Synchronising power

- A synchronous machine tends to maintain synchronism with the supply (or network in the case of a generator on an infinite bus
- Suppose that a generator is operating at a steady-state load point P_1 at δ_1 but the speed of the generator starts to fall. Then the load angle starts to reduce since the rotor and stator field are not in perfect synchronism (i.e. some relative velocity occurs). This causes the power delivered to the grid to drop and so reducing the mechanical load on the prime mover and so the speed starts to correct itself and return the load angle to its original value.
- The generator will stay synchronised with the grid, providing the change in load angle brings about a change in power called the synchronising power
- For a generator operating at a steady state-point, the power being delivered is

$$P = -\frac{V_a E_a \sin\delta}{X_s}$$

The synchronising power *per radian* is given by:

$$p_s = \frac{dP}{d\delta} = -\frac{V_a E_a \cos\delta}{X_s}$$

Which is a maximum for δ=0° and a minimum for δ=90°.

Numerical examples

- Returning to the 4 operating conditions considered previously for the 1.5MW, 8 pole machine, then the synchronising power per can be established at the various operating points:

  a) On no load with 1.0 per unit excitation:
  Recalling that δ = 0° for this case, then:

$$p_s = \frac{dP}{d\delta} = -\frac{V_a E_a \cos\delta}{X_s} = \frac{1 \times 1 \times 1}{1.25} = 0.80\, p.u\, per\, rad(elec)$$
$$= 1.20MW\ per\ rad\ (elec)$$

  Since this is a 8 pole machine (i.e. 4 pole pairs) the synchronising power can be expressed in terms of mechanical radians or degrees

$$p_s = 0.80 \times 4 = 3.2\, p.u\, per\, rad\ (mech) = 0.056\, p.u\, per\, {}^o mech$$

  If required, then this can be expressed in terms of a synchronising torque per measure of angular displacement, noting that for an 8-pole machine the synchronous speed on a 50Hz network is 750rpm (78.5 rad/s) :

$$T_s = \frac{3.2 \times 1.5 \times 10^6}{78.5} = 61\ kNm\ per\ rad\ (mech)$$

b) As a compensator with 2.0 per unit excitation

Substituting in for Ea = 2.0 p.u; δ = 0°; Va = 1.0 p.u yields:

$$p_s = \frac{dP}{d\delta} = -\frac{V_a E_a \cos\delta}{X_s} = \frac{1 \times 2 \times 1}{1.25} = 1.60\, p.u\ per\ rad(elec) = 2.4MW\ per\ rad\ (elec)$$

c) As a motor on full-load (1.0 per unit) operating at leading power factor of 0.87

Substituting in for Ea = 2.12 p.u; δ = -36°; Va = 1.0 p.u yields:

$$p_s = \frac{dP}{d\delta} = -\frac{V_a E_a \cos\delta}{X_s} = \frac{1 \times 2.12 \times 0.81}{1.25} = 1.37\, p.u\ per\ rad(elec) = 2.06MW\ per\ rad\ (elec)$$

d) As a generator delivering a real power of 0.75 per unit at a power factor of 0.78 leading

Substituting in for Ea = 2.0 p.u; δ = -+28°; Va = 1.0 p.u yields:

$$p_s = \frac{dP}{d\delta} = -\frac{V_a E_a \cos\delta}{X_s} = \frac{1 \times 2 \times 0.88}{1.25} = 1.41\, p.u\ per\ rad(elec) = 2.12MW\ per\ rad\ (elec)$$

In the above 3 cases, we can express these synchronising powers in mechanical radians or degree or convert them to synchronising torques using the same approach as in (a)

Hunting

- The synchronising torque which retards or accelerates the rotor to maintain synchronisation imparts to the rotating system and angular acceleration and hence a change in kinetic energy.
- A machine will therefore over-swing beyond the steady state equilibrium angle, build up an opposing synchronising torque which retards it.
- This leads to an oscillation about the steady state angle, a process which is referred to as hunting.
- In order to manage this in practice, it is necessary to dissipate the kinetic energy associated with this hunting, by introducing appropriate damping.
- The natural undamped angular frequency of the hunting is given by:

$$\omega_0 = \sqrt{\frac{T_s}{J}}$$

Where T_s is the synchronising torque and J is the moment of inertia of the rotating parts.

Need to ensure that T_s is expressed in terms of Nm / rad (mech or elec) as this is the SI unit which yields and angular frequency in rad/s (mech or elec) - do not use degrees in this expression

Hunting – numerical example

Consider the 4 operating points defined previously for the 1.5MW, 8-pole machine and noting that the moment of inertia of the rotating components is 3100 kgm^{-2}

a) On no load with 1.0 per unit excitation:

$$\omega_0 = \sqrt{\frac{61000}{3100}} = 4.44\, rad(mech)\ /s$$

i.e. an oscillation frequency of 0.71 Hz or one complete swing in 1.4s

b) As a compensator with 2.0 per unit excitation

$$\omega_0 = \sqrt{\frac{122000}{3100}} = 6.28\, rad(mech)\ /s$$

c) As a motor on full-load (1.0 per unit) operating at leading power factor of 0.87

$$\omega_0 = \sqrt{\frac{105000}{3100}} = 5.80\, rad(mech)\ /s$$

d) As a generator delivering a real power of 0.75 per unit at a power factor of 0.78 leading

$$\omega_0 = \sqrt{\frac{108000}{3100}} = 5.90\, rad(mech)\ /s$$

Important to note that the undamped hunting frequency changes with load condition