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VAR Support from Distributed Wind Energy Resources

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Abstract

As the size and quantity of wind farms and other distributed generation facilities increase, especially in relation to local grids, the importance of a reactive power compensator or VAR support from these facilities becomes more significant. Poorly done, it can result in cycling or inadequate VAR support, and the local grid could experience excessive voltage regulation and, ultimately, instability. Improved wind turbine and distributed generation power control technologies are creating VAR support capabilities that can be used to enhance the voltage regulation and stability of local grids. Locating VAR support near the point of consumption, reducing step size, and making the control active all improve the performance of the grid. This paper presents and discusses alternatives for improving the integration of VAR support from distributed generation facilities such as wind farms. We also examine the relative effectiveness of distributed VAR support on the local grid and how it can be integrated with the VAR support of the grid operator.

KEY WORDS—Energy storage, reactive power compensator, static VAR compensator, VAR support, harmonics, voltage regulation, wind turbine, wind farm, synchronous generator, induction generator, power system, distributed generation, renewable energy

1. Introduction

The Tehachapi, California, wind resource area is one of the best in the country, and started to develop early, with substantial "wind farm" distributed power generation facilities on a weak 66 KV grid. As wind power generation in the area continues to expand, reactive power compensation, or VAR support, will be required, along with energy storage to maximize grid utilization. In the early days of wind farm development, operators were required to compensate each wind turbine with the reactive power needed when the turbine was operating at no load (no wind). Today, most of the wind turbines in the area are induction generator (constant frequency) machines; thus, they require reactive power to be supplied separately. Therefore, it is necessary to provide reactive power locally, as close as possible to the actual demand.

An induction generator also requires an increasing amount of reactive power as the amount of generated power increases. Without proper compensation, the voltage at the point of injection of power into the grid will vary along with variations in wind speed, ultimately resulting in voltage collapse if not adequately compensated. Thus, a reactive power compensator is an important element of wind power generation.

This paper explores the use of compensating reactive power [1,2,6] for wind farms, using Tehachapi 66 KV grid installations as examples. Both fixed and adjustable compensation are examined to maintain the voltage as close to acceptable limits as possible. A combination of reactive power compensation and energy storage could also be used [3]; however, one must balance the cost against the realizable benefits. Although wind speeds are quite diverse at the Tehachapi wind farms, in this paper we consider only a hypothetical "worst-case" situation in which all the wind farms generate the same amount of power. A more detailed discussion of simulations of wind farm aggregation is found in Muljadi, Butterfield, and Gevorgian [4].

Here, we explore reactive power compensation at both central and distributed locations. Section 2 describes the Tehachapi wind farm layout. Section 3 discusses the methods and assumptions of the load flow analysis. Section 4 investigates the role of reactive power and Section 5 presents the conclusions. The Power System Simulation for Engineers (PSS/E) program from Shaw Power Technologies Inc. was used in this study.

2. The Tehachapi Wind Farms

There are four major groups of wind farms in the Tehachapi area. The power plants are modeled as regular generators and real and reactive power varies with wind speed. The four groups generate 345 MW (nameplate) collectively, variable with wind speed, and each wind farm consists of many turbines. The output of each wind farm is characterized by the P-Q (real-reactive) relationship measured at the point of common coupling (i.e., the interconnection point of the wind farm), based on actual data. They are grouped as follows: WINDFARMS, WINDPARKS, WINDLANDS and BREEZE. Here, WINDFARMS and WINDPARKS represent the names of groups of wind farms.

The WINDFARMS group generates the most power: 192 MW at maximum (nameplate) rating. This group has six subgroups: Dutchwind, Flowind, Canwind, Enwind, Varwind, and Arbwind. Each subgroup contains wind farms except Varwind, which has 14.4 MVAR SVC switched capacitors. The other three groups are similarly arranged, but smaller. Only major groups of wind farms are represented.

The layout is shown in the line diagram in Figure 1. The sub-transmission network shown includes only main paths. Minor connections are not shown. Most of the power from the wind farms is channeled through CalCement and Monolith. These two substations are the cornerstones for the evaluation in this project.

3. Load Flow Analysis

Twenty-four wind farms and three conventional generators are modeled. The wind farms are connected to the sub-transmission network. Bus 1, Antelope Substation, 40 km from CalCement is the gateway to a much larger network outside the area and is treated as an infinite bus. Each wind farm has the following characteristics:

1. The worst-case scenario is simulated and computed by load flow analysis. The diverse wind speeds in the Tehachapi area are not simulated.
2. The P-Q electrical characteristic of individual wind farms are represented.
3. Real output power is stepped from 30% up to 100%, and voltage at important busses is plotted against output power.

Each wind farm is assumed to be a generator producing the same percentage of rated electrical output power. The corresponding reactive power is found from the P-Q characteristic of that wind farm.

