21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Transmission-Level Multi-Facility Coordinated Voltage Control for the Integration of Inverter-Based Resources into a Weak Grid

B. RYAN, C. MOUW, C. SIFONTES LOPEZ, C. CANINE, M. NELSON
POWER Engineers, Inc.
USA

A. WILSON
Xcel Energy
USA

H. SURIYAARACHCHI, A. RUPASINGHE
Transgrid Solutions
USA

S. GHIOCEL
Mitsubishi Electric Power Products, Inc.
USA

SUMMARY

As the penetration of inverter-based resources continues to offset the retirement of synchronous generation, long radial transmission and weak interconnects will become more common. Diminishment of the short-circuit strength, coupled with the variable nature of the resources can lead to rapidly fluctuating reactive power demands on the system. As system complexity increases and generation resource power becomes less dispatchable, the demands on system operators will continue to increase. This paper discusses implementation of a novel, automatic, multi-facility, coordinated voltage control system, called the Automatic Voltage Setpoint Optimizer (AVSO). The system improves 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.

KEYWORDS

Automatic voltage control, renewable energy sources, substation automation, sustainable development, wind power grid integration

Benjamin.Ryan@powereng.com

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 and optimize reactive power 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-long, radial 345 kV transmission line with various lengths of interconnecting gen-tie lines.

The original system 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 increased the difficulty of offsetting the impacts of changing real and reactive power flows and regulating the Missile Site Substation 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 objectives of the system are to reduce operator workload and to keep transmission voltage 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 its main power transformer (MPT) with voltage droop controls using the reactive capabilities of the turbines and collector bus-connected MSCs and MSRs. Due to operating considerations on the adjacent network system, it was necessary to maintain the POU voltage within a tight bandwidth by independently adjusting the voltage setpoint of each facility at its' MPT.

The radial system also incorporates a +/-150 Mvar STATCOM at the Pronghorn Substation. The STATCOM also uses voltage droop controls, but it does not have any switched reactive devices associated with it. 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). Manual operation increased the time system operators invested, especially during wind ramp events when line charging characteristics change dramatically. Voltages at each facility were independently evaluated and cross-referenced against the Missile Site POU voltage before making any voltage reference changes. Automating these tasks would reduce both the operator workload and the likelihood of miscoordination of the assets.

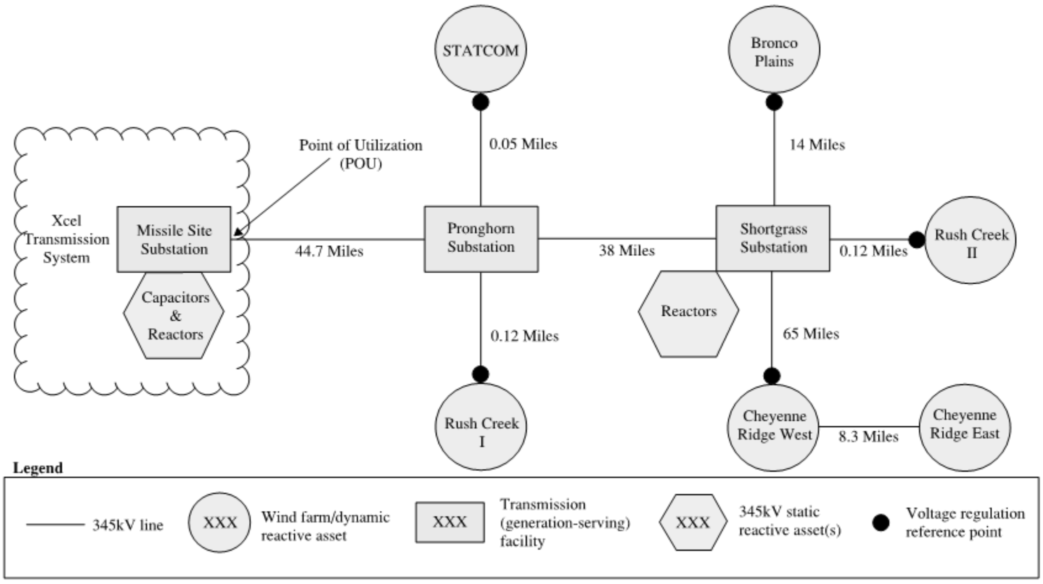


Figure 1. Simplified representation of the radial transmission system

III. CONTROLLER EVALUATION

To support the design of the AVSO controller, a quasi-static simulation was performed considering the new wind facilities and associated reactive equipment. The objective of the analysis was to provide insight on the interactions among the wind facilities and equipment along the Missile Site–Pronghorn 345 kV tie line to determine the following:

- The steady-state voltage regulation settings (voltage reference, voltage droop) for all voltage regulators along the Missile Site gen-tie line.
- The voltage thresholds for switched capacitors at Missile Site 345 kV and reactors at Shortgrass 345 kV.
- Slow reactive regulator response parameters of the STATCOM at Pronghorn 345 kV.
- The capability of voltage regulators to maintain steady-state voltages along the Missile Site gen tie line under normal operation considering various wind generation scenarios and equipment availability scenarios.
- Performance of the system with the AVSO and interaction with wind facilities and reactive equipment.

IV. MODELLING AND SIMULATION

Quasi-Static Modelling and Simulation

The latest WECC operating power flow case was updated to represent relevant system conditions in the Missile Site and surrounding areas.

The quasi-static analysis was intended to model and simulate the long-term voltage control dynamics of the system, representing dynamics taking place in the seconds to minutes time frame. This type of analysis bridges a gap between classical power flow analysis, which represents steady-state snapshots of the system, and transient stability analysis, which is typically performed for up to 30 seconds and captures the rotor angle dynamics and electromechanical behavior of the system.

For the purposes of the quasi-static analysis, equivalent models of the equipment along the Missile Site gen-tie line were developed according to the long-term time frame to be simulated.

Power Flow Model

Wind plants were modeled as aggregate representations based on their expected performance from the perspective of their MPTs. Each aggregate wind plant was modeled as an ideal voltage source representing the overall power plant controller (PPC) with reactive power limits tuned to provide the minimum 0.95 pf leading and lagging based on the actual real power output of the plant. Note the 0.95 pf represents the minimum required reactive power at the high side of the MPT, but the final design may allow for additional capability.

The STATCOM was modeled as an ideal voltage source with reactive power limits set to ±150 Mvar to represent the reactive capability of the STATCOM. The rest of the Xcel system was set up according to expected operating conditions. Table 1 contains the dynamic model parameters which were tuned during the quasi-static analysis along with their final values. Note the finalized parameter values incorporated equipment capability and dynamic performance considerations from the detailed manufacturer-provided models, in addition to the quasi-static analysis results.

Table 1. Wind plant PPC model parameters

Parameter	Rush Creek I	Rush Creek II	Bronco Plains	Cheyenne Ridge West	Cheyenne Ridge East
Droop (% on Machine Base)	2.0%	2.0%	2.5%	2.0%	2.0%
Voltage Control Response or Rise Time (s)	4.0	5.0	10.0	5.0	5.0
Voltage Deadband (pu)	0.001	0.001	0	0.001	0.001
Machine Base (Qbase) for Voltage Control	121.60	70.40	316.15	83.84	71.36
Voltage Reference (pu) (without STATCOM)	1.010	1.020	1.030	1.030	1.030
Voltage Reference (pu) (with STATCOM)	1.020	1.025	1.033	1.030	1.030
Voltage Control Point (345 kV bus)	Pronghorn	Shortgrass	Bronco Plains	Cheyenne Ridge West	Cheyenne Ridge West
Maximum Active Power Reference Ramp Rate	2.5%/sec	2.5%/sec	2.5%/sec	2.5%/sec	2.5%/sec

Dynamic Models for Quasi-Static Simulation

The voltage control dynamics of the wind plant PPCs were represented as first-order regulators, with time constants based on the rise time settings of each power plant controller. This model provides an approximation of the response of each PPC and allowed for sensitivity analysis considering the tuned response time of each plant.

