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Integration of Wind Energy into Electricity Systems: Technical Challenges and Actual Solutions

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Abstract

Wind energy is the current "star" in the field of renewable energy for electrical production. Still, the power generated by wind turbines over time is characteristically uneven due to the unpredictable nature of their primary source of power. This only increases the problems inherent to the integration of a great number of wind turbines into power networks, making their contribution rather difficult to manage (regulating voltage and frequency, wind-farm operation, etc.) The integration of wind power in the power system is now an issue in order to optimize the utilization of the resource and in order to continue the high rate of installation of wind generating capacity, which is necessary in order to achieve the goals of sustainability and security of supply. This paper presents the main technical challenges that are associated with the integration of wind power into power systems. These challenges include effects of wind power on the power system, the power system operating cost, power quality and power imbalances (stability of grid). In addition, the paper presents the solutions will be offered to improve the management of wind power generation and increase its penetration in the overall electrical energy production.

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Keywords: Wind energy, energy storage, compressed air, hybrid systems, diesel engine, wind-diesel, turbocharging, turbo charger.

1. Introduction

The wind power production is decentralized in the regions with high average wind speeds. This is different to the conventional production units of large capacity, connected to the high-voltage grids, whose location and power have been planned. These types of production are centrally controlled to

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participate in the control of the frequency and voltage of grid. The fundamental characteristic of the decentralized production is to be lead in most cases by other factors than the electricity demand. For example, the weather conditions for which performed wind turbines. These factors cause uncertainties on the geographical location, the dynamics of the development, the levels and times of the production activity. Theses consequences influence the development, the management and the exploitation of power systems. These last ones must be ready on one hand, absorbing the decentralized production when it is active, and on the other hand, delivering the replacement power when the production is inactive.

Because it's unpredictable in the short term, the wind power is beneficial only in particular situations when there is a good correlation between the production and the consumption, or between the production and the specific needs of the grid. The advantages of the decentralized wind generation appear at maximizing incomes from the production with minimal impact on the power system reliability.

Currently, the wind turbines do not participate in the production settings. The mentality has already been changed; the decentralized production is destined to grow part into centralized production plant. The randomness of wind results that a single wind turbine cannot adapt the production to the consumption. Nevertheless, this adaptation should be done by the intervention of sources having a power reserve allowing a fast regulation of the production.

2. Impacts of the wind nature on the controllability of the wind energy production

The impact's evaluation of wind variability on the production is very important given perspectives and growth targets for the wind energy worldwide [1]. Two characteristics coming from the transfer of the climatic vagaries to the produced power and from the automation of production processes allow concluding that the wind technology offers uncontrollability on the generated production. So, this energy is variable (Fig. 1) and weakly predictable.

Indeed, the mechanical processes of power production from wind turbines transfer all the variability of the wind to the electric production as defined "intermittent". This intermittence corresponds here to the weakly predictable variation of the wind energy. It is characterized by high variability with regard to the forecasts established of the production for one day early. Because the climatic variations of the wind (gusts, variations of speeds, change of direction) are directly transmitted to the production, each variation of wind speed increase or decrease the generated power. Then, the wind energy is considered variable. The variability is defined here as the high frequency of change in output power and variability according to different time scales: second, minute, hour, day, week, month, season or year [2].

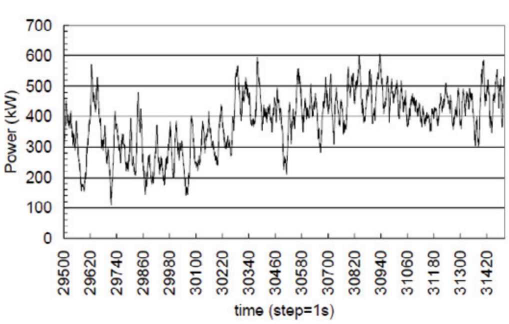

Fig. 1. Example of wind power fluctuation on a microscale [3]

