Hybrid Wind and Advanced Gas Turbine Farms: Firm Dispatchable Power for Weak Grids

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Abstract - **The variability of power generation from wind farms presents an operational challenge for power systems with significant penetration of wind generation. In weak or relatively small systems, control of system frequency and power exchange can impact the viability of wind farms. The emergence of highly maneuverable, high efficiency simple-cycle gas turbines allows for hybrid wind/gas turbine systems with superior dynamic performance.**

Index Terms - Wind Generation, Hybrid Systems

I. INTRODUCTION

Under certain circumstances, the successful integration of wind generation into a power system will require the ability to dispatch, or control, power output. This is most likely in small, relatively weak systems, or systems with significant penetration of wind generation. However, even systems with moderate levels of penetration can have operational challenges that are physically and/or temporally localized.

The concept of 'firming' wind power by balancing it against other controllable resources (generation, storage, controllable loads) is not new. However, the enabling technology for fast, flexible, economic, modular deployment has been lacking. The challenging requirements placed on the alternative power source include the following:

- High maneuverability
- High efficiency, even at partial load
- Fast starting
- Low initial capital costs (consistent with moderate to low capacity factors)
- Good environmental characteristics

GE's new LMS100™* simple-cycle gas turbine (GT) has all of these characteristics, making a high performance hybrid wind-GT system now possible.

This paper presents a concept, as well as a realistic example of a wind-GT hybrid, that meets performance and economic requirements for successful integration of wind generation into relatively weak power systems.

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II. CONCEPT OVERVIEW AND PHILOSOPHY

A. Power System Requirements

Secure and reliable operation of power systems requires that system frequency, system voltage and power exchange (tie-line flow) with neighboring systems be maintained within acceptable limits. Power systems rely on the ability to control various transmission system elements and generation to meet these performance requirements.

The voltage control issues normally associated with wind generation are largely resolved with modern wind farm control systems [1], and will not be further addressed in this paper.

Variation in frequency and tie-line flow is driven by variations in system load and generation from non-dispatchable resources. In the shortest time frame of variation, from tens of cycles to several seconds, frequency control is normally provided by fast autonomous control of individual turbine-generators (e.g., governor control). Over a slightly slower time frame, centralized area generation control (AGC) directs selected generators to adjust output to satisfy both frequency and tie-line objectives. Generation options for AGC are typically maneuverable hydro and steam plants, and occasionally gas turbines.

Additional control functions act in still longer time frames. For example, load following occurs in the range of ones to tens of minutes, and unit dispatch and commitment occurs from hours to days ahead.

B. Wind Farm Characteristics

Wind farms have variable output due to continuously changing wind speed. This variation in output contributes to deviations in frequency and tie-line flow. While emerging technologies have some degree of control over these variations, there are limits since wind cannot be turned on. Annual capacity factors for economic farms range from around 30% to approaching 50%.

The variability of power output from wind farms is a function of wind behavior and spatial diversity. Statistical distributions of wind variability have been widely examined. A recent National Renewable Energy Laboratory (NREL) report [2] closely examines the variability of actual operating farms. The results reported there are quite extensive, but for the purpose of this paper they can be distilled into the rough approximations presented in TABLE 1.

TABLE 1. TYPICAL WIND FARM POWER VARIABILITY

Control Requirement	Time Frame of Variation	Approximate Standard Deviation, σ (% of Wind Plant Rating)
Regulation (AGC)	1 second	0.2 %
Load Following	1 minute	1 %
Dispatch and Commitment	1 hour	10 %

The size of the wind farm relative to the system load and other generating resources (i.e., penetration) is the primary determinant of the operational impact of wind generation on the host system. There are periods during which wind power from a specific resource will be zero. In systems with a multiplicity of wind plants, the statistical value of wind generation for capacity is non-zero. For small systems (with high granularity), however, the system must have alternative generation with sufficient capacity to at least meet critical loads, if not total peak load.

C. Advanced Gas Turbine Characteristics

Small gas-turbines derived from aircraft engines, so-called aero-derivative turbines, are compact, modular, and cyclable.

