Voltage Master Control System for Wind Farms

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Abstract

This paper describes the Power Plant Controller (Voltage Master Control Systems) installed in a new wind farm commissioned during fall 2015. Renewable Energy power plants such as Wind and Solar farms are subject to utility grid code compliance especially in regards to voltage control. This control is done by either generating or absorbing reactive power (VAR) at the Point of Connection (POC). This could mean installing complex and costly STATCOM (Static synchronous Compensator), Static VAR Compensators (SVC) and/or mechanically switched loads like capacitor banks and/or shunt reactors. Furthermore, some installations also have energy storage systems that could benefit integration with a unified control system.

Some energy production sources rely on electronic inverters to convert asynchronous or DC generators to synchronous AC. By default, those inverters can act as reactive power generators to either supply or absorb VAR. The installed PPC measures the active and reactive power generation at the point of connection and use the wind turbines inverters to perform voltage regulation. The PPC also controls the installed mechanically switched loads.

To meet the stringent system performance requirements, the PPC uses a Phasor Measurement Unit (PMU) to precisely acquire the voltages and currents at the point of connection and calculate synchrophasor quantities. The substation automation controller receives those IEEE C37.118 phasor frames 120 times per second, twice the network frequency, and calculates the required compensation based on proportional-integral-differential (PID) loops. The VAR set point calculated by the PPC is communicated to the wind turbines inverters via the turbine power management system. The extra reactive power that exceeds the wind turbines inverters production capacity can be obtained with the integration of low-cost MSR and MSC in the farm.

The PPC is supplied with a local human-machine-interface (HMI) with animated graphics that displays the status of the regulation system. It also provides a means to set the PPC regulation strategy in voltage, VAR, or Power Factor regulation. The PPC integrates a communication interface to exchange data with the wind farm and Utility SCADA systems using either MODBUS, DNP3, IEC60870 or IEC61850 protocols.

To guarantee its maximum availability, the PPC hardware is fully redundant (hot standby configuration) allowing the equipment to be serviced while in live operation.

The system will be tested with the TSO during spring 2016 to demonstrate that it can contribute to the control of the voltage at the Point of Connection (POC), in a dynamic, continue and reliable way, as required by the grid code.

Introduction

The Plant Power Controller (PPC) enables a power producer (like a wind farm operator) to meet the Transmission System Operator’s (TSO) grid code requirements by regulating the voltage on the network. This regulation is based on measurements of electrical quantities at the Point of Connection to the grid (POC).

Based on those values, power quantities are calculated (P, Q, S, or real power, reactive power and apparent power, respectively) and sent to the regulator.

The PPC supports three modes of regulation, selected according to the TSO requirements:

- Pure voltage control: This is done by comparing the positive sequence voltage at POC to a set point.
• Reactive power control: This is done by comparing the reactive power calculations (VARs) to a set point.
• Power factor control: This is done by comparing the calculated power factor at POC to a set point.

Voltage Regulation = Reactive Power Control

Resistive loads (lighting, heating, etc.) consume real power (or active power), or watts on a power system. Therefore, the energy producer has to provide customers with active power generated from any energy source (hydro, fossil fuel, nuclear, solar, wind, etc.).

In the case where it is desired to use electricity for mechanical work, we use “motors”, which are devices that use a magnetic field to convert the real power (watts) into true mechanical energy. To produce magnetic fields, we must provide inductive power (where the current is phase-shifted by 90 degrees with respect to the voltage). Because of this phase shift, vector multiplication “current” x “voltage” is equal to zero which means that power is not real, therefore are not watts. Since this amount is not real, we call it reactive power (volt-amperes reactive, or VAR).

At the energy producer level, that reactive power (as well as the one required by other devices such as neon lamps, transformers, conductors, etc.) must be generated in addition to the active power required by its customers. The vector sum of watts and VARs produces the “volt-amperes” or “VA”, also called apparent power. The following diagram shows these values (using multipliers kW, kVAR and kVA).

![Figure 1: Relationship Active, Reactive and Apparent Power](image)

It should be noted from figure 1 that the amplitude of the vector S1 (apparent power VA) is greater than the required power P (in W). Since the producer must provide the power “S1”, this correlates to providing more current. More current is supplied and distributed which means the thermal and ohm losses in the cables are higher. For a constant output voltage, the voltage at the point of use will therefore depend on the current flowing in the cables.

