Relationship between Production Capacity of Wind Power Stations and Needs of Ancillary Services

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Abstract—**Number of wind power stations has been increasing in the world for last years. Of course, this causes that electrical power amount produced by this kind of power station and subsequently delivered to electricity transmission systems has also been growing. On one hand, this brings positive effects with respect to living environment because production of coal, gas or nuclear power stations can temporarily be reduced while wind blows. On the other hand, this sets enhanced demands on needs of ancillary services. This paper deals with these connections and demonstrates obvious consequences that arise from them.**

I. INTRODUCTION

Wind energy produced by wind power stations is one of renewable resources that has become very popular and used world wide in recent years. It brings many benefits to mankind particularly with respect to living environment. For instance, production of other types of power stations such as coal, gas or nuclear is supposed to be reduced due to wind blowing because, as a result, wind power stations produce extra electrical power that is delivered to electricity transmission systems. This implies that living environment is less polluted because production of 'messy' power stations is restrained.

Nevertheless, the problem is that time periods within which wind is going to blow together with volume of blowing is hardly ever reliably predictable to the future. This causes that production of wind power stations cannot be scheduled in advance. Therefore, the production is not usually taken into account while electricity transmission system operation planning performed by TSOs (Transmission System Operators) is under construction. On the contrary, extra electrical power produced by wind power stations and delivered to electricity transmission systems (while wind blows, of course) is classified as a failure that exhibits by way of temporary power surplus in the systems. Consequently, such a failure is assumed to be decayed by employment of appropriate types of ancillary services performed by TSOs as well. It is obvious that this matter of fact puts increased requirements towards needs of particular types of ancillary services.

Seeing that wind blowing 'strategy' can be considered as a random variable, the approach presented in the paper and dealing with relationship between production capacity of wind power stations and needs of ancillary services is based on probability theory and mathematical statistics [1], [2]. Fundamentals of the approach focused on stochastic modelling [3], [4] of electricity transmission system operation from both technical and economical points of view have already been established in other papers [5], [6], [7], [8]. Therefore, only main ideas of the approach will be introduced at the beginning of the paper. Subsequently, it will be presented that extra electrical power delivered to electricity transmission systems by production of wind power stations under the circumstance that wind blows causes growth of power reserves of certain types of ancillary services. In other words, TSOs are forced to assure larger amount of certain types of ancillary services when electricity transmission system operation planning is under construction. It is obvious that this implies financial cost increase with respect to operation of the system.

II. MAIN IDEAS OF THE APPROACH

At the beginning, relevant monitored data and measured signals have been recognized from the system operation reliability point of view. Since the reliability of the system operation is particularly linked with power balance control, those data and signals have included a power balance deviation in the closed loop mode $dP_{ct}(t)$, power control injections $R(t)$ supplied to the system by activations/deactivations of ancillary services, starts and ends of forced power unit outages and time durations related to the outages (times between failures and of repairs). The deviation $dP_{ct}(t)$ is then decomposed.

A. Decomposition of $dP_{ct}(t)$

It holds that:

$$dP_{ot}(t) = dP_{ct}(t) + R(t), \tag{1}$$

$dP_{ot}(t)$ is a power balance deviation in the open loop mode. The deviation represents behavior of the system without any control actions and it is easily obtained from (1). The deviation can be expressed as follows:

$$dP_{ot}(t) = dP_{o}(t) + T(t), \tag{2}$$

$dP_{o}(t)$ is a power balance deviation in the open loop mode of undisturbed system operation (without any forced power unit outages) and $T(t)$ constitutes the outages. The deviation is obtained by excluding sectors where the outages occur from $dP_{ot}(t)$. Those sectors are identified in virtue of the information about the starts and ends of the outages. The components $dP_{o}(t)$ and $T(t)$ are modelled.

B. Probabilistic model of $dP_o(t)$

Whereas $dP_o(t)$ is a random variable, it is modelled by a proper distribution from a probabilistic viewpoint. It has been proved by fit tests that the most proper distribution for modelling $dP_o(t)$ is the Gaussian distribution:

$$f_G(dP_o) = \frac{1}{\sqrt{2\pi}\sigma_{dP_o}(t)} e^{-\frac{[dP_o - \mu_{dP_o}(t)]^2}{2\sigma^2_{dP_o}(t)}}, \quad (3)$$

$f_G(dP_o)$ is a probability density function. The parameters of the distribution (mean $\mu_{dP_o}(t)$ and standard deviation $\sigma_{dP_o}(t)$) are computed from the real signal $dP_o(t)$.

