

Module 8

**GENERATOR AND
TRANSMISSION LINE
STABILITY**

OBJECTIVES:

After completing this module you will be able to:

- 8.1 Explain, with the aid of equivalent circuits and vector diagrams, how the load angle varies with load in each of the following:
 - a) A generator,
 - b) A transmission line,
 - c) A generator and transmission line.
- 8.2 Explain each of the following using the “power transfer curve”:
 - a) The relationship between active power transfer and load angle,
 - b) The relationship between load angle and steady state stability.
- 8.3 List and explain:
 - a) The factor influencing steady state stability,
 - b) The problem caused by steady state instability,
 - c) One precaution and two actions that are taken to minimize the risk of steady state instability occurring.
- 8.4
 - a) Explain the difference between steady state stability and transient stability.
 - b) List and explain the three factors which can cause transient instability in the generator and the four factors which can cause transient instability in the transmission lines.
 - c) List and explain the precautions or actions taken to minimize the risk of transient instability occurring for each of the factors in objective 8.4 b).
- 8.5 Explain the consequence of transient instability.
- 8.6 Using single or multiple power transfer curves, explain generator behavior during a transient.

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INSTRUCTIONAL TEXT

INTRODUCTION

In course 230.2, Electrical Equipment, generator off load and on load operation were considered, and diagrams were drawn showing the effects of armature reaction. In the first part of this module, the following conditions are examined:

- a) how the load angle in a generator varies with load,
- b) how the load angle in a transmission line varies with load,
- c) how the composite load angle for the generator and line varies with load,
- d) the relationship between load angle and active power transfer,
- e) the relationship between load angle and steady state stability.

The later part of this module deals with transient stability, where the behavior of the generator and lines are considered under fault conditions.

STEADY STATE STABILITY

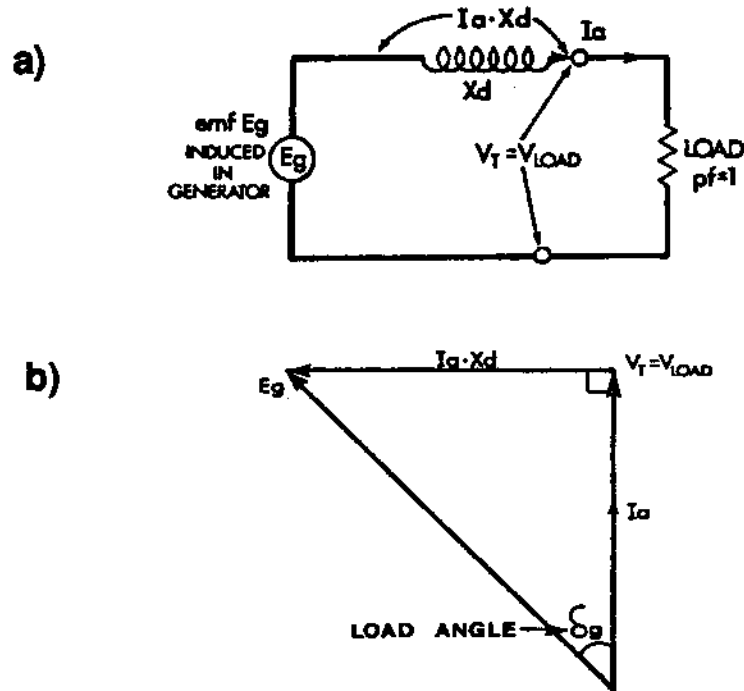
Variation of Generator Load Angle With the Load

Obj. 8.1 a) ⇔

Lesson 230.25-1 showed that as a generator is loaded, the load angle increased. The magnitude of the load angle depends upon the generator load current, the generator reactance and the power factor. Since the internal reactance of the generator remains unchanged, it will be neglected as a variable.

NOTES & REFERENCES

Figure 8.1 a) shows the equivalent circuit for a generator directly connected to a resistive ($\text{pf}=1$) load. The product of the load current I_a and the generator internal reactance X_d produces the internal voltage drop $I_a X_d$. For a given load current, I_a and terminal voltage, V_T , a load angle of δ_g is produced in the generator. Figure 8.1 b) shows the resulting vector diagram.

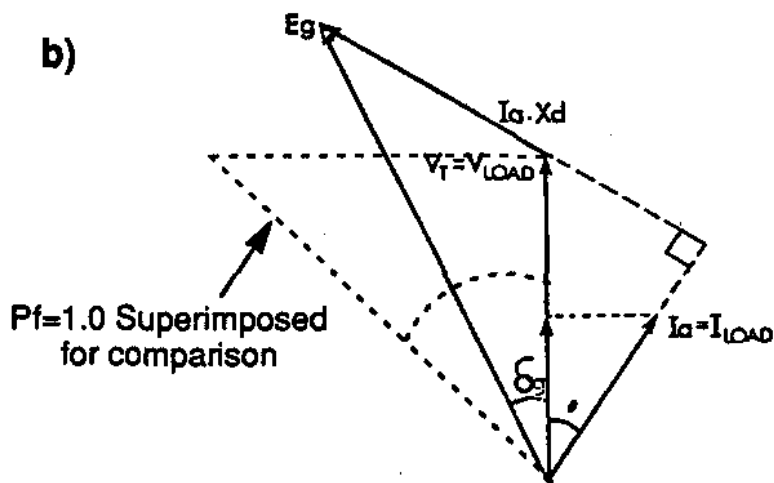
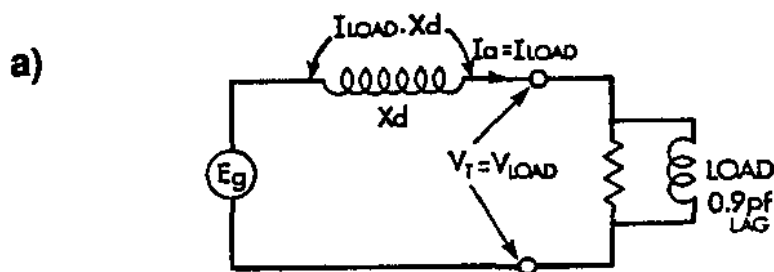


Figures 8.1a) & b): EQUIVALENT CIRCUIT FOR A GENERATOR OPERATING AT PF=1 WITH VECTOR DIAGRAM

From this diagram we can see the relationship between $I_a X_d$ and the load angle. For example, if the load current I_a is increased (all else constant), the $I_a X_d$ product increases, causing the load angle to increase. (Recall the effect of armature reaction – ie. the increase in stator current causes an increase in magnetic flux around these windings. Since this increase in flux opposes rotor flux, the terminal voltage will drop, requiring an increase in field current to maintain terminal voltage – ie. E_g must also increase to compensate for an increase in internal voltage drop $I_a X_d$.)

NOTES & REFERENCES

Figures 8.2 a) and b) show the conditions when the same generator is connected to a 0.9 pf lag load while delivering the same value of active current (MW load) as in the previous example. Thus, the active power and the terminal voltage V_T are the same as those in Figures 8.1 a) and b). But as the power factor is now 0.9 lag, the load current has increased (it now has both active and reactive components). By increasing the load current, the product $I_L X_d$ has increased ($I_L X_d$ is still at 90° to I_L , since it is purely reactive*), with the results shown in Figure 8.2 (b)). From this diagram, we can clearly see that the load angle δ_L has decreased. (As in the previous example, an increase in load current causes more armature reaction, which requires AVR action to restore the terminal voltage V_T)



Figures 8.2a) & b): EQUIVALENT CIRCUIT FOR A GENERATOR OPERATING AT 0.9 PF LAG WITH VECTOR DIAGRAM

* This was discussed in the 230.25-2 Electrical Equipment Course.

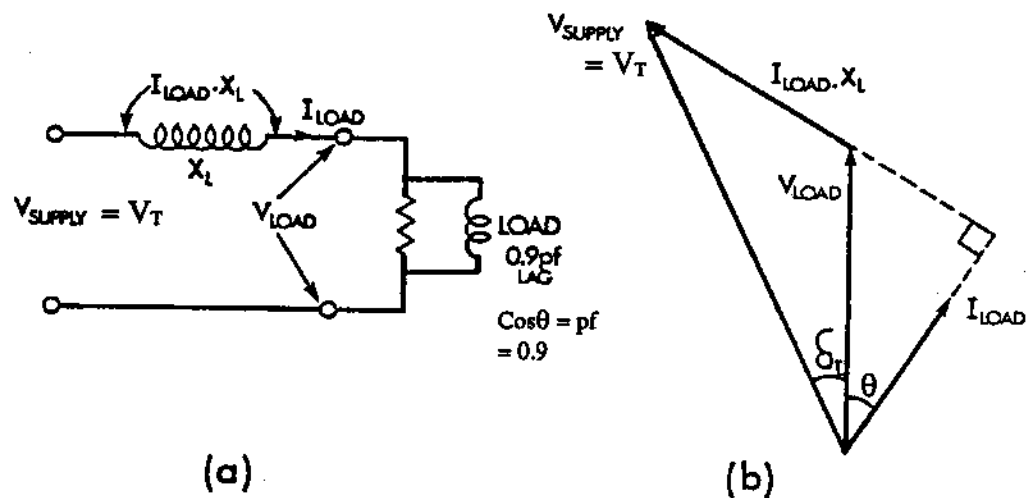
NOTES & REFERENCES

Further diagrams can be drawn to show that, when operating with a leading power factor and delivering the same active current, the $I_L X_d$ component will also increase (current again has active and reactive components), but the load angle δ_L will increase. (In this case, rotor current may require a decrease to maintain terminal voltage. This is because the magnetic field produced around the stator winding will provide less weakening to the field flux – less armature reaction.)

Variation of Transmission Line Load Angle With Load

Obj. 8.1 b) ⇔

When a transmission line is loaded, a load angle δ_L is produced across the line. Figure 8.3 a) shows the equivalent circuit for a line having a reactance of X_L ohms and load is operating with a pf of $\cos \theta$ lag. The resistance of the line is very small compared with its reactance, and will be neglected in this lesson. When the line is operating at 0.9 pf lag, the supply voltage has to be considerably larger than the load voltage (which is kept constant). This is illustrated in the vector diagram, Figure 8.3 b). Note that a large load current I_L on a line having a large value of X_L will give a large load angle δ_L .