For the STATCOM voltage regulator, the response time was assumed to be instantaneous considering the minutes time frame of interest. In practice, the STATCOM voltage regulator would be expected to be significantly faster than the wind plant PPC voltage regulators, and effectively instantaneous in the minutes time frame of the quasi-static simulation. However, the slow reactive power reset controller of the STATCOM typically operates with a time constant of 60+ seconds and acts as a bias on the voltage reference to reset the STATCOM output to a desired steady-state deadband to allow other devices to support reactive power needs. Therefore, this controller was modeled using a first-order regulator on the voltage reference of the STATCOM.

Capacitor banks and reactors were modeled using voltage thresholds with associated timers to place in-service or out-of-service, in accordance with typical operating practices. Two different timers were implemented for each capacitor and reactor to account for fast response for large voltage deviations and a slower response for smaller voltage deviations.

The simulation was performed using a Python-based simulation engine, which includes the models described previously and connects to the WECC power flow case using the Python APIs for Siemens PSS/E. In this simulation environment, the PSS/E model serves as the network solution for the quasi-static analysis, analogous to the network solution in a transient stability simulation.

The AVSO was modeled by incorporating the FORTRAN code and model developed for the PSCAD model of the AVSO into the quasi-static simulation. The code was incorporated into a dynamic model within the Python-based simulation engine.

Analysis and Results

The quasi-static analysis was performed considering different equipment availability scenarios, contingency events, and parametric variations. The cases included various combinations of capacitor and reactor availability amongst Missile Site, Pronghorn, and Shortgrass. Each these cases were also evaluated using multiple PPC voltage set reference profiles applied across the wind farms.

Generation ramping events were analysed considering variations of plant online/offline status, and different combinations of wind plants ramping. The generation ramping scenario was expected to provide a worst-case condition for the voltage regulation on the gen-tie, because of the increase in reactive power required to support the increased active power during the ramping event. Table 2 shows the list of generation ramping events studied in the quasi-static analysis.

Table 2. Generation ramping events

Generation Scenario	Rush Creek I	Rush Creek II	Bronco Plains	Cheyenne Ridge West	Cheyenne Ridge East
A	Ramp 0 – 100%	Ramp 0 – 100%	Ramp 0 – 100%	Ramp 0 – 100%	Ramp 0 – 100%
B	Offline	Offline	Ramp 0 – 100%	Ramp 0 – 100%	Ramp 0 – 100%
C	Offline	Offline	Offline	Ramp 0 – 100%	Ramp 0 – 100%
D	Full Output	Full Output	Full Output	Ramp 0 – 100%	Ramp 0 – 100%
E	Full Output	Ramp 0 – 100%	Ramp 0 – 100%	Offline	Offline
F	Offline	Ramp 0 – 100%	Ramp 0 – 100%	Full Output	Full Output
G	Ramp 0 – 100%	51.7% Output	51.7% Output	51.7% Output	51.7% Output

The following is an example of the quasi-static simulation output, showing the performance of the system considering all wind plants ramping (Scenario A). The results in Figure 2 show the voltage dip as the wind plants ramp up and power transfer increases. The voltage recovers as the PPCs and STATCOM provide reactive power support, and the shunt capacitors energize to support the steady-state voltage.

