

(a) If the no-load terminal voltage is 13.8 kV, the required field current can be read directly from the open-circuit characteristic. It is 3.50 A.

(b) This generator is Y-connected, so $I_L = I_A$. At rated conditions, the line and phase current in this generator is

$$I_A = I_L = \frac{S}{\sqrt{3}\ V_L} = \frac{50\text{ MVA}}{\sqrt{3}\left(13800\text{ V}\right)} = 2092\text{ A at an angle of } -25.8°$$

At rated conditions:

The phase voltage of this machine is $V_\phi = V_T/\sqrt{3} = 7967\text{ V}$. The internal generated voltage of the machine is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$\mathbf{E}_A = 7967\angle 0° + \left(0.20\ \Omega\right)\left(2092\angle -25.8°\text{ A}\right) + j\left(2.5\ \Omega\right)\left(2092\angle -25.8°\text{ A}\right)$$

$$\mathbf{E}_A = 11544\angle 23.1°\text{ V}$$

=> Note: $V_{T,OC}$ = Sqt(3)*11544=19,994.8V

(c) The phase voltage of the machine at rated conditions is $V_\phi = 7967\text{ V}$

From the OCC, the required field current is 10 A. => For 19,994.8V

(d) The equivalent open-circuit terminal voltage corresponding to an E_A of 11544 volts is

$$V_{T,\text{oc}} = \sqrt{3}\left(11544\text{ V}\right) = 20\text{ kV}$$

From the OCC, the required field current is 10 A.

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(e) If the load is removed without changing the field current, $V_\phi = E_A = 11544$ V. The corresponding terminal voltage would be 20 kV. ; ($V_{T,OC}$ = Sqt(3)*11544=19,994.8V)

(f) The input power to this generator is equal to the output power plus losses. The rated output power is

$$P_{OUT} = (50 \text{ MVA})(0.9) = 45 \text{ MW}$$

$$P_{CU} = 3I_A^2 R_A = 3(2092 \text{ A})^2 (0.2\ \Omega) = 2.6 \text{ MW}$$

$$P_{F\&W} = 1 \text{ MW}$$

$$P_{core} = 1.5 \text{ MW}$$

$$P_{stray} = (\text{assumed } 0)$$

$$P_{IN} = P_{OUT} + P_{CU} + P_{F\&W} + P_{core} + P_{stray} = 50.1 \text{ MW}$$

Therefore the prime mover must be capable of supplying 50.1 MW. Since the generator is a four-pole 60 Hz machine, to must be turning at 1800 r/min. The required torque is

$$\tau_{APP} = \frac{P_{IN}}{\omega_m} = \frac{50.1 \text{ MW}}{(1800 \text{ r/min})\left(\frac{1 \text{ min}}{60 \text{ s}}\right)\left(\frac{2\pi \text{ rad}}{1 \text{ r}}\right)} = 265{,}800 \text{ N} \cdot \text{m}$$

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Not covered in Course Outline and Lecture!

(e) The rotor current limit of the capability curve would be drawn from an origin of

$$Q = -\frac{3V_\phi^{\ 2}}{X_S} = -\frac{3(7967\ \text{V})^2}{2.5\ \Omega} = -76.17\ \text{MVAR}$$

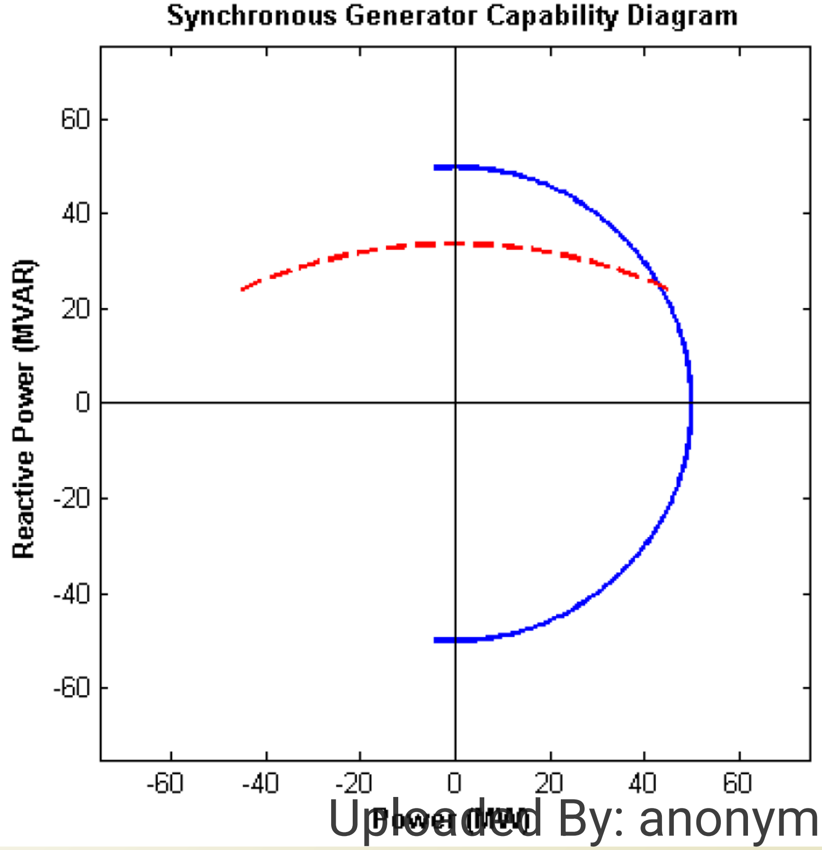
The radius of the rotor current limit is

$$D_E = \frac{3V_\phi E_A}{X_S} = \frac{3(7967\ \text{V})(11,544\ \text{V})}{2.5\ \Omega} = 110\ \text{MVA}$$

