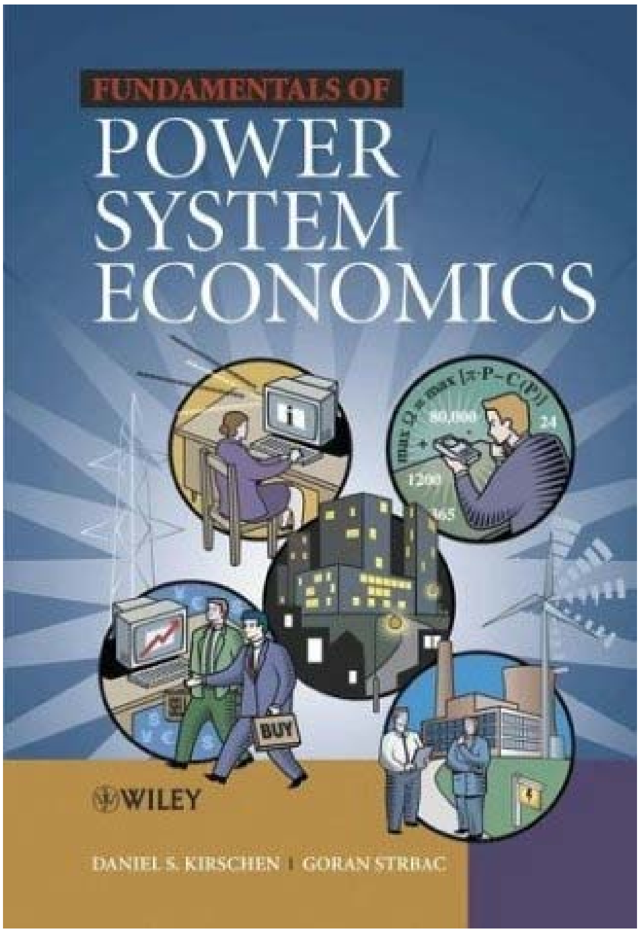
SOLUTIONS MANUAL



CHAPTER 5

SYSTEM SECURITY AND ANCILLARY SERVICES

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Chapter 5

5.1 *A power system is supplied by three generating units that are rated at respectively* 150, 200 *and* 250 MW. *What is the maximum load that can be securely connected to this system if the simultaneous outage of two generating units is not considered to be a credible event*?

If the simultaneous outage of two generating units is not deemed to be a credible event, the worst-case scenario that we must consider is the outage of the largest generating unit. Under these circumstances the maximum load that can be securely supplied is: $P_A^{max} + P_B^{max} = 150 + 200 = 350$ MW.

5.3 *A small power system consists of two buses connected by three transmission lines. Assuming that this power system must be operated according to the N-1 security criterion and that its operation is constrained only by thermal limits on the transmission lines, calculate the maximum power transfer between these two buses for each of the following conditions:*

a. *All three lines are in service and each line has a continuous thermal rating of* 300 MW
b. *Only two lines rated at* 300 MW *are in service*
c. *All three lines are in service. Two of them have a continuous thermal rating of* 300 MW *and the third is rated at* 200 MW.
d. *All three lines are in service. All of them have a continuous thermal rating of* 300 MW. *However, during emergencies, they can sustain a* 10% *overload for* 20 *minutes. The generating units on the downstream bus can increase their output at the rate of* 4 MW *per minute*.
e. *Same conditions as in* d, *except that the output of the downstream generators can only increase at the rate of* 2 MW *per minute*.
f. *Low temperatures and high winds improve the heat transfer between the conductors and the atmosphere. Assume that this dynamic thermal rating increases the continuous and emergency loadings of* (d) *by* 15%.

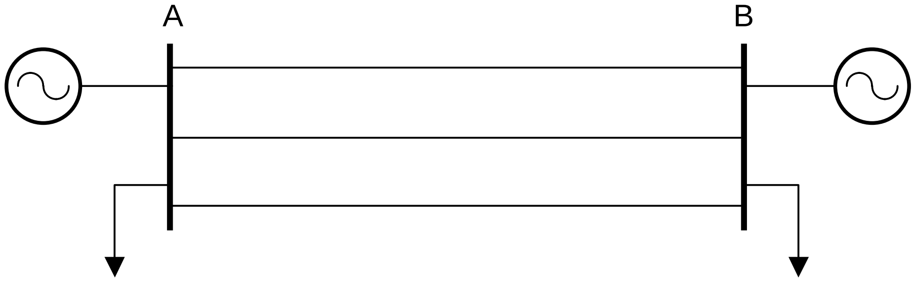


Figure P5.3 Power system for problem 5.3

a. If all three lines are in service and each line has a continuous thermal rating of 300 MW, the maximum power that can be transferred from one bus to the other is given by:
$(3-1)\times 300 = 600 \text{ MW}$

