Impact of Wind Speed Correlation on the Operation of Energy Storage Systems

Mathieu Davril[1,a],Xiaoyuan Xu[1] and Zheng Yan[1]

[1]*Key Laboratory of Control of Power Transmission and Conversion, Ministry of Education, Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

Abstract. Renewable resources technologies such as wind power currently demonstrate a worldwide popularity thanks to their environmental friendly status and their economic potential. The variability of the wind power output implies the use of practical solutions such as energy storage systems in order to retain the power system stability and reliability. The wind geographical correlation between different wind farms also impacts the system reliability. This paper studies the effects of the wind speed correlation level on the performance of the associated energy storage system (ESS). Wind correlated model using Weibull probability distribution and Nataf transformation is presented. Energy storage system model and energy management algorithm are developed. Both are applied to a modified IEEE-RTS power generation and load model. The case simulation results indicate that the wind speed correlation level between two wind farms impacts the power distribution inside energy storages and that it needs to be considered in order not to overestimate ESS benefits on the system.

1 Introduction

Renewable energies are seen as a way to fight against environmental issues. They are mainly subject to intermittency and randomness due to resource uncertainty. That introduces technical challenges, such as power quality, control and reliability [1]. With the increase of the renewable energies penetration rate, it becomes important to develop methods to evaluate the impact of these resources generation on power system reliability and to manage this power output more efficiently.

The use of the energy storage system (ESS) has shown promising results in this area, and many publications discuss about this topic. Analytical procedures were proposed to evaluate operational reliability and energy utilization efficiency of power systems with high wind power or solar power penetration [2]. The impact of the initial stored energy and the rated capacity of energy storage on the system reliability has been shown [3]. Operation and control methodology of battery ESS were investigated [4]. Energy management algorithm and rule-based control method for the integration of wind and solar power were proposed [5, 6].

Wind farms at relatively close geographical locations can have their wind speeds strongly correlated. A multitude of methods has been developed to simulate correlated wind speed [7-9]. The important impact of a high correlation among wind farm on locational marginal prices has been studied [8].Taking the correlation level into account has also been found relevant on the study of

[a] Corresponding author: davril.mathieu@gmail.com

economic dispatch [9].The significant impact of the wind geographical correlation level on reliability studies has been demonstrated [10].However no study has been realised about the impact of the correlation level among wind farm on the energy storage system associated.

The added value of this paper is the consideration of an ESS working together with wind farms of different correlation degrees. The model of wind farms with different correlation levels and the ESS model are descripted. There are applied to an updated version of the IEEE-RTS system. Correlated wind speeds are obtained thanks to an algorithm based on the Weibull probability distribution and the Nataf transformation. An energy management algorithm is also elaborated. System adequacy assessments indices as well as energy storage characteristics are studied. Simulations are carried on the MATLAB software. The impact of the correlation on the system adequacy assessment indices and on the characteristics of the ESS is finally analysed.

2 System Modelling

2.1 Generating and Load Model

Two-state models are used to simulate the generating units operating cycles. A unit can move from an available state to an unavailable state following a failure rate (λ) and returns to an available state with a repair rate (μ). The time to failure (TTF) and the time to repair (TTR) are then used to produce an up-and-down operating cycle of the unit.Peak load models are usually used in reliability analysis. The load model used in this paper is an hourly varying load curve over a simulation period of 1-year. Although more accurate models for short operating periodslike 5 min exist, it is more useful to simulate the effect of unit ramp rates, a part that is not considered in this paper. It is assumed that load level within an hour is constantand the hourly time varying load model has been adopted.

2.2 Correlated wind Speed Model

Given as input data the Weibull distribution of random variables $v = (v_1, \dots, v_N)$ and their associated correlation matrixR_v:

$$R_v = \begin{pmatrix} 1 & \rho_{1,2} & \cdots & \rho_{1,N} \\ \rho_{2,1} & 1 & \cdots & \rho_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{N,1} & \rho_{N,2} & \cdots & 1 \end{pmatrix} \tag{1}$$

where N is the number of wind farms and $\rho_{i,j}$ the correlation coefficient between farm i and farm j.It is possible to generate a set of correlated standard normal values $w = (w_1, \dots, w_N)$ from a set of independent standard normal values $y = (y_1, \dots, y_N)$. First, a Gaussian quadrature technique is used to generate the correlation matrix R_w of the set of correlated normal values from the correlated matrixR_v of the random variable following a Weibull distribution. Then the set of correlated normal values w is generated through an orthogonal transformation, i.e.:

$$w = Ly \tag{2}$$

where L is the lower triangular matrix of the Cholesky decomposition of the correlation matrixR_w.

