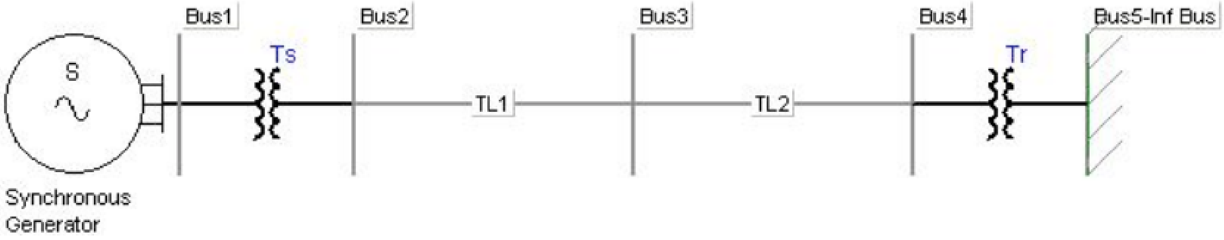
ECE4464: Lab 1

Objectives

In this lab, our objective is to simulate a simple single-machine infinite-bus configuration using the PowerWorld Simulator software. We design a local generator system (a synchronous generator) having a nominal generation capacity of 500MW and with no predefined peak generation (that is, the generator is modelled as having infinite generation capability).

In this manner, we can explore various phenomena like power transfer, power system stability and the effect of shunt compensation on the midline. We model a 600km span of transmission line with a shunt compensation device installed at the midline (300km from both ends) and determine the stability limit with and without this compensation device enabled.

Single-Line Diagram



Methodology

Because PowerWorld does not have a concept of an infinite bus system, we simulate it by using a generator on the slack bus that does not enforce power generation/absorption limits, allowing it to generate or absorb as much power as necessary. Both the local synchronous machine and the infinite bus generator are set to have Automatic Voltage Regulation (AVR) in order to maintain the voltage magnitude at 1.0 per unit.

Observations

The following table lists some observations without any mid-line compensation:

Generated	Sending Line Voltage	Midline Voltage	Infinite Bus Voltage
100 MW	1.000 ∠5.06°	1.151 ∠2.12°	1.000 ∠0°
200 MW	1.000 ∠10.25°	1.148 ∠4.71°	1.000 ∠0°
300 MW	1.000 ∠15.50°	1.142 ∠7.34°	1.000 ∠0°
400 MW	1.000 ∠20.86°	1.133 ∠10.02°	1.000 ∠0°
500 MW	1.000 ∠26.39°	1.122 ∠12.78°	1.000 ∠0°
600 MW	1.000 ∠32.16°	1.107 ∠15.67°	1.000 ∠0°
700 MW	1.000 ∠38.27°	1.089 ∠18.72°	1.000 ∠0°
800 MW	1.000 ∠44.89°	1.065 ∠22.03°	1.000 ∠0°
900 MW	1.000 ∠52.28°	1.034 ∠25.73°	1.000 ∠0°
1000 MW	1.000 ∠61.02°	0.993 ∠30.09°	1.000 ∠0°
1100 MW	1.000 ∠72.79°	0.927 ∠35.98°	1.000 ∠0°
1167 MW	1.000 ∠90.35°	0.812 ∠44.76°	1.000 ∠0°
1170 MW	Catastrophic power system failure		

All voltage measurements are in per-unit with a 1000MVA system base.

As indicated from the above chart, local generation of 500MW results in a midline voltage of 1.122 per unit. The challenge, then, is to design a compensation device (a shunt inductor installed at the midline bus) to bring the voltage down to the desired 1.050 per-unit value.

Using a continuous shunt compensation element (which essentially models the operation of a synchronous condenser) installed at the midline, we can determine the exact amount of reactive power needed to bring the voltage down to our desired value. At 500MW, the condenser behaves as an inductor that consumes 236.6 Mvar of reactive power and the midline voltage is 1.050 as desired.