b. If only two lines rated at 300 MW are in service, then the maximum power transfer is:
$(2-1)\times 300 = 300 \text{ MW}$

c. If all three lines are in service but two of them have a continuous thermal rating of 300 MW and the third is rated at 200MW, then, the worst case scenario is for one of the lines rated at 300 MW to be disconnected. The maximum power that can be transferred is thus: 300 + 200 = 500 MW

d. Since all three lines can sustain a 10% overload for 20 minutes, the remaining lines can carry (300 + 300)×1.1 = 660 MW for 20 minutes. During these 20 minutes, the generating units on the downstream side should increase their output to remove the temporary overload. Since they can ramp up at a rate of 4 MW/min, the maximum increase in power output that they can deliver is 4×20 = 80 MW. Because these generators are located at the receiving end of this transmission corridor, an increase in their output relieves the overloading of the lines. Since this potential increase is larger than the 60 MW temporary overload that the lines can tolerate, the maximum power transfer is thus 660 MW in this case.

e. If the output of the downstream generators can only increase at a rate of 2 MW per minute, the maximum increase that can be achieved in 20 min is 2×20 = 40 MW. An overload of 60 MW could therefore not be corrected before the emergency rating expires. In this case, the maximum power that can be transferred is thus limited at 640 MW by the ramp rate of the generators.

f. If the cooling effect of the wind and ambient temperature increases the thermal rating of the lines by 15%, two lines are able to carry (300+300)×1.15 = 690 MW continuously. The 20-minute emergency rating is then 690×1.1 = 759MW. In this case, the difference between the emergency and continuous ratings is 69 MW, which is less than the maximum increase in output that the downstream generators can deliver in 20 minutes if the ramp rate is 4 MW/min. In this case, the maximum power transfer is thus 759MW.

5.4 *A generator is connected to a large power system by a double circuit transmission line. Each line has a negligible resistance and a reactance of* 0.2 *p.u. The transient reactance of the generator is* 0.8 *p.u. and its inertia constant is 3 s. The large power system can be modeled as an infinite bus and the voltages are kept at their nominal value. Assume that single circuit faults on the transmission line are cleared in* 120 *ms. Using a transient stability program, calculate the maximum power that this generator can produce without risking instability*.

This problem can be solved using any commercial transient stability program. If you do not have access to such a program, you can use the simple MATLAB® transient stability programs that you will find in file P5_4and5_5.m (which the requires the files P5_4and5_5a.m, P5_4and5_5b.m, P5_4and5_5ba.m, P5_4and5_5bb.m and P5_4and5_5bc.m in the same path). This program first calculates a power flow solution to obtain the initial conditions (internal voltage magnitude and angle of the generating unit) for the dynamic simulation. Once these initial conditions have been obtained, the swing equations (5.4.1 and 5.4.2) can be integrated numerically using the Ordinary Differential Equation (ODE) solver built in MATLAB®.

$$\frac{H}{\pi\ f_0}\frac{d\,\Delta\omega}{dt} = P_m - P_e = P_a \qquad (5.4.1)$$

$$\frac{d\,\delta}{dt} = \Delta\omega \qquad (5.4.2)$$

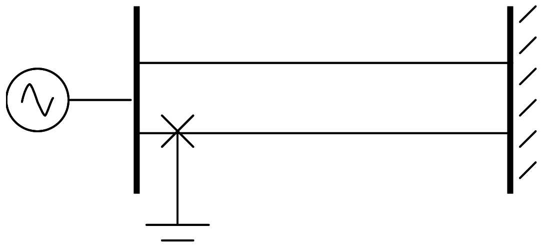


Figure 5.4-a: One-machine infinite bus power system used for problems 5.4.