From the set of correlated normal values$w$, it is then possible to generate samples of correlated wind speed $v = (v_1, \dots, v_N)$ thanks to the inverse of the Nataf Transformation[11, 12]as follow:

$$v_q = F_q^{-1}(\phi(w_q)); q = 1, \dots, N \tag{3}$$

where F_q^{-1} is the inverse of the cumulative distribution function (cdf) of v_q, and $\phi(.)$ is the cdf of the correlated standard normal variables. The samples of correlated wind speed values finally obtained follow the correlation matrix R_v and a Weibull probability distribution.

2.3 Power Output Model of the Wind Turbine Generators

Wind speed values can be converted in power output values by using the power curve of the installed wind turbine generator (WTG). The power curve of a WTG can be easily modelled as follows

$$P_{wt} = \begin{cases} P_r \times (v_t - v_{in}) \div (v_l - v_{in}) & v_{in} < v_t < v_r \\ P_r & v_r < v_t < v_{out} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where P_{wt} is the WTG power output at hour t, v_t is real wind speed at hour t, P_r is the WTG rated power, v_r is the rated wind speed, and v_{in} and v_{out} are the WTG cut-in and cut-out wind speed.

2.4 Energy Storage Model

In this paper, atypical energy storage is studied: the battery. Battery energy storage can be characterized by four parameters: the charging/discharging rate, the maximum storage capacity, the discharging limit and the state of charge (SOC). The SOC is the available energy remaining in the battery unit. In fact, one of the main advantages of the battery is its fast charging/discharging rate. Our simulations do not take in account the ramp rate of conventional generators (CGs). The charging/discharging rate of battery units will not be considered in our study. The charging/discharging cycle will be modelled as a step function.

3 Evaluation Method

The operating strategy instigated in this paper is described as follows. Each wind farms possess the same number n of WTGs with the same parameters. The maximum total wind farm power output will coincide with a fixed percentage F_{pl} of the peak load. This percentage will be considered as the integration percentage of wind power into the energy production of our system and will be equally dispatched between wind farms. In other words, for a total number m of wind farms connected to the grid, each wind farm WTGs rated power P_r is given by equation (5).

$$P_r = F_{pl}/(m \times n) \tag{5}$$

The coordination strategy of the ESS can be described as follows: when the power amount of the generating system is more than the load at time t, the ESS is in charging mode. The power output of wind farms is used to charge the ESS. If the SOC is less than the amount of power available, the energy storage (ES) will charge at its maximum capacity and the remaining energy will be added as surplus power in the system. If the power amount of the generating system without wind farm is less than the load at time t, but it becomes more when we take in account the wind farms production, there is a surplus of power. Then the ESS is still in charging mode. The excess of power from wind farms is used to charge up the ES to the limit of batteries maximum capacity. Finally if the power amount from the generating system including wind farm is less than the load at time t, the ESS is in discharging mode. The remaining energy in ES is dischargeduntil the minimum energy allowed in the storage. The model of ES following this operating strategy is givenby

$$P_{mt} = P_{gent} + P_{wft} - P_{lt} \tag{6}$$

$$P_{est} = \begin{cases} -\min(P_{mt}, P_{wtf}, E_{SOCt-1}) \\ -\min(P_{mt}, E_{SOCt-1} - E_{msc}) \end{cases} \quad \text{if} \quad \begin{matrix} P_{mt} \geq 0 \\ P_{mt} < 0 \end{matrix} \tag{7}$$

where $P_{mt}$the power margin at hour t is, P_{gent} the generating system power output at hour t, P_{wft} the total amount of power generated by all wind farms at hour t, and P_{lt} the load at hour t. P_{est} represents the amount of power provided or saved at hour t by the ESS. It can be either positive when the ES is discharging, or else negative. $E_{SOCt}$is the available energy in the energy storage at time t and E_{msc} represents the maximum storage capacity.

It is then possible to evaluate if the system is at failure state or provide a surplus of power at hour t thanks to the followingequation:

$$P_{s/ft} = P_{mt} + P_{est} \tag{8}$$

where $P_{s/ft}$ stands for the power lack or surplus at hour t.

In order to show the impact of the correlation level on the energy storage improvement for the wind power management,we will analyzethe system reliability by using adequacy assessment indices: theloss of load expectation (LOLE) and the loss of energy expectation (LOEE). Another index used is the expected energy stored in the energy storage (EESES) [13]. This last index enables us to determine how much energy the ESs will be able to save from the surplus of power coming from the global generating system.

