XIII ERIAC
DÉCIMO TERCER ENCUENTRO
REGIONAL IBEROAMERICANO DE CIGRÉ
Puerto Iguazú
Argentina
24 al 28 de mayo de 2009
XIII/PI-C6 -09

Comité de Estudio C6 - Sistemas de Distribución y Generación Dispersa

WIND ENERGY AND ENERGY STORAGE IN POWER SYSTEMS

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Abstract – *Power systems around the world require performing various tasks at the same time. The necessity to generate electricity at low cost, with less or null pollution and the cost increase of petroleum, put power utilities on a large and permanent stress. Renewable energy sources like wind generation is today part of a solution for various utilities problems. They are in first place concerning low pollution and the combustible has null cost, but have unfortunately the big problem of being an unpredictable energy source. Especially in the case of wind for short periods it is difficult to assure its generation. Power systems operator cannot take into account wind farms in operational planning stage. In this sense, this paper discusses the conditions for wind energy to be able of taking part of the power system spinning reserve and makes a proposal to include wind farms in spinning reserve with the aid of energy storage systems.*

Keywords: wind generation – energy storage – power reserve – power system security

1 INTRODUCTION

Nowadays, electric power systems (hereinafter power systems) supply electric power mainly through hydraulic and thermal generators. In both cases the primary energy source is ensured within certain limits, thus, its operation can be programmed and predicted (the reserve) respect variations in the energy consumption and possible system faults. In the operation system planning the spinning reserve determined acts immediately after a contingency or unforeseen load variation. This reserve is composed, mainly, of generators that using non-renewable energy sources generate a smaller percentage of its nominal power.
The present world energetic crisis caused by the scarcity and high cost of non-renewable fuels, as well as the environmental problems caused by these fuels, has forced to use renewable energy sources in order to overcome this crisis and reduce pollution effects. Besides, the financial support and the achieved advances in conversion systems make possible the use of renewable energies at large scale, even, at the same level of conventional power generating units.
Among the large variety of electric power generators with renewable resources, wind energy generators are the ones that, nowadays, present the greatest advance and technological development. The large group that form the so called wind farms (WF) are the aim of this paper. If the generation of these farms has an elevated relation respect the power generation with non-renewable sources, then it is said that there is a large penetration level in the system.
When the wind is used as primary energy source, although there is no fuel cost involved and there is a low or null environmental impact, there appears the randomness problem of this resource. Mainly, when dealing with the spinning reserve, the wind generation is not considered safe to carry out calculations for the power operation planning. Therefore, when the penetration level is high, it is considered that it affects directly the power system security [1, 2].

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In addition to the uncertainty of the wind resource, it appears the problem of transforming the primary energy source: the wind. The energy supplied by WF is difficult to predict and it also presents the characteristic of producing energy when the system or the system operators do not require it, thus, it is usually lost. Wind prediction can be used to solve these disadvantages. Before installing large wind farms statistical studies are carried out to determine the medium values of wind speed. These medium values are useful first, to determine the technical-economical feasibility of the project and then, to carry out the long term operation planning of the system. Nevertheless, for the short term operation planning, as the spinning reserve, these values can not be used. A determination of medium values in very short time, due to the high rate of variation of the wind, would not guarantee the availability of the resource. For those power systems that count with a high penetration of renewable energies as the wind one, the planning and the determination of the spinning reserve represent an important challenge, which has not been solved yet.

The possibility of using energy storage systems (ESS) is put forward here as one of the solutions to the unpredicted characteristic of the energy produced by wind units. In this paper it is analysed, first, the problematic of dealing with the possible types of energy storage systems to be used and then, an operation scheme of wind systems with their storage systems for their participation in the power system short term reserve. Wind farms present a dilemma not only for the system reserve but also for their operation and security. These problems are due to the characteristic of the energy source as well as to the type of generators. Among other problems WF introduce harmonics, flickers in the electric system and have reactive power requirements particularly during the start up. All these affect the power system locally, so some of them will be taken into account in this work and in the solution proposed.