C. Probabilistic model of $T(t)$

The forced power unit outages $T(t)$ are modelled by the Markov process with two states (see Fig. 1) [9], [10].

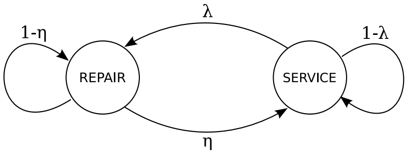

Fig. 1. State diagram of Markov process

The transient rates are given by the relations:

$$\lambda = \frac{1}{MTTF}, \; \eta = \frac{1}{MTR}, \quad (4)$$

$MTTF$, MTR are mean times between failures and of repairs. The mean times are obtained through statistical processing of given times between failures and of repairs for particular units. The model is described by the equations:

$$\frac{d}{dt}\begin{bmatrix} p_s(t) \\ p_r(t) \end{bmatrix} = \begin{bmatrix} -\lambda & \eta \\ \lambda & -\eta \end{bmatrix} \begin{bmatrix} p_s(t) \\ p_r(t) \end{bmatrix}, \; p_s(t) + p_r(t) = 1, \quad (5)$$

$p_s(t)$ is a service probability and $p_r(t)$ a repair probability.

The forced outages are mostly caused by mechanical failures (e.g. seizure, leakage, fatigue, etc.). Therefore, dependencies among co-temporary outages are not considered in the model. Partial outages are not taken into account either because they are not very frequent, their durations are usually short and amplitudes small. This means that they do not have any substantial effect on the reliability of the system. Modelled power units inhere in the bottom of the well - known bathtub curve with respect to their life cycles. This means that the failure and repair rates are about constant. Thus, the Markov process is precise enough for the modelling.

D. Probabilistic model of $dP_{ot}(t)$ and $R(t)$ determination

Consequently, the probabilistic models of $dP_o(t)$ and $T(t)$ are aggregated into a model of the power balance deviation in the open loop mode $dP_{ot}(t)$ that is described by the Gaussian sum [11], [12] with the probability density function:

$$f_{G_s}(dP_{ot}) = \sum_i \frac{P_i(t)}{\sqrt{2\pi}\sigma_{dP_o}(t)} e^{-\frac{[dP_{ot} - \mu_{dP_o}(t) - T_i]^2}{2\sigma^2_{dP_o}(t)}}, \quad (6)$$

where $P_i(t)$ are probabilities of the outages and all their possible combinations and T_i are appropriate amplitudes. The sum is used for determination of the overall positive and negative volumes of ancillary services $R^+(t)$, $R^-(t)$ under a required reliability level of the system operation. The level is given as a percentage share of $dP_{ct}(t)$ amplitudes larger than $\pm 100MW$ along all of its possibly existing amplitudes (the share is called as **Value at Risk** – VaR):

$$R^+(t) = F_{G_s}(1 - \frac{VaR}{2}), \; R^-(t) = F_{G_s}(\frac{VaR}{2}). \quad (7)$$

Since an analytical formula of a cumulative distribution function of the Gaussian sum F_{G_s} is not known, $R^+(t)$ and $R^-(t)$ have to be computed by a numerical algorithm.

E. Decomposition of $R(t)$ and economical optimization

The overall volumes are then divided into power reserves of particular ancillary services on behalf of statistical and dynamical characteristics of specific components involved in $dP_{ot}(t)$ that should be decayed by corresponding types of the services (a random component ⇒ secondary frequency and power control, a direct - energetic component ⇒ tertiary control, a forced outage ⇒ quick - start, a long - time power imbalance ⇒ non - spinning stand - by reserve, emergency assistance, control energy purchase, etc.).

Finally, the power reserves are economically optimized. The reserves are re - disposed by the optimization in such a way that the required reliability level (VaR) is kept and costs to their purchase are minimized at the same time.

