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Lab 2

Objectives

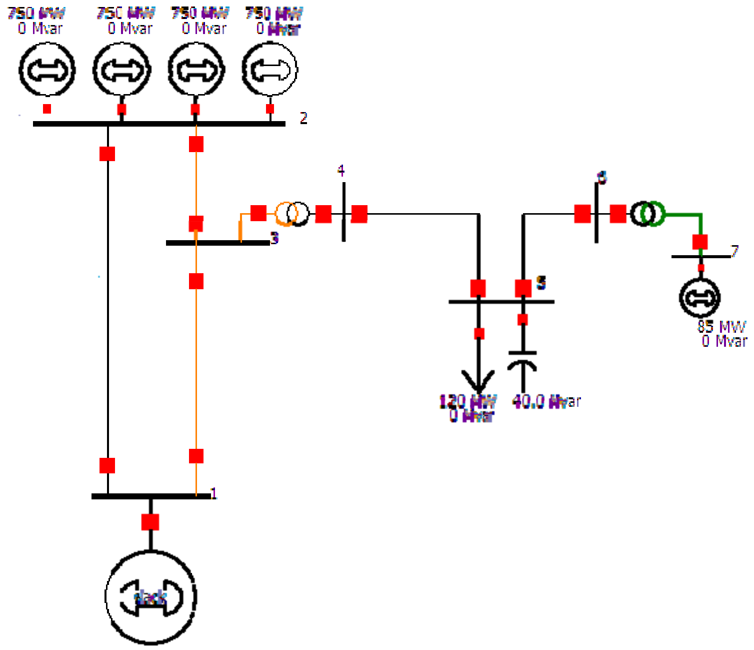
In this lab, our objective is to study the potential impact of integration of distributed generation (in particular, a wind farm) using the PowerWorld Simulator software. We simulate a very large capacity plant (a nuclear plant consisting of four reactors producing 750 MW each). Because these reactors are large, they will provide some voltage regulation by supplying or consuming MVARs.

The nuclear plant serves a large city via two parallel transmission circuits, as well as the smaller city at the mid-line of one of these lines. To simplify this lab, we model the large city as an infinite bus, which consumes any excess power generated by the plant.

In this manner, we can explore various phenomena resulting from distributed generation systems like wind farms, including the effects on power transfer and power system stability. This lab provides insight on two very important issues in power systems, notably, the addition of distributed generation and the challenges involved with electrifying remote communities.

Single Line Diagram

Based on the lab description (four nuclear reactors supplying the majority of the power to a large city modelled as an infinite bus, with a small town and a proposed wind farm some distance away from the rest of the system), we construct the following 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. One of the four reactors at the nuclear power plant provides voltage regulation (to 1.05 per unit) while the infinite bus is set to have Automated Voltage Regulation (AVR) in order to maintain the voltage magnitude at 1.0 per unit.

Distributed generation installations such as wind turbine generators and photovoltaic panels usually produce direct current (DC) power that creates single-phase alternating current (AC) power using a grid-tie inverter (GTI). These power conversion devices are synchronous with the mains frequency inject voltage and current that are in-phase (they have unity power factor). Thus, for the purposes of this study, these grid-tie inverters essentially appear to the grid as synchronous machines with a fixed unity power factor.

Observations

Base Case

This table illustrates the effects of the small town’s changing power consumption throughout the day:

Time	Load	Voltage (pu)
00:00	50 MW + 20 MVAr	1.055 ∠14.26°
02:00	50 MW + 20 MVAr	1.055 ∠14.26°
04:00	50 MW + 20 MVAr	1.055 ∠14.26°
06:00	50 MW + 20 MVAr	1.055 ∠14.26°
08:00	50 MW + 20 MVAr	1.055 ∠14.26°
10:00	100 MW + 20 MVAr	1.009 ∠6.62°
12:00	100 MW + 20 MVAr	1.009 ∠6.62°
14:00	100 MW + 20 MVAr	1.009 ∠6.62°
16:00	100 MW + 20 MVAr	1.009 ∠6.62°
18:00	120 MW + 20 MVAr	0.982 ∠3.16°
20:00	70 MW + 20 MVAr	1.040 ∠11.33°
22:00	70 MW + 20 MVAr	1.040 ∠11.33°

Note that the shunt capacitor is set to inject 40Mvar (nominal) to the small town bus. Whenever the voltage is not 1pu, the actual compensation delivered by the capacitor will vary. However, the load reactive power at the small town bus will always remain at 20 Mvar (per the email), since it is part of the load model.