2 THE SPINNING RESERVE REQUIREMENT IN POWER SYSTEMS

One of the main requirements in the operation of power systems is their stable and secure operation. The most direct index of the power system operation stability is the frequency value, which remains as a stable value if the generation equals the consumption. If frequency decreases this is the first index of a lack of balance in the system due to generation, transmission fault or demand variation. In any case, the generation should be corrected immediately according to this variation to avoid that the frequency continuous decreasing and finally collapse the whole system.

When the frequency falls bellow the dead band lower limit of speed regulators of regulating units, the spinning reserve is activated producing a quick increase of active power of generators. This type of control is known as primary frequency control (PFC), being all power plants obliged to participate in this control. In the case of thermal power plants, the control acts directly over the steam inlet valve to increase as fast as possible the generation of the power plant. The balance is obtained when the generation increase equals the unbalance of the initial power. This is reached normally about the 20 or 30 seconds after the disturbance, depending on the size of the system and the fault, the type of power plants involved in the PFC and on the amount of spinning reserve maintained in the system under this control. If this unbalance of powers is not covered by this type of control, the system frequency goes on decreasing and activates the protection relays of synchronic generators increasing the unbalance produced and leading to the final collapse of the system. Nowadays, WF do not participate in this type of regulation, therefore they do not collaborate in the spinning reserve to help maintaining the system frequency.

Under severe disturbances, when the reserve results not enough to restore the power balance, the system can turn to external measures such as the load shedding, as the last alternative to stop the fall of frequency and to avoid in that way the total system collapse. The load disconnection is normally used in all power systems having or not the wind generation type. This type of help for the system reserve, is based on the coordination of sub frequency relays that detect automatically, either a very low level of frequency (level relays) or a sudden reduction of frequency (gradient relays), after which they disconnect the load associated to the node in which they are connected. Some authors considered this type of control as part of the spinning reserve.

The PFC, with characteristics of proportional control, leaves as a result a frequency deviation respect the reference value (error in steady state). Therefore, it is suggested a higher control level of proportional-integral characteristics, called secondary frequency regulation (SFR). Thus, the frequency is restored to its reference value, through the activation of the minute reserve. This control acts over the varying load of generators that participate of the secondary frequency control, assuming these ones the required generation to face the disturbance; thus, restoring the generators that participate of the primary control to theirs initial state previous to the disturbance. In case of conventional thermal power plants the control acts over the fuel that feeds the heater to generate more steam. In case of WF, they do not participate on this type of regulation.

3 SPECTRAL WIND DENSITY

Time scales of wind variations can be represented through the spectral distribution of wind described by Van der Hoven [3] and presented in Fig. 1. The morning peak depends on daily variations of the wind speed, while the synoptic peak is originated by the weather changing patterns, which typically vary in daily or weekly form, even during the seasons of the year. The turbulent peak is due mainly to gusts of wind whose range of time varies between fractions of seconds to various minutes.

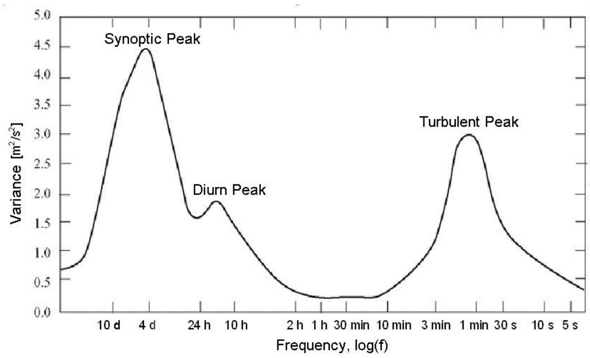

Fig. 1: Spectral Wind Density according to Van der Hoven

Synoptic and diurnal peaks affect the power balance in the long term power system, and it is this period in which an appropriate weather prediction is of vital importance for the correct balance between the system generation and demand. Turbulent variations affect the balance of power in the electric system in the short term (seconds to minutes) and therefore the power quality supplied by the wind generator.

Unfortunately, due to turbulent variations it is difficult that the wind generation contributes with the PFC or the SFC due to the amounts of power and energy involved which should be considered as sure.

