INTEGRATION OF WIND FARM WITH COMPRESSED AIR ENERGY STORAGE

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Abstract *–This paper proposed two methods to reduce the intermittent nature of renewable and makes it dispatchable by integrating wind farms with energy storage systems. In the first proposed method wind farm is integrated to grid and electricity of wind farm is used to drive the compressors to generate compressed air. With the second proposed method wind farm is totally separate from the grid and still generating compressed air by placing the compressor on the nacelle of wind tower. Energy is stored in underground caverns in the form of compressed air or in high pressure pipelines which is called compressed air energy storage (CAES). An analysis considering economically and technically aspects is made. A comparison of two hybrid systems is also made.*

Index Terms-Wind power, energy storage, reliability, and compressor

I. Introduction

Fossil fuel provides most of the energy, but their resources are limited and the rate of present consumption depleted it in the coming decades. Simultaneously, there is a strong political opposition against the use of nuclear power plants, which does not allow the production of energy in contributing to this deficiency. In order to overcome these problems renewable energy can play an important role [1].

Among all the renewable energy sources, wind technology is the most mature technology. Most of the wind farms are directly connected to the grid and are very far away from load centers and it can produce problem related to voltages. Fluctuation in voltages provided by wind farm can affect the performance of grid and any disturbances on grid also affect on induction generators of wind farms because it draws reactive power from grid [2-4]. These problems will be severe when a large potential of wind farms are connected to grid. The fluctuating power generated by wind farms makes power grid unreliable [5].The drawback of renewable source is intermittency in nature and not always available when demand is at its peak. The availability of energy storage system is a driving force to solve the problems related to renewable sources. Therefore, the best option is to integrate renewable source with energy storage system and it has numerous advantages [6]. Hybrid system is a combination of renewable source with an energy storage system. This hybrid system provides a positive solution of energy crisis [7].

The energy storage has been a great challenge for electrical utilities. From the consumer side, electricity can be stored in the range of watt. However, large utilities can store the energy in the range of MW, so that they can demand some extra price for the stored energy. Till present, only two compressed air energy storage is available in the world in which the energy of base load power plant is used to drive the compressor and the compressed air is stored in underground cavern [8].

Most of the wind farms are very far away from the load centers. In India, the installed capacity of wind farm is approximately 10,000 MW whereas its total capacity is assumed to be 45,000 MW. The problems related to wind farms would be increased as soon as this capacity would be installed. Then the energy of compressed air in surface storage might be an attractive option for most of the independent power producers.

In this paper, the drawbacks of wind-farm are solved by integrating it with the energy storage systems like CAES. The different energy storage technologies and its benefits are described in section II. In section III the first proposed scheme "Wind farm-compressed air energy storage is explained. Another proposed scheme "compressor on nacelle of wind tower" is introduced in section IV. Different types of compressors are introduced in section V. A detailed analysis of CAES is available in section VI. A qualitative analysis of hybrid projects is available in section VII, while section VIII provides the analytical comparison of two schemes. Conclusions are stated in section IX.

II. Energy Storage Technologies

Electrical energy can be stored in many forms. At the time of peak (i.e. more demand), and blackouts (i.e. no generation) the same amount of stored energy can be used to generate electricity. Storage of electrical energy plays a vital role in energy industry. Energy storage ensures secure and continuous supply to consumers from more distributed and intermittent supply bases. Characteristics of energy storage devices are:

- Energy density i.e. the amount of energy available in per unit weight. The unit of energy density is kWh/Kg.
- Discharge time i.e. the duration of time in which device releases the same stored energy.

Classification of Energy Storage Technologies

Classification of energy storage is made according to the types of energy storage which is as follows

- Electrochemical: This type of storage uses batteries and hydrogen storage that has range of few watts up to some kilowatts.
- Electrical: It uses capacitors and magnetic energy storage and has small range. To increase the range; it needs super capacitors and super magnetic energy storage.
- Mechanical: This type of storage uses compressed air energy storage and can deliver the energy in the range of MW for several hours.
- Thermal: This type of storage the oil is used to store the heat (i.e. adiabatic process) and still under research work.

