EE330A: Tutorial 3

Question 1

A star connected 3 phase source is generating both real and reactive power at 132kV and power factor being 0.95. A delta connected load is connected to source through a transmission line having per phase reactance of $j30\Omega$. The source is delivering 1 MW real power. Find the following,

a) Load voltage (line to line)
b) Complex power consumed by load
c) Load power factor

Solution 1

Solution 1

$V_{t,ll} = 132kV \Rightarrow |V_{s,ph}| = \frac{132kV}{\sqrt{3}} = 76.2102kV$. The source power factor $\cos\theta_s = 0.95$ lagging as the source is delivering reactive power to a lagging or inductive load. $Z_{line} = j30\Omega$. The transmission line has no resistance. Hence, it is lossless and real power generated by source is the real power absorbed by load which is $P_{3\varphi} = 1MW \Rightarrow P_\varphi = 0.3333MW$. The magnitude of source phase current is thus

$$|I_{ph}| = \frac{P_\varphi}{|V_{s,ph}|\cos\theta_s} = 4.6041A$$

If $V_{s,ph} = 76.2102\angle 0°kV$, then $I_{ph} = 4.6041\angle -\theta_s = 4.6041\angle -18.1949°A$ as source power factor is lagging. The load end voltage is thus,

$$V_{l,ph} = V_{s,ph} - I_{ph}Z_{line} = 76.1672\angle -0.0987°kV$$

a) Line to line load end voltage is $\sqrt{3}|V_{l,ph}| = 131.9255kV$ **(Ans)**
b) Complex power consumed by load $S_{l,3\varphi} = 3V_{l,ph}I_{ph}^* = (1 + j0.32677)MVA = 1.052\angle 18.0962°MVA$ **(Ans)**
c) Load power factor $\cos\theta_l = 0.95054$ lagging where $\theta_l = 18.0962°$, as load is consuming reactive power. **(Ans)**

Question 2

A 3 phase, 11kV, 10MVA synchronous generator is connected to an inductive load with power factor of 0.85. Synchronous reactance and armature resistance per phase of machine are $j30\Omega$ and 1Ω, respectively. The per phase impedance of the line connecting generator and load is (1+j5) Ω. If the generator is producing rated current at rated voltage, find the following,
a) Load voltage (line to line)
b) Internal voltage angle of generator with respect to terminal voltage

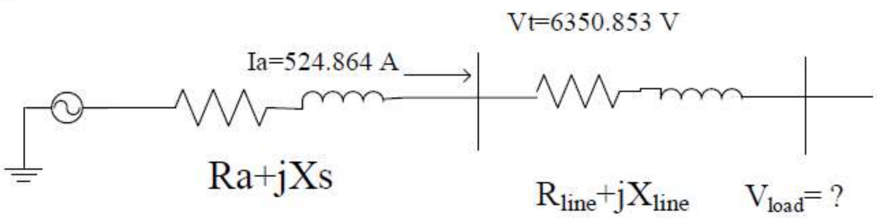
Solution 2

Given, $V_{t,ll} = 11kV \Rightarrow |V_{s,ph}| = \frac{11kV}{\sqrt{3}} = 6.3509kV$, $S_{3\varphi} = 10MVA$, load power factor $\cos\theta_l = 0.85$ lagging due to inductive load, $X_s = 30\Omega$, $R_a = 1\Omega$ and $Z_{line} = (1 + j5)\Omega$. Generator is producing rated current at rated voltage which is

$$|I_{ph}| = \frac{S_{3\varphi}/3}{|V_{s,ph}|} = 524.8639A$$

Let load end phase voltage be reference i.e. $V_{l,ph} = |V_{l,ph}|\angle 0°V$. Then, line current is $I_{ph} = 524.8639\angle -\theta_l = 524.8639\angle -31.7883°A$ as the load power factor is lagging.

The source end phase voltage be $V_{s,ph} = 6.3509\angle\theta_s°kV$ where θ_s is with respect to $V_{l,ph}$.



Also,

$$V_{s,ph} = V_{l,ph} + I_{ph}Z_{line}$$

$$\Rightarrow 6.3509\angle\theta_s°kV = |V_{l,ph}|\angle 0°V + 524.8639\angle -31.7883° \times (1 + j5)\Omega$$

The above equation has two unknowns. Solving separately for the real and imaginary parts of the equation yields $\theta_s = 17.9209°$ and $|V_{l,ph}| = 4214.143V$.

a) Line to line load end voltage is $\sqrt{3}|V_{l,ph}| = 7299.1098V$ **(Ans)**
b) The per phase internal induced voltage is

$$E_f = V_{s,ph} + I_{ph}(R_a + jX_s) = 21104.6995\angle 45.5340°V$$

Thus, torque angle is $\delta = 45.534 - \theta_s = 27.6131°$ **(Ans)**

Question 3

A 3 phase, star-connected, cylindrical rotor, 20MVA, 11kV synchronous generator is supplying half of the rated power to a unity power factor load. The terminal voltage and real power input to the machine are kept constant. A purely inductive load is now switched in parallel to the unity power factor load, so that the load draws power at 0.85 power factor lagging. What is the percentage increase in the field excitation current under the new operating condition, if the per phase synchronous reactance of the machine is 5Ω? Assume linear flux - current relationship for the field.