In the early hours of the morning, the power draw is relatively low, so the voltage at the bus is higher than the desired value of 1.0pu – at 1.055pu, it is actually a bit higher than permitted by the grid code;

however, as most electrical codes permit a variation between ±5% of the nominal (1.0pu) voltage, this is borderline-acceptable. As the day progresses and the current draw increases, the voltage drop across the transmission lines increase, resulting in a lower bus voltage. At 6pm, the voltage is 0.982pu, which is very close to the lower boundary.

Wind Turbine Generator

As mentioned earlier, wind turbine generators (or wind farms) produce power at unity power factor and usually do not provide any means of automatic voltage regulation. Once a wind farm is interconnected with the grid at the small town, the daily voltage profile changes accordingly.

The following table illustrates the effect of adding distributed generation (in this case, wind power) to a remote bus:

Time	Load	Town Voltage	Generated
00:00	50 MW	$1.066 \angle 26.08^\circ$	85 MW
02:00	50 MW	$1.066 \angle 26.08^\circ$	85 MW
04:00	50 MW	$1.066 \angle 26.08^\circ$	85 MW
06:00	50 MW	$1.066 \angle 26.08^\circ$	85 MW
08:00	50 MW	$1.066 \angle 26.08^\circ$	85 MW
10:00	100 MW	$1.048 \angle 14.22^\circ$	50 MW
12:00	100 MW	$1.048 \angle 14.22^\circ$	50 MW
14:00	100 MW	$1.048 \angle 14.22^\circ$	50 MW
16:00	100 MW	$1.048 \angle 14.22^\circ$	50 MW
18:00	120 MW	$0.998 \angle 4.95^\circ$	10 MW
20:00	70 MW	$1.049 \angle 12.81^\circ$	10 MW
22:00	70 MW	$1.049 \angle 12.81^\circ$	10 MW

Wind strength varies cyclically due to several environmental factors and climate conditions, so the power generated from wind farms usually varies quite widely as well. To make matters worse, the periods of highest power generation (in the early morning or late night hours) usually coincide with periods of lowest power consumption, particularly because cooking, comfort heating/cooling and washing machines represent some of the largest varying residential loads.

In the worst case, the generated power will result in a much higher voltage than desired – the worst part of the day is the early morning hours, where the wind farm generates much more power than is necessary to serve the load at the town, resulting in a voltage of 1.066 per unit. During the town’s peak loading in the early evening, however, the voltage is more desirable than without the wind farm, since it remains closer to the nominal voltage. In reality, however, there is only a 1-2% difference in the voltage at 6pm, with or without the generation system.

Since there is no load connected directly to the same bus as the distributed generation system, we are not concerned with the voltage regulation at that bus. In practice, this is usually not the case and many distributed generation projects have direct connections buses that serve other loads. However, for some commercial projects (which are the largest and have the most influence on overall power system stability), this is a reasonable simplification to make.

Wind Turbine Generator without Shunt Compensation

The town currently has a shunt compensation system available to raise the bus voltage under normal loading conditions (to prevent a voltage sag/brownout). In the early morning hours when the small town’s load is low and the wind farm’s generated power is at its peak, the shunt capacitor causes voltage to rise above the maximum parameters permitted by the local grid code. Disconnecting the shunt compensation (opening the circuit breaker) can help alleviate this problem, providing a lower voltage that is within the tolerance guidelines set by the government.