Energy storage can be further classified as short term storage and long term storage. There are many techniques available for short term storage such as super capacitors, and flywheels, lead acid battery etc [9]. For long term storage, CAES and pumped hydro plant are attractive options.

Table 1 show, the different type of devices which are used to improve power quality, small and long duration energy storage. Flywheels, super capacitors and super magnetic energy storage improve the power quality. Advanced batteries and long duration flywheel are used for small power storage. Hydrogen storage and flow batteries can deliver power for long duration but up to 10 MW. Pumped hydro power plant and compressed air energy storage are only two options which can deliver huge amount of power in the range of some hundreds of MW for few hours [10]. But the problem of hydro power is that availability of two storages at different altitude is difficult while compressed air energy storage is available in many parts of the world.

Table 1: Different Energy Storage Technologies

Discharge Time		System Power Ratings						
	Long Power Storage	Hydrogen Storage and Flow Batteries					Hydro Pumo and CAES	
		Metal Air Batteries			Flow Batteries			
	Short Power Storage	High Energy Super Capacitors						
		Lead Acid Batteries						
	Power Quality	High Power Flywheels						
			Super Capacitors		SMES			
		1 kW	10 kW	100 kW	1 MW	10 MW	100MW	300 MW

Utilization of Energy Storage

In Fig.1, an arrow represents the shifting of energy from time of low demand to time of peak demand. Below the horizontal line AB; energy is stored at off peak times. The same amount of stored energy is utilized to generate electricity at the time of peak demand. From this figure the authors try to explain that the additional energy from renewable sources is stored at off peak times. It can be used again when demand is higher than generation from conventional power plants.

Hence, it improves the load factor of conventional power plants. The definition of load factor is: average load divided by peak load in a specific time interval.

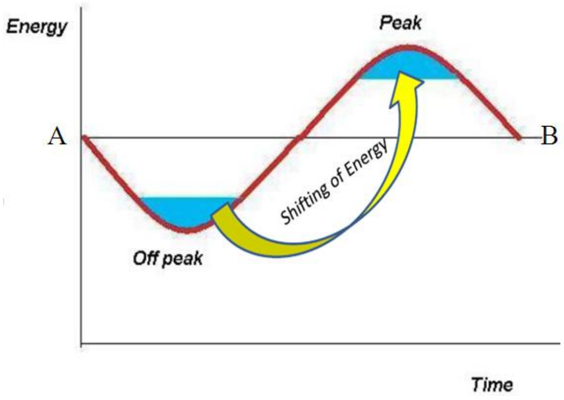

Fig 1: Utilization of Energy

Advantages of Energy Storage

Some advantages of stored energy are as follows:

- It is used for load leveling, means balance between supply and demand.
- It provides frequency support due to intermittent nature of renewable.
- It enhances transient and dynamic stability, which means system comes to a stable operation in case of some faults or overvoltage/under voltage conditions.
- It provides VAR compensation, which means feeding reactive power to transmission line for impedance matching in order to make power factor unity [11].
- It helps to enhancing security and reliability of power system; which means energy is available at desired time [12].
- It helps in shifting of load in very less time at peak demand [13]
- Stored energy provides continuous supply but at high prices.
- Integration of renewable sources with energy storage system enhances effective load carrying capability[6].
- Energy storage system can contribute into electrical market as ancillary services [14]

III. Proposed Scheme 1: Wind Farm-Compressed Air Energy Storage

In this scheme the energy is stored in the form of mechanical energy. The compressor uses the electricity of wind farm and off–peak electricity from conventional power plants to generate compressed air. The compressed air is stored in cavern or gas wells at a very high pressure. The air turbines use this compressed air to generate electricity at the time of peak or blackouts.

Fig. 2 shows the scheme of integration of wind farm with energy storage system. The grid substation at CAES power plant used to integrate wind farm with base load power plant. If the electricity from wind farm is not sufficient enough to operate motor compressor set then the extra electricity of base load power plant is used to compensate the deficiency. Simultaneously the surplus energy from wind farms feed to transmission line.

