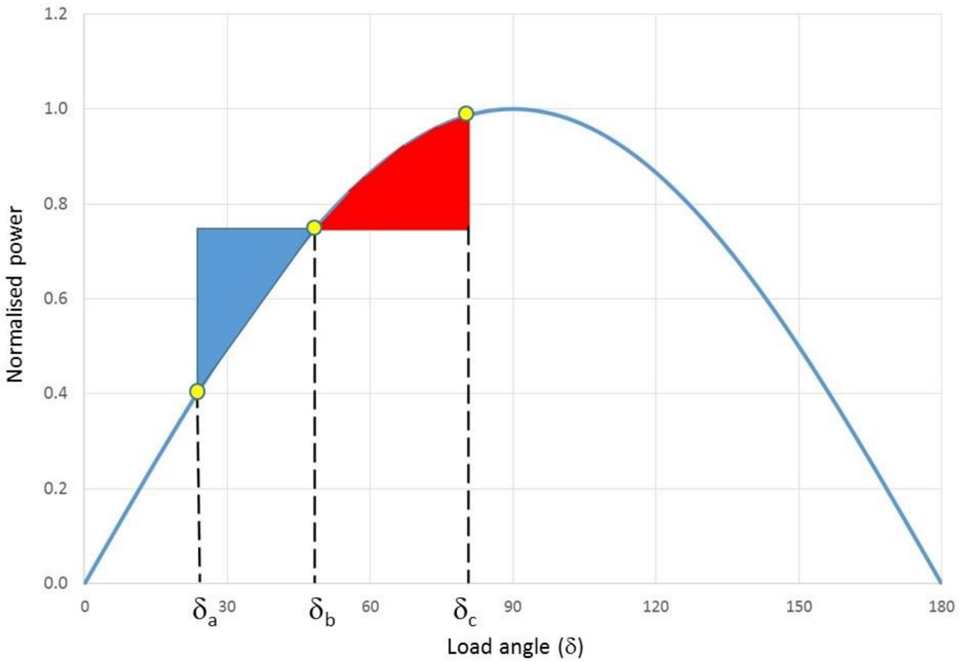
Transient Stability

- Transient stability captures the capability of a system to return to a steady-state operating condition following a large disturbance. Examples include:
    - Loss of major load on the network
    - Loss of a large generator on the network
    - Fault on the network
- Dealing firstly with the less extreme cases of load changes on the network (shedding of the load or the loss of a generator elsewhere)
- Steady-state analysis would suggest that an additional load on the network could be met providing the resulting value of δ does not exceed 90°
- However, as shown when considering synchronising torque and hunting, there is a dynamic element which must be considered with any transient behaviour

  such consideration tend to reduce operating values of δ to much less than 90°
- In principle, the power of the mechanical prime-mover and the magnitude of the excitation can be controlled to accommodate load changes in a controlled manner.
- However, such remedies are slow acting in the context of transient stability and hence it is commonplace to model stability assuming that both these features remain constant during the important initial stages of transient load changes (and indeed faults as discussed later). This provides a prudent worst case.