Figure 5.4-a shows a diagram of the power system that we consider in this problem. The worst-case scenario that we must consider is a three-phase fault on one of the circuits, close to the busbar where the generator is connected. This fault is cleared in 120 ms by disconnecting the line. In this simple example, this line remains disconnected for the duration of our simulation. The integration method used to integrate the swing equations is “ode45” which is based on an explicit Runge-Kutta formula. The upper bound on the integration step size was set at 1×10^{-3} s.

Figure 5.4-b shows how some of the variables evolve during our simulation. The system is originally in steady state. Once the fault is applied the power transferred from the generator to the infinite bus becomes zero because the voltage is zero at one point along this path. Once the fault has been cleared by removing the faulted circuit, the system follows its dynamics until it reaches another steady state. The stability limit is reached when area A_1 is exactly equal to area A_2. If the power transferred before the flow is excessive, the system looses stability. In a numerical simulation, this means that the rotor angle does not reach a new steady. In practice, the generator gets disconnected by its protection system.

Using the program in a “trial and error” manner we can determine that, if the power system operates at 60 Hz, the maximum amount of power that can be transferred is 87.85

MW (0.8785 p.u. on a 100MW basis). The simulation shows that the system becomes unstable for any generation level beyond that amount. Figure 5.4.2 illustrates the dynamic behavior of the system for the limit computed with the dynamic program generated. For such power generated, the system still remain stable, but any further increase in the power generated and the system will become unstable. This means that for this case the area 2 is slightly bigger than area 1 and if damping were considered the system would return to the original initial conditions of operation.

Using a similar technique, we find that the maximum power that can be transferred is 92.5 MW if the system operates at 50 Hz.

Note that we have adopted an exceedingly simple generator model. Much more sophisticated models are used for actual transient stability calculations.

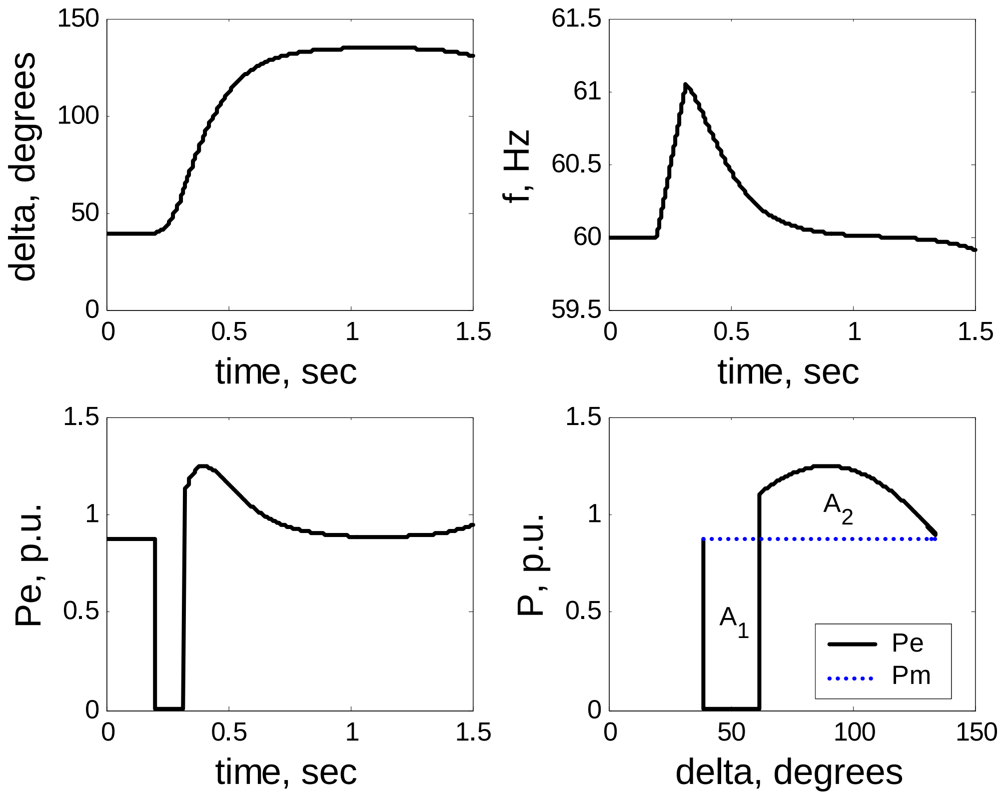


Figure 5.4-b Different variables in the power system for the pre-fault, during fault and post fault conditions for 60 Hz

5.5 *Repeat the calculations of Problem 5.4 for the case where the generator is connected to the power system by two identical double circuit transmission lines.*

The same MATLAB® program used for Problem 5.4 can be used for this problem. If the power system operates at 60 Hz the maximum power that can be transferred without risking instability is 101.73 MW. Figure 5.5-a illustrates this result graphically. If the system operates at 50 Hz, the maximum power that can be transferred without risking instability is 108.4 MW.