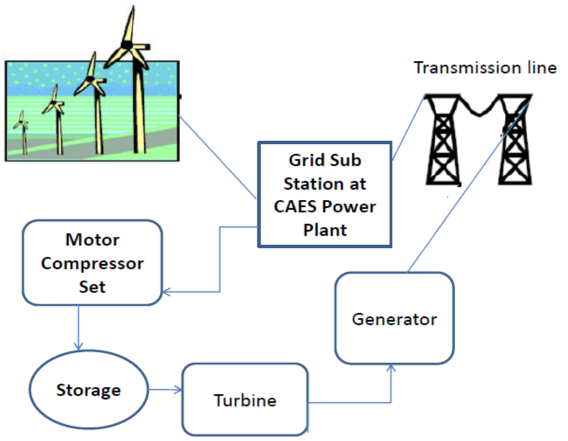

Fig 2: Integration of Wind Farm with Energy Storage

Compressed Air Energy Storage (CAES)

The world first CAES plant built in the year 1978, at Bremen, Germany. After 13 years, another compressed air plant built in McIntosh, USA. In the table 2 a comparison is made for CAES storage according to the different parameters.

Table 2: Comparison of CAES Plants

Location	Huntorf, Germany	McIntosh, USA
Commissioned	1978	1991
Plant Capacity (MW)	290	110
Generation Hours	3	26
Compression/ Generation	4 Hours	1.6 Hours
Volume	150,000 m^3	538,000 m^3
Cavern	2	1
Fuel	Gas	Gas/Oil
Energy Required for 1 kWh Peak Electricity	0.8 kWh Electricity	0.69 kWh Electricity
	1.6 kWh Gas	1.17 kWh Gas
Pressure Tolerance	$50*10^5$ Pa–$70*10^5$ Pa	$45*10^5$ Pa–$76*10^5$ Pa
Heat Rate (BTU/kWh, HHV)	6050	4510
Remark	World first CAES Plant	First CAES Plant with Recuperator

Components of CAES

The scheme of CAES power plant is same as gas power plant where the difference is that in CAES power plant the compressor are driven separately from electrical supply where as at gas power plant compressor are driven by the turbine shaft. Components of CAES are shown in fig 3 and explain in brief in following line

- Compressor: It increases air density by decreases its volume. In this process, system does work on the fluid and its temperature is increased.
- Intercooler: With the help of intercooler, the temperature of air decreases while increases its density.
- Reservoir: These are underground storage and surface storage.
- Reheater: In order to do some additional work, the air temperature is increases before expansion in the low-pressure turbine.
- Regenerator: It is used for energy exchange; the heat of the flue gases comes from the expansion turbine injected into the air, which is entering in the expansion air turbine.
- Compressed Air Engine: It is pneumatic actuator, which converts the potential energy of compressed air into kinetic energy as rotary motion, which finally drives the turbine.
- Turbines: The expansion of hot air in turbines rotates the generator.

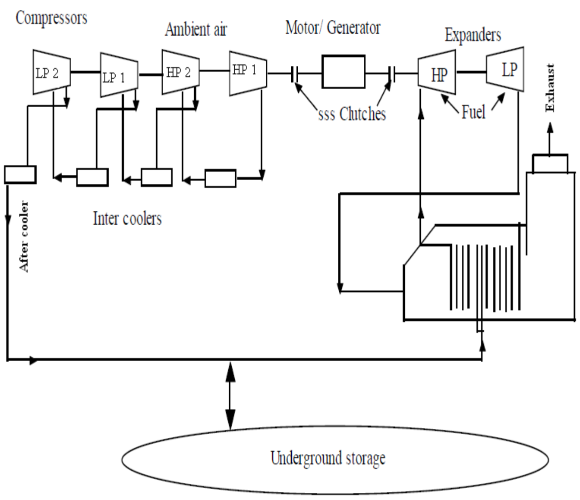

Fig 3: Scheme of CAES

Advantage of CAES

As energy storage device there are many advantages of CAES power plant which are described in the following lines [10].

