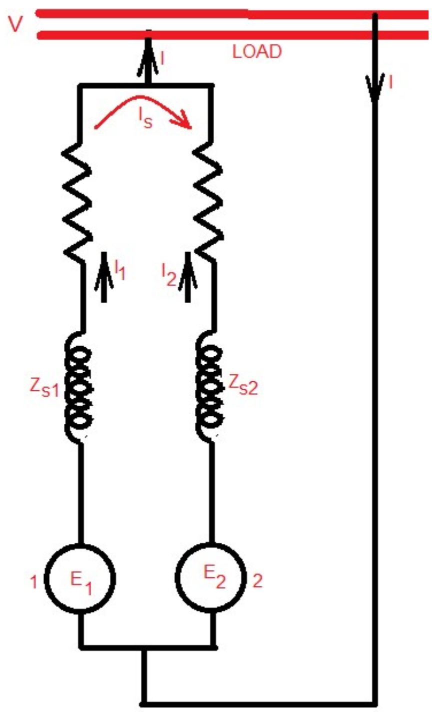
Parallel Operation of Synchronous Generators:

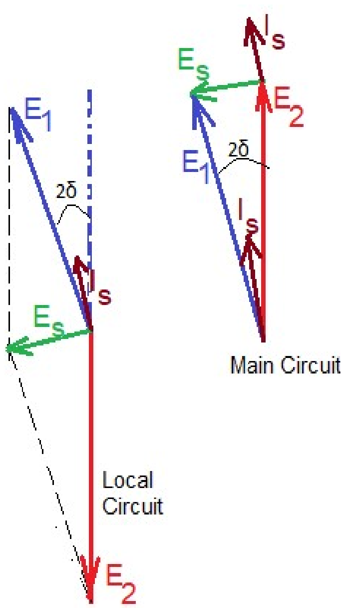
In the power systems generators are connected to the nodes of o large grid composed of a network of transformers and transmission lines. A national grid may comprise hundreds of generators and hundreds of kilometers of transmission line. Here we will consider parallel operation of two finite size synchronous generators



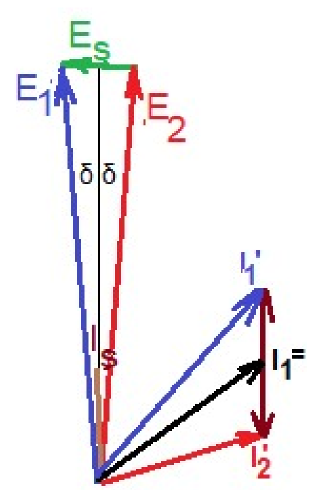
(a)

When two generators are connected in parallel , they have an inherent tendency to remain in step, on account of the changes produced in their armature currents by a divergence of phase. Consider two identical generators 1 and 2 are operating in parallel, as shown in fig. (a). with respect to the load their EMF-s are in phase; but respect to the local circuit formed by the two generators the EMFs are in phase opposition.

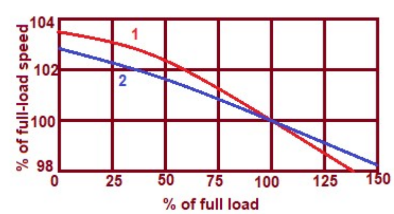
Suppose there is external load. If due to some reason machine ‘1’ accelerates, E_1 goes ahead of E_2. The resulting phase difference is 2δ. EMFs are no longer in phase opposition in the local circuit., so there will be a local EMF E_s, which will circulate a current I_s. As the local circuit is predominately reactive, I_s lags E_s by 90^o. So, machine ‘1’ produces power $P \approx E_1 I_s$ as a generator and supplies power to machine ‘2’ acting as a motor. So, machine ‘1’ decelerates and machine ‘2’ accelerates. Within the limits therefore it is not possible to destroy synchronism of two synchronous generators operating in parallel, as divergence of their angular position results in production of synchronizing power, which loads the forward machine and accelerates the backward machine.



