Case Study: Integrating and Stabilizing Renewable Energy on a Transmission Line Using Multiple Wind and Solar Farms

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***Abstract*—This paper reviews the implementation of a multiple power plant controller (MPPC) that manages the integration of multiple wind and solar farms along a transmission line. The system consists of two wind parks and one solar farm that connect to a 138 kV transmission line. The total generation capability of the combined facilities is 102.7 MW. The power plant controller's primary objective is to manage the facilities' combined output at the point of interconnection (POI) with another transmission line. Operators have the ability to place facilities in a local mode with a fixed output, and the controller automatically adjusts the other facilities to meet the POI requirements. Typically, the controller operates in voltage regulation mode but allows operators to transition the system to achieve a target MVAR set point at the POI. One of the challenges of managing reactive power at this facility is handling reactive losses, which can exceed over 2 MVARs from the substation to the POI, which is about a 10-mile distance. To reduce reactive power losses, several capacitor banks are used in the system to improve the power factor of the generation facilities.**

Some of the challenges encountered in the integration of these facilities included:

- **Integrating multiple wind park controllers that have different behavior.**
- **Integrating multiple types of inverter generation.**
- **Managing facilities that have different response timing and ramping capabilities.**
- **Stabilizing voltage at the POI.**
- **Implementing verification testing of the power plant controller and system response.**

This paper discusses the technology used to generate the solution, the design approaches, and the operator control interfaces that helped overcome these challenges, as well as the lessons learned from this project.

I. Introduction

This paper discusses the multiple power plant controller (MPPC) that manages the point of interconnection (POI) of a transmission line that contains two wind parks and a solar farm. The objectives of this controller are as follows:

- Comply with the Generator Interconnection Agreement (GIA) by keeping resources within acceptable margins and complying with U.S. Federal Energy Regulatory Commission (FERC) Order No. 827, which addresses reactive power with VAR-002 automatic voltage regulator (AVR) and voltage regulations.
- Comply with FERC Order No. 842, which pertains to frequency response.
- Coordinate real and reactive power to meet the POI requirements from the wind parks, solar farm, and capacitors connected to the transmission line.
- Provide operators with an operational screen for analysis and control.

In this system, the MPPC issues set points to another power plant controller, which manages the individual inverters at each facility. Wind Park 1 has 21 turbines with a total capacity of approximately 72 MW. Wind Park 2 has 14 turbines with a total capacity of approximately 28 MW. The solar farm has 14 photovoltaic (PV) inverters with a combined output of approximately 2 MW. These facilities provide a significant portion of power to the upper peninsula of Michigan and contribute power to a variety of industrial facilities and approximately 24,000 residential homes.

II. Operational Requirements

A. FERC Order No. 827

Prior to June 2016, wind generation was exempt from needing to provide reactive power. Order No. 827 requires that nonsynchronous generators would "be required to provide dynamic reactive power within the range of 0.95 leading to 0.95 lagging at the high side" of the transformer at the generation facility [1]. Initially, it was expensive for these wind generation facilities to have the capabilities to provide reactive power and would have created obstacles to the development of wind generation. Since the beginning of wind generation, the technology has significantly advanced to the point where these facilities are now able to provide reactive power [1], and this order brings these assets back to more traditional generation requirements. Even so, Order No. 827 makes an important distinction between how synchronous and nonsynchronous generation is treated. Wind generation is only required to provide the specified reactive power at the high side of the transformer at the substation, while synchronous generation is required to provide the reactive power at the POI [1].

B. FERC Order No. 842

Issued in February 2018, Order No. 842 requires all synchronous and nonsynchronous generation that has a Large Generator Interconnection Agreement or a Small Generator Interconnection Agreement to "operate equipment capable of providing primary frequency response as a condition of interconnection." Primary frequency response is an automatic increase or decrease in real power output when the measured frequency transitions outside an established deadband of 60 Hz [2]. Prior to Order No. 842, nonsynchronous generation, including wind power, was not required to provide primary frequency response as a condition of interconnection.