By varying the inductance around the 236-Mvar region, we find that a nominal rating of -214.0 Mvar results in an actual reactive power consumption of 236.0 Mvar, bringing the midline voltage down to 1.050 for 500MW of generation.

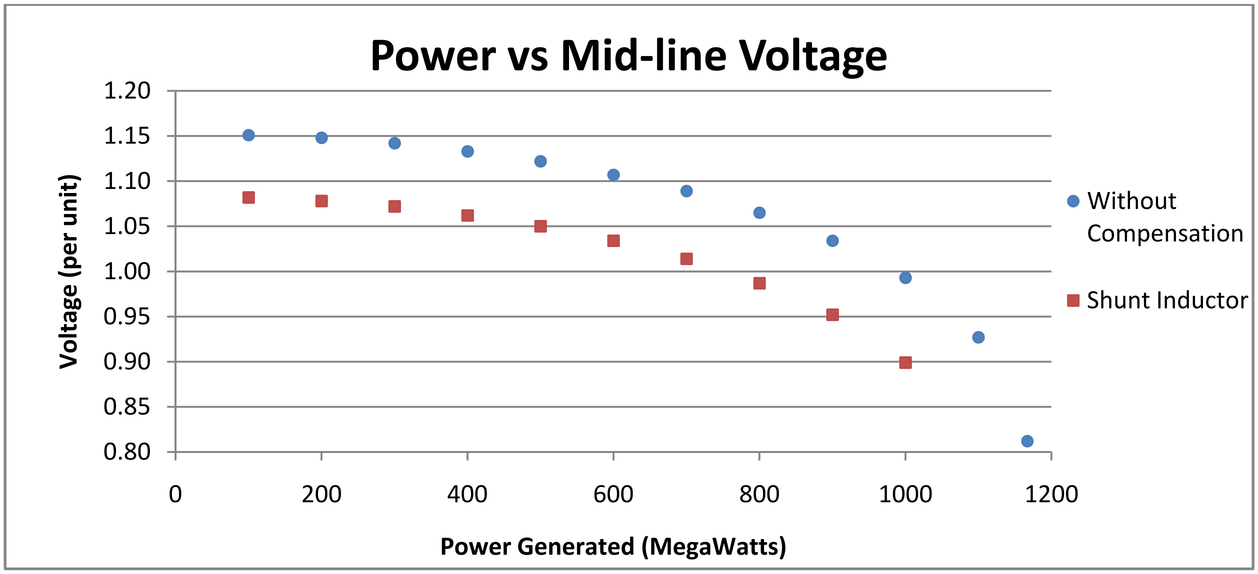
The following chart shows the system voltages after installation of the shunt inductor:

Generated	Sending Line Voltage	Midline Voltage	Infinite Bus Voltage
100 MW	1.000 ∠5.46°	1.082 ∠2.55°	1.000 ∠0°
200 MW	1.000 ∠10.99°	1.078 ∠5.31°	1.000 ∠0°
300 MW	1.000 ∠16.58°	1.072 ∠8.11°	1.000 ∠0°
400 MW	1.000 ∠22.32°	1.062 ∠10.98°	1.000 ∠0°
500 MW	1.000 ∠28.26°	1.050 ∠13.94°	1.000 ∠0°
600 MW	1.000 ∠34.50°	1.034 ∠17.07°	1.000 ∠0°
700 MW	1.000 ∠41.19°	1.014 ∠20.41°	1.000 ∠0°
800 MW	1.000 ∠48.55°	0.987 ∠24.09°	1.000 ∠0°
900 MW	1.000 ∠57.05°	0.952 ∠28.34°	1.000 ∠0°
1000 MW	1.000 ∠67.80°	0.899 ∠33.72°	1.000 ∠0°
1100 MW	1.000 ∠90.88°	0.760 ∠45.26°	1.000 ∠0°
1101 MW	Catastrophic power system failure		

In this case, because of the reactive compensation installed in shunt with the (invisible) line-charging capacitances, the reactance of the inductor compensates for a portion of the Ferranti effect and brings the voltage down. However, this results in power system instability earlier than in the uncompensated case, giving a maximum power transfer of only 1100MW. Note from the above that the 1.00pu midline voltage value occurs with a sending-side generation of between 700 and 800MW, rather than at the SIL of 1000MW.