Additionally, wind synoptic and diurnal variations make even complex the work that should be carried out by the other conventional plants of the system. Conventional power plants, after including intermittent energies as the wind one, should be able to balance unbalances through:

- Temporal or permanent load variations,
- Faults in the transmission system,
- Faults in conventional generators, and additionally
- Through reduction in the generation due to wind generation variations
    - turbulent,
    - diurnal and
    - synoptic

It may occur, that with large values of wind penetration, in which it should be counted with more reserve of conventional power plants or that the introduction in the electric system of wind generation do not reduce the conventional generation park. In this sense, it is useful to determine the capacity of the WF credit, which is defined as the percentage value in which the conventional generation of the system can be reduced without interfering in the security after introducing a wind farm [4].

Thus, it is settled the importance of the spinning reserve to overcome not only contingencies that occur in the electric system, but also, when there is an important grade of wind generation penetration in the system. In this last case, if the wind speed is reduced, then it suddenly becomes zero or there is a tornado, the electric system needs to have enough reserve to face the lost of partial or total generation that injected the wind generation and to avoid its collapse. As the penetration in power systems of this type of generation increases it becomes necessary the research of alternatives to provide the system enough generation reserve, not only to act in the stage of the PFC, but also in the SFC.

4 POSSIBLE SOLUTIONS FOR THE POWER SYSTEM SECURITY RESERVE

Söder et al [5] analyzes five power systems with different grades of wind energy penetration. Among these systems it is underlined the level of penetration and power in Germany and Denmark power systems.

Denmark has the highest grade of wind penetration in the world and Germany the greatest amount of power installed. Nevertheless, in both cases the required reserve to maintain the system security is supplied from abroad of the regions in which the wind farms are settled. In particular, the spinning reserve of the system in these cases is comprised by conventional power plants outside the region of wind generation. This implies that in spite of the great inclusion of renewable energy sources there still depend on non-renewable energies.
Although in Germany, the electrical energy generated by any form of renewable energy has transport priority in transmission networks, due to delay problems in such lines, it is not always possible to transport all the energy produced. Therefore, it was necessary to develop a special procedure called "generation management" based on intermittent reduction of wind generation. Additionally, security reserves and associated costs are higher than other power systems [6]. On the other hand, in Denmark, very specific situations appeared as regards the management of energy supplied by wind plants increased by market conditions: during various hours per year it was necessary to export free wind energy [7].
As it can be seen, the wind generation with great levels of penetration in Germany and Denmark, involves a complex situation to conform the spinning reserve. Even though, this problem can be studied considering different aspects, in this work, it will be analyzed from two points of view, starting form the previously mentioned power systems. The first problem to be solved is that of the reserve out of the network region where the wind energy is generated and the second one within the region itself.
The solution of the problem of spinning reserve outside the network depends, basically, on interconnection lines with other network regions. Imposed limits are usually smaller than the maximum admissible value of overheating by temperature and they depend on technical and economical factors. Limit values after which certain problems of voltage and frequency instability can occur should be mentioned from the technical point of view. There appear also, limitations due to components installed in lines such as breakers or compensation elements. From the economic point of view, there are also limits due to eventual contracts of energy transference among system agents or additional costs associated to transport.
In order to solve the problem *within the network region,* various possible solutions can be mentioned:

1. Reduce the WF output:
    - § stop or outage of one or various wind generators of the WF.
    - § controlling the position of wind generator blades [8]
    - § use power electronics controllers
2. Use conventional power plants near the WF
3. Controlling power flows in lines using FACTS devices (Flexible AC Transmission Systems)
4. Use energy storage systems

The stop or outage of various wind generators is not always useful to be considered as spinning reserve. Specially, in large wind generators the starting time can take various minutes, which implies a lot of time to recover the frequency of the power system. Another disadvantage of this procedure can be the reduction of the factor of usage of the WF and therefore a decrease in the recovering of the installation.
The control of blades position together with the use of controllers or static converters is one of the most effective forms to vary the output power of wind generators [2]. In this form of variation is maintained, nevertheless, the uncertainty of the power generated when there is no wind or the power plant has been stopped due to the excessive value of wind.
When system workers can not operate the wind generators blades or reduce power with the help of power electronic converters, they should use the spinning reserve control in power plants based on conventional non-renewable energies. Unfortunately, in some cases the inclusion of wind energy does not produce a reduction of pollution in the environment since the amount of conventional generation due to security conditions can not be reduced.
The control of power flows using FACTS devices is carried out in order to obtain ways of power flow within zones of generators that offer spinning reserve and the consumption centres. This alternative is quite restrictive since it requires the availability of enough transmission capacity reserve, a certain meshed grade in the transmission system to allow the energy transport and/or the construction of additional lines of CC to interconnect FACTS devices, which represents a very high cost. The last option to conform the spinning reserve is given by the energy storage systems. This option will be dealt with in more detail hereinafter.