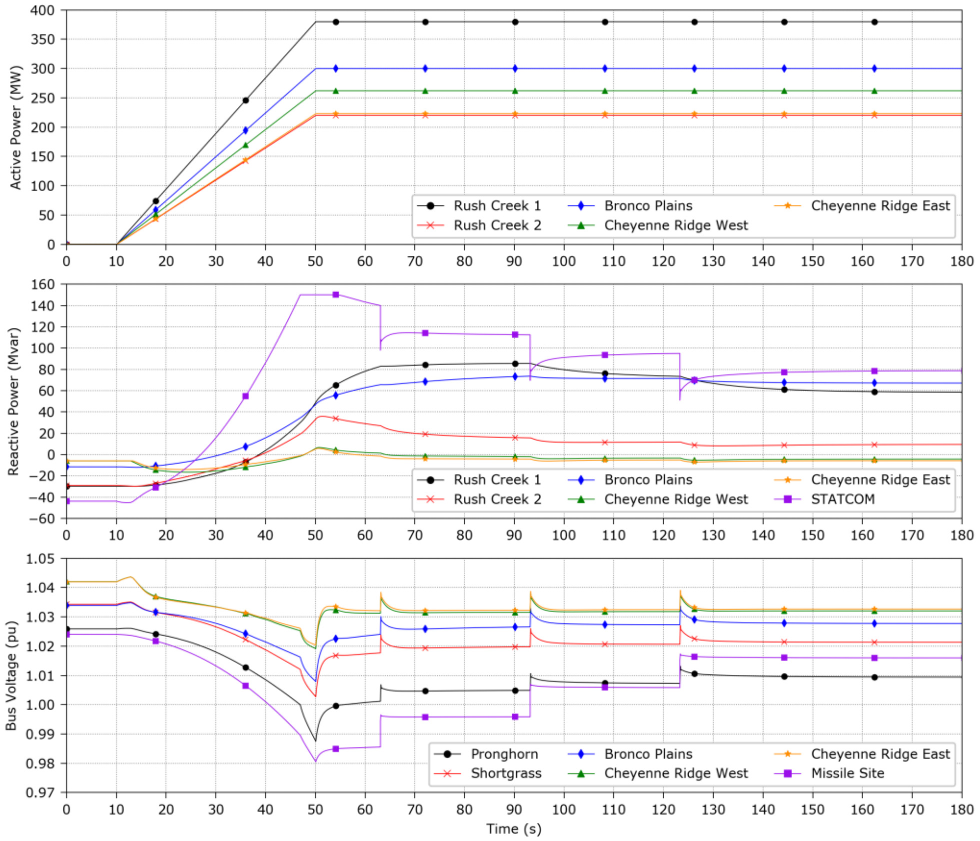


Figure 2. Simulation response for generation scenario A

V. SYSTEM IMPLEMENTATION

Control System

The following conclusions were derived from initial study results:

- Generating facilities in 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 to comply with the interconnect agreement, specific medium voltage 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 highly variable 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 modelling. When the measured POU voltage is below the desired voltage and all other required conditions are met, the AVSO increases by a single step the voltage reference for each facility. 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. Should operators wish to adjust reactive power flows, they may manually send an override voltage reference to any available facility at any time without interrupting automatic operation.

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 and Shortgrass 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.

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

Generators closer to the POU have more impact on regulating the POU voltage than those farther away. Modeling shows the facilities closest to the POU will 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 farther 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.

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 after a predetermined delay, automatically take over the primary AVSO controller role. 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 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.

VI. SYSTEM VERIFICATION AND TESTING

Since the Rush Creek gen-tie was already in operation at the time the AVSO was installed, it was preferred to avoid 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-static. 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 modelling 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 (HIL) testing and subjected to extensive simulations representing real-world operating scenarios.

The facilities connected to the gen-tie were included in the AC system model. Considering that manufacturer models were not available and that the AVSO operates in a quasi-static time frame, only the PPC voltage control function is modelled for the wind farms. The turbines are modelled as voltage-controlled PQ sources. The sources were tuned to closely match the PPC response time of each plant. They were benchmarked with the full PSCAD model made available for each plant. The voltage controller and the slow-Mvar controller function of the STATCOM were modeled. Similar to the wind farm models, the performance of the STATCOM model in the RTDS was also benchmarked against the manufacturer-provided PSCAD model. All the measurements the AVSO and AVCs require and all the setpoints and the breakers they operate were included in the RTDS model.

The RTDS model was interfaced with the AVCs and the AVSO by way of a GTNETx2 card using the DNP3 communication protocol. The AVSO and AVC devices function as a DNP Master to the wind farms and the STATCOM and a Slave to the EMS. An SEL-3505 RTAC was used as an EMS emulator. The EMS emulator collects the required data from the RTDS and transmits it to the AVSO and AVCs. A schematic diagram of the RTDS HIL setup is shown in Figure 3.