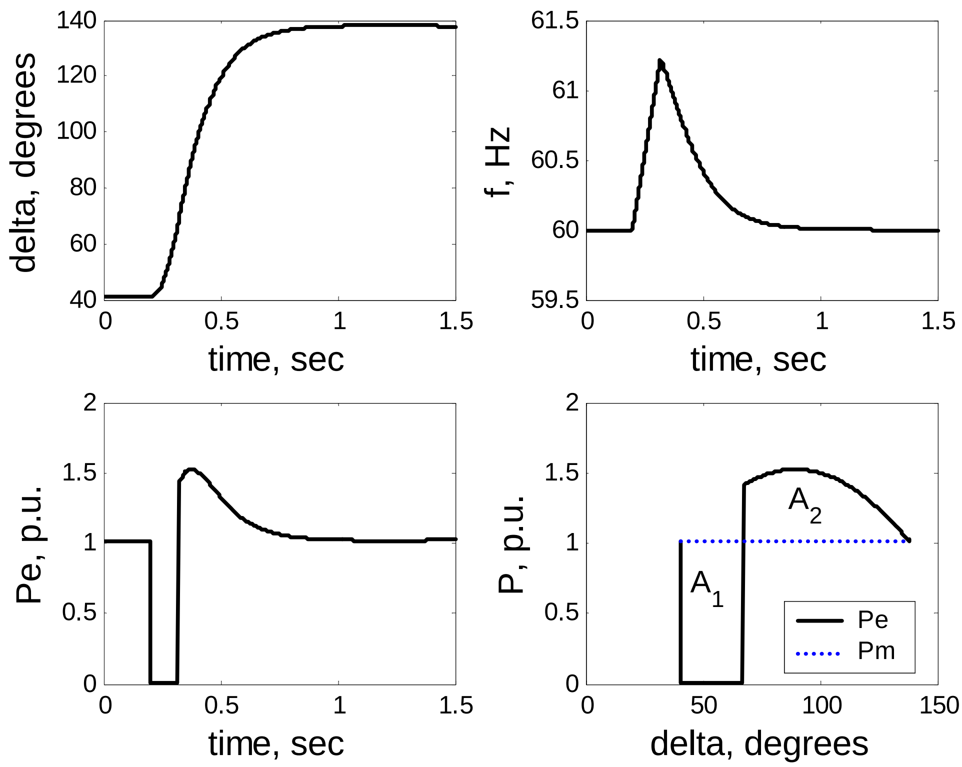


Figure 5.5 Different variables in the power system for the pre-fault, during fault and post fault conditions for 60 Hz

In Figure 5.5 a system operating at 60 Hz is shown for the case in which it still remaining stable. For any further generation beyond 101.73 MW the system would become unstable. Again, as in the previous problem, the area 2 is slightly bigger than the area 1, and therefore if damping were considered, the system would eventually return to the initial conditions of operation.

5.6 *Consider a power system with two buses and two lines. One of these lines has a reactance of* 0.25 *p.u. and the other a reactance of* 0.40 *p.u. The series resistances and shunt susceptances of the lines are negligible. A generator at one of the buses maintains its terminal voltage at nominal value and produces power that is consumed by a load connected to the other bus. Using a power flow program, calculate the maximum active power that can be transferred without causing a voltage collapse when one of the lines is suddenly taken out of service under the following conditions*:

a. *The load has unity power factor and there is no reactive power injection at the receiving end*
b. *The load has unity power factor and a synchronous condenser injects* 25 MVAr *at the receiving end*
c. *The load has a* 0.9 *power factor lagging and there is no reactive power injection at the receiving end.*

This problem can be solved using the educational version of the PowerWorld™ software, which can be downloaded from www.powerworld.com.