The following table illustrates the effect of adding distributed generation (in this case, wind power) to a remote bus, after removing the shunt compensation:

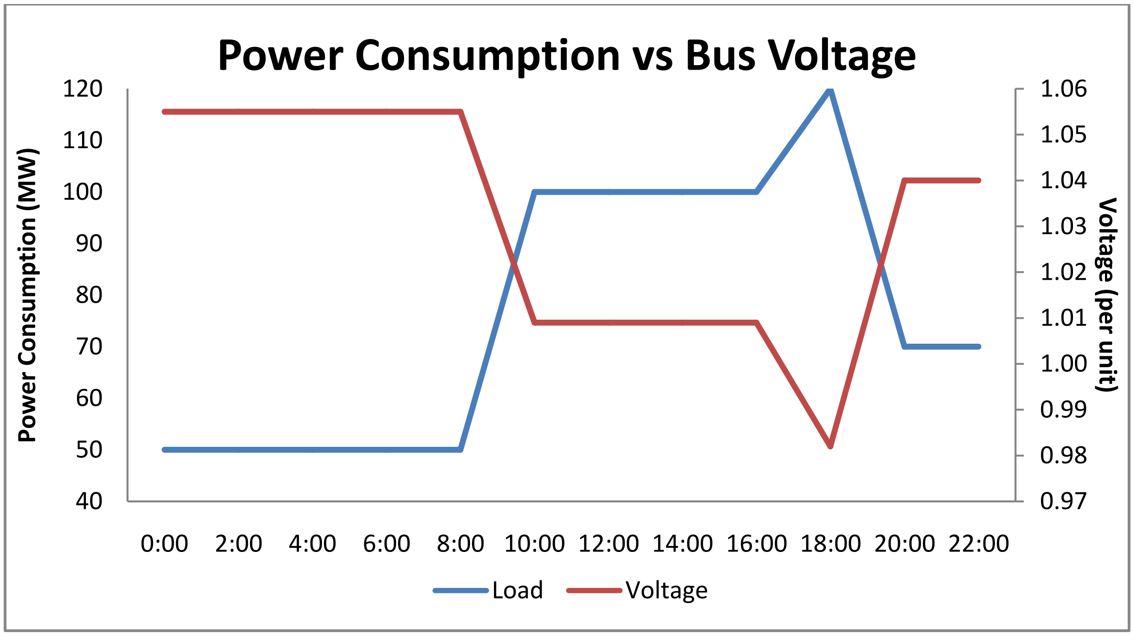
Time	Load	Town Voltage	Generated
00:00	50 MW	$0.943 \angle 27.48°$	85 MW
02:00	50 MW	$0.943 \angle 27.48°$	85 MW
04:00	50 MW	$0.943 \angle 27.48°$	85 MW
06:00	50 MW	$0.943 \angle 27.48°$	85 MW
08:00	50 MW	$0.943 \angle 27.48°$	85 MW
10:00	100 MW	$0.932 \angle 14.15°$	50 MW
12:00	100 MW	$0.932 \angle 14.15°$	50 MW
14:00	100 MW	$0.932 \angle 14.15°$	50 MW
16:00	100 MW	$0.932 \angle 14.15°$	50 MW
18:00	120 MW	$0.879 \angle 3.51°$	10 MW
20:00	70 MW	$0.935 \angle 12.60°$	10 MW
22:00	70 MW	$0.935 \angle 12.60°$	10 MW

The above chart illustrates that removing the 40 MVAr capacitor will result in unacceptably low voltages at the town bus. Unfortunately, turning the capacitor on would raise the voltage above the acceptable operating range. Changing the state of the fixed shunt capacitor will have no impact on the power generated.

