Coordination Of Conventional System, Wind Energy Storage System And Hybrid System For A 40-Megawatt Wind Farm For Operation WITH The Electrical Power Grid[1]

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1.0 MOTIVATION

There are two important factors that relate to attaching Wind Farm power to the electric utility grid:

(1) SWITCHING ALLEVIATION BENEFIT: Power system simulation modules include algorithms for the analysis of Power Flow, Fault Analysis, Harmonic Analysis, Stability Analysis, as well as Transient analysis. The electrical power grid is composed of interacting networks that use complicated Network Control Theory and also huge switches. Note that a 5-fold change in wind speed leads to a $5^3 = 125$-fold change in delivered electric power. Since the wind power delivers these large variations in power over short time intervals, the switching is troublesome. In this area our concept offers a strong advantage by smoothing out the power variations.

(2) PEAK POWER TRANSMISSION BENEFIT: The use of the power grid line capacity is important in planning. Thus if it is expected that there will be a specified peak power to be delivered for a small percent of the time, the power grid capacity is not being used effectively. In this area our concept offers a strong advantage by delivering a higher power to the grid than a Wind Farm without storage tanks.

The objective of the proposed system is to combine three different wind turbine systems to deliver power to the electrical power grid at two or three constant power levels per day, where one of the constant power levels can persist for 10 to 20 hours per day. It is better to switch two or three times per day than hundreds of times per day.

2.0 TECHNICAL APPROACH

The following three sets of wind turbine systems comprise the Wind Farm:

(1) Conventional wind turbine system that supplies electric power directly to the grid (mode 1),

(2) Wind turbine system that converts wind power into stored pneumatic energy for supplying electric power to the grid at selected times (mode 2), and

(3) Hybrid wind turbine system that switches partially among modes 1 and 2.

Based on the forthcoming day's wind speed predictions, the three wind turbine systems combine their outputs to supply constant power to the electrical grid for long periods during the day.

The example design presented herein uses:

- Site Data for Wind Turbine Performance: Berlin Germany site: 14.545°C, 70-meters altitude, 100.4864-kPa and 1.217 kg/m^3 air density.
- Wind Distribution Data: k = 2.31 Weibull shape parameter, 5.8476 m/s mean wind speed, 6.6 Weibull scale parameter, 50 m height, Roughness length 0.055m and wind class 1.5.

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[1] Patent Pending. The information in this report is the subject of multiple United States and Foreign patent applications.

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- Wind Turbine Data: Nordex N50/800, 800 kW, 3 m/s cut-in wind speed, 25 m/s cut out wind speed, 50 m rotor diameter and 50 m hub height
- Wind Histories for Wind Farm Site: 1996, Kansas Site, Kansas Wind Power LLC

- Wind Turbines 49 N50/800 Wind Turbines
    - 24 Standard Wind Turbine Systems @ 800 kW each
    - 19 Hybrid Wind Turbine Systems @ 800 kW each
    - 6 Dedicated Storage Tank Feed Wind Turbines @ 800 kW each
- 62 Storage Tanks: Each @ 60 feet long, 10 feet diameter and rated at 600-psig

3.0 LIMITING ASSUMPTIONS

The wind turbine swept area is able to extract 32.5% of the available wind power.

The 85% efficient compressors supply 3.25 SCFM per hp of compressed air to the tank, and the 85% efficient turboexpander requires the use of 8 SCFM/hp of compressed air the turboexpander to deliver its electrical power. By using small time increments (3-minutes) we add and remove small but noticeable masses of air from the tank. This portion of the process is linear so that we only need to be assured that we do not take such large gulps that we dump all the air in the tank in one step of the calculation.

The heat transfer process inside the tank is non-linear. Therefore, to assure that we credibly follow the actual exchange of heat between the air and the solid masses inside the tank, we need to advance the solution in small 3-minute steps to approximate the non-linear behavior.

The dynamics of the heat exchange is one of the issues that require the construction of a Demonstrator Model that accurately represents the heat flow from the outer annulus of the anti-freeze in the copper tubing, through the copper tubing walls, and into the air; and the heat transfer from the inner surface of the tank wall. It is vital that the Demonstrator Model be of sufficient scale to assure accuracy.

The dynamic performance of the compressor and the turboexpander needs to be confirmed even though their steady state operation is well established.

These factors need to be determined accurately in order to consider attempting to gain further efficiencies by using higher than 600-psig storage pressures wherein these heat transfer efficiencies are increased. The key to the successful system operation is the dependence on the performance of the thermal inertia effects.

