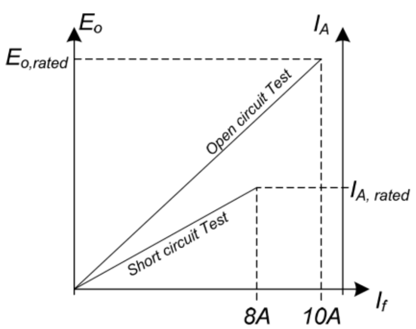
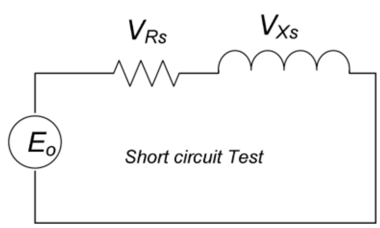
EE3124 Tutorial 4 (Solution)
Synchronous Generator

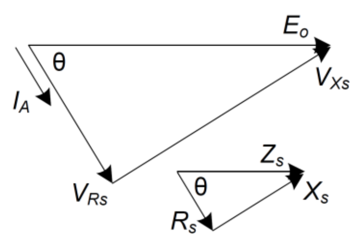
Name: **Student No.:**

Q1 - A three-phase star-connected cylindrical synchronous generator is rated at 20 MVA and 11 kV. In an open-circuit test, a DC excitation current of 10 A is required to produce the open-circuit line voltage of 9 kV. In a short-circuit test, a DC excitation current of 8 A can circulate the rated current in the armature winding. It has an armature resistance of 0.5 Ω per phase. Assuming no magnetic saturation, calculate the synchronous impedance. Determine the no-load EMF and hence the voltage regulation when the generator supplies the rated current at 0.8 power factor lagging to an 11 kV infinite busbar.

Solution







Rated current is: $I_{rated} = \dfrac{S_{rated}}{V_{rated}} = \dfrac{20\times10^6/3}{11\times10^3/\sqrt{3}} = 1049.7A$

Phase EMF at 8A: $E_o = \dfrac{9\times10^3}{\sqrt{3}}\left(\dfrac{8}{10}\right) = 4156.9\text{V}$

Synchronous impedance: $|Z_s| = \dfrac{E_o}{I_{rated}} = \dfrac{4156.9}{1049.7} = 3.96\ \Omega$

$$Z_s = 3.96\angle\cos^{-1}\left(\frac{0.5}{3.96}\right) = 3.96\angle 82.7^\circ\ \Omega$$

On supplying the rated current to 11 kV busbar:

$$I_{rated} = 1049.7\angle\cos^{-1}(0.8) = 1049.7\angle-36.87^\circ$$

$$
\begin{aligned}
E_o &= V_{rated} + I_{rated} Z_s \\
&= \frac{11\times 10^3}{\sqrt{3}} + (1049.7\angle -36.87°)(3.96\angle 82.7°) \\
&= 9716.1\angle 17.9°\ V
\end{aligned}
$$

On-load voltage regulation:

$$
\begin{aligned}
VR &= \frac{E_o - V}{V}\times 100\% \\
&= \frac{9716.10 - 11\times 10^3/\sqrt{3}}{11\times 10^3/\sqrt{3}}\times 100\% \\
&= 53\%
\end{aligned}
$$

Q2 - A 100-MVA, 14.4-kV, 0.8-PF-lagging, 50-Hz, two-pole, Y-connected synchronous generator has a synchronous reactance of 2.281 **Ω** and an armature resistance of 0.0228 **Ω**.

(a) What is the magnitude of the internal generated voltage E_A at the rated conditions? What is its torque angle δ at these conditions?

(b) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at full load?

Solution

(a) 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

$$
\begin{aligned}
\mathbf{E}_A &= \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A \\
\mathbf{E}_A &= 8314\angle 0° + (0.0228\ \Omega)(4009\angle -36.87°\text{ A}) + j(2.281\ \Omega)(4009\angle -36.87°\text{ A}) \\
\mathbf{E}_A &= 15{,}660\angle 27.6°\text{ V}
\end{aligned}
$$

Therefore, the magnitude of the internal generated voltage E_A = 15,660 V, and the torque angle δ = 27.6°.

(b) Ignoring losses, the input power would equal the output power. Since

$$
P_{\text{OUT}} = (0.8)(100\text{ MVA}) = 80\text{ MW}
$$

and

$$
n_{\text{sync}} = \frac{120 f_{se}}{P} = \frac{120(50\text{ Hz})}{2} = 3000\text{ r/min}
$$

the applied torque would be

$$
\tau_{\text{app}} = \tau_{\text{ind}} = \frac{80{,}000{,}000\text{ W}}{(3000\text{ r/min})(2\pi\text{ rad/r})(1\text{ min}/60\text{ s})} = 254{,}700\text{ N}\cdot\text{m}
$$

Q3 -A 480-V 60-Hz, Δ-connected, four-pole synchronous generator has the open circuit characteristic (OCC) shown in the following figure. This generator has a synchronous reactance of 0.1 Ω and an armature resistance of 0.015 Ω. At full load, the machine supplies 1200 A at 0.8 PF lagging. Under full-load conditions, the friction and windage losses are 40 kW, and the core losses are 30 kW. Ignore any field circuit losses.