The data for this system in PowerWorld™ format can be found in file P56.pwb. Figure 5.6 shows the one-line diagram for this system. By progressively increasing the load and running a power flow calculation with only one line in service each time, we find that the maximum power that can be transferred is 200 MW. If we try to transfer a larger amount of power, the power flow fails to converge. This is usually an indication that the system has reached the point of voltage collapse.

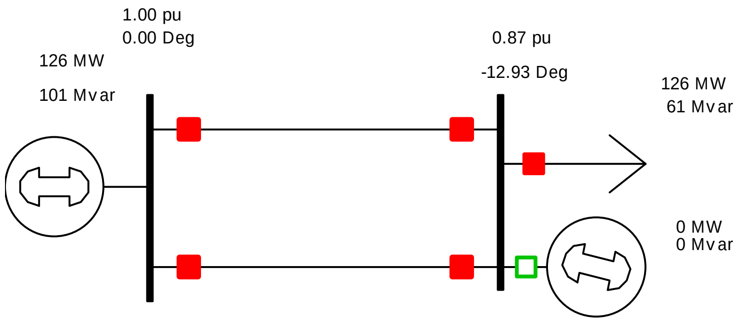
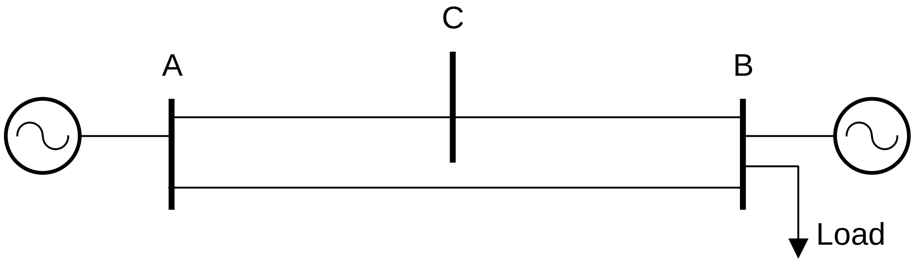


Figure 5.6: Powerworld™ diagram of the system of Problem 5.6

When the load has a unitary power factor but there is an injection of 25 MVAr at the receiving end the power transfer limit is 222 MW. This situation is simulated by putting in service the generator connected to the load bus and setting its output at 0 MW and 25 MVAr.

Finally, when the load has a power factor of 0.9 lagging and there is no reactive injection at the receiving end the power transfer limit is 125.1 MW.

5.7 *Consider the small power system shown in the figure below. Each line of this system is modeled by a π equivalent circuit. The parameters of each line are given in the table below.*



Line	R [p.u.]	X [p.u.]	B [p.u.]
A-B	0.08	0.8	0.3
A-C	0.04	0.4	0.15
C-B	0.04	0.4	0.15

Using a power flow program, study the reactive support requirements as a function of the amount of power transferred from bus A to bus B for both normal conditions and abnormal conditions (i.e. avoiding a voltage collapse following the sudden outage of a line). Consider both a unity power factor and a 0.9 *power factor lagging load at bus B. Analyze and discuss the usefulness of a source of reactive power at bus C.*

A PowerWorld™ model of this system can be found in the file P57.pwb. Figure 5.7-a shows the corresponding one-line diagram.

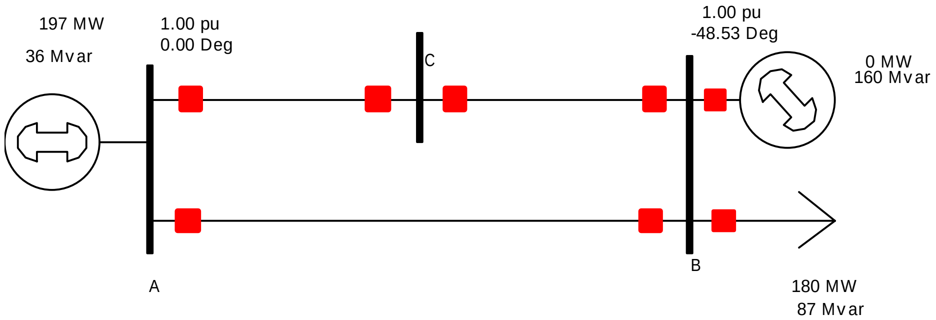


Figure 5.7-a Power world model

Figure 5.7-b shows the reactive support requirements as a function of the power transferred for a unity power factor load under normal conditions when the voltage at bus B is kept at 1 p.u.