The good news is that the amount of current can be decreased by reducing the apparent power Q. This concept is illustrated below where the reactive power is decreased from Q1 to Q2.
The consequence of reducing the reactive power to $Q_2$ is the decrease of the apparent power from $S_1$ to $S_2$. Assuming that we could reduce the reactive power $Q$ to zero, the apparent power ($S$) would be equal to the active power ($P$), which would be the optimal condition that eliminates all the losses.

Since the apparent power ($S$) determines the magnitude of the current, eliminating the reactive power $Q$ would also result in the lowest possible current flow and the minimum losses in the power system. Therefore, regulating the voltage to a constant magnitude at the POC will also result in a higher and constant voltage at the point of use. As a first conclusion, when managing reactive power at the POC of a power plant, it also controls and regulates the voltage on the grid.

**Traditional Control of Reactive Power**

Reactive power can be inductive (as shown in the previous section) or capacitive. In the latter case, the vector is in opposition to the inductive power as shown in the following figure:

Since power calculation is a sum of vectors, capacitive power will actually compensate, or subtract, “inductive” reactive power.

The reactive power supplied by a wind power plant will therefore be combined with the reactive power already present on the network, and contribute to increase or decrease the later.

Moreover, as mentioned previously, reactive power helps to “regulate” the voltage on the network. This regulation is done by managing production or absorbing reactive power (VAR) in addition to the active power (watts) produced.

Traditionally, specialized power equipment such as Static synchronous Compensator (STATCOM) or Static VAR Compensator (SVC) were installed on the site of the wind power plant to enable the
producer to meet the requirements (normally called “grid code”) of the transmission system operator (TSO). However, the cost of such equipment is not negligible at up to 50,000 US$ per MVAR [1] and even 300,000 US$ per MVAR for STATCOM solutions.

Also because of grid code requirements in some installations, MSR and MSC mechanically switched reactive devices are used to supplement the functions of the SVC or STATCOM.

**Voltage master controller**

It should be noted that some wind generation technologies use an inverter to convert the raw power produced by a wind turbine (asynchronous AC) into an alternating synchronous current which is then collected on a medium voltage (MV) network distributed over the wind farm area to the main substation and eventually connected to the grid.

This is the case of type-3 wind turbine generators, also called “Double Fed Induction Generator” (DFIG) or “Double Fed Asynchronous Generator” (DFAG) and type-4 wind turbine generator “Full Converter Unit” [2].

![Figure 4: Type-3 DFAG and type 4 (full converter) wind turbine generator](image)

The same type of architecture can be found in photovoltaic power plants where, in this case, the source of power is direct current (DC) elements [3]. However, the conversion to grid synchronous AC is done by the same kind of power electronic devices called inverter.

![Figure 5: Typical photovoltaic generator](image)

By design, a four-quadrant inverter is able to generate positive or negative reactive power in addition to the active power and therefore produces or absorbs VAR.

The voltage controller is designed to be installed in a wind (or solar) farm where the power source is able to produce or absorb reactive power in addition to the real power. It may also be associated with one or more mechanically switched reactive elements, such as capacitor banks or shunt inductors.
The next figure shows a typical installation such as the 74 MW Mont-Rohtery wind farm, commissioned in 2015 in Quebec (Canada). This site uses 37 type-3 DFAG wind turbine generators.

In the above figure, the wind farm POC is a 161 kV HV transmission line where the electrical quantities are measured using a Phasor Measurement Unit (PMU). The PMU acquires a three-phase voltage (Vpoc) and three-phase current (Ipoc), extract and filters the nominal power signal to calculates its frequency, the rate of change of frequency (ROCOF) and the positive sequence voltage and current. Those measurements are then sent 120 times per second (twice the network frequency) to the Substation Automation Controller (RightWON Plus) using the C37.118 synchrophasor communication protocol.

The controller carries out the regulating algorithm (the details are explained later) then sends its set point to the Turbine Power Management Unit (seen in the previous figure). This power management unit distributes and directs instructions to individual wind turbines to meet the required generation or absorption of reactive power.