Figures 8.3a) & b): EQUIVALENT CIRCUIT FOR A TRANSMISSION LINE OPERATING AT 0.9 PF LAG WITH VECTOR DIAGRAM

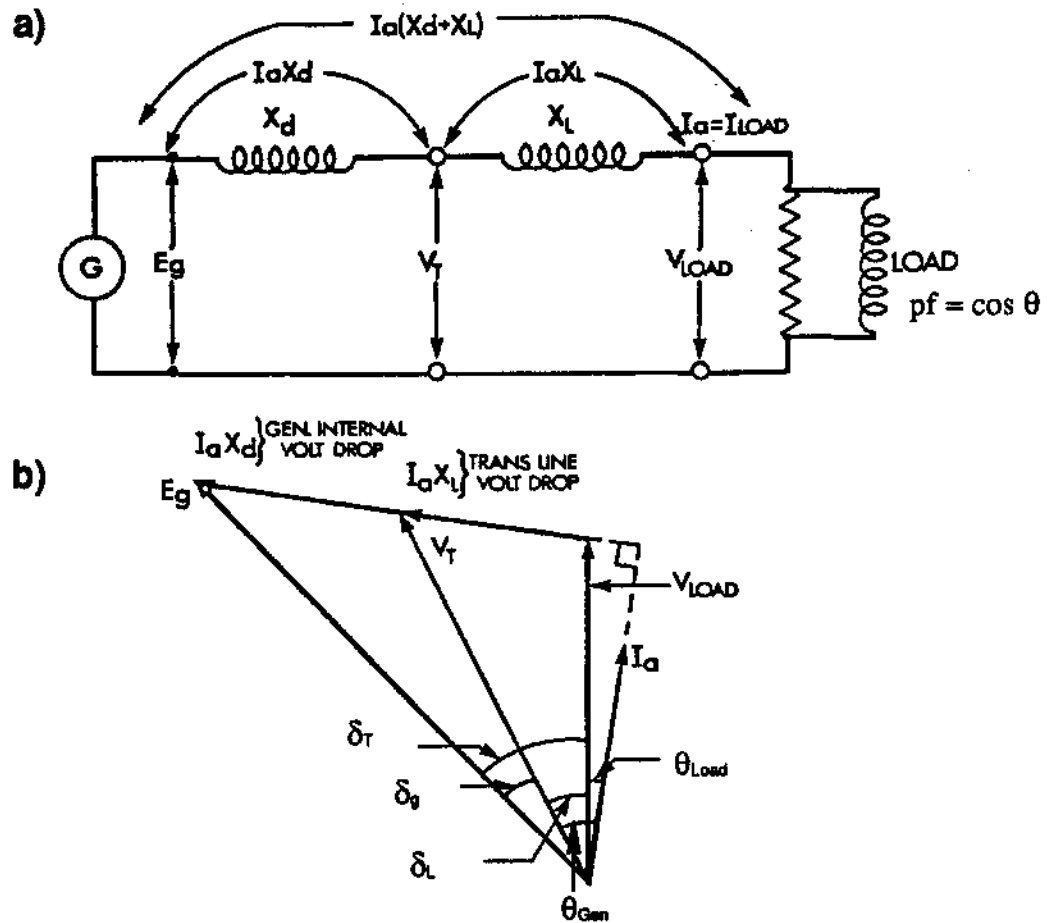
From the diagram, we can also see the result of changes in load angle caused by changes in load power factor (changes in θ). As θ becomes more lagging (increases clockwise), δ_L decreases. And conversely, as θ becomes more leading, δ_L gets larger. Remember that this is only true in this example if the MW load remains constant.

NOTES & REFERENCES

Obj. 8.1 c) ⇔

Variation of generator and line load angle with load

Figure 8.4 a) shows an equivalent diagram of a generator feeding a load via a transmission line. The generator operates with a load angle of δ_g and the line operates with a load angle of δ_L . The load is operating with a pf of $\cos \theta$.



Figures 8.4a) & b): EQUIVALENT CIRCUIT FOR A GENERATOR, LINE AND LOAD WITH VECTOR DIAGRAM

Note that:

- a) the generator operates at a power factor angle of θ_{gen} which is greater than θ_{load} .
- b) ⇔ generator and line operate together at an angle of δ_T , which is the sum of δ_g and δ_L .

Any change in the load angle of the line or the generator, will result in a change in the total load angle for the generator/line. Factors that affect these individual load angles have already been discussed, and are summarized below.

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- The load angle in a given generator increases with increasing load current I_L .
- The load angle in a given generator also increases with operation at a more leading pf, if the MW load is held constant.
- Conversely, the load angle decreases with a decrease in load and/or operation at a more lagging pf, if the MW load remains constant.
- The load angle for a given transmission line increases as the load on the line increases. As the load power factor for a transmission line becomes more leading, the load angle will increase.
- The total load angle for a generator/line is the sum of the individual load angles. Changes in load angle for the individual component will directly affect the load angle of the grouped components.

The Relationship between load angle and active power transfer.

Obj. 8.2 a) ⇔

In the system shown in Figure 8.4 a), the resistance of the generator and the lines is neglected, and consequently the system can be taken to be loss free, i.e. there will be no active power loss between the generator terminals and the load.

As losses are neglected:

$$P_{gen} = P_{load}$$

If the line has reactance X_L , we can develop* what is known as the “power transfer equation”.

$$P = \frac{V_T V_{load} \sin \delta_L}{X_L} \quad (1)$$

Where δ_L is the line load angle.

And, for the generator:

$$P = \frac{V_T E_g \sin \delta_g}{X_d} \quad (2)$$

Where δ_g is the generator load angle and X_d is the reactance of the generator.

The power transfer equation for the generator and line together is:

$$P = \frac{V_{load} E_g \sin(\delta_g + \delta_L)}{X_d + X_L} \quad (3)$$

* Appendix A at the end of this module shows the development of the power transfer equations.

NOTES & REFERENCES

Equation 3 shows that for maximum active power transfer P :

- X_d and X_L should be kept as low as possible. A generator has a value of X_d which cannot be altered. However, X_L can be kept low by having short transmission lines or many lines in parallel.
- E_g and V_T or V_{load} should be kept at a constant value. If E_g is allowed to fall, or if V_T or V_{load} falls due to fault conditions, then less power will be transferred.
- The composite load angle should not exceed 90° , ie, $(\delta_g + \delta_L)$ should not exceed 90° .

Transmission Line Steady State Stability Characteristics

In the case of a *loss free* power line, the power at both ends of the line will be the same, ie,

$$P_{in} = P_{out}$$

From equation 1,

$$P_{in} = P_{out} = \frac{V_T V_{load} \sin \delta}{X_L}$$

When $\sin \delta = 1.0$, $\delta = 90^\circ$ which is the condition for maximum power transfer, ie.

$$P_{in} = P_{out} = P_{max}$$

For conditions other than maximum power transfer, the power transmitted or received will be

$$P_{in} = P_{out} = P_{max} \sin \delta$$

Therefore the power transmitted or transferred from one end of the line to the other is a function of $\sin \delta$ and a power transfer curve can be drawn, which has a sine wave shape.

Figure 8.5 shows curves of power, P , transmitted between two ends of a line having reactance X_L , and voltages V_T at one end and $V_L (=V_{load})$ at the other. Generator characteristics are not included in this curve.

When 100% power is being transmitted and the line is operating on curve 1 the line will have a load angle of δ_1 . If, for instance, the sending end voltage V_T is increased, then the power transfer *capability* for the line will be increased. When this happens, we shift to curve number 2 and the line will operate at an angle δ_2 which is less than δ_1 . If the line voltage is decreased, the power transfer capability of the line will shift to curve 3 and angle δ_3 , and if the voltage is reduced further the line will operate on curve 4 and angle δ_4 .

NOTES & REFERENCES

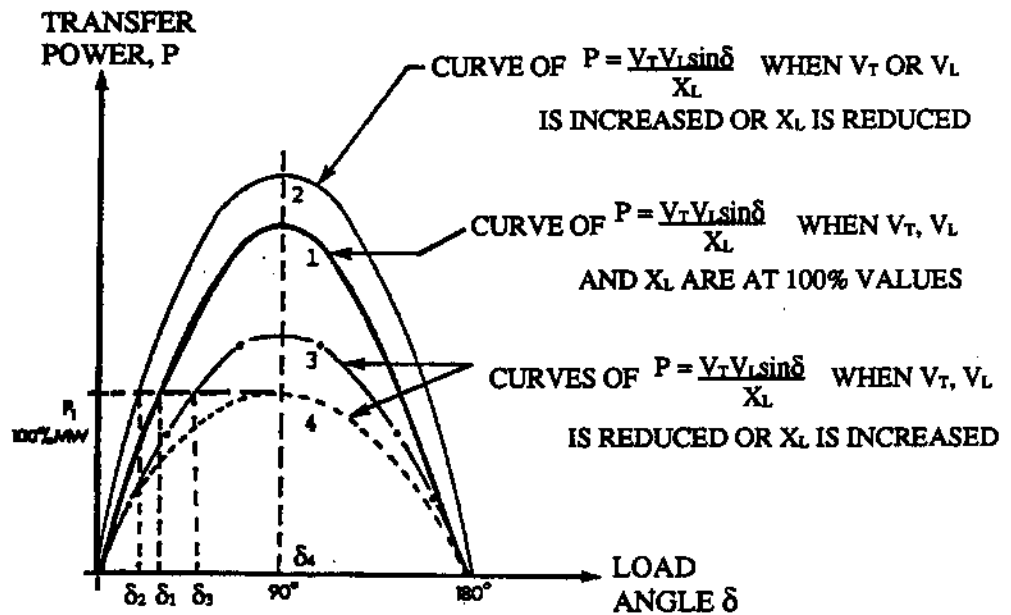


Figure 8.5: STEADY STATE STABILITY POWER TRANSFER CURVES FOR TRANSMISSION LINES

Obj. 8.3 a) ⇔
Obj. 8.2 b) ⇔

When δ_4 is reached, the line is operating at a 90° load angle. Any further reduction of the height of the curve or any further increase in power to be transferred will result in the power input exceeding the power that can be transferred. Assuming the mechanical power output from the turbine is constant, and line voltage decreases further, the generator will not be able to convert the mechanical power into electrical power. There will now be an excess of mechanical power produced over the electrical power being transferred. This excess power will cause the whole turbine generator shaft to accelerate.

Obj. 8.3 b) ⇔

The net result is that the two ends of the line will no longer remain in synchronism and instability will result.

Applying these curves to a generator, as soon as the load angle exceeds 90° the power input to the generator will be greater than the power it can convert or transfer into electrical active power. Therefore, the generator will start to speed up and, unless corrective actions are immediately taken, the generator will pole slip.

The pole slip is the result of excessive mechanical input power causing the magnetic link between the generator and the electrical system to stretch excessively, causing synchronism to be broken. The stronger the magnetic link between the generator and the electrical system, the more difficult pole slipping will be.

NOTES & REFERENCES

Let's use a simplified comparison here. Try to visualize the magnetic link between the generator shaft and the electrical system as an elastic band. As the torque on the generator shaft increases, the elastic band connecting the generator shaft and the electrical system stretches, and the "load angle" between the shaft connection and the grid increases. When the torque exceeds the strength of the elastic band (exceeds magnetic field strength), the band breaks, and the load angle continues to increase (pole slip). The stronger the elastic band, the harder it will be to break it (pole slip).

Obj. 8.4 a) ⇔

Steady state stability deals with slow changes in system conditions. This means that the movement between operating curves is a "slow" process, and **load angle changes are small and slow**. Thus, the "worst case" steady state condition will occur when the operating point moves to the peak of an operating curve, with $\delta = 90^\circ$ (eg. curve 4 shown in Figure 8.5). Instability, as described above, will result if conditions change. The corrective actions that can be taken to avoid steady state instability in this situation are:

Obj. 8.3 c) ⇔

- a) **Reduction in mechanical power input.**
- b) **An increase in field current which will boost the flux and E_f** (ie. cause the operating point to move to a "higher" curve) { this was described in Module 5}.

Instability can be prevented by operating with total load angles well below stability limits. Maintaining a reasonable "operating margin" of load angle will ensure unstable conditions are not reached, even if transmission lines are removed from service. This will be shown in the examples below.

Examples

Practically, we can apply the above information to examples of transmission line/generator systems.

