Coordination of Controls of Renewable Power Plants to Meet Steady State and Dynamic Response Requirements for Voltage Control and Reactive Power Supply

Dinemayer Silva
Phone: 518-395-5169
Fax: 518-346-2777
dinemayer.silva@siemens.com

Daniel Feltes
Phone: 518-395-5170
Fax: 518-346-2777
daniel.feltes@siemens.com

James W. Feltes
Phone: 518-395-5083
Fax: 518-346-2777
james.feltes@siemens.com

Siemens Power Technologies International Inc.
Consulting Services
400 State Street
Schenectady, New York 12305

1 Introduction

The growing penetration of renewable energy resources has increased the need for these energy sources to supply the ancillary services traditionally supplied by conventional generation services. This need has resulted in regulations that require renewable energy facilities to supply these services and demonstrate compliance with these requirements. This paper focuses on two of these ancillary services: the control of voltage and reactive power.

The paper addresses the control of voltage and reactive power from both a steady state and dynamic perspective. It uses as an example an actual wind facility consisting of four wind farms connected by a 121 kV network and stepped up to a 500 kV utility connection. The controls included on-load tap changer (OLTC) controls to adjust the taps on the main facility transformer, OLTC controls on the 121/34.5 kV transformers at each of the four wind farms, switchable capacitor banks, the wind farm controllers and the wind turbine generator controls. Each of these controls has unique characteristics with respect to its impact and timing. Thus careful coordination of these controls is necessary to ensure the desired accuracy, robustness and speed of response are obtained without undesirable interactions.

The paper describes the capabilities of the various controls and gives a detailed explanation of the implementation of the overall control coordination strategy, demonstrating how the controls achieve a fast transient response to system events while coordinating the slower controls to maintain the transient capability and ensure that the system steady state requirements are met. The control strategy described was designed for this specific wind farm and its equipment, requirements and the details and settings are not necessarily applicable to other facilities. However, it is a good example of how a strategy is developed and tested which is generally applicable to other renewable facilities.

2 System Overview

The general configuration of the wind farm is shown in Figure 1. The wind farm's point of interconnection (POI) to the grid is a 500 kV grid substation that tapped an existing 500 kV line. Thus, two 500 kV circuits connect the wind farm to the system. The substation contains two 525/121 kV autotransformers to step down to the wind farm 121 kV system which is used to interconnect the four wind farms. There is a 121 kV line of about 7.8 miles from the 500/121 kV substation to a 121 kV substation. This substation is the hub for the connection of the four wind farms. From this substation, there is a 121/34.5 kV substation for Wind Farm 1, a 7 mile line to Wind Farm 3 and a 9.7 mile 121 kV line to Wind Farm 2. At Wind Farm 2's 121 kV bus, there is a 9.1mile line to Wind Farm 4. In Figure 1, each of the wind farms are shown schematically, representing an equivalent 34.5 kV feeder, padmount transformer and wind turbine generator.

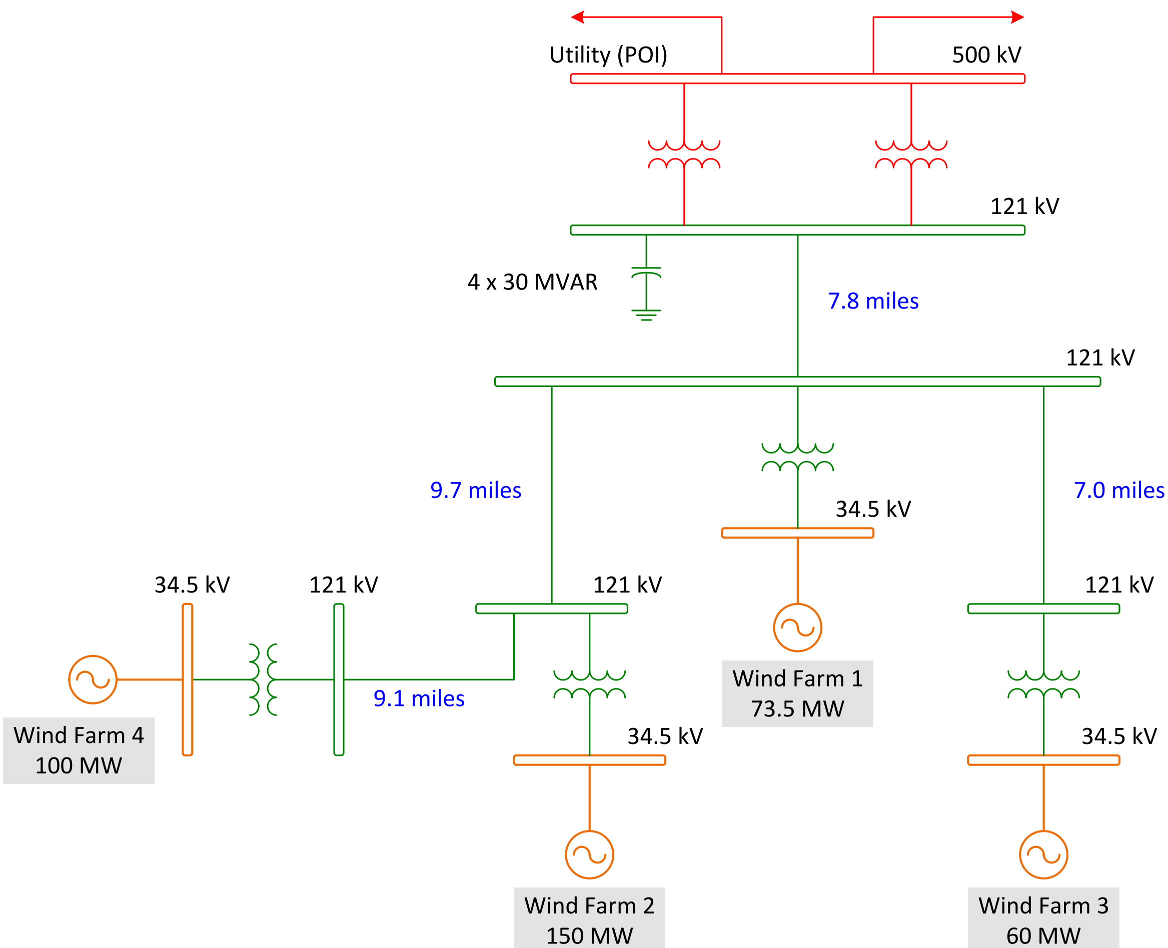

Figure 1. General Configuration of the Four Wind Farms

The nominal MW capabilities of the four wind farms are shown in Table 1.

Table 1. The wind farm generation

Wind Farm	# Turbines	MW	Turbine Manufacturer
1	45	73.5	GE
2	92	150.0	GE
3	37	60.0	GE
4	46	100.0	Siemens
Total	**220**	**383.5**	

A full model of the wind farm was built to analyze the wind farm controls and ensure correct operation.

Every turbine, padmount transformer and feeder cable section was modeled in the both the load flow and dynamics models. The representation included the four 121 kV lines described above with a total length of 33.6 miles and approximately 171 miles of 34.5 kV collector cables.

3 Control Requirements

The local ISO had the following requirements defining the reactive power capabilities and performance characteristics that all generation interconnecting to the system must meet:

> *Inject or withdraw reactive power continuously (i.e. dynamically) at a connection point up to 33% of its rated active power at all levels of active power output except where a lesser continually available capability is permitted by the ISO.*

and

> *Exhibit connection point performance comparable to an equivalent synchronous generation unit with characteristic parameters within typical ranges.*

While both of these requirements are dynamic and call for continuous control, the time frame of this control is quite different. The time frame of the response needed for the first requirement is on the order of generation control, many seconds to minutes, and primarily driven by steady state capabilities. The time frame needed for the second requirement is on the order of that associated with excitation control, a few seconds, and primarily driven by the fast, transient response capabilities of the equipment.

