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ENERGY STORAGE SYSTEM FOR WIND FARM APPLICATIONS: APPLICATION METHODOLOGY

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ABSTRACT
This paper proposes a methodology for determining the optimal size of an energy storage system (ESS) for wind farm applications. Calculations are based on wind-related power fluctuation, wind farm capacity and ramp rate limits (MW/minute).

KEY WORDS
Wind farm, energy storage system, power fluctuation, isolated system.

1. Introduction

Wind power is the fastest growing source of energy in the world today [1] and its growth rates have exceeded 30% per year over the past decade.
Figure 1 shows the new MW capacity installed by year by the two largest wind power developers; Europe and USA [2]. The cumulative global wind energy generating capacity reached closed to 40.000MW by the end of 2003 [3].

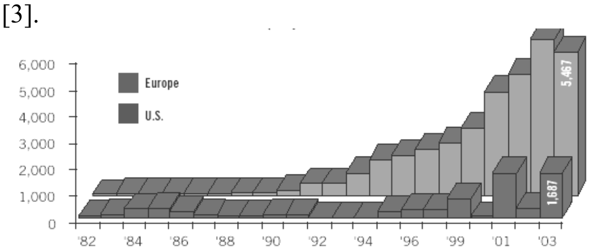

Figure 1.- Comparing European and American Growth[2]

The main drivers for the development of the wind industry in the United States are:
- Federal Renewable Energy Policies such as the Production Tax Credit (PTC)
- State-Level Renewable Energy Initiatives, such as the renewable Portfolio Standard and the green power purchasing.

These jurisdictional supports together with technological advances and the need for a new source of energy capable of meeting the world's growing power demand, make the wind power one of the most promising industries in the future.
According to the European Wind Energy Association and Greenpeace, there exist no barriers for the wind to provide 12% of the world's electricity by 2020. In the case of the United States, the American Wind Energy Association forecasts that wind power will provide 6% of the US's electricity by 2020 if the wind industry maintains an annual growth rate of 18%.
However, wind power plants, like all other energy technology, have some environmental impacts. Some of these drawbacks are:
1. Environmental Issues, such as sound from the turbines, birth deaths and wind tower/blades shadow effects.
2. Interconnection Issues: The connection of any wind turbine to parallel operate with the electric power system influences the system operating point (load flow, nodal voltages, power losses, etc). These changes in the electric power system state bring up new system integration issues that system operators and power quality engineers must take into account. These interconnection issues can be divided in two, operational issues and electrical issues.

a. Operational Issues

The operational issues include the unit commitment and the spinning reserve.

i. Unit Commitment

The unit commitment problem is to schedule specific or available generators (on or off) on the utility system to meet the required loads at a minimum cost subject to system constraints. This schedule is usually made at least 24 hours in advance.
The most conservative approach to unit commitment and economic dispatch is to discount ANY contribution from interconnected wind resources due to the wind variability.

ii. Operation Reserve

A grid's operating reserve consists of all reserves available to serve customers connected to that grid. Utilities carry operating reserve to assure adequate system performance and to guard against sudden loss of generation, unexpected load fluctuations, and/or unexpected transmission line outages. Operating reserve is further defined to be spinning or non- spinning reserve. Typically, one-half of systems operating reserves are spinning, so that a sudden loss of generation will not result in a loss of load. Any probable load or generation variations that cannot be accurately forecast, such as wind power, have to be considered when determining the amount of operating reserve to carry.

b. Electrical Issues

These factors will be considered in the following section in a more detailed form.

2. Electrical Issues

There is some negative influence related to wind turbine generator system operation in power systems. This influence on the electric power system depends on wind variations and on the wind turbine technology. The impacts on the electric power system can be group as follows:

- Power quality: Voltage variations, flicker, harmonics, power-flow variations
- Voltage stability
- Angle stability
- Protection and control

The IEEE 1547 [5] and the IEC 61400-21 [6] can be considered the bases to standardize and evaluate the impact of such wind turbine generation systems on the electric power system.