(b)



(c)



(d)

The development of synchronizing power is due to predominating reactive circuit. If the circuit was resistive, then the synchronizing current will be in phase quadrature with the generated EMFs and would not contribute any power to slow the faster and speed up the lower machine.

If the machines are equally loaded, the synchronizing power is developed to reduce the load of the lower machine and to increase the load of the faster machine; as shown in fig. (c).

Actually in practice the machines are not identical. Actually it is not essential for the machines to be identical, nor to have equal excitation or power supplies. In general machines will have different synchronous impedances Z_{s1} and Z_{s2}; different EMFs E_1 and E_2 and different speed regulations. When two machines are operating in parallel, active and reactive power supplied to the common load are controlled by their prime mover inputs and field excitations respectively. The outputs from the prime movers are controlled by governors. The speed governors belong to the class of regulating system which are of type zero, a reduction of speed is necessary to increase the developed power. As the speed (frequency) droops, an error signal is generated. This error signal is utilized to control the throttle for regulating the turbine speed. Unless the governor speed – load characteristics are identical, the machines can never share the load in accordance with their ratings, the load will be shared accordance to the relative load values at the running frequency, as the synchronous machines must run at same speed.

From fig. (b), the common terminal voltage is

$$V = E_1 - I_1 Z_{s1} = E_2 - I_2 Z_{s2} = IZ \ \ and \ \ I_1 + I_2 = I$$

$$\therefore \ E_1 - E_2 = I_1 Z_{s1} - I_2 Z_{s2} \ \ or \ I_1 = \frac{E_1 - E_2 + I_2 Z_{s2}}{Z_{s1}}$$

$$E_1 = I_1 Z_{s1} + IZ = I_1(Z_{s1} + Z) + I_2 Z$$

$$E_2 = I_2 Z_{s2} + IZ = I_2(Z_{s2} + Z) + I_1 Z$$

$$E_1 = I_1(Z_{s1} + Z) + I_2 Z = \frac{E_1 - E_2 + I_2 Z_{s2}}{Z_{s1}}(Z_{s1} + Z) + I_2 Z$$

$$or, E_1 Z_{s1} = (E_1 - E_2 + I_2 Z_{s2})(Z_{s1} + Z) + I_2 Z\, Z_{s1}$$

$$or, E_1 Z_{s1} = (E_1 Z_{s1} - E_2 Z_{s1} + I_2 Z_{s2} Z_{s1}) + (E_1 Z - E_2\, Z + I_2 Z_{s2} Z) + I_2 Z\, Z_{s1}$$

$$or, \quad (E_2 - E_1)Z + E_2 Z_{s1} = I_2 Z_{s2} Z_{s1} + I_2 Z\,(Z_{s1} + Z_{s2})$$

$$or, I_2 = \frac{(E_2 - E_1)Z + E_2 Z_{s1}}{Z_{s2} Z_{s1} + Z\,(Z_{s1} + Z_{s2})}$$

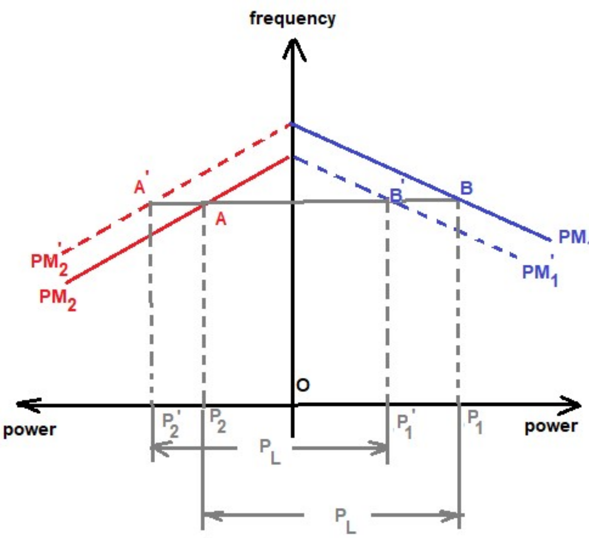
$$\therefore \ I_1 = \frac{(E_1 - E_2)Z + E_1 Z_{s2}}{Z_{s2} Z_{s1} + Z\,(Z_{s1} + Z_{s2})} \quad and \ \ I = \frac{E_1 Z_{s2} + E_2 Z_{s1}}{Z_{s2} Z_{s1} + Z\,(Z_{s1} + Z_{s2})}$$

