Development and Implementation of a Wide Area Automated Voltage Control System

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Abstract— **Integrating inverter-based energy resources into the transmission grid introduces the potential for voltage stability concerns due to the variable nature of wind and solar generation and increasing grid weakness as inverter-based resources replace fossil fuel generation. These concerns manifest primarily in the responses to contingencies and in the amount of interaction required by grid operators. As inverter-based energy portfolios continue to expand, long radial transmission and weak interconnects will become more common. This paper discusses implementation of a novel automatic multi-facility coordinated voltage control system, called the Automatic Voltage Setpoint Optimizer, to improve grid stability and reactive power control of multiple inverter-based generation facilities on a low short circuit ratio transmission line. Project conception, implementation details, testing, and observed benefits of the voltage control system are presented.**

I. INTRODUCTION

At large scales, the volatility of wind resources can have significant impacts on the transmission system [1]. Undesirable voltage swings can occur due to production changes caused by variable winds or generation dispatch. System operators are often tasked with making manual voltage setpoint adjustments to these wind farms to compensate for the changing production. For a single wind farm, a well-tuned volt/var droop control system can often handle these voltage swings. However, as the scales and quantities of closely coupled wind farms increase, the controls needed to maintain system integrity become more complex and often require manual intervention from operators. A comprehensive understanding of the transmission system, voltage schedules, and system capability is required to maintain stability. This was the case for the Rush Creek region, with 1,400 MW of wind generation distributed among five wind farms connected along a 150-mile radial 345 kV transmission line with various lengths of interconnecting gen-tie lines.

The original Xcel Energy planning study did not identify the expected range of system short circuit ratio (SCR) but did identify the need for stand-alone mechanically switched reactors and capacitors (MSR and MSC) and a dynamic reactive resource (STATCOM) to offset transmission line reactance and enhance transient responses to disturbances. As noted in [2], the net reactance of the transmission line varies from highly capacitive under light real-power loading to highly inductive under heavy loading, and the voltage drop across each line segment varies significantly. The low SCR at the remote end of the radial line exacerbated the difficulty of offsetting the impacts of changing real and reactive power flows and regulating the Missile Site bus voltage.

This paper discusses the implementation of a novel automation controller, the Automatic Voltage Setpoint Optimizer (AVSO), to manage the complexity of operating the radial line and its connected facilities. The primary intentions of the system are to reduce the operator workload and to keep the voltages at each facility in the correct operating band to allow the full reactive power range needed to respond to transient disturbances. This paper describes the AVSO's design, engineering approach, and implementation while highlighting some of the operational benefits.

II. EXISTING SYSTEM AND OPERATOR DEMAND

Xcel Energy owns and operates all the radial 345 kV transmission line and facilities shown in Figure 1 except the Bronco Plains wind farm and its line connecting to Shortgrass Substation. For the purposes of this paper, the point where the aggregate radial system connects to the Xcel Energy network is labeled as the Point of Utilization (POU). The five wind farms consist of Type III and IV turbines: Rush Creek I (380 MW), Rush Creek II (220 MW), Cheyenne Ridge West (268 MW), Cheyenne Ridge East (230 MW), and Bronco Plains (300 MW). Each wind farm controller regulates voltage to the high side of the main power transformer with voltage droop controls using the reactive capabilities of the turbines and collector bus connected MSCs and MSRs. The STATCOM also uses voltage droop controls, but it does not have any switched reactive devices associated with it.