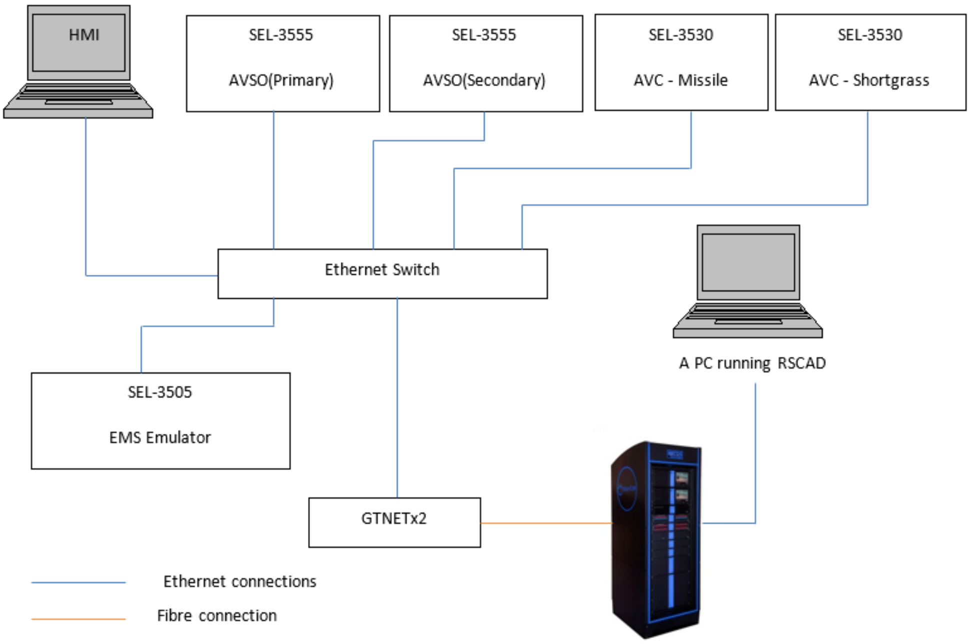


Figure 3. Schematic diagram of the RTDS HIL test setup

A wide range of operating scenarios covering voltage changes, power ramps, facility trips, line trips, energization, loss of signals, continuous operation, and primary and secondary controller change-over were used for the testing. For the continuous operation testing, actual gen-tie loading recorded for 8 hours was used (see Figure 4). Also shown in Figure 4 are the Missile Site voltage, Q from Missile Site capacitors, voltage reference, measured voltage, total reactive power, and total reactive power capability of the Rush Creek I wind farm. Note that due to the space limitation, only Rush Creek I plots are shown.

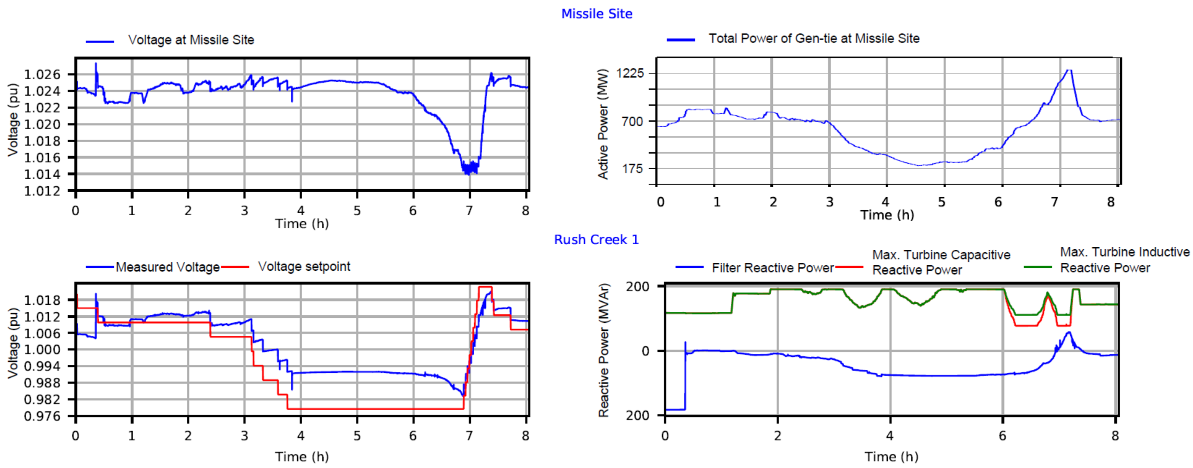


Figure 4. RTDS results from eight-hour gen-tie loading

As the gen-tie loading fluctuates during the 8 hours, the AVSO adjusts the voltage references to the wind farms to maintain the Missile Site voltage within the control range of 1.015-1.025 pu. During this period no capacitor switching was initiated by the Missile Site.