The stator current limit is a circle at the origin of radius

$$S = 3V_\phi I_A = 3(7967\ \text{V})(2092\ \text{A}) = 50\ \text{MVA}$$

If a MatLab code can be prepared, the plot will be as shown next.



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4-8. A 200-MVA, 12-kV, 0.85-PF-lagging, 50-Hz, 20-pole, Y-connected water turbine generator has a per-unit synchronous reactance of 0.9 and a per-unit armature resistance of 0.1. This generator is operating in parallel with a large power system (infinite bus).

(a) What is the speed of rotation of this generator's shaft?

(b) What is the magnitude of the internal generated voltage E_A at rated conditions?

(c) What is the torque angle of the generator at rated conditions?

(d) What are the values of the generator's synchronous reactance and armature resistance in ohms?

(e) If the field current is held constant, what is the maximum power possible out of this generator? How much reserve power or torque does this generator have at full load?

(f) At the absolute maximum power possible, how much reactive power will this generator be supplying or consuming? Sketch the corresponding phasor diagram. (Assume I_F is still unchanged.)

SOLUTION

(a) The speed of rotation of this generator's shaft is

$$n_{\text{sync}} = \frac{120 f_{se}}{P} = \frac{120(50\text{ Hz})}{20} = 300\text{ r/min}$$

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(b) The per-unit phase voltage at rated conditions is $\mathbf{V}_\phi = 1.0\angle 0°$ and the per-unit phase current at rated conditions is $\mathbf{I}_A = 1.0\angle -25.8°$ (since the power factor is 0.9 lagging), so the per-unit internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$
$$\mathbf{E}_A = 1\angle 0° + (0.1)(1\angle -25.8°) + j(0.9)(1\angle -25.8°)$$
$$\mathbf{E}_A = 1.69\angle 27.4° \text{ pu}$$

The base phase voltage is

$$V_{\phi,\text{base}} = 12 \text{ kV} / \sqrt{3} = 6928 \text{ V}$$

so the internal generated voltage is

$$\mathbf{E}_A = (1.69\angle 27.4° \text{ pu})(6928 \text{ V}) = 11{,}710\angle 27.4° \text{ V}$$

(c) The torque angle of the generator is $\delta = 27.4°$.

(d) The base impedance of the generator is

$$Z_{\text{base}} = \frac{3\ V_{\phi,\text{base}}{}^2}{S_{\text{base}}} = \frac{3(6928 \text{ V})^2}{200{,}000{,}000 \text{ VA}} = 0.72\ \Omega$$

Therefore the synchronous reactance is

$$X_S = (0.9)(0.72\ \Omega) = 0.648\ \Omega$$

and the armature resistance is

$$R_A = (0.1)(0.72\ \Omega) = 0.072\ \Omega$$

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(e) If the field current is held constant (and the armature resistance is ignored), the power out of this generator is given by

$$P = \frac{3V_\phi E_A}{X_S} \sin\delta$$

The max power is given by

$$P_{\max} = \frac{3V_\phi E_A}{X_S} \sin 90° = \frac{3(6928 \text{ V})(11{,}710 \text{ V})}{0.648\ \Omega} = 376 \text{ MW}$$

Since the full load power is $P = (200 \text{ MVA})(0.85) = 170 \text{ MW}$, this generator is supplying 45% of the maximum possible power at full load conditions.

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(*f*) At the maximum power possible, the torque angle $\delta = 90°$, so the phasor $\mathbf{E}_A$ will be at an angle of 90°, and the current flowing will be

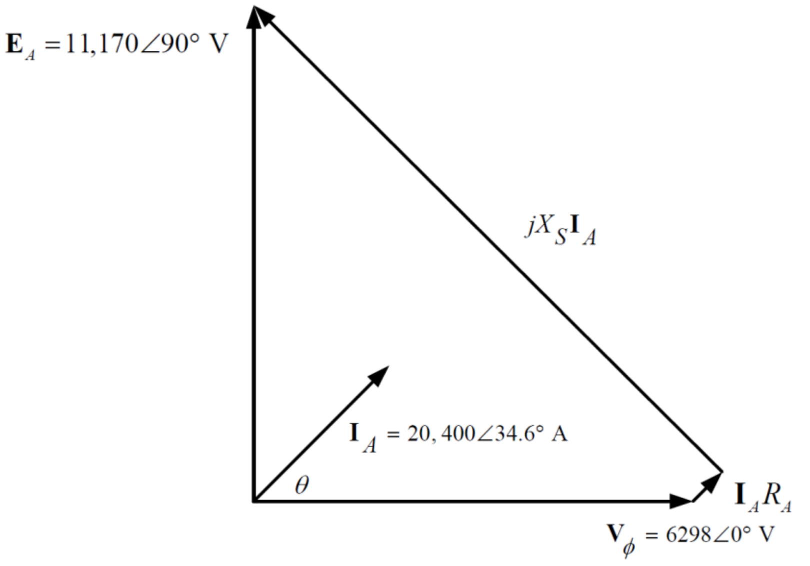
$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$\mathbf{I}_A = \frac{\mathbf{E}_A - \mathbf{V}_\phi}{R_A + jX_S}$$