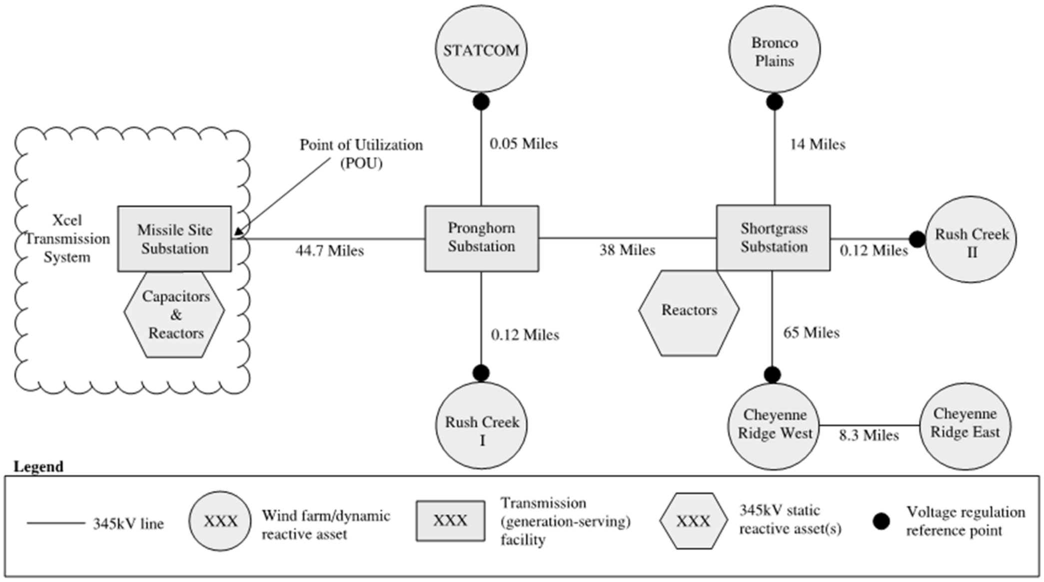

Figure 1. Simplified representation of the radial transmission system

The radial system also incorporates a +/-150 Mvar STATCOM at the Pronghorn Substation. The switched reactive devices on the system include three 120 Mvar and one 50 Mvar shunt capacitors, one 60 Mvar and one 40 Mvar shunt reactor located at the Missile Site Substation. Two additional 30 Mvar reactors are installed at the Shortgrass Substation.

The initial radial system was built in 2018 to connect the Rush Creek I and Rush Creek II wind farms to Missile Site. Cheyenne Ridge West, Cheyenne Ridge East, Bronco Plains, the STATCOM, and most of the switched reactive devices were put into service in 2020. To ensure optimal and stable performance, operators manually sent voltage references to each generating facility (wind farms and the STATCOM). This increased the time commitment for the system operators, especially during wind ramp events when line charging characteristics change dramatically. Voltages at each facility had to be independently evaluated and cross-referenced against the Missile Site POU voltage before making any voltage reference changes. Automation of these tasks would reduce the operator workload and reduce the likelihood of miscoordination of the assets.

III. IDENTIFICATION OF CONTROLLER NEED

Several factors were identified which suggested the need for automated controls. Given the geographical separation of the generating facilities and diversity of wind across the region, it was possible to have significant reactive power swings from different facilities along the gen-tie. Generators closer to Missile Site Substation had far greater influence on POU voltage regulation than those near the remote end of the transmission line. Additionally, differences in turbine and control technologies among the generating facilities yielded sub-optimal reactive power distribution along the line. Furthermore, additional detailed system modeling indicated the possibility of wind farms tripping due to overvoltage conditions in response to system disturbances and oscillations from control interactions. Transmission line characteristics, low SCR, and initial wind farm and turbine settings increased the potential for issues, especially during system disturbances.

These issues supported the benefit of a single controller that would regulate the reactive power output of all wind farms connected to the radial transmission system and coordinate their voltage references with the dynamic and static assets to maintain the POU voltage.

IV. CONTROLLER DESIGN GOALS

Specific goals for the AVSO were determined during the planning stages:

- The AVSO needed to be automatic, with minimal to no input from operators during typical day-to-day operation so that system operators can pay attention to more critical responsibilities elsewhere.
- Controller hardware selections must align with existing utility equipment standards to reduce engineering and field overhead during design, installation, and commissioning. Equipment and software must also integrate with existing network security protocols and maintenance procedures to comply with NERC CIP regulations.
- The AVSO needed to regulate transmission voltage at the Missile Site 345 kV POU within a user-settable band while maintaining healthy generation facility and substation bus voltages. Voltage regulation at the POU is mandated by Transmission Operations, and local wind farm voltage regulation is required for extended equipment life, reliable power flow, and reduced maintenance costs. Additionally, the generating facilities should always remain in voltage droop control to allow for the fastest response to voltage events.

- The AVSO needed to be designed with a consistent design approach that would be easy to use, troubleshoot, and expand. Updates to accommodate potential additional facilities and reconfigurations of the line topology must be readily accomplished without excessive alterations to the operating philosophy, executing code, or communication system. The modular approach to the architecture should also be employed to the extent possible on all possible aspects of the controller system design.