The latest generation of aero-derivative GTs are bigger than the aero-derivatives that have achieved wide acceptance in the industry. These machines have better heat rates and are cleaner, especially at partial load, than is typical of their smaller predecessors. They are still highly maneuverable.

The example in this paper is based on GE's new LMS100™ simple-cycle GT, with a nominal rating of 100MW. The maximum power output of this GT varies with configuration and ambient conditions. A key feature of this machine, however, is high efficiency over a wide range of power output. Fig. 1 shows the efficiency curve for the GT. Note that it has a higher partial-power efficiency than most GTs have at rated power. These machines are designed to achieve a very low level of emissions: 25ppm NOx (better with optional SCR) and 85dBA at 3 feet (or better).

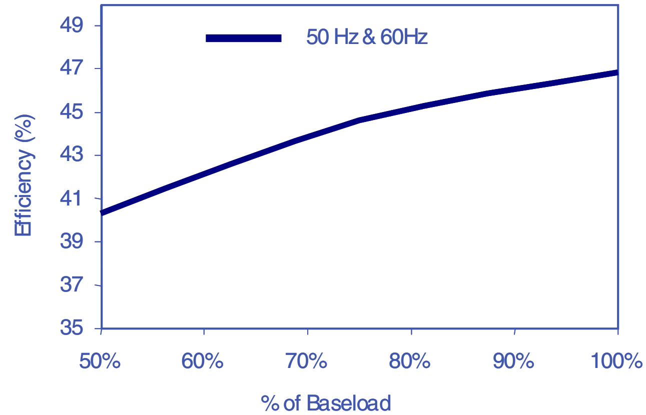

Fig. 1 Gas Turbine Efficiency

III. EXAMPLE SYSTEM

A. Base System Representation

Fig. 2 shows a simple representation of the test system. The system topology is representative of the type of system for which a hybrid system may be attractive. Specifically, the system is relatively small, with approximately 2300MW of installed generation, and spread over a significant geographic area. Load and generation reside mostly in a few clusters, interconnected by the bulk transmission grid. All generation in this system is fossil thermal, with a mix of steam and gas turbines. This particular system also has a smaller remote subsystem connected by relatively long, and essentially radial, transmission lines.

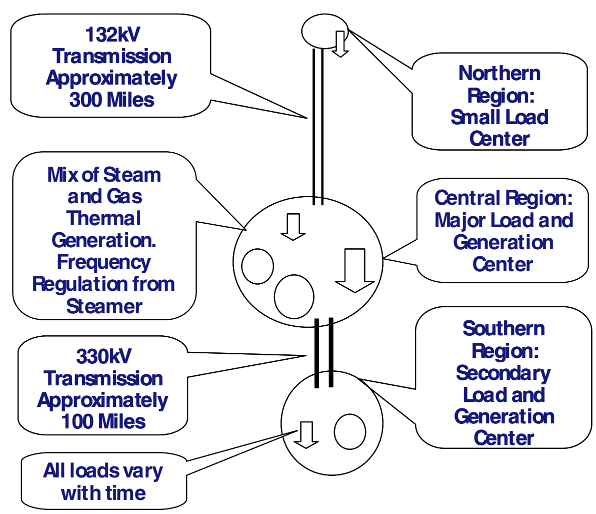

Fig. 2 Base System

The system exhibits seasonal and diurnal variations. For the example, a near minimum load condition is examined, with a corresponding limited generating unit commitment. AGC is provided through control of one of the large steam plants in the central load/generation region. The loads are represented by four distinct aggregates (arrows in the figure), each of which exhibits typical load variability (based on system measurements). All loads and generators are represented with full dynamic representations of typical modern equipment, including exciters and governors. The loads are modeled with voltage sensitivity.

B. Hybrid System Representation

The northern region of this system has good wind resources as well as access to natural gas. Fig. 3 shows the system with a wind farm and a gas turbine added. Both the wind farm and gas turbine, which need not be at exactly the same site, are shown connected by moderately short (about 20 miles) dedicated radial transmission lines. The dotted line encloses the wind farm, the gas turbine and the regional load center. The hybrid farm control (HFC), discussed in the following section, provides an integrated supervisory control for this regional subsystem.