Some of the main advantages of CAES plant are as follows:

- CAES plant consumes less than half of the gas in comparison to gas power plant.
- Quick start up and fast ramp; it reaches zero load to full load in less than 15 minutes.
- Environment friendly; it means 60% less emission than simple cycle power plants and 40% less emission than combined cycle power plants.
- It provides supplement reserve. This capacity does not connected with the grid but it is available within a short interval.
- It helps to support VAR, it means feeding reactive power to transmission line for impedance matching in order to make unity power factor.
- It has less CO_2 emission in comparison to gas and coal power plant.
- Improvement in the load factor of base load power plants.
- It provides high revenue by selling off-peak electricity at higher cost.
- CAES does not pay carbon tax as in coal power plant and it does not have fuel disposal problem as in nuclear power plant.
- It has lower operation and maintenance cost as the number of personnel requirement is less, compared to conventional power plants.
- It maximizes the use of present infrastructure.
- It minimizes the use of additional infrastructure.
- It avoids shut down of wind converters when there is a high wind in case of low load demand.

Economical Analysis of Energy Storage

The electricity prices from the conventional power plants can be divided into three categories which are as follows

(a) Off peak (low) prices
(b) Average prices
(c) Peak (high) prices

These prices are highly dependent upon the load demand. But the prices from the renewable like wind farm are always more than conventional power plants due to its high constructions cost and low capacity factor of wind farms [15-16].

At the time of low load demands the prices from conventional power plants are low but if the same time if there is high wind availability than independent power producer must have to feed its energy to grid at lower cost and they are in loss, and simultaneously it can be problem of grid stability.

In order to avoid these problems the energy from wind farms would drive the compressors to generate compressed air and it can be stored in salt domes or gas wells. The utilities can demand the high prices for the stored energy and it can be used for load leveling and VAR compensation.

Efficiency of Wind - CAES System

To generate 1 kWh, peak electricity by CAES it uses 0.75 kWh off peak electricity or Wind energy and 1.26 kWh of natural gas.

Output= 1 kWh

Total Input = 0.75 kWh + 1.26 kWh = 2.01 kWh

The efficiency of CAES is 1/2.01 kWh = 50%

The efficiency of CAES can be improved by utilizing the heat produced by compressor for heating the air. This is known as adiabatic process.

IV. Proposed Scheme 2: Compressor on Nacelle of Wind Tower

Instead of generating electricity from wind turbines, it is possible to generate compressed air with the help of a compressor. In this scheme, generator is replaced by compressor at the nacelle of wind turbines. The compressed air can be stored in underground or at surface for example in gas wells, large vessel or in high-pressure gas pipeline technology. The air turbines use this compressed air to generate electricity even when there is no wind. This scheme is shown in fig 4.

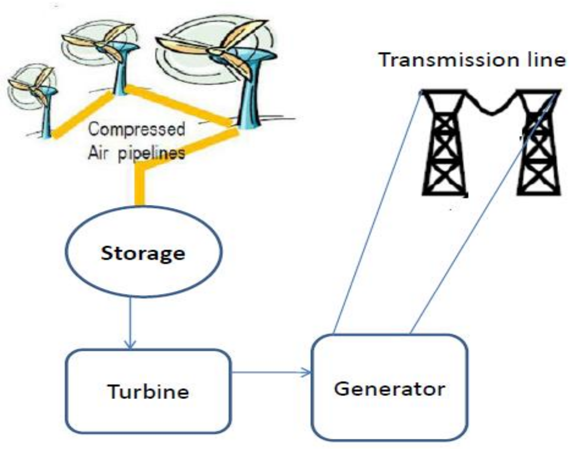

Fig 3: Compressor on Nacelle of Wind Tower

Efficiency

In this scheme compressor are driven by the wind energy so it needs only natural gas as a fuel. Therefore in order to generate 1 kWh peak electricity it needs only 1.26 kWh natural gas.

Input = 1.26 kWh

Energy output = 1 kWh

Efficiency = 1/1.26 = 79%

This scheme has greater efficiency as compared to scheme 1.

Advantages of this scheme are as follows:--

- Because of the air is stored at very high pressure in pipelines, the energy density would be improved.
- Compressor is directly coupled by the shaft of blades; hence there is no inefficiency of compressor as in electrically drive compressor.
- Air is stored in high pressure pipelines which are tightly sealed as compare to underground storage therefore there is no loss of pressure due to leakage as in underground storage.
- Avoid shut down of wind converter if there is high wind in case of low demand.

V. Compressor For CAES Scheme

Compressor used in the above two schemes is explained the following line

A compressor is a machine that compresses the fluid and increases its pressure [17].