The controller also controls the circuit breakers associated with the MSC and MSR. In order to confirm the switching of these loads, the medium voltage feeder current is also measured by the PMU.
Hardware architecture

The voltage controller is a system built out of two fully redundant sets of the following equipment:

- Phasor Measurement Unit (PMU), which measures the voltage and current at the POC
- Substation Automation Controller, which performs the voltage regulation function based on the selected strategy
- Digital/Analog converter to communicate the reactive power production set point to the plant power management unit
- Local HMI built from a touch screen embedded PC
- Communication subsystem made of an Ethernet Switch (behind panel)

As mentioned before, the output from the master voltage control is sent to the wind turbine power management system. Even though the controller supports many energy communication protocols, such as MODBUS, DNP3, IEC60870, IEC61850 and its variant for wind energy, IEC 61400-25, a 4–20 mA current loop (representing the required reactive power set point) was used in this project.

The figure 8 shows the connections between these devices.
Both equipment run independently and in parallel for all operations (hot stand-by redundancy). The selection of the output that will be directed to power the power management unit is made by a voting scheme between the two RightWON Plus units. This voting scheme is based on the health of major units (PMU to read the analog quantities, the Controller to process them and the D/A converter to send the output) and then of secondary quality indicators (the link integrity flag of the communication with SCADA, presence of an actively connected HMI, etc.).

Control Principle

As previously mentioned, the voltage master control supports three regulation strategies (see figure 9):

- Voltage control: This is done by comparing the positive sequence voltage at POC to a set point.
- Reactive power control: This is done by comparing the reactive power calculation, MVARs produced (+) or absorbed (-) to a set point.
- Power factor control: This is done by comparing the calculated power factor at POC to a set point.

There is only one active regulation strategy set according to the TSO requirements. It is also possible to dynamically change one regulation mode to another based on external conditions.
All the values in the previous diagram are expressed in per-units (PU), and all the electrical quantities are measured at the POC using the PMU.

The top section of the diagram is the voltage regulation loop based on the positive sequence (fundamental frequency symmetrical component) on which a droop control is done (see droop section below). The resulting quantity is subtracted from the set point and the error is directed to a proportional integral block ("PI" block).

The PI block uses two of the three methods supported by standard PID block (proportional-integral-differential). The error at the input is multiplied by a constant gain ("proportional" gain). The same error at the input is also integrated over time and the result is also multiplied by its own gain ("integral" gain). The sum of these two quantities is fed to the regulation mode switch.

The same principle is shown for the other two regulation modes (reactive power and power factor). While supported by the calculation algorithms, the droop is normally not used (set to 0) for those two modes.

The outputs of the 3 "PI" blocks are directed to a control switch mode, shown as a three-position switch. If the voltage controller operates in a reactive power regulation mode, the "PI" output of the bottom block (reactive power) is used and directed towards a limiter (to clamp the output and freeze the integrators).

Finally, if a mechanically switched load (inductor or capacitor) is installed, the voltage master control system will assess if it is in the circuit and if such is the case, the reactive power (positive or negative) is subtracted from this value before being sent to the wind turbine power management system.

Again because all calculations are done in per-units (PU), the output can be directly used (without scaling) as the required reactive power request of the wind turbine power management system.

**Explanation of the droop concept**

The wind farm is normally not the only source of reactive power in the transmission system network. To avoid having multiple sites racing to supply the reactive power requirements, each production site could be configured to supply proportional values of reactive power based on its production capacity.

The droop concept allows a PID regulation loop to include a precise amount of planned error when it reaches the steady state. As shown in Figure 9, the droop coefficient is applied to the measured reactive power and subtracted from the measured voltage at POC. This subtraction corresponds to the steady state error of the PID loop.
Another way to explain this is to say that in voltage control the droop value is the percentage of variation of the measured voltage at PCR from the set point that would require the installation to supply (or absorb) reactive power equal to the rated power of the site.

Even if the site nominal voltage was 161 kV, the average voltage was measured, over a long time, at 166 kV with excursions between 161 and 170 kV.

The figure below shows a typical example of a 166 kV average site, using a 5.8% droop value based on a 74 MW site capacity and with actual limits of reactive power generation of -31.6 MVAR and +38.3 MVAR.