The analyzed system is fully defined using off-the-shelf hardware. The computer program describing the performance uses exact energy balances and reasonable approximations to the dynamics of the heat transfer process. It is necessary to build a Demonstration Model.

The turboexpander is a two-stage system. Currently, we are using the final two-stage output of extremely cold air for air conditioning a community in a hot climate that needs air conditioning.

The use of 600-psig tank peak pressure permitted the use of commercially, off-the-shelf hardware to be selected for each of the components. This included a selection of compressors and turboexpanders that could process large volumetric flows. There was little difficulty in getting timely bids to assemble the proposed system. Unfortunately, delivery of the compressor and turboexpander/generator may take more than 90 days.

The compressor needs to be 4-stage and the turboexpander needs to be 2-stage.
In the conventional CAES plants it is necessary to burn fuel to drive the compressors and to burn fuel to heat the air entering the turboexpander, whereas in the proposed system we are using thermal inertia of the steel storage tank, copper tubing, copper tubing support frame and antifreeze to assure efficient temperatures at the turboexpander inlet.

In the proposed energy storage system we are using 1,200-psig in the storage tank and a pilot controlled regulator to feed the turboexpander a preset 600-psig at its intake. As the storage tank decays in pressure, the regulator maintains a constant feed pressure to the turboexpander.

In the AEC 100-MW CAES plant, the high-pressure combustors operate at 625-psia. The multiple combustors burn either natural gas or No.2 fuel oil and provide inlet temperatures of 1,000°F to the high-pressure turboexpander and 1,600°F to the low-pressure turboexpander. This process uses 4,133 BTU of fuel consumption per 0.79 kW-Hr of off-peak electrical energy generation.

In the Huntorf 290-MW plant, the source pressure is 1,100-psia. The corresponding temperatures feeding the turboexpander are 1,022°F and 1,652°F. At 290-MW the specific fuel consumption is 4,300 kJ (fuel) / kW-Hr (electrical).

Approximately 1 kW-Hr of generated electricity requires 0.75 kW-Hr of compression Energy and 4,200 kJ of fuel. Fuel needs to be burnt to compress air and to meet the higher temperature requirements at the turboexpander inlet.
Consider the air in our storage tank wherein we expand from 600-psia and 70°F to 14.67-psia. For an isentropic process of no heat exchange the final temperature would be –279.7°F. An expansion process that is 82.05% efficient will result in –215.28°F. These source temperatures would not only be ineffective for blowdown wind tunnels but would also be ineffective for inlet conditions to a turboexpander.

The proposed concept increases the surface area within the storage tank by adding internal pipes, and it adds heat capacity by adding antifreeze inside the pipes. There is 3% of the cross section of each tank filled with copper tubing (1.125-inch outside diameter and 1.025-inch inside diameter). Thus a typical tank contains 411 tubes filled with anti-freeze.

Thus the example design uses compression energy obtained from the wind turbines, and uses the thermal inertia of the storage tank contents to sustain isothermal flow to the inlet of the turboexpander. It is important to note that the tank not only increases pressure but also temperature during its compression. The thermal inertia is able to absorb the temperature increase and surrender this temperature energy to the compressed air outflow.

4.0 OPERATIONAL SEQUENCE

2.1 WIND HISTORY SELECTION

The wind histogram for a site, say, in Kansas is the first chart to be considered. The wind histories include the hourly wind speeds for the month of November in 1996. Three different types of days were selected to show how the smoothing operation works on days that had strong wind speed variations. These are the days that need the stored energy tanks. The actual wind histogram is plotted against a Weibull function histogram with a mean speed of 9.5 m/sec and k=2.5. The lower cut-off limit speed is 3 m/sec, and the design wind speed is13 m/sec.

Figure 1 shows six wind histories during the first week in November 1996 at a site in Kansas. The detailed hourly wind histories of November 1, 5 and 6 were selected because they included a low wind speed day, a high wind speed day, and a period where there was a very low wind speed.