$$\mathbf{I}_A = \frac{11{,}710\angle 90° \text{ kV} - 6928\angle 0° \text{ kV}}{0.072 + j0.648\ \Omega} = 20{,}400\angle 34.6° \text{ A}$$

The impedance angle $\theta = -34.6°$, and the reactive power supplied by the generator is

$$Q = 3V_\phi I_A \sin\theta = 3(6928 \text{ V})(20{,}400 \text{ A})\sin(-34.6°) = -219 \text{ Mvar}$$



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4-10. Three physically identical synchronous generators are operating in parallel. They are all rated for a full load of 100 MW at 0.8 PF lagging. The no-load frequency of generator A is 61 Hz, and its speed droop is 3 percent. The no-load frequency of generator B is 61.5 Hz, and its speed droop is 3.4 percent. The no-load frequency of generator C is 60.5 Hz, and its speed droop is 2.6 percent.

(a) If a total load consisting of 230 MW is being supplied by this power system, what will the system frequency be and how will the power be shared among the three generators?

(b) Create a plot showing the power supplied by each generator as a function of the total power supplied to all loads (you may use MATLAB to create this plot). At what load does one of the generators exceed its ratings? Which generator exceeds its ratings first?

(c) Is this power sharing in *(a)* acceptable? Why or why not?

(d) What actions could an operator take to improve the real power sharing among these generators?

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SOLUTION

(a) Speed droop is defined as

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\% = \frac{f_{nl} - f_{fl}}{f_{fl}} \times 100\%$$

so
$$f_{fl} = \frac{f_{nl}}{\frac{SD}{100} + 1}$$

Thus, the full-load frequencies of generators A, B, and C are

$$f_{fl,A} = \frac{f_{nl,A}}{\frac{SD_A}{100} + 1} = \frac{61 \text{ Hz}}{\frac{3.0}{100} + 1} = 59.223 \text{ Hz}$$

$$f_{fl,B} = \frac{f_{nl,B}}{\frac{SD_B}{100} + 1} = \frac{61.5 \text{ Hz}}{\frac{3.4}{100} + 1} = 59.478 \text{ Hz}$$

$$f_{fl,C} = \frac{f_{nl,C}}{\frac{SD_C}{100} + 1} = \frac{60.5 \text{ Hz}}{\frac{2.6}{100} + 1} = 58.967 \text{ Hz}$$

and the slopes of the power-frequency curves are:

$$S_{PA} = \frac{100 \text{ MW}}{61 \text{ Hz} - 59.223 \text{ Hz}} = 56.27 \text{ MW/Hz}$$

$$S_{PB} = \frac{100 \text{ MW}}{61.5 \text{ Hz} - 59.478 \text{ Hz}} = 49.46 \text{ MW/Hz}$$

$$S_{PC} = \frac{100 \text{ MW}}{60.5 \text{ Hz} - 58.967 \text{ Hz}} = 65.23 \text{ MW/Hz}$$

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(a) The total load is 230 MW, so the system frequency is

$$P_{\text{LOAD}} = s_{PA}\left(f_{\text{nlA}} - f_{\text{sys}}\right) + s_{PB}\left(f_{\text{nlB}} - f_{\text{sys}}\right) + s_{PC}\left(f_{\text{nlC}} - f_{\text{sys}}\right)$$

$$230 \text{ MW} = (56.27)\left(61.0 - f_{\text{sys}}\right) + (49.46)\left(61.5 - f_{\text{sys}}\right) + (65.23)\left(60.5 - f_{\text{sys}}\right)$$

$$230 \text{ MW} = 3433 - 56.27 f_{\text{sys}} + 3042 - 49.46 f_{\text{sys}} + 3946 - 65.23 f_{\text{sys}}$$

$$170.96 f_{\text{sys}} = 10191$$

$$f_{\text{sys}} = 59.61 \text{ Hz}$$

The power supplied by each generator will be

$$P_A = s_{PA}\left(f_{\text{nlA}} - f_{\text{sys}}\right) = (56.27 \text{ MW/Hz})(61.0 \text{ Hz} - 59.61 \text{ Hz}) = 78.2 \text{ MW}$$

$$P_B = s_{PB}\left(f_{\text{nlB}} - f_{\text{sys}}\right) = (49.46 \text{ MW/Hz})(61.5 \text{ Hz} - 59.61 \text{ Hz}) = 93.5 \text{ MW}$$

$$P_C = s_{PC}\left(f_{\text{nlC}} - f_{\text{sys}}\right) = (65.23 \text{ MW/Hz})(60.5 \text{ Hz} - 59.61 \text{ Hz}) = 58.1 \text{ MW}$$

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(c) The power sharing in *(a)* is acceptable, because all generators are within their power limits.