Example 1: A generator is operating at a load angle of 30° and transmitting power over two parallel lines. The load angle across the lines is 10° . If all of the load is slowly shifted to one power line, will the line and generator remain stable?

Answer: Using the power transfer equation for the line

$$P = \frac{V_T V_L \sin \delta_L}{X_L}$$

Transposing gives:

$$\sin \delta_L = \frac{P X_L}{V_L V_T}$$

If P , V_L and V_T remain constant then $\sin \delta_L$ is proportional to X_L .

NOTES & REFERENCES

When δ_L is 10° , $\sin \delta_L = 0.173$ with reactance X_L . When X_L increases to $2X_L$, $\sin \delta_L$ will increase to $2(0.173) = 0.347$. This gives a new value δ_{L2} for the line load angle where $\delta_{L2} = \arcsin 0.347 = 20.3^\circ$, ie. the line load angle is approximately doubled.

The combined load angle for the generator and line are $30^\circ + 20.3^\circ$ or 50.3° which is considerably less than 90° and so the generator and line will remain stable.

Example: 2. A generator is operating at a load angle of 30° and transmitting power over two parallel lines. The load angle across the lines is 25° . If all of the load is slowly shifted to one power line, will the line and load remain stable?

Answer: Using the same power transfer equations as before, and assuming P , V_L and V_T all remain constant, then $\sin \delta_L$ is proportional to X_L .

When δ_L is 25° , $\sin \delta_L = 0.423$ with line reactance of X_L . When X_L increases to $2X_L$, $\sin \delta_L$ will increase to $2(0.423) = 0.845$.

This gives a new value of δ_{L2} for the line load angle where $\delta_{L2} = \arcsin 0.845 = 57.6^\circ$, this gives a combined load angle for the generator and line of $(30^\circ + 57.6^\circ) = 87.6^\circ$.

Under this condition the generator and line are operating at just less than 90° and will therefore remain stable. It should be appreciated that any slight change in generator output or other conditions will cause the system to become unstable. It would be most undesirable to operate under these conditions.

Obj. 8.4 a) ⇔

Again, let's emphasize that **steady state stability deals with slow changes in the system only**. Rapid changes in the system will cause "large" swings in load angles. This is discussed in the following portion of the module.

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- Active power transfer across power lines varies with the Sine function of the total load angle δ .
- Steady state stability is affected by total load angle, which is the sum of the generator load angle and line load angle.
- If the load angle exceeds 90° , stability will be lost, resulting in pole slipping.
- To prevent steady state instability, the mechanical power (input) must be reduced to match the electrical power (output) that can be produced, or the field flux increased, which increases terminal voltage and causes a shift to a higher power transfer curve.
- Operating without excessive load angles will ensure that stability limits are not reached, even under upset conditions.

Pages 30–35 ⇔

You can now do assignment questions 1 – 8.

TRANSIENT STABILITY

Obj. 8.4 a) ⇔

The following section of the module will relate to transient stability. **Transient stability** examines the behavior of the generator and lines **when faults or rapid changes occur**. Remember that steady state stability involved gradual changes only.

Obj. 8.5 ⇔

Transient stability can result in **large swings of load angles, and possible instability (pole slipping)**.

Obj. 8.6 ⇔

GENERATORS

Figure 8.6 shows two power transfer curves. Curve 1 is the power transfer curve used when the generator feeds the load with normal excitation. When the excitation is reduced, the power transfer capability is reduced to curve 2. The shape and height (amplitude) of the curves were discussed in a previous section of this module. There are two ways of modelling the generator response to a transient, the two curve and the one curve method. Each of these are discussed below.

NOTES & REFERENCES

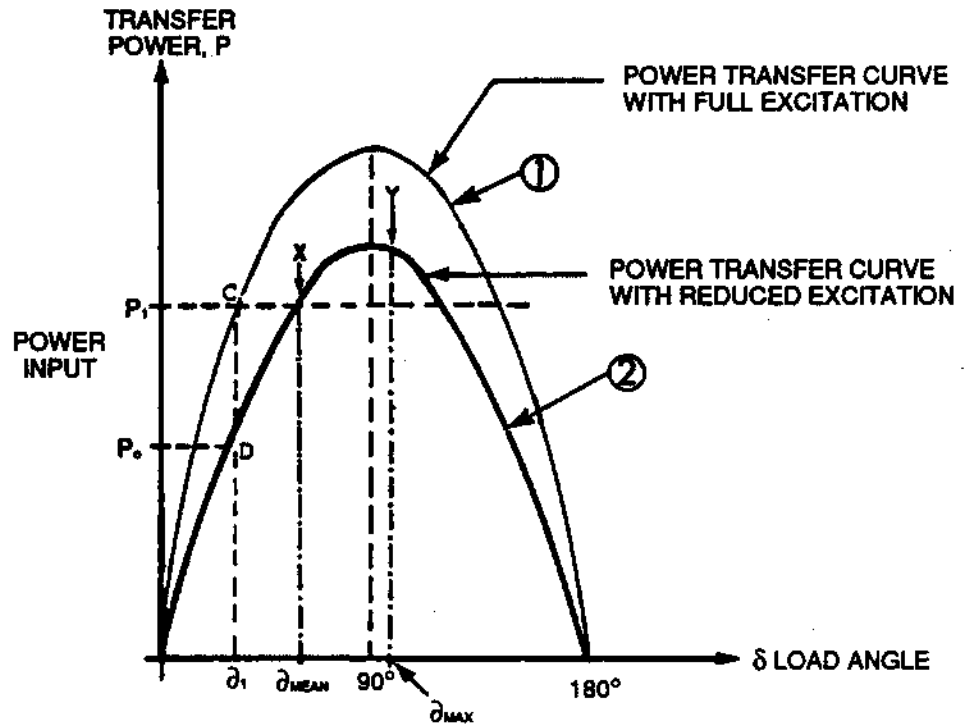


Figure 8.6: POWER TRANSFER CURVES FOR A GENERATOR

Generator Behaviour During A Transient: Two Curve Method

Figure 8.6 above shows the power transfer curves for a generator before and after a transient. At the instant before the transient, i.e. the instant before the excitation is reduced, the generator is operating at point “C” on curve 1 with a load angle of δ_1 . Power input (mechanical) equals the power output or power transferred (electrical).

At the instant after the transient, the generator cannot operate at point “C” on curve 1 because curve 1 has been reduced in height to curve 2 (lower excitation). The generator is still operating with the same load angle, δ_1 , as before, but the operating point has shifted to point “D”. Examining the conditions at point “D” on curve 2, we see that the power transfer capability is only P_0 . Because P_1 is considerably more than P_0 , there is more mechanical power input to the generator than there can be power output from it. This difference in power, i.e. $P_1 - P_0$, will cause the generator to accelerate.

As the generator accelerates, the magnitude of its load angle will grow first from δ_1 to δ_{MEAN} at point X, see Figure 8.6, where the mechanical input power to the generator equals the electrical power sent out. But as the speed of the

NOTES & REFERENCES

generator is now *greater* than synchronous, the magnitude of its load angle will continue to *increase* until the rotor is slowed down by the output power being greater than the mechanical input power. This occurs at point “Y”.

At point “Y”, as the generator output power is greater than the input power, the generator’s speed will decrease, the rotor angle will reduce to δ_{mean} . At this point, the rotor speed is less than synchronous, causing the rotor angle to reduce to near δ_1 . The rotor will start to accelerate once more, resulting in oscillation of the rotor angle. The rotor will then continue to oscillate back and forth about δ_{mean} until the oscillation is damped out (due to the inertia of the system), see Figure 8.7.

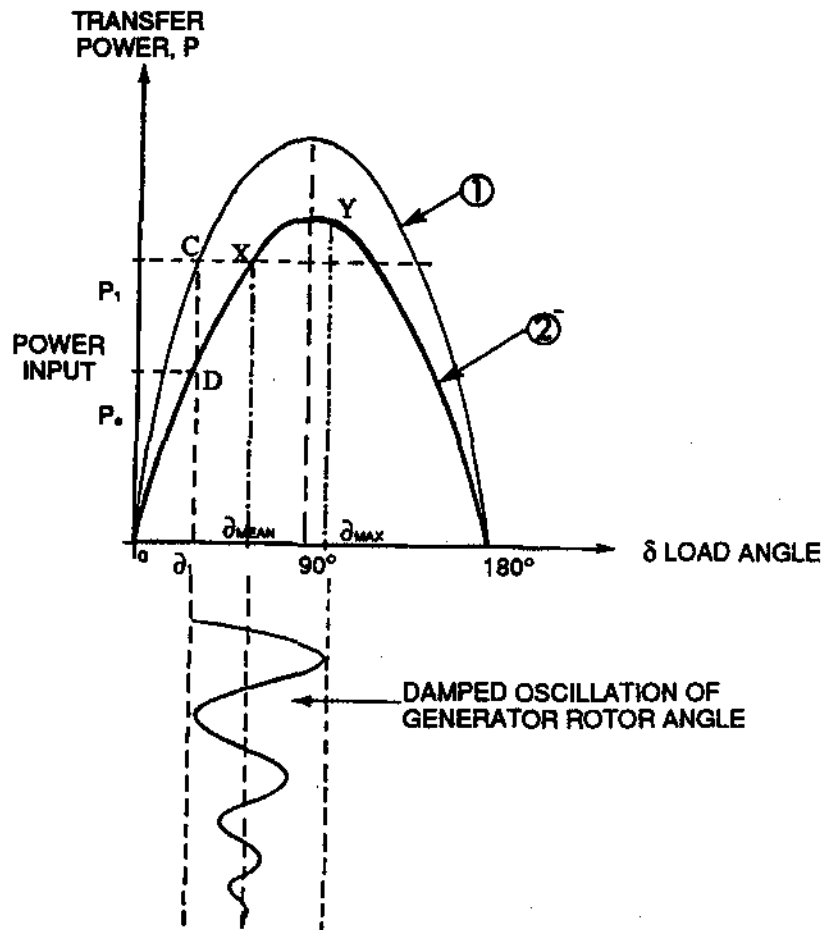


Figure 8.7: HOW ROTOR AND ROTOR ANGLE IN A GENERATOR OSCILLATE FOLLOWING A TRANSIENT FAULT

NOTES & REFERENCES

The location of point Y is critical and depends on the equal area criteria where (refer to Figure 8.8) :

- The area "A" represents the excess in energy produced by the turbine over the energy sent out by the generator. This area is often known as the accelerating area and represents kinetic energy gain for the rotor.
- Area "B" represents the excess in energy sent out over the energy produced. This area is often known as the braking area and represents kinetic energy dissipated, ie. sent out into the load.

When area "A" = area "B", the equal area criteria is satisfied, ie, the energy gained during acceleration is balanced by the energy sent out during braking.

