Review of the Impacts of Intermittent Wind Power Integration into Electricity Systems: Technical Problems and Proposed Solutions

H. Ibrahim[1], C. Arbez[1], A. Ilinca[2], D. Rousse[3], M. Ghandour[4], M. Dimitrova[1], D. Boulay[1], M. Adegnon[1]

Abstract-- **The wind power generation, naturally decentralized, offers a supply security for consumers while respecting the environment. Directly competitive for remote areas, where grid connection costs are very high, the wind farms are most often directly connected to the central grid of transmission and distribution of electricity. However, the randomness of the generated wind power requires the establishment of design, sizing and uses rules of these systems to exploit them at best.**

This paper will analyze the various problems appeared during the setting up and operation of the wind turbines. These problems were generally due to the variability of its primary source: the wind. Afterward, solutions will be offered to improve the management of decentralized renewable power generation and increase its penetration in the overall electrical energy production.

Index Terms—wind energy, intermittence, energy storage, grid management, hybrid systems.

I. 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 participate in the control of the frequency and voltage of grid [1].

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 electricity grid (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 [1].

Because it's unpredictable in the short term, the wind power, fundamentally decentralized, 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 (grid) 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.

II. 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 [2].

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.

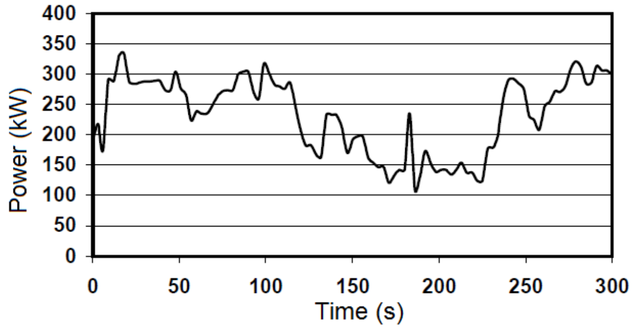

Fig. 1. Profile of power generated by 300 kW fixed speed wind turbine

[1] Wind Energy TechnoCentre, 51 Ch. de la mine, Murdochville, QC, G0E 1W0, hibrahim@eolien.qc.ca, carbez@eolien.qc.ca, dboulay@eolien.qc.ca, mdimitrova@eolien.qc.ca, madegnon@eolien.qc.ca

[2] Wind Energy Research Laboratory, Université du Québec à Rimouski, 300 Allée des ursulines, Canada, adrian_ilinca@uqar.qc.ca

[3] Industrial research chair in technologies of energy and energy efficiency, École de Technologie Supérieure, Canada, daniel@t3e.info

[4] Lebanese University, Faculty of Engineering, Beirut, Lebanone, drmazengh@yahoo.com

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 [3]-[6].

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 [7]-[8]. 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], [7], [9] 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 [7]. 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 [10].

III. PROBLEMS DUE TO THE INTEGRATION OF THE WIND ENERGY INTO THE GRID OF ELECTRICITY

The wind production is considered as intermittent, variable and not easily programmable energy source. This type of energy production involves a series of new challenges and additional constraints for the operation on the electricity grid. The problems due to the integration of the wind turbines into the grid are caused by [11]:

- production random and very unpredictable
- absence of power-frequency control
- limited participation in voltage control for variable speed wind turbines, and no participation in this setting for wind turbines which are directly connected to the grid
- high sensitivity to voltage dips and frequency variations for some technologies
- very sensitive to fast variations of the wind strength

Furthermore, the wind power production is rarely synchronized with the demand. The demand variations are:

- A long-term trends to grow (more or less highlight) [12];
- seasonal variations are quite marked because of the conjunction of economic needs and the influence of thermal uses (heating, air conditioning);
- daily and weekly variations related by alternation behaviour of consumers (firms or individuals) [12];
- instant random variations those are quite important.

Nevertheless, the production and the consumption of electricity must be equal all the time for the following causes:

- a momentary imbalance would result in a variation of the kinetic energy in the alternators (generators), that results on their rotation speed, and the frequency of the grid, which is acceptable only in very narrow limits
- a persistent imbalance would lead to the initiation of the plant safety systems.

As the wind power produced over time is characterized by its fluctuation. The wind power increases the problems caused by integrating large numbers of wind turbines in networks: difficulty to participate in the system services and to stabilize the electrical grid (due to imbalance between the production and the consumption).