V. SYSTEM IMPLEMENTATION

A. *Control System*

The project team performed extensive modeling to determine the operating requirements of the AVSO. Modeling analysis included quasi-steady state, steady state contingency, and transient studies. These studies were performed across a variety of system conditions, including low and high generation cases, generation ramp up and ramp down, facility outages, substation and line contingencies, and cases where portions of the system were at high output while others were at low output to simulate the diversity of wind across the various facilities. From these results, the following conclusions were derived:

- Generating facilities in close electrical proximity should receive identical voltage references to prevent reactive power oscillations and to minimize circulation of reactive power.
- Although all capacitor banks on the facility collector busses are required to demonstrate power factor capability for interconnect agreement compliance, specific banks need to be disabled to ensure overvoltage ride-through of the turbines during certain system contingencies.
- An appropriate AVSO operation interval timer should be used to coordinate with the static reactive asset switching, dynamic turbine response, and STATCOM response. This needed to be slower than the facility controllers but quick enough to respond to changing wind and system conditions.
- Turbine controller droop gains and voltage reference limits must be coordinated among all the generating facilities.

With the high variability in power from the wind farms, the AVSO was designed to accommodate expected operating scenarios and minimize the potential for reactive power oscillations within the system. The AVSO acts as a steady-state system optimizer that adjusts the voltage references to the wind farm and STATCOM droop controllers based on voltage deviations from POU voltage setpoints. This was achieved by implementing logic that generates discrete voltage reference step changes rather than PID-calculated voltage references. Each wind farm and STATCOM starts voltage regulation with an initial preferred voltage reference informed by system modeling. When the measured POU voltage is below the desired voltage and all other required conditions are met, the AVSO increases the voltage reference for each facility by a single step. The reverse is true for overvoltage at the POU. The AVSO issues a discrete voltage reference step change to a facility only if it has available reactive power capability and if there are no blocking conditions that would prevent the facility from successfully following the issued voltage reference. The system recognizes that the reactive capability of each facility varies with the level of real power output. With this system of bounded changes in voltage reference, the AVSO controls each facility and the STATCOM independently based on their capabilities and status and contributes to the overall goal of POU voltage regulation.

The AVSO's controlling setpoints are highly customizable and can be modified at any time during operation. Operators can define custom limits (high and low) for voltage regulation for each facility as well as define the size of the discrete voltage step issued by the AVSO. An operator may manually send an override voltage reference to any available facility at any time without interrupting automatic operation should the operator wish to manually adjust reactive power flows.

System operators can send all AVSO setpoints and parameters remotely through dedicated interfaces. Operational feedback and alarming are provided to the Xcel Energy control center. Under normal operation, the AVSO autonomously makes voltage reference adjustments to maintain POU voltage. System operators can enable or disable any facility or asset from AVSO control at any time. This allows for continuity of multi-facility control in the event of wind farm maintenance, testing, or outages.

The AVSO regulates system voltage in conjunction with dedicated automatic voltage controllers (AVCs) which command operation of switched reactive assets. Dedicated AVCs are located at Missile Site Substation and at Shortgrass Substation to automatically switch 345 kV shunt capacitors and reactors. This helps maintain desired substation bus voltage while the AVSO adjusts voltage references to the droop controllers of the generation facilities and STATCOM. The AVC and AVSO controllers were modeled and designed to operate independently of each other. The results of system studies determined 345 kV capacitor and reactor voltage cut in/out setpoints.

The time coordination of the AVSO and AVC was also considered. Given a change in voltage at the power plant controller voltage regulation reference point, the droop controllers of the inverter-based facilities and STATCOM were found to respond within about 10 seconds. Next to respond would be the AVC controlling the static switched assets at the substations, performing operations with a 10–30 second delay upon deviation from local voltage setpoints. Finally, the AVSO adjusts wind farm voltage references as needed every 2 minutes.

As noted, the generators closer to the POU are more impactful in regulating the POU voltage than those farther away. Modeling shows the facilities closest to the POU are expected be the first to reach their reactive power capability limits. With these facilities at their reactive limit, the fast droop response to POU voltage transients is left to the available reactive capability of the assets further down the line, which have reduced impact on the POU voltage. To retain reactive margin at the facilities near the POU for system contingencies, reactive power reduction logic was implemented. As the available reactive power of a facility drops below an operator-determined threshold, the voltage reference step size is proportionally reduced until it reaches zero as the facility reaches its maximum reactive power capability. As a result, generation facilities further away from the POU provide an increased share of the reactive power needed to maintain the POU voltage so that facilities closer to the POU retain more dynamic reactive capability to support system transient events.