Graphs

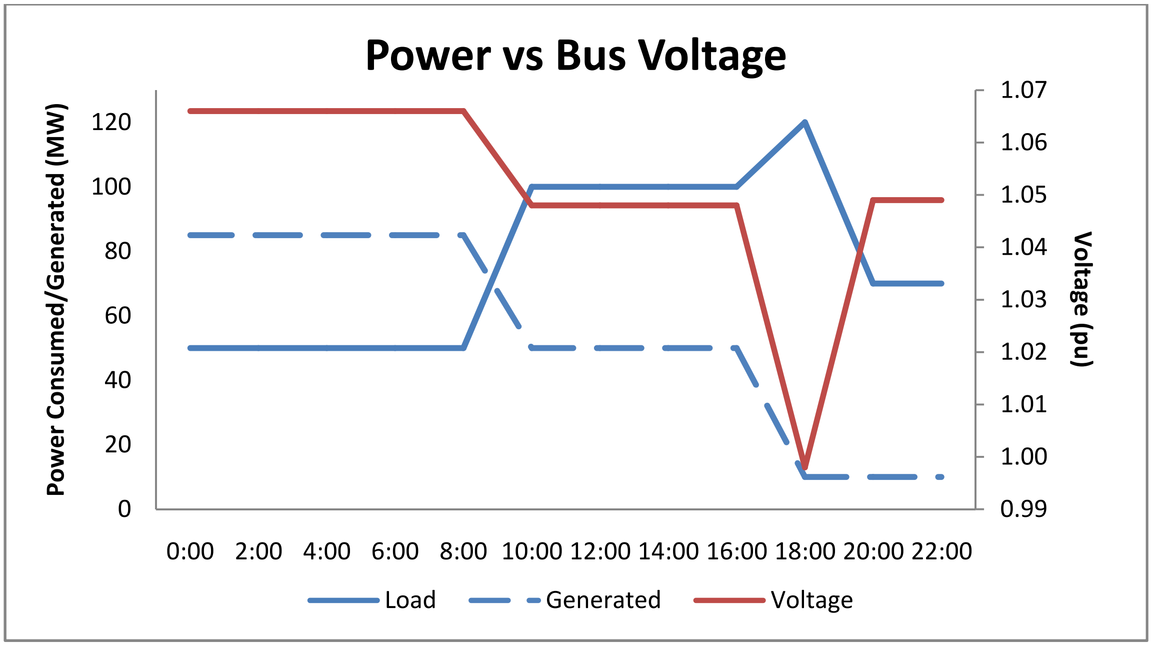
Base Case

This graph demonstrates the impact of changing power demand and voltage, without the wind farm:

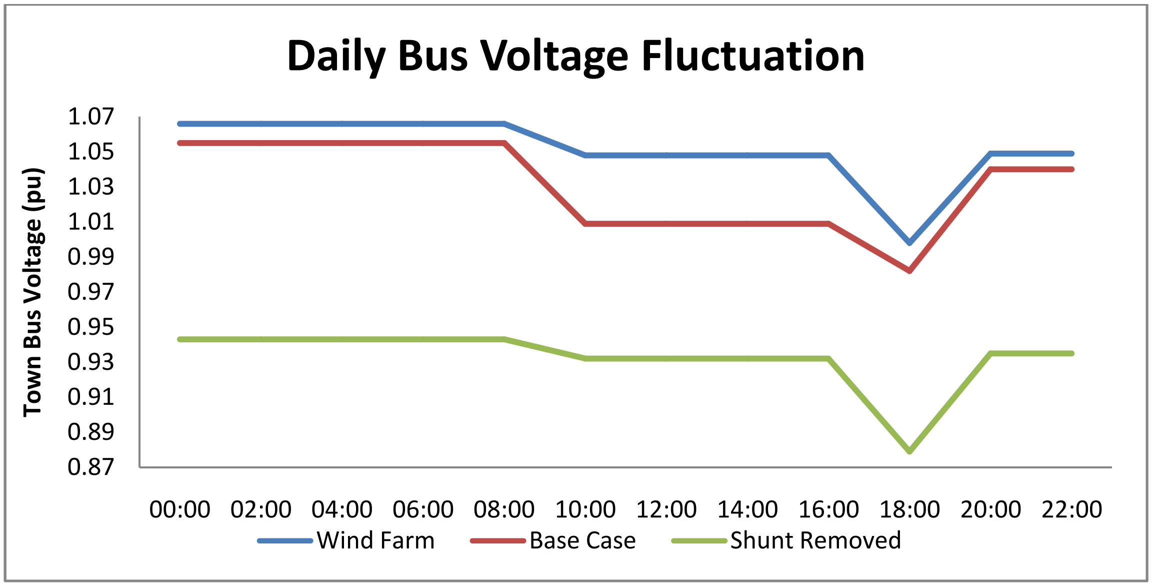


Wind Turbine Generator

The following graph illustrates the impact of changing power demand as well as fluctuating power generated:



Voltage Fluctuations



Discussion

What is the effect of the proposed wind farm? Explain.