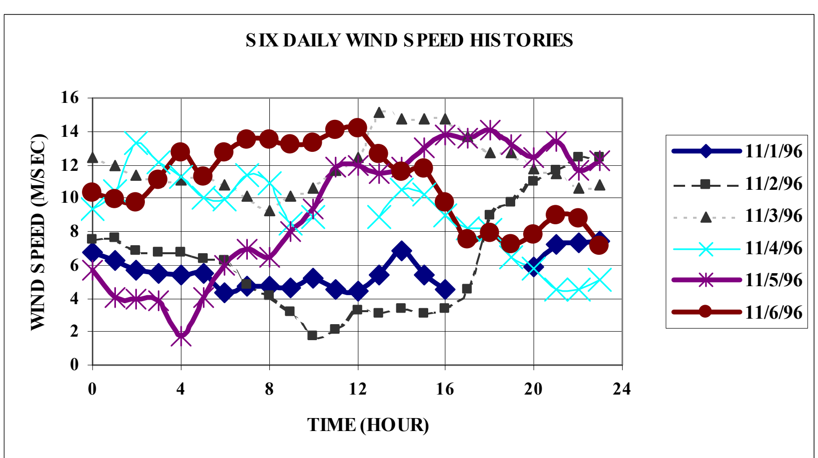


Figure 1. Six Consecutive Days of Wind Speed Histories

It is clear that if the daily wind history has little variation from hour to hour, no storage tanks are needed to smooth the electric power developed from the wind turbines even though a 10% variation in wind speed leads to a 30% variation in wind power. At the other extreme, when there is a stronger variation in wind speed, the greater the number of tanks required to smooth the electric power input to the grid.

2.2 WIND TURBINE SELECTION

We selected a Nordex N50/800 wind turbine system. It has a 50-meter diameter blade, a 50-meter tower height and a swept area of 1,964 square meters. It cuts on at 3 m/sec and has a design wind speed of 14 m/sec. This size was selected because the power is large enough to comprise the 100 to 1,000 MW Wind Farms, but small enough to still be transported by truck and rail.

In the previous design described in our AWEA 2003 and EWAEA 2003 technical papers we were dealing with <4 MW applications associated with farmers and small town users remote from the electric power grid. In the current design we are dealing with 40 and 400 MW applications associated with towns and cities attached to the grid. There are no new factors that are considered between the old (<4 MW) and this new 40 MW design.

We have three design considerations to determine how we split the incoming wind energy between current user and storage:

- Peak pressure in the storage tanks never shall exceed 600- to 800-psig
- Minimum pressure in the storage tanks never fall below 100-psig
- The final tank pressure at the end of the day must be larger than the initial tank pressure at the beginning of the day

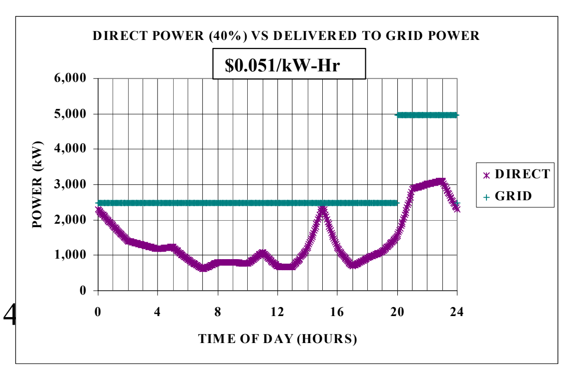
More recently we have used 1,200-psig tanks that supplies a constant 600-psig source to the turboexpander intake.

The hybrid systems appear in the case of large Wind Farms. After accumulating the calculations for the power split between current users and stored usage for a multitude of daily scenarios, a table of results is prepared. The smallest percentage of each current user is selected, and the smallest percentage of stored system is selected. The remaining percentage is apportioned completely to the hybrid system.

This apportionment process is not different for the old and new setups. In both cases of new (<4 MW) and old (>40 MW) systems, the apportionment is controlled by steadily selecting ratios that minimize the cost per kilowatt-hour.

2.3 DAILY PERFORMANCE

It is assumed that the wind speed forecast is known 24-hours earlier. Thus one programs the power history to be delivered to the electric power grid using a series of constant power levels and minimizing the number of power swings. Figure 2 shows November 1, 1996 wind history and a Wind Farm comprised of forty-nine Nordex N50/800 wind turbine systems. The difference in the two charts in Figure 1 is the percentage of wind systems apportioned to the direct delivery of power.



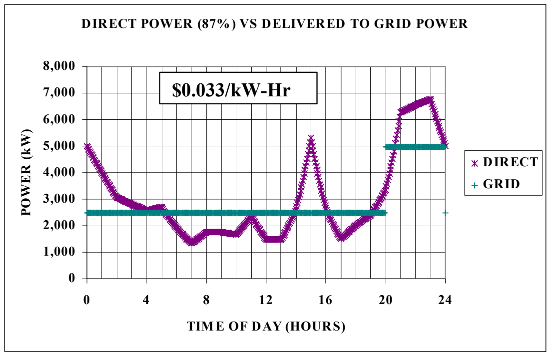


Figure 2. Two Different Distributions of 49 N50/800 Wind Turbines to Deliver Same Power History to Grid (11/1/96)

Comparison of the two graphs shows that although much of the direct power is lost (presumably by feathering the rotor blades), it represents the cheaper $0.033 per kilowatt-hour mode of operation compared to the $0.051 per kilowatt-hour mode of operation. The cost savings comes about because of the use of fewer storage tanks.