The P-Q characteristic is derived from measured data collected over time to represent a wind farm's MW output and MVAR demand net of VARs installed at the wind farm. The P-Q characteristic is modeled from measured data using polynomial equations and represents the required reactive power Q for a given real power output P. The collective output real power for one wind farm is used to find its corresponding reactive power requirement. The P-Q characteristic thus changes each time new turbines or new reactive power compensations are added to a wind farm. A typical P-Q characteristic is shown in Figure 2. See [6] for old to new wind turbine VAR changes.

4. Reactive Power Compensation

A reactive power compensator may be implemented by using a fixed capacitor or a switched capacitor (see Figures 3,4). In this study, both fixed capacitors and switched capacitors are evaluated to compensate the reactive power in the wind farms. At the CalCement substation, 18 MVAR compensation is installed. Other buses in the area are compensated to a total 77.3 MVAR. The total load (including surrounding small towns) is about 259 MW and 46.4 MVAR. Kern River and Bailey generate 24 MW and 20 MW, respectively. For a wind farm power system, IEC Standard 61 400-21 states that 10-minute average of voltage fluctuation should be within $\pm$ 5% of its nominal value [5].

The power network within the Tehachapi wind farms is relatively stiff between substations in the area, but the area is relatively weak in connection to the rest of the transmission/sub-transmission system with 560 MVA Short Circuit Duty at CalCement. A reactive power compensator was installed at the Monolith substation (Bus 24). The voltage magnitude at the CalCement and Monolith is very close at high generation, indicating no major voltage drop between the two busses.

A. Compensation at Monolith Substation

In this simulation, real and reactive power from the wind farms passes through two major buses: CalCement and Monolith; other power is dispersed through surrounding loads. The line between Bus 22 and Bus 1 is heavily loaded by the real power the wind farms generate and the reactive power the wind farms needs. This creates a major bottleneck between the CalCement and Antelope substations. Antelope is treated as an infinite bus representing the network outside the area; only the main path is shown on the graph. The path must pass a large amount of real and reactive power at high wind speeds.

The voltage at CalCement, Monolith, and Oakwind is shown in Figure 3. The voltage dip goes as low as 0.85 p.u. when power is generated at a high wind speed. When compensation added at Monolith is fixed at 45 MVAR, the resulting voltage varies from over-voltage above 1.05 p.u. at a low wind speed to under-voltage below 0.95 p.u. at a high wind speed. Induction generators, the most common ones in this area, require a large amount of reactive power from separate sources when operating at rated power. At low wind speeds, the reactive power needed is low. Thus, we can conclude that fixed compensation at Monolith is not suitable for the varying needs of this area.

B. 45-MVAR Switched Capacitor Installed at Monolith

In this case, 45 MVAR switched capacitor is installed. Three steps of 15 MVAR are switchable, depending on the voltage at Monolith. The control dead zone of the switch-control is within a 4% tolerance band (0.98-1.02 p.u.); above 1.02 p.u., switch off one step of capacitor; below 0.98 p.u., switch in one step of capacitor compensation.

Figure 4 shows significant improvement in the lower power region; there is no over-voltage during low power generation. However, during higher power generation, although all of the reactive power compensation available (all 45 MVAR) at Monolith has been switched in, there is still a need for additional reactive power compensation for the voltage to be within the acceptable tolerance band (0.95 p.u. to 1.05 p.u.).

C. Compensation at Each Wind Farm

Here we compare the impact of compensation at each wind farm in comparison to the studied reactive power compensation at a central location. With this concept, the entire wind farm generation region can be controlled so that voltage is in the acceptable range (0.95-1.05 p.u.). Using the same operating conditions as in the other simulations, we increase the internal reactive compensation of each wind farm to modify the resulting PQ characteristic of each one. The advantage is that the reactive power is provided locally and thus does not have to travel a long distance to where it is needed. Another advantage is that each wind farm provides a greater portion of its reactive power compensation, which allows better control over voltage regulation at each wind farm.

The control strategy or time constant for local compensation should be different from that of the main reactive power compensation for the Monolith substation. The main compensation at that substation is controlled to keep the voltage at the bus constant. Reactive power compensation at each individual wind farm is controlled based on the level of real power generated by each wind farm, with voltage limits. Thus, there is no conflict in the control objective, and the stability of the control system is assured.

Added local compensation was chosen to reduce the required VARs from the grid by one-third. At each wind turbine, capacitors are switched in and out depending on the level of real power generation. Figure 5 shows that the voltage characteristic is within the acceptable range. The level of VAR support provided internally from new wind farms is generally greater than evaluated here, and may be beneficial for harmonics considerations within the grid as well as for better grid stability. Further evaluation of such VAR support is warranted, but beyond the scope of this paper. For additional information see [6,7].

5. Conclusions

The original installations of reactive power compensation at the Tehachapi wind farms were not sufficient to regulate the voltage in the area from substation provided VARs. Initially, it was decided that the size of the reactive power placed at each wind turbine should be equal to the reactive power required at no load. With added fixed capacitor compensation of 45 MVAR at Monolith substation, the voltage at major buses shows an over-voltage at low power generation levels and an under-voltage at higher power generation levels. This indicates that there is overcompensation at low wind speeds and a need for greater reactive power compensation at higher wind speeds.