IEEE 1547 abstract:

"The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency and accuracy in the measurement and assessment of power quality characteristics of grid connected wind turbine generator systems (WTGS)"

IEC 61400-21 abstract:

"This standard focuses on the technical specifications for, and testing of, the interconnection itself. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. It includes general requirements, response to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests."

The following table summarizes technical specifications for interconnection and power assessment covered in both standards.

	Interconnection system response to excursions	Power Quality Assessment
IEEE	➢**Voltage** ➢**Frequency**	
IEC	➢**Voltage** ➢**Frequency**	➢**Voltage fluctuation** – **Continuous operation** – **Switching operation** ➢ **Harmonics**

Table 1.- IEC and IEEE technical specifications

As can be inferred from the previous table, both standards overlooked one the most significant signature of wind farms, it variability, i.e. power fluctuations.

These power fluctuations are due to [7]:

1. Gusty wind variations
   a. Spectral Frequencies from 1-10 Hz.
2. Shadow effect
   a. Spectral Frequencies from 1-2 Hz
   b. Torque variations up to 30%
3. Complex oscillations of the turbine tower, rotor shaft, gear box, and blades
   a. Spectral Frequencies from 2-100Hz
   b. Torque variations up to 10%

Fig.2 shows the actual output power data of two large wind power plants with 35MW and 150 MW rated capacity.

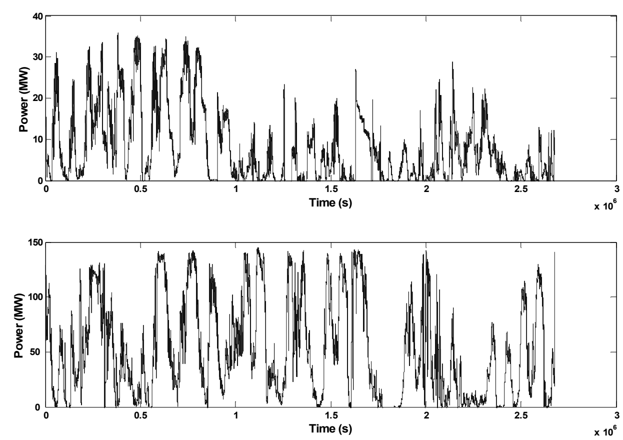

Figure 2.- Wind power output for two wind farm during one month (May 2003)

Even though the technology used in the construction of the small wind farm is more than a decade older than the large one, power fluctuations are still an issue. Fig. 3 is a zoom in of the previous figure and shows the magnitude of these power fluctuations.

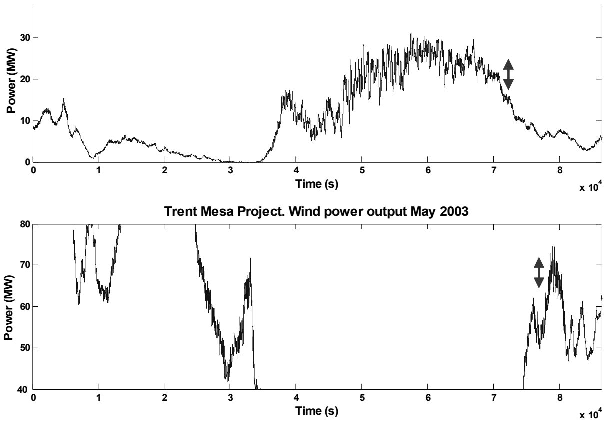

Figure 3.- Power fluctuation comparison

Wind turbine manufactures usually provide power curves (Fig.4) to developers in order to determine the amount of power that will be transferred by into the grid for a single turbine, given the wind speed. However, those figures represent only the mean values, since there are a series of stochastic values that cannot be controlled, and that create additional power fluctuations.