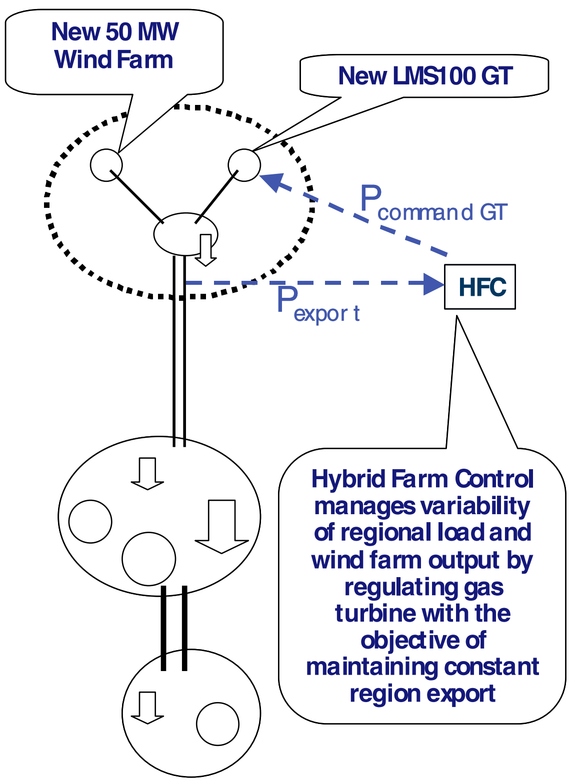

Fig. 3 Hybrid System

C. Hybrid Farm Control Concept

The HFC in Fig. 3, is structured to provide a coordinated control of the wind farm and the gas turbine to achieve a set of grid friendly performance objectives. In the example provided here, the performance objective is to maintain constant power output from this regional subsystem. A range of other control objectives are possible, including all variations on dispatchability consistent with the reliable and economic operation of a power plant embedded into a bulk power system.

The HFC incorporates measurements from, and control signals to, the constituents of the system. The signals most important to this example, measured power export from the subsystem and power command to the GT, are shown in the figure as dashed arrows. Other signals are not shown, including regional voltage control, consisting of measured voltage at the regional substation and reactive power commands to the wind farm.

IV. DYNAMIC PERFORMANCE

A. Simulation Overview

The performance test presented in this section is for a sequence of three comparable ten-minute simulations. The three cases are shown in each of the subsequent figures, with each case represented by a specific line texture. The three cases are:

- Base (dotted line)
  - no wind farm or new GT
  - load varies
- Wind (dot-dash line)
  - wind farm only
  - wind speed and load varies
- Hybrid Farm Control (solid line)
  - wind farm, GT and HFC
  - wind speed and load varies

In all cases, each regional load varies with time according to different individual profiles based upon field measurements.

In the two cases with wind generation, the wind farm power output varies with wind speed. Again, this data is based upon field measurements.

B. Generation Behavior

Fig. 4 shows the active power output of four key generating resources in the example.

The upper left plot actually includes two traces, one on top of the other, for the wind farm power output. This variability is representative of a farm experiencing substantial wind volatility.

The lower left plot shows GT power output for the hybrid case – the only one that included the GT.

In the upper right plot, the power output of the large steam plant is shown. In each case, the output varies because of the combined effects of the unit governor and the AGC.

The lower right plot shows another unit in the southern system. Its variability is due only to governor action.

In the base case (dotted line), the power output of the central steam unit is highest. The output variation is solely due to response to load variation.