(d) To improve the power sharing among the three generators in *(a)* without affecting the operating frequency of the system, the operator should decrease the governor setpoints on Generator B while simultaneously increasing them in Generator C.

(b) The equation in part *(a)* can be re-written slightly to express system frequency as a function of load.

$$P_{\text{LOAD}} = (56.27)(61.0 - f_{\text{sys}}) + (49.46)(61.5 - f_{\text{sys}}) + (65.23)(60.5 - f_{\text{sys}})$$

$$P_{\text{LOAD}} = 3433 - 56.27 f_{\text{sys}} + 3042 - 49.46 f_{\text{sys}} + 3946 - 65.23 f_{\text{sys}}$$

$$170.96 f_{\text{sys}} = 10421 - P_{\text{LOAD}}$$

$$f_{\text{sys}} = \frac{10421 - P_{\text{LOAD}}}{170.96}$$

A MATLAB program that uses this equation to determine the power sharing among the generators as a function of load can be prepared…

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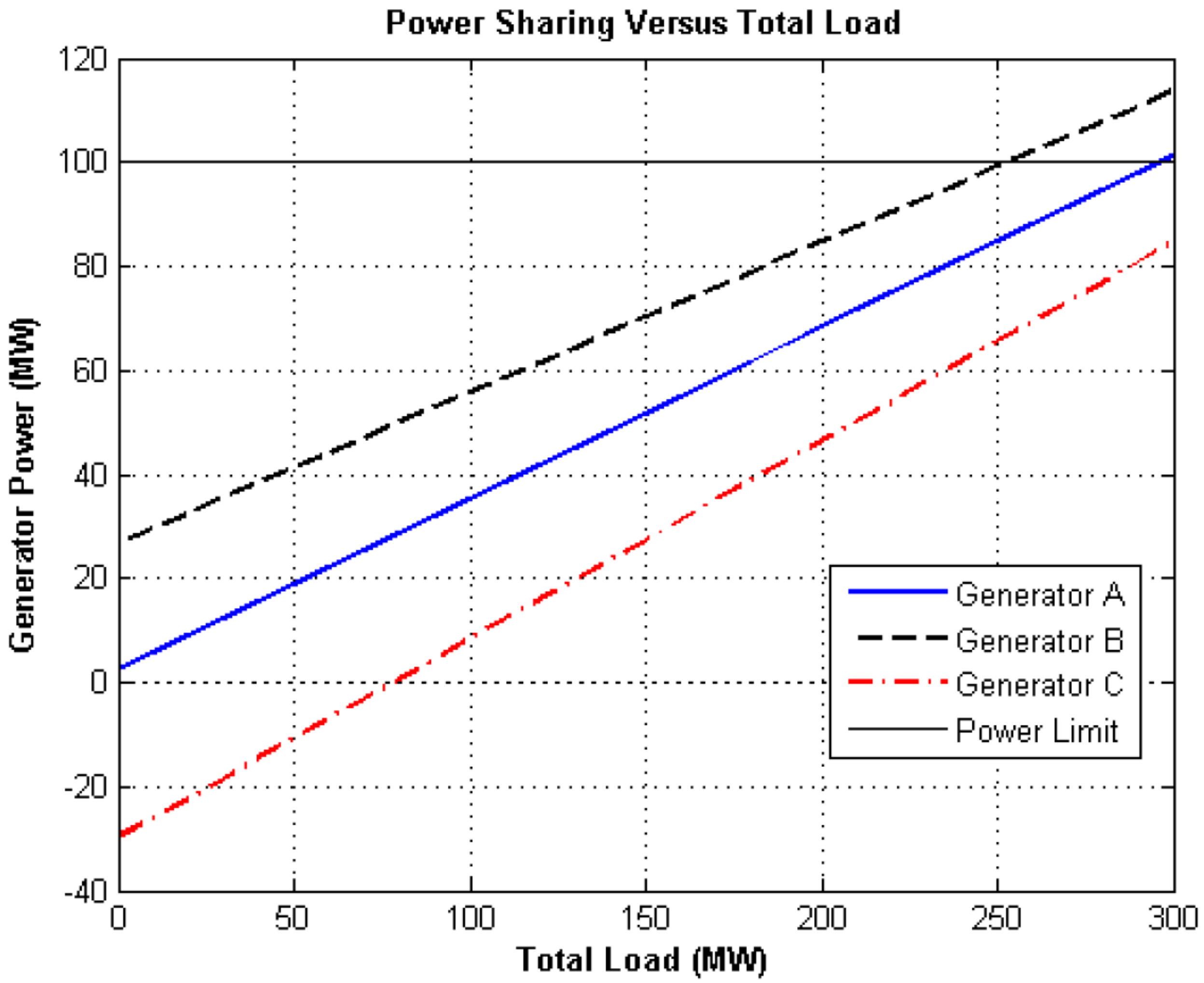
The resulting plot is shown below:



This plot reveals that there are power sharing problems both for high loads and for low loads. Generator B is the first to exceed its ratings as load increases. Its rated power is reached at a total load of 253 MW. On the other hand, Generator C gets into trouble as the total load is reduced. When the total load drops to 78 MW, the direction of power flow reverses in Generator C.