C. VAR-002 AVR and Voltage Regulation

The VAR-002 standard ensures that generation facilities have AVR and automatic voltage control working for 98 percent of operating hours. This requirement outlines rules for AVR system maintenance and component failures to keep generation facilities in compliance. VAR-002 also outlines requirements for quarterly reports detailing the following:

- The hours the generation facility was online
- The number of hours the AVR was out of service
- The percentage that the AVR was in service

The outlined data must be kept for four years after the data are collected or since the last time an audit was performed, whichever time period is longer [3].

III. Managing POI Reactive Power

Managing real power at the POI from the generation facilities is straightforward. Operators have a few different modes to meet real power requirements through the human-machine interface (HMI) on the MPPC, though managing reactive power at this POI is more challenging due to the high voltage that is frequently present at the POI. This section highlights the operational modes that operators have available to them to manage the high voltage above nominal and the system conditions that create the higher voltage. Fig. 1 shows the online diagram from the operator HMI screen on the MPPC.

The system can operate in two primary modes for reactive power. Operators can select a single VAR set point or a voltage set point at the POI. The controller then calculates the necessary amount of VARs to be produced by the generation facilities to meet the POI set points. The reactive power set points are split between the two wind parks, and the solar farm is kept at unity power factor. Capacitor banks are utilized to improve the power factor of the wind parks. The next capacitor bank closes in when the wind parks are producing more than an operator-configurable percentage capability of the capacitor banks. For example, the operation threshold is 75 percent, the next capacitor has a capacity of 100 kVARs, and the parks are collectively asked to produce 80 kVARs. Since 80 kVARs exceeds the operator-configurable parameter of 75 percent, the next capacitor is closed in. In this example, the wind parks now consume 20 kVARs instead of producing 80 kVARs, improving the power factor of the wind parks [4].

At full capacity, the system is designed for the MPPC to either consume or produce 34 MVARs at the POI. The system is designed to operate at 138 kV nominal; however, it typically ranges between 140 and 142 kV because the POI of the transmission lines is in a remote location far away from any major load or generation sites. The distance of the transmission lines builds capacitance, increasing the reactive power on the lines, in turn increasing the voltage at the POI. The wind parks typically consume reactive power in an attempt to keep the voltage under 142 kV. If the MPPC at the POI is unable to keep the voltage below 142 kV, operators are notified to make modifications to the system to keep it under 145 kV, which the GIA requires. Unfortunately, these system conditions make it difficult to stay within the 0.95 lagging and leading power factor requirements that the GIA stipulates. The implemented control solution manages the voltage well below the requirements in the GIA and is a significant improvement to the prior system conditions before the installation of the MPPC at the POI.