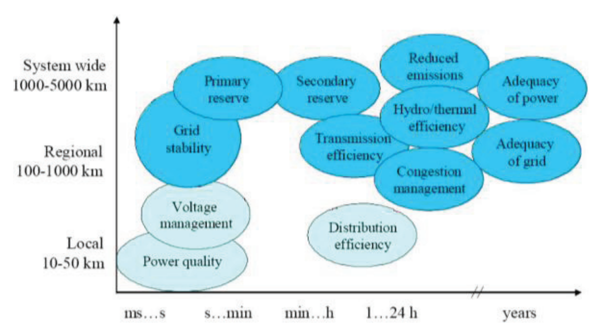

Fig. 2: Impacts of wind power in power systems [4]

The controllability analysis of wind energy requires the ability to anticipate these variations in order to afford itself some degree of production controllability. The foreseeability of the wind energy is the key to managing its variability [5]. Indeed, a better knowledge of instantaneous power foreseeability of wind energy allows a greater control on the wind energy production. For lack to control the output of the wind turbine technology, the foreseeability would allow a correct anticipation of the injections into the grid. There is easier to manage the balance between the production and the consumption.

However, it is difficult to anticipate the electric production which will be generated by wind turbines [5] because the forecasting tools are not design to reproduce all the variations of the wind. The models of forecast estimate the power production by compiling climatic data (an average speed of the wind over a specific period of time) and technical data of wind turbines.

Thus, it is possible to estimate more or less exactly wind production in a broad time: between 5 minutes at 72 hours before delivery. Nevertheless, more the duration between the forecasting and the time of delivery is long, more the forecasts are unreliable. When the estimation of wind power generation is realized one day early, the error degrees of production is around 10%. While the forecast is realized four hours before delivery, an average rate of error was around 4% of the produced energy [5]. However, these estimates are averaging, which can mask important differences. In some situations, the forecast may have an error about 40% of the installed capacity. For example.in 2003, in the area regulated by E. ON Netz in Germany, more than 2,900 MW of wind capacity have disappeared from the grid during few hours [6].

3. Effects of wind power on the electric system

Adding wind power to power systems will have beneficial impacts by reducing the emissions of electricity production and reducing the operational costs of the power system as less fuel is consumed in conventional power plants. Wind power will also have a capacity value to a power system. However, possible negative impacts will have to be assessed to make sure that they will not offset too large a part of the benefits and also to ensure the security of the power system operation [4]. The limited predictability and high inter-temporal variations of wind power cause a full spectrum of problems, ranging from shorter term frequency deviations to longer term balancing problems and involves a series of new challenges and additional constraints for the operation on the electricity grid. The possible impacts of wind power on power system reliability and efficiency are depicted in figure 2, divided into different timescales and how wide the impacts stretch.

Power system size, generation capacity mix (inherent flexibility) and load variations have an effect on how intermittent production is assimilated into the system. If the proportion of intermittent power production is small and if wind power production is well dispersed over a large area and correlates with the load then wind power is easier to integrate into the system [7].

In short term, mainly the variations in wind power production affect power system operation. This refers to the allocation and use of extra reserves as well as cyclic losses of conventional power production units, and transmission or distribution network impacts. In a large system, the reserve requirements of different loads and wind power interact and partly compensate each other. The power system operation then needs only to balance the resulting net regulation [7]. The variability introduced by wind power will not be significant until variations are of the same order as the variability of the random behaviour of electricity consumers. On the time scale of seconds and minutes (primary control), the estimates for increased reserve requirement have resulted in a very small impact. On the time scale of 15 minutes to 1 hour, the estimated increase in reserve requirement is of the order of 2-10% of installed wind power capacity, when the wind energy penetration level is 10% [8]. In long-term, the expected wind power production at peak load hours has an impact on the power system adequacy. It is expressed as the capacity credit of wind power. For a low system penetration, the capacity credit equals that of a completely reliable plant generating the same average power at times when the system could be at risk. As the penetration increases, variable sources become progressively less valuable for saving thermal capacity.