F. Monte-Carlo simulation

In order to make sure that the whole optimization procedure of the system operation planning is well done, a Monte - Carlo simulator is employed to verify that the power reserves of particular ancillary services are large enough for guaranteeing the required reliability level of the system operation. The simulator models and simulates electricity transmission system operation in the closed loop mode. This means that it involves models that constitute the open loop (model of undisturbed system operation, model of forced power unit outages) as well as models that constitute the feedback (models of the ancillary services mentioned above). The simulator works then under saturation limits of the services that are given by their corresponding limited power reserves.

Remark: The approach/method presented in the paper has been developed for the TSO of the Czech Republic - CEPS a.s. since 2005 in terms of the Center for Applied Cybernetics. It is routinely used by the Czech TSO for electricity transmission system operation planning. Therefore, all results, which will be presented here, have been obtained through analyses and simulations of the Czech electricity transmission system operation. Nevertheless, the approach/method is general enough in order that it is applicable to any other areas. As a consequence, appropriate results and conclusions obtained can also be considered as sufficiently prevailing despite the approach/method being developed for the concrete area and its TSO.

III. WIND SPEED AND POWER

A. *Wind speed variability*

Electrical power produced by wind power stations is dependent on time - position wind speed variability. Position wind speed variability is given by landscape articulation. Whereas, time wind speed variability is assessed by changes of weather conditions. Moreover, wind speed variability is also influenced by various random fluctuations that represent chaotic wind behavior. Therefore, it is quite useful to describe wind speed by its statistical characteristics – mean and standard deviation. Values of these characteristics depend on a position of being situated. In other words, they depend on longitude, latitude and altitude values, respectively. Values of the characteristics for the area of the Czech Republic are illustrated on Fig. 2, 3.

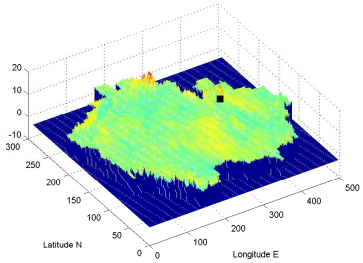

Fig. 2. Mean of wind speed

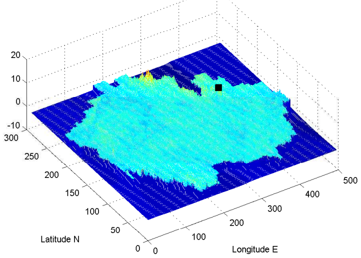

Fig. 3. Standard deviation of wind speed

B. *Wind power variability*

As a matter of course, wind power produced by a wind power station and speed of wind, which blows around the station, are closely associated with each other. The formula that connects wind power produced by a wind power station and wind speed around the station is the following:

$$P(t) = \frac{1}{2}\eta\rho u^3(t) \qquad (8)$$

where $P(t)$ is wind power produced by a wind power station, η is an efficiency coefficient of a wind power station, ρ is air density and $u(t)$ is wind speed. The coefficient η and the density ρ are assumed to be constant. On the other hand, the power $P(t)$ and the speed $u(t)$ are supposed to be time - varying. This means that they can vary within a specified time horizon of production. Subsequently, the formula (8) can be used for determination of mean and standard deviation of wind power produced by a wind power station whose position is given by specification of its longitude, latitude and altitude:

$$P_m = \frac{1}{2}\eta\rho u^3,\; u^3 = (\alpha u_m + \beta u_{std})^3 \qquad (9)$$

where P_m is mean of wind power produced by a wind power station within a specified time horizon of production, u_m is mean of wind speed within the horizon and u_{std} is its standard deviation within the horizon. The coefficients α, β are known.

$$P_{std} = \frac{\bar{u}^3}{PD},\; \bar{u}^3 = \frac{u_{std}u^3}{0.35u_m} \qquad (10)$$

where P_{std} is standard deviation of wind power and the coefficient PD is also known. The coefficients α, β and PD and the constant 0.35 have been identified from data.

Consider a wind power station whose location is marked on Fig. 2, 3. Curves of mean and standard deviation of wind speed and corresponding mean and standard deviation of wind power produced by the station are shown in Fig. 4, 5, 6, 7.