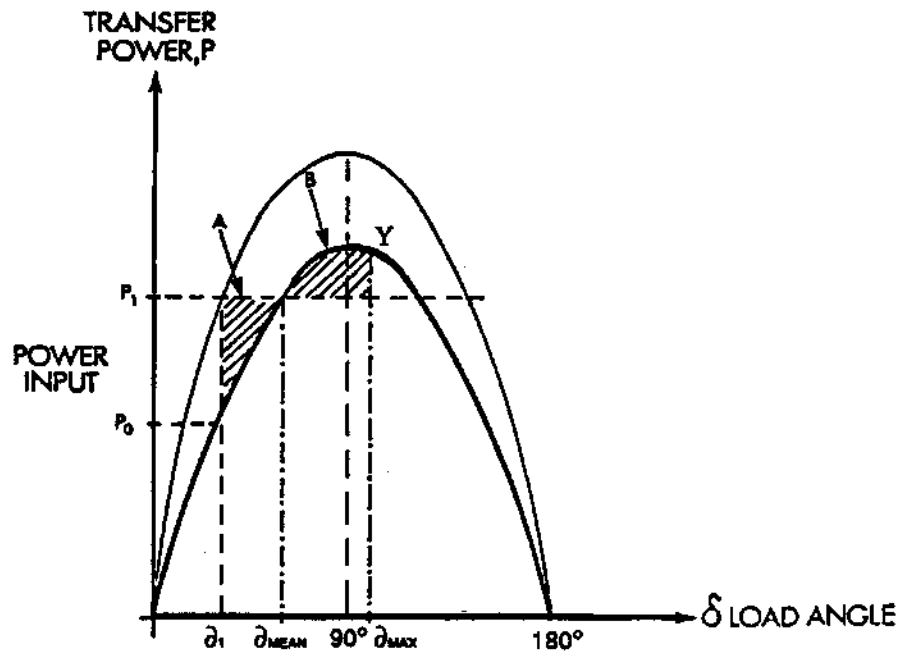


Figure 8.8: EQUAL AREA CRITERIA WHERE AREA "A" EQUALS AREA "B"

NOTES & REFERENCES

Figure 8.9 shows the condition where curve 2 has been reduced, by lowered excitation, to the level where the whole of the area between curve 2 and the P_1 line is used up for braking. Point "Z" shows the critical stability position or angle for the rotor. If this load angle is exceeded, the generator will become unstable.

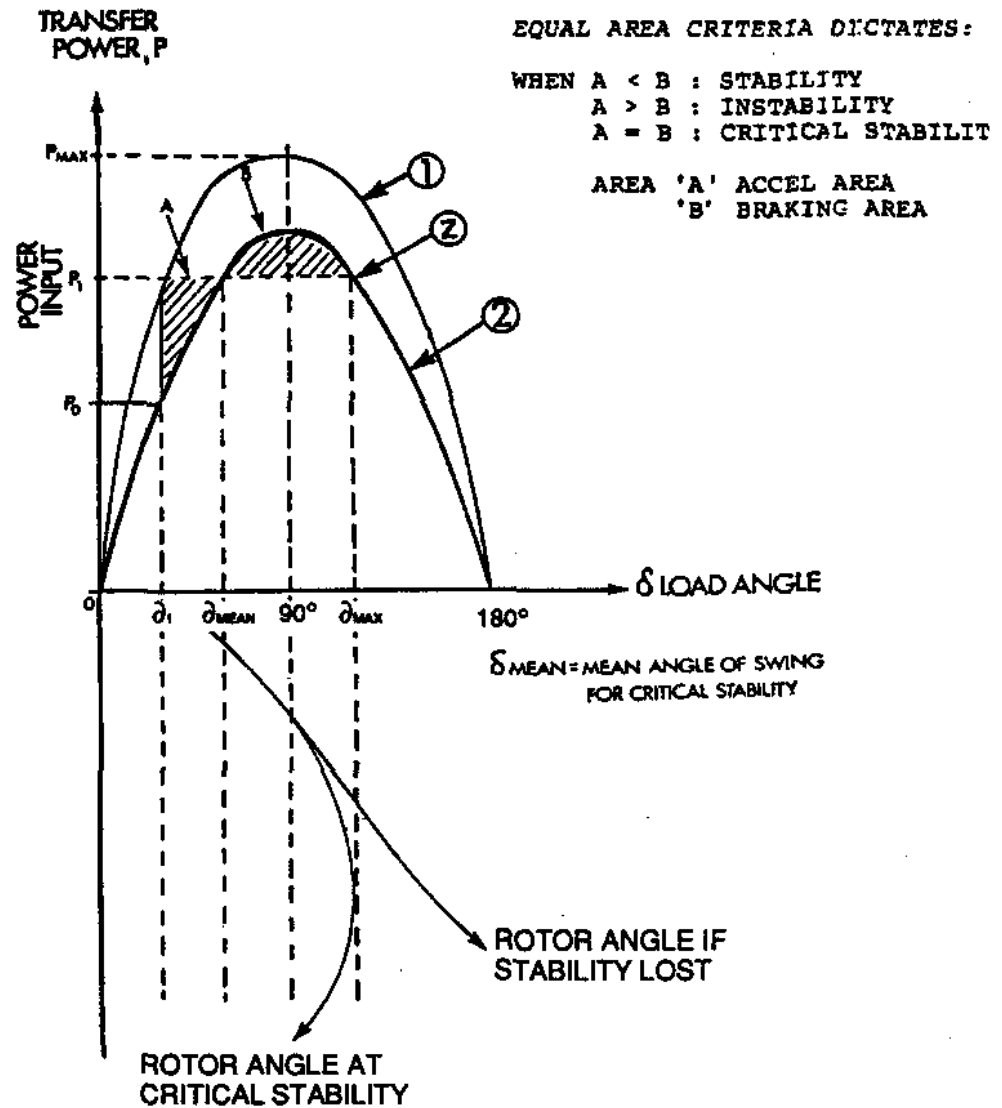


Figure 8.9: CRITICAL STABILITY UNDER TRANSIENT CONDITIONS

NOTES & REFERENCES

Figure 8.10(a) shows the condition where a generator remains stable and Figure 8.10(b) shows the condition where a generator will become unstable. There is insufficient braking energy in this second case.

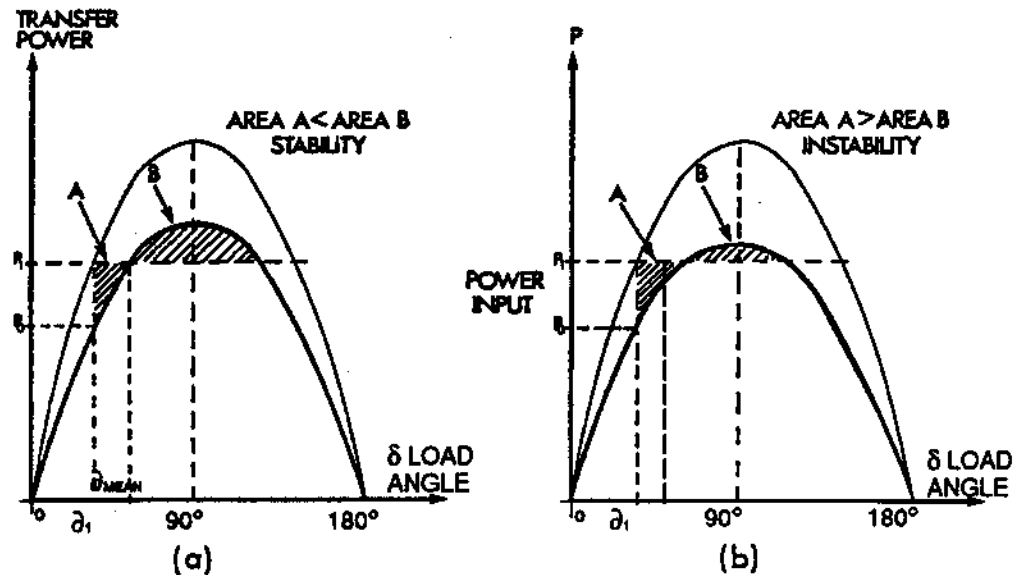


Figure 8.10: TRANSIENT CONDITIONS SHOWING GENERATOR STABILITY AND INSTABILITY

Generator behaviour during a transient: One curve method.

If only the normal operating curve and the maximum angle of swing are known, then an examination of the curve and the conditions occurring at the maximum swing angle can determine whether the generator will remain stable. Figure 8.11 shows the condition where a system transient caused the generator load angle to swing from δ_1 to a maximum angle "A".

NOTES & REFERENCES

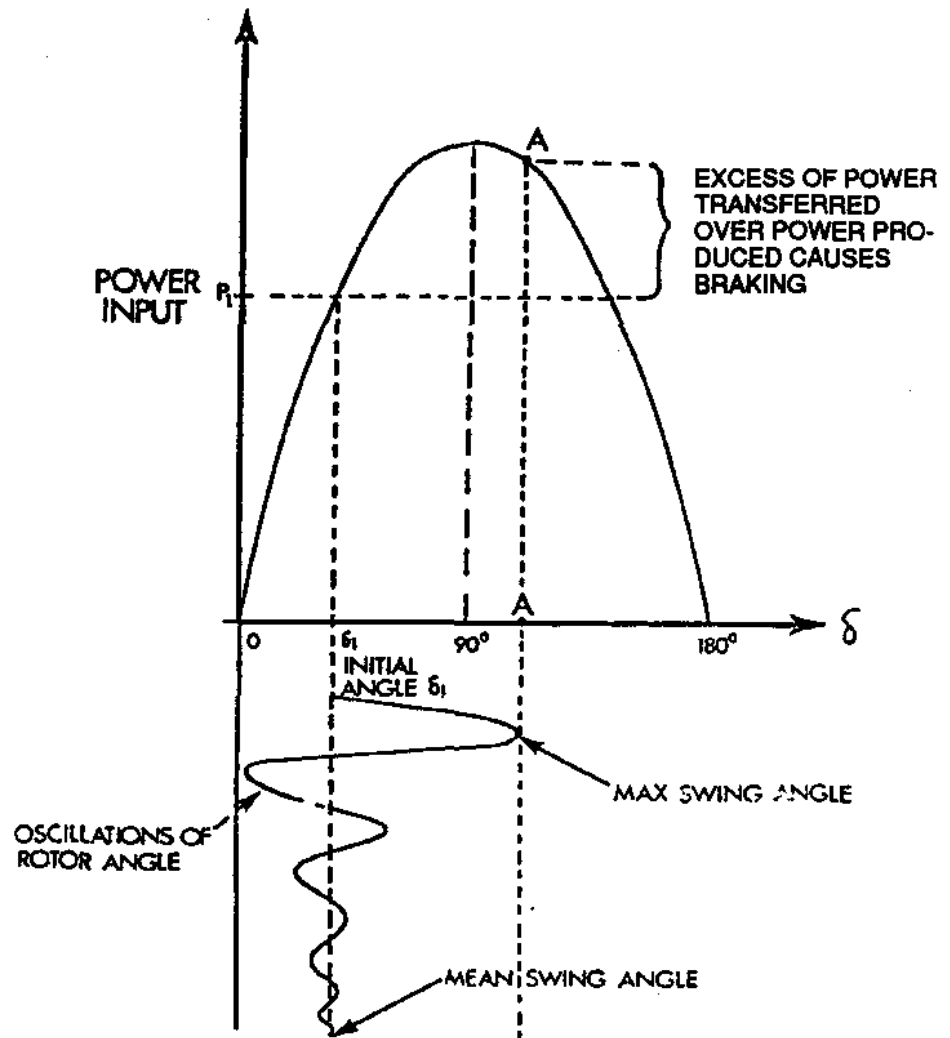


Figure 8.11: GENERATOR REMAINS STABLE

For the load angle to swing from δ_1 to A, a transient increase in input power and/or a transient decrease in power transfer capability must have occurred. This could have been due to a transmission line fault or some other cause.