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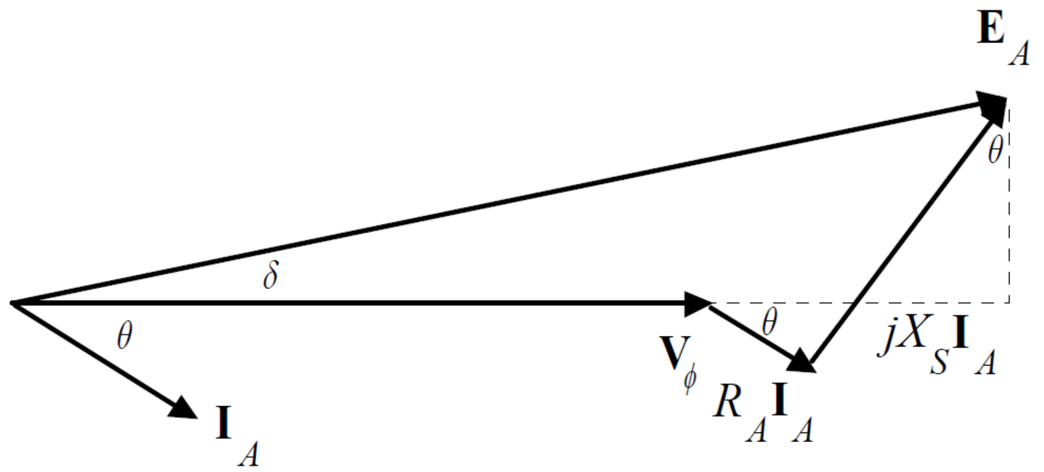
4-25. Assume that the generator's field current is adjusted so that the generator supplies rated voltage at the rated load current and power factor. If the field current and the magnitude of the load current are held constant, how will the terminal voltage change as the load power factor varies from 0.9 PF lagging to 0.9 PF leading? Make a plot of the terminal voltage versus the load **impedance angle**.

SOLUTION If the field current is held constant, then the magnitude of $\mathbf{E}_A$ will be constant, although its angle δ will vary. Also, the magnitude of the armature current is constant. Since we also know R_A, X_S, and the current angle θ, we know enough to find the phase voltage V_ϕ, and therefore the terminal voltage V_T. At lagging power factors, V_ϕ can be found from the following relationships:



By the Pythagorean Theorem,

$$E_A^2 = \left(V_\phi + R_A I_A \cos\theta + X_S I_A \sin\theta\right)^2 + \left(X_S I_A \cos\theta - R_A I_A \sin\theta\right)^2$$

$$V_\phi = \sqrt{E_A^2 - \left(X_S I_A \cos\theta - R_A I_S \sin\theta\right)^2} - R_A I_A \cos\theta - X_S I_A \sin\theta$$

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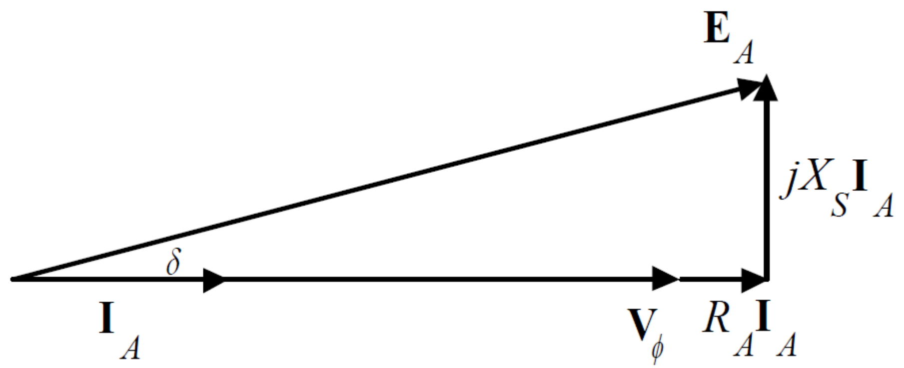
At unity power factor, V_ϕ can be found from the following relationships:

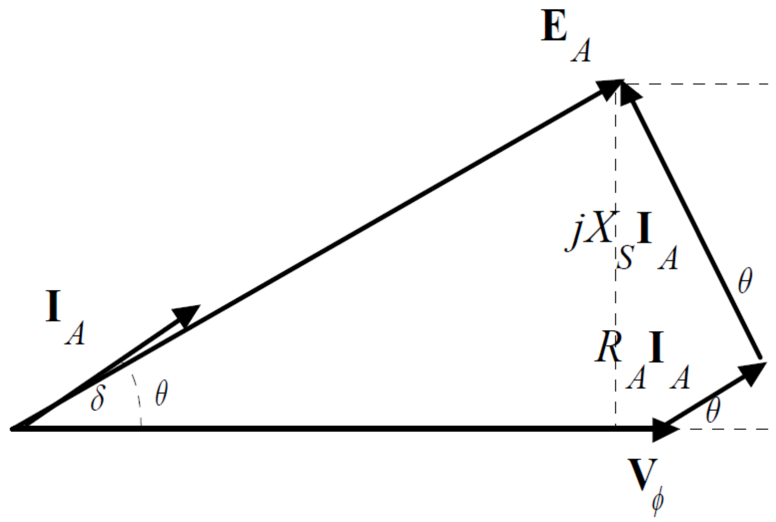


By the Pythagorean Theorem,

$$E_A^2 = \left(V_\phi + R_A I_A\right)^2 + (X_A I_A)^2$$

$$V_\phi = \sqrt{E_A^{\,2} - (X_S I_A)^2} - R_A I_A$$

At leading power factors, V_ϕ can be found from the following relationships:



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By the Pythagorean Theorem,

$$E_A{}^2 = \left(V_\phi + R_A I_A \cos\theta - X_S I_A \sin\theta\right)^2 + \left(X_S I_A \cos\theta + R_A I_A \sin\theta\right)^2$$

$$V_\phi = \sqrt{E_A{}^2 - \left(X_S I_A \cos\theta + R_A I_S \sin\theta\right)^2} - R_A I_A \cos\theta + X_S I_A \sin\theta$$

If we examine these three cases, we can see that the only difference among them is the sign of the term $\sin\theta$. If θ is taken as positive for lagging power factors and negative for leading power factors (in other words, if θ is the *impedance angle*), then all three cases can be represented by the single equation:

$$V_\phi = \sqrt{E_A{}^2 - \left(X_S I_A \cos\theta - R_A I_S \sin\theta\right)^2} - R_A I_A \cos\theta - X_S I_A \sin\theta$$

A MATLAB program that calculates terminal voltage as function of impedance angle can be prepared…

Recall $V_\emptyset$ for lagging pf was:

$$V_\phi = \sqrt{E_A{}^2 - \left(X_S I_A \cos\theta - R_A I_S \sin\theta\right)^2} - R_A I_A \cos\theta - X_S I_A \sin\theta$$

and $V_\emptyset$ for Unity pf was:

$$V_\phi = \sqrt{E_A{}^2 - \left(X_S I_A\right)^2} - R_A I_A$$

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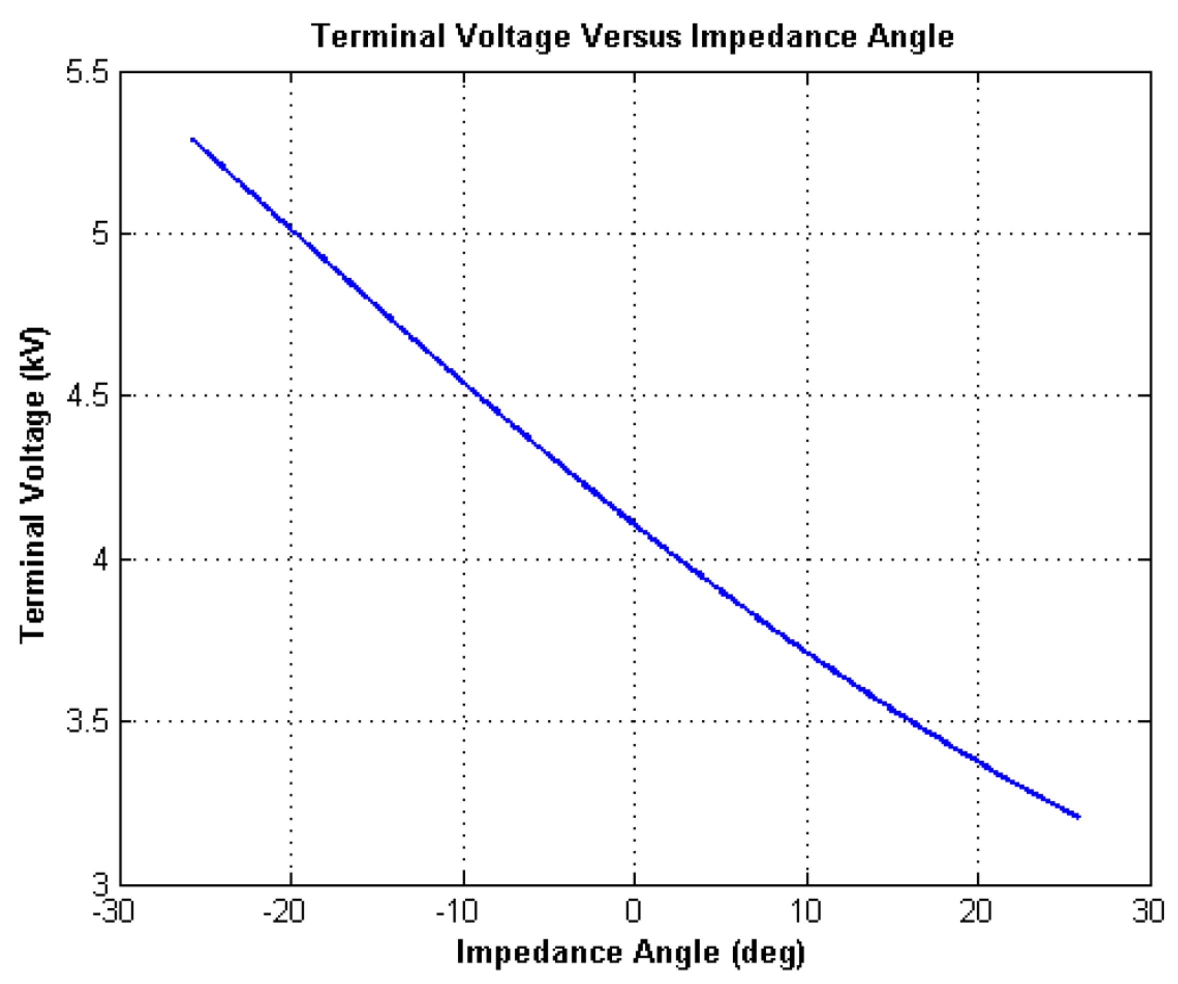
The resulting plot of terminal voltage versus impedance angle (with field and armature currents held constant) is shown below:



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4-29. A 100-MVA, 14.4-kV 0.8-PF-lagging, Y-connected synchronous generator has a negligible armature resistance and a synchronous reactance of 1.0 per-unit. The generator is connected in parallel with a 60-Hz, 14.4-kV infinite bus that is capable of supplying or consuming any amount of real or reactive power with no change in frequency or terminal voltage.

(a) What is the synchronous reactance of the generator in ohms?

(b) What is the internal generated voltage $\mathbf{E}_A$ of this generator under rated conditions?

(c) What is the armature current $\mathbf{I}_A$ in this machine at rated conditions?

(d) Suppose that the generator is initially operating at rated conditions. If the internal generated voltage $\mathbf{E}_A$ is decreased by 5 percent, what will the new armature current $\mathbf{I}_A$ be?

(e) Repeat part *(d)* for 10, 15, 20, and 25 percent reductions in $\mathbf{E}_A$.

(f) Plot the magnitude of the armature current I_A as a function of E_A. (You may wish to use MATLAB to create this plot.)

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SOLUTION

(a) The rated phase voltage of this generator is 14.4 kV / $\sqrt{3}$ = 8313 V. The base impedance of this generator is

$$Z_{\text{base}} = \frac{3V_{\phi,\text{base}}^{\;2}}{S_{\text{base}}} = \frac{3(8313\text{ V})^2}{100,000,000\text{ VA}} = 2.07\ \Omega$$

Therefore,

$$R_A \approx 0\ \Omega \quad \text{(negligible)}$$

$$X_S = (1.0)(2.07\ \Omega) = 2.07\ \Omega$$

(b) The rated armature current is

$$I_A = I_L = \frac{S}{\sqrt{3}\ V_T} = \frac{100\text{ MVA}}{\sqrt{3}(14.4\text{ kV})} = 4009\text{ A}$$

The power factor is 0.8 lagging, so $\mathbf{I}_A = 4009\angle -36.87°\text{ A}$. Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$\mathbf{E}_A = 8313\angle 0° + j(2.07\ \Omega)(4009\angle -36.87°\text{ A})$$

$$\mathbf{E}_A = 14,858\angle 26.54°\text{ V}$$

(c) From the above calculations, $\mathbf{I}_A = 4009\angle -36.87°\text{ A}$.

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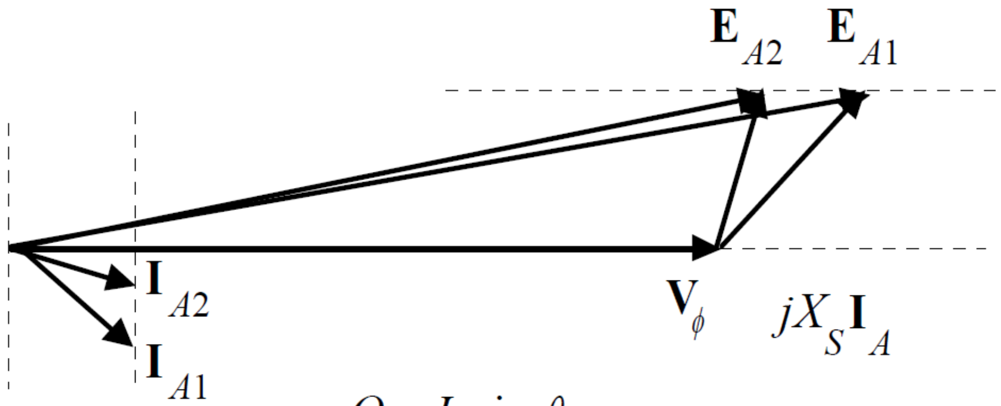
(d) If E_A is decreased by 5%, the armature current will change as shown below. Note that the infinite bus will keep V_ϕ and ω_m constant. Also, since the prime mover hasn't changed, the power supplied by the generator will be constant.



$$Q \propto I_A \sin\theta$$

$$P = \frac{3V_\phi E_A}{X_S}\sin\delta = \text{constant}, \text{ so } E_{A1}\sin\delta_1 = E_{A2}\sin\delta_2$$