$$\therefore terminal\ voltage\ V = IZ = \frac{E_1 Z_{s2} + E_2 Z_{s1}}{Z_{s2} Z_{s1}/Z + (Z_{s1} + Z_{s2})}$$

$$also, \ I_1 = (E_1 - V)/Z_{s1} \ \ ; \ \ I_2 = (E_2 - V)/Z_{s2} \ and \ I_s = (E_1 - E_2)/(Z_{s1} + Z_{s2})$$

Active Power Sharing of Two Generators with Similar Speed-Power Characteristics:

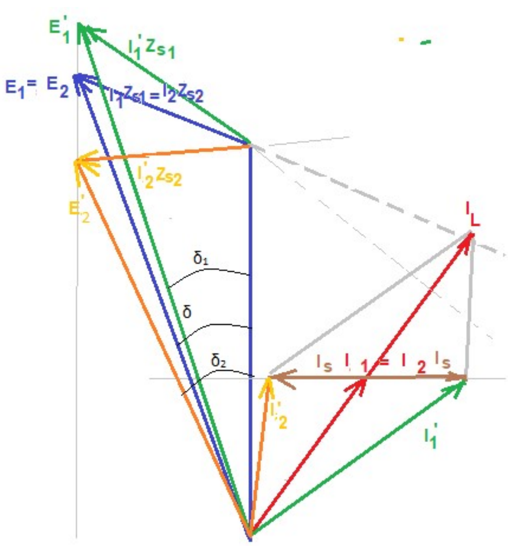
The active power sharing depends on the slop of the Speed-Power characteristics. These characteristics can be slided up or down by adjusting the set points of the governors.



(e)

For characteristics PM_1 and PM_2 the total load P_L is shared by the alternators are P_1 and P_2 at rated frequency. If we want to increase the load on generator 2, then its power frequency characteristics must be raised and if we want to keep the frequency constant then characteristics of generator 2 must be lowered. Such that new sharing is P_1' and P_2'. $P_1 - P_1' = P_2' - P_2 = \Delta P$ amount of load is transferred from generator '1' to generator '2'. If the generator setting of only one machine is changed, then the frequency will change. During the process the system undergoes load frequency transients which would soon die out (assuming the governors are properly damped) and steady load frequency conditions established with new load sharing.

Changing excitation of the parallel operating generators with constant prime mover input, affects the terminal voltage and the reactive power flow.



(f)

let us consider two generators with same excitation E_1=E_2, are operating in parallel. If Z_{s1}=Z_{s2} then I_1=I_2. Now if excitation of generator 1 is increased to E_1' and that of generator 2 is decreased to E_2', then circulating current Is will start flowing and currents of the two generators will be I_1' and I_2', such that $I_L = I_1' + I_2'$. As the mechanical input is constant the active power is constant. The reactive power supplied by machine '1' increases and that by machines '2' decreases. If the excitation of one of the machines is only changed, the terminal voltage will change.

Problem 1:

Two generators operating in parallel have following characteristics:

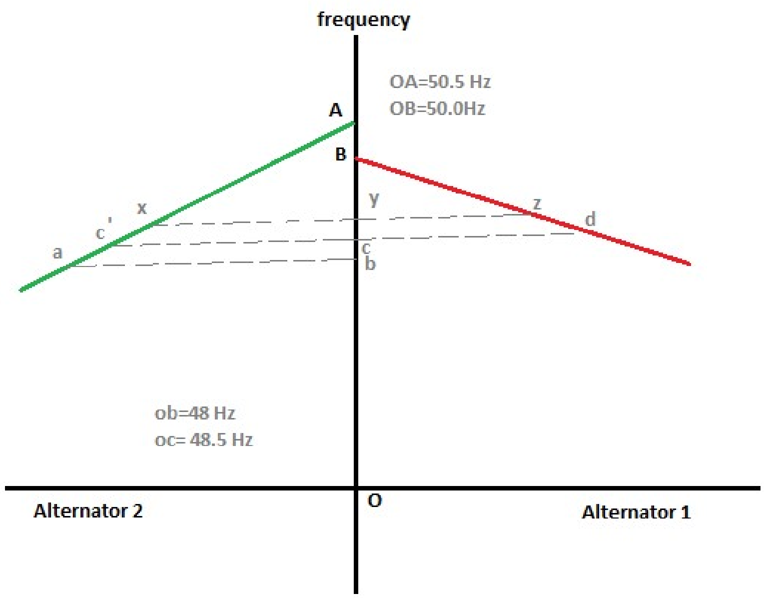
Alternator 1: capacity 700 kW; frequency drops from 50 Hz to 48.5 Hz at full load

Alternator 2: capacity 700 kW; frequency drops from 50.5 Hz to 48.0 Hz at full load

Speed regulations are linear. Calculate:

a) How a load of 1200kW is shared and what is the bus bar frequency?
b) What is the maximum load these two units can deliver

Solution:



$$xy + yz = 1200\ kW$$

$$\Delta Aab\ and\ \Delta Axy\ are\ similar$$

$$\therefore \frac{xy}{ab} = \frac{Ay}{Ab}\ ;\ \therefore \frac{xy}{700kW} = \frac{oA - oy}{oA - ob}\ \therefore xy = \frac{50.5 - f}{50.5 - 48} \times 700 = \frac{700}{2.5}(50.5 - f)$$

$$\Delta Bcd\ and\ \Delta Byz\ are\ similar$$

$$\therefore \frac{yz}{cd} = \frac{By}{Bc}\ ;\ \therefore \frac{yz}{700kW} = \frac{oB - oy}{oB - oc}\ \therefore yz = \frac{50.0 - f}{50.0 - 48.5} \times 700 = \frac{700}{1.5}(50.0 - f)$$

$$xy + yz = 1200\ kW\ \therefore \frac{700}{2.5}(50.5 - f) + \frac{700}{1.5}(50.0 - f) = 1200$$

$$\therefore \frac{12}{7} = \frac{151.5 - 3f + 250 - 5f}{7.5}\quad \therefore f = 48.58\ Hz$$

$$load\ on\ alternator\ 2 = xy = \frac{700}{2.5}(50.5 - 48.58) = 537.6\ kW$$

$$load\ on\ alternator\ 1 = 1200\ kW - 537.6\ kW = 662.4\ kW$$

(b)

Observation reveals that alternator 1 will be loaded first. Max. load on alternator 1 is for point 'd'. cd=700 kW is obtained at 48.5 Hz. Corresponding to this output of alternator 2 will be cc'

$$\Delta Aab\ and\ \Delta Acc'are\ similar$$

$$so\ \frac{cc'}{ab} = \frac{Ac}{Ab}\quad ;\quad \therefore \frac{cc'}{700kW} = \frac{oA - oc}{oA - ob}\quad \therefore xy = \frac{50.5 - 48.5}{50.5 - 48} \times 700 = \frac{700}{2.5} \times 2 = 560kW$$

$$\therefore maximum\ load = 700kW + 560\ kW = 1260\ kW$$

Problem 2:

Three alternators are operating in parallel. Bus frequency is 50 Hz. Loads are:

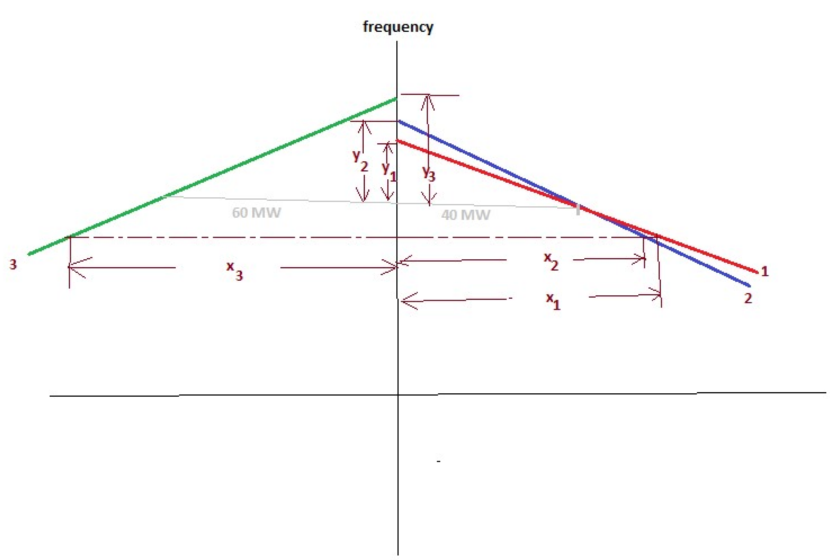
Alternator 1- 40 MW; Alternator2– 40 MW and Alternator3 – 60 MW

Rating of each alternator 100MW. Governor setting for alternators are such that frequency drop from no load to full load are

Alternator 1- 1.25 Hz; Alternator2– 1.50Hz and Alternator3 – 2.00Hz

How will the three alternators share a total load of 250 MW? What is the bus frequency?

Solution:



For alternator 1

$$\frac{y_1}{40MW} = slope\ of\ regulation\ curve = \frac{frequency\ drop\ from\ no\ load\ to\ full\ load}{full\ load} = \frac{1.25}{100}$$

$$\therefore\ y_1 = \frac{4}{10} \times 1.25 = 0.50\ Hz\ \ \therefore no\ load\ frequency = 50\ Hz + 0.5\ Hz = 50.5\ Hz$$

For alternator 2

$$\frac{y_2}{40MW} = slope\ of\ regulation\ curve = \frac{frequency\ drop\ from\ no\ load\ to\ full\ load}{full\ load} = \frac{1.5}{100}$$

$$\therefore\ y_2 = \frac{4}{10} \times 1.5 = 0.60\ Hz\ \ \therefore no\ load\ frequency = 50\ Hz + 0.6\ Hz = 50.6\ Hz$$

For alternator 3

$$\frac{y_3}{60MW} = slope\ of\ regulation\ curve = \frac{frequency\ drop\ from\ no\ load\ to\ full\ load}{full\ load} = \frac{2}{100}$$

$$\therefore\ y_3 = \frac{6}{10} \times 2 = 1.2\ Hz\ \ \therefore no\ load\ frequency = 50\ Hz + 1.2\ Hz = 51.2\ Hz$$

For load of 250 MW:

For alternator 1

$$\frac{40}{x_1} = \frac{y_1}{50.5 - f} = \frac{0.5}{50.5 - f} \quad \therefore\ x_1 = 40 \times \frac{50.5 - f}{0.5}$$

For alternator 2

$$\frac{40}{x_2} = \frac{y_2}{50.6 - f} = \frac{0.6}{50.6 - f} \quad \therefore\ x_2 = 40 \times \frac{50.6 - f}{0.6}$$

For alternator 3

$$\frac{60}{x_3} = \frac{y_3}{51.2 - f} = \frac{1.2}{51.2 - f} \quad \therefore\ x_3 = 60 \times \frac{51.2 - f}{1.2}$$

$$x_1 + x_2 + x_3 = 250$$

$$\therefore 40 \times \frac{50.5 - f}{0.5} + 40 \times \frac{50.6 - f}{0.6} + 60 \times \frac{51.2 - f}{1.2} = 250$$

$$or, 80 \times (50.5 - f) + 66.67 \times (50.6 - f) + 50 \times (51.2 - f) = 250$$

$$or, \quad 4040 - 80f + 3373.5 - 66.67f + 2560 - 50f = 250$$

$$or, \quad 196.67f = 9973.5 - 250 = 9723.5$$

$$\therefore f = 49.44\ Hz \quad and \quad x_1 = 84.8\ MW;\ \ x_2 = 77.3\ MW\ ;\ \ x_3 = 88\ MW$$