Load changes - Swing curve

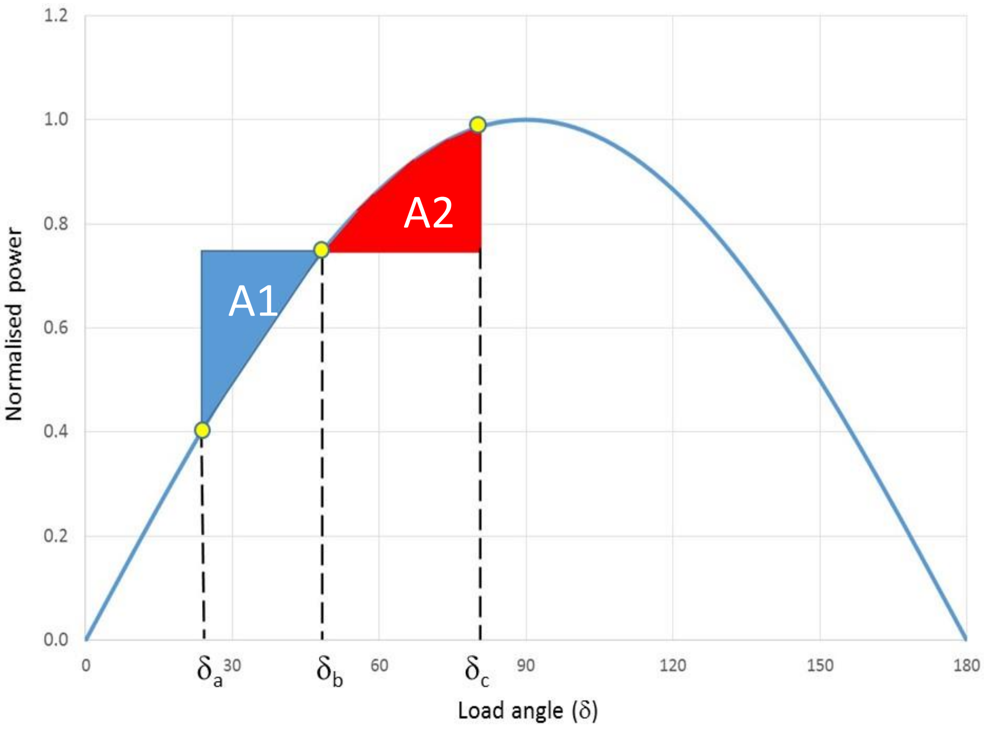
- In a 3-phase non-salient synchronous machine, the power for a given value of V_a and excitation is proportional to sin δ
- Consider a case where the output power is initially P_a with a load angle δ_a
- If the load on the generator suddenly increases to P_b, and assuming that the mechanical prime mover and excitation controller do not respond immediately, then there will be an deficit of torque provided by the mechanical prime-mover and so the rotor will decelerate, increasing the load angle towards $\delta_{b.}$



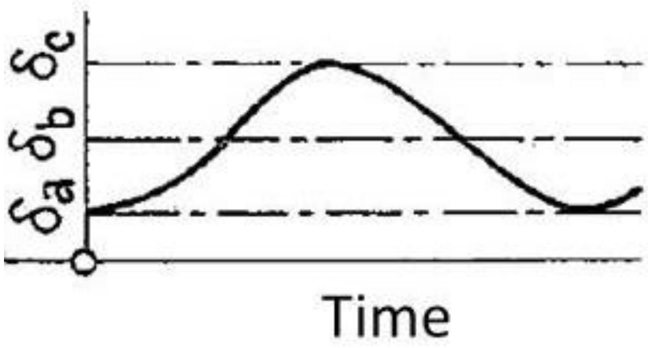
- In effect, the power deficit is being made up by the stored kinetic energy
- However, when the load angle reaches δ_b the rotor has acquired a relative velocity (relative to the rotating field) by virtue of the net deceleration applied between δ_a and δ_b so the load angle continues to increase beyond δ_b
- When the load angle increase beyond δ_b then there is power supplied by the generator is greater than that required by the load and so the synchronising torque reverses slowing the rotor relative velocity until at δ_c it reaches zero relative velocity. The rotor is then further accelerated, causing δ to reduce back towards δ_b

- The decelerating and accelerating energies are represented by the shaded energy.
- As will be apparent from the previous discussion, there must be sufficient torque energy on the 'other side' of the new load point to 'catch' the rotor and bring it to a standstill before it loses synchronism.
- Interestingly, the machine can be transiently stable even when the excursion of δ exceed $90°$