4 Available Controls

The control of voltage and reactive power is accomplished by the following controls:

- On-Load Tap Changer (OLTC) controls to adjust the taps on the 525/121 kV autotransformers
- OLTC controls to adjust the taps on the 121/34.5 kV transformers at each of the four wind farms
- Switching of the four 30 Mvar capacitor banks located at the 121 kV bus near the POI (the low side bus of the 525/121 kV transformer at the 500 kV POI)
- the wind farm controllers (i.e., the GE WindCONTROL and Siemens Park Pilot controllers)
- the wind turbine generator controls

Each of these controls has unique characteristics with respect to its impact and timing. Thus careful coordination of these controls is necessary to ensure the desired accuracy, robustness and speed of response is obtained without undesirable interactions.

As noted above, there are two time frames of control. One is the transient time frame, on the order of a few seconds and primarily driven by the fast, transient response capabilities of the equipment. The second is slower, on the order of many seconds to minutes and primarily driven by steady state capabilities.

Described below are the capabilities of the various controls at the wind facility for each of these time frames. A detailed explanation follows for the implementation of the overall control coordination strategy.

5 Transient Timeframe (0 to 5 seconds)

The voltage and reactive power controls that are active in the transient time frame are the controls of the wind farm controllers and the controls of the wind turbine generators. The OLTC tap controls and the capacitor bank controls are not active in this time frame.

5.1 GE Wind Turbine Controls

The GE wind turbines employ doubly-fed induction machines. Their power electronics allow them to quickly control their terminal voltage or terminal reactive power output either in response to system events or in response to normal control signals.

The GE wind turbines at this wind farm are configured to operate in reactive power control mode. A reactive setpoint is communicated to each turbine by the GE WindCONTROL (wind farm controller) configured to operate in voltage control mode.

5.2 GE WindCONTROL Wind Farm Controller

The GE WindCONTROL wind farm controller performs many functions and has many features that can be configured. Here we are only discussing the control of voltage and reactive power.

In a typical wind farm employing GE wind turbines, there is a single GE WindCONTROL wind farm controller that performs supervisory control over all of the wind turbines in the wind farm. At this facility, there are three wind farms employing GE wind turbines, i.e., Wind Farm 1, Wind Farm 2 and Wind Farm 3 of Figure 1 and Table 1. All three of these wind farms are used to control the voltage at the main 121 kV bus, i.e., the low side bus of the 525/121 kV transformer at the 500 kV POI. The voltage setpoint is determined by a Programmable Logic Controller (PLC) at this substation as described in more detail in a following section. Note that if each of these three wind farms employed its own WindCONTROL controller to control main 121 kV bus voltage, there would inevitably be unequal sharing of the required reactive supply and potentially control interaction. This potential for interaction was removed by placing all three of the wind farms with GE turbines under one WindCONTROL controller located at Wind Farm 1. This controller sends a reactive power setpoint to each of the turbines at Wind Farm 1, Wind Farm 2 and Wind Farm 3 and, using line drop compensation, allows the voltage at the main 121 kV bus to be regulated.

The WindCONTROL controller determines the appropriate reactive power setpoints for the wind turbines using a non-linear, closed loop control algorithm. The input to the control is a measurement of the 121 kV voltage at the Wind Farm 1 substation and the current on the 121 kV line from Wind Farm 1 to the main 121 kV substation. The voltage at the main 121 kV substation is then calculated using line drop compensation. The controller compares the calculated voltage to the reference voltage and determines the appropriate reactive power setpoints for the wind turbines to increase or decrease the voltage to reduce the error between the calculated voltage and voltage setpoint.

Note that due to the communication requirements from the WindCONTROL controller to the wind turbines which are distributed over a large geographic area, there are some communication latencies involved in the response, on the order of 300 milliseconds. However, this is somewhat compensated for by the fast response characteristics of the power electronics of the wind turbine generators, which can rapidly adjust the terminal voltage and current of the wind turbines. Thus the WindCONTROL controller is able to perform such that the voltage is restored to its desired value in 1 to 2 seconds following a system event, thus exhibiting a control characteristic similar to the response of the excitation system of a conventional generator.

5.3 Siemens Wind Turbine Controls

The Siemens wind turbines employ a full power electronic converter. Their power electronics allow them to quickly control their terminal voltage either in response to system events or in response to normal control signals.

The Siemens wind turbines at Wind Farm 4 are configured to operate in voltage control mode. A voltage setpoint is communicated to each turbine by the Siemens Park Pilot wind farm controller.

5.4 Siemens Park Pilot Wind Farm Controller

The Siemens Park Pilot wind farm controller performs many functions and has many features that can be configured. Here we are only discussing the control of voltage and reactive power.

As described above for the GE controller, in a typical wind farm employing Siemens wind turbines, there is a single Siemens Park Pilot wind farm controller that performs supervisory control over all of the wind turbines in the wind farm. It is generally configured to control voltage at the POI, typically with reactive droop.

However in this case, Wind Farm 4 is located electrically downstream of the other three wind farms. Having all of the wind farms controlling voltage could result in control interaction and undesirable reactive power sharing. In order to avoid this interaction, Wind Farm 4 is configured in reactive power control mode, controlling the reactive power output of the wind farm. The reactive power of the Wind Farm 4 is controlled at the high voltage side of the Wind Farm 4 121/34.5 kV transformer.

The Park Pilot controller of Wind Farm 4 determines the appropriate voltage setpoints for the wind turbines. The input to the control is the measurement of the voltage and current at the Wind Farm 4 121 kV substation from which reactive power is calculated. The controller compares the calculated reactive power to the reactive power reference and determines the appropriate voltage setpoints for the wind turbines to increase or decrease their reactive power outputs to reduce the error between the calculated reactive power and the reactive power setpoint.

The Siemens controller performs this function approximately every 150 milliseconds. The Siemens wind turbines respond to the revised voltage reference very quickly due to the characteristics of the power electronics of the wind turbine generators, which can rapidly adjust the terminal voltage and current of the wind turbines. Thus the Park Pilot controller is able to control the reactive power at Wind Farm 4's 121 kV bus relatively quickly, again with a performance comparable to that of the excitation system of a conventional generator operating to control reactive power.

Note that the control strategy described above is for normal operation. The control strategy for Wind Farm 4 can be changed if this wind farm is operating alone, that is, if the other three wind farms are all out of service.

5.5 Function and Control Strategy of the main 121 kV substation PLC

A PLC was installed by the wind farm owner at the main 121 kV substation to perform calculations and control actions necessary to control the voltage and reactive power of the wind facility.

One function of the PLC is to receive voltage setpoints from the ISO. The ISO communicates a desired 500 kV voltage schedule to wind farm owner via a phone call and this setpoint is entered into an application that interfaces to the PLC. The PLC reads this setpoint once every program scan or about every 20 milliseconds. A control algorithm calculation is performed by the PLC using this signal and local measurements to calculate the voltage reference for the main 121 kV bus. This voltage reference is then communicated to the Wind Farm 1 WindCONTROL controller.

Note that the response characteristic of this outer loop voltage controller is, by design, significantly slower than the WindCONTROL controller response characteristic. Thus any change in the voltage reference of the WindCONTROL controller during the transient time farm is not significant.

5.6 Function and Control of the Main 121 kV Substation Capacitor Banks and the Transformer OLTC's

The status of the 121 kV capacitor banks and the tap positions of the 525/121 kV autotransformers and the four wind farm's 121/34.5 kV step-up transformers will not be adjusted during the transient time frame. The function and control of these devices is to control the steady state or quasi-steady-state voltages and reactive flows on the wind facility system. They must coordinate with the transient controls, but will not directly interact with them as their speed of response is much slower.