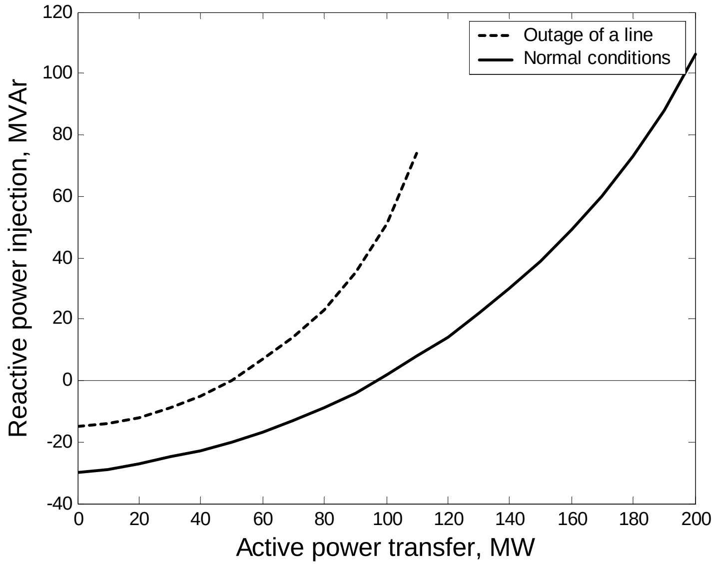


Figure 5.7-b Reactive power injection required at bus B to keep the voltage at nominal value as a function of the active power transfer.

For power transfers lower than around 96 MW the reactive source at bus B must absorb the reactive power produced by the shunt capacitance of the transmission lines to maintain the voltage constant. On the other hand, for larger power transfers, this reactive source must inject reactive power. If the possibility of a sudden line outage is considered, the reactive requirements are as shown by the dotted line on the same graph. Considering this contingency thus significantly increases the reactive support requirements for the same amount of power transferred. Put another way, for a given reactive power support capacity, the power than can be transferred from A to B is smaller when contingency conditions are considered.

If the load at bus B has a power factor of 0.9 lagging then the reactive power requirement as a function of the active power transfer is as shown in Figure 5.7-c.

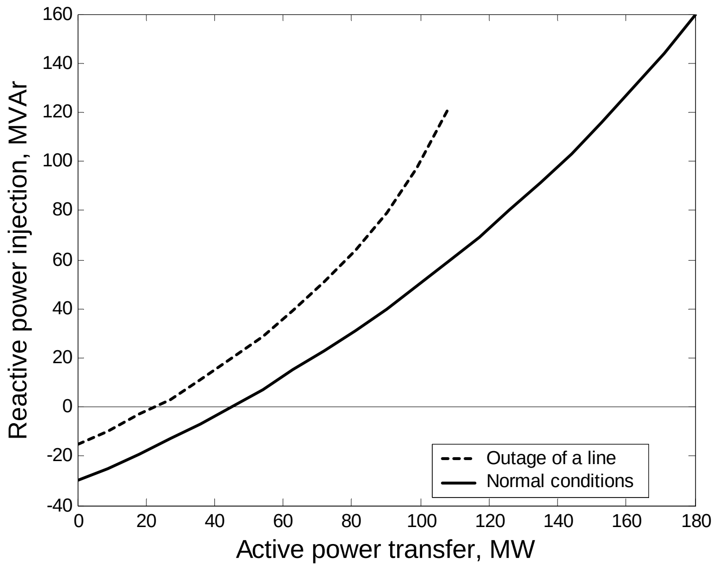


Figure 5.7-c Reactive power required at bus B to keep the voltage at nominal value as a function of the active power transfer when the load has a power factor of 0.9 lagging.