If the proposed wind farm is installed as-is without any other means of compensation, the daily bus voltage will rise far above the voltage of the base case, throughout the entire day. As we can see from the "Daily Bus Voltage Fluctuation" graph, the voltage will remain higher than that of the base case throughout the entire day; while this is not problematic for most of the day, the early morning voltage (at 1.066pu instead of 1.05pu) will exceed the grid code parameters by a significant amount – 1.6%. In order to reduce the bus voltage, the town's first reaction may be to switch off the shunt capacitor; unfortunately, doing so will result in a lower-than-desired voltage of only 0.943 per unit and an error of almost 4% (from the lower boundary of 0.98 per unit).

The Canadian Standards Association (CSA) specifies that the service voltage should have variations from the nominal voltage of 5% for normal operating conditions and up to 8% under extreme operating conditions (required as part of standard CAN3-C235-87, or the latest edition). If the system ever exceeds normal operating conditions while remaining under the extreme operating limit, the utility is responsible for conducting planned corrective measures for the system. However, if the system is under "extreme operating conditions," the system is in a state of emergency and the utility is responsible for making the necessary repairs as soon as possible.

Given that the local grid code provides for fluctuations between 0.98 and 1.05pu, they must be within ±3.45% of the nominal voltage of 1.015pu. Under Canadian guidelines, the system is still operating in acceptable conditions; however, if the load is particularly sensitive, the guarantee of 1.105pu ± 3.45% could be more important (especially when there are any service-level agreements made with the town).

Based purely on the impact on the system, would you allow this proposed wind farm to be installed? Explain.

In the absence of any other proposed protection measures or changes in the load profile, the town should not permit the proposed wind farm installation to connect with the grid. Assuming that the wind generation project was proposed for Ontario, neither the provincial nor the federal governments place the requirement on utilities to integrate such large-scale generation projects with the grid.

In particular, the peak power generation at the wind farm coincides with the time of day that the town has its lowest power consumption. Because the town has historically low power consumption during the early morning hours, current loading conditions result in a bus voltage, which is 0.5% above the “maximum” of 1.05 per unit defined in the grid code. While this is probably not a significant issue in itself, it means that the system is on the edge of the margin of safety and the local power utility could be liable for damage to equipment.

Under the proposed wind farm project, injecting the full 85MW into the power system will result in a bus voltage of 1.066 per unit during the early morning hours. This, once again, stems from the classic power transfer equation:

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

If we want to increase power transferred between two buses, our only option is to raise our local bus voltage (which will also have an effect on the remote voltage). In particular, since the town is a “weak bus,” it has relatively poor voltage regulation capability. Without compensation for the bus voltage/angle (via shunt compensation), the line reactance (via series capacitors) or both (using a Unified Power Flow Compensator), only raising the voltage provide the desired power transfer capability for this system.

Propose at least three methods to mitigate any ill-effects of the proposed wind farm. Briefly discuss the viability of these methods, both in terms of effectiveness and potential cost.

1. **Disconnecting the shunt capacitor** at the town will bring the voltage down in the early morning hours; however, doing so will result in a lower-than-desired voltage at the bus under normal generation conditions. Because the large generation project comprises four 750MW reactors, they will cause the system to become more “stiff” – that is, it reduces the ability for smaller generators to have an impact on the bus characteristics. Despite adding 85MW to the grid, the wind generator is unable to raise the bus voltage at the town by any significant amount.

   With the proposed wind farm completely disconnected, the bus voltage will be 0.941; connecting it to the grid brings the bus voltage at the town up to 0.943, which is inadequate according to the grid code. This solution is neither viable nor sustainable in the long-term, since it does not bring the voltage into the range required by the grid code.

2. **Limiting the power generated** by the plant based on time of day can help to regulate the remote voltage at the town as mentioned above. If we disconnect the wind generator from the grid entirely (open the circuit at the line between the town bus and the high-tension bus of the transformer), then the bus voltage will be the same as the case without the wind farm (1.055pu, which is above the grid code restriction).