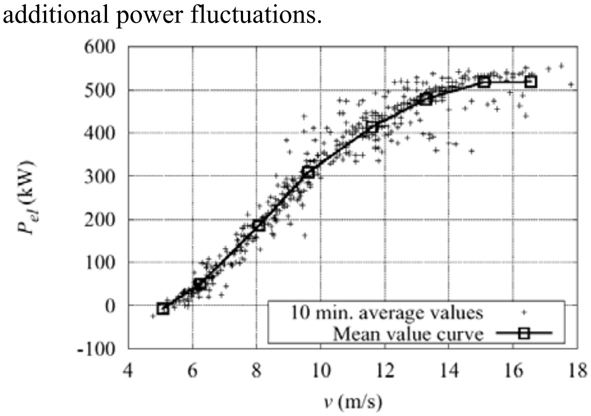

Figure 4.- Typical power curve of a wind turbine

3. Power Fluctuation effects

Wind output power fluctuations can have different effects on the electric power system, but the most significant ones are voltage variation, and frequency variation in small or isolated systems.

As the power changes, the reactive power required by the turbines changes, and therefore the voltage variations are expected, especially when the wind farm is located at weak points of the system. In order to compensate for such voltage variations and keep the voltage close to its rated value, several solutions are available, such as simple capacitor banks, Static Voltage compensator (SVC), or Static Compensators (STATCOM).

A different approach must be taken for frequency variations due to power fluctuations. Normally, for wind farm connected to big systems do not present a major problem in terms of frequency variations, due to the stiffness of the system. However, small or isolated systems, with slow or no automatic generation controls a mismatch between generated and absorbed can have a significant impact of the system frequency unless significant spinning reserve are present.

In order to fight back against these negative effects, countries and small isolated systems with high wind penetration factors have developed special purchase power agreements (PPA) requirements or indexes for wind farm developers. Table 2 shows a summary of some of these new indexes of power requirements.

	Ramp Rate dP/dt	Instantaneous	Average (Max variation)
Netherlands	<12 MW per min		
Denmark	$<0.1*P_{nom}$ per min		<0.05 P_{nom} per 60 sec period
Hawaii	<2 MW per min	1 MW change per 2 sec scan	<0.3MW per 60 sec period
Germany	<0.1 P_{nom} per min		
Scottish Grid Code	No limit for P_{nom}<15 MW per min P_{nom}/15 for P_{nom}=[15-150] MW per min 10 MW for P_{nom}>150 MW per min		

Table 2.- Wind farm output power requirements

These power requirements will guarantee minimum impact on the system voltage and frequency control. However, today's wind farms have LIMITED capacity to reduce the rate of change of power, especially the down ramp rate.

At high wind speed (above the rated wind speed) active and stalled pitch control among other strategies can help to keep the output power under control. However, modern wind turbines are design to obtain as much power as possible at low wind speeds (Fig. 5) making them very vulnerable to wind variations.

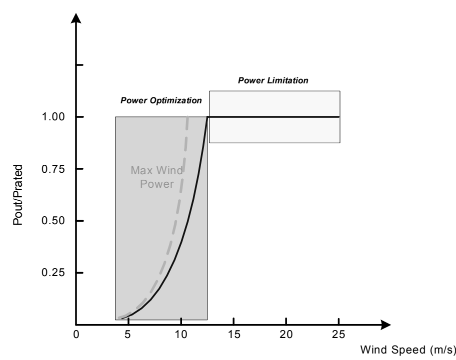

Figure 5.- Control strategies along the power curve

4. Solutions

In order to reduce the effects of wind power variations and meet the power purchase requirements required by the electric utilities two solutions can be considered

- Higher spinning reserves.
- Wind turbines operating below the power level in the wind conditions (spilling energy).
- Energy storage systems.

The increase of the spinning reserves in order to face fast wind power variations it is a very costly solutions.
A better approach would be the use of an energy storage system that could deliver the required power when needed.
Work has been done on developing large scale energy storage that potentially overcomes these issues by absorbing undesirable power fluctuations and therefore providing firm peaking capacity [8]. However, a less costly solution should be explored based exclusively on ramp rate limits.

