WIND POWER PLANT RESILIENCE

by

Naim H. AFGAN [a*] ***and Dejan B. CVETINOVIĆ*** [b]

[a] Instituto Superior Tecnico, Lisbon, Portugal
[b] Laboratory for Thermal Engineering and Energy, Vinča Institute of Nuclear Sciences,
University of Belgrade, Belgrade, Serbia

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A wind energy system transforms the kinetic energy of wind into mechanical or electrical energy that can be harnessed for practical use. Mechanical energy is most commonly used for pumping water in rural or remote locations. Electrical energy is obtained by connecting wind turbine with the electricity generator. The performance of the wind power plant depends on the wind kinetic energy. It depends on the number of design parameter of the wind turbine. For the wind power plant the wind kinetic energy conversion depends on the average wind velocity, mechanical energy conversion into electricity, and electricity transmission. Resilience of the wind power plant is the capacity of the system to withstand changes of the following parameters: wind velocity, mechanical energy conversion into electricity, electricity transmission efficiencya and electricity cost. Resilience index comprise following indicators: change in wind velocity, change in mechanical energy conversion efficiency, change in conversion factor, change in transmission efficiency, and change in electricity cost. The demonstration of the resilience index monitoring is presented by using following indicators, namely: average wind velocity, power production, efficiency of electricity production, and power-frequency change. In evaluation of the resilience index of wind power plants special attention is devoted to the determination of the resilience index for situation with priority given to individual indicators.

Key words: *wind power plant, wind kinetic energy, electricity cost*

Introduction

State-of-the-art wind power plants use large spinning blades to capture the kinetic energy in moving wind, which then is transferred to rotors that produce electricity [1]. At the best wind sites, wind plants today are nearly competitive with the conventional natural gas-fired combined-cycle plants – even when natural gas prices have recently been at historically low levels. Regions where average wind speeds exceed 5.4 m/s are currently the best wind power plant sites [2].

Current costs of wind-generated electricity at prime sites approach the costs of a new coal-fired power plant. Wind power is the lowest-cost renewable energy technology available

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[*] Corresponding author; e-mail: afgan@sbb.rs

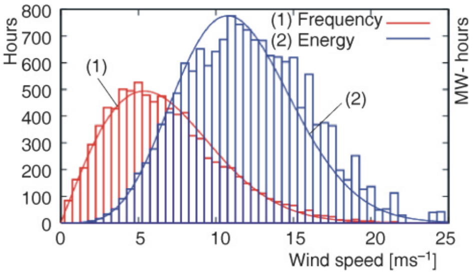

Figure 1. Frequency and energy probability

on the market today. Costs of wind power are projected to continue to fall and may rank the cheapest electricity source of all options by 2020.

The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there. To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data. Different locations will have different wind speed distributions. The Rayleigh model closely mirrors the actual distribution of wind speed measurements at many locations; see fig. 1 [3].

Because so much power is generated by higher wind speed, much of the energy comes in short bursts. The consequence is that wind energy from a particular turbine or wind farm does not have as consistent an output as fuel-fired power plants; utilities that use wind power provide power from starting existing generation for times when the wind is weak thus wind power is primarily a fuel saver rather than a capacity saver. Making wind power more consistent requires that various existing technologies and methods be extended in particular the use of stronger inter regional transmission to link widely distributed wind farms since the average variability is much less; the use of hydro storage and demand-side energy management [4]. The Earth is unevenly heated by the Sun resulting in the poles receiving less energy from the Sun than the equator does. Also, the dry land heats up (and cools down) more quickly than the seas do. The differential heating drives a global atmospheric convection system reaching from the Earth's surface to the stratosphere which acts as a virtual ceiling. Most of the energy stored in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/h occur. Eventually, the wind energy is converted through friction into diffuse heat throughout the Earth's surface and the atmosphere.

The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources [5]. An estimated 72 TW of wind power on the Earth potentially can be commercially viable [6], compared to about 15 TW average global power consumption from all sources in 2005.

To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data. Different locations will have different wind speed distributions. The Rayleigh model closely mirrors the actual distribution of hourly wind speeds at many locations.Rayleigh flow refers to a flow through a constant area duct where the effect of heat addition or rejection is considered, see fig. 2. Compressibility effects often come into consideration, although the Rayleigh flow model certainly also applies to incompressible flow. For this model, the duct area remains constant and no mass is added within the duct.