   However, this means that any power available at the wind farm will go to waste – definitely not something very cost-effective for the wind farm owner, since the opportunity cost is significant: the plant will be wasting 85MW during the peak power production between 10:00pm and 08:00am; in other words, 850MWh will be lost every day. Since the current Feed-in-Tariff (FIT) proposal ensures the sale of green power to the utility at a rate of 19¢/kWh (offshore wind generation), this reflects an opportunity cost of $161,500 each day.

   Source: http://fit.powerauthority.on.ca/

3. **Use a battery energy storage system (BESS)** or other energy storage system as a buffer between the wind turbine generation system and the power grid. The induction machines driven by the wind turbine would charge the energy storage system prior to inverting it to AC power using a grid-tie inverter. In effect, this would have similar effect on the power system to limiting generated power based on time-of-day; however, the market price of electricity should help to offset the initial cost of adding a battery system: during peak load, supply and demand dictates that power will have a higher price per kilowatt-hour.

   There are a variety of technologies available for this purpose, including:

   - traditional lead-acid batteries, which have a long service life and relatively low maintenance cost
   - vanadium batteries, which are quickly becoming preferred for high-power applications
   - hydrogen fuel cells, which are a much-hyped but rarely-used technology
   - supercapacitors or ultracapacitors, which are still in the research phase

   Because they are a historically well-understood technology and are inexpensive (relative to other solutions), I would recommend using lead-acid batteries for most distributed generation installations. As long as they are not subject to deep cycles (complete discharge followed by a recharge cycle), these batteries can last a long time and are relatively maintenance free. Furthermore, these batteries would not need rapid discharge capability in this application, meaning they need fewer internal electrolyte plates and are therefore less expensive overall.

   Vanadium batteries are quickly replacing lead-acid batteries for high-power applications (especially because they have a discharge/recharge durability of over 10,000 cycles). However, because they are not currently a consumer product, pricing can vary significantly from project to project; thus, it is difficult to compare them to conventional batteries.

   The following chart compares the power density versus cost of each of these systems:

	Cost of Capacity	Energy Density	Service Life	Cycle Durability
Lead-Acid Battery	USD$142/kWh	60-75 Wh/L	variable	500-800 cycles
Vanadium Battery	unknown	15-25 Wh/L	10-20 years	10,000 cycles

Source: Wikipedia

If we installed 850MWh of storage capacity, it would require 14,000 cubic metres of space and have a capital cost of over $120-million. Depending on financial incentives, such as reduced cost due to the specific type of battery required (slow charge/slow discharge), amortization schedules (capital cost allowance), tax rebates and bulk purchase discounts, this may or may not be a viable option.

The following table illustrates a possible scenario for power storage and sale. Essentially, we simulate injecting as much power as possible into the power system while remaining the small town’s bus voltage within the acceptable operating range of 0.98—1.05pu. We assume that batteries have a power storage efficiency of 80%.

Time	Generated (MW)	Town Load	Energy Sold (MWh)	Energy Stored (MWh)	Town Bus Voltage	Effective Power (MW)
00:00	85	50	0	136	1.055	0
02:00	85	50	0	272	1.055	0
04:00	85	50	0	408	1.055	0
06:00	85	50	0	544	1.055	0
08:00	85	50	0	680	1.055	0
10:00	50	100	110	672	1.050	55
12:00	50	100	110	664	1.050	55
14:00	50	100	110	656	1.050	55
16:00	50	100	110	648	1.050	55
18:00	10	120	327	402.4	0.980	163.5
20:00	10	70	316	165.6	0.980	158
22:00	10	70	226	0.8	1.047	113

To calculate the total stored power, we use the formula:

$$E_{stored} = \left(2hours \times P_{gen} - E_{sold}\right) \times 80\% + E_{stored}^{prev}$$

The surplus of power generated (versus power injected into the system and sold) is stored in batteries, which have 80% conversion efficiency in this case. The effect is additive and assumes that power lost through natural discharge of the battery is negligible, since power is stored for only a 24-hour period.

The average power transfer over a two-hour period is equal to the change in energy over that period. As a result, we can model the wind farm as generating that amount of power for the two-hour period in order to calculate bus voltage. Therefore:

$$P_{effective} = \frac{E_{sold}}{2hours}$$

This chart does not account for the charge required to prevent a *deep cycle* – that is, batteries must maintain a nonzero charge at all times to keep from depolarizing permanently, damaging the battery. Lead-acid batteries can only handle a handful of these deep charge/discharge cycles (in the range of ten to twenty), so it is necessary to maintain some charge at all times to ensure long-term viability of the system.