5. Application Methodology

In 2000, the National Renewable Energy Laboratory (NREL) began a Wind Program to accurately assess ancillary services burdens or benefits of wind powered electricity [9]. To accomplish this goal a systematic monitoring and analysis of several wind farm facilities is being undertaken.

The data used in our study is the actual output power data collected by NREL from two large wind power plants in the United States, from May 2003 to August 2003 on a second-to second bases. Table 3 describes the sites while Fig. 6 shows the power output of both wind farms during August 2003.

Sites	Number of Turbines	Capacity
Site 1	≈100	150 MW
Site 2	≈100	35 MW

Table 3.- Wind farm sites overview

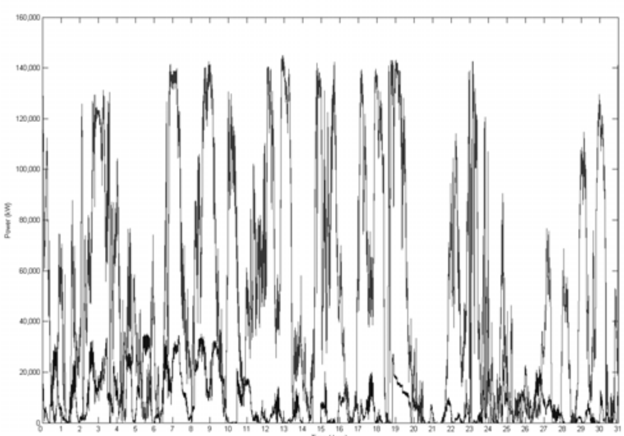

Figure 6.- Wind Farms Power Output during August 2003

5.1. Control scheme

As we have seen in section 3, there are different indexes that can be used as reference to limit the wind farms power fluctuations. However, among them, the most representative and common one is the ramp rate index. The results shown in this study are exclusively based on the ramp rate limits.

The formula for measuring the ramp rate of the wind farms is presented below, Eq. (1), and assumes that the power fluctuations are monitored using a 1 second scan-rate.

$$RR = P(t) - P(t-60) \qquad (1)$$

where:
RR = Ramp Rate
P(t) = Instantaneous wind farm power output, present scan
P(t-60) = Instantaneous wind farm power output 60 seconds prior the present scan

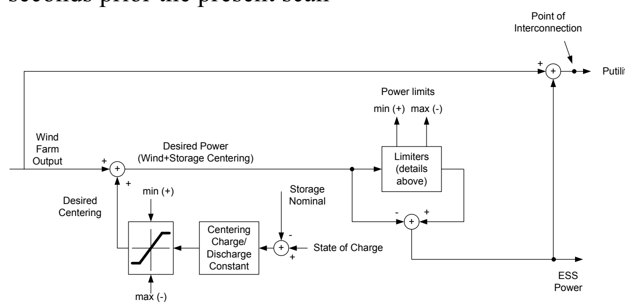

Figure 7.- Energy Storage system for wind farm systems. System overview

Fig. 7 shows an overview of the proposed control structure for the Energy Storage System (ESS). The ESS is a shunt connected device that will inject/absorb energy into/from the system in order to meet the purchase power agreement at the point of interconnection.

A more detailed block diagram of the control algorithm is shown in Fig.8. The Ramp Rate Limiter will compare the new input value to the "corrected" power, one minute ago. If the change in power is more (less) than the "corrected" power one minute ago plus (minus) the Ramp Rate (RR) limit, the output of the limiter is set to the value one minute ago plus (minus) the RR limit.
In order to keep the ESS at its nominal value, a method to center the system is required. This mechanism also causes power to flow in and out the grid; therefore it must be included in the control scheme.
The buffered values (or "corrected" power) will be ones that actually flow in/out the grid; either the limited wind far output power or the limited desired power. This decision will be based on the ESS needs to maintain its nominal energy storage.