5 POTENTIAL ENERGY STORAGE SYSTEMS USED AS SPINNING RESERVE

Within the storage alternatives to be used as spinning reserve, a classification based on the applied alternatives can be done or other based on potential alternatives or about to be used [9]. In this work the interest is in these potential types of storage due to their qualitative advantages respect to the existent ones. The greatest interest is in the storage with a short time of response such as Flywheels, Super-Capacitors, SMES and Flow batteries. All these storages are characterized by having a response time less than the network frequency cycle (less than 5 ms). The most important characteristics of these technologies are described briefly in table I [9].

Although SMES, Flywheels and Super-Capacitors are very complex and have high installation costs, they result very attractive for the application proposed in this work due to the excellent characteristics that they present, essentially, their good dynamic behaviour and their promissory projection of cost reductions in a near future.

TABLE I. CHARACTERISTICS OF MAJOR ADVANCE ENERGY STORAGE DEVICES

ENERGY STORAGE	SUPER-CAPACITORS	SMES	FLYWHEELS	FLOW BATTERIES
Energy Density [Wh/kg]	5 - 20	0.5 - 5	5 - 50	30 - 200
Power Density [W/kg]	2000 - 18000	180 - 1800	1000	100 - 700
Efficiency [%]	> 95	> 90	> 80	80 - 85
Life Time [Cycles]	> 106 (20 years)	> 106 (20 years)	> 106 (20 years)	> 13.000
Charge Time [s]	30 - minutes	30 - minutes	60 - minutes	10 minutes
Discharge (bridging) time [s]	1 - 30	1 - minutes	1 - minutes	1 - hour
Response Time [ms]	0.5	0.5 - 5	5	1
Power [MW]	0.1	0.3 - 3	1 - 6	10
Capacity of Actual Storage per unit [MJ]	1 - 10	0.3 - 180	7 - 120	100 - 40.000
Terminals Voltage in Standard Models [kV]	0.45 (CC)	2 - 3 (CC)	0.45 (CA)	0.45 (CC)
Portability	Medium	Good	Good	Medium
Reliability	Very High	High	High	High
Commercial use of the Technology	Recent	Medium (>20 years)	Recent - Medium	Very Recent
Long Term Feasibility	Increase of Capacity, Development of New Materials	Increase of Capacity, Incorporation of HTS	Increase capacity, Development of New Materials (Rotor), Use of HTS	Increase capacity, Development of New Materials, Penetration in Industry

Super Capacitors are recognized by their excellent response, very low maintenance requirements and high robustness. Flywheels, on the other hand, have a high energy density, small installation costs and they cause a minimum environmental impact. SMES systems have an excellent dynamic performance, competitive costs and important perspectives of reducing costs in a near future. They also have a high storage capacity and portability. Nevertheless, the most outstanding difference with the rest of ESS is their greater use in industrial applications with excellent results.

In Vanadium Redox flow batteries (VRB), the nominal power and energy storage capacity can be modified through the replacement of the battery cell and the electrolyte tanks, respectively. Another important characteristic of the VRB is its high life time, with more than 13.000 charge and discharge cycles. Besides, there are no CO_2 emissions and the electrolyte is recyclable, in such a way that the battery does not pollute the environment. Having into account all these characteristics, the Redox flow battery is an effective system for load level applications, correction of voltage flickers and regulation of fluctuant wind power [10].

6 PROPOSAL OF INTEGRATION OF ENERGY STORAGE WITH WIND GENERATORS

A wind farm coupled with energy storage could work as any conventional power plant with non-renewable sources. It may be able to provide support not only of spinning reserve but also of reactive power, voltage support and other ancillary services that a standard thermal plant can give at this moment. It could participate of the primary and secondary frequency control. Some authors define the group or generation units that can work as conventional power plants or as “virtual power plants” [2].