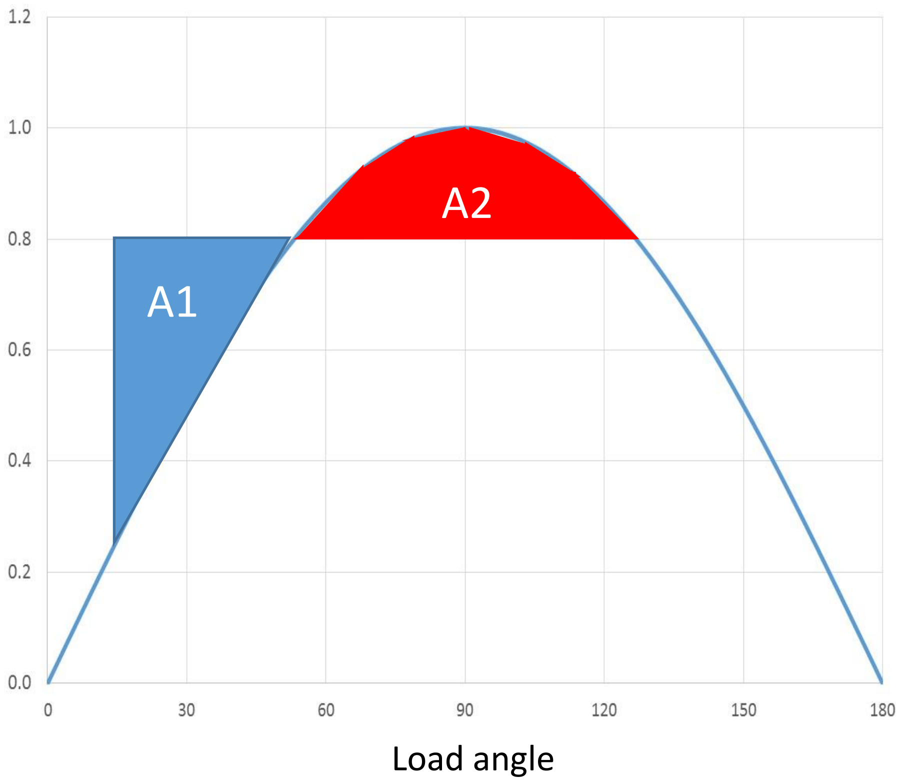
Stable operation



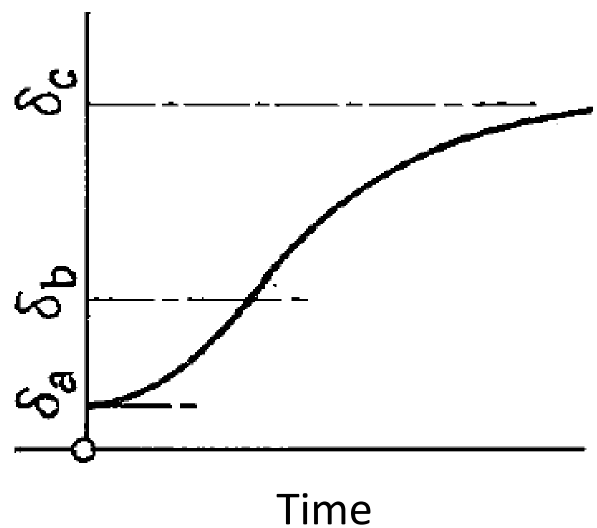
In this case the over-swing energy is able to readily match the area A1 and the rotor will (in the absence of any damping) oscillate about δ_b, although though not necessarily symmetrically in terms of δ