After the fixed capacitor is replaced by switched capacitors of 3x15-MVAR, the overcompensation at low power generation disappears. At higher power generation, available reactive power is not sufficient and low voltage results. Finally, 33% added local compensation at each wind farm reduces the required reactive power from the grid, and the voltage characteristic becomes acceptable in all ranges of generation. There may be an opportunity for further effective utilization of wind farm VARs to improve the grid.

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References

1. Miller, T.J.E., ed., *Reactive Power Control in Electric Systems*, New York: John Wiley & Sons, 1982.
2. Mathur, R.M., ed., *Static Compensators for Reactive Power Control*, Winnipeg, Manitoba, Canada: Cantext Publications, 1984.
3. Muljadi, E.; C.P. Butterfield; R. Yinger; and H. Romanowitz, "Energy Storage and Reactive Power Compensator in a Large Wind Farm," presented at the 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 5-8, 2004.
4. Muljadi, E.; C.P. Butterfield; and V. Gevorgian,"The Impact of the Output Power Fluctuation of a Wind Farm on a Power Grid," Conference Record, Third International Workshop on Transmission Networks for Offshore Wind Farms, Royal Institute of Technology, Stockholm, Sweden, April 11-12, 2002.
5. IEC Standard 61 400-21, Measurement and Assessment of Power Quality of Grid Connected Wind Turbines.
6. Ackermann, T., ed, *Wind Power in Power Systems*, John Wiley & Sons, 2004
7. Federal Energy Regulatory Commission, *Order 2003-A*, 2004

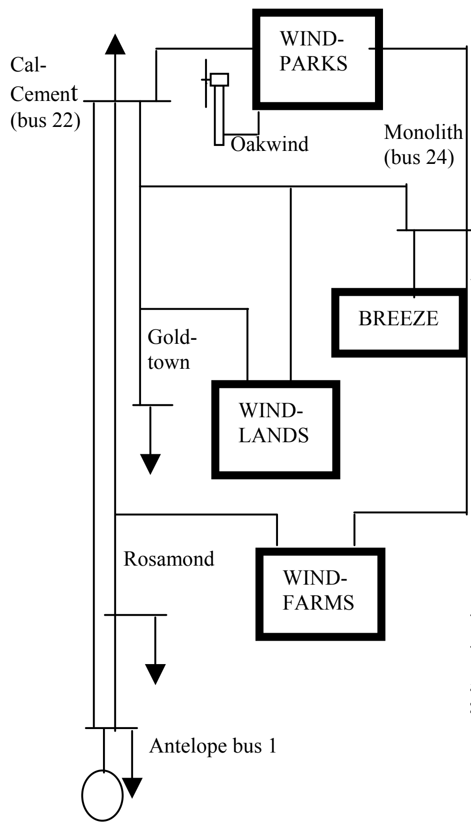

Figure 1. Single line diagram of major distribution network.

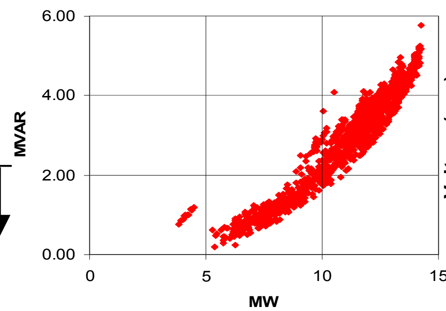

Figure 2. A typical PQ characteristic of a wind farm.

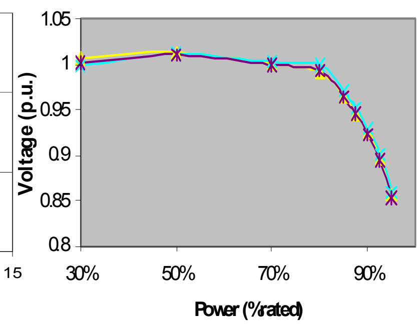

Figure 4. Voltage characteristic of a wind farm after three step switch capacitors are installed at Monolith substation.

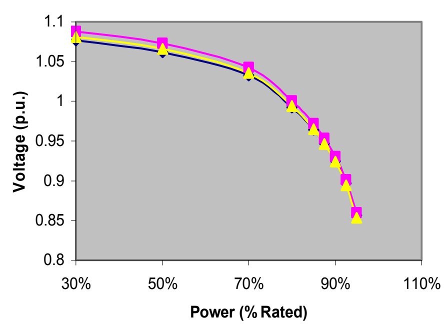

Figure 3. Voltage at busses for a fixed compensation.

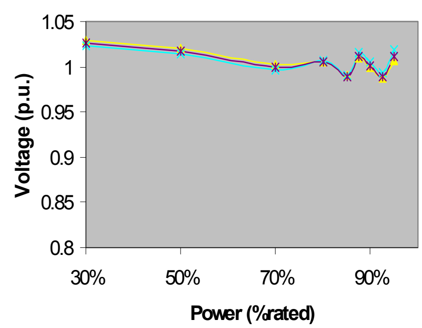

Figure 5. Voltage-power characteristic after local compensations are added at each wind farm.

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