The problems due to the large scale integration of wind power plants into power system increase the difficulty to participate in the system services (control of the voltage and the frequency, self-start or black-start, possibility to operate in islanding, etc.) and to stabilize the electrical grid strongly dependent of the supply-demand balance. The no-implication in the system services brings wind turbines to behave as passive generators from electrical aspect [9]. Then, the regulation of the voltage and the frequency is postponed on the classic power plants. The high sensitivity of the wind energy to the grid disturbances, such as voltage dips or frequency variations, often causes a disconnection of production during incidents on the grid. This disconnection can aggravate an imbalance between the production and the consumption. By domino effect, it accelerates the advent of a major incident in the grid [1].

There are no technical limits to the integration of wind power. However, as wind capacity increases, measures have to be taken to ensure that wind power variations do not reduce the reliability of power systems. Then, the penetration rate of wind energy must be limited in order to guarantee the stability of the electrical system and grid under acceptable conditions [10]. The Denmark's experience showed that stability problems occur when the penetration rates are superior to 20% or 30% [10].

The limited capacity of the grid (lines and stations) can constitute in the case of wind energy an acute problem, because the places of production (windy sites) are often far from the consumption areas. The adaptation and the intensification of the posts (connection points) can concern the distribution grid (change protections, increase the power of short-circuit …) [1]. To avoid the congestion of the transmission lines and ensure grid security, new lines should be built especially at the interconnections between the grids managed by different operators. It should be noted that the deadline for building a post is about 5 years and the construction period of a new line is about 10 years. This construction can be subject to acceptance criteria from the people.

Other technical problems come from the fluctuations of the wind resource. For example, in the case of energy production, the fluctuations have consequence that the converter must be sized to support the peak of production. This design results that the converters underutilized most of the time. This conception bring about additional cost at the time of the installation (large oversized compared with average power output) and energy losses because the performance of the converters is often worse at partial load (except if it has been designed to keep good performance at partial loads). Another cause of energy losses is that many converters have an inertia that prevents their controller to "follow" the fluctuations of the source in order to use an optimal regime. Also, these fluctuations complicate the management of the produced energy. Indeed, most applications require a constant power. In the case of public distribution grid of energy, the possibility to control the consummated power by varying slightly the voltage cannot be realized by the multiplication of the automatic systems that maintain constant the consummate power despite these variations [11].

4. Wind generation impacts on the power quality

The location and intermittent nature of wind turbine machines can cause power quality problems such as voltage stationary variations (drops, interruptions and rises of voltage (voltage dips)), voltage temporary variations (flicker), harmonics, frequency variations, and low power factor. Wind turbines, especially inductive machines, tend to absorb reactive power from the system and produce a low power factor. If wind turbines absorb too much reactive power, the system can become unstable [7]. The main problems of the electric power quality produced by wind turbines are expressed in Table 1 [12].

The way in which the wind turbine locally affects the node voltages depends on whether fixed or variable-speed turbines are used. In fixed-speed turbines, there is a fixed ratio among the speed of the rotor, the active power, the reactive power and the voltage in the terminals. As a result, they cannot affect the node voltages by adapting the interchange of reactive power with the grid. On the other hand, variable speed turbines have, at least in theory, the capacity to vary the reactive power to affect the voltage in the terminals; however, in practice, it depends on the power electronic converters used. The flicker is a feature of wind turbines. Poor power quality can cause the end user's equipment to operate inefficiently, i.e., lights to flicker, or the utility system becomes unstable and disrupts power to the customer. Several factors contribute to the voltage flicker in terminals of a wind generator: aerodynamic phenomena (turbulence in the wind, tower shadow, etc.), short circuit power in the connection point, number of turbines, and types of control systems of wind turbines. Harmonic distortion generally occurs with variable-speed turbines because they have power electronics, an important source of harmonics. However, in the cases of modern power electronic converters with high switching frequencies and advanced control algorithms and filtering techniques, harmonic distortion would not be a main problem.

Frequency variations are produced when differences in the power balance between generation and demand exist. Wind speed variations, connection and disconnection of wind turbines cause differences in the generation; such differences can, in turn, cause frequency variations depending on the power system.