Nevertheless, based on the energy source, storage and wind generators characteristics it should be taken into account that the operation form can not be exactly equal than of a conventional power plant. Having into account the high costs of storage systems and wind generators it must be defined:

- A scheme for storage implementation,
- a control and operation strategy to be used in storage systems and wind generators,
- types, amount and size of storage systems to be used ,

in order that the system operator can see these type of power plants as conventional ones.

6.1 Proposal and control strategy

The wind energy conversion system (WECS) scheme is firstly defined, as it is observed in Fig. 2. The generator output voltage is rectified, then adjusted through a DC/DC converter (or chopper) and eventually converted back again into AC by a static power inverter. This regulation scheme allows using non-controlled AC/DC converters which make them simpler and more economic, since the voltage is adjusted only by the chopper and the AC/DC converter [12].

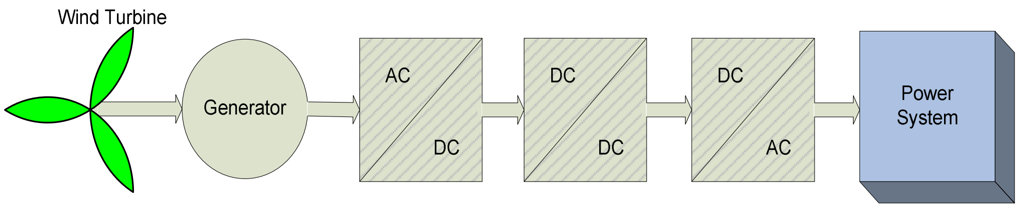

Fig. 2: Scheme of energy conversion of a wind generator

After defining the scheme, it is necessary to establish the way of controlling the frequency. Thus, two alternatives can be stated: *a continuous control mode*, in which the performance of the storage device to balance the continuous changes of demand and small contingencies is permanently required, or *a control mode under severe contingencies,* in which the grade of performance of the storage device is smaller, but the power requirements and those of dynamic response are quite large.

In this work, a *hybrid double energy storage scheme* is proposed which considers two controls and times of activation. A continuously controlled *short term energy storage* for small load and frequency changes, but that can also be used with some voltage problems (flickers, reactive support and voltage sags) and *a long term energy storage* scheme with a control mode that serves as support for the spinning reserve and the secondary control reserve in case of severe contingencies or unpredicted wind interruptions. This storage scheme would solve either local or global stability problems, including not only the PFC but also the SFC.

Either for the long term storage or for the short term one, the separation into two functional modules is proposed. The first one is an energy converter that converts the electrical energy into the energy to be stored and the second module that is the storage system itself. In case of using batteries, the energy converter would be a CC/CC chopper and the energy storage device, the battery itself.

The proposed operation scheme for the WECS with energy storage systems is described in Fig. 3. It is noted that this scheme includes a pitch control of blades for the wind generator; i.e. the possibility of regulating the position of turbine wind blades when.

For the control and management process of power flows, it is suggested the definition of an *energy manager* that, integrated with the main converter of Fig. 2, manages the power from the wind generator/wind farm to the power system and to the energy storage devices.

The energy manager would have basically the functions of managing the energy that flows between the generator, storage devices and the network. It should adapt the CC/CC output converter of Fig. 2 to the input of the power converter of the storage device. The manager would serve also for compensation of reactive power at the start up of the wind generator and for the eventual control of turbine blades in case of being necessary and feasible. Besides the addition of energy storage devices, and in order that the power system operator can actually see the WF as a conventional power plant, it is necessary that reference values of frequency and output power required by the operator are entered to the energy manager as control signals. After this consideration, it should be settled the way in which the wind plant will manage its resources to fulfil the requirements of the system operator. Thus, a strategy of joint operation of the wind generator and the storage devices should be defined. Those factors that should be taken into account are detailed bellow:

- Charge cycles:
  - § when the power system operator requires it
  - § when it can not be possible to transmit due to congestion
  - § when there is no more storage reserve
- The way that batteries are charged
  - § to the top
  - § to the bottom
- The eventual need of reducing the energy given to the power system in order to charge the batteries