With a 5% decrease, $E_{A2} = 14{,}115 \text{ V}$, and

$$\delta_2 = \sin^{-1}\left(\frac{E_{A1}}{E_{A2}}\sin\delta_2\right) = \sin^{-1}\left(\frac{14{,}858 \text{ V}}{14{,}115 \text{ V}}\sin 26.54°\right) = 28.0°$$

Therefore, the new armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_{A2} - \mathbf{V}_\phi}{jX_S} = \frac{14{,}115\angle 28.0° - 8313\angle 0°}{j2.07} = 3777\angle -32.1° \text{ A}$$

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(e) Repeating part *(d)*:

With a **10%** decrease, $E_{A2} = 13,372$ V, and

$$\delta_2 = \sin^{-1}\left(\frac{E_{A1}}{E_{A2}}\sin\delta_2\right) = \sin^{-1}\left(\frac{14,858\text{ V}}{13,372\text{ V}}\sin 26.54°\right) = 29.8°$$

Therefore, the new armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_{A2} - \mathbf{V}_\phi}{jX_S} = \frac{13,372\angle 29.8° - 8313\angle 0°}{j2.07} = 3582\angle -26.3°\text{ A}$$

With a **15%** decrease, $E_{A2} = 12,629$ V, and

$$\delta_2 = \sin^{-1}\left(\frac{E_{A1}}{E_{A2}}\sin\delta_2\right) = \sin^{-1}\left(\frac{14,858\text{ V}}{12,629\text{ V}}\sin 26.54°\right) = 31.7°$$

Therefore, the new armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_{A2} - \mathbf{V}_\phi}{jX_S} = \frac{12,629\angle 31.7° - 8313\angle 0°}{j2.07} = 3414\angle -20.1°\text{ A}$$

With a **20%** decrease, $E_{A2} = 11,886$ V, and

$$\delta_2 = \sin^{-1}\left(\frac{E_{A1}}{E_{A2}}\sin\delta_2\right) = \sin^{-1}\left(\frac{14,858\text{ V}}{11,886\text{ V}}\sin 26.54°\right) = 34.0°$$

Therefore, the new armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_{A2} - \mathbf{V}_\phi}{jX_S} = \frac{11,886\angle 34.0° - 8313\angle 0°}{j2.07} = 3296\angle -13.1°\text{ A}$$

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With a **25%** decrease, $E_{A2} = 11{,}144\text{ V}$, and

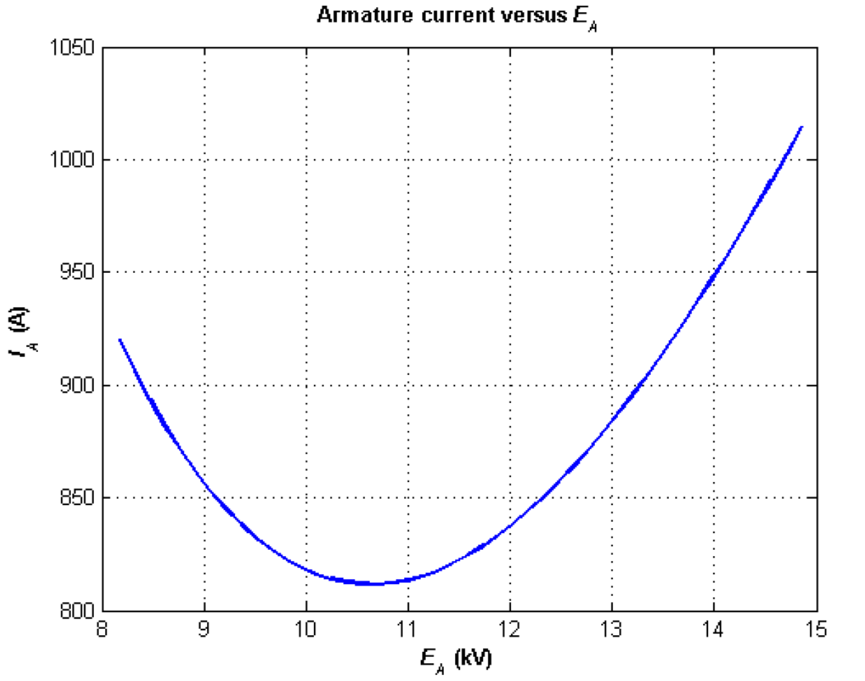
$$\delta_2 = \sin^{-1}\left(\frac{E_{A1}}{E_{A2}}\sin\delta_2\right) = \sin^{-1}\left(\frac{14{,}858\text{ V}}{11{,}144\text{ V}}\sin 26.54°\right) = 36.6°$$

Therefore, the new armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_{A2} - \mathbf{V}_\phi}{jX_S} = \frac{11{,}144\angle 36.6° - 8313\angle 0°}{j2.07} = 3224\angle -5.4°\text{ A}$$

(f) A MATLAB program to plot the magnitude of the armature current I_A as a function of E_A can be prepared…

The resulting plot is shown below:



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Many Thanks

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Reference

- Instructor's Solutions Manual to accompany Electric Machinery Fundamentals by Stephen Chapman, 5th Ed., McGraw-Hill, Inc., 2012.

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