If isolated systems or micro-grids are considered, the problems introduced by wind power generation in the power quality are accentuated. In particular, the frequency variations are more important in these systems that in strongly interconnected systems. Furthermore, in these systems, wind power fluctuations demand more from the generation plants, which are responsible for closing the power balance.

Table 1. Summary of different problems related to the power quality

Characteristic	Description	Cause
Voltage variations	Change of the voltage effective value during several minutes or more	Average production of wind power
Flicker	Voltage fluctuations in frequencies between 0.5 Hz and 30 Hz	- Change operations - Shadow tower effect - Failure of the rotor orientation - Shear effect - Wind speed variations
Harmonics and inter-harmonics	Voltage fluctuations in frequencies between 50 Hz (60 Hz for the north America countries) and 2.5 kHz	- Frequency converters - Thyristor controllers - Capacitors
Power factor	Reactive power consumption	Inductive components

5. Wind power impacts on electric power system operating Costs

Wind power plants generate electricity when the wind is blowing, and the plant output depends on the wind speed. Wind speeds cannot be predicted with high accuracy over daily periods, and the wind often fluctuates from minute to minute and hour to hour. Consequently, electric utility system planners and operators are concerned that variations in wind plant output may increase the operating costs of the system. This concern arises because the system must maintain balance between the aggregate demand for electric power and the total power generated by all power plants feeding the system. This is a highly sophisticated task that utility operators and automatic controls perform routinely, based on well-known operating characteristics for conventional power plants, sophisticated decision-support algorithms and systems, and a great deal of experience accumulated over many years. In general, the costs associated with maintaining this this balance are referred to as ancillary-services costs [13].

System operators are concerned that variations in wind plant output will force the conventional power plants to provide compensating variations to maintain system balance, thus causing the conventional power plants to deviate from operating points that are chosen to minimize the total cost of operating the entire system. The operators concerns are compounded by the fact that conventional power plants are generally under their control and thus are dispatchable, whereas wind plants are controlled instead by nature. Although these are valid concerns, it is important to understand that the key issue is not whether a system with a significant amount of wind capacity can be operated reliably, but rather to what extent the system operating costs are increased by the variability of the wind.

Recently several investigations of wind power impact on electric power system operating costs have been conducted. These studies addressed utility systems with different generating resource mixes and employed different analytical approaches [7]. The conclusion of these studies is that the operating cost impacts are small at low penetration levels and moderate at higher penetration levels.

6. Actual solutions based on the management of wind power

The management of wind power comes from the grid stabilization, its reliability and the uniform service for the supplied power. These three characteristics help to control to the intermittency of this energy source and increase the penetration rate of wind turbines. The traditional approach of management requires adding a complementary power plant to ensure the supply at all times. This consists to compensate the intermittency of wind energy with producing by a more controllable source (hydro, thermal diesel power plants, etc..) or by connection of these turbines to the transmission and distribution high voltage grids (it is the most common solution) or by connection to the energy storage systems to have an additional reserve of energy and acting as a buffer system between the producer and consumer.

7. Management of the wind generation by connection of wind power plants to the transmission grid

To function properly and produce electricity, the majority of wind turbines require a powerful grid that imposes the frequency and the voltage. Moreover, this grid must also be able to supply the necessary reactive power to the asynchronous generators, for example, and be able to absorb continuously the power produced by the wind turbines [14].

For the wind production units, the interface with the grid includes the power electronics equipment. Compared to conventional power plant using the synchronous or asynchronous rotating machines, they introduce new possibilities in terms of adjustments. Thus, the related control strategies can aim directly the adjustment of the production on the one hand and the service quality of the grid on the other hand. The flexibility obtained by this type of connection can provide to the grid manager many services, in particular:

- the control of the active power
- the compensation of the reactive power
- the strengthening of the grid by local control of the effective value of the voltage [15]
- and, in a general framework, a filtering of the disturbances introduced by the polluting loads connected to the considered portion of the grid [15].