Adding up the total amount of energy sold each day, we find that the wind turbine project would sell 1309MWh of electricity, which represents daily revenue of $248,710 at a rate of $0.19/kWh. Note that since energy stored represents the amount of power we can extract (once converting from battery back to AC power), the maximum amount of stored energy is not representative of the total capacity we need. In fact, we would require the full 850MWh of energy storage capacity.

Is such a battery system a good investment?

The Principal Cost (P) is $120-million (assuming there are no reimbursements or tax incentives). If we disconnect the system in the mornings, we will have $87,400 in revenue (460 MWh at $0.19/kWh). If we install the energy storage system, we will draw $248,710 in revenue, so the expected annual savings will be $1,935,720. Assuming that the battery system will have an operating lifetime (T) of at least ten years, we can calculate the return on investment of this process, using Mathematica:

$$\frac{P}{S} = \frac{1 - e^{-RT}}{R}$$

In this case, $R = -0.2963$ (from Mathematica), which corresponds to a net Return on Investment of -29.63%. The only way to increase the ROI figure is either to reduce the principle investment or increase the expected lifetime of the storage system. (Source of ROI equation: Journal of Policy Engagement, Vol. 1 No. 2)

4. **Use a synchronous condenser** or static compensator (STATCOM) system, which can vary capacitance based on the current bus voltage at the town and keep it within the required range. While this would work very well, it is also a very expensive option and only needed when there are loads that fluctuate in unpredictable ways.

Assuming that the bus loading profile remains consistent every day, using a dynamic compensation system is not strictly necessary. However, depending on issues like excessive harmonic distortion and voltage fluctuations, it may be necessary to install this type of corrective mechanism. Given that the town has already invested in a shunt capacitor, it would not make financial sense to replace it with a synchronous condenser at this time.

5. **Add a second shunt compensator** to the small town bus, with a nominal capacitance of 20 MVAr. In the early mornings, switching the 40 MVAr capacitor off while switching the 20 MVAr capacitor on will result in a voltage of 1.002pu at the small town bus while transferring 85 MW of power. Due to the existing 40 MVAr compensator at the bus, the incremental investment cost is very low.

   While inexpensive and quite effective, this scheme will result in some voltage flicker outside the normal system operating range. Around 10:00pm, disconnecting the 40 MVAr shunt capacitor brings the bus voltage down to 0.935pu (the uncompensated voltage with the wind turbine generator) temporarily, until the 20 MVAr capacitor is brought online. With a computer control, this will probably not last any longer than a few cycles, but might still cause lights to flicker.

6. **Replace the shunt compensator** with two 20 MVAr capacitors. While more expensive than simply adding one additional capacitor, replacing the 40 MVAr capacitor with two 20 MVAr capacitors provides more granularity in terms of the reactive power supplied to the bus. In the above scenario, disconnecting a nominal 40 MVAr capacitor and connecting a 20 MVAr capacitor brings the effective reactance to 20 MVAr, except it results in a brief period without any compensation. If we use two capacitors, rated at 20 MVAr each, we can achieve the same effect, albeit at slightly higher cost, but without the transient period where there is no bus capacitance.

   This chart shows the various states of load/generated power flow versus the bus voltage:

Generated	Load	Compensation	Voltage
85 MW	50 MW	20 MVAr	1.002pu
50 MW	100 MW	20 MVAr	0.987pu
10 MW	120 MW	40 MVAr	0.998pu
10 MW	70 MW	40 MVAr	1.049pu
10 MW	70 MW	20 MVAr	0.989pu

   For the 10MW generated/70MW loading, both 40MVAr and 20MVAr produce an acceptable voltage.

7. **Use a fixed inductor** on the small town bus with a nominal reactance of -20 MVAr. Thus, we get the same effect as replacing the fixed capacitor with two 20 MVAr capacitors while still making use of the existing capital. In this case, we have a 40 MVAr contribution from the capacitor, but we can lower it to an effective 20 MVAr rating when by connecting the inductor. Depending on the cost of an inductive element versus capacitive elements, this can be a potentially worthwhile investment.