5.7 Function and Control Strategy of the Wind Farm 4 PLC

Under normal conditions, the voltage controller will be controlling the 121 kV voltage, maintaining the appropriate combined wind farm reactive power contribution at the 500 kV. Wind Farm 4 will be controlling the reactive power output at the high voltage side of its 121/34.5 kV transformer.

However, if a large voltage change occurs, it is desired to have a transient contribution from Wind Farm 4 to improve the combined wind facility response. This is accomplished by a change in the reactive power setpoint of the Wind Farm 4 controller. The logic to implement this change in reactive power reference is shown in Figure 2.

The Wind Farm 4 reactive power reference will be changed transiently if the voltage at the Wind Farm 4 121 kV bus deviates from its steady state value by a given threshold. This is accomplished by comparing the measured voltage to an "averaged" value. The measurement time constant Tm is quite small while the averaging time constant Ta will be much larger. Thus the output of the averaging block will not vary significantly immediately following a disturbance and thus appears as a reference voltage. This allows the calculation of the change in voltage due to the disturbance while still allowing the reference to track the normally occurring, slower changes in the 121 kV voltage due to either changes on the system or changes in wind power output.

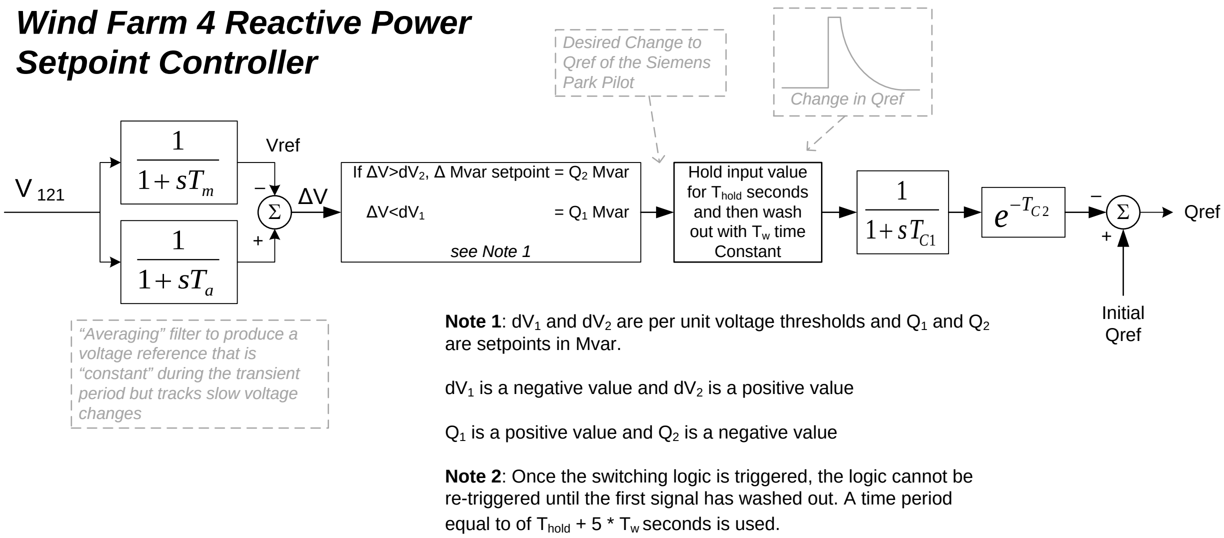

Figure 2. Block Diagram of Wind Farm 4 Reactive Power Setpoint Controller

In the control structure in Figure 2, two voltage thresholds are specified, each corresponding to a specified change in reactive power setpoint. Obviously, for sudden drops in voltage (positive ΔV), the reactive setpoint needs to be increased (a positive ΔQref), and the opposite is also true.

Since the required response from Wind Farm 4 is needed transiently but not in steady state, the change in reactive power setpoint is held for a time T_{hold} seconds and then washed out (allowed to decay exponentially to zero with a time constant of T_w seconds). There is thus no steady state change to the reactive power setpoint and the GE units at the other three wind farms and the 121 kV capacitor banks will take care of the steady state system reactive power requirements.

Communication delay between the PLC and the Siemens controller is represented in the controller by the time constant T_{C1} and/or the delay T_{C2}.

The implementation of this controller in the PLC used the following settings and characteristics. The measurement time constant Tm is quite small, 100 milliseconds or less. A 5 second moving average is used to perform the averaging (approximated in the model in Figure 2 by time constant Ta). The change in reactive power setpoint is held for a time T_{hold} of 5 seconds and then washed out with a time constant T_w of 5 seconds (the signal is thus effectively returned back to zero in about four time constants, 20 seconds). There are no intentional delays in the communication of the signals and the inherent communication delay between the PLC and the Siemens controller (represented in the model by the time constant T_{C1} and/or the delay T_{C2}) is small.

The two voltage thresholds are + or – 2.5%. A sudden drop in voltage (positive ΔV) of 2.5% results in an increase in the reactive setpoint of 30 Mvar (positive ΔQref). A sudden rise in voltage (negative ΔV) of 2.5% results in a decrease in the reactive setpoint of 30 Mvar (negative ΔQref).

6 Steady State Timeframe (5 Seconds to Several Minutes)

The fast controls of the wind farm were described above. This section describes the controls that are active in the period following the transient period up to several minutes.

6.1 GE Wind Turbine Controls

The GE wind turbines employ doubly-fed induction machines and their power electronics allow them to quickly control their terminal voltage or terminal reactive power output. The GE wind turbines at the Wind Farm 1, 2 and 3 are configured to operate in reactive power control mode and a reactive setpoint is communicated to each turbine by the GE WindCONTROL wind farm controller. These local controls are very fast and reach their steady state in one to two seconds, well within the 5 second period and thus can be considered to be at their controlled setpoint, unless controller limits are hit.

6.2 GE WindCONTROL Wind Farm Controller

The GE WindCONTROL wind farm controller at Wind Farm 4 performs supervisory control over all of the wind turbines in Wind Farm 1, Wind Farm 2 and Wind Farm 3. The WTGs of the three wind farms are used to control the main 121 kV bus voltage to a setting determined by the PLC at this substation.

The WindCONTROL controller located at Wind Farm 1 determines the appropriate reactive power setpoints for the wind turbines. As noted in the transient response section, the WindCONTROL controller is able to perform such that the voltage is restored to its desired value in 1 to 2 seconds following a system event. Thus these controls are also fast and reach their steady state well within the 5 second period and thus can be considered to be at their controlled setpoint, unless controller limits are hit.

6.3 Siemens Wind Turbine Controls

The Siemens wind turbines employ a full power electronic converter. Their power electronics allow them to quickly control their terminal voltage either in response to system events or in response to normal control signals. The Siemens wind turbines at Wind Farm 4 are configured to operate in voltage control mode. A voltage setpoint is communicated to each turbine by the Siemens Park Pilot wind farm controller.

These local controls are very fast and reach their steady state in one to two seconds, well within the 5 second period and thus can be considered to be at their controlled setpoint, unless controller limits are hit.

6.4 Siemens Park Pilot Wind Farm Controller

The Siemens Park Pilot wind farm controller controls the reactive power output of Wind Farm 4, measured at the high voltage side of its 121/34.5 kV transformer. The Park Pilot controller determines the appropriate voltage setpoints for the wind turbines and is able to control the reactive power at the 121 kV bus relatively quickly. Thus these controls are also fast and reach their steady state well within the 5 second period and thus can be considered to be at their controlled setpoint, unless controller limits are hit.