In figure 10, the dashed blue line corresponds to the +/- 74 MW limit equal to 5.8% of difference from the nominal 166 kV voltage (156.4 kV is the +74 MW and 175.6 kV is the -74 MW). This is the “raw” droop curve.

The red line follows the blue line but its amplitude is limited to what the wind farm can actually supply. For example, from the graph we can see that if the POC voltage is 166 kV, no reactive power will be supplied nor absorbed. If the voltage at POC diminishes to 164 kV, the system will have to supply 15MVAR to contribute to sustaining the voltage. If the voltage at POC rises to 170 kV, the system will need to absorb 30MVARs.

**User Interface**

The voltage master control, quite like a protective relay, operates in an automatic way and does not require human intervention. If set point value changes are required, the normal interface is done
through the main power plant SCADA system. The VIZIMAX system supports all energy communication protocols, from MODBUS, DNP 3, IEC60870 to IEC 61,850 and its variant for wind power plants, IEC 61400-25.

Information sent from the voltage master control to the SCADA are status (local/remote mode, in/out of service, main circuit breaker position, mechanically switch load positions, etc.), alarms (health of equipment and communication links, MSL position vs load current discrepancy, etc.) and active values (kV, Amps, P, Q, S, power factor at POC, frequency, active set point values and regulation mode, etc.)

From the SCADA interface, the site operator can send the set point for the 3 regulation strategies (voltage, reactive power, power factor) and dynamically change the regulation mode.

Using the RightWON Plus native animated graphical web server, it is also possible to get information and even operate the system through the local HMI installed in the voltage master control panel.

The interface is through the RightWON Plus web server HMI on a simple embedded computer with tactile screen and running a web browser like Google Chrome.

Note: The nature of the web server also allows a concurrent access remotely through the TCP/IP communication infrastructure. This would be done through a distant PC, also running a web browser. Because both instances run from the same web server, they are both called “local operation”.

The first HMI screen shows the communication status of the two redundant systems (#1 being the master system by default and #2 the backup system). The active master system components are in green (the backup in gray). The communication links are shown in green when healthy and will flash red if a link is broken or down.

From top to bottom we see the SCADA communication gateway (labeled as SMP), communicating with the voltage master control system by DNP3 in this case. Then there is the touch-screen local interface (HMI) communicating by HTTP (web), and below the phasor measurement unit communicating by C37.118.

There is also an exchange communication link between the two controllers (RightWON Plus) and this link is monitored for its integrity.

Finally, at the bottom, we see the digital-to-analog converters with its 4-20 mA current loop output to the site power management system. A “toggle switch” shows which set of devices is the master that supplies the current loop output.

The HMI also supports detailed information screens when the user points (click) on either the PMU or the RightWON box.

The second HMI screen shows that regulation controller values (status page).
Figure 12 shows the active regulation mode (red target), the measurements at the point of connection (voltage, power factor, reactive power, real power, apparent power and current).

There are two sets of set points; one is the “remote” set, received from the SCADA and the “LOCAL” set that can be manually entered on the HMI. The indicator below shows which mode (remote or local) is currently active.

The right side shows the state of the mechanically switched loads. Both a capacitor bank (XC) or a shunt inductor (XL) can be configured and controlled by the system. The visual indicator shows if they are currently in service (connected to the MV bus) or if the circuit breaker is open. The MSL current is also displayed. In the picture above, no load is connected and the current is 0 amps.

The bottom area allows setting the operation mode of the system. The system is normally in the automatic mode, where the output of the PI regulation loop is sent to the site power management system. The system can also be operated in manual mode, where the user would directly set how much reactive power to absorb or supply at POC. The third mode puts the system offline.

Of course, before making any changes, authorized users must be authenticated and identified (via the green lock on title bar) through an access code without which no values can be modified.

The system allows historical data to be reviewed. For example, the figure below shows the actual real power production over a period of about 24 hours.
Added benefit of using a PMU for measurements

In the voltage master control, the voltage/current measurements at the point of connection is done by the VIZIMAX Phasor Measurement Unit (PMU). The main reason being to provide the regulation algorithm precise values at a rate of 120 frames per second; not normally found in a power meter that typically perform calculations 1 to 10 times per second. This allows the regulation system a much more responsive loop time.