The no implication in the system services (control of the voltage and the frequency, self-start or black-start, possibility to operate in islanding, etc.) brings wind turbines to behave as passive generators from electrical aspect [13]. The regulation of the voltage and the frequency is postponed on the classic power plants. The penetration rate of wind energy, that is the power generated by the wind turbines with regard to the consumption total power, must be limited in order to guarantee the stability of the electrical system and grid under acceptable conditions [14]. The Denmark's experience showed that stability problems occur when the penetration rates are superior to 20% or 30% [14].

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.

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 …). 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 [15]. 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 [16].

IV. Impacts of the wind energy on the electric production QUALITY

The fundamental objective of the electricity networks is to provide electric energy with perfect continuity, in the form of perfectly sinusoidal voltages, with predetermined values of amplitude and frequency (depending to the connection point) [17]. Any deviation from the standards represents a disturbance that may be aggravating operation of the connected loads.

The notion of "quality of electric production" is linked to the level of user satisfaction. It refers to the stability (sustainability, viability and quality) of the voltage, the frequency stability and the total harmonic distortion. This notion has recently taken an important place due to several factors [17]:

- The nature of the loads connected to the grid (in particular those connected through a rectifier, harmonic generator)
- The nature of the installed energy productions (including the installation of the distributed production after the development of electricity market);
- The progress made towards control of power electronic interfaces

The wind generators belong to these three categories because they are part of the decentralized energy production, they are harmonic generators (essentially at low frequencies) and they are power electronic interfaces to be connect at the grid.

If a wind turbine is connected to a weak electrical grid (i.e. connected to the main power through a line having low-capacity energy transportation), falling voltage and power excursions may occurs [18]. It may necessary to strengthen the grid.

The main problems of the electric power quality produced by wind turbines are expressed in Table 1 [19]-[20].

TABLE I
SUMMARY OF DIFFERENT PROBLEMS OF THE QUALITY OF ELECTRICAL PRODUCTION

Characteristic	Description	Cause
Voltage variations	Change of the effective value of the voltage 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

The technical requirements to connect a power plant in the transmission grid impose that the power quality must be verified in respect of contractual, regulatory or standard margins [11]:

- characteristic parameters of the voltage and current waves of the grid
- continuity and reliability of power supply of the consumers

This criterion of continuity and reliability depends largely on the availability of the upstream source, the wind, which by its nature obviously raises problems. The quality of voltage and current waves at the connection point with the grid depends strongly of the wind turbine technology types.

V. Solutions: Management of the wind power

The management of wind power come 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 power plant, diesel plant, 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.

A. Management of the wind power: Connection at the 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 [21].

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 [16]
- and, in a general framework, a filtering of the disturbances introduced by the polluting loads connected to the considered portion of the grid [16].

All this is very complex to manage because the power produced by wind turbines is fluctuating because of the vagaries of the wind [22]. 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 [22].

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 [23].

The grid manger can rely on the wind turbine to help her in the grid power factor correction [24]. 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 [23].

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 [24], or then associate the wind turbines with other generation sources as diesel generators in the case of the autonomous grid for remote areas [25].

B. Management of the wind power: Connection at the energy storage systems

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 (for example, case of wind turbine during 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 [26].

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 [27]. 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 [27]. 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. 2). 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).

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. 3), wind-pumped hydro storage (Fig. 4), wind- batteries, etc.

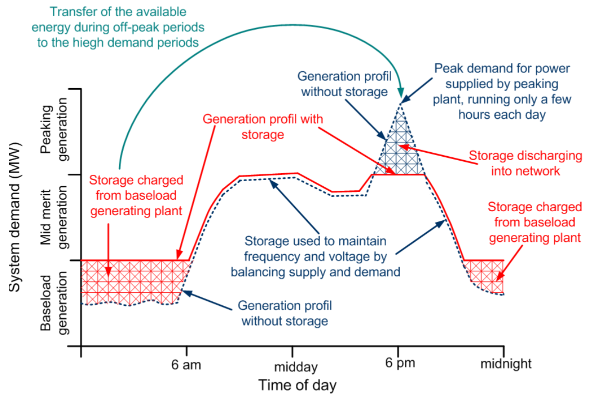

Fig. 2. Elimination of the peak load and smoothing of the power by the energy storage system [28]

