BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LVIII No. 2 bis / 2006	147-154	Seria Tehnică

Estimation of the Wind Generator Systems Efficiency

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Abstract

In this paper, the performance of variable speed and constant speed wind turbine concepts regarding efficiency of generated power are investigated. A method to calculate annual energy loss distribution of a wind generator system is presented. The losses of different components of two variable-speed wind generator topologies of 3 MW using Doubly-Fed Induction Generators are evaluated with regards to their energy production.

Key words: *Wind generator systems, Weibull and Rayleigh distribution, OptiSpeed and OptiSlip Wind Turbine concepts.*

Introduction

Modern wind turbines typically have availabilities exceeding 98 % and perform with capacity factor of (35 to 45) % in good wind resource areas [1, 2].

Different wind energy systems are compared mainly regarding cost per kWh [3, 4]. Therefore, several things should be investigated: the average power captured by the turbine, the system cost, the efficiency and the availability of the systems. The efficiency is very important when comparing different systems the losses reduce the average power produces by the wind energy converter and, thereby, they reduce the incomes.

This paper discusses some details about annual wind distribution, energy production and annual energy loss distribution in large wind turbine applications.

Loss distribution: losses in the generator, gear box and power converter

The losses of the wind generators can be divided into several types depending on different variables.

The gear losses can be divided into the gear mesh losses and the no load losses. The gear mesh losses only depend on the transmitted power and not on the turbine rotor speed. The no load losses are bearing losses, oil churning losses and wind age losses [7]. They are independent of load but are speed-dependent. The generator losses are calculated according to the conventional electric machine theory. The losses are: copper losses, hysteresis and eddy current core losses, wind age and friction losses and additional losses. The copper losses are dependent on the currents, the hysteresis and eddy current core losses depend on the flux linkage and the frequency, the friction losses only depend on the generator speed and the additional losses can be assumed to depend only on the current.

In the variable speed wind generators the losses of the frequency converters have to be included. The converter losses are copper losses, voltage drop losses and no load losses for the rectifier, the dc step-up converter, and the inverter, depending on the power converter topology [3].

Calculation Method

Because one of the wind turbine topology is a constant speed wind generator system while the other two are variable-speed wind generator systems, the energy captured by the turbine differs. Therefore, the comparison should be made only on the average efficiency from wind turbine shaft to the grid. This means that a variable-speed wind turbine will capture a few percentage (10-15) more energy than a constant-speed turbine [8].

To find the average efficiency, the average power production of the turbine (P_{Tav}) and average losses (P_{Lav}) must be calculated. This can be done by using a probability density distribution (w) for the wind speed (v). The aerodynamic power of wind turbine ($P_T(v)$) is multiplied by the probability density and integrated from the wind speed v_{min}, at which the turbine starts, to the wind speed v_{max}, at which it is stopped. By definition the integral of the probability density function over wind speeds from zero to infinity is exactly one. The value of this integral is the average power captured by the turbine:

$$P_{Tav} = \int_{v\min}^{v\max} P_T(v) \cdot w(v) \cdot dv \tag{1}$$

The average losses can be calculated in the same way as the average power. The average efficiency can then be calculated as:

$$\eta_{av} = 1 - \frac{P_{Lav}}{P_{Tav}} \tag{2}$$

The probability density of different wind speeds may be approximated by a Weibull distribution. A typical wind speed probability density distribution and typical losses of a wind energy converter are shown in Fig. 1.

In Fig. 2 the product of the probability density and the losses is shown.

The losses at wind speeds bellow 8 m/s are much more important for the average losses than the losses above rated wind speed, 12-15 m/s, because the loss density is much higher at low wind speed than above the rated wind speed.

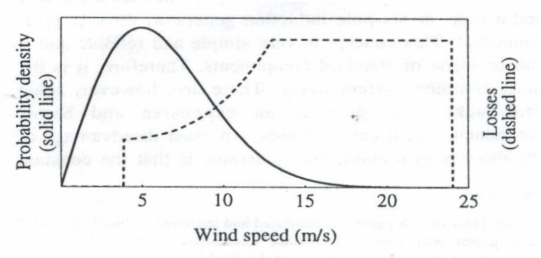


Fig. 1. Wind speed probability density and losses of a constant speed wind energy converter [7].

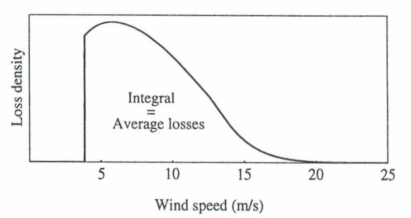


Fig. 2. The loss density and average losses [7].