However, at point "A", the generator has reached its maximum angle of swing and it is once more operating on the curve shown. At point "A", there is an excess of power being transferred over the power being produced by the turbine. Consequently the load angle will decrease. A minimum angle will be reached before the angle increases again producing an angular oscillation which will damp out after a short time. The generator will remain stable, see Figure 8.11.

NOTES & REFERENCES

If the maximum swing angle shown at “B” is now considered, see Figure 8.12, at the end of the transient swing, there is an excess of power produced over the power being transferred. Consequently there is a resultant accelerating force and the load angle δ will continue to grow. The generator will pole slip and become unstable.

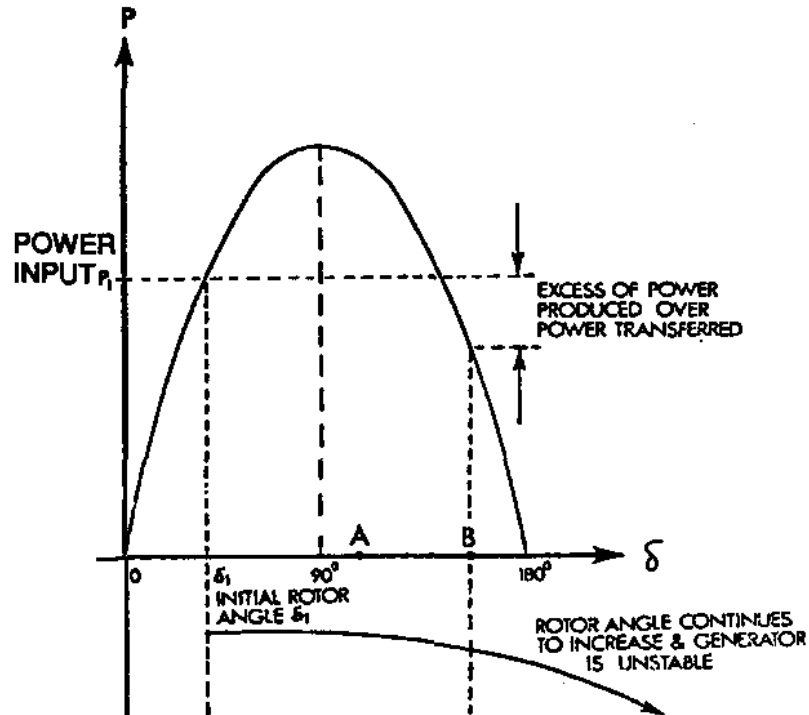


Figure 8.12: GENERATOR BECOMES UNSTABLE

Factors Affecting Generator Transient Stability

Obj. 8.4 b&c) ⇔

An adequate stability margin must be allowed. This is to ensure stability under transient conditions*. To achieve this the following should be noted:

- a) Under normal loading, the generator load angle should not be allowed to exceed a specified low value (about 30°). This is achieved by not exceeding the generator MW rating, and by keeping sufficient excitation on the machine. (The reactance X_d , which affects the load angle, will by design, be kept to a minimum. This will keep the internal voltage drop $I_a X_d$, and hence the load angle, to a minimum. This is a design constant, over which you have no control. We will ignore this factor's contribution from a stability viewpoint.)

* The operator can do nothing to maximize the response to transient effects. It is all handled by automatic actions.

NOTES & REFERENCES

- b) A fast acting AVR is required to ensure that, under fault conditions, E_g and V_T are not allowed to fall excessively. It should be noted that for steady state stability a slow acting AVR is satisfactory; this is certainly not true where transient stability is concerned.
- c) Faults on transmission lines and on other parts of the system must be cleared quickly by protective relaying and breakers. This will prevent the system from operating on “low” transfer curves for an appreciable time. It follows that protection schemes and breakers must have fast operating times (2 cycles). Figure 8.13 a) shows how the load angle increases during fault conditions.

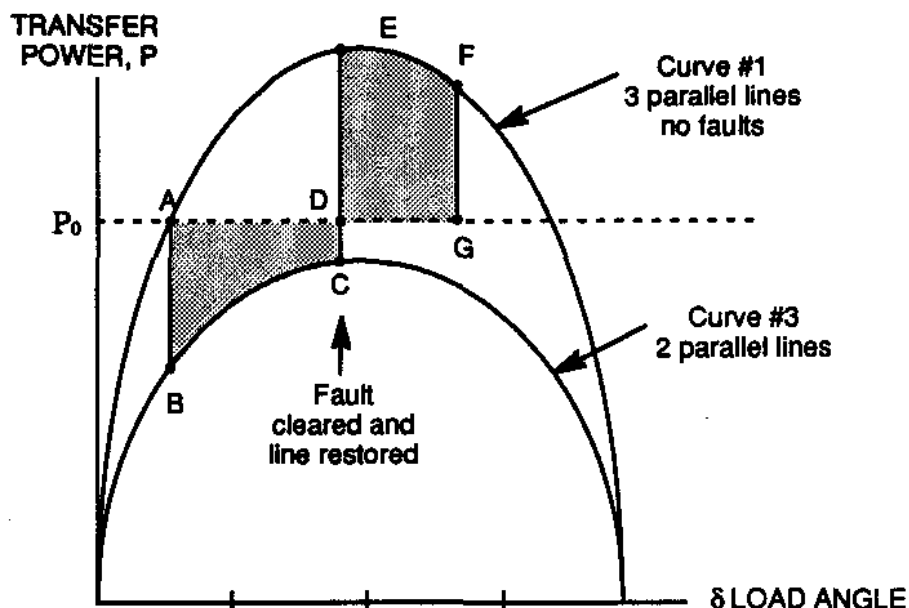


Figure 8.13 a): HOW LOAD ANGLE INCREASES DURING A FAULT

The upper curve in Figure 8.13 a) represents power transfer under healthy conditions. For this example, let's assume that this represents power transfer through three parallel transmission lines. If a line is temporarily lost, say trips due to a lightning strike, power transfer is shifted to the capacity of the two remaining lines. This shifts the operating point to “B” on the lower curve. Since the power produced is still at P_0 , which is greater than the power that can be transferred, the turbine generator will accelerate, and the load angle increases. When the fault clears and the line is restored, the power transfer will shuttack up to the upper curve. The maximum swing of the load angle after the fault clears will again be determined by the equal area criteria (ie. area A-B-C-D = area D-E-F-G). It follows that the longer the fault persists the longer the generator is operating on the lower curve and the greater the load angle becomes (with a greater risk of instability).

NOTES & REFERENCES

Let's look at another fault example, where the fault does not clear and the line is not restored, as seen in Figure 8.13 b). The Curve #1 represents power transfer under healthy conditions. For this example, let's assume that this represents power transfer through two parallel transmission lines, and we are currently at operating point A. If a fault develops on one line, power transfer is shifted to the capacity of the lines under faulted conditions, which shifts the operating point to Curve #3 at point B. Since power produced is still at P_0 , which is greater than power that can be transferred, the turbine generator will accelerate, and the load angle increases. When the breakers open to clear the faulted line (at point C), the power transfer will shift back up to Curve #2 for the remaining line, at operating point D. Again, power produced is still at P_0 , which is greater than power that can be transferred, the turbine generator will continue to accelerate. The maximum swing of the load angle after the fault clears will again be determined by the equal area criteria (ie. area A-B-C-D-E = area E-F-G). Again, the longer the fault persists, the greater the load angle becomes with an increased risk of instability.

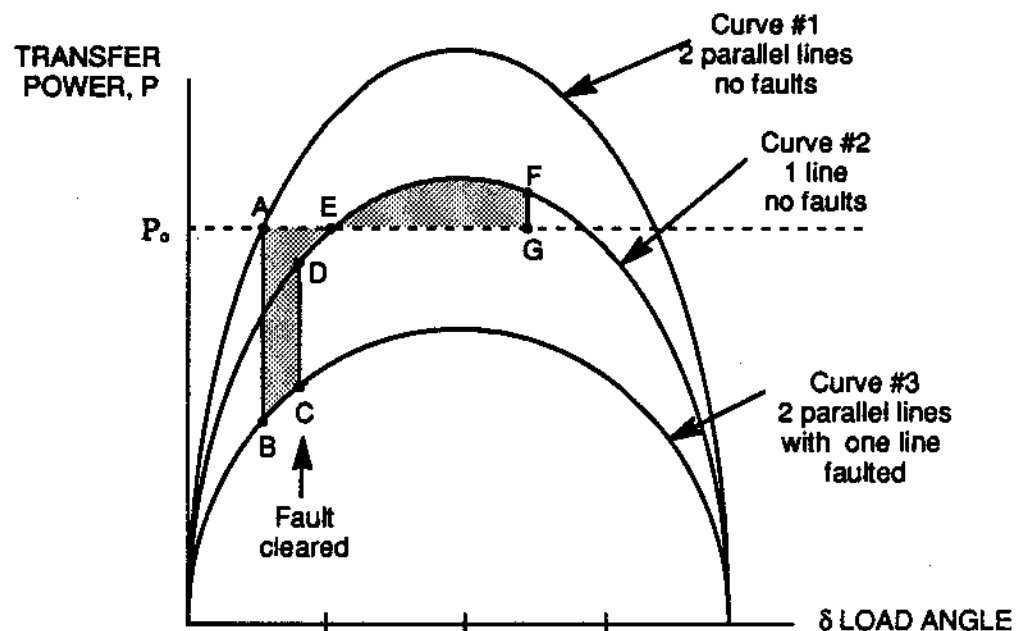


Figure 8.13 b): HOW LOAD ANGLE INCREASES DURING A FAULT

- d). Another factor to be considered is that generators should have large inertias, which will slow the rate of increase in load angle under transient conditions. Again, this is a design constant, over which you have no control. We will ignore this factor's contribution from a stability viewpoint.

NOTES & REFERENCES

Obj. 8.4 bac) ⇔

Transient Stability: Transmission Lines

The power transfer capability of a transmission line is proportional to the product of the supply and load end voltages. To keep the power transfer capability to its maximum, and for the line to remain stable under transient conditions, the following features are employed:

- a) Fast acting AVRs are used on the generators at the supply end. This keeps the supply voltage constant. Manual operation cannot provide the response required during a transient.
- b) Synchronous condensers* are used to keep the load end voltage almost constant. It has been shown earlier in this module that you will operate on a “higher” power transfer curve by keeping V_L higher. Having an interconnected system will also aid in keeping the load voltage constant.
- c) The reactance X_L in ohms per kilometer for a line is essentially constant and the only way of reducing X_L is to operate with short transmission lines, using more lines in parallel. Although we cannot change the distance to the loads, we can control the number of lines (up to the number available). Hence, operation should be with as many parallel transmission lines as possible (use of few lines should be avoided).
- d) As with generators, fast acting protection schemes and breakers are required to minimize the time that transient conditions exist. Manual action may be required if faults are not cleared rapidly and generator protective trips have failed. Also, preventive maintenance and testing of protection schemes, to ensure correct operation, is important for the above reasons.

* A synchronous condenser is a generator connected to the grid, with no motive force driving it. By varying excitation on the machine, it can produce/consume reactive power. By locating it near the load, it will counter the effect of load power factor, allowing I^2R losses in the line to decrease (reduced reactive current flow), thus increasing voltage at the load.