B. Communication System

A robust communications architecture was implemented for AVSO telemetry via dedicated high-speed fiber with additional copper back-haul paths for selected segments. This system carries only AVSO communication traffic, increasing bandwidth availability and reducing potential packet loss. Communication nodes were created at each substation, generation facility, and STATCOM, and all AVSO traffic is supervised by firewall devices at each communication node. The system is configured to allow automatic packet forwarding using connectivity fault management in the event of a disruption to a portion of the communication network.

In addition to the dedicated communication system, the AVSO architecture was designed for physical redundancy and the use of dedicated hardware. The AVSO controller logic utilizes fully integrated hardware failover with redundant and identical AVSO controller hardware – AVSO A and AVSO B. AVSO code loaded to both controllers is identical to reduce revision control and support faster troubleshooting. Under normal operating conditions, AVSO A defaults to the primary controller and AVSO B defaults to the secondary controller. Both AVSO controllers are constantly communicating with each other, checking for hardware and software failures, and passing all user-defined setpoints between each other. In the event of a failure of the primary AVSO controller, the secondary AVSO will detect this failure and automatically take over the primary AVSO controller role after a predetermined delay. The secondary controller becomes responsible for calculating necessary voltage reference setpoints and issuing them to the facilities as required. Upon failure of either AVSO controller, system operators receive an alarm, allowing for repair before a second failure and a system outage. Operators can also force either AVSO controller to assume the primary AVSO controller responsibilities at any time, allowing for seamless maintenance and troubleshooting.

Because the Missile Site Substation POU is the critical point of control, dedicated redundant metering hardware was installed. In normal circumstances AVSO A and B each obtain metering information from the primary meter source. In the case of primary meter failure, the AVSO controllers detect the failure and automatically utilize the remaining good meter source, thereby reducing potential controller downtime and increasing resiliency.

Both AVSO controllers are designed to communicate with the wind farm and STATCOM Remote Terminal Units (RTUs) to retrieve necessary operating data and send voltage reference setpoints. Considering the need to provide data to both AVSO controllers and the existing Xcel Energy EMS SCADA connection, the wind farm substation RTUs were designed to support multiple master DNP connections by utilizing a single network server port implementing IP and DNP-based reservations.

VI. SYSTEM VERIFICATION AND TESTING

Since the Rush Creek gen-tie was already in operation at the time the AVSO was installed, it was not preferred to perform initial testing on the live transmission system. Instead, custom Fortran code to simulate the AVSO and AVC controller logic was developed in PSCAD and utilized for advanced testing of the control logic using time-domain modeling. This logic was also translated for PSS/E implementation to validate the approach in quasi-steady state. An overall system model containing an equivalent of the Xcel Energy network, the radial transmission lines, each wind farm, and the STATCOM was developed within PSCAD using site-specific models provided by vendors. The PSCAD model was then converted to RSCAD for real-time digital simulation modeling and testing (RTDS). The actual AVSO controller programming was loaded into the actual controller hardware, which was then integrated into the digital model for hardware-in-the-loop testing and subjected to extensive simulations representing real-world operating scenarios.

In addition to the simulation and RTDS testing, a detailed commissioning test plan was created and executed on-site before placing the AVSO into service. Commissioning procedures consisted of communication verification, data source verification, setpoint verification, reference verification, and functional testing. The communication verification confirmed that all communication channels were working correctly and metering devices, I/O devices, and all RTUs were communicating with the AVSO. Data were verified by simulating real operating conditions and monitoring the provided system status and alarms.

Setpoint verification involved the validation of the analog, status, alarm, and control setpoints required by the AVSO. The analog and control setpoints were verified from both a local human-machine interface and Xcel Energy Management System. Reference verification validated the generation facilities and STATCOM followed the AVSO voltage references as expected. This testing was performed on the live system as conditions allowed.

Finally, functional testing incorporated the validation of all parameters calculated within the AVSO controller logic, as well as confirmation of the fiber optic ring redundancy, POU metering redundancy test, AVSO controller hardware redundancy test, AVSO blocking logic test, reactive power reduction logic test, and the voltage control logic test. Each wind farm was functionally tested independently while the other generators operated to a static voltage reference. Upon successful independent tests, all generators were tested simultaneously to verify whole-system operations.