Whereas power is dissipated by the wind turbines supplying the direct power, the power directed into the storage tanks is accumulating and not being lost.

In the final extrapolation wherein there are no storage tanks, the cost of the purchased system is cheaper than the $0.033 per kilowatt-hour, but less power is delivered. However, the storage tank configuration permits the delivery of more power at any time.

It is presumed that the daily wind speed forecast has come a few hours before midnight on October 31, 1996. Based upon the forecast, a series of constant power levels are assigned as the demanded power from the electrical power grid.

Figure 2 shows the expected power that would become available from the 49 N50/800 wind turbines when driven by the November 1,1996 wind history. A portion of the power (87%) would go directly to the grid from the conventional wind turbine system. Note that the direct power from the wind turbines exceed the power sent to the grid. This sacrifice is made to deliver a constant level of power to the grid.

During these periods, the storage tank is being pressurized so that the 13% portion of the wind power going to storage is not wasted. Figure 2 describes the remaining portion of the wind power (13%) that is processed through a storage tank.

- If the demanded power of the grid happened to match the sum of the conventional system and the modified system, the compressor would put into the tank as much power as would be taken out of the storage tank. This comment ignores the inputs of the waste heat from the compressor, the solar heat and any heat from the fossil fuel burner.

- If the demanded power exceeds the sum of the direct power and the modified system power, the storage tank will release the required power to meet the set demand by the power grid.

- If the demanded power is less than the sum of the direct power and the modified system power, the storage tank will not release power to the grid. Rather, the air in the storage tank will increase its pressure and increase its temperature. If there is still excess air being compressed into the storage tank to above 600-psig, either the tank will vent or the compressor will be shut down.

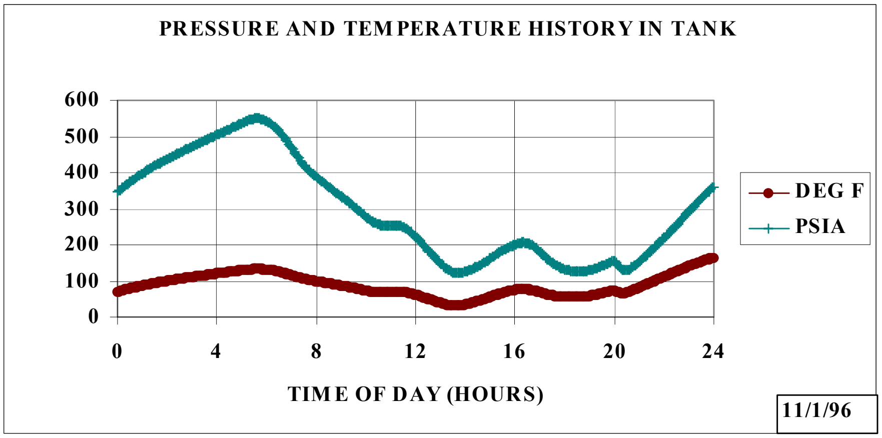


Figure 3. Energy in Storage Tank and Partition into Pressure and Temperature (11/1/1996 Wind History)

There is the possibility of trying to raise the power offered to the grid at about 1500 hours where there is a 3-hour period of higher velocities. However, Figure 3 shows that the tank pressure is too low, approaching the (100-psia) boundary for efficient operation of the turboexpander. There is room for further optimization. However, the Figures 3a and 3b show how the system operates.

Note the 20-hour period of constant power delivery to the electrical power grid.

Figure 3 (lower) shows the temperature rising with time. The net effect of the compression process, the thermal inertia effects and the expansion of the compressed air as it is fed to the turboexpander…is a rise in temperature. Thus the turboexpander inlet, as is desirable, is receiving air at ever increasing temperature.

This particular day, November 1 is used to illustrate the use of an on-design condition wherein there is high use of the storage tank to meet the required electric power of the grid.