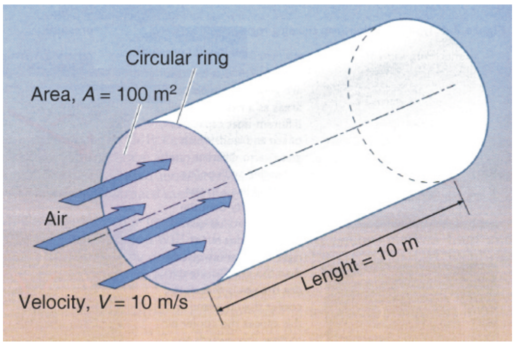

Figure 2. Wind power model

Wind power density (WPD) is a calculation relating to the effective force of the wind at a particular location, frequently expressed in terms of the elevation above ground level over a period of time. It further takes into account wind velocity and mass.

Since wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. Typical capacity factors are 20-40%, with values at the upper end of the range in particularly favorable sites. For example, a 1 MW turbine with a capacity factor of 35% will not produce 8.760 MWh in a year (1 24 365), but only 1 0.35 24 365 = 3,066 MWh, averaging to 0.35 MW. Online data is available for some locations and the capacity factor can be calculated from the yearly output [7].

Unlike fueled generating plants, the capacity factor is limited by the inherent properties of wind. Capacity factors of other types of power plant are based mostly on fuel cost, with a small amount of downtime for maintenance. Nuclear plants have low incremental fuel cost, and so are run at full output and achieve a 90% capacity factor. Plants with higher fuel cost are throttled back to follow load. Gas turbine plants using natural gas as fuel may be very expensive to operate and may be run only to meet peak power demand. A gas turbine plant may have an annual capacity factor of 5-25% due to relatively high energy production cost.

According to a 2007 Stanford University study published in the Journal of Applied Meteorology and Climatology, interconnecting ten or more wind farms, see fig. 3, can allow an average of 33% of the total energy produced to be used as reliable, baseload electric power, as long as minimum criteria are met for wind speed and turbine height.

The best way of measuring wind speeds at a prospective wind turbine site is to fit an anemometer to the top of a mast which has the same height as the expected hub height of the wind turbine to be used. This way one avoids the uncertainty involved in recalculating the wind speeds to a different height.

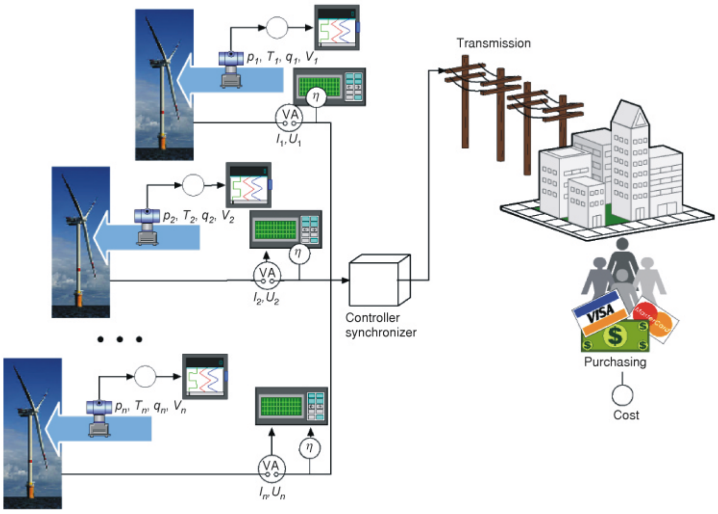

Figure 3. Schematic presentation of wind power plant

By fitting the anemometer to the top of the mast one minimises the disturbances of airflows from the mast itself. If anemometers are placed on the side of the mast it is essential to place them in the prevailing wind direction in order to minimize the wind shade from the tower.

Wind energy and power

Calculation the energy available in the wind [8] relies on knowledge of basic geometry and physics behind kinetic energy. Kinetic energy of collection of objects *KE* with total mass *M* and velocity *V* is given by expression:

$$KE \quad \frac{1}{2} M V^2 \tag{1}$$

In order to define kinetic energy we can define volume of the air particles in the shape of a huge hockey pack with thickness *D* that has geometry of collection of air particles passing through the *A* plane of a wind turbine blade over a given time.

The volume of the pack is determined by $Vol = AD$ if $\rho = M/Vol$. Then we can write that:

$$KE \quad \frac{1}{2} \rho V^3 A T \tag{2}$$

If the kinetic energy is divided by time, *T*, the power available from air parcel can be expressed as $Pwr \quad 1/2 \rho V^3 A$.

If the *Pwr* is divided by the cross-section of parcel, *A*, then we can obtain expression:

$$\frac{Pwr}{A} \quad \frac{1}{2} \rho V^3 \tag{3}$$

This term is called the WPD. It can be noticed that the WPD depends the density of air and the wind speed and the size and wind power plant efficiency.

The wind speed is defined with average wind velocity obtained by the geometry of rotor and its local position.