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

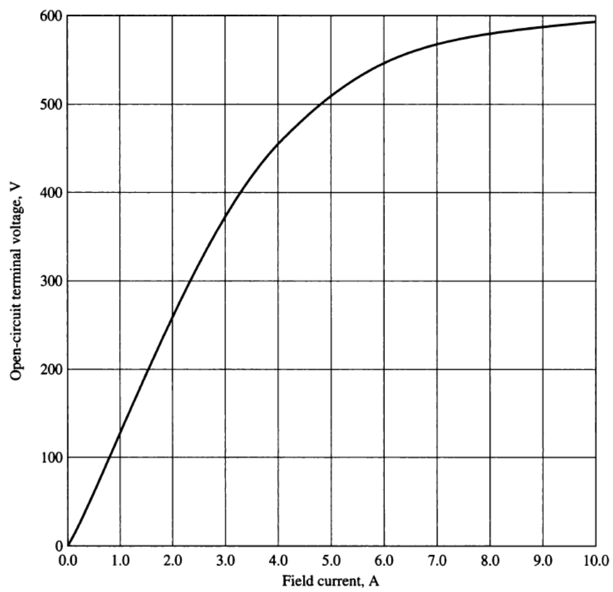
(b) How much field current must be supplied to the generator to make the terminal voltage 480 V at no load?

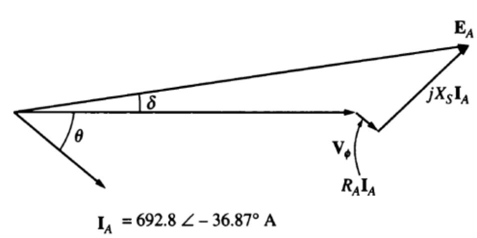
(c) If the generator is now connected to a load and the load draws 1200 A at 0.8 PF lagging, how much field current will be required to keep the terminal voltage equal to 480 V?

(d) How much power is the generator now supplying? How much power is supplied to the generator by the prime mover? What is this machine's overall efficiency?

(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?

(f) Finally, suppose that the generator is connected to a load drawing 1200 A at 0.8 PF leading. How much field current would be required to keep VT at 480 V?





Solution

This synchronous generator is Δ-connected, so its phase voltage is equal to its line voltage $V_\phi = V_T$, while its phase current is related to its line current by the equation $I_L = \sqrt{3} I_\phi$.

(*a*) The relationship between the electrical frequency produced by a synchronous generator and the mechanical rate of shaft rotation is given by Equation (3–34):

$$f_{se} = \frac{n_m P}{120}$$

Therefore,

$$n_m = \frac{120 f_{se}}{P}$$

$$= \frac{120(60\text{ Hz})}{4\text{ poles}} = 1800\text{ r/min}$$

(*b*) In this machine, $V_T = V_\phi$. Since the generator is at no load, $\mathbf{I}_A = 0$ and $\mathbf{E}_A = \mathbf{V}_\phi$. Therefore, $V_T = V_\phi = E_A = 480$ V, and from the open-circuit characteristic, $I_F = 4.5$ A.

(*c*) If the generator is supplying 1200 A, then the armature current in the machine is

$$I_A = \frac{1200\text{ A}}{\sqrt{3}} = 692.8\text{ A}$$

The phasor diagram for this generator is shown in Figure 4–23b. If the terminal voltage is adjusted to be 480 V, the size of the internal generated voltage $\mathbf{E}_A$ is given by

$$\begin{aligned}
\mathbf{E}_A &= \mathbf{V}_\phi + R_A \mathbf{I}_A + jX_S \mathbf{I}_A \\
&= 480\angle 0^\circ\text{ V} + (0.015\ \Omega)(692.8\angle -36.87^\circ\text{ A}) + (j0.1\ \Omega)(692.8\angle -36.87^\circ\text{ A}) \\
&= 480\angle 0^\circ\text{ V} + 10.39\angle -36.87^\circ\text{ V} + 69.28\angle 53.13^\circ\text{ V} \\
&= 529.9 + j49.2\text{ V} = 532\angle 5.3^\circ\text{ V}
\end{aligned}$$

To keep the terminal voltage at 480 V, $\mathbf{E}_A$ must be adjusted to 532 V. From Figure 4–23, the required field current is 5.7 A.