The average losses

To be able to use the proposed method to calculate the average losses, the losses must be expressed as a function of the wind speed. By defining the parameters that determine the losses as functions of the wind speed, all the losses can be expressed as a function of wind speed. The copper losses decrease in the electrical generators as the wind speed decreases. The core losses and the friction losses are not reduced in a constant speed wind generator grid connected because the flux linkage and the speed remain approximately constant. In the variable-speed wind generator systems the wind age and friction losses decrease when the generator speed decreases. The core losses of the conventional synchronous generator decrease when the wind speed is below 12 m/s [7], since the flux linkage is reduced by the excitation control. It can be seen that the copper losses decrease much faster than the other types of losses in all the generators. Because of that, the core losses and friction losses are more important for average losses than the copper losses, especially in grid-connected generator but normally also in variable-speed configurations. Even in the directly-driven generator, which has three times higher copper losses at rated load, the average core losses are still somewhat higher than the average copper losses [7].

The average efficiency

The comparison shows that the variable-speed wind generators can be more efficient than the constant-speed wind generator system even though the efficiency at rated load is about 3 % lower.

At a typical site the variable-speed system is 0.5 % less efficient, at a low-wind speed sites it is 2 % more efficient, and at a high-wind speed sites it is 1.6 less efficient than the constant-speed system. It is also found that the directly-driven variable-speed generator is more efficient than the generator equipped with gear box both at low and high-wind speed sites [7].

The difference in efficiency between constant-speed and variable-speed systems is depending on how efficient the frequency converter (FC) is. If a higher harmonic content is acceptable in the grid current an IGBT inverter can be used and the efficiency of the variable-speed system will be higher.

Generated power

The cost of wind-generated electricity has declined about 90 % over the last 20 years. Today, large new wind farms at excellent wind sites generate electricity at a cost of 0.04 to 0.06 US dollars / kWh [3, 9]. That places the cost of power from the most efficient wind farms in a range that is competitive with that of electricity from new conventional power plants.

Using the calculated power transmitted to the hub and subtracting all losses (generator losses, converter losses, and gear box losses), the generated power versus wind speed can be found.

Annual wind distribution

To determine the advantages of a specific configuration of a wind turbine, the annualized energy production of the turbine needs to be considered. This involves looking at a standard distribution of wind and combining that with the characteristic of the turbine control to estimate the annual energy production. This may be done by using a probability distribution to determine the number of hours of a particular wind speed which occur in a given year, such as the Weibull distribution or the Raileigh distribution [3, 5, 6]. This distribution may be used with the aerodynamic power generated at a given average wind speed to determine the total energy generated during the year.

The Weibull distribution is a generalized gamma distribution, and the Rayleigh is a special condition of the Weibull distribution. The Weibull distribution allows for more parameter adjustments, making it more flexible than the Rayleigh distribution, but at the price of being more complicated. It is often suggested for use when estimating the cost of energy [5, 6]. Because of the additional flexibility, wind data for the specific site is required.

The procedure for calculating the total energy produced for a given wind distribution is performed by first finding the total number of hours per year for a particular wind speed. This is possible by finding the probability of a particular wind speed for the desired distribution and multiplying it by the numbers of hour per year. The probability that the wind lies between two wind speeds is given by:

$$P_r(u+\Delta u)-P_r(u-\Delta u)=p(u)\Delta u \; ..... \qquad (3)$$

where $P_r(u)$ is the probability function, and $p(u)$ is the probability density function. For the Rayleigh distribution, the probability distribution function is given by:

$$p(u)=\frac{\pi\cdot u}{2\cdot u_a}\cdot\exp\left[-\frac{\pi}{4}\left(\frac{u}{u_a}\right)^2\right] \qquad (4)$$

where u_a is the average wind velocity. From this, the number of hours when a wind turbine is operated at a given speed is estimated as:

$$H(u)=8760\cdot p(u)\cdot\Delta u \qquad (5)$$

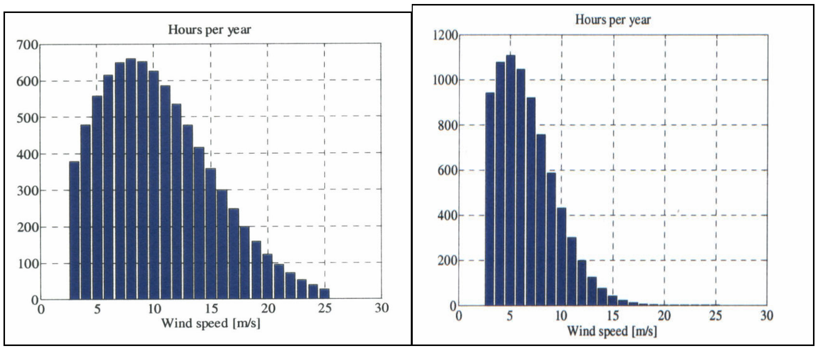
where 8760 represents the total number of hours in a 365-day year. Once the hours a particular wind speed occurs is determined, the amount of power is calculated for the given turbine control at the particular wind speed. The power is then multiplied by the time for the wind speeds for a given year to find the total energy production:

$$E(u)=P(u)\cdot H(u) \qquad (6)$$

where P(u) is the developed power for a given wind turbine. This procedure is repeated through all the wind speeds, and the sum will give the estimate of the total annualized wind energy [5]:

$$E_t=\sum_u E(u) \qquad (7)$$

The calculation for the annual energy production is based on an annual wind distribution, where it is assumed that the turbine has a total availability of 8760 hours per year, as shown in Fig. 3.



a) b)

Fig. 3. Comparison between annual wind distribution for a site in IEC class 1, a) with an average wind speed of 10 m/s and for a site in IEC class 4, b) with an average wind speed of 6 m/s.

Annual energy production

Constant speed wind turbines must be concerned with limitations of the overall system. Since the speed is held essentially constant, there is not a concern that the system will be running above rated speed under normal operation conditions. Since the power generated is related to the tip speed ratio, the amount of the energy produced would depend on the speed of turbine rotor, as well as the average wind speed. With a generator operating at constant speed, the turbine's speed would depend on the gear ratio chosen. When choosing a gear ratio it is therefore important to consider the average wind speed of the site.

The annual energy production for a variable-speed wind system must be calculated over the same range of average annual wind speeds as the constant-speed systems. For these computations, a Rayleigh distribution may be assumed for the wind speed [5, 6].

The comparison between annual energy production with constant-speed and variable-speed wind turbines (Fig. 4) points out that although improvements can be made by matching the gear ratio to the wind profile, while the variable speed operation can improve the wind production further. The variable-speed wind turbines show improved energy production over the constant-speed systems.

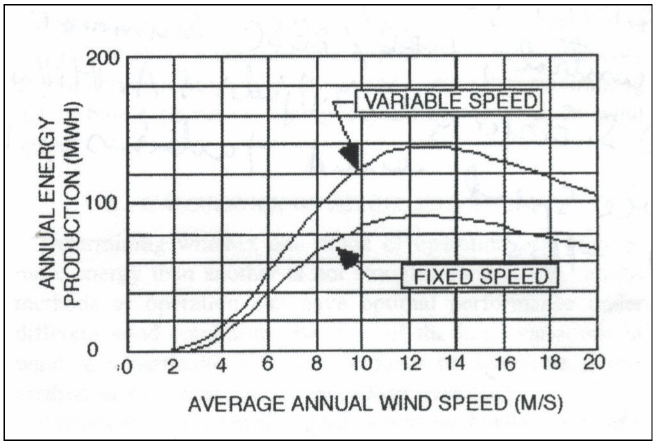


Fig. 4. Annual energy production versus average annual wind speed [7].

Annual energy loss distribution

Nowadays there is a trend towards application of variable speed wind turbines, in particular for turbines in the MW range. Therefore, for optimal energy extraction, the wind turbines should operate at variable speed.

In this section the losses of the different components of two variable speed wind generator systems are evaluated, with regards to their annual energy production [2]. Besides paying attention to the annual energy production, the evaluation has to point out in which part of each turbine concept the main part of the energy is dissipated.

The candidates are 3 MW variable speed wind turbines based on the DFIG with two PWM-VSI Frequency Converters (Back to Back Converter) and with passive external elements in the rotor side.

Having the wind distribution for a given site and the models of the system components, it is possible to predict the annual wind energy production. The Fig. 5 shows a general model for calculating the produced power for a given wind power.

