Grid Connection of Renewable Generation
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This paper discusses technologies such as S&C’s DSTATCOM® Distributed Static Compensator which have been successfully applied to allow renewable generation meet the reactive power requirements of the local grid code, and also support installations connected to a weak grid. The paper also considers the role that large-scale energy storage and Community Energy Storage have in reducing the intermittency of renewable generation and in increasing the profitability of renewable generation in the local supply and ancillary service market.

Power Factor Control is Essential

Many different grid codes are in effect around the world. They vary according to the requirements of the local grid operators and the condition of the grid. Grid codes typically require that wind power plants control the power factor to meet system operating conditions.

Although modern wind turbine generators (WTGs) can dynamically control power factor or voltage at the terminals of the generator, not all turbines have this capability. In such instances, the S&C PureWave DSTATCOM Distributed Static Compensator is often applied. This device utilizes voltage source inverter technology, and employs pulse-width modulation to synthesize the necessary voltage—either greater than or less than the bus voltage at the point at which the PureWave DSTATCOM is connected.

In instances in which the WTGs can dynamically control power factor or voltage at the terminals of the generator, they can be applied such that any additional requirements are provided by the PureWave DSTATCOM.

Hybrid Reactive Power Compensators are Ideal

A substation-based hybrid reactive power compensator solution—comprised of a PureWave DSTATCOM and a switched shunt device(s)—is one of the most cost-effective means for dynamically controlling power factor at the Point Of Connection (POC). Its response time is dictated by the intentional delays associated with switching of Switched Shunt Devices (SSDs). Through local collector bus voltage and current sensing, and “slow” feedback of voltage and current at the POC through SCADA, the PureWave DSTATCOM can dynamically control power factor at the POC using a line-drop compensation algorithm.

Figure 1 shows the actual measurements associated with a hybrid reactive power compensator applied at a 90-MW wind power plant, where the POC is at 345 kV, 37 km away from the collector substation. In this case, the compensator is controlling the power factor at the POC at unity (i.e., zero net MVAR at the POC).

A hybrid reactive power compensator offers several advantages over mechanically switched power factor correction capacitors applied at the WTG low-voltage terminals:

- The power factor of the wind power plant can be dynamically controlled without changing the power factor set points of individual WTGs, thus increasing the overall speed of response.
- The power factor at the WTG terminals can be independently controlled at or near unity power factor, thus minimizing reactive current flow through the WTG step-up transformers and the collector system. This effectively reduces active and reactive power losses in the wind power plant.
- A wind farm management system is not required to control reactive power in the wind power plant.
- The available reactive power from the compensator can be utilized to compensate for collector cable charging (capacitive) reactive power at zero, low power output, or to provide reactive power.

A hybrid reactive power compensator also provides a number of advantages over mechanically switched capacitor banks applied without a compensator at the collector substation:

- The power factor at the POC can be controlled more precisely over the entire output range of the wind power plant.
- The dynamic reactive power range of the inverters substantially reduces the number of capacitor bank switch-
ing operations, thus increasing the life of the capacitor bank switching devices.

- The PureWave DSTATCOM control algorithm distributes the switching duty among the capacitor banks, resulting in more even wear on the switching devices and prolonged capacitor life in multi-bank applications.
- The severity of the switching transients associated with the energization of the capacitor banks is reduced by the inverter control action.

As in any situation in which shunt capacitor banks are applied, the application of a hybrid reactive power compensator must include a review of potential harmonic resonance conditions. This is particularly true where the wind farm is connected to a grid with low available fault current. The review typically includes a detailed harmonic resonance analysis, including impedance frequency scans for various operating conditions of the wind power plant, and a harmonic distortion analysis based on representative “ambient” harmonic levels (i.e., harmonics present in the system without the wind power plant) or harmonic currents injected by WTGs.

In cases wherein the WTGs are furnished with power factor correction capacitors, careful attention must also be paid to potential resonance conditions caused by these capacitors. If resonance conditions with high local impedances are identified at characteristic harmonic frequencies (e.g., 5th, 7th, 11th, 13th, etc.), the capacitor banks of the hybrid reactive compensation solution can be converted to harmonic filter banks. A damped C-type filter is commonly used to lower the local impedance of the wind power plant over a wide range of frequencies.

In wind power plants utilizing doubly-fed induction WTGs or full-converter WTGs with appreciable levels of harmonic current injection, a high-pass filter must sometimes be applied to prevent some of the harmonic currents from flowing into the system, which can cause high levels of harmonic voltage and current distortion. If a hybrid reactive power compensator is applied in this situation, one or more of the capacitor banks can be converted to high-pass filters to address this issue.

The PureWave DSTATCOM has a short-term capability of 264%, allowing it to compensate for the longer reactive power requirements of some turbines, as well as supplement any shortfall in the low-voltage ride-through capability of the turbines. The hybrid reactive power compensator can be set up such that the WTGs operate as the “master” and the PureWave DSTATCOM as the “slave,” thus providing a very economical solution.

In the UK, wind power plants are increasingly being connected to networks with low available fault level. In such instances, voltage fluctuations between maximum generation and no generation are quite high. A substation-based solution can handle this situation and maintains voltage within statutory limits. Figure 2 illustrates how a PureWave DSTATCOM provides voltage control for a single 850-kW turbine.