Type of Compressors (Machine)

(a) Dynamic compressor (Rotary Motion) (Linear Motion)

(b) Positive Displacement (Linear Motion)

(a) Dynamic Compressor

The basic idea of dynamic compressor is that working fluid is allowed to pass through a rotor which increases its velocity and then velocity is converted into pressure with the help of diffusion process.

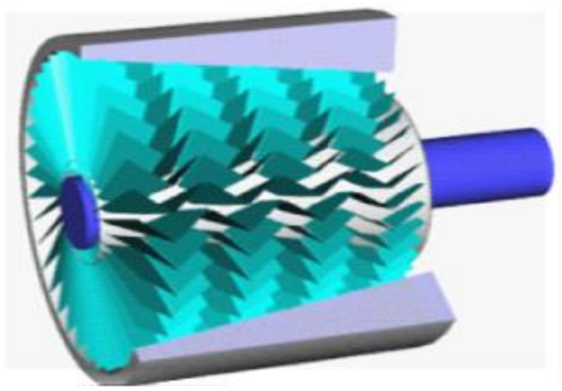

Fig 4: Axial Flow Compressor

A shaft drives the drum. This drum consists of array of blades. The blades consist of rotor and stator. The rotors consist of rotating blades and stators consist of stator blades. These rotor and stator are alternating. The rotor increases the kinetic energy of the fluid and stator convert this kinetic energy into pressure through diffusion process. This type of compressor has a higher flow rate and most suitable for continuous operation.

This type of compressor is used for continuous operation hence this is best suitable for scheme 1.

(b) Positive Displacement Compressor (Reciprocating Type)

In this process, a crankshaft drives a piston, which increases the pressure of the working fluid. It delivers the same volume of air at high pressure.

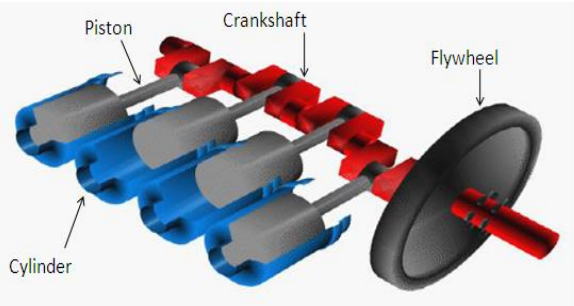

Fig 5: Positive Displacement Compressor

The spinning of crankshaft delivers force to the piston that results in the compression of the air, but a reverse function exist in engine operation. The expansion of the gases in the cylinder creates force on the piston, which results in spinning of the crankshaft.

This type of compressor can be stationary and portable, and it can be used for variable duty cycle and delivers wide range of pressure. Due to these characteristics this is best suitable for scheme 2.

Pressure and Energy Density

Pressure of air in the underground storage is between (45 – 76) *10^5 Pa (Mclntosh USA), whereas pressure of simple cylindrical flask is 10 – 20 Mpa where chromium rich steel tanks contains pressure up to 350 * 10^5 Pa

$$W = \frac{E}{V} = -\frac{\Delta HP}{RT}$$

This equation says that for a given volume and temperature, the energy density of storage is increased if pressure is increased. Since surface storage system stores the air at high pressure than underground storage, we can get the more energy with this system.

VI. Analysis of CAES

(1) Balance of Air Mass

The rate of change of air mass of the underground storage $\frac{dM_c}{dt}$ is equal to the difference between supply M_s and leakageM_l.

$$\frac{dM_c}{dt} = M_s - M_l$$

If Volume is V, pressure is P and density is ρ then calculation of Mc is as follows:

$M_C = \rho_C V_C = \frac{P_c V_c}{RT_c}$; Here c denotes for cavern. ($PV = nRT$=constant)

The leakage of air can occur from the supply of pipes (joints at receiving and sending points) or from underground storage (salt dome) because of variable pressure. It may also because of non-uniform temperature distribution inside the cavern at the initial stage.