6.5 Function and Control Strategy of the PLC at the Main 121 kV Bus

As described above, the GE WindCONTROL wind farm controller at Wind Farm 1 performs supervisory control over all of the wind turbines in Wind Farm 1, Wind Farm 2 and Wind Farm 3 and adjusts the setpoints of the WTGs of the three wind farms to control the main 121 kV bus voltage to a setting determined by the PLC at that substation. This section describes how this PLC determines that setting.

The steady state requirements are to supply reactive power to the 500 kV system with a 4% reactive droop setting, based on a required reactive capably of 127 Mvar, corresponding to 0.95 power factor at the total nameplate power if all four wind farms are on line. Thus the wind farm should supply 127 Mvar when the 500 kV voltage is 4% below its setpoint (typically 545 kV, 1.09 pu), supply zero Mvar when the voltage is at its setpoint, absorb 127 Mvar when the 500 kV voltage is 4% above its setpoint and operate linearly to supply reactive power proportional to the voltage deviation between these points.

The reactive power injection into the 500 kV system is measured at the high side of the 525/121 kV autotransformers. An error signal is formed by subtracting the measured 500 kV voltage from the desired 500 kV voltage setpoint as communicated from the ISO. The reactive droop voltage (Q_{500} • Droop / Q_{max}) is then subtracted from this quantity as shown in Figure 3. This error signal is controlled using a PI controller (the derivative term shown in Figure 3 is not used) to adjust the reference for the GE WindCONTROL wind farm controller. The PI controller is tuned to provide a slow controlled response of the reference (reset time of 3.5 minutes), ensuring it does not interact with the fast voltage controls of the GE WindCONTROL controller. The parameter Droop in Figure 3 is 0.04 (4%) and the value of Qmax is 127 (maximum reactive power requirement of the wind facility, consistent with the ISO requirements. The time constant Tc in Figure 3 represents the communication delay, which is about 2 seconds, small compared to the speed of the controller.

As the maximum reactive power requirement is to supply 127 Mvar to the 500 kV, the controller stops increasing the voltage reference if the measured reactive power exceeds this amount. In a similar manner, the minimum reactive power requirement is to absorb 127 Mvar from the 500 kV and thus the controller stops decreasing the voltage reference if the measured reactive power is less than -127 Mvar.

This control thus couples with the control action of the GE WindCONTROL controller to achieve fast transient voltage control while also meeting the steady state reactive droop requirements.

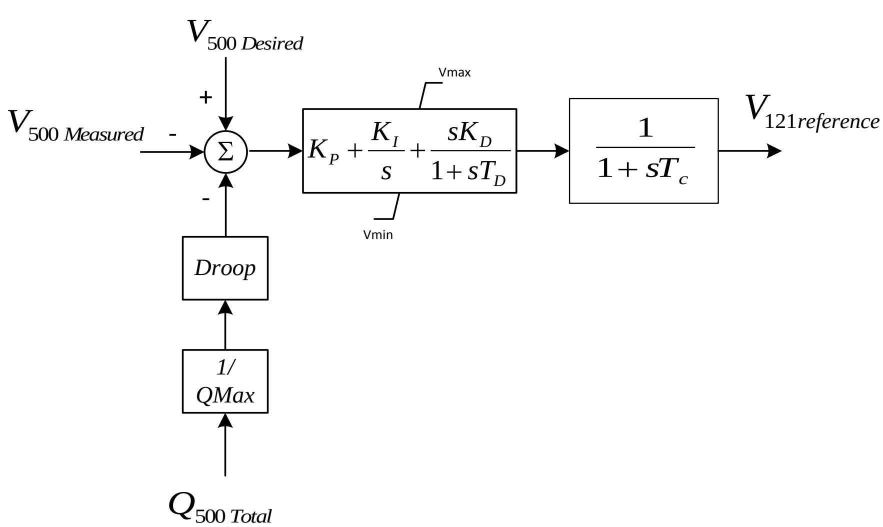

Figure 3. Outer Loop Controller to Adjust the Reference Voltage of the GE WindCONTROL Controller to Implement the Reactive Power Droop at the 500 kV Bus

6.6 Function and Control of the 121 kV Capacitor Banks

The objective of the control of the 121 kV capacitor banks is to supply steady state reactive power when needed. As noted above, the wind farm is required to supply reactive power to the 500 kV system with a 4% reactive droop setting, based on a required reactive capably of 127 Mvar. Thus the wind farm should supply 127 Mvar when the 500 kV voltage is 4% below its setpoint and absorb 127 Mvar when the 500 kV voltage is 4% above its setpoint. The capacitors are obviously only useful when the 500 kV voltage is low and the requirement is to supply Mvar.

For transient events, the wind turbines will respond to supply the required change in reactive power, as they will respond quickly to maintain their control setpoints. The capacitors should only be switched in when those system reactive needs are required for a longer period of time. When the wind turbines are supplying a large amount of steady state reactive power, they have less dynamic reactive response capability to respond to transient events on the system. Thus the capacitor banks give the wind facility the flexibility to switch in the capacitors as needed to reduce the steady state supply of reactive power by the wind turbines and thus to maintain the dynamic reactive capability for transient events. Put simply, if we have a steady state need of 60 Mvar at the main 121 kV bus to supply reactive power up through the 525/121 kV transformers to the 500 kV system, then it is better to get those Mvars from the capacitor banks, as this leaves the wind turbines at a reactive output close to zero and thus with nearly their full range available to respond dynamically to any sudden large system event.

Figure 4 shows the controls for the four 121 kV 30 Mvar capacitor banks. The reactive power flowing into the main 121 kV bus from Wind Farm 1 is measured. The capacitor banks should not be switched, either in or out, for short duration events as these events are easily handled by the capabilities of the wind turbines. Thus the reactive power measurement includes an "averaging" filter, which is implemented by a time constant of 15 seconds. If this reactive flow exceeds 20 Mvar, and not all of the banks are in service, one of the capacitor banks is switched in. If this reactive flow is less that -20 Mvar (20 Mvar flowing to Wind Farm 1), and not all of the banks are out of service, one of the capacitor banks is switched out. The minimum time between switching two consecutive banks in or out is 30 seconds.

While not a component of the control strategy, the switching logic controls the switching operations required of the four banks so that all four banks have similar duty cycles. The switching methodology also accounts for the discharge time of the capacitor banks, on the order of 5 to 10 minutes.

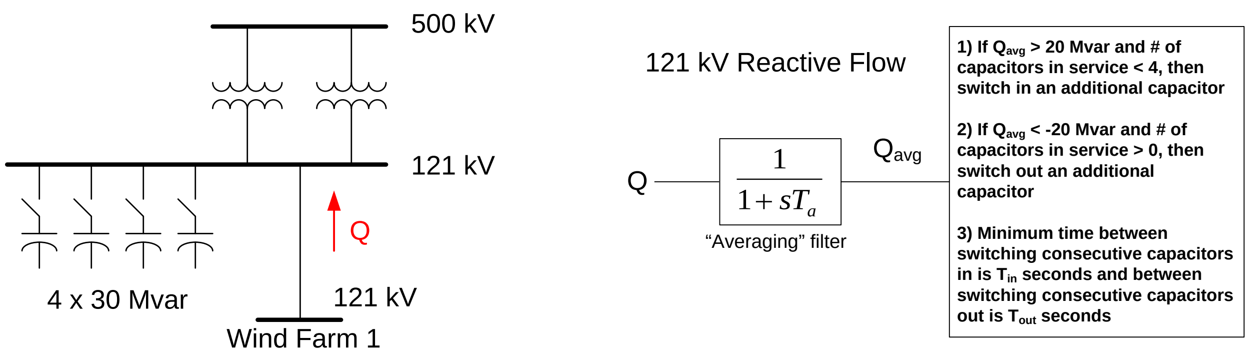

Figure 4. Control Logic for the Four 121 kV 30 Mvar Capacitor Banks

6.7 Function and Control of Wind Farm 121/34.5 kV Step-Up Transformer's OLTC's

Each of the four wind farms has a 121/34.5 kV transformer equipped with on-load tap changing (OLTC) taps. The taps on each of these transformers are controlled with a Beckwith OLTC controller. The objective of these controllers is to maintain the 34.5 kV collector system in a voltage range amenable to both the supply and absorption of reactive power by the wind turbines. This objective means that the voltage should be kept near nominal, as operating at a high collector system voltage will potentially limit the ability of the wind farms to absorb reactive power voltage from the system while operating at a lower voltage will potentially limit the ability to supply reactive power. To accomplish this, the OLTC controls on 121/34.5 kV transformers are set to hold approximately 1.02 pu voltage (35.19 kV) on the 34.5 kV collector bus (low side of the 121/34.5 kV transformer). The OLTC controls need to control the 34.5 kV voltage to be within a voltage band around this setpoint, that is, they cannot control the 34.5 kV voltage to exactly this value due to the discrete OLTC taps. The voltage control range around this setpoint must also be consistent with the tap step size of the transformers. A band of +-0.66% on 34.5 kV base was used.