2.4 WIND FARM DEFINITION

Figure 4 shows the split of the Wind Farm into its constituent wind turbine systems:

- Direct
- Storage
- Hybrid

<table>
<tr><th></th><th></th><th colspan="2">HYBRID TANKS</th><th></th><th></th><th></th></tr>
<tr><th>WIND HISTORY DATE</th><th>NUMBER OF TURBINES DIRECT TO GRID</th><th>NUMBER OF TURBINES DIRECT TO GRID</th><th>NUMBER OF TURBINES DIRECT TO TANK</th><th>NUMBER OF TURBINES DIRECT TO TANK</th><th>NUMBER OF TANKS</th><th>COST** PER kW-Hr (20 yrs)</th></tr>
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</table>

* 62 TANKS NEED BE PURCHASED
** COST IF THAT WIND HISTORY PERSISTED FOR 20 YEARS

Figure 4. Wind Farm Definition

The hybrid systems appear in the case of large Wind Farms. After accumulating the calculations for the power split between current users and stored usage for a multitude of daily scenarios, a table of results is prepared. The smallest percentage of each current user is selected, and the smallest percentage of stored system is selected. The remaining percentage is apportioned completely to the hybrid system.

In all cases, all 49 wind-turbines are operational. During the first day, the same 49 wind turbines produce less power because of the low wind speeds available during November 1. During the second and third day, the same 49 wind turbines produce more power because of the high wind speeds available during November 5 and 6.

During each day, the hybrid wind turbine switches the wind turbines under its control to the proper percentage of current user power and to storage.

The tanks are also made available on a daily basis. It is necessary to purchase 62 storage tanks to handle the worst case. On days that all the tanks are not needed it is necessary to shut down the extra tanks to assure the required pressure buildup.

5.5 NUMBER OF STORAGE TANKS

The benefit of delivering more power because of the use of storage tanks in itself is not sufficient to justify its use. However, the benefit available from easier switching is the key.

Furthermore, most natural winds that are nearly smooth during the day still benefit from the use of some of the purchased tanks. Consider the following example.

In the final extrapolation wherein there are no storage tanks, the cost of the purchased system is cheaper than the \$0.031 per kilowatt-hour, but less power is delivered. However, there are very **few** of these super smooth wind histories. Consider the November 1 wind history.

November 1 was used as an example of a relatively smooth wind history, and certainly smoother when compared to November 2, 3, 4 and 5. However, even in this smooth wind speed environment 15 tanks were required to deliver a smooth power history. Indeed 21 hours of constant power delivery became possible!

When there is a stronger variation in wind speed, the greater the number of tanks required to smooth the electric power input to the grid.

Over a one-year period the \$0.031 per kilowatt-hour is competitive with the cost of NO tanks, but the use of tanks offers the advantages of reducing the switching problems.

5.0 SITE DESIGN

There are 24 wind turbines assigned to the direct user's of the wind turbines, 19 wind turbines assigned to the hybrid wind turbines and 6 wind turbines assigned to the wind turbines dedicated to the storage tank system. Thus the Wind Farm is comprised of 49 wind turbine systems. Figure 4 shows the over-all configuration during the three example days.

It is necessary to purchase 62 storage tanks to handle the worst case. On days that all the tanks are not needed it is necessary to shut down the extra tanks to assure the required pressure buildup.

The cost developed in the cases presented in Figure 4 assumes the same wind condition applies over the 20-year period. Since most of the CAES components are robust, and the replacement parts inexpensive, the lifetime of the CAES system is more like 40 years.

It is necessary to consider many more days of wind histories, taken at different seasons of the year, and develop the costs that apply across the entire 20-years with all its various wind conditions. This was not done. Rather, an example is used to illustrate the operation of the system, and the method for evaluation of the cost.

6.0 CONCLUSION

The use of deep-buried caverns with large overburdens of soil that can support high-pressure compressed air storage is commonly called Compressed Air Energy Storage (CAES). There are a number of variations on this design, and optimization efforts have been extensively reported in the literature.

The proposed system has fundamentally different principles of operation. The compressed air is stored in steel pressure vessels above ground on concrete slabs. If there were no provision for thermal inertia in the storage tanks, there would be a severe drop in temperature as the compressed air flowed out and into the inlet of a turboexpander. This proposed system has not been explored in the literature except for recent papers by the authors in the AWEA 2003 (Austin, Texas) Proceedings and in the EWEA 2003 (Madrid, Spain) Proceedings.

The key advantages are:

- The proposed system uses a 40-MW Wind Farm that uses wind turbines that feed the electric power grid directly, and uses another set of wind turbines whose energy is stored and whose power is fed out according to a fixed program to fill in lulls in the wind. Thus the electric power grid can be fed with constant levels of wind power rather than having to live with the severe oscillations in the power delivered by wind turbines.

- Also, the system can be used to deliver uninterrupted power to small communities depending on about 4 MW of power, where the community is located remote from the power grid.