![Figure 2. Voltage control on a weak grid.](image)

**Electronic Shock Absorber**

Hawaiian Electric Company (HECO)—unlike electric utilities on the U.S. mainland—has a standalone transmission system that is not connected to other utility grids. That makes HECO particularly susceptible to the problems of utilities having a high percentage of wind generation. Such problems can be especially pronounced at night, when customer load can drop to very low levels and winds can vary significantly.

S&C designed and built an Electronic Shock Absorber for HECO that allows them to accept more power generated by the wind. This device is essentially a PureWave DSTATCOM with the addition of energy storage. When the wind gusts and the wind plant produces too much power, the Electronic Shock Absorber stores the excess power in ultracapacitors. When the wind drops off and the wind plant produces too little power, the Electronic Shock Absorber discharges power from the ultracapacitors into the output of the wind plant.

The graphs in Figure 3 illustrate Electronic Shock Absorber performance against performance parameters set by HECO as part of local Power Purchase Agreements.
The “ESA Power” graph shows how the Electric Shock Absorber compensates for variations in the parameters it monitors. In this example, the average power does not go outside of its limits, so the Electronic Shock Absorber does not need to react to compensate. The “Ramp Rate” graph reaches its lower limit and the ESA compensates for this by injecting energy into the system, most noticeably around the 70-second point. The “Instantaneous” graph shows that power hits its upper limit at 90 seconds; the Electronic Shock Absorber absorbed energy at that point.

The ESA can also provide voltage and/or power factor control, as well as assist with low-voltage ride-through requirements.

Distributed Generation

As more distributed generation is introduced closer to the load, the ability to dispatch this energy has become highly desirable. Typically, a 100-MW wind farm will only average 30 to 40 MW, resulting in a network utilization of only 30% to 40%.

The Economic Research Council—Britain’s oldest economic think tank—has noted that because wind-generated electricity is often produced at night, when demand is low, the energy tends to be lost, and that a mechanism is needed to balance or store the energy to meet demand when needed. The UK Department of Trade and Industry, further, has pointed out that 6 to 10 hours of energy storage can increase dispatch reliability up to 95%, and that—depending on the power purchase agreement—could increase revenue 2% to 35%, or more. Additional work in the UK has shown that 1 MW of energy storage could be used to remove 3 MW of transmission and distribution capacity constraint.

S&C has the ability to integrate multiple energy storage technologies. Most have utilized NaS batteries for energy storage, with a PureWave DSTATCOM applied for power conditioning. The PureWave DSTATCOM provides voltage and power factor control as well as assists with low-voltage ride-through—with the added benefit of controlling the power fed into the utility system.

The first Smart Grid SMS™ Storage Management System, which S&C installed for American Electric Power in Charleston, West Virginia, has the ability to provide 7 MWh of storage. It is charged at night and used to shave peak demand during the day. It could also be used to improve dispatch reliability if it was connected and charged by a renewable energy source. The system has deferred the need for costly asset upgrades. Its modularity allows it to be relocated wherever it is needed on the AEP system.

Several other systems are now connected on the AEP system, including projects connected to renewable energy sources.

A recently published report by Xcel Energy, covering the use of NaS batteries in wind farm applications, concludes that energy storage not only has the ability to move peaks but can also provide economic dispatch, frequency control, wind leveling, and smoothing.

Figure 3. Performance of Electronic Shock Absorber.
NGK has demonstrated NaS technology for load smoothing at a wind farm on the Tokyo Electric Power System, on Hachijo-Jima Island. Here the NaS battery is used in a constant state of charge and discharge to provide a smooth output from the wind farm, as shown in Figure 4.

**Figure 4. NaS battery applied for smoothing wind farm output.**

**Community Energy Storage**

To date, distributed energy storage projects have been implemented primarily to address the disruptive effects of large-scale renewable generation upon the grid. Distributed energy storage makes low-/no-carbon renewable generation more predictable and allows this generation to be stored and dispatched when needed.

The interest in small-scale renewable generation by consumers has created a demand for Community Energy Storage. Through its close proximity to the small-scale renewable generation, Community Energy Storage can address issues such as demand management, Volt/VAR optimization, power quality, etc. S&C is currently involved with Community Energy Storage projects that can provide 25 kW peak for up to 2 hours. Community Energy Storage can be integrated into a utility Smart Grid program to allow consumers to sell their excess renewable energy, with the added benefits of deferring capital investment by the utility and improving network reliability.

**Conclusion**

The European Union’s twin objectives of sourcing 20% of its energy requirements from renewable sources by 2020, and reducing CO₂ emissions 80% by 2050 will result in renewable energy connections being made in areas where the grid has a low available fault level, creating the need for dynamic voltage control. S&C’s PureWave DSTATCOM technology has been successfully used in such applications for many years, and will continue to be used even with advancements in turbine technology.

The use of large-scale energy storage, such as provided by S&C’s Smart Grid SMS™ Storage Management System will continue to increase as the economics make it more viable. And the application of Community Energy Storage will also increase to help shift peaks and smooth the impact of consumer-furnished intermittent renewable generation.