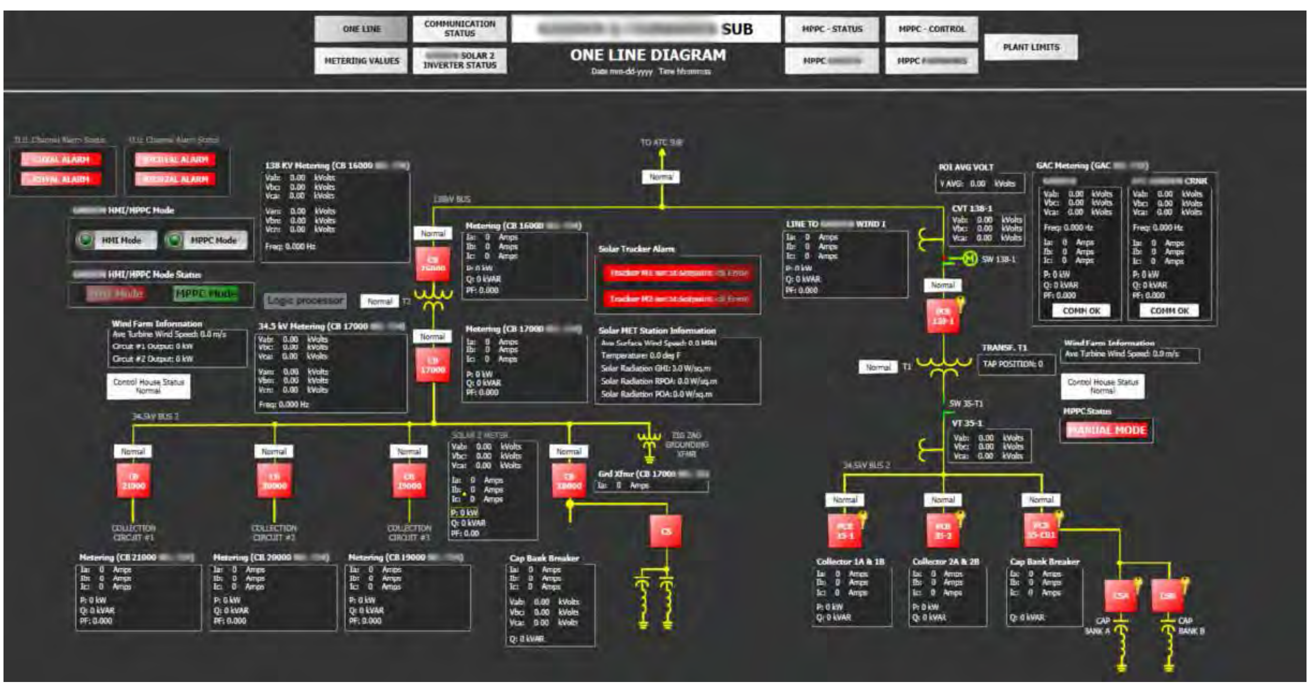

Fig. 1. Facility one-line diagram operator screen.

The MPPC uses a proportional integral (PI) controller to drive the POI to the desired operation set point. This design allows the PI controller to account for all losses in the system without understanding any topology or needing to calculate anticipated losses based on line impedances. The closed-loop control system takes the system set point and drives the system metered value at the POI to the desired set point. In Fig. 2, a model of the voltage control algorithm is shown.

The voltage set point needs to be translated to a VAR set point for each of the wind parks, as shown in (1) [4].

$$\text{System VAR set point} = \text{Plant Q} + \frac{(\text{V set point} - \text{Plant V})}{\text{dvdq}} \quad (1)$$

The difference between the current-voltage measurement and the target voltage set point is divided by the relationship of how many VARs are necessary to create a one-volt change at the POI. This quantity is added to the existing metered reactive power value at the POI [4]. The PI controller then drives the system to this value. This system VAR set point is re-evaluated each time the PI controller is executed. The system VAR set point is proportionally split between the wind parks based upon their capabilities. An important part of (1) is the relationship in the change in VARs and the corresponding change in voltage (dvdq). If dvdq is an accurate representation of system conditions, the system VAR set point can be correctly determined within one or two evaluations of this equation. If dvdq does not accurately reflect system conditions, the controller will initially over- or undershoot the necessary VAR set point to achieve the voltage set point. Over time, it is likely that the correct VAR set point will be identified with an incorrect dvdq due to the periodic evaluation of this equation, but it will limit the responsiveness and accuracy of achieving the voltage set point. It is recommended that this value be calculated empirically on site through testing various VAR set points. In this case, placing the controller into closed-loop reactive power mode was recommended. Then the reactive power set point was changed, and the differentials in both VARs and voltage were recorded. Once the measurements are recorded, (1) can be used to find the relationship. If dvdq is significantly different through a range of reactive power set points, it is recommended to average the measured dvdq values and use that as the input to the controller.

