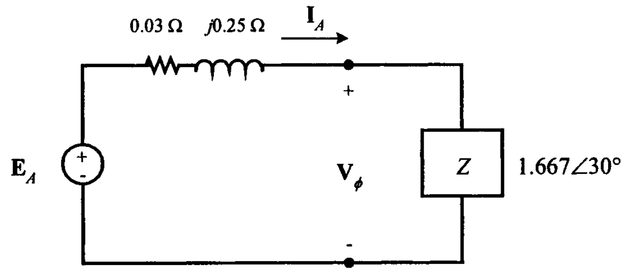
1. Problem 5-3 on textbook (Chapman, page 318)
   A 480-V, 200-kVA, 0.8-PF-lagging, 60-Hz, two-pole, Y-connected synchronous generator has a synchronous reactance of 0.25 Ω and an armature resistance of 0.04 Ω. At 60 Hz, its friction and windage losses are 6kW, and its core losses are 4kW. Assume that the field current of the generator has been adjusted to a value of 4.5 A (**so that the open-circuit terminal voltage of the generator will be about 477 V**).
   (a) What will the terminal voltage of this generator be if it is connected to a Δ-connected load with an impedance of $5\angle 30^{\circ}$ Ω?
   (b) Sketch the phasor diagram of this generator.
   (c) What is the efficiency of the generator at these conditions?
   (d) Now assume that another identical Δ-connected load is to be paralleled with the first one. What happens to the phasor diagram for the generator?
   (e) What is the new terminal voltage after the load has been added?
   (f) What must be done to restore the terminal voltage to its original value?

SOLUTION

(a) If the field current is 4.5 A, the open-circuit terminal voltage will be about 477 V, and the phase voltage in the generator will be $477/\sqrt{3} = 275\text{ V}$.

The load is Δ-connected with three impedances of $5\angle 30^{\circ}\ \Omega$. From this Y-Δ transform, this load is equivalent to a Y-connected load with three impedances of $1.667\angle 30^{\circ}\ \Omega$. The resulting per-phase equivalent circuit is shown below:



The magnitude of the phase current flowing in this generator is

$$I_A = \frac{E_A}{|R_A + jX_S + Z|} = \frac{275\text{ V}}{|0.03 + j0.25 + 1.667\angle 30^{\circ}|} = \frac{275\text{ V}}{1.829\ \Omega} = 150\text{ A}$$

Therefore, the magnitude of the phase voltage is

$$V_\phi = I_A Z = (150\text{ A})(1.667\ \Omega) = 250\text{ V}$$

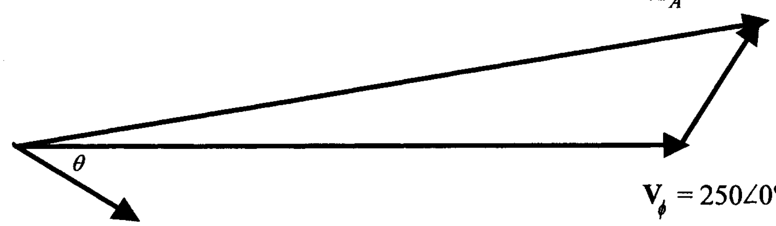
and the terminal voltage is

$$V_T = \sqrt{3}\,V_\phi = \sqrt{3}\,(250\text{ V}) = 433\text{ V}$$

(b) Armature current is $\mathbf{I}_A = 150\angle -30^{\circ}\text{ A}$, and the phase voltage is $\mathbf{V}_\phi = 250\angle 0^{\circ}\text{ V}$. Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$
$$\mathbf{E}_A = 250\angle 0^{\circ} + (0.03\ \Omega)(150\angle -30^{\circ}\text{ A}) + j(0.25\ \Omega)(150\angle -30^{\circ}\text{ A})$$
$$\mathbf{E}_A = 275\angle 6.3^{\circ}\text{ V}$$

The resulting phasor diagram is shown below (not to scale):



(c) The efficiency of the generator under these conditions 3can be found as follows:

$$P_{\text{OUT}} = 3V_\phi I_A \cos\theta = 3(250\text{ V})(150\text{ A})(0.8) = 90\text{ kW}$$

$$P_{\text{CU}} = 3I_A^2 R_A = 3(150\text{ A})^2(0.03\,\Omega) = 2\text{ kW}$$

$$P_{\text{F\&W}} = 6\text{ kW}$$

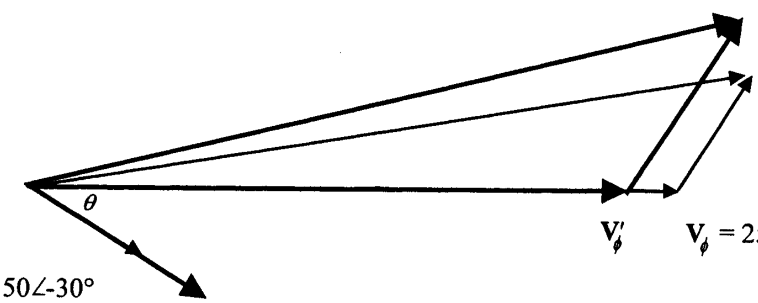
$$P_{\text{core}} = 4\text{ kW}$$

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

$$P_{\text{IN}} = P_{\text{OUT}} + P_{\text{CU}} + P_{\text{F\&W}} + P_{\text{core}} + P_{\text{stray}} = 102\text{ kW}$$