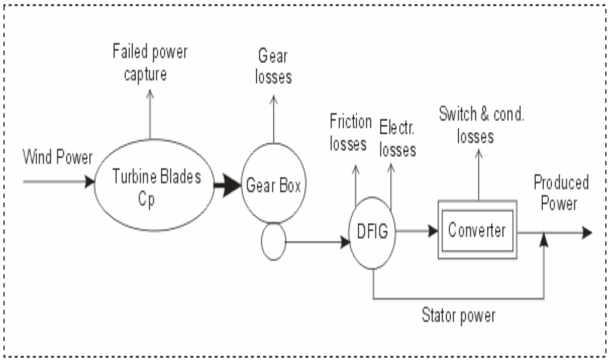
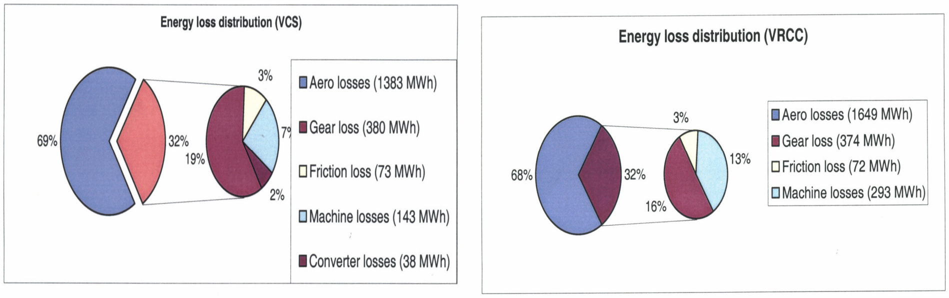


Fig. 5. The model for calculating the produced power for a given wind power of a wind turbine with DFIG.

In order to point out which part of the turbine accounting for the major parts of the energy losses, the annual energy loss distribution for both configurations are calculated as depicted in Fig. 6. The calculations included power losses due to the Cp coefficient variation, losses in the gear train, mechanical and electrical losses in the generators and finally converter losses.

The calculations of the aero-dynamic losses assume a theoretical maximum utilization of the wind energy of 0.59 whenever the produced output power is below 3 MW. The aero losses and friction losses are equals for both concepts while the gear drive losses (16 % and 19 %). and machine losses (7 % and 13 %) are different, as can also be seen in Fig. 6.



a) b)

Fig. 6. Annual energy loss distribution for different components of a variable-speed wind turbines of 3 MW with DFIG and back-to-back frequency converter a) (Vestas-OptiSpeed concept), and with DFIG with passive elements, b) (Vestas-OptiSlip concept) [2].

The machine losses are different due to the fact that the OptiSlip concept includes the losses of the external controllable rotor resistance. Regarding to the loss distribution it is concluded that the energy losses due to the turbine blades accounted for the major part of the losses for both systems. The losses in the gear drive are the second largest while the losses in the converter and the friction losses are the least significant for the considered topologies.

The comparison between both topologies presented before, point out that the OptiSpeed concept has a very high utilization of the wind energy while the OptiSlip concept has a slightly lower utilization of the wind energy.

Discussion and conclusion

The state of the art of wind turbines seen from electrical point of view includes old and new potential concepts of generators and power electronics based on technical aspects and market trends. Several generic types of generator are possible candidates in wind turbines. The squirrel cage induction generator has been frequently applied commercially. A second popular type is the induction generator with wound rotor, while the third is the current excited synchronous generator.

More research is also necessary in the classical solutions using power electronics. Especially, it is important to be able to predict the losses in order to keep a high reliability. As the back-to-back converter is state of the art today in wind turbine applications it can be used as a reference in a benchmark of the other converter topologies regarding the number of the components and their ratings, the efficiency, the harmonic performances and implementation.

The main challenges related to technology development are to reduce the technical uncertainties relating to production and durability for future wind energy project all over the world, to maintain the development towards a more optimal, reliable and cost-optimized technology, to improve the power plant characteristics of the wind turbine plants, developed the wind turbine technology for future applications, such as hybrid systems for smaller/isolated communities, the integration of a variable energy source into the energy system (HVDC transmission system), energy storage technologies, power flow control, compensation units and production forecasting and control of the power plants.

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Estimarea eficienței sistemelor de generatoare eoliene

Rezumat

In acest articol sunt studiate performanţele a două topologii de turbine eoliene, atât cu viteza constantă cât şi cu viteză variabilă, în funcţie de puterea activă generată. De asemenea, este prezentată o metodă de determinare a pierderilor de energie a generatoarelor eoliene. Pentru a evidenţia diferenţa dintre pierderile elementelor componente ale unei turbine de vânt utilizând maşina de inducţie cu rotorul bobinat, s-a realizat o comparaţie între două generatoare eoliene de 3 MW, unul cu viteza variabilă şi convertor de frecvenţă bidirecţional (OptiSpeed) iar celălalt cu viteză limitat variabilă şi reostat suplimentar în rotor , controlat printr-un chopper (OptiSlip).