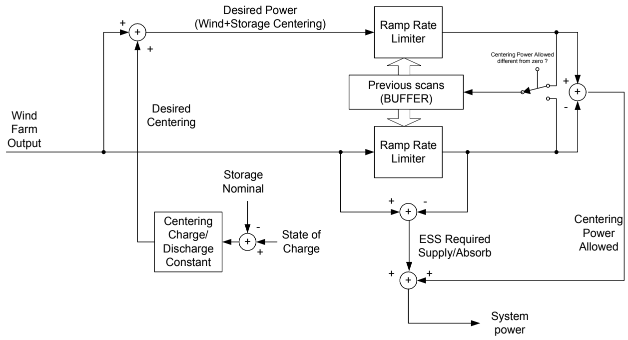

Figure 8.- Energy Storage system for wind farm systems. Power limiter details

5.2. ESS Restrictions

The ESS under study is not designed to compensate the wind farm power fluctuation during start-ups, shut-downs or during anomalous conditions, such as maintenance periods or faults situations. Therefore a statistical analysis must be carried out to discriminate wind related power fluctuations from operational events.

These statistical studies also help avoid possible outliers due to errors in the measurement system.

Fig. 9 and Fig.10 show the probability density function (PDF) of the ramp rate index for site 1 and site 2 (from May 2003 to August 2003). Wind farm capacities have been scaled to 100 MW to be able to compare results.

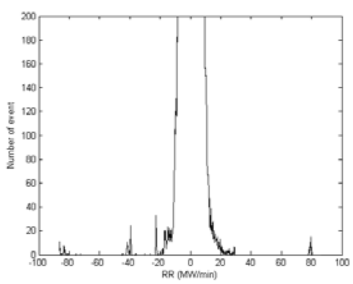

Figure 9.- RR probability density function for site 1 (150MW scaled down to 100 MW). Zoom In.

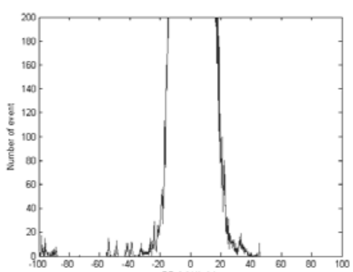

Figure 10.- RR probability density function for site 2 (35MW scaled up to 100 MW). Zoom In.

One possibility is to limit the maximum ramp rate that the ESS should compensate for. Thus, Fig. 11 would show the ESS compensation range/s for both wind farms.

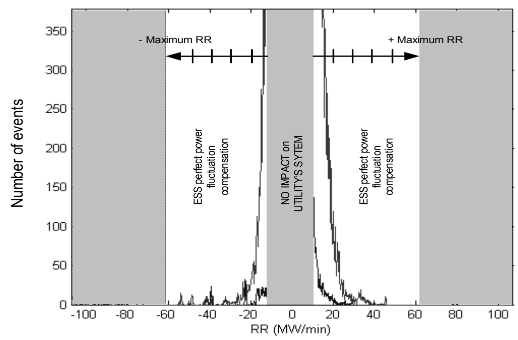

Figure 11.- ESS correction range

However, analysis of the power and energy required to compensate for such ranges is not the optimal one. Figures 12 to 15 show the ESS requirements for different maximum ramp rate limits. The minimum Ramp Rate limit was kept constant to $0.1*P_{nom}$ (or 10 MW/min for a 100 MW wind farm) based on Table 2.

A close observation of the results revealed that some of the points were unique, and therefore with low probability of occurrence.

In order to minimize the size of the ESS a different approach is proposed:

1. Find the ESS energy probability density function (PDF) using algorithm shown in section 5.1.
2. Select the most probable Energy range based on the PDF from 1. Cost/Benefit analysis could help determine the optimal range.
3. Using exclusively the energy range selected, find the ESS Power PDF.
4. Select the most probable Power range based on the CDF from 1. Cost/Benefit analysis could also help determine the optimal rated power.