During RTDS testing, revisions to the AVSO algorithm were identified to improve the performance of the system. Occasionally, specific wind farms would receive voltage references up to their maximum capability, preventing additional dynamic support if a system event were to disturb the gen-tie. Since this was observed only under specific operating conditions, likely, this would not have been identified during the commissioning. Furthermore, as the testing used the actual hardware of the AVSO and the AVC, the testing was able to reveal some communication problems. In addition to testing the AVSO and AVC controllers in a safe environment through the RTDS HIL testing the following was achieved:

- Demonstrate the benefit of the Gen-tie AVSO and AVCs to different groups within Xcel Energy using a wide range of operating conditions
- Understand the operation of the AVSO under different operating conditions
- Increase the confidence of the network operators in the performance of the AVSO and AVCs

In addition to the simulation and RTDS testing, a detailed commissioning test plan was developed and executed on the live system 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. AVSO SCADA was verified by simulating real operating conditions and monitoring the provided system statuses and alarms.

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.

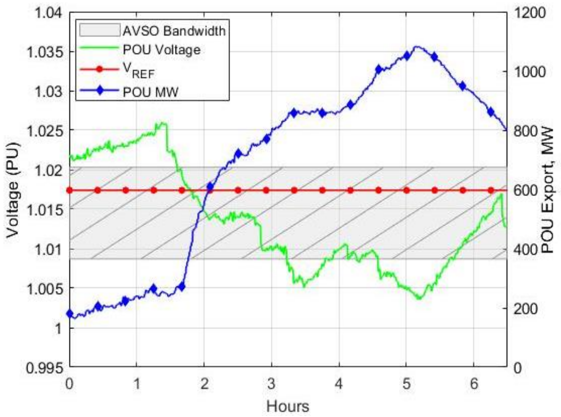
VII. DEMONSTRATED BENEFITS

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 5 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 6 shows POU voltage and power flows during a similar wind-ramp event after implementation of the AVSO. Time scales were aligned for comparison. During this ramp, the AVSO automatically made voltage reference updates within 30 minutes, resulting in tighter voltage regulation at the POU while operators focused on other immediate tasks.



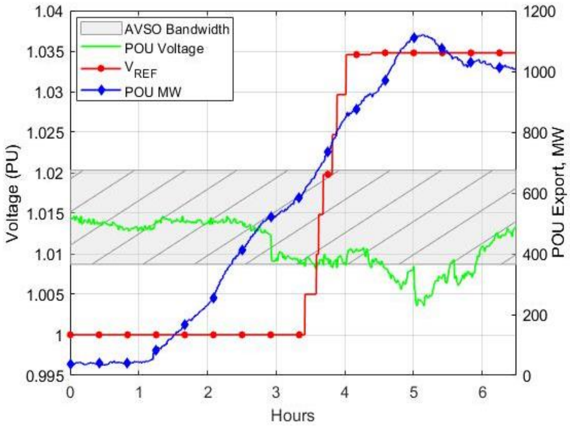


Figure 5. System response to wind-ramp event pre-AVSO implementation

Figure 6. System response to wind-ramp event post-AVSO implementation

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 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.

BIBLIOGRAPHY

[1] CIGRE Working Group B4.62, "Connection of wind farms to weak AC networks," CIGRE, Paris, France, Technical Brochure 671, 2016. ISBN: 978-2-85873-374-3.

[2] North American Electric Reliability Corporation, "Integrating inverter-based resources into low short circuit strength systems: reliability guideline," NERC, Atlanta, Georgia, Dec. 2017. Available: www.nerc.com