(*d*) The power that the generator is now supplying can be found from Equation (4–16):

$$P_{\text{out}} = \sqrt{3} V_L I_L \cos\theta \qquad (4\text{–}16)$$

$$= \sqrt{3}(480\text{ V})(1200\text{ A})\cos 36.87°$$
$$= 798\text{ kW}$$

To determine the power input to the generator, use the power-flow diagram (Figure 4–15). From the power-flow diagram, the mechanical input power is given by

$$P_{in} = P_{out} + P_{elec\ loss} + P_{core\ loss} + P_{mech\ loss} + P_{stray\ loss}$$

The stray losses were not specified here, so they will be ignored. In this generator, the electrical losses are

$$P_{elec\ loss} = 3I_A^2 R_A$$
$$= 3(692.8\text{ A})^2(0.015\ \Omega) = 21.6\text{ kW}$$

The core losses are 30 kW, and the friction and windage losses are 40 kW, so the total input power to the generator is

$$P_{in} = 798\text{ kW} + 21.6\text{ kW} + 30\text{ kW} + 40\text{ kW} = 889.6\text{ kW}$$

Therefore, the machine's overall efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{798\text{ kW}}{889.6\text{ kW}} \times 100\% = 89.75\%$$

(e) If the generator's load were suddenly disconnected from the line, the current $\mathbf{I}_A$ would drop to zero, making $\mathbf{E}_A = \mathbf{V}_\phi$. Since the field current has not changed, $|\mathbf{E}_A|$ has not changed and $\mathbf{V}_\phi$ and V_T must rise to equal $\mathbf{E}_A$. Therefore, if the load were suddenly dropped, the terminal voltage of the generator would rise to 532 V.

(f) If the generator were loaded down with 1200 A at 0.8 PF leading while the terminal voltage was 480 V, then the internal generated voltage would have to be

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$
$$= 480\angle 0°\text{ V} + (0.015\ \Omega)(692.8\angle 36.87°\text{ A}) + (j0.1\ \Omega)(692.8\angle 36.87°\text{ A})$$
$$= 480\angle 0°\text{ V} + 10.39\angle 36.87°\text{ V} + 69.28\angle 126.87°\text{ V}$$
$$= 446.7 + j61.7\text{ V} = 451\angle 7.1°\text{ V}$$

Therefore, the internal generated voltage E_A must be adjusted to provide 451 V if V_T is to remain 480 V. Using the open-circuit characteristic, the field current would have to be adjusted to 4.1 A.

Q4 - The internal generated voltage of a 2-pole, Δ-connected, 60 Hz, three phase synchronous generator is 14.4 kV, and the terminal voltage is 12.8 kV. The synchronous reactance of this machine is 4 **Ω**, and the armature resistance can be ignored.

(a) If the torque angle of the generator δ = 18°, how much power is being supplied by this generator at the current time?

(b) What is the power factor of the generator at this time?

(c) Sketch the phasor diagram under these circumstances.

(d) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at these conditions?

Solution

(a) If resistance is ignored, the output power from this generator is given by

$$P = \frac{3V_\phi E_A}{X_S}\sin\delta = \frac{3(12.8\text{ kV})(14.4\text{ kV})}{4\ \Omega}\sin 18° = 42.7\text{ MW}$$

(b) The phase current flowing in this generator can be calculated from

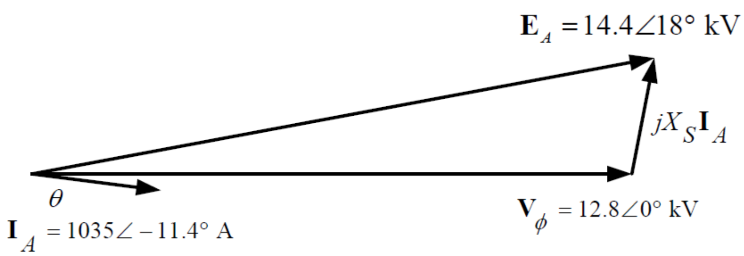
$$\mathbf{E}_A = \mathbf{V}_\phi + jX_S\mathbf{I}_A$$

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

$$\mathbf{I}_A = \frac{14.4\angle 18°\text{ kV} - 12.8\angle 0°\text{ kV}}{j4\ \Omega} = 1135\angle -11.4°\text{ A}$$

Therefore the impedance angle $\theta = 11.4°$, and the power factor is $\cos(11.4°) = 0.98$ lagging.

(c) The phasor diagram is



(d) The induced torque is given by the equation

$$P_{\text{conv}} = \tau_{\text{ind}}\omega_m$$

With no losses,

$$\tau_{\text{app}} = \tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{42.7\text{ MW}}{2\pi(60\text{ hz})} = 113{,}300\text{ N}\bullet\text{m}$$

Q5 -Suppose that you were an engineer planning a new electric co-generation facility for a plant with excess process steam. You have a choice of either two 10 MW turbine-generators or a single 20 MW turbine generator. What would be the advantages and disadvantages of each choice? What are the conditions before you synchronize your power to the power grid?

Solution

A single 20 MW generator will probably be cheaper and more efficient than two 10 MW generators, but if the 20 MW generator goes down all 20 MW of generation would be lost at once. If two 10 MW generators are chosen, one of them could go down for maintenance and some power could still be generated.

1. The RMS line voltages of the two generators must be equal.
2. The two generators must have the same phase sequence.
3. The phase angles of the two phases must be equal.
4. The frequency of the new generator, called the oncoming generator, must be slightly higher than the frequency of the running system.