Graphs

The following graph demonstrates the change in the midline voltage with power generated (and therefore transferred) across the lines. Note that the power generated does not equal the actual power transferred across the lines because some of it is lost during transmission (as heating of the lines).



The above plot includes information from the first part of the lab (without compensation) as well as the second part, where a fixed inductor is installed at Bus 3. If a synchronous condenser is placed at the midline instead of the fixed inductive element, the midline voltage will remain at the 1.050 setpoint regardless of the other system voltages, due to the reactive power dynamically injected into or removed from the system.

Discussion

What is the effect of varying power flows on midline voltage? Explain.

As we can see from the graph, the mid-line voltage is higher than that at both the sending and receiving ends, a phenomenon known as the Ferranti effect. Physically, it is due to the line-charging capacitances (line-to-line and line-to-ground via the air). As the generated power increases, however, the series inductance of the line begins to play a greater role. When we are transferring power at a rate higher than the SIL limit (we only have two such measurements of this before the system goes unstable), we can see that the uncompensated voltage drops below 1.0 per unit.

The voltage is very close to 1.00pu at the Surge Impedance Loading (SIL), which is, in this case, 1000MW. This particular figure is consistent with the given line parameters (500 kV, R=0.028 Ω/km, X_L=0.325 Ω/km, B_C=5.2 µS/km) according to Appendix H: Transmission Line Parameters. The SIL as indicated on Appendix H is indeed 1000MW.

Because it is significantly less expensive—both in terms of initial investment and ongoing maintenance costs—to install solid-state power electronic components on high-voltage lines, I simulated a simple fixed reactor (inductor) installed at Bus 3. As we can see from the above graph, the shunt inductor results in a constant per-unit voltage drop, but the power vs. mid-line voltage relationship remains the same.

Was there a limit to the output power of the synchronous generator? Explain.

By default, the generator is set to have a generation limit of 1000MW and an unlimited amount of reactive power (both capacitive and inductive). In my experiment, I raised the generation maximum limit to 3000MW to allow me to see what other factors limit the power transferred from the local machine to the infinite bus.

With that limit aside, there are other factors limiting the total stability of the system. Most notably, both sides (the machine and the infinite bus) of our system maintained a voltage of 1.0 per unit, which is necessary if there are other loads connected to a nearby local bus. This results in a tightly restricted voltage profile.

From the classic power transfer equation, neglecting the resistance on the transmission lines:

$$P_{12} = V_1 V_2 \frac{1}{X} \sin\delta$$

Because the bus voltages must necessarily remain the same, the only thing we can do to increase transferred power from the generator to the infinite bus is to increase the difference in power angles. However, the system is limited because increasing the angle over 90 degrees results in instability.

In our simulation, we measured a difference in sending and receiving angles that exceeded 90 degrees and yet remained stable; this is probably due to a flaw in PowerWorld. Even so, note that the angle is still close to 90 degrees. In the compensated configuration, we had a difference of 90.88° between the local system and slack bus—before the system became unstable.

What happened when that limit was reached?

When the power system reached its maximum stability limit, there was a catastrophic failure resulting in a blackout.

What effect did the compensator that you designed have on the bus voltages and angles?

Because the compensator counteracts the effects of line-charging capacitance, it resulted in a lower midline voltage than would have been possible otherwise. However, in order to ensure the same power transfer while having a lower midline voltage, the power angle must increase slightly (per the above power transfer equation). As a result, the system becomes unstable earlier, at 1101MW instead of 1167MW.

Conclusions

In this computerized simulation, we saw the effect of changing power transfer on the sending, mid-line and infinite bus voltages. We performed a load flow study under various load/generation conditions. We saw the effect of compensation installed at the midline bus on power system stability. We also learned how to make use of various features of the PowerWorld Simulator software to model and learn from power systems.