One of the challenges of using a PI controller in this system is integrating the different response characteristics of the different generation facilities. Several factors impact achieving a smooth response for closed-loop control systems:

- POI ramp rate
- Generation facility ramp rate
- Generation facility response time
- Evaluation period of PI controller

Ideally, each facility contributes a proportional amount of power to the POI set points. For example, if Wind Park 1 has 100 MVARs and Wind Park 2 has 50 MVARs, Wind Park 1 would carry 66.67 percent of the set point and Wind Park 2 would carry 33.33 percent of the set point. When generation facilities have similar response times and ramping capabilities, the facilities respond at the same rates when the controller issues set points. The MPPC calculates the error between the current production value and the set point and generates new set points for the generation facilities. However, when one generation facility responds to its set points significantly faster than the other facility and the MPPC evaluates new set points faster than the slower facility can reach the previous set points, the controller builds additional error, which causes overshoot and a mismatch in the proportional response from the generation facilities. There are a few solutions to this challenge. Depending upon the system objectives and the design of the system, any one of these may be implemented:

- *Set the execution rate of the PI controller to the effective response rate of the slowest operating facility.* This solution slows the response of the entire system to the slowest facility or asset in the system but allows a smooth, proportional relationship to be maintained between assets during transition periods between set points. This works because the PI controller does not run as frequently as the slowest facility, so if the feedback signal is not changing quickly or accurately, the controller builds less error over time. This also reduces the likelihood of overshoot or oscillations, making the tuning process simpler.

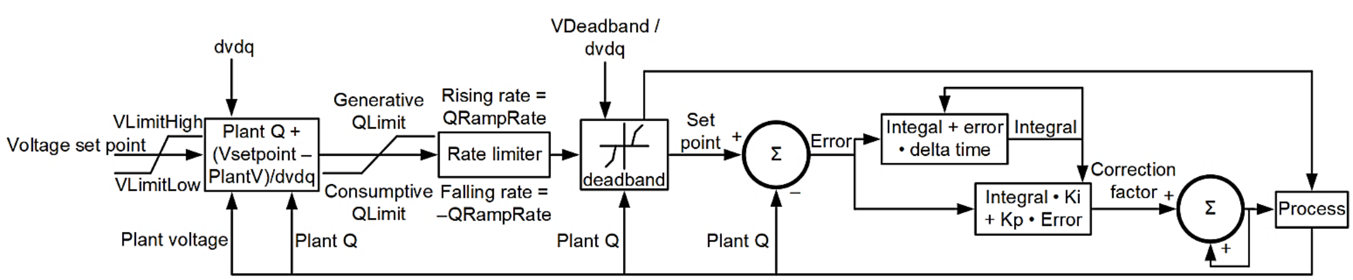

Fig. 2. Voltage control algorithm.

- *Configure all facilities to have the same ramp rate regardless of their capabilities, or configure the POI ramp rate to match the slowest operating facility.* This solution is similar to the previous solution as it focuses on slowing down the overall system response to match the slowest facility or asset to ensure smooth, proportional responses from all facilities and reduce the likelihood of overshoot. The main difference between this solution and changing the rate of the PI controller execution is that the PI controller is handed set points at a slower rate, decreasing the amount of potential error that can be built over time.
- *Tune the controller to minimize overshoot and oscillations, which are likely to occur with mismatched capabilities.* This solution minimizes the overshoot that is likely to occur as the faster responding facility picks up a greater proportional share of the set point due to the error that is building in the PI controller. Once the production value reaches the target set point, the slower responding facility will meet its expected production values and the PI controller will rebalance the facilities so they have a proportional relationship while producing the target set point at the POI. This approach is likely to make the system response fluctuate near the deadband of the target value for a short time period after the set point has been achieved. This approach is likely to offer the fastest response of the options discussed in this paper, but with some instability during the initial transition.

