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# ANALYSIS OF RELIABILITY ASPECTS OF WIND POWER GENERATION IN ROMANIA USING MARKOV MODELS

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## Abstract

Wind power has some characteristics that affect its integration into power systems: variability, unreliable accuracy of the output prediction, and the remote insertion into the network. A critical issue facing the integration of the wind power production is the reliable prediction of its contribution to meet the system's load demand. The authors propose to use tools specific for the reliability analysis of the systems, assuming discrete-time Markov processes, with a view to determine reliability index-type of characteristics for the wind power production.

## Notation

$E$  {1, 2, ..., s} set of points for the system's state space

$E_{WP}$  subset of  $E$  with the property that the wind power takes values at least greater than the power level threshold  $WP$

$E_{\overline{WP}}$  subset of  $E$  having the property that the wind power takes values less than or equal to the power level threshold  $WP$

$J$   $(J_n)_{n \geq 0}$ : a Markov chain with values in  $E$

$J_0, J_1, \dots, J_n, \dots$  are the consecutive states visited by the process

$MRP$   $(J, S) = (J, S)_{n \geq 0}$ : Markov Renewal Process

$MUT_{WP}$  Mean Up Time: the expected length of time the process visits the  $E_{WP}$  subset

$N(t)$   $\sup\{n \geq 0; S_n \leq t\}$ : number of jumps of  $MRP$  in the time interval  $(0, t]$

$N_i(t)$  number of  $MRP$  visits to state  $i$ , until time  $t$

$$N_i(t) = \sum_{k=1}^{N(t)} 1_{\{J_k=i\}} = \sum_{k=1}^{\infty} 1_{\{J_k=i, S_k \leq t\}}$$

$N_{ij}(t)$  number of  $MRP$  jumps from state  $i$  to state  $j$ , up to time  $t$

$$N_{ij}(t) = \sum_{k=1}^{N(t)} 1_{\{J_{k-1}=i, J_k=j\}} = \sum_{k=1}^{\infty} 1_{\{J_{k-1}=i, J_k=j, S_k \leq t\}}$$

$P_i(n)$  state  $i$  probability at time  $n$ :  $\Pr\{J_n = i\}$

$P(n)$   $[P_1(n), P_2(n), \dots, P_i(n), \dots, P_s(n)]$ : state probability vector at time  $n$

$\pi$   $[\hat{\pi}_1, \hat{\pi}_2, \dots, \hat{\pi}_i, \dots, \hat{\pi}_s]$ : steady state probability vector

$p_{ij}$   $\Pr\{J_{n+1} = j | J_n = i\}$  for  $i, j \in E$ : transition probability from state  $i$  to state  $j$

$S$   $(S_n)_{n \geq 0}$ : jump times with values in  $[0, \infty)$

$X$   $X_n = S_n - S_{n-1}$ , for  $n \geq 1$ : the length of time the process visits state  $n$ , with  $X_0 = 0$ .

$(Z_t, t \geq 0)$   $Z_t = J_n$ , if  $S_n \leq t \leq S_{n+1}$ : the corresponding Markov process

## 1 Introduction

One of the most sensitive problems of wind power is its dependence on the randomness of the wind. Depending on the timescale of wind variability different aspects of wind production are affected: in the seconds to minutes timescale, the individual wind turbine generator's control systems; in the

days to weeks timescale, the integration of wind power production in the power system operation.

The following types of applications of the wind prediction models can be identified:

- optimization of the scheduling of the conventional power plants by functions such as economic dispatch. The prediction horizon can vary between 3 to 10 hours depending on the size of the system and the type of conventional units included in the generation mix.
- optimization of the value of produced electricity in the market. Such predictions are required by different type of end-users: utilities, TSO's, energy traders, power generators and for different functions including unit commitment, economic power dispatch, dynamic security assessment, participation in the electricity market. These functions are executed over time scales between 0 to 48 hours.
- maintenance planning of large power plant components, wind turbines or transmission lines, which typically require even longer time scales. The accuracy of weather predictions decreases dramatically for time horizons beyond 5-7 days. Improved weather prediction tools are emerging but they are still far from achieving a reasonable accuracy performance.