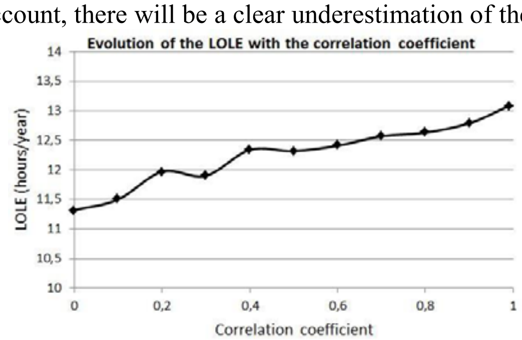
4 Case Study

The simulations are carried on a generating system created on the basis of IEEE-RTS. The original IEEE-RTS is a 24 bus system with 32 conventional units.The peak demand had been increased to 3150MW in order to simulate the impact of WTGs and ESSs.In order to study the impacts of wind speed correlation level, two wind farms are considered in this study.Wind speeds follow the Weibull models. For one Weibull model, the scale parameter is set to 7.5 and the shape parameter is 3. For the other model, the scale parameter is set to 7 and the shape parameter is to 2. The wind speed correlation level variation is studied from 0 to 0.99. ES capacities are taken from 50MW to 175MW. The wind power integration percentage varies from 5% to 25% of the load demand.

4.1 System Adequacy with ES and Wind Speed Correlation

The variation of LOLE and LOEE indices with the increase of wind speed correlation level is shown in Figure1. The ES capacity is 150MW and the wind power integration percentage is taken at 20%. It can be observed that the LOLE and the LOEE will increase with the increase of the correlation level.

Figure 2 shows the variation of the LOLE and the LOEE function of ES capacity and wind speed correlation level. It can be observed that the decreasing rate for both the LOLE and the LOEE is slightly higher with the increase of the wind speed correlation level. Results show that the wind speed correlation level impacts lightly the beneficial contribution of the ES capacity to the system adequacy. However it has to be noticed that for a fixed ES capacity, the LOLE and the LOEE are always higher with a greater wind speed correlation level. If the wind speed correlation level is not taken into account, there will be a clear underestimation of the LOLE, the LOEE and the benefit of adding ES.



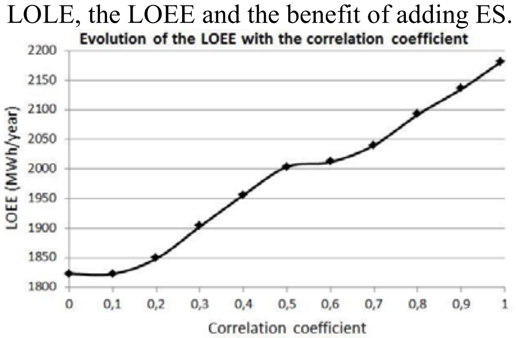


Figure 1. Effects of the wind speed correlation level on LOLE and LOEE.

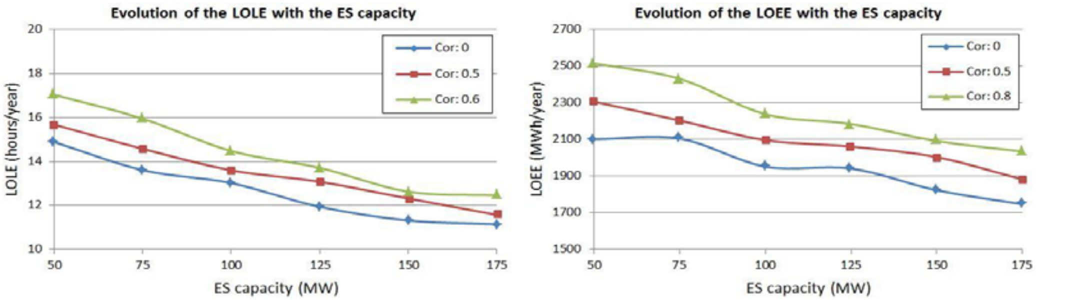


Figure 2. Effects of ES capacity on LOLE and LOEE.

4.2 Evolution of the Energy Stored in ES with Wind Speed Correlation

Figure 3 gives the effects of wind power integration percentage and ES capacity on EESES. For the figure in the left, the ES capacity is fixed at 100MW. It can be seen that although in the case of a wind speed correlation level of 0 the EESES noticeably decrease with the integration percentage, it decreases much slowly with a correlation level of 0.5 or 0.8. At a low correlation level,the variance of the power output of the two wind farms added together can be considered as low.Hence,the combination of low wind power variance and more power available lead to a decrease of EESES. In the case of a high correlation level, the probability of wind power output peak increases.With the increase of wind power integration, those peaks involve a bigger power surplus and consequently a growth of the EESES. This increase implies more charging/discharging cycles for the batteries and a more frequent utilization of the ES capacity.