6.8 Function and Control of the Two 525/121 kV Autotransformer's OLTC's

The two 525/121 kV autotransformers are equipped with on-load tap changers and thus give added flexibility to the control of voltage and reactive power. However, this flexibility must be carefully coordinated with the other controls to be useful.

Generally, the OLTC controls of such autotransformers are used to control the voltage on their low voltage bus. However as noted above, the voltage on the this 121 kV bus is controlled by the GE WindCONTROL wind farm controller at Wind Farm 1 which performs supervisory control over all of the wind turbines of Wind Farm 1, Wind Farm 2 and Wind Farm 3. The voltage on the 121 kV bus is controlled using reactive droop to supply the desired amount of reactive power to the 500 kV system. Thus typical OLTC controls trying to maintain a scheduled voltage on the 121 kV bus would be counterproductive, as they would adversely interfere with the voltage controls of the wind farms.

An alternate OLTC control strategy was developed to avoid this interaction, while maintaining appropriate 121 kV voltages under the expected range of operating conditions. The controls for the OLTC taps of the autotransformers are shown in Figure 5. The tap selection logic is based solely on the voltage of the 500 kV bus (with some limitations as described below). This removes the potential for control interaction between the tap controls, the control of the 121 kV voltage by wind farms and the control of the 121 kV capacitor banks.

The transformer taps should only be moved in response to steady state voltage changes on the 500 kV system, that is the taps should not try to chase transient voltage deviations as these are handled by the much faster voltage controls of the wind turbines. Thus the 500 kV voltage should be measured using an "averaging" filter, shown in Figure 5 as a simple time constant. Since the taps should be the slowest of the several layers of control and only respond to true steady state changes, this time constant should be longer than that used in the other controls. A simple time constant of 300 seconds (5 minutes) is used.

Steady state analysis was performed to determine a simple, yet effective tap control strategy that would work over a range of operating conditions. Due to the variability of the wind, the power output of the wind farm varies over a wider range than that of a conventional generating unit. Thus the analysis looked at operation from low power output to full power output.

The analysis also looked at variations in the steady state voltage on the 500 kV system. The steady state requirements are to supply reactive power to the 500 kV system with a 4% reactive droop setting. The tap must result in an appropriate 121 kV voltage and also allow operation at levels from full reactive power absorption to full reactive power supply to the 500 kV system.

A series of calculations were performed to develop plots of the variation in the main 121 kV voltage (y-axis) versus the reactive power flowing into the 500 kV system from the wind facility (x-axis). The calculation was performed for different 525kV/121kV autotransformer taps and for wind farm generated power from zero to full power. Note that since these calculations look at only the 500 kV and 121 kV voltages and the real and reactive power flows through the transformers, the calculations are not dependant on how the power or reactive power is supplied to the 121 kV bus, in particular they are not dependant on whether the reactive power is supplied by the 121 kV capacitors or the wind turbines.

In Figure 6, the 500 kV voltage was held at 1.09 pu (545 kV), the usual desired voltage setpoint as communicated to the wind farm by the ISO. The calculation was performed for 525kV/121kV autotransformer taps of 1.0, 1.05 and 1.1 pu. One can see that the curves are relatively linear. A 5% change in tap causes about, but not exactly, a 5% change in voltage on the 121 kV. As the taps are on the 500 kV side of the transformers and we are holding the 500 kV voltage fixed in this calculation, an increase in tap causes a decrease in the 121 kV voltage. One can also see that as we vary the reactive power supplied by the wind farm to the 500 kV, we require a very different 121 kV voltage to accomplish this flow. For example, with a tap of 1.1 pu, the voltage on the 121 kV bus needs to be in the range of 1.04 pu to supply the full reactive requirement of 127 Mvar to the 500 kV system, with the required voltage also depending on the power level. On the other hand, the voltage on the 121 kV bus needs to be in the range of 0.95 pu to absorb the full reactive requirement of -127 Mvar from the 500 kV system. It should be noted that the voltage change on the 121 kV system from full supply of reactive power to full absorption of reactive power is about 9% for whatever tap position we use or whatever the power level is. It is also important to note that the voltages also change with power level, with the 121 kV voltage about 1.25% higher at full power than it is at zero power, with all other parameters held constant.

Similar calculations were performed for 500 kV voltages 5% higher (1.14 pu) and 5% lower (1.04 pu) and the results are shown in Figure 7 and Figure 8, respectively. They clearly show the same relationships discussed above, simply with the whole set of lines shifted up or down by approximately 5%.

At a given tap position and system voltage, we need to be able to supply 127 Mvar to the 500 kV system and also absorb 127 from the system. While doing this, we also need to maintain the voltages on the 121 kV, as well as the rest of the wind farm, within its steady state voltage capabilities.

In Figure 6 where the 500 kV voltage is 1.09 pu, we see that with a tap of 1.1 pu, it is possible to supply the full reactive range while maintaining the 121 kV voltage in the range of 0.95 pu voltage to 1.05 pu voltage for conditions from zero to full power (it can be seen that the voltage actually goes a bit below 0.95 for maximum reactive absorption at low power output). Keeping the voltage in this 0.95 pu to 1.05 pu range is compatible with both the equipment capabilities and good utility practice. If the tap is set at a significantly lower value, it can be seen that the 121 kV voltage will be too high when supplying a large amount of reactive power to the system. Alternately, if the tap is set at a significantly lower value, the 121 kV voltage will be too low when absorbing large amounts of reactive power from the system.

In Figure 7, where the 500 kV voltage is 1.14 pu, we see that with a tap of 1.15 pu, it is possible to supply the full reactive range while maintaining the 121 kV voltage in the range of 0.95 pu to 1.05 pu for conditions from zero to full power. Again, if the tap is set at a lower value, the 121 kV voltage will be too high when supplying a large amount of reactive power to the system and if the tap is set at a lower value, the 121 kV voltage will be too low when absorbing large amounts of reactive power from the system.

In Figure 8, where the 500 kV voltage is 1.04 pu, we see that with a tap of 1.05 pu, it is possible to supply the full reactive range while maintaining the 121 kV voltage in the range of 0.95 pu to 1.05 pu for conditions from zero to full power.

The conclusion is that if the tap is about 0.01 pu higher than the 500 kV voltage in pu, then the wind farm will be able to both supply the full reactive power requirement to the system and also absorb the full reactive power requirement from the system while maintaining the main substation 121 kV bus voltage at acceptable levels. The autotransformers are equipped with 33 taps and thus the control logic should pick the tap that is closest to this target (500 kV pu voltage + 0.01 pu).