European transmission and distribution operators (in Germany, Denmark, Spain, Dutch, Ireland, Greece, Italy) accumulated already over 15 years of experience with different wind prediction tools, and USA and Australia are developing their approaches as well [2] - [8]. The developments concentrated primarily on the improvement of prediction accuracy at wind farms level.

However as the amount of wind energy in the electricity power systems increases, new challenges emerge. Initially built for conventional power sources, the power systems are not yet fully adapted to the predicted penetration levels of wind power production, and nor are the ways in which the power systems are designed and operated.

In this context and taking into account the high interest for constructing and operating wind power parks in Romania we explored in this work possibilities to characterise the wind power production from a reliability point of view. The paper includes an overview of the present situation in Romania and the implications on the operation of the transmission system. We introduced in section 4 an outline of the approach used to identify reliability characteristics for the wind power production at national level. Using recent records collected by the national transmission system operator we demonstrate the range of reliability measures that can be calculated. These are expected to be included in a prediction tool that will be developed in the near future. An outline of future work is included in the last section of the paper.

## **2 Wind energy resources in Romania and electricity generated in wind farms**

Many parties are presently interested for wind power parks' development and construction in Romania. Pre-feasibility studies for the connection into the national transmission

network were carried out already for more than 18,000 MW wind power parks in aggregate. Technical connection offers were issued for approximately 2,650 MW which imply that the necessary transmission capacity was already reserved for these developments. The aggregate wind power production capacity forms a significant penetration level in comparison with the national transmission system's capacity. The power parks are anticipated to be realised within the next few year when they will introduce a significant degree of uncertainty over the power production at transmission system level.

Applications for transmission system connection from wind power parks with installed capacity in the range from 0.5 to 600 MW are still in the process. An interim total of all applications already submitted and under consideration is just under 31,000 MW.

In 2010-2011 the new wind power parks connected into the transmission system, at approximately 570 MW aggregate installed capacity, exceeded the total of new conventional sources that were connected to the system.

The hourly prediction of the wind power parks' power output is quite challenging and has problematic accuracy. Greater wind power production penetration levels may be facilitated by the presence of fairly flexible conventional power sources with short start-up times and available for output reduction or even rapid shutdown.

For the medium-term load demand development scenario Romania expects that the peak demand will not exceed 10,000 MW and the load valley should not fall below 5,500 MW. These predictions demonstrate that the maximum wind power production will be necessarily constrained in order to avoid adverse impacts on the national transmission system stability and operational security.

The vast majority of the wind power parks in operation are concentrated on the eastern side of the country, in Dobrogea (~75 % of total installed capacity) and in Moldova (~20 % of total installed capacity). These regions usually experience correlated wind regimes.

The main integration challenges faced by the wind power production are:

a) The wind energy is capable of limited dislocation of the conventional generation sources. Wind power production depends heavily on the wind regime such that the maximum production cannot be guaranteed even when the availability of the transmission connection is 100 %. Typical power system operation arrangements require that conventional power stations retain a spinning reserve proportional with the wind power production included in the generation mix.

b) The accuracy of wind power production's is limited. The transmission system operator has an obligation to balance out continuously the generation and load demand such that any shortfall between predicted and realised generation is offset. The volume of spinning reserve required for this instantaneous balancing may be reduced when improved accuracy is obtained from the wind power predictions.

The wind power connection to the national power system has technical and economical implications:

- significant power flow changes generated by sudden variations of the wind power output. The balancing of the discrepancies between predicted and realized wind power production may be achieved by spinning reserve located in other parts of the transmission system. This may cause power system stability issues which can be mitigated by introducing power flow controllers.
- construction of additional power transmission corridors may be considered to relieve transmission capacity issues although these transmission lines are expensive and require long construction times. The wind power park capacity factors and the possibility that many of the proposed projects may not be realized have to be considered thoroughly.
- increased operation demands will be placed on the conventional power stations as these have to provide the output flexibility that is necessary to mitigate the imbalance between predicted and realized wind power output. Operation at partial loading, more frequent start-ups and shutdowns will become more frequent. This operation pattern will increase operation costs and reduce the lifetime of equipment in conventional power stations with adverse economic consequences.
- transmission capacity congestion may occur which could be mitigated by introduction of power electronic-based transmission devices, such as FACTS, and by adopting new management methods for transmission system's operation. The smooth integration of wind power parks in the generation mix would ultimately require that the wind power parks meet performance requirements similar with those requested from the conventional power stations.