The average wind velocity is characterized by two parameters: wind frequency and wind speed. Since both of these parameters are time dependent their measurement will require respective models for their evaluations to use the monitoring WPD.

For the density measurement the air temperature measurements are necessary.

Indicators

As shown on fig. 4 the monitoring of wind power plant is based on the number of indicators. The definition of each indicator is specified by the respective wind power model as presented in following description.

Wind power density

These evaluations lead us to the definition of the tree parameters to be as the monitoring of the WPD, namely: pressure and temperature of the air, average wind velocity, and frequency of the wind.

Efficiency of wind power plant

Mechanical energy obtained by the wind energy is converted to the electricity by the electric generator with respective efficiency defined by:

$$\eta \quad \frac{E_{\text{power}}}{WDP \quad A} \tag{4}$$

Monitoring parameters are: WDP and E_{power}.

Power frequency

Power frequency is parameter needed for the wind power plant synchronization. Together with electric power measured by the electric currency in amperes and grid voltage in volt, it is stability constrain for the connection to the grid. It requires monitoring of following parameters: frequency fluctuation and voltage fluctuation in the grid.

Electricity cost

Cost of the electricity produced by the wind power plant is defined as the total amount of plant expenses divided by power produced. The expenses are defined by the cost of manpower and maintenance cost.

Monitoring scheme

Figure 4 shows the schematic structure of the monitoring positions. Monitoring system for the wind energy power plant comprise measurement individual parameters as they are shown on fig. 4. It will include the measurement of following parameters: air pressure, air temperature, wind frequency, average wind velocity, efficiency of wind power plant, electric current, electric voltage, and electricity cost.

Data monitoring and processing

Data processing is organized with the appropriate definition of the sustainability index. As shown in fig. 4, the first step in data processing is the data normalization with the aim to obtain specific indicators to be agglomerated in the Sustainability index. It is assumed that the sustainability index [9] is a linear agglomeration function of products between specific indicators and corresponding weighting coefficients, in the form of additive convolution. If it will be adapted that each of the specific indicator is weighted by the respective weighting coefficient. The sum of specific indicator multiplied with the corresponding weight coefficient will lead to the sustainability index, $Q(t)$, with the following mathematical formulation:

$$Q(t) \qquad {}_{n}\; \omega_n q_n(t) \tag{5}$$

where ${}_n$ is the weighting coefficient for the n^{th} specific indicator, and q_n – the n^{th} criterion for sustainability assessment.

The evaluation of wind energy system as the complex system is the prestigious goal of modern approach to the validation of the energy system. In this context it is introduced notion of the resilience index as the agglomerated indicator for the measurement of the wind energy system quality [10]. Resilience index is the property of wind energy system based on the assumption that the wind energy system is a complex system with time change of main system parameters. Resilience index presented in fig. 5 is graphical presentation of the sudden sustainability index change in time and its recovery to the initial state of the system. The integral value of the sustainability index recovery after sudden change leads to the definition of resilience index.

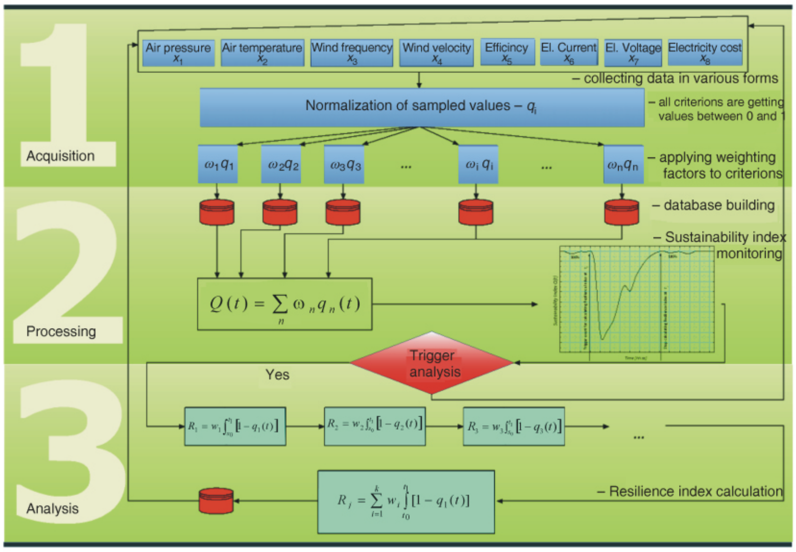

Figure 4. Schematics structure of the wind power plant monitoring system

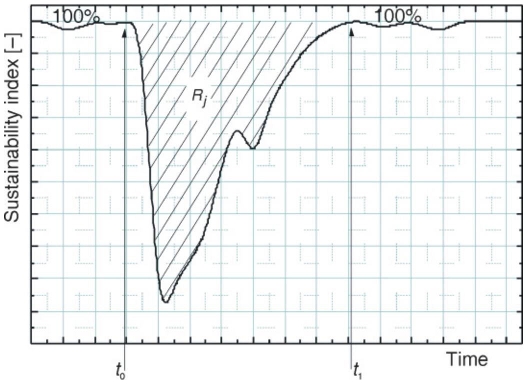

Figure 5. Graphical presentation of resilience index

The second step in the data processing is the determination of the resilience index component corresponding to the sudden change of the specific indicators. It is anticipated the total resiliency index is the sum of the resiliency index components.