This logic was tested by a series of load flow cases looking at a range of power levels and a range of 500 kV voltages and system reactive power requirements. In general, it was found that an OLTC tap that is 0.01 higher than the 500 kV voltage (where both are expressed in per unit) gives good controllability. That is, such a tap position results in steady state voltages on the 121 kV system that coordinate with the capacitor controls and leaves the wind turbines in a position where they can respond to transient events requiring either an increase or a decrease in the reactive power output.

The taps are discrete, so the logic must ensure that oscillations in tap position do not occur. This is accomplished by only moving the tap when the desired tap change is 1.5 times the tap step size. Time delays are required between consecutive tap steps to allow the other controls to respond and potentially affect the need for any additional tap movements. A time delay between consecutive tap steps of 1 minute is used.

There is also some additional logic required to ensure appropriate tap selection in case of voltage conditions on the 500 kV that are outside of the usual operating range. Note that this strategy may need to be modified when only one of the 525/1221 kV autotransformers is in service.

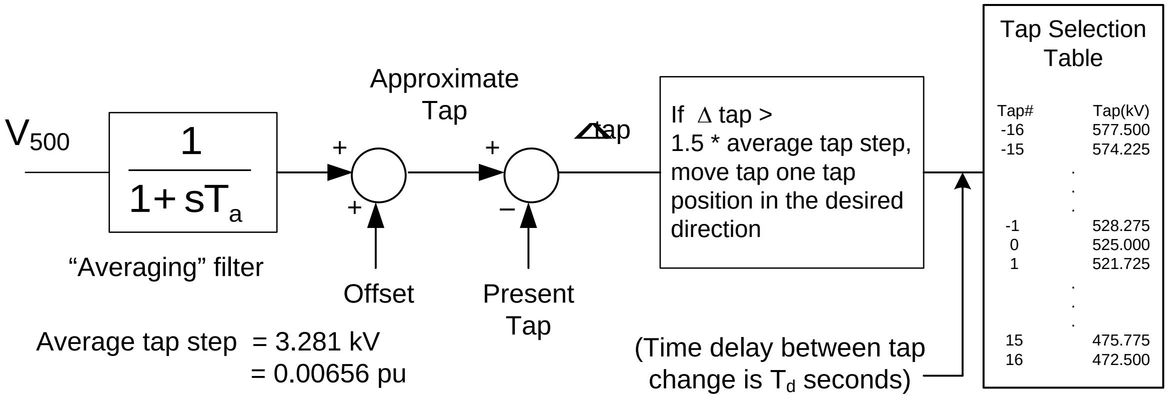

Figure 5. Control Logic of the Two 525/121 kV Autotransformer's OLTC's at the Main Substation

6.9 Function and Control Strategy of the Wind Farm 4 PLC

Under normal conditions, Wind Farm 4 will be controlling the reactive power output at the high voltage side of its 121/34.5 kV transformer. The setpoint for the reactive power control is zero Mvar.

However, there is additional logic implemented in the PLC to adjust this reactive power setpoint if this 121 kV voltage gets too high. If the 121 kV voltage exceeds 130 kV (1.0744 pu), then the reactive power reference is decreased by 10 Mvar (i.e., set to -10 Mvar) to reduce the voltage. The reactive power reference is returned to 0 Mvar when the voltage drops back below 127 kV (1.0496 pu).

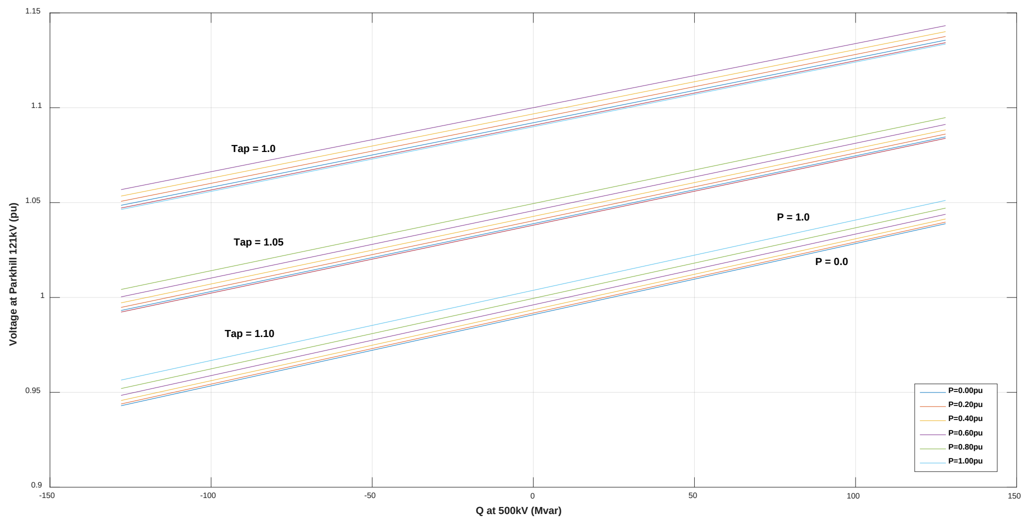

Figure 6. Variation in Main Substation 121 kV Voltage vs. Reactive Power Supply for a 500 kV Voltage of 1.09 pu

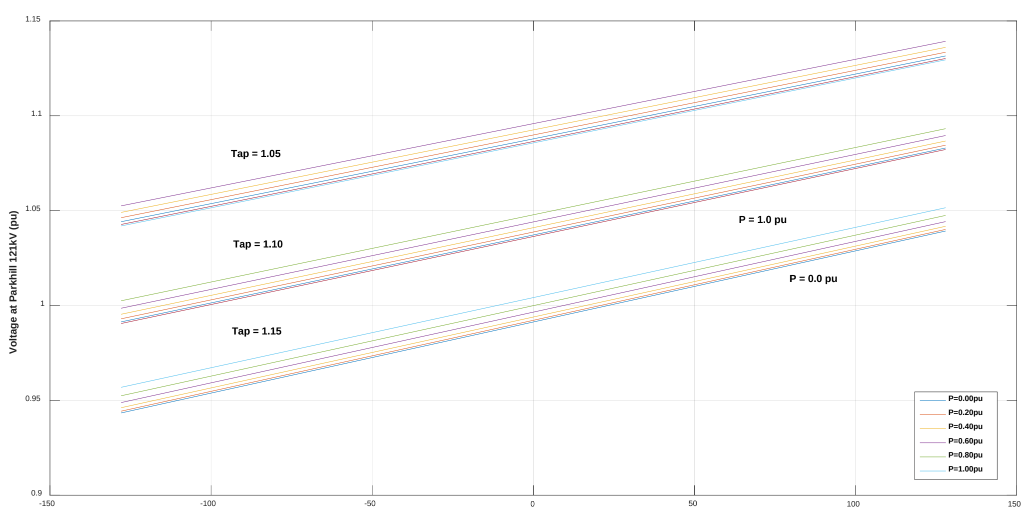

Figure 7. Variation in Main Substation 121 kV Voltage vs. Reactive Power Supply for a 500 kV Voltage of 1.14 pu