The share of the electricity produced by wind turbines in 2011 in the total electricity production was about 0.8% in January, 1.9% in February, 2.2% in March and 2.1% in April.

### 3 Reliability of Power Wind Generation: a Markovian approach

We apply a Markovian approach [1] with a view to determine the reliability of the wind power generation based on observations of the aggregate power output. In order to assess the time variability of the power wind generation the aggregate power output is clustered into a discrete number of contiguous classes, as presented in Table I.

As long as the wind speed remains constant, the process visits one of the above-mentioned states. The visiting time in each state is treated as a random variable exponentially distributed. This means a process characterised by lack of memory; the trajectory of the process (states and duration of states) is defined by the present position.

During the first stage of the analysis the probabilities of transition between states would be assessed. Assuming an ergodic Markov behaviour, such estimators are defined and computed as follows:

State $i$	Wind Power Cluster [MW]
1	0-5
2	6-11
3	12-17
...	.....
s	-----

Table I. Power thresholds used for definition of states

$$p_{ij} = \lim_{t \rightarrow \infty} N_i(t) / N_{ij}(t) \quad (1)$$

The Romanian national transmission system operator Transelectrica monitors continuously the power production from conventional (coal, gas, liquid fuel, nuclear and hydro) generation sources as well as from the expanding wind power sources. Data is published every 10 minutes on the operator's website at

[www.transelectrica.ro/openflash/grafic.php?ofc=date.php](http://www.transelectrica.ro/openflash/grafic.php?ofc=date.php).

Thus, starting from Transelectrica measurement data, we may now compute the estimator of the steady state probability vector  $\pi = [\hat{\pi}_1, \hat{\pi}_2, \dots, \hat{\pi}_i, \dots, \hat{\pi}_s]$  solving the following system of linear equations:

$$\left\{ \begin{array}{l} \hat{\pi}_1 = \sum_{j=1}^s \hat{\pi}_j \cdot p_{j1} \\ \hat{\pi}_2 = \sum_{j=1}^s \hat{\pi}_j \cdot p_{j2} \\ \dots \\ \hat{\pi}_s = \sum_{j=1}^s \hat{\pi}_j \cdot p_{js} \\ \sum_{j=1}^s \hat{\pi}_j = 1 \end{array} \right. \quad (2)$$

Mean Up Time (MUT) is the expected value of the time when the wind power production visits states when the power output is at least greater than the power level (WP) shown in the x-axis in Figure 1. For a given WP threshold, an estimation of the MUT is provided by the following equation:

$$MUT_{WP} = \left( \sum_{k=1}^{Card\{E_{WP}\}} \hat{\pi}_k \right) / \left( \sum_{k=1}^{Card\{E_{WP}\}} \sum_{j=1}^{Card\{E_{WP}\}} \hat{\pi}_k \cdot p_{kj} \right) \quad (3)$$

Figure 1 presents a possible MUT variation for the wind power production exported into Transelectrica network. The MUT interrupts as soon as the power production falls below the state threshold.

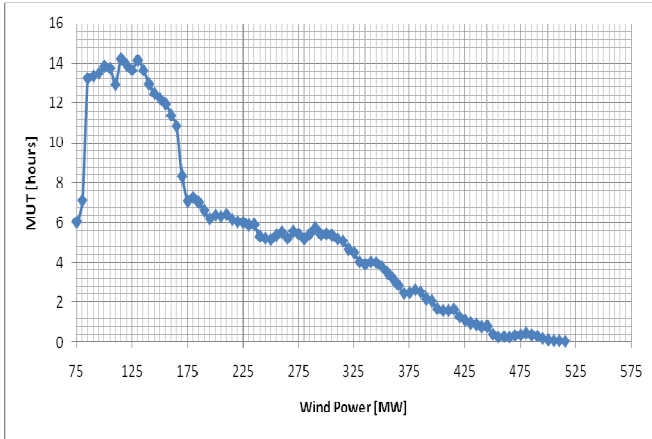


Figure 1. MUT variation for the wind power production exported into Transelectrica network

The intermittency of the wind power production is such that including in the analysis states with lower tiers of production (i.e. production below 75 ... 100 MW) causes a reduction of the MUT for these states. This is the effect of strong correlation between lower tiers of wind production with less prolific production states (0 ... 70 MW).