Solution 3

Given, $V_{t,ll} = 11kV \Rightarrow |V_{ph}| = \frac{11kV}{\sqrt{3}} = 6.3509kV$, $S_{3\varphi} = 10MVA$, load power factor $\cos\theta = 1 \Rightarrow P_{3\varphi} = 10MW$, $X_s = 5\Omega$. The magnitude of the armature phase current is

$$|I_{ph}| = \frac{P_{3\varphi}/3}{|V_{ph}|} = 524.8639A$$

Since, there is no transmission line between generator and load, the load power factor is same as source power factor. Hence, if $V_{ph} = 6.3509\angle 0°kV$, then $I_{ph} = 524.8639\angle 0°A$ as power factor is unity. The per phase internal induced voltage is

$$E_f = V_{ph} + I_{ph}(jX_s) = 6.87171\angle 22.4515°kV = (6.3508 + j2.6243)kV$$

Since, $V_{t,ll}$ and $P_{3\varphi}$ are kept constant, $|I_{ph}|\cos\theta = constant$ and $|E_f|\sin\delta = constant$ for any different operating point of the machine. Hence, with the purely inductive load in parallel to exisiting load, new power factor is $\cos\theta' = 0.85$ lagging. Hence, new armature phase current is

$$|I'_{ph}| = \frac{|I_{ph}|\cos\theta}{\cos\theta'} = 617.4869A$$

As phasor, $I'_{ph} = 617.4869\angle -\cos^{-1}0.85 = 617.4869\angle -31.7883°A$ as new power factor is lagging. Thus, new internal induced voltage is

$$E'_f = V_{ph} + I'_{ph}(jX_s) = 8.3978\angle 18.2099°kV = (7.9773 + j2.6243)kV$$

It can be noted that the imaginary part of internal induced voltage is still constant. Thus, % increase in rotor excitation current (with given linear flux - current relationship for field) is $\frac{|E_f'|-|E_f|}{|E_f|} \times 100 = 22.21\%$. **(Ans)**

Question 4

A $10kV$, star connected salient-pole synchronous generator is delivering $21MVA$ power to a 0.85 lagging power factor load at rated voltage. What is the torque angle? Quadrature axis reactance of generator is 3.38Ω. Neglect armature resistance.

Solution 4

Given, $V_{t,ll} = 10kV \Rightarrow |V_{ph}| = \frac{10kV}{\sqrt{3}} = 5.7735kV$, $S_{3\varphi} = 21MVA \Longrightarrow S_\varphi = 7MVA$, load power factor $\cos\theta = 0.85$ lagging, $X_q = 3.38\Omega$. The armature phase current is

$$|I_{ph}| = \frac{S_\varphi}{|V_{ph}|} = 1212.4356A$$

Since, there is no explicit transmission line between generator and load, the load power factor is same as the source power factor. Hence, if $V_{ph} = 5.7735\angle 0° kV$, then $I_{ph} = 1212.4356\angle -\theta = 1212.4356\angle -31.7883° A$ as power factor is lagging. From the voltage and current relationships of the salient-pole generator,

$$|V_{ph}|\sin\delta = I_q X_q$$
$$I_q = |I_{ph}|\cos(\theta + \delta)$$

where, δ is the torque angle. Substituting I_q from second equation to first equation and after rearranging terms,

$$\delta = \tan^{-1}\left\{\frac{|I_{ph}|X_q\cos\theta}{|V_{ph}| + |I_{ph}|X_q\sin\theta}\right\}$$

Since, all terms in LHS of above equation are known, hence, on substituting the known values, $\delta = 23.7079°$. **(Ans)**

Question 5

Calculate the inductive reactance in Ω/km of a bundled $60Hz$ three phase line having three ACSR *Rail* conductors per bundle with $45cm$ spacing between conductors in a bundle. The three phase line has flat horizontal spacing with $9m$ as distance between adjacent conductors. Consider std. GMR of ACSR rail conductor as 0.01176 m

Solution 5

Given GMR of ACSR *Rail* conductor is $0.01176\,m$. Each phase of line consists of three such bundled conductors with spacing between them as $45cm$, i.e. $0.45m$. The effective GMR due to bundling is $GMR = \sqrt[3]{0.01176 \times 0.45 \times 0.45} = 0.13356m$

The GMD for the given distance between conductors is

$$GMD = \sqrt[3]{9 \times 9 \times 18} = 11.3393m$$

The inductance per phase is ($1mile = 1609.344m$)

$$L = 2 \times 10^{-7}\ln\left(\frac{GMD}{GMR}\right) H/m = 8.88296 \times 10^{-7} H/m$$

Inductive reactance per phase is

$$X_l = 2\pi f L = 3.348796 \times 10^{-4}\Omega/m = 0.334879\Omega/km$$