All this is very complex to manage because the power produced by wind turbines is fluctuating because of the vagaries of the wind [16]. A wind turbine of 1 MW cannot produce permanently this rated output. For this reason, there is interesting to interconnect a large number of wind turbines together on several sites to have a stabilized production (profusion effect).

However, the wind turbines can provide the system services because they equipped with power electronics systems. Also, it is possible to adjust the power output by changing the blade pitch. If during a period of strong wind there is an excess of electrical power injected in the grid, which can destabilize the frequency, it is possible to limit the power produced by the wind turbines. This system is executed by the action on the control of the electronic part and on the pitch angle of the blade to reduce the performance of the rotor. This area of research is now studied by many laboratories to contribute for innovative and effective solutions [16].

Furthermore, the action on the command of inverters associated to the generator can vary the value of the reactive power produced by wind farm. Depending of the chosen conversion chain, it is possible to absorb or to supply a reactive power and control the voltage level of the grid.

The grid manger can rely on the wind turbine to help her in the grid power factor correction [17]. This option is now incorporated in most wind turbines using doubly fed induction machines. If a windless period, the operator of the electricity grid cannot rely on wind turbines as a source of electric power with a few days early. This depends on weather conditions and does nothing changes when the wind speed decreases.

Traditionally, the grid operators have managed the variation of the demand on the grid by using various operating strategies to balance the load with the generation capacity. In the process to balance load and production, they must maintain the frequency of the grid within very strict standards. With the progress of wind generation, additional production reserves are required to keep the system performance within recommended limits. This solution allows solving the problem due to the wind generation impact on the operation of the electricity grid, analyzing the integration and balancing costs.

The most recent studies have shown that the reserve capacity needed to integrate wind power is lower than initially expected. In the worst case, it may reaching 10% of the nominal capacity of wind power plants Most of the time; it is between 3% and 5% of this power.

For greater versatility and efficiency of the system, it should store the energy during the periods of high wind speed and restore it when there is no wind [17], or then associate the wind turbines with other generation sources as diesel generators in the case of the autonomous grid for remote areas.

8. Management of the wind generation by connection of wind power plants to energy storage device

In the absence of a grid interconnecting consumers and producers, the need to store the energy is imperative if the electricity will be consumed by the demand, even when the production is zero (period of no wind). When the electrical grid exists (this one provides a pooling of resources and smoothing effect), the consumer forgets that the problem continues to exist. However, grid stability is subject to equal and permanent instantaneous production and consumption.

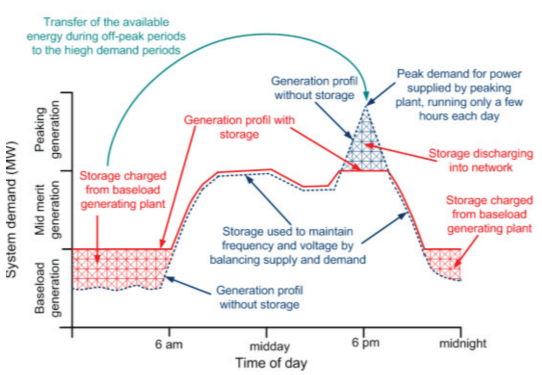

Fig. 3. Fundamental idea of the energy storage [18]

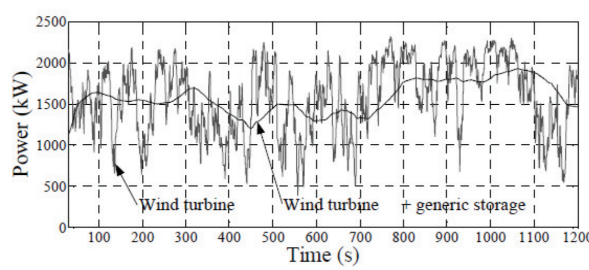

Fig. 4: Wind power generation with and without storage

The fundamental idea of the energy storage is to transfer the excess of wind power produced during the periods of weak load (or high penetration of wind energy) to the peak periods or low wind penetration (Fig. 3). Initially, electricity must be transformed into another form of storable energy (chemical, mechanical, electrical, or potential energy) and to be transformed back when needed.