While not specifically used in the voltage master control system, the main difference between a PMU and other measuring devices (power meter, energy meters, protective relays, etc.) is the fact that the output values (phasors) are time synchronized on a global level.

Phasors are a representation of sinusoidal data by their magnitude and angle [4]. Phasor angle needs a reference. In traditional meter or protective relays, the A-phase voltage is used as the reference. This is why the angle of the A-phase voltage is always zero. Then other phasors (voltage and current) are calculated with their phase angle difference from A-phase voltage. For example, B-phase voltage normal value would be -120 degrees because B-phase voltage is lagging 120 degrees.

In synchrophasor however, the reference is a time-absolute value, the “top of the second” of absolute UTC time. This means that wherever you are on the planet, this time reference is exactly the same. While this was extremely difficult to implement a few decades ago, some measurements were made as early as 1977 by a team from Hydro-Quebec [5]. This changed drastically with the advent of the global positioning system (GPS) allowing precise time references to be distributed at a reasonable cost.

While most people know GPS as a device installed in a car to help in directions, the GPS system is an array of satellites orbiting the earth that receive signals from base station atomic clock sources and transmit back the signal to the ground. However, the exact position of each satellite being known, with the assistance of advanced calculations, a GPS receiver can calculate its position on the earth (or above it) and reconstruct a global time reference, the time when the value of the second goes from 59 to 0. Best of all is the precision of such time reference, in the order of 1 µs to less than 100 ns.

A synchrophasor is then a phasor that uses this absolute time reference. The actual angle is the time between the “top of the second” and the measured signal positive peak value of the sine wave. The devices that process synchrophasors are called Phasor Measurement Units (PMU).

The IEEE has standardized PMU and test specification (C37.118) and now has a program to certify Phasor Measurement Units to ensure that they will interoperate and comply with strict performance. At this moment the VIZIMAX PMU is one of only two to receive IEEE certification. [6].

This universal synchronization method allows devices, installed far apart, to have a common reference for their measurements. The main benefits are the possibility to globally view a network and eventually operate algorithms on that synchronous data gathered everywhere.

This PMU based technology is called wide-area measurement systems (WAMS). This same principle can be applied to monitoring, control and/or protection objectives.

Aside from the PMU as the source of synchrophasor data, the other important device in the wide area system architecture is the phasor data concentrator (PDC). The PDC gathers in a database, synchrophasor data from multiple sources and allows the interrogation of the databases, either dynamic or post-mortem.

The voltage master control system does not use the primary feature of the synchrophasor; the “top of the second” time synchronized measurements. However, the data measured by the PMU can still be sent to a PDC for easy archival and post-mortem analysis. For this reason, the voltage master control can be supplied with an optional PDC that would serve as a high performance, long-term disturbance analyzer.

The site mentioned in this paper, the Mont-Rothery wind farm, use this feature. A PDC is installed on site to record all data from both PMUs. This allows analysis of any data at anytime since commissioning of the system.

Below are few examples of the PDC recorded values showing both active and reactive power at POC.
Figure 14 above shows the small variation of reactive power at the point of connection when the system switches over a redundant set of equipment. At the beginning of the trace, the equipment set #2 was the master system (because units #1 were voluntarily put offline).

Then the “normal” situation, where the equipment set #1 (the primary) retrieved its status as a master, the transition was done without disturbance and during a short period. This confirmed that the system was performing equipment switchover seamlessly without causing disturbances outside acceptable limits.

Figure 15 shows a typical 24-hour period with large wind fluctuations enabling generation of between 22% to nearly 100% of active power (blue trace) while the controller was set to maintain reactive power regulation to absorb 10 MVAR (-10 MVAR on the chart). This proved the quality of the regulation system that was tested during that period.
Figure 16 shows how the system reacts to step changes of voltage at the point of connection while configured to regulate based on the voltage. This was not recorded on the installed site but during a live test in the laboratory using a programmable test set. The top trace shows the induced positive sequence voltage at POC and the bottom trace shows the response, the reactive power at POC. The effect of both the proportional and integral parts of the PI regulation loop is clearly visible.

The next and final case shows how the installed system was used for “post-mortem” diagnostic.