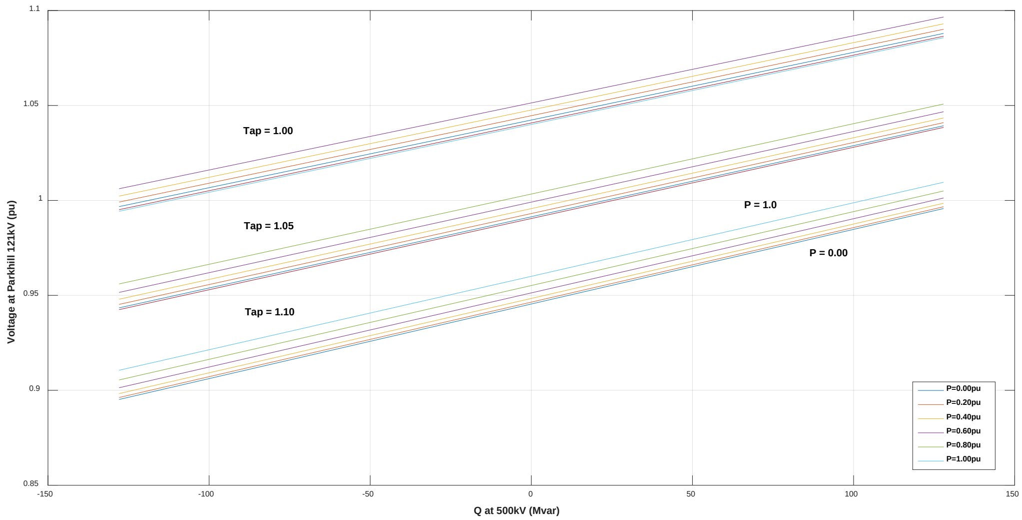

Figure 8. Variation in Main Substation 121 kV Voltage vs. Reactive Power Supply for a 500 kV Voltage of 1.04 pu

7 Demonstration of the Operation of the Control Logic

The response of the fast voltage controls of the four wind farm’s wind turbines were tested through simulation analysis and the control parameters adjusted to ensure the response was fast enough to meet the ISO requirements. These controls were tested in the field by staged tests involving simultaneous switching of the four 30 Mvar capacitor banks at the main substation 121 kV bus. Figure 9 shows a comparison of the actual response (green curve) and the ISO requirement (red curve). The measure of compliance was the integral under the curves, that is, the measured response should be, on average, below the requirement. Simulations of the switching of the capacitors have shown to be a good match to the recorded responses. Note that the response to voltage changes on the 500 kV grid would show a similar response.

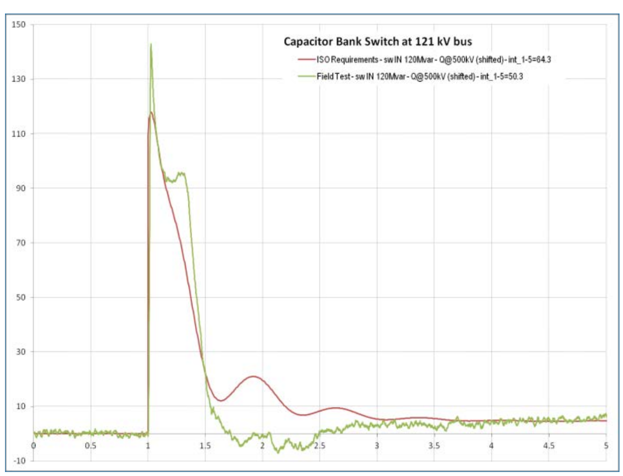

Figure 9. Comparison of the Wind Farm Response to a Staged Test and the ISO Response Requirement

To demonstrate the response of the slower controls, a simulation was performed modeling a three percent step increase in voltage applied to the 500 kV system. The base case for this simulation had two of the 121 kV capacitors on line (60 Mvar total) and the tap on the 525/121 kV transformer was set to 1.1025 pu. The four wind farms were at full power. The simulation results of the three percent step in voltage are shown in Figure 10. The plot on the left shows the response of the machines and the controls on a shorter time scale of 20 seconds. The voltage change occurs at 1.0 seconds. This is followed by the response of the fast controls, seen in the first second or so following the step change in voltage. Note that the fast response to the voltage change is similar in nature to that seen in the capacitor switch field test above. The wind farms reduce their reactive outputs in response to the system voltage change and absorb additional reactive power. The black curve is the reactive flow from the wind facility into the 500 kV system. The red curve is the reactive flow into the 121 kV side of the two 525/121 kV transformers. The pink curve is the reactive flow on the 121 kV line from the four wind farms. The difference in these last two reactive flows is the reactive contribution of the capacitor bank, initially about 60 Mvar. The scales of the red and pink curve are offset by 60 Mvar (-40 to 60 and 0 to -100 respectively). This to show the impact of the switching of the capacitor bank. At about 5 seconds into the simulations, one can see a capacitor is switched out, reducing the amount of capacitors to 30 Mvar from the original 60 Mvar. Before this time, the red and pink curves are the same, albeit offset by 60 Mvar. Following the capacitor switch, we see the total reactive flow into the transformers returns to its previous value while the reactive flow from the wind farms decreases by about 30 Mvar. The capacitor switch has thus “freed up” the fast reactive capability of the units and their ability to respond to any subsequent event while maintaining the same reactive flow to the POI.

The plot on the right is the same simulation, but showing a longer time scale of 500 seconds. In this time frame there is another capacitor switch (from 30 Mvar to 0 Mvar total) at about 35 seconds which reduces the reactive power absorption requirements from the wind farms to only about 10 Mvar. The plots also show the effect of the tap on the 121/500 kV transformer which is raised to 1.109 at 205 seconds and then raised again at 429 seconds. The longer time scale also shows how the wind facility meets its reactive droop control requirement and the effects of the time constants on the switching logic of the different controllers. The capacitors have smaller time delays and therefore will react first. The tap changers, with their longer control time delay, will also subsequently operate as needed.

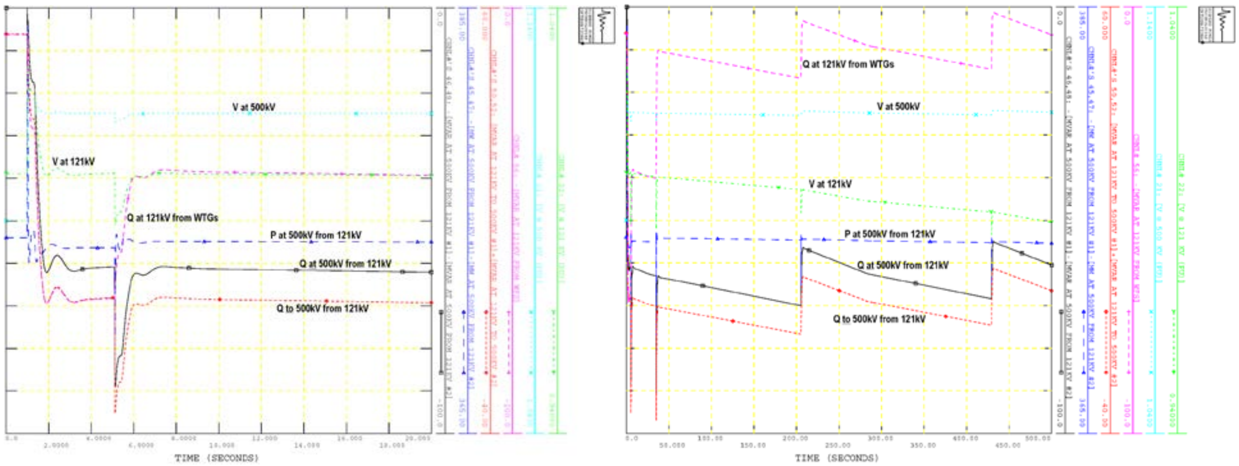

Figure 10. Control Response Due to a Step in POI Voltage

Wind facilities exhibit a wide variation in their outputs due to the changes in the prevailing wind speed. To show how the controls adjust to power variations, a simulation of a ramp in wind farm power was performed. The initial base case for this simulation modeled the wind farms at 20 percent power and had none of the 120 Mvar capacitors in service. Figure 11 shows the simulation. The time scale is 1000 seconds, about 17 minutes.

The blue curve in Figure 11 is the power into the 500 kV. The power output of the wind facility rises from the initial 20% to 100% in about 330 seconds. Note that this is not a simulation of the rise in power due to an actual wind gust or ramp, but is simply to show the response of the controls as the wind facility goes from low to full power.