The energy storage plays a flexible and multifunctional role in the grid of electric power supply, by assuring more efficient management of available wind resources. The combination with the power generation systems by the conversion of renewable energy, the energy storage systems (ESS) provide, in real time, the balance between production and consumption [19]. Also, they increase the value of the energy generated by the wind farms, especially if the energy accumulated during periods shall be restored during peak periods [19]. The ESS will also avoid the power unbalancing case of overproduction; improve the management and the reliability of the grid. Furthermore, the ESS makes easier the integration of the wind turbines in the energy system, increases their penetration rate of energy and the quality of the supplied energy by better controlling frequency and voltage. Strategically placed, the ESS can increase the efficiency of the existing system of transmission and distribution of electric energy. The ESS can be used to reduce the peak load (power smoothing) in a power plant (Fig. 4). It can eliminates the extra thermal power plant operating only during the peak periods, enabling better utilization of the plant functioning permanently and outstanding reduction of emission of greenhouse gases (GHG).

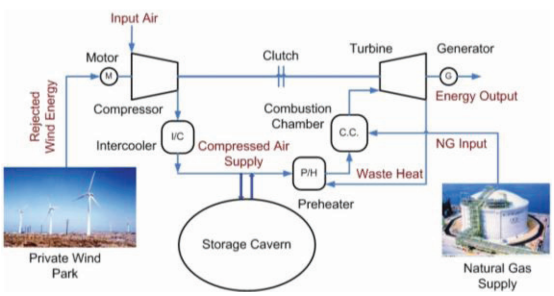

Fig. 5. Wind-Compressed air energy storage hybrid system

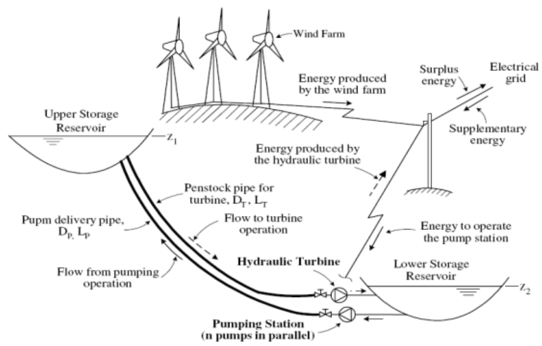

Fig. 6. Wind-Pumped hydro energy storage hybrid system

Then, the storage represents the key of the penetration of wind power on the electricity grid. It provides a technical solution for the grid manager to assure in real time the balance between production and consumption, but it allows optimizing the wind resources by avoiding an unbalancing power in case of overproduction. Together with local wind energy resources, a decentralized storage also has the advantage to improve the robustness of the grid by allowing an islanding operation mode for the areas supplied by this resource. Different types of hybridization between wind energy and storage technologies may exist such as: wind-flywheel, wind-hydrogen storage, wind-compressed air energy storage (Fig. 5), wind-pumped hydro storage (Fig. 6), wind- batteries, etc.

9. Management of the wind generation by hybridization between wind energy and another sources

Generally, a hybrid system of energy production combines and exploits several energy sources available and easily mobilized these resources. Combining several sources of energy especially renewable can maximize the power generation systems, either technical or economic standpoint. The new technological solutions proposed for the hybrid generators, have a considerable evident interest because their incomparable flexibility, their suppleness of operation and their cost. Traditionally, these new system are very complex compared to current single-source solutions.

However, these solutions require a preliminary laborious designed based on a thorough knowledge of the field of renewable energy of the site preparation. This set-up and management can be only giving by an expertise that only the experience in engineering of energetic systems can provide. This careful management of energy based on the intelligence of the adjustment and control devices is made possible by very powerful software. Several combinations of hybrid systems may exist such as: wind-photovoltaic (PV), wind-diesel, wind-diesel-storage system (Fig. 7 & 8), wind-photovoltaic-diesel-storage system, etc.