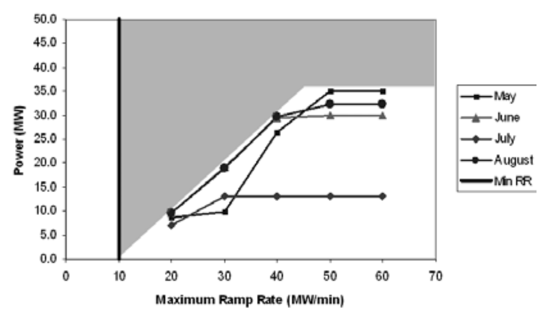

Figure 12.- ESS Power site 1 (scaled down to 100MW)

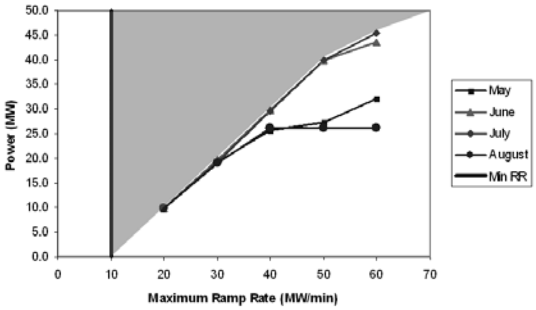

Figure 13.- ESS Power site 2 (scaled down to 100MW)

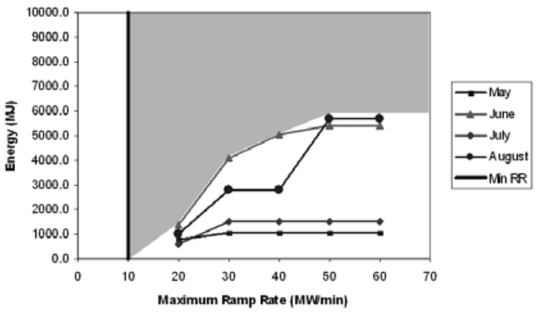

Figure 14.- ESS Energy site 1 (scaled down to 100MW)

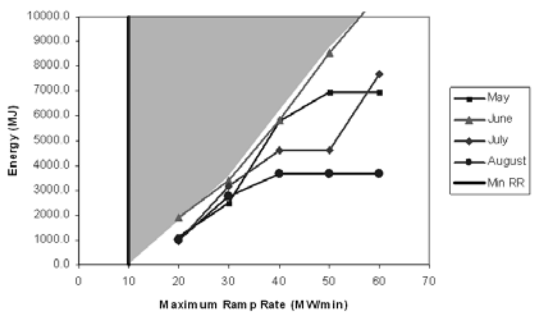

Figure 15.- ESS Power site 2 (scaled down to 100MW)

6. Results

The control scheme was implemented in MATLAB as well the algorithm to calculate the PDF. All the wind power data were scaled to 100 MW and the Ramp Rate limit was kept constant to 0.1*$P_{nominal}$ or 10 MW/min.

6.1. Step 1: Energy PDF.

Fig. 16 shows the distribution of the ESS energy among 10 MJ bins for both wind farms.

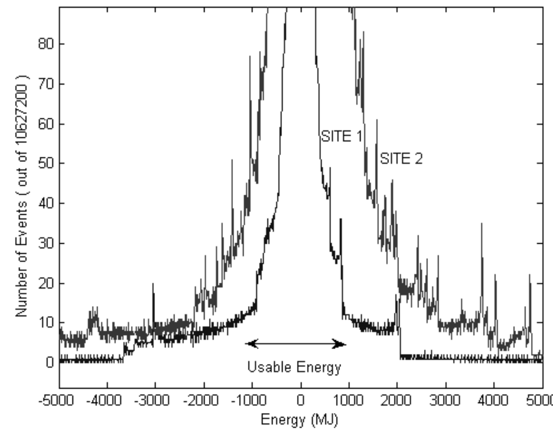

Figure 16.- Energy PDF

The energy storage results shown in Figures 16 are of the usable range, assuming a zero nominal energy value. The total energy required by the ESS may change according the system deployed. Thus, an ESS based on an inverter-chopper topology, with capacitor as an energy storage, will have a nominal energy point of 5/8 p.u.. This is assuming that a symmetric energy range is desired (Fig. 17).