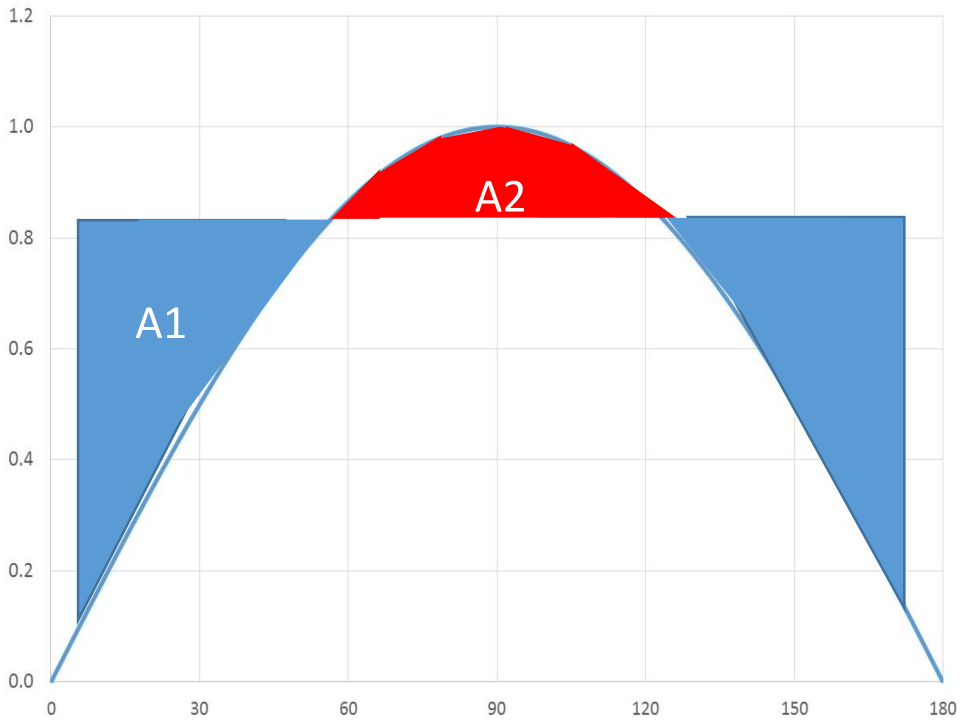
Critically stable



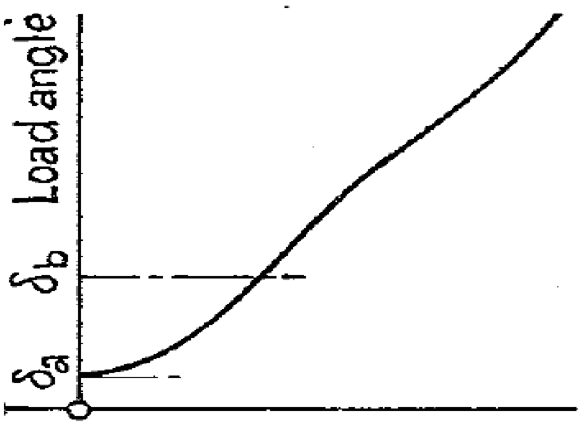
- In this case, the maximum possible over-swing energy (i.e. for values of δ which result in an excess of power) only just matches the A1 and hence the system is on the very limit of stability



Unstable



- In this case, the maximum possible over-swing energy (i.e. for values of δ which result in an excess of power) is not sufficient to match A1 and the rotor continues past the point at which there is a further deficit (rhs shaded area) and the load angle continues to increase into an unstable mode



Swing curves with change in effective load impedance on the generator

The preceding analysis was based on a fixed value of effective reactance to an infinite bus. If the terminals of the machine can be regarded as an infinite bus, then this effective reactance was simply the synchronous reactance of the generator.

A more realistic model might be that there is some additional reactance between the generator and the point on the bus that can be regarded as voltage stiff, e.g. connection lines etc.

Consider a numerical example in which the effective reactance changes from healthy operation through a fault period and a subsequent period after the fault has been cleared.

A 25MVA, 33kV (rms), 50Hz, 2-pole, 3 phase generator is delivering a steady load of 20MW over a transmission line to an infinite busbar. A 3 phase fault occurs and the fault is then cleared after an interval. Using the following data, establish the load angle by which the fault must be cleared if stability is to be retained.

Generator emf = 34kV rms line to line
Infinite busbar voltage = 33kV line to line
Effective reactance to infinite busbar

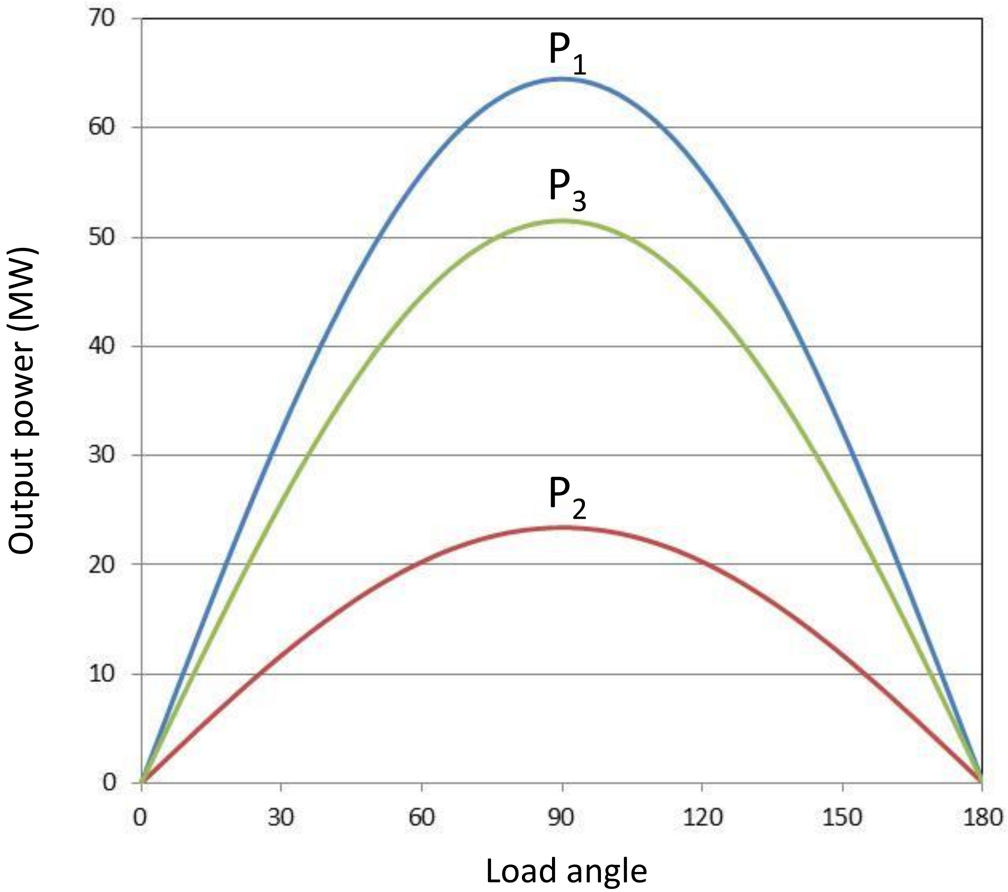
Prior to fault = 17.4 Ω/phase
During fault = 48.0 Ω/phase
After fault clearance = 21.8 Ω/phase