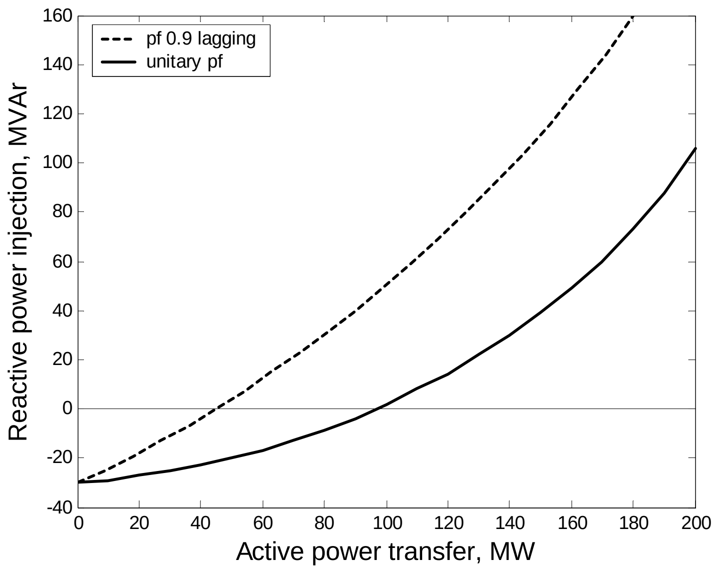


Figure 5.7-d Comparison of the two load cases for the normal conditions

Figure 5.7-d gives a comparison of the reactive power requirements for the previous two cases. It shows clearly that a lagging power factor load requires considerably more reactive power support than a unity power factor load.

If there were a reactive power source at bus C but none at bus B, there would be no direct way to control of the voltage at bus B. Figure 5.7-e illustrates this situation. However, this reactive power support at bus C makes it possible to transfer more power from A to B than if there was no reactive support at all.

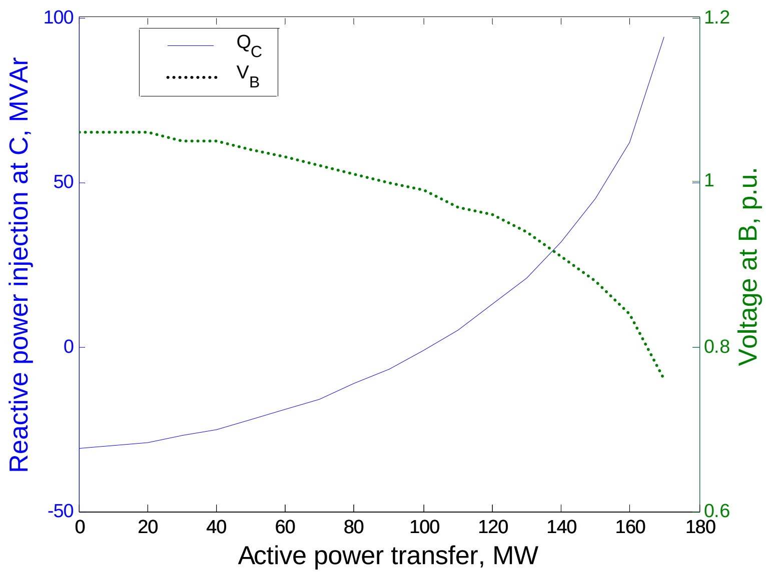


Figure 5.7-e   Reactive support required at bus C and the voltage at bus B

On the other hand, as shown in Figure 5.7-f, if there is reactive support at both buses C and B, the reactive support required at bus B would be smaller than if there were no support at C.

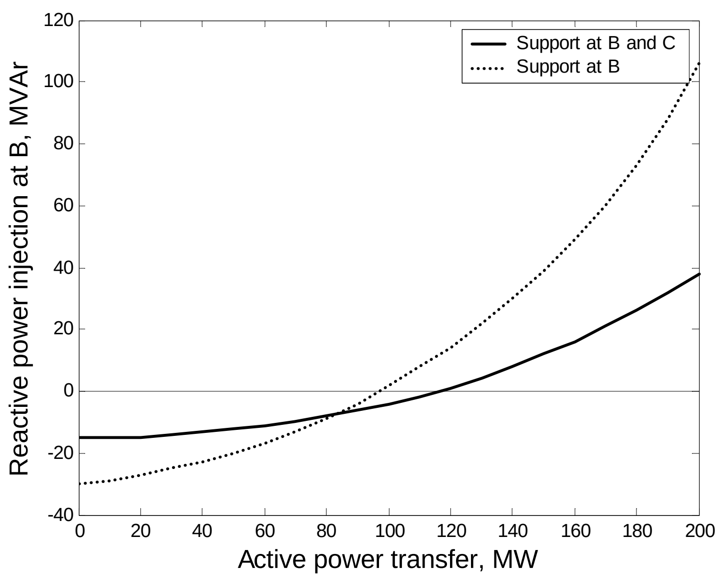


Figure 5.7-f   Reactive support at bus B as a function of the power transferred