Each of these solutions asks the system designer or implementer to prioritize the following system characteristics to make a solution selection:

- Overall response time
- Proportional response of generating facilities
- Smooth, stable system response

At the facilities discussed in this paper, the load tap changers (LTCs) and capacitor bank operations had built-in time delays after the controller had issued signals for the assets to operate. The wind parks also had different ramping capabilities. Because the rate at which these assets operated was significantly slower than the rate at which the controller executed new set points from the PI algorithm, it built additional error, asking for additional reactive power from the wind parks. After the LTC or capacitor banks finally operated, they may have exceeded the voltage limits on the turbines and caused the wind parks to trip offline. The solution for these facilities was to take the first discussed approach and reduce the execution rate of the PI controller to accommodate the speed of the slowest performing asset in the system.

IV. Lessons Learned

A. Simulation

During the testing and commissioning of this system, it became apparent that having a simulator that represented the modeled response of each facility would provide significant benefits to the project. During the commissioning of the MPPC, the responses from the wind parks did not meet the expectations of the engineers designing and implementing the control system. These responses required changes in the programming of the MPPC, causing delays in testing and commissioning the MPPC. If a simulator that modeled the responses of the generation facilities had been available, some of the testing and design changes could have occurred before onsite work began. Future projects will consider simulations to be included in contract agreements for wind generation facilities.

B. Operator Manuals

A detailed operation manual of the operator screen for the MPPC is an important part of the project that can be easily overlooked. After the commissioning and testing of the plant controller is complete, the personnel that did that work typically turn the facilities over to an operations group that may have varying levels of experience with the control system during development and commissioning. Often, the operation group will have operators switch between power plants. As new staff come on board, they need to have the ability to operate the facility. While significant effort is made to make the HMI intuitive and user-friendly, it is important for the operators to have confidence when a set point or mode change is issued, which means they need to know exactly what will happen. Having a very detailed operation manual, which details each mode and set point with screen shots, expected responses, and order of operation information, provides operators with confidence and familiarity with the system, which may or may not be similar to other facilities in the system. This makes it easier for operators to switch managing different power plants.

C. Data Recording

Many regulations from FERC, the North American Electric Reliability Corporation (NERC), and other regulatory bodies mandate data recording for a number of operational points. This recording typically needs to occur at POIs and represents the aggregate generation output. Typically, these data are collected through a data concentrator, passed to supervisory control and data acquisition (SCADA), and then recorded at SCADA. However, there are significant advantages to recording significantly more data than just the regulatory requirements. There are four major logical levels in this control system:

1. SCADA
2. MPPC
3. Generation facility controller
4. Individual inverter assets

Data logging set points and responses at each logical level is extremely beneficial. For example, during the project, there was an issue with ramp rates from one of the generation facilities. Examining data logs comparing the set points from the MPPC to the generation facility and the responses from the generation facility showed that the MPPC issued set points according to the ramp rate for the POI but the individual generation facility did not respond with the expected ramp rate. This resulted in a response at the POI that did not meet operational requirements. Having this level of logged data allowed the engineers to accurately diagnose the issue and contact the manufacturer to help implement a solution in the generation facility.

Logging all the data necessary for detailed troubleshooting at SCADA is often not practical since the amount of data passed between connections may exceed device capabilities or overwhelm some data recording systems. It can be beneficial to create detailed logs at either the MPPC or the generation facility controller. This may require collecting files from multiple locations, but with accurate time-stamping, the benefits outweigh the collection or configuration work during troubleshooting.

D. Switching Between Manual and Closed-Loop Controls

The control system offers the ability for individual facilities to be placed in manual modes in which the operator issues direct set points to the facilities, bypassing the MPPC. Since the MPPC uses a closed-loop control algorithm to account for losses in the system, the MPPC continuously takes the differential between the set point and current metered value at the POI. The controller continuously asks for more or less power over time to meet the set point requirements according to the differential measured between the current production value and the set point. If the plant controller's set points are not being sent to the generation facilities, the controller needs to be told to reset the control algorithm when control of the system is returned to the MPPC or is not executed when the manual control is active. If the closed-loop algorithms are not reset, set points that have significant amounts of error built in are passed to the facilities, often causing undesired responses.