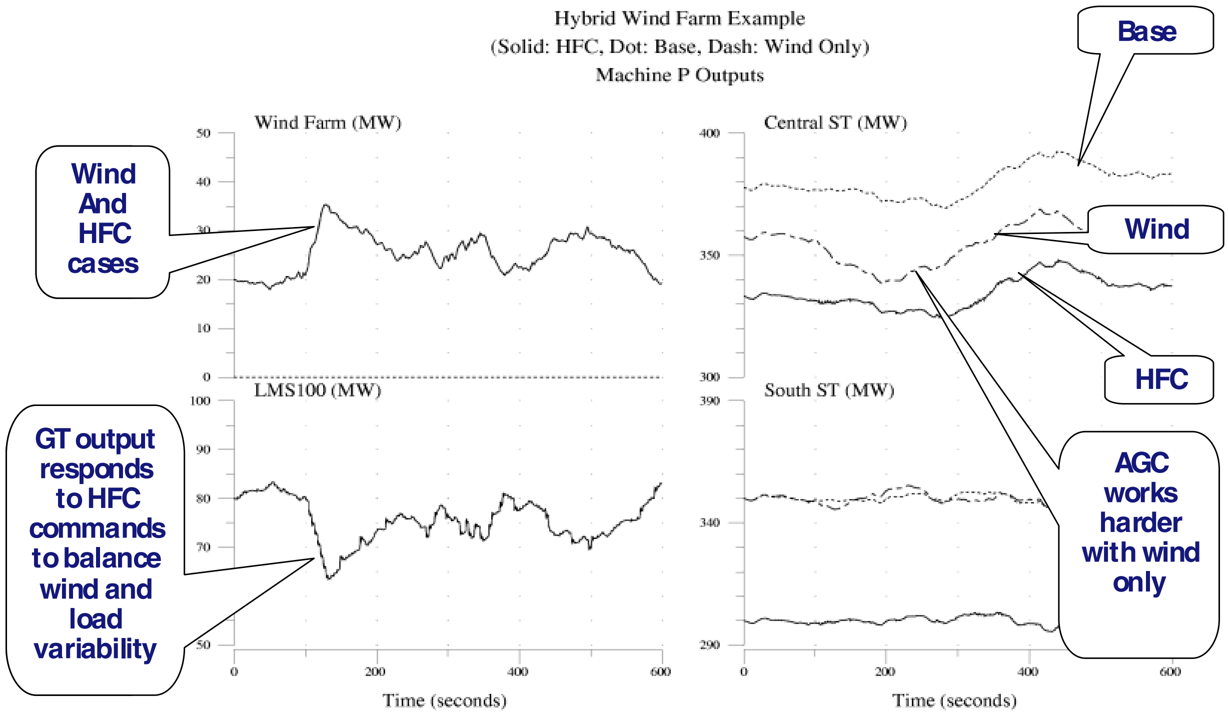

Fig. 4 Generator Response

In the wind only case (dot-dash line), the central steam unit output is reduced by the amount of power from the wind farm and varies a great deal more than in the base case. This variation represents a cost penalty in terms of wear and tear on the steam unit. It also indicates that the maximum rate of change for such a unit can dictate both the level of wind penetration and unit commitment strategy. At high levels of wind generation, without the capabilities of a hybrid system, the steam unit will ultimately encounter operational limits.

In the hybrid case (solid line), the central steam unit output is reduced by about half of the power from the combined wind/GT system while the southern steam unit is reduced by the other half. This redispatch is performed to match total system load and generation. The central steam unit's variability is comparable to that of the base system, whose variability was only due to the load. Thus, the hybrid farm eliminates incremental regulation burden on the existing system.

C. Tie Flow Behavior

Fig. 5 shows the power export from the hybrid farm (HF) region (top plot) as well as the flow from the southern to central regions of the example system.

In the base case (dotted line), the HF region imports approximately 25MW to serve its load. Power flow from the south to the central region is approximately 200MW. Variations in both flows are due only to the 10-minute load profile.

In the wind only case (dot-dash line), the HF region export varies with the wind. The south-central flow is still nominally around 200MW but the variability is increased.

In the hybrid case (solid line), the HF region serves its own load (about 25MW) and exports a firm 75MW to the rest of the system. The south-central flow is reduced by about half the total hybrid farm output as part of the redispatch to accommodate the hybrid system output.

D. AGC and Load Behavior

Fig. 6 shows the AGC's area control error (ACE) in the top plot and total system load in the bottom plot. The total load is the same across all three simulations, so the traces are directly on top of each other and look like one.

ACE in the wind only case (dot-dash line) exhibits greater variability than that observed in the base case (dotted line). ACE in the hybrid case (solid line) is comparable to that in the base case.