The same reactive flows shown in Figure 10 are also shown in Figure 11. They show the effect of the switching in of a 30 Mvar capacitor bank at 322 seconds due to the reactive power flow from the wind farms (pink curve) dropping below the -20 Mvar threshold shown in Figure 4. As noted above, this capacitor switching frees up the reactive capability of the faster wind farm controls. After the capacitor switch the reactive power flow from the wind farms reaches a steady state value around -12 Mvar.

The operation of the controls to adjust the voltage setpoints to achieve the reactive power into the 500 kV associated with the reactive droop requirement (Figure 3) can be in the rise in the reactive power supplied to the 500 kV in the period from 400 to 500 seconds. Note that the reactive droop control is relatively slow compared to the other controls as its purpose is to achieve the appropriate steady state operating point. Normally, it would operate fast enough to keep up with the power changes, but in this case we have modeled a very fast ramp in power and the reactive droop controls are still responding after the power ramp has ended.

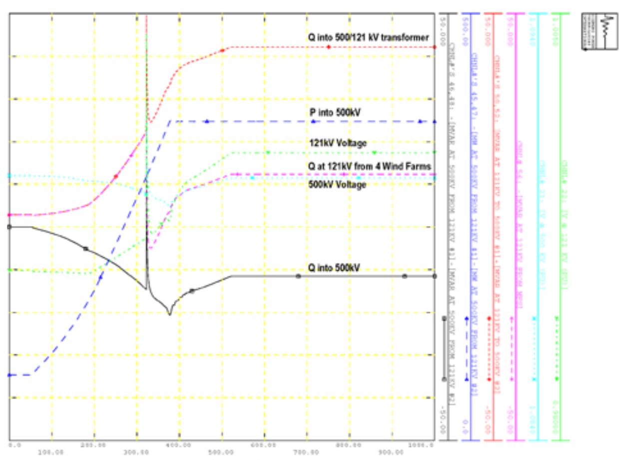

Figure 11. Control Response Due to a Ramp in Power

8 Other Points to Note

Other control strategies are possible. However, some have the potential for control interaction and undesirable sharing of the reactive power requirements between the four wind farms. The response of the whole facility will be best if all four wind farms work in concert and share the control approximately proportional to their respective sizes.

The potential for interaction between transformer OLTC controls and voltage controls was mentioned above when describing the selected control for the tap changers on 525/121 kV transformers. Generally, the OLTC controls of such transformers are used to control the voltage on their low voltage bus. However if other controls are controlling the voltage at that bus or a upstream bus, then the typical OLTC controls trying to maintain a scheduled voltage on that bus would be counterproductive, as they would adversely interfere with the voltage controls. As the voltage controls are generally faster than the tap controls, this interaction would typically drive the transformer taps to inappropriate tap settings and possibly even their tap limits.

One potential voltage control strategy is to have all four wind farms control the main 121 kV bus voltage. This control strategy could cause the four wind farm's controllers to interact with each other. This strategy would require the communication of the main 121 kV bus voltage to the controllers at each of the four wind farms. Each wind farm controller would receive the measured voltage with a bit different timing (different communication delays) and also likely not exactly the same signal (small changes due to conversions and communications). For example, looking at the communication time differences, one wind farm might start to adjust its reactive output based its received signal and this change would then impact the 121 kV voltage. Meanwhile another of the wind farms may have just received the previously transmitted value and thus it responds to a voltage that is slightly different than the actual one. If these differences are significant, it can result in these two wind farms responding differently and even potentially with one controller undoing the changes the other is trying to make. We also note that the use of line drop compensation to calculate the voltage at the main 121 kV bus using local voltage and current signals, rather than communicating that signal, is not possible in a network of wind farms such as this facility. The voltage drops on some of the lines are a function of more than one wind farm output and line drop compensation would require even more signal communication and would probably increase the potential for control interaction.

Another possible voltage control strategy is to have each wind farm control its local 121 kV voltage, that is, the high side of its 121/34.5 kV transformer. In this case, the wind farm closest to the POI will react the most to a change in the system. This is shown in Figure 12, where a three percent step in voltage was applied to the 500 kV system. Figure 12 shows the reactive output of each the four wind farm and also the 500 kV voltage. The voltage change occurs at 1.0 seconds. The left plot shows the first 20 seconds of the simulation and the right shows 500 seconds. It can be seen that all four wind farms initially reduce their reactive power in response to the high 500 kV voltage. However within the first few seconds, the responses begin to diverge. The reactive output of Wind Farm 1, the closest to the POI, continues to decrease while the reactive outputs of the other three wind farms start to increase, returning their reactive outputs back to approximately their initial outputs. The longer time scale plot on the right shows that nearly all of decrease in reactive power is supplied by Wind Farm 1, with the other three wind farms doing relatively little. This occurs because when Wind Farm 1 controls its 121 kV voltage and this essentially isolates the other three downstream wind farms from the change in the POI voltage. This is obviously not exhibiting the desired sharing of the reactive requirements.

These are just a few examples of control strategies that have the potential for suboptimal results. Detailed modeling and simulation is an effective means to test and refine the controls.

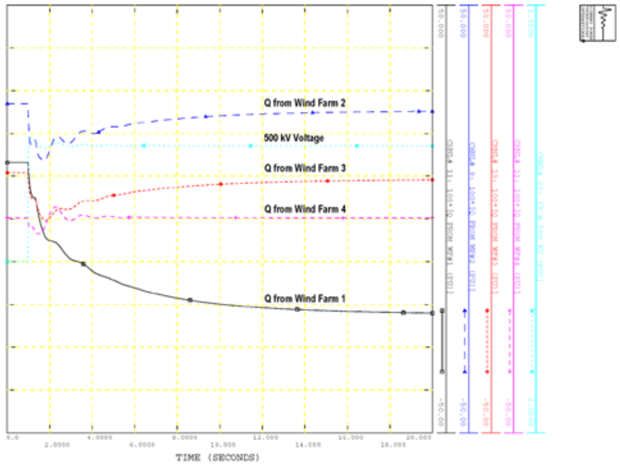

Figure 12. Reactive Reponses of the Four Wind Farms When Controlling Their Local 121 kV Voltages

9 Conclusions

The growth in the amount of renewable energy facilities and their impact on system performance has caused a need for more attention to be paid to the control strategies for these facilities. System requirements are increasing and renewable facilities are being often being required to operate in a manner similar to conventional generation and supply the same auxiliary services. The ability of these plants to demonstrate their capabilities to supply such services may be a condition of their interconnection and is also seeing increased attention by such entities as NERC.

This paper demonstrated a strategy for the control of voltage and reactive power from a wind facility consisting of four wind farms covering a large geography area. It addressed both steady state and dynamic performance. The controls included OLTC controls on the main transformer and the four wind farm transformers, switchable capacitor banks, the wind farm controllers and the wind turbine generator controls. Each of these controls has unique characteristics with respect to its impact and timing and careful coordination of these controls is necessary.

The paper demonstrates the usefulness of simulation in the development of the control strategy, the tuning of the responses of the controllers and the testing and validation of the overall response. Field tests of the controls must also be performed as part of the commissioning process. However, such field tests are expensive, requiring additional staff time associated with the test and, usually most critical, a loss in revenue due to reduced energy production due to the testing. The use of simulation to “work out the bugs” in the controls minimizes the testing time required. It is also a significantly faster process to develop the control strategy. Control changes and tuning in the field are time consuming and have, if mistakes are made, the potential for exposure of the equipment to undesirable conditions.

As the paper shows, it is possible to achieve both a fast transient response to system events while coordinating the slower controls to maintain the transient capability and ensure that the system steady state requirements are met. As a final note, the wind facility discussed passed its commissioning tests about a year ago and has been operating successfully.