E. Integration Challenges

As with most projects, interoperability between different manufacturer equipment and data communication can be a hurdle to getting application logic the appropriate information to operate correctly. In this particular project, the turbines from both wind parks were from the same manufacturer but used different firmware revisions. Some noted differences between the firmware versions included the following:

- The versions included different registers for application values.
- One version did not report gross MW and MVAR metered values from the facility.
- One version did not always report the correct operation state of individual turbines.
- Both versions had different diagnostics.
- Turbines had a regulator setting that allowed power production from the turbines, but this setting was managed only by the manufacturer. Several times during the project, turbines would not be available due to this regulator setting, requiring the wind park manufacturer to turn the individual turbines back on.

Working through integration challenges can be time-consuming and contribute to project delays. Having good documentation from manufacturers helps reduce this effort. In cases where documentation is not available, having good contacts at manufacturers with knowledgeable subject matter experts helps work through these issues. Of course, having consistent status and data mapping between firmware versions reduces time spent on integration challenges. Identifying the proper contacts at each manufacturer, prior to starting testing or commissioning, to work through integration issues and understand expected response times reduces time spent when issues are encountered on site.

F. Power Factor Limits

The three generation facilities in this system all have significantly different capabilities for providing reactive power and operational limits for power factor limits at the individual connection of the generating facility to the transmission line. These limits are not always the same as the power factor limits of the POI where the transmission line connected to the rest of the system. The control system had to restrict reactive power set points at each facility to maintain power factor compliance at each facility and at the transmission line POI.

V. Conclusion

The main benefit of implementing an MPPC to integrate several inverter-based generation facilities at their intertie to the rest of the grid was to manage the voltage at the POI. The MPPC was successful at improving the voltage conditions at the POI. This paper discussed some of the unique challenges that these generation facilities faced due to geography, but many of the lessons learned are applicable to all projects where a controller is installed to manage multiple generation facilities. Future projects will take these lessons learned into greater consideration at the time of request for proposal.

VI. References

[1] U.S. Federal Energy Regulatory Commission, "Order No. 827: Reactive Power Requirements for Non-Synchronous Generation," June 16, 2016. Available: ferc.gov.

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[4] *Programming Reference*. Available: selinc.com.

VII. Biographies

Andy Guibert (Andre Guibert de Bruet) is a specialist consultant at DTE Electric with 20 years of experience in power systems and supervisory control and data acquisition (SCADA). Having held both engineering and operations roles, his areas of focus are renewable energy, distributed generation, and distributed energy resource (DER) management. His knowledge continues to be an asset for DTE's Electric System Operations Center, and his aggregation and cybersecurity research has been included in publications on the U.S. Department of Energy's Office of Scientific and Technical Information and energy.gov websites.

Brian Waldron is a senior automation engineer with Schweitzer Engineering Laboratories, Inc. (SEL). He has over a decade of experience in designing and troubleshooting automation systems and communications networks. He has authored several technical papers, application guides, and teaching presentations focusing on integrating automation products. Brian graduated from Gonzaga University with a BS degree in electrical engineering.

Lee Garrison received his Bachelor of Science degree in electrical engineering from Oakland University in Auburn Hills, Michigan, in 2007 and a Master of Science in electrical engineering from the University of Idaho in 2014. He has over 15 years of experience in power system engineering, including protection, system fault studies, design, field testing, and project management for utility and industrial customers. He also has technical training in substation components and safety, relay programming and testing, and substation commissioning. He joined SEL Engineering Services, Inc. (SEL ES) in Plymouth, Michigan, in 2008 as an associate engineer. He is a licensed professional engineer in the states of Michigan, Indiana, and Wisconsin.

Sabitha Raman is an automation engineer with Schweitzer Engineering Laboratories, Inc. (SEL). She received her BE degree in electronics and instrumentation from Anna University in Chennai, India, in 2011 and an MS degree in electrical engineering from Wayne State University in 2019. She has over nine years of experience in automation system design, development, and commissioning for the oil and gas and renewable energy industries.

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