For the figure on the right, the evolution of the EESES with the increase of ES capacity is depicted. The wind power integration percentage is taken at 20%. The EESES increases with the augmentation of ES capacity for each of the three correlation levels. It can be explained by the increase of storage available for wind power peaks. But it can be observed that the increasing rate of the EESES becomes higher with the growth of the wind speed correlation level. From the smallest ES capacity to the largest, the EESES increases of 484MWh, 547MWh and 617MWh for respectively the case of a correlation level of 0, 0.5 and 0.8. This result is justified by the wind power output peaks that are likely to be largest in the case of a strong correlation compared to a weaker one.

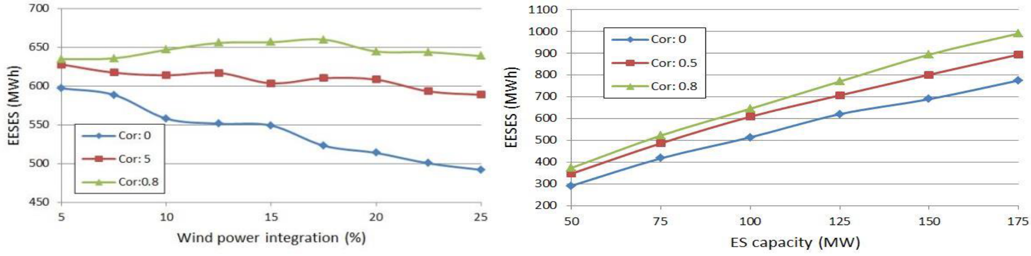


Figure 3. Effects of wind power integration percentage and ES capacity on EESES.

4.3 Evolution of the Allocation of the Energy Inside the ESwith Wind Speed Correlation

The allocation of the energy stored inside the ES is studied, and results are shown in Figure 4 with respectively wind power integration percentage of 10% and 20%. The ES capacity is chosen to be 100MW. The utilization frequency of the ES capacity globally decreases with the augmentation of wind power integration percentage thanks to the increase of available power capacity ensuing. It can be observed that for both studies, the utilization frequency of the ES being charge between 20% and 30% of its capacity increase with the correlation level. It means that ES are more frequently put in a state of deep-discharge in the case of a high correlation level than on a lower. We can also notice that the gap between the three correlation level increases with the integration percentage for the same charging state of 20/30%. For an integration percentage of 10%, the difference between the case of a correlation level of 0 and 0.8 is 0.5 hours/year. For an integration percentage of 20%, it becomes 1.8 hours/year. The frequency of ES deep-discharge state increases with the wind power integration growth. This result is in accordance with the one extracts from Figure3.

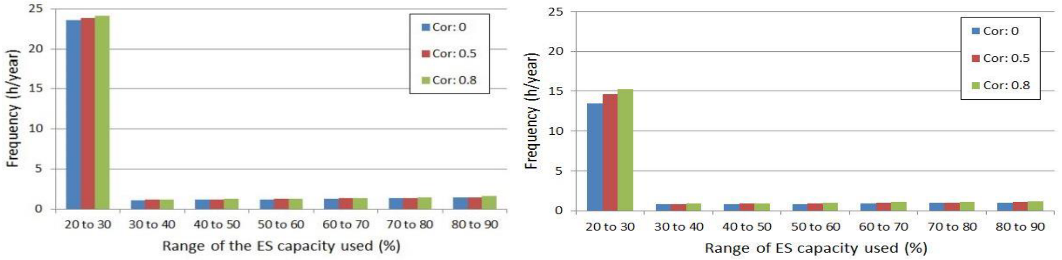


Figure 4. Allocation of the energy stored inside the ES for 10% and 20% of wind power integration.

5 Conclusion

This paper proposes a study of the effects of wind speed correlation on operation of the energy storage system (ESS) associated with wind farms. Generating system and load, wind speed and EES models have been presented. The Weibull probability distribution and the Nataf transformation have been used to simulate correlated wind speeds. The effects of wind speed correlation on energy storage characteristics are studied through the evolution of the energy stored inside the energy storage and the allocation of this energy. The results show that not considering the wind speed correlation could lead to an underestimation of adequacy assessment indices and an overestimation of the profit of adding ESS. It also shows that a strong correlation level will put more pressure on energy storage (ES): it will cause an increase of the number of charge/discharge cycles and of deep-discharge states. Besides not considering the wind speed correlation could lead to an overestimation of the lifetime of the ESs as well as underestimatethe associated costs.

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