The expected frequency  $F_{WP}$  for the aggregate wind power output to deliver at least a selected power level ( $WP$ ) is the inverse of the mean return time into those states when the power output is at least greater than the power level ( $WP$ ) shown in the x-axis. For a given  $WP$  threshold the estimator of the expected frequency is provided by the following equation:

$$F_{WP} = 1 / \left( \sum_{k=1}^{Card\{E_{WP}\}} \sum_{j=1}^{Card\{E_{WP}^-\}} \hat{\pi}_k \cdot p_{kj} \right) \quad (4)$$

The variation of expected frequency for the same data set used in illustrating the MUT variation is shown in Figure 2.

The analysis of preliminary records indicates that a wind power production of at least 410 MW is expected to be observed twice a year, while at least 100 MW are expected to be delivered to the system around 60 times a year or nearly 5 times in a month.

## 4 Conclusion

Romania gears itself for integrating the wind power resources into the renewable energy quota commitments assumed under the EC regulation. The transmission system operator has an obligation to balance the load demand with the generation such that the commitments for the renewable energy share in the generation mix are fulfilled. A good knowledge of the generation capacity and availability are instrumental in achieving this obligation. The reliability characteristics of the wind power production calculated according to the methodology shown here will contribute to the assessment of generation mix composition availability.

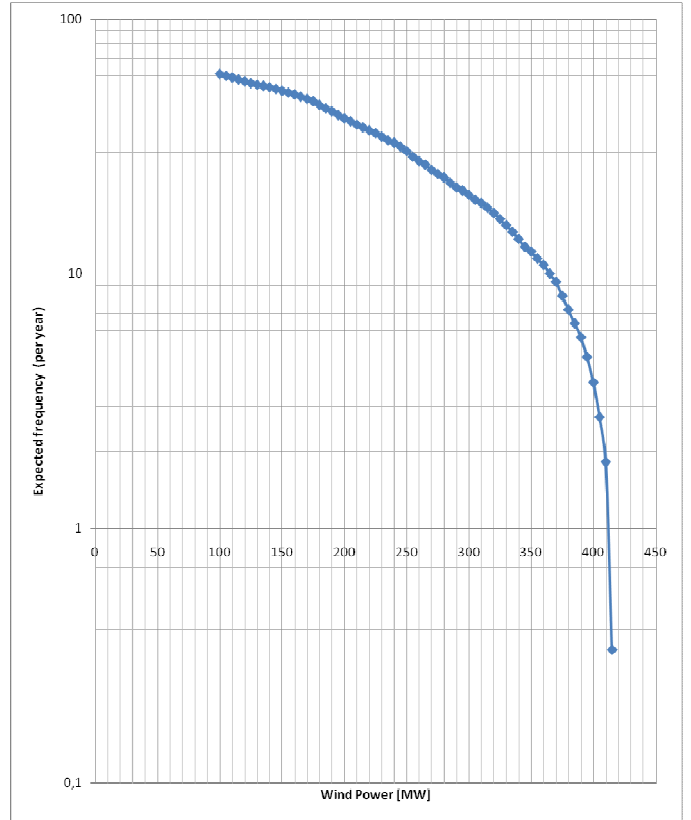


Figure 2. Variation of the expected frequency for the wind power production exported into Transelectrica network

It is anticipated that further accumulation of data records will enable us to provide the transmission system operator with an enhanced set of indicators that will include, at a minimum, the following. Residual operation time at a wind power output that is greater than or at least equal to a predefined power level assuming that the wind power production fulfilled this condition for a set period before. We also anticipate that the reliability indicators may enable us formulating a method to identify precursors of critical situations such as sudden decrease of the wind power production.

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