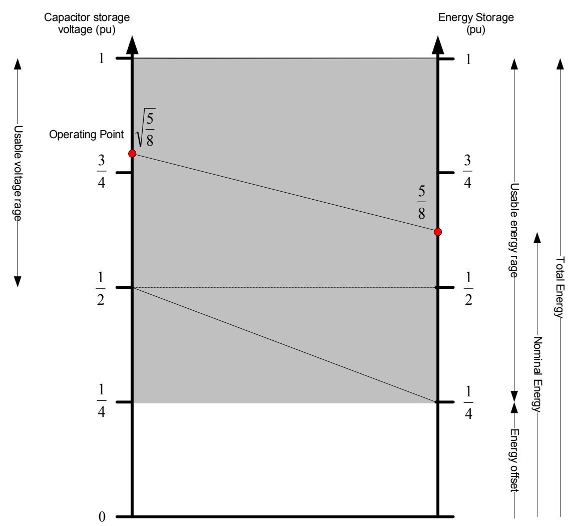

Figure 17.- Energy range vs. Chopper capacitor voltage

6.2. Step 2: Usable Energy range

Given the Energy PDF a usable energy range must be determine based on

- the event probability occurrence
- cost of the energy system
- system requirements

For this example ±200MJ (or 400MJ of usable energy) was selected based on the low probability of higher energy values.

6.3. Step 3: Power PDF.

Fig. 18 shows the ESS power probability density function, based EXCLUSIVELY on the periods when the ESS Energy is within the ±200MJ range.

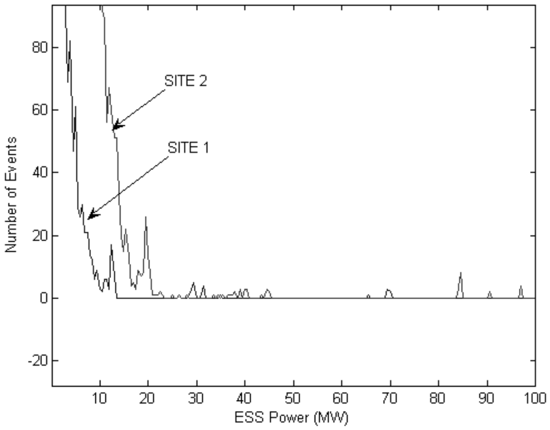

Figure 18.- Power PDF for Energy=[-200 +200] MJ

In this particular case, a good estimation could be between 10 and 20 MW for the ESS.

7. Conclusions

This paper proposes a methodology for determining the optimal size of an energy storage system for wind farm applications.

The main advantage of the proposed ESS compared to large scale energy system is the reduction in size, yet meeting the system requirements for the majority of events.

This approach presents the following limitations

- Data set.
  In order to get accurate results, a large historical data set in needed.
- Wind turbine technology & diversity factor.
  It is not possible to obtain a general equation that determines the ESS requirements given the wind farm capacity. As can be inferred from previous results technology and/or diversity factors have an effect on the size of the ESS. However, as a rule of thumb we could say that the requirements for the ESS are:

a.- **Power ESS ≈ 15% of $P_{\text{wind farm capacity}}$**. For example a wind farm with a capacity of 100 MW wind farm, would need an ESS of 15 MW for a Ramp Rate limit of 10 MW/min.

b.- **Energy ESS/ P_{ess} ≈ 25 secs**

The main goal of this application methodology is to help the development of a new ESS technology that allows for a higher wind power penetration factor in small or isolated systems.

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