(2) **Energy Balance**

By applying thermodynamic first law the rate of change of energy of the storage $\frac{dE_c}{dt}$ is sum of energy entering in storage minus energy loss due to leakage and other medium.

$$\frac{dEc}{dt} = \frac{dEs}{dt} - \frac{dEl}{dt} + \frac{dWs}{dt} - \frac{dWl}{dt} - \frac{dQ}{dt}$$

Where, $\frac{dEc}{dt}$ = rate of change of energy

$\frac{dEs}{dt}$ = energy stored in the cavern

$\frac{dEl}{dt}$ = energy loss due to leakage

$\frac{Ws}{dt}$ = work done by the stored air, it means increment in pressure

$\frac{Wl}{dt}$ = work done by the leakage air, it means decrement in pressure

$\frac{dQ}{dt}$ = heat absorb by the surrounding rocks

These above equations simplifies in terms of specific heat, temperature, pressure, and mass of air

$\frac{dEs}{dt} = C_v T_s M_s$

$\frac{dEl}{dt} = C_v T_l M_l$

$$\frac{Ws}{dt} = \frac{MsPs}{\rho s} = RTsMs$$

$$\frac{Wl}{dt} = \frac{MlPc}{\rho c} = RTcMl$$

Now the final equation is

$$\frac{dEc}{dt} = (Cv + R)TsMs - (Cv + R)TlMl - \frac{dQ}{dt}$$

VII. Qualitative Comparisons of Hybrid Projects

Table 3: Comparisons of Hybrid Projects

	Wind – CAES Scheme	Compressor on nacelle of wind tower
Energy Conversion	Electrical to Mechanical Mechanical to Electrical	Mechanical to Electrical
Type of storage	Underground	Surface storage
Volume of storage	538,000 m^3 (Mclntosh, USA)	Not High as Wind-CAES scheme
Pressure tolerance	$45*10^5$ Pa– $76*10^5$ Pa (Mclntosh, USA)	High than wind – CAES system
Delivered energy	110 MW up to 26 hrs (Mclntosh, USA)	10 – 15 MW up to 4 hrs
Compressor type	Dynamic	Positive displacement
Compression process	Isothermal	Polytropic
Problem with compressor	Multiple compressor not optimized	Vibration at nacelle of tower
Energy taken by compressor	Less	high
Operation and maintenance cost	High	Low as wind –CAES Scheme
Efficiency	50%	79%

VIII. Analytical Comparisons of Two Schemes

Wind-CAES Scheme

With this scheme compressor uses the electricity from wind farm. We assume that efficiency of generator is 95 % and efficiency of motor, which is driving compressor, is 95%. Then this scheme generates overall 10% losses in addition to the electrical transmission losses.

In this scheme, generally, 2 compressors are, connected in series (one unit) and output flow of one compressor entering into next compressor in order to further increase its pressure. In the process of compression, the temperature of fluid rises, because work is done on the fluid. Hence, intercoolers are used between two compressors in order to cool the air. With the help of intercoolers, the rating of next compressor would be lower or we can say the same rating of compressor will be very efficient. In the end, aftercooler is used to cool the air before entering in to the storage. We have to do this because at lower temperature the density of air increases.

Compressor on Nacelle of Wind Towers

With this scheme, the rotor of wind turbine drives the compressor. The combined 10% losses of generator and motor are not involved in this scheme. In another words the efficiency improves by 10%. Moreover, we do not have any electrical transmission losses. Nevertheless, we have losses in long pipelines, which carry the air to storage.

In this scheme, the motion of pistons in to the cylinders of positive displacement compressors generates compressed air. The positive displacement compressors contain air-cooling system.

IX. Conclusions

This paper evaluates the potential of integrating renewable sources with energy storage system. The advance techniques of renewable and with its high penetration rate, it is necessary to integrate it with large storage system like CAES. Till now CAES use caverns to store high pressure air but it is not available everywhere.

Geographical site is an issue while thinking about it. It is very easy by proposed scheme 1, to use the electricity from renewable to drive the compressor at CAES power plants. But still it has some problem of related to grid integration as discussed in paper. But now by the proposed scheme 2, it is possible to separate it from grid and still it produce compressed air, by replacing generator with a compressor at the nacelle of wind tower. The storage volume would not be very high as in caverns as it used high pressure pipelines with a greater efficiency and it offers a good solution.

X. References

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