NOTES & REFERENCES

Examples

Let's have a look at a few more examples of the previous concepts.

Question:

A generator and transmission system are operating at point P_1 on curve 1 on the diagram shown in Figure 8.14. Between the generator and the load are two transmission lines. Due to a lightning strike, one line trips and the generator and remaining line operate on curve 2. Explain whether the generator and line will remain stable. If the generator remains stable, show maximum and mean angles of swing and sketch in any oscillations in load angle.

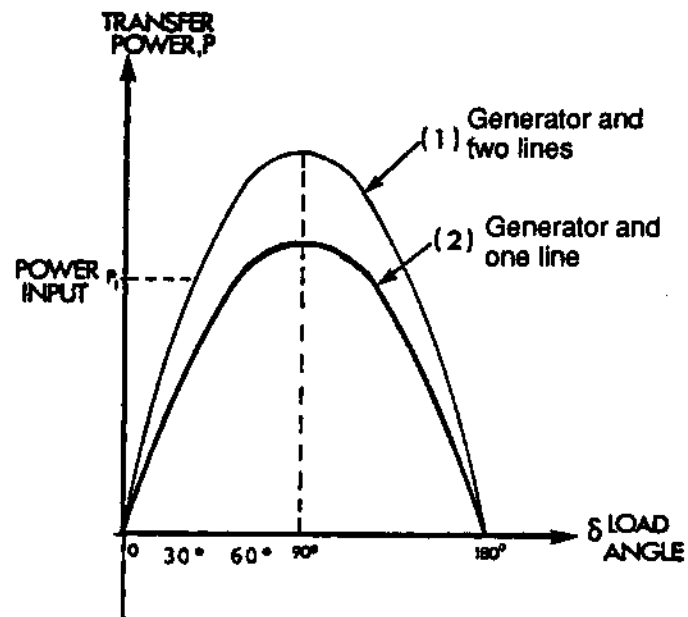


Figure 8.14: POWER TRANSFER CURVES FOR A GENERATOR AND TRANSMISSION LINES

Answer:

The equal area criteria must be satisfied for stability to exist.

Figure 8.15 shows the power transfer curves for a generator and two lines (Curve 1), and a generator and one line (Curve 2). Area "A" represents the condition where the power input from the turbine is greater than the power being transferred and the generator accelerates. The generator's speed and hence load angle δ increases. Area "B" represents the condition where the output power is greater than the turbine power and the generator brakes or slows down, this causes δ to decrease. The equal area criteria is satisfied and stability is maintained.

NOTES & REFERENCES

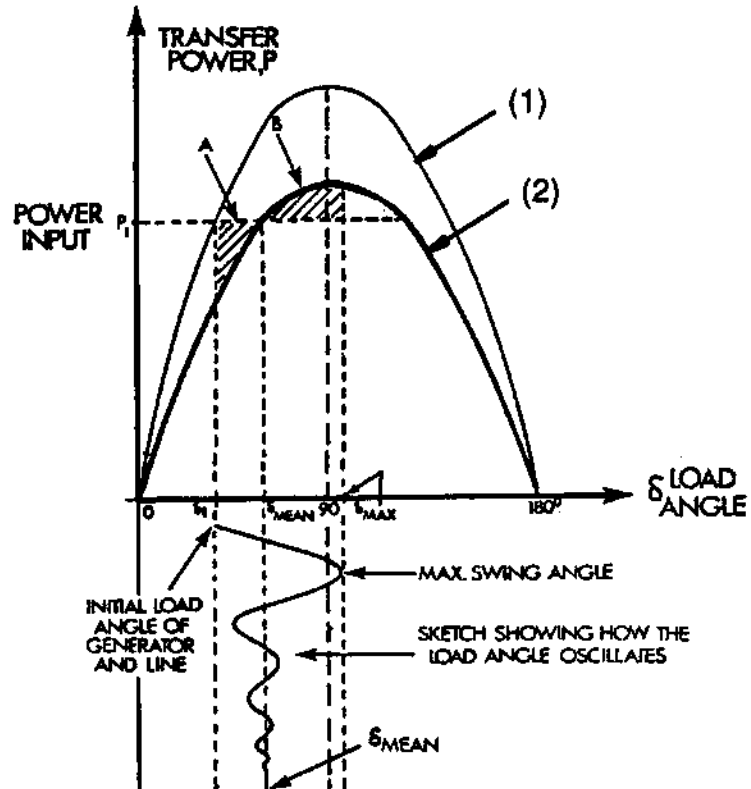


Figure 8.15: TRANSIENT STABILITY

When the line trips, the generator speed and line load angle will increase to δ_{\max} because the input power is greater than the power being transferred. But, at the δ_{\max} point, because the power output is greater than the power input, the load angle will begin to reduce (eventually to a value near δ_1). The load angle will oscillate and finally stabilize at a steady value of δ_{mean} (see diagram).

As the generator and line are stable after the one line has tripped, the system will remain stable.

NOTES & REFERENCES

Question:

The power transfer curve for a generator is shown in Figure 8.16. Due to a transient system disturbance, the load angle, δ , increases. A, B and C on the diagram, are maximum angles of swing for the three different system disturbances. For each disturbance explain clearly whether the generator would remain stable or unstable. If the generator remains stable, show on your diagram the angle at which the generator will stabilize; if it is unstable show how the angle continues to increase.

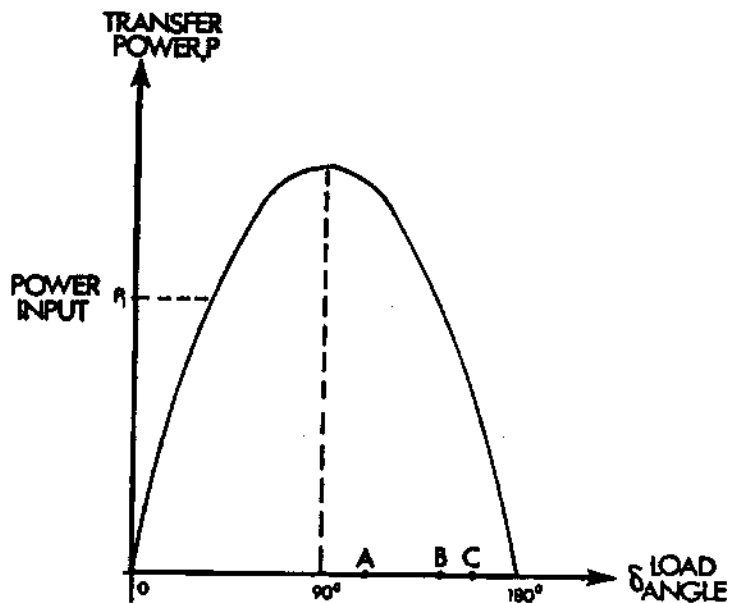


Figure 8.16: POWER TRANSFER CURVE FOR A GENERATOR

Answer:

Only one power transfer curve is given together with the maximum load angles for each condition. Therefore it is assumed that, apart from each of the initial transient conditions, the generator only operates on this curve.

The input power to the generator, P_1 is constant. When the power being transferred by the generator is greater than P_1 , the generator brakes or decelerates. When the power being transferred by the generator is less than P_1 the generator accelerates. It is this acceleration/deceleration which produces the change in load angle δ .

NOTES & REFERENCES

Figure 8.17 shows that when P_1 is less than the power being transferred (point "A" on the power transfer curve), the excess power transferred over that produced creates braking force. The generator will decelerate from the condition which caused its angle to increase to the maximum value $\delta=A$. Therefore δ decreases and after oscillating, will return to its original angle of δ_1 . The generator will remain stable.

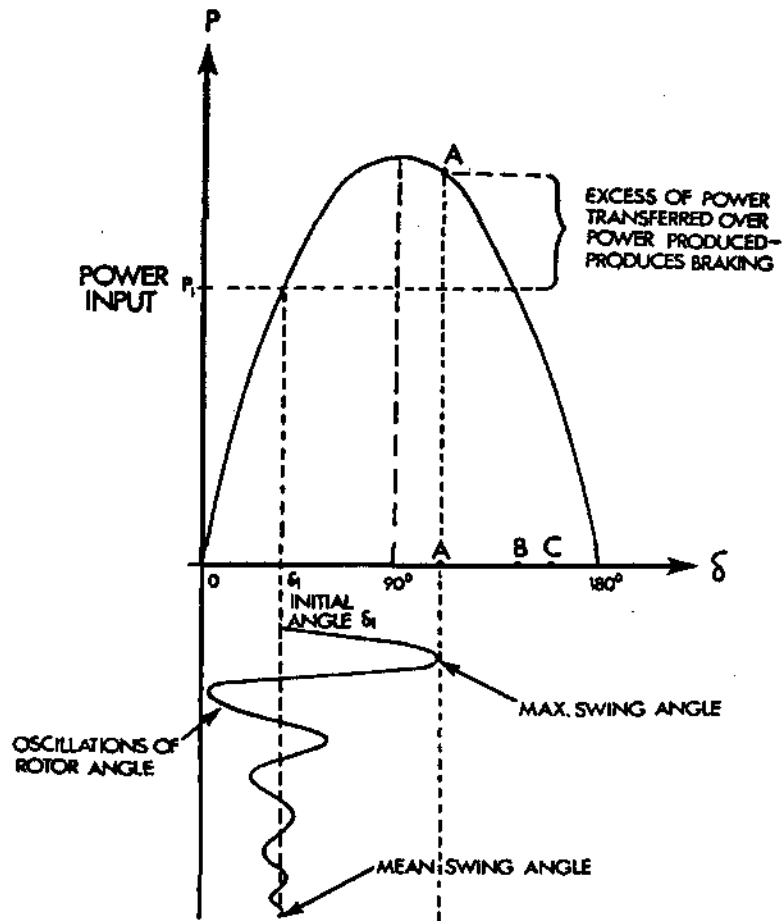


Figure 8.17: **CONDITION "A" SHOWING GENERATOR REMAINS STABLE**

NOTES & REFERENCES

For condition B, Figure 8.18 shows that when the maximum swing angle becomes $\delta = B$, the braking force is still greater than the power produced so the rotor will, after oscillating, return to its original angle of δ_1 . The generator will remain stable.