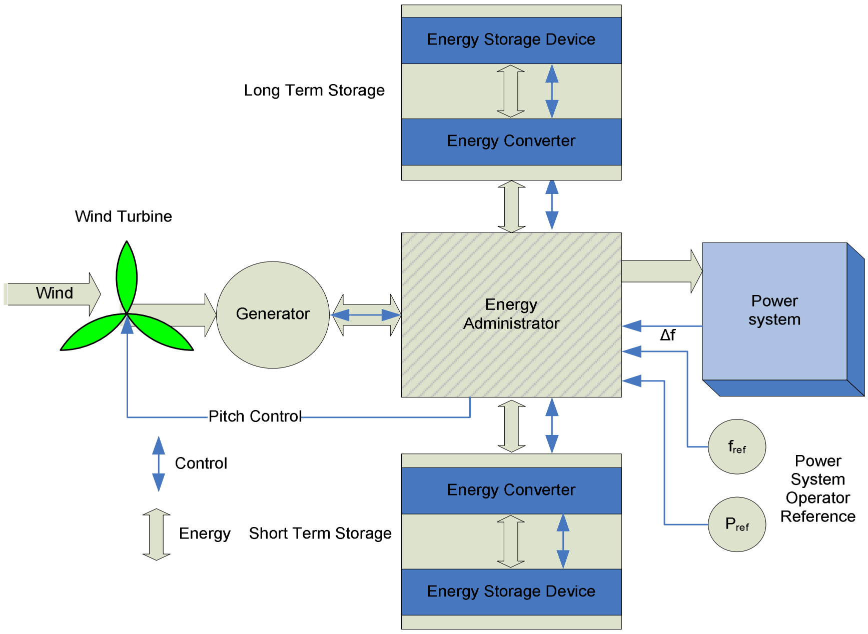

Fig. 3: Complete scheme of wind generator, storage devices and control

After defining the operation mode, an analysis of the storage device scope should be carried out as well as the selection of the type of storage device to be used, everything together with the power system and in accordance with the control-economic policies settled. Those factors that are considered important at the time of determining the storage devices capacity will be mentioned hereinafter as a technical-economical trade-off:

- The capacity of the tie lines surrounding the intermittent generation
- The capacity to vary the position of the rotor blades of wind generators
- Factors that increase the generation variability such as:
  - § wind low average velocities
  - § low factor capacity
  - § dispersion lack in the geographical location of each generator
- Credit capacity without storage i.e. the supply level of the spinning reserve of the system without considering storage.
- The capacity factor of the WF
- The correlation between wind variability and daily curve
- The time before which it is done the dispatch of generators of all the system
- The feasibility of lost of energy supply accepted in the system

6.2 Proposal of type of energy storage devices

The minimum requirements for the short term storage would be:

- Minimum discharge (bridging) time of 30 seconds
- Response time no longer than 1 second
- High discharge rate and re-charge
- Long life time, higher than 2000 cycles [13]

- Units from medium up to large scale according to the system to be protected

The minimum requirements for the long term storage would be:

- Minimum discharge (bridging) time of 60 seconds
- Response time no longer than 1 second
- Minimum requirements of location
- Units of large scale according to the system to be protected

These general requirements provide a base for the selection of the ESS type having into account that the final evaluation of the device should be carried out jointly with the power system with which it should interact and considering the control-economy policies settled. At a first stage, it is considered that for the long term storage, it should be appropriate to use VRB batteries and for the short term SMES ones [9].

7 CONCLUSIONS

Storage and energy generation systems using renewable energy sources have reached a maturity such that they can be used at the same level of large conventional power plants. Their inclusion is, nevertheless, problematic in some cases, mainly when they are based on variable energy sources as wind generators. The solution to these problems is proposed in this work with the joint consideration of these generators with energy storage systems. Nevertheless, costs of these storage devices oblige to carry out not only an exhaustive analysis about their control modes but also technical-economical feasibility studies that ensure their success.

New concepts and strategies should be developed for those power systems, which having a great penetration of intermittent power, want that these power plants collaborate with the power system security. Those system operators who count with a high penetration of wind generation should carry out a deep adaptation in the planning and operating system form. Besides, the construction of new models of storage devices should be considered, as well as control and operation strategies to support the electric system security reserve.

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