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{90\text{ kW}}{102\text{ kW}} \times 100\% = 88.2\%$$

(d) When the new load is added, the total current flow increases at the same phase angle. Therefore, $jX_S\mathbf{I}_S$ increases in length at the same angle, while the magnitude of E_A must remain constant. Therefore, $\mathbf{E}_A$ "swings" out along the arc of constant magnitude until the new $jX_S\mathbf{I}_S$ fits exactly between $\mathbf{V}_\phi$ and $\mathbf{E}_A$.



(e) The new impedance per phase will be half of the old value, so $Z = 0.8333\angle 30°\,\Omega$. The magnitude of the phase current flowing in this generator is

$$I_A = \frac{E_A}{|R_A + jX_S + Z|} = \frac{275\text{ V}}{|0.03 + j0.25 + 0.8333\angle 30°|} = \frac{275\text{ V}}{1.005\,\Omega} = 274\text{ A}$$

Therefore, the magnitude of the phase voltage is

$$V_\phi = I_A Z = (274\text{ A})(0.8333\,\Omega) = 228\text{ V}$$

and the terminal voltage is

$$V_T = \sqrt{3}\,V_\phi = \sqrt{3}\,(228\text{ V}) = 395\text{ V}$$

(f) To restore the terminal voltage to its original value, increase the field current I_F.

2. Problem 5-7 on textbook (Chapman, page 319)
   A 13.5-kV, 20-MVA, 0.8-PF-lagging, 60-Hz, two-pole, Y-connected steam-turbine generator has a synchronous reactance of 5.0 Ω per phase and an armature resistance of 0.5 Ω per phase. This generator is operating in parallel with a large power system (infinite bus).
   (a) What is the magnitude of E_A at rated conditions?
   (b) What is the torque angle of the generator at rated conditions?
   (c) If the field current is constant, what is the maximum power possible out of this generator?
   (d) 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 phase voltage of this generator at rated conditions is

$$V_\phi = \frac{V_T}{\sqrt{3}} = 7794\text{ V}$$

The armature current per phase at rated conditions is

$$I_A = \frac{S}{\sqrt{3}\,V_T} = \frac{20{,}000{,}000\text{ VA}}{\sqrt{3}(13{,}500\text{ V})} = 855\text{ A}$$

Therefore, the internal generated voltage at rated conditions is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$
$$\mathbf{E}_A = 7794\angle 0° + (0.5\,\Omega)(855\angle -36.87°\text{ A}) + j(5.0\,\Omega)(855\angle -36.87°\text{ A})$$
$$\mathbf{E}_A = 11{,}160\angle 16.5°\text{ V}$$

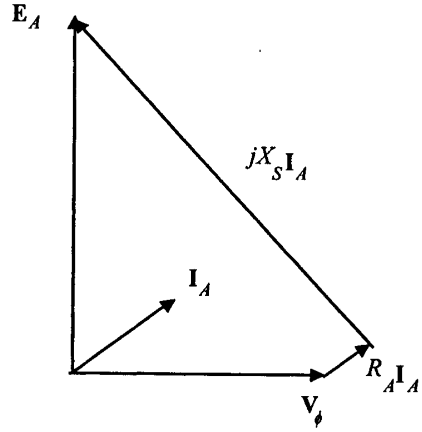
The magnitude of E_A is 11,160 V.

(b) The torque angle of the generator at rated conditions is $\delta = 16.5°$.

(c) Ignoring R_A, the *maximum output power* of the generator is given by

$$P_{\text{MAX}} = \frac{3V_\phi E_A}{X_S} = \frac{3(7794\text{ V})(11{,}160\text{ V})}{5\,\Omega} = 52.2\text{ MW}$$

(d) The phasor diagram at these conditions is shown below:



Under these conditions, the armature current is

$$\mathbf{I}_A = \frac{\mathbf{E}_A - \mathbf{V}_\phi}{R_A + jX_S} = \frac{11{,}160\angle 90^\circ\ \text{V} - 7794\angle 0^\circ\ \text{V}}{0.5 + j5.0\,\Omega} = 2790\angle 39.5^\circ\ \text{A}$$

The reactive power produced by the generator is

$$Q = 3V_\phi I_A \sin\theta = 3(7794\ \text{V})(2790\ \text{A})\sin(0^\circ - 39.5^\circ) = -41.5\ \text{MVAR}$$

The generator is actually consuming reactive power at this time.