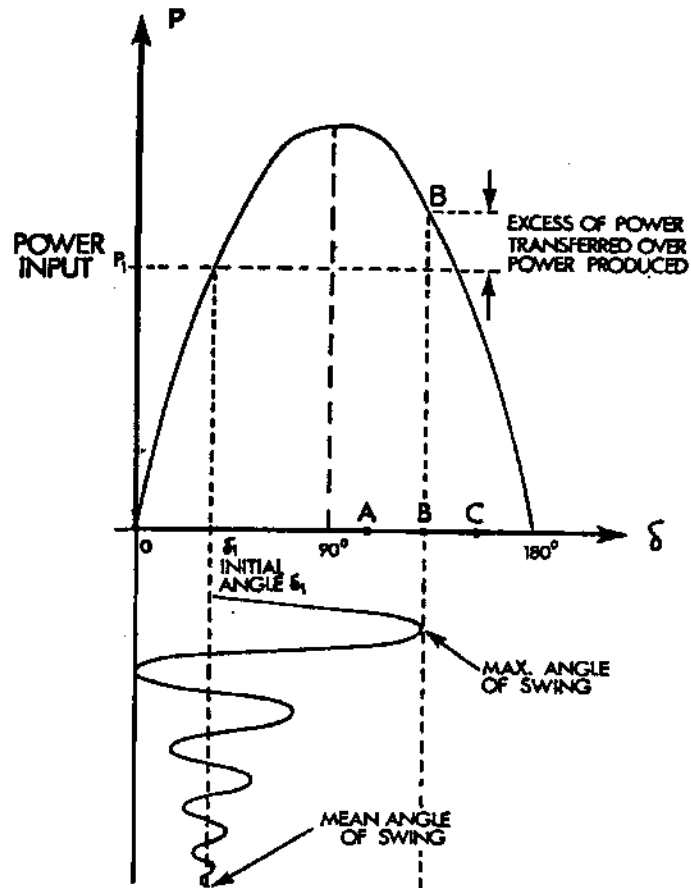


Figure 8.18: CONDITION "B" SHOWING GENERATOR REMAINS STABLE

NOTES & REFERENCES

For condition C, Figure 8.19 shows that when the maximum swing angle becomes $\delta = C$, the braking force is less than the power produced (P_1 is greater than the power being transferred) so the rotor will not return to its original angle of δ_1 . The rotor angle will continue to increase and the generator will pole slip and become unstable.

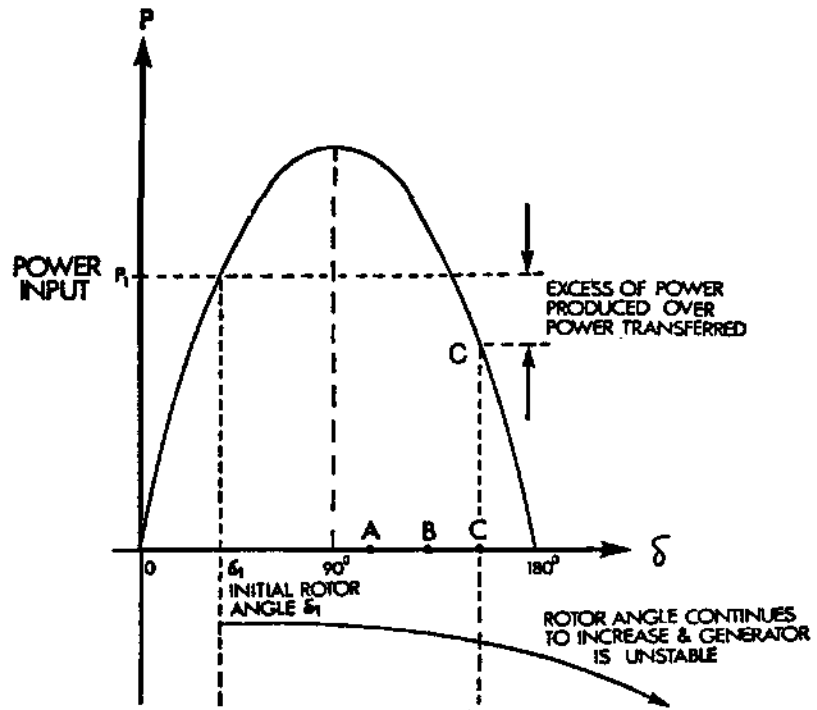


Figure 8.19: CONDITION "C" SHOWING GENERATOR BECOMES UNSTABLE

NOTES & REFERENCES

SUMMARY OF THE KEY CONCEPTS

- Transient instability can result in pole slipping.

For the generator:

- Control of generator load angle will help ensure transient stability. Exceeding generator MW rating should be avoided.
- AVRs are used to keep generator terminal volts V_T constant and improve transient stability. Manual operation cannot compensate for fast changes required during transient conditions.
- Protection schemes and breakers must rapidly clear faults to prevent large swings in load angles during transient conditions. Preventive maintenance and testing are important to ensure that protection schemes are operational.

For the transmission line:

- Multiple power lines are used in parallel (ie. keep X_L low). Operation with many parallel lines in service is recommended.
- Automatic voltage regulation is used to keep supply end voltage constant (as discussed above).
- Synchronous condensers and interconnections are used to keep load end volts constant. This minimizes voltage drops, reducing chances of transient instability.
- Protection schemes and breakers must rapidly clear faults.

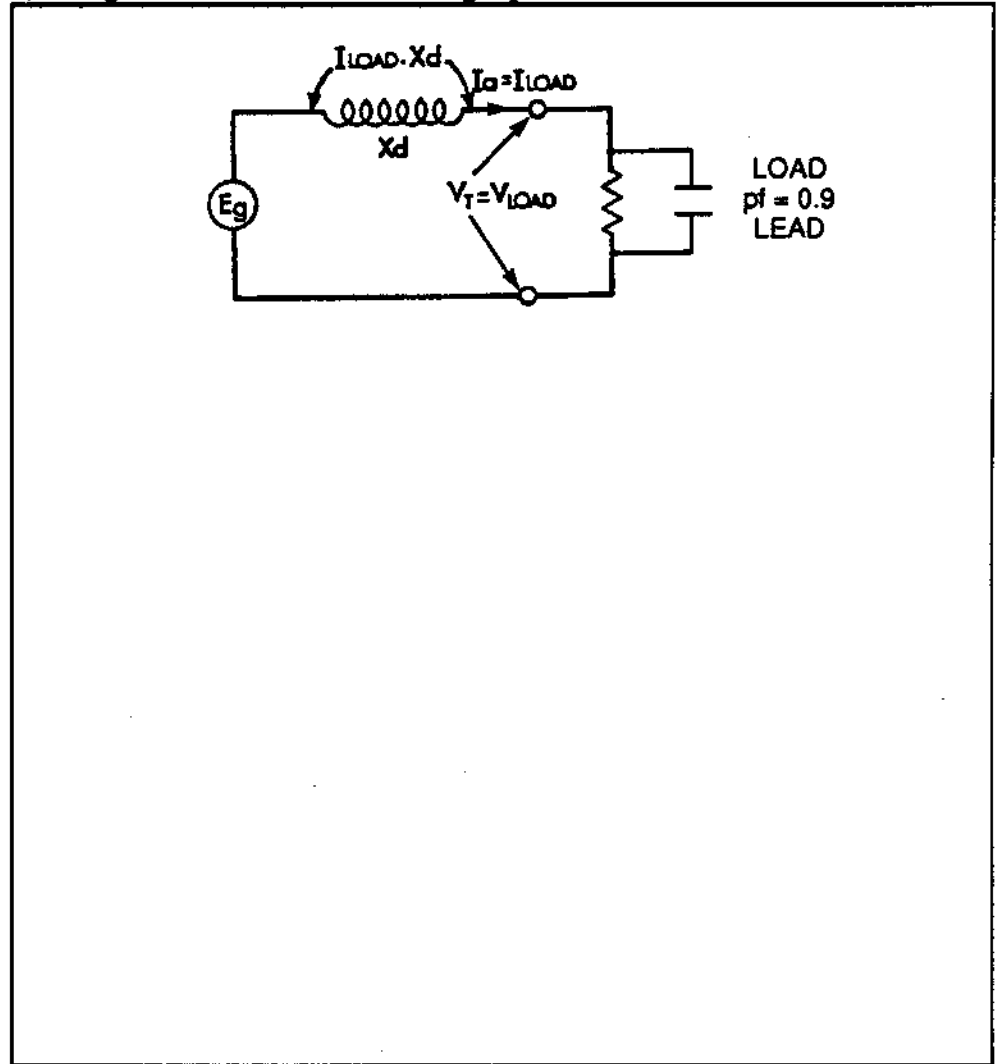
Pages 35–41 ⇔

You can now work on assignment questions 9 – 16.

NOTES & REFERENCES

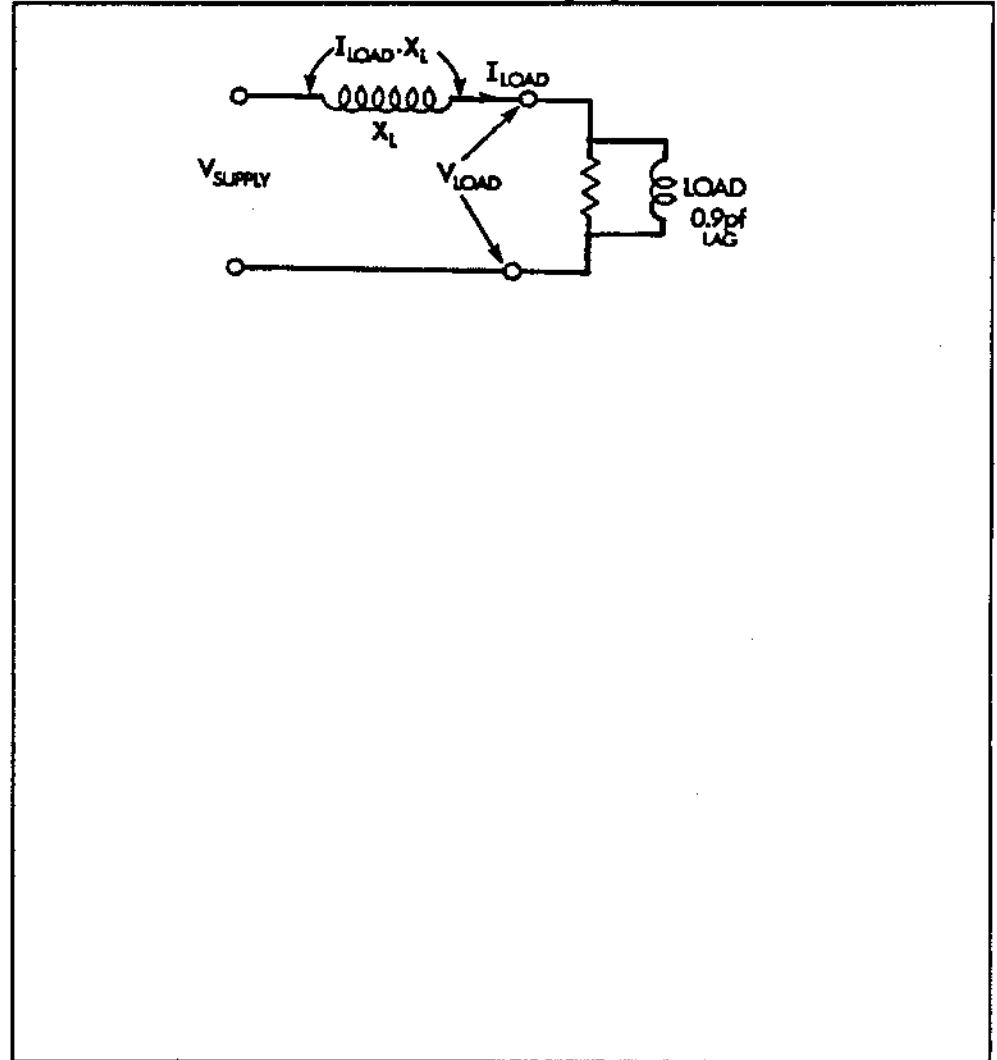
ASSIGNMENT

1. Explain, with the aid of vector diagrams, how a load angle is produced and varies, in:
 - a) A generator with the following equivalent circuit;