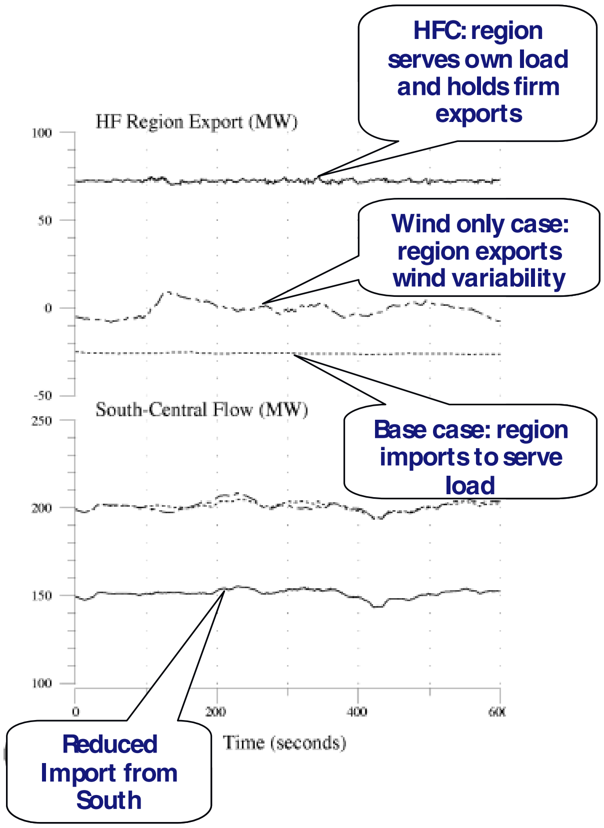

Fig. 5. Intertie Flow

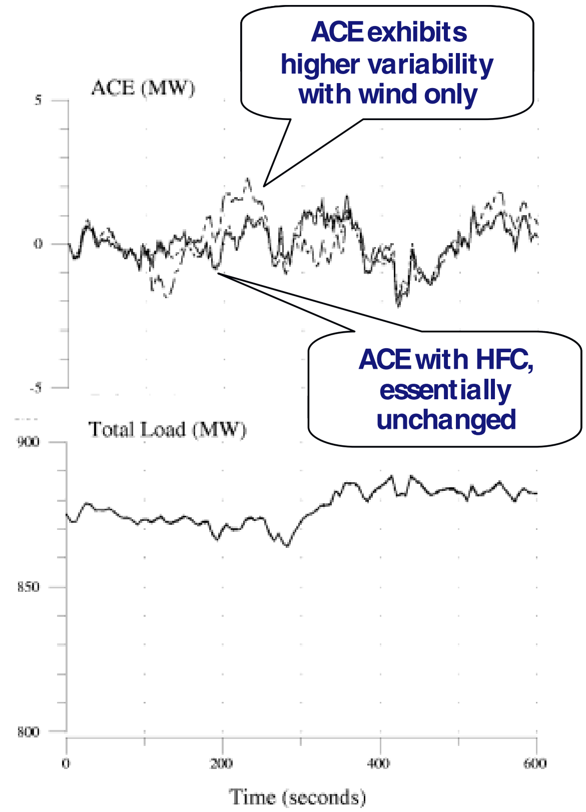

Fig. 6. Load and ACE Response

V. CONCLUSIONS

Hybrid systems of modern wind farms and the latest generation of advanced gas turbines present a viable solution to many of the problems associated with high penetration of wind generation.

In this paper, a concept and illustration for a hybrid solution that can provide firm and constant power is shown. The hybrid system illustrated provides system performance benefits by eliminating incremental regulation duty on existing generation and improving voltage regulation and reliability in the vicinity of the farm.

From an operations perspective, challenges associated with wind variability and wind forecast errors are eliminated, allowing seamless integration of a hybrid farm in regional power system markets.

VI. REFERENCES

[1] Miller, Nicholas W., Einar V. Larsen, Jason M. MacDowell; "Advanced Control of Wind Turbine-Generators to Improve Power System Dynamic Performance," IEEE International Conference on Harmonics and Quality of Power, September, 2004.

[2] Yih-huei Wan, Demy Bucaneg; "Short-term Power Fluctuation of Large Wind Power Plants," NREL report NREL/CP-500-30747, January 2002