For each of the 3 intervals, the peak output power can be calculated from:

$$P = -\frac{V_a E_a \sin\delta}{X_s}$$ with $\delta = 90°$ Note: X_s is the per phase value

Which yields: P_1 = 64.5 MW, P_2 = 23.4MW and P_3 = 51.5MW

We can plot the power versus load angle characteristic for the machine during the 3 intervals



Initially the generator is operating at 20MW on the 64.5MW characteristic which yields a load angle of

$$\delta = sin^{-1}\left(\frac{PX_s}{EV}\right) = 18^{\circ}$$

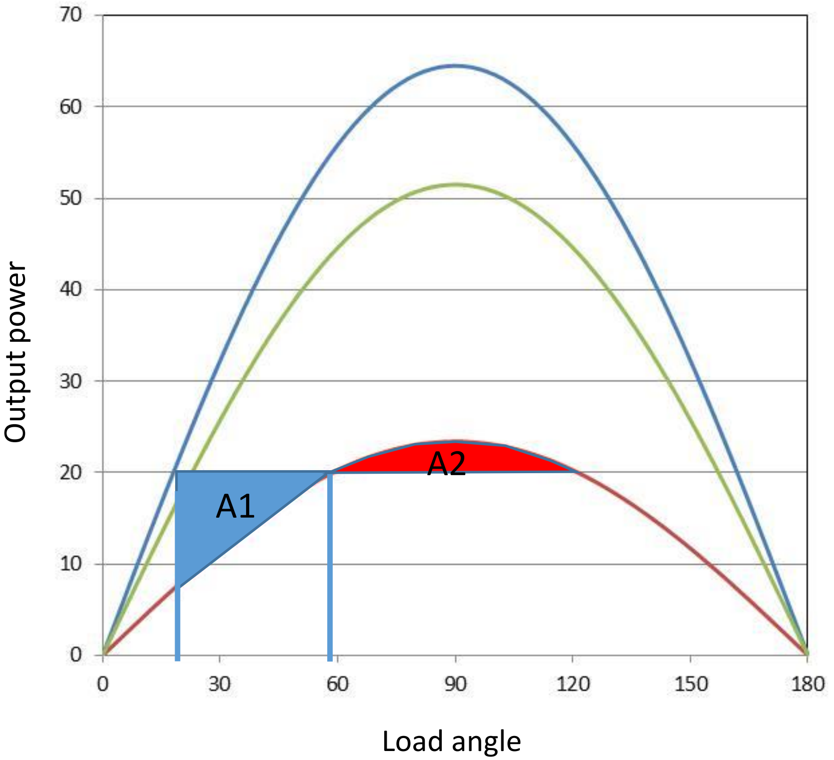
When the fault occurs, the generator is on the 23.4MW characteristic and so the load angle changes to

$$\delta = sin^{-1}\left(\frac{PX_s}{EV}\right) = 59^{\circ}$$

When the fault occurs, the excess power causes acceleration of the rotor towards this greater load angle

The area A_2 is less than A_1 and hence if the fault persists then the generator is unstable and loses synchronism

However if the fault is cleared with a sufficiently short interval, then there may be an opportunity to recover synchronous operation



By trial, it can be established that if the fault is cleared before $\delta = 138^\circ$ then the areas A_2 and A_4 just match A_1 and A_3 and so synchronism is maintained (but only just!)

By solving the equations of motion for the rotor (a procedure which is commonly done in power systems analysis by time-stepping) then the maximum clearance time for the fault can be established.