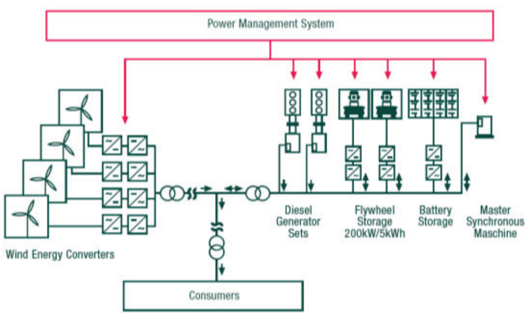

Fig. 7. Example for wind-diesel-energy storage system

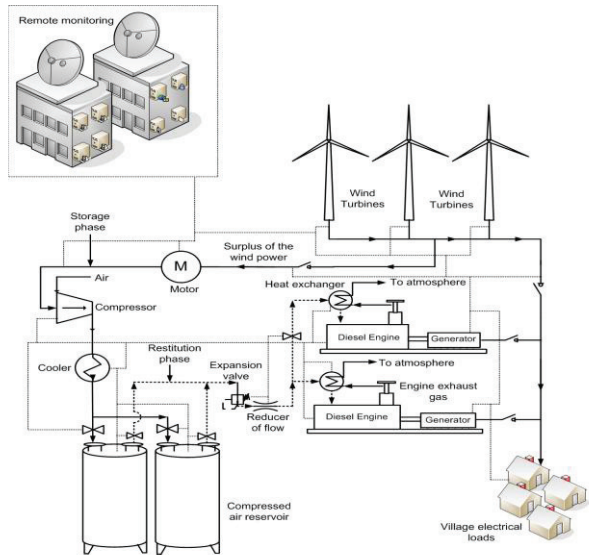

Fig. 8. Wind-diesel-compressed air hybrid system [19]

These hybrid systems exploit and optimize the renewable resources to provide electricity in the autonomous grid. It is an ideal solution for remote communities. These systems are adapted to reduce the dependence towards the fossil fuel by using the solar and wind resources. Some approaches, "wind-diesel-hybrid system", are currently used in northern communities in Canada and Alaska and in several remote sites around the world.

The integration design allows an interesting fuel saving (50-80% depending on the wind resource). Also, this design reduces the operating deficits of the autonomous grids whose main output is produced by diesel generators. The major cost reductions are obtained for the maintenance and the replacement of diesels. Furthermore, an efficient adjustment system that maintains the diesel groups above their minimum power for good functioning will optimize their reliability and the wind energy penetration rate.

10. Conclusion

The main technical challenges and possible solutions that are associated with the integration of wind power into power systems were presented in this paper. The challenges include effects of wind power on the power system, the power system operating cost and power quality. Work conducted to date shows that wind power's impacts on system operating costs are small at low wind penetrations (about 5% or less) and moderate at higher penetration levels (about 20%). This study concludes that to ensure and maintain the reliability of the wind energy development into the grid, it is important:

- to accelerate the procedures for the construction of new lines,
- to define a minimum rate of stability required for the wind farms operators,
- to maintain in service a traditional power plant near windy areas and
- to elaborate a vast and comprehensive planning of the wind energy that would avoid an over-concentration of wind turbines in a given region [20].

The integration of the wind energy can be promoted by:

- The use of the electronics power equipment to connect the wind turbines at the electricity grid. So, the wind energy has the possibility to participate in the regulation of the frequency and the voltage to maintain their connection on the grid in the presence of voltage dips.

- The development of the short and long term energy storage technologies associated with wind power plants [20].
- The development of hybrid systems, combining wind power with conventional or other random sources, with an integrated and optimized management of energy.

Finally, the development of the wind energy can be greatly facilitated by better forecasting of the wind energy potential at a time scale of several hours to several days. Wind forecasting has substantial value. Its payoff is primarily in the day-ahead time frame through its influence on unit commitment decisions. Most of the value of forecasting is already available through state-of-the-art capabilities. What remains is to integrate these techniques into the day-to-day operation of power systems.

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