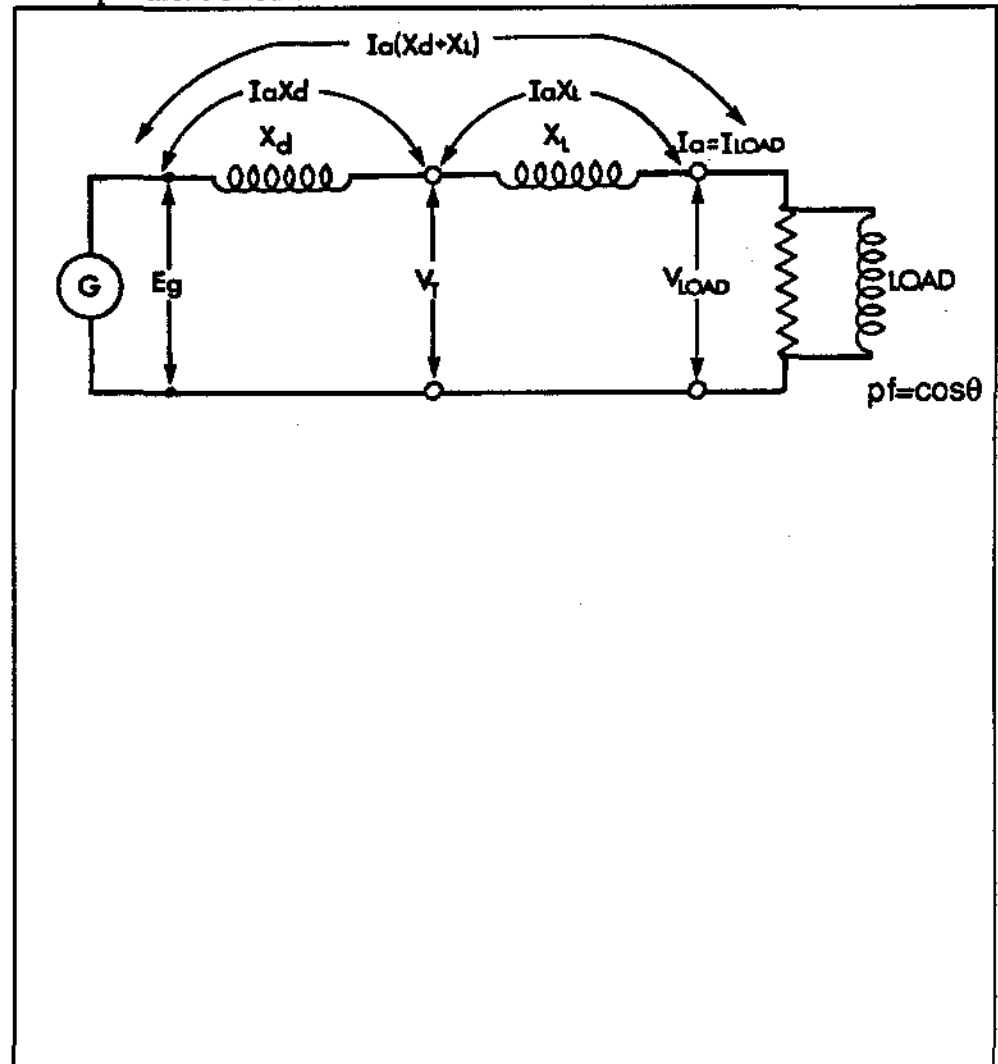
NOTES & REFERENCES

b) A transmission line with the following equivalent circuit;



NOTES & REFERENCES

- c) A generator and transmission line combination with the following equivalent circuit:



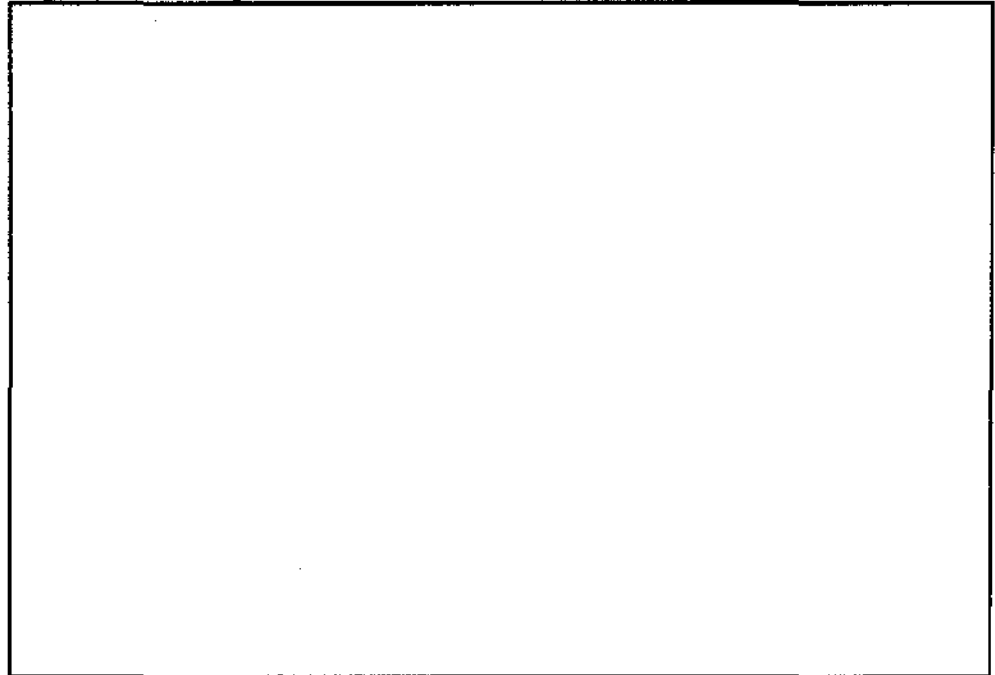
NOTES & REFERENCES

2. A generator is operating at *half* load with a load angle of 20° and transmitting power over a line whose load angle at full load is 50° . Explain why additional parallel transmission lines are required to produce full load.

3. A generator is operating at *half* load with a load angle of 10° and transmitting power over a line whose load angle at full load is 25° . Explain why the generator can produce full load without risk of steady state instability.

NOTES & REFERENCES

4. Explain, using a power transfer curve, the relationship between load angle and active power transfer.



5. Explain the relationship between load angle and steady state stability:

NOTES & REFERENCES

6. Steady state instability causes:

7. Explain the two actions that can be performed to prevent imminent steady state instability:

a)

b)

8. Explain the precaution that should be used to minimize the chance of steady state instability:

9. Explain the difference between steady state stability and transient stability:

NOTES & REFERENCES

10. Under steady state stability conditions, the load angle cannot exceed 90° but, under transient conditions, the load angle can exceed 90° with stability still maintained. Explain why this is so.

11. Explain the three factors that affect transient stability for the generator:

a)

To minimize the risk of transient instability due to this factor, we can:

b)

To minimize the risk of transient instability due to this factor, we can:

NOTES & REFERENCES

c) _____

To minimize the risk of transient instability due to this factor, we can:

12. Explain the four factors that affect transient stability for transmission lines:

a) _____

To minimize the risk of transient instability due to this factor, we can:

b) _____

To minimize the risk of transient stability due to this factor, we can:

NOTES & REFERENCES

c) _____

To minimize the risk of transient instability due to this factor, we can:

d) _____

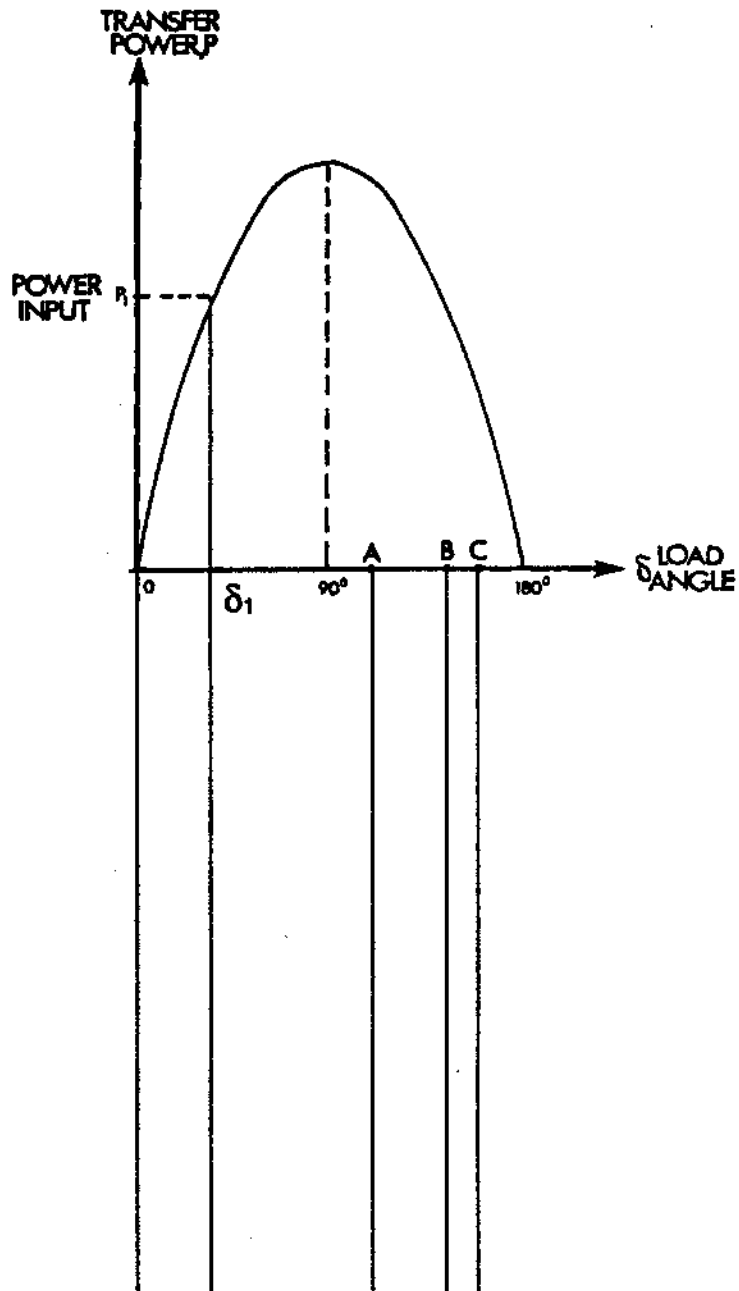
To minimize the risk of transient instability due to this factor, we can:

13. The result of transient instability will be:

14. A generator must feed its load via long transmission lines. To minimize the risk of instability during lightning storms, the output from the generator is reduced. Explain why this is done.

NOTES & REFERENCES

16. The power transfer curve for a generator is shown in the figure below. Due to a transient system disturbance, the load angle δ increases. A, B and C on the diagram, are maximum angles of swing for the three different system disturbances. For each disturbance explain clearly whether the generator would remain stable or unstable. If the generator remains stable, show on your diagram the angle at which the generator will stabilize; if it is unstable show how the angle continues to increase.



NOTES & REFERENCES

a) _____

b) _____

c) _____

Before you move on to the course checkout, review all of the course objectives and make sure that you can meet their requirements.

Prepared by: Nick Ritter, WNTD
Revised by: Paul Bird, WNTD
Revision date: July, 1992