The voltage control logic testing also presented a unique opportunity for the system operators and field specialists to become familiar with AVSO operation. Each test was discussed with the field specialists and system operators, including expected outcomes and contingency plans. An interactive spreadsheet that calculates the expected new voltage targets was used to facilitate the learning and testing operations during AVSO commissioning.

VII. DEMONSTRATED BENEFITS

Analysis of seven days of operational data pre-AVSO and post-AVSO demonstrated tighter voltage regulation at the POU. Following AVSO implementation, the seven-day average POU voltage was 1.017 PU, the seven-day average minimum POU voltage was 1.006 PU, and the seven-day average maximum POU voltage was 1.026 PU. This corresponds to tighter regulation compared to the pre-AVSO seven-day values of average POU voltage of 1.020 PU, seven-day average minimum POU voltage of 1.007 PU, and seven-day average maximum of 1.031 PU.

The Missile Site POU 345 kV cap banks saw an 83% reduction in switching operations due to tighter regulation from the generating facilities and coordination with the voltage cut-in points of the AVC system. Reduction in high-voltage cap bank operation is expected to yield cost savings through increased intervals between breaker maintenance activities and prolonged capacitor life.

Figure 2 shows POU voltage and power flows during a wind-ramp event which occurred prior to implementation of the AVSO. This plot shows the measured voltage at the POU fluctuating between 1.004 and 1.026 PU with the wind ramp. The voltage reference sent to the Rush Creek facility remains constant during this ramp due to high operator workload.

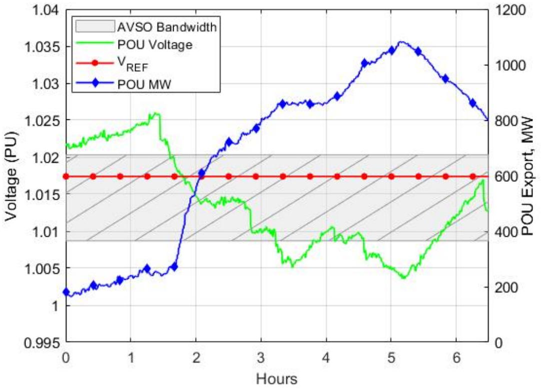

Figure 2. System response to wind-ramp event pre-AVSO implementation

Figure 3 shows POU voltage and power flows during a similar wind-ramp event after implementation of the AVSO. Time scales have been aligned for comparison. During this ramp, the AVSO automatically made voltage reference updates within 30 mintues, resulting in tighter voltage regulation at the POU while operators focused on other immediate tasks.

The two events were similar enough to make observations on the performance of the AVSO. Both events ramped production from less than 200 MW to approximately 1100 MW over a five-hour span. The AVSO began increasing the voltage reference setpoint as the measured POU voltage dropped below

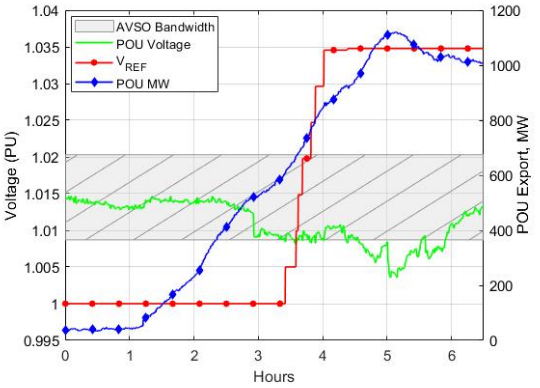

Figure 3. System response to wind-ramp event post-AVSO implementation

1.0087 PU. Due to the adjustments made by the AVSO, the system was able to regulate the POU voltage with less reactive power demand from the grid and without the need for intervention by operators.

VIII. CONCLUSIONS

Inverter-based resource integration is becoming prevalent at the utility scale. Gen-tie lengths are increasing while POU SCRs are decreasing. With grid expansion and diverse generation portfolios, control center operator responsibilities are becoming complex and widespread.

The Rush Creek gen-tie connects high-capacity wind energy on a complex collection system into a weak grid. Wind volatility combined with long line length and a weak grid interconnect demands a high-level automatic system control to assist with management, task offload, and voltage coordination. Benefits of AVSO implementation have included operational maintenance cost savings and reduction in routine workload for operators, allowing them to focus on critical and unplanned system events. RTDS and field testing provided operators and engineering confidence that the AVSO would handle unique operating scenarios. The AVSO demonstrates how these engineering problems can be addressed and provides operational benefits to the line.

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