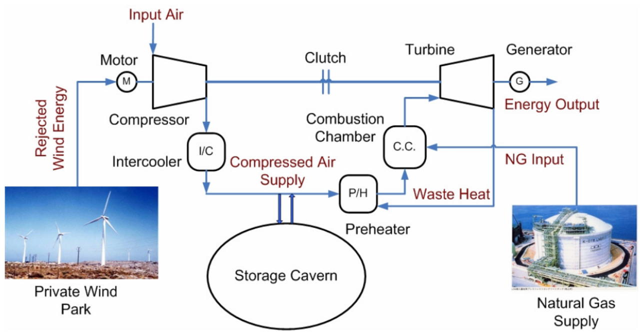

Fig. 3. Wind-Compressed air energy storage hybrid system

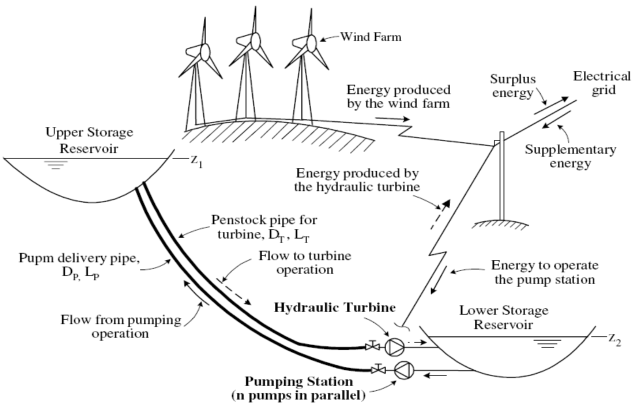

Fig. 4. Wind-Pumped hydro energy storage hybrid system [29]

C. Management of the wind power: Connection at another source – hybrid systems

Generally, a hybrid system of energy production combines and exploits several energy sources available and easily mobilized these resources [30]. 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, wind-diesel, wind-diesel-storage system (Fig. 5 & 6), wind-photovoltaic-diesel-storage system, etc.

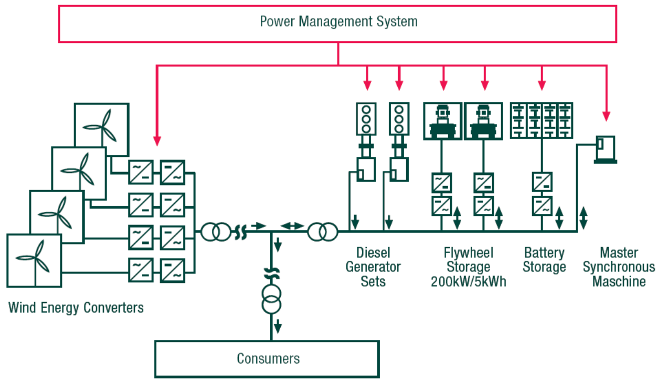

Fig. 5. Example for wind-diesel-energy storage system

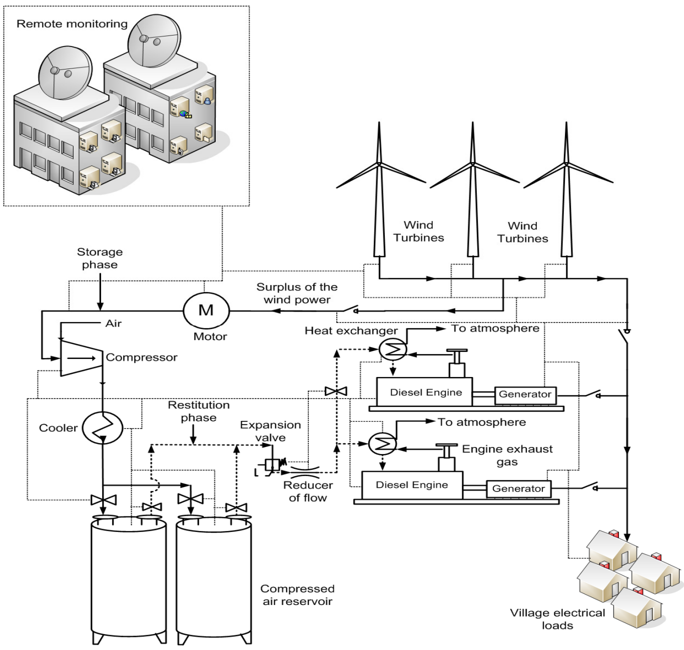

Fig. 6. Wind-diesel-compressed air hybrid system [31]

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 penetration rate of the wind energy.

VI. Conclusions

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 [11].

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 [32].
- 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.

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