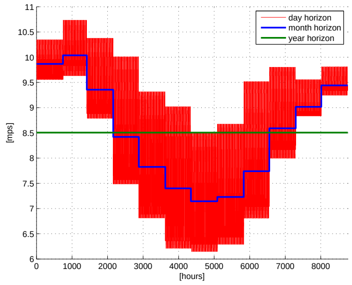

Fig. 4. Mean of wind speed

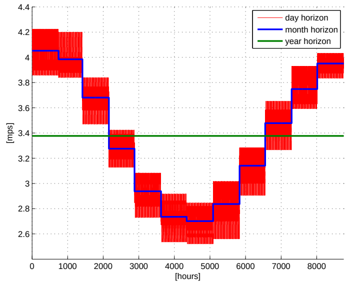

Fig. 5. Standard deviation of wind speed

Remark: Values of means and standard deviations of wind speed and wind power are periodic with a time period that is equal to 1 day (24 hours) in terms of the day horizon. The reason is that the values are about consistent for the same hours through particular days of a month.

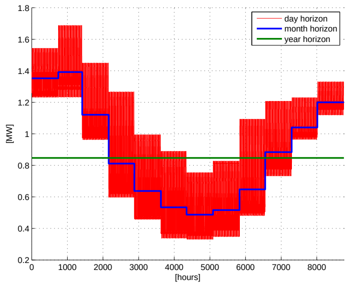

Fig. 6. Mean of wind power

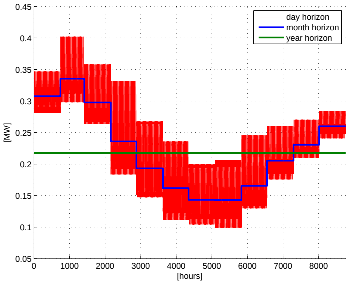

Fig. 7. Standard deviation of wind power

IV. NEEDS OF ANCILLARY SERVICES

As a matter of fact, extra electrical power produced by wind power stations and delivered into electricity transmission systems while wind blows influences overall volumes of ancillary services $R^{+}(t)$ and $R^{-}(t)$ defined by (7). The volumes appear larger in comparison with that case when the power is not considered in terms of standard computations. The reason is that means and standard deviations of the power, which becomes a part of the power balance deviation in the open loop mode $dP_{ot}(t)$, are included in means and standard deviations of this quantity whose mathematical model is given by the Gaussian mixture (6). Consequently, power reserves of certain kinds of ancillary services also get larger. This fact is illustrated with the help of values in the following tables:

1) take a wind power station with installed power 1 GW:

SC	TC^{+}	TC^{-}
+11%	-54%	+190%

2) take a wind power station with installed power 2 GW:

SC	TC^{+}	TC^{-}
+42%	-74%	+479%

It is clear from the values mentioned in the tables that wind power stations with their extra power production cause increased demands (in comparison with standard electricity transmission system operation without any wind power station built) on needs of secondary control - SC (a spinning ancillary service working in an automatic mode that responds to a given setpoint up to 10 minutes), increased demands on needs of negative tertiary control - TC^{-} (a spinning or non-spinning ancillary service working in a dispatcher mode that responds to a given setpoint up to 30 minutes) and decreased demands on needs of positive tertiary control. The demands are especially laid on the negative tertiary control. The reason is that actual power production of base - load power units has to be restricted due to random extra power production of wind power stations so that power balance equilibrium within electricity transmission system operation under 50Hz frequency is guaranteed. Unfortunately, these restriction procedures result in life cycle reduction of power units whose actual power production is restrained in such a way.

V. CONCLUSION

The paper presents relationship between production capacity of wind power stations and needs of ancillary services. It is demonstrated here that extra power production of wind power stations puts increased demands on power reserves of certain types of ancillary services. Consequently, this implies that financial costs of electricity transmission system operation with wind power stations involved are higher in comparison with the operation without any wind power station plugged in. Furthermore, stability of the system with wind power stations gets worse because their power production level is hardly ever predictable and this induces that electricity transmission system operation gets more control - intensive.

ACKNOWLEDGMENT

The work was supported by the Ministry of Education of the Czech Republic under the project No. 1M0567.

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