Figure 17 was used while doing a diagnostic of the loss of communication between the SCADA and our devices a few times per week and always around 8:30 PM EST (PDC data is referenced to UTC, so around 1h30 AM). While we initially suspected a DNP3 driver problem in our devices (because
both of them recorded alarms around the same time), the problem was elsewhere entirely as we discuss below.

What is shown is the positive sequence voltage from the 3 monitored PMU. The bottom traces (relatively identical) are the data from both PMU in the voltage master control system (PMU #1 and #2) and the top trace was acquired from a protective relay on the HV side. The important thing to note is the absence data from the protective relay for about 25 seconds.

Because the all our equipment (PMU, RightWON Plus, and the PDC) are in the same network segment, logically separated from the SCADA and the other protective relays, we could assume that the problem was between both network segments. This led us to believe a problem with the substation router/gateway/firewall. Sharing this information with people responsible for information technology (IT) of the substation, they finally realized that the router was switching itself off to install new updates/firewall rules every other day at the same time. During that “short” period, all Ethernet traffic within the substation was halted. Of course, once the problem was identified, it was promptly corrected.

**Conclusion**

This project has proved that PMU can be successfully used in advance wind farm controllers. One of the benefits in the scope of this project is the availability of accurate measurements in a very short period of time. Usually, transducers that provide such measurements have a 0.5 second time lag. We have also found that many other functions can be realized as shown in figure 18. In this project, we have developed Volt/VAR control loop and Power/Frequency that can also easily be implemented. To improve VAR compensation, it is also possible to switch manually controllable loads such as reactors or capacitors.

In a near future, anticipated frequency control will be implemented to help support power system inertia. Frequency control in islanding mode is also possible. New protective functions, such as reverse power flow or wind farm instability detection, can also be implemented.

![Diagram of Power Plant Controller Functions](image-url)

**Figure 18: Power Plant Controller Functions**
Figure 19 shows a proposed architecture for Advanced Wind Farm Controller. The PPC communicates directly with the wind farm SCADA, the wind turbine controller, the Battery storage system and possibly the STATCOM to adjust their voltage and power set points. Moreover, it controls the operation of breakers to connect/disconnect capacitors or reactors.

**Figure 19: Power Plant Controller Architecture**

**References**


About the authors

Marc Lacroix is VP Business development at Vizimax. Marc Lacroix worked for more than 32 years for Hydro-Quebec. He received his BSEE and his Master’s degree in Engineering from Polytechnique Montreal, the Engineering School of the University of Montréal. During his career, he has developed a unique expertise related to automation technologies applied to Transmission and Distribution. He was responsible for designing and implementing Special Protection Systems and automation systems used in substations and power plants. During his last assignment at Hydro-Quebec, he was responsible for the smartgrid deployment and for Cybersecurity governance.

Marc Lacroix was involved as Project director in many control centers projects around the world. He has also been active on IEEE standard committees for more than 20 years. He is a member of IEC TC95 and TC57 WG 10, 15 and 17 and is also active in the new IEC SmartEnergy, SyC committee.

Michel Mont-Briant is Project Manager at Vizimax. He received his B.ing. from Sherbrooke University in 1984, he is a registered engineer in the province of Québec, and had been working for Snemo Ltd since 1981 as R&D manager, then R&D director and finally General Manager. Snemo Ltd R&D was involved in designing, testing and protective relays, automation platform and control systems for power utilities, including the flagship products “CBSC” and “SynchroTeq” circuit breaker controlled switching devices. Michel Mont-Briant owns a Canadian patent on a device for controlling VHV or UHV circuit breaker.

Since the merger of Snemo Ltd and STR into Vizimax Inc, Michel is mostly involved in special project management.

Francis Chartrand is Manager Electrical, SCADA and telecom at EDF EN Canada. He received his B.ing. from École de technologie supérieure in 2006 and his Master Engineering degree from Polytechnique Montreal in 2013.

Francis joined EDF EN Canada in July 2010. His role consist of managing all electrical matter related to the renewable energy projects, including the interconnection of the projects to the electrical grid, the electrical system design, the SCADA and telecom design and the energization of the project. He acquired a unique expertise, after completing successfully the interconnection of over 1 GW of wind energy in Canada. Francis also contributes his knowledge and expertise for the development of new renewable energy projects.