Resilience index is the variable immanent to the specific potential hazard. This means that resilience index as the parameter which quantifying the potential probability for the malfunction of the system. Resilience index is expressed with following mathematical formulation:

$$R_j \qquad {}_{i\ 1}^{k} \, w_i \; {}_{t_0}^{t_1} [1 \quad q_i(t)] \tag{6}$$

In this definition it is anticipated that there is time independent constant for every indicator.

In the processing of the resilience index components a following simplification is introduced. The sudden change of the specific indicator from the initial value will be recovered within the time period t_0.

The resilience index is composed of sub-indicators. In the same way the economic, environmental, technological, and social resilience element could be obtained, as follows.

Under the assumption that the sudden indicator change resumes is a linear function of time, then we can write:

$$R_j \quad \frac{1}{2} w_i (\Delta q_i \Delta t) \tag{7}$$

If it is assumed that the time interval for resuming starting state is equal for all indicators than and then the resilience index for the individual case is:

$$R_j \quad \frac{\Delta t_0}{2} w_i \Delta q_i \tag{8}$$

The total resilience index is an additive function of all resilience indexes as follows:

$$R_{\mathrm{TOT}} = R_{\mathrm{WPD}} + R_{\mathrm{EWPP}} + R_{\mathrm{PF}} + R_{\mathrm{EC}} \tag{9}$$

where R_{TOT} is the total resilience index, R_{PWD} – the wind power density, R_{EWPP} – the efficiency of wind power plant, R_{PF} – the power frequency, and R_{EC} – the electricity cost.

Demonstration of resilience index monitoring

The monitoring of individual indicators is performed by the respective instrument. It is anticipated that instruments are calibrated to appropriate scale for individual unites. Signal processing includes a following operation: instrument calibration, signal digitalization and signal acquisition within the respective time increment, and calculation of the resilience indicator.

Following determination of the resilience index in the appropriate time period reflecting sudden change of the individual period the agglomerated value of the total resilience will be monitored.

In this exercise we will assume that every indicator is measured in the time interval Δt_0. Also, it is assumed that the air temperature and air pressure are constant during this exercise. Indicators nominal values and sudden changes are as given in tab. 1.

Table 1. Object indicators

Objects	Wind power density (WPD) [ms^{-1}]	Efficiency of wind power plant (EWPP) [%]	Power frequency (PF) [A]	Electricity cost (EC) [€/kWh]
1	4/20	2.5	1.25	0
2	2	5/100	2.5	1.25
3	1	1.25	5/50	2.5
4	0	0	0	5/20

In this demonstration exercise we have taken into a consideration the situations defined as the objects of the demonstration with the sudden changes of individual indicators.

Following situations are taken into a consideration: change of wind power density, change of efficiency of wind power plant, change of frequency, and change of electricity cost.

In the design of the objects under consideration it is introduced assumption that the sudden change of indicators is triggered at the same moment for all indicators. Also, the change of indicators are normalized and the maximum change for each of the indicator expressed in normalized value. It is of particular interest for this demonstration to have each object defined as the composition simulations sudden changes of all indicators as shown in tab. 1.

The total resilience index is determined in following cases:

Case 1: WPD > EWPP = PF = EC,
Case 2: EWPP > WPD = PF = EC,
Case 3: PF > WPE = EWPP = EC, and
Case 4: EC > WPPD = EWPP = PF.

Table 2. Object rating list

Case	Resistance index
Case 1	0.755
Case 2	0.866
Case 3	0.612
Case 4	0.647

The results obtained for these cases are shown in tab. 2.

The resilience index is a stability parameter of any system and can be used as the measuring parameter for the assessment of the potential hazard events. As regards the wind power plant analysis it proves that the most stable case in sudden change of the indicators is the Case 2 when the priority of the indicators is given to the efficiency wind power plant.

As a conclusion it is of interest to mention that the resilience index is the parameter of the system which can be used as the diagnostic tool in the assessment of the potential hazard event of the system as it is clearly sown in the paper. As regards wind energy power plant hazard events can lead to mal function of the wind power plant elements.

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