8. **Adding a fixed series capacitor** on the line toward the large city (main power grid) will provide better voltage regulation at the small town bus. Adding a series capacitance counteracts the natural reactive impedance of the power transmission line, thus reducing the voltage drop across the transmission line. In doing so, the maximum power transfer potential is increased according to the classic power transfer equation:

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

Ultimately, this means the voltage at the town will remain closer to the voltage of the "semi-infinite" bus, which has voltage regulation support from the nuclear generating station. Furthermore, forward and reverse power flows will experience less impedance, which increases power system stability. The natural line reactance of the 115kV line between the low-tension midline and the town bus is j2.27 pu, while the transformer has an internal reactance of j0.15 pu.

As a result, we need a series capacitor that counteracts roughly 2.5-3.0 pu reactive power. With a series reactor consuming 2.5 pu of reactive power, we have the following bus voltages at the small town:

Time	Load	Generated	Town Voltage
00:00	50 MW	85 MW	$1.026 \angle 22.34°$
02:00	50 MW	85 MW	$1.026 \angle 22.34°$
04:00	50 MW	85 MW	$1.026 \angle 22.34°$
06:00	50 MW	85 MW	$1.026 \angle 22.34°$
08:00	50 MW	85 MW	$1.026 \angle 22.34°$
10:00	100 MW	50 MW	$1.003 \angle 21.74°$
12:00	100 MW	50 MW	$1.003 \angle 21.74°$
14:00	100 MW	50 MW	$1.003 \angle 21.74°$
16:00	100 MW	50 MW	$1.003 \angle 21.74°$
18:00	120 MW	10 MW	$0.986 \angle 21.32°$
20:00	70 MW	10 MW	$1.000 \angle 21.63°$
22:00	70 MW	10 MW	$1.000 \angle 21.63°$

The bus voltage at the town remains much more consistent (closer to the nominal value) throughout the day. This particular arrangement is more beneficial than traditional fixed shunt compensation, though it can be more difficult to install and maintain. Essentially, the line "appears" shorter (its series impedance is equivalent to that of a much shorter transmission line), which improves system stability.

> Enabling or disabling the shunt capacitors while the system uses fixed series compensation does not have a significant impact on the bus voltage, which makes sense since the impedance on the transmission line (to the midline low-voltage side) is very low.

What counter proposal would you return to the owner of this wind farm, this should allow the farm to generate as much electricity as possible, while maintaining the bus voltage limits at the small town?

I would propose that the owner of the wind farm and the small town utility work together in a joint venture project to install a 20 MVAr nominal shunt inductor to reduce the reactive power injected by the 40 MVAr capacitor. This is a quick and cost-effective way of reducing the high voltage in the mornings, while still allowing the wind farm owner to produce as much power as possible. There may be some minor issues further down the line if the load profile of the town changes, which should prompt another review of the compensation scheme; a series capacitor may be a better choice in the future since it is more sustainable in the long term.

Another idea might be to implement a control system at the town bus to trigger the inductive compensation on demand, especially using thyristor control to determine the firing angle (and thus the effective inductance or capacitance seen by the bus). This idea could be useful in the future and should be part of any network planning effort, but there is no need for this type of investment at this time.

Conclusion

Firstly, recent changes in legislation and a push to “green” power are leading to a projected increase in distributed generation capability, which has a positive effect on the environment as well as detrimental implications for the existing power system infrastructure. Maintaining power quality for remote loads (especially those in suburban and rural areas) is challenging both because fluctuations in power draw will have a more pronounced impact in these areas, while the regions are also prime candidates for installations of high capacity distributed generation projects.

In this lab, we analyzed the impact of reverse power flows (that is, the flow of power from a smaller system to the larger grid). Because crown corporations like Ontario Power Generation traditionally manage the entire grid, these small- and medium-scale distributed generation projects pose new challenges to those responsible for distribution of power, such as Hydro One and London Hydro. We can see that the addition of large new projects (especially wind, which generates the most power during nighttime hours when demand is historically lowest) necessitates operations planning effort.