Efficiency of three wind energy generator systems

Anders Grauers
Department of Electric Power Engineering
Chalmers University of Technology
S-412 96 Göteborg, Sweden

Abstract—This paper presents a method to calculate the average efficiency from the turbine shaft to the grid in wind energy converters. The average efficiency of three 500 kW systems are compared. The systems are: a conventional grid-connected four-pole induction generator equipped with a gear, a variable-speed synchronous generator equipped with a gear and a frequency converter, and a directly driven variable-speed generator equipped with a frequency converter. In this paper it is shown that a variable-speed generator system can be almost as efficient as one for constant speed, although it has much higher losses at rated load. The increased turbine efficiency that variable speed leads to has not been included in this paper. It is also found that a directly driven generator can be more efficient than a conventional four-pole generator equipped with a gear.

KEYWORDS
Losses, Efficiency, Wind energy, Constant speed, Variable speed, Directly driven generator, Gear, Generator, Frequency converter.

I. INTRODUCTION

A standard wind energy converter of today has a constant turbine speed of 30 to 50 rpm and uses a gearbox and a four- or six-pole induction generator, directly grid-connected. This concept is very simple and reliable and it can be made of standard components. Therefore, it is the most common system today. There are, however, some drawbacks. The gear is an expensive and heavy component and it causes losses. An other disadvantage of the directly grid-connected generator is that the constant speed only allows the turbine to operate at its maximum efficiency at one wind speed. These drawbacks can be eliminated by using variable speed and a directly driven generator.

Variable speed is considered mainly because it can slightly increase the energy captured by the turbine and because it can reduce some mechanical loads.

A directly driven generator leads to a system without the expensive gearbox and its losses. Such generators have been proposed by, for instance, [1,2] and today one wind energy converter manufacturer produces 200 kW and 500 kW directly driven wind energy generators. The drawbacks of directly driven generators are that they are large and often have high losses. In the design of a directly driven generator, variable speed is also an advantage for two further reasons. The first is that the nominal generator frequency can be chosen freely allowing a better generator design. The second one is that the frequency converter can control the generator power and, thereby, reduce the demands on efficient damping in the generator. (It is difficult to obtain sufficient electrical damping in low-speed generators with a small pole pitch.)

Different wind energy converter systems are compared mainly regarding cost per kWh. Therefore, several things should be investigated: the average power captured by the turbine, the system cost, the efficiency, and the availability of the systems. In this paper one of these aspects, the efficiency, is investigated. The efficiency is important when comparing different systems because the losses reduce the average power produced by the wind energy converter and, thereby, they reduce the incomes. The average power production is, of course, determined by the average efficiency and not by the efficiency at rated load. Earlier, it has often been assumed that a variable-speed system must be less efficient than a constant-speed system simply because a frequency converter is added to the system and it has losses [3].

The purpose of this paper is to show, theoretically, that a variable-speed generator and converter system can be about as efficient as a directly grid-connected generator, although its efficiency at rated load is much lower. The paper also shows that a directly driven variable-speed system can be more efficient than a four-pole generator equipped with a gearbox.
II. CALCULATION METHOD

Because one of the compared systems is a constant-speed system while the other two are variable-speed systems the energy captured by the turbine differs between the systems. The comparison in this paper is made only on the average efficiency from turbine shaft to the grid. This means that the results do not include that a variable-speed turbine will capture a few percent more energy than a constant-speed turbine.

To find the average efficiency, the average power production of the turbine $P_{\text{av}}$ and average losses $P_{\text{av}}$ must be calculated. This can be done by using a probability density distribution $w$ for the wind speed $v$. The turbine power $P(v)$ is multiplied by the probability density and integrated from the wind speed $v_{\text{min}}$, at which the turbine starts, to the wind speed $v_{\text{max}}$, 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

$$P_{\text{av}} = \int_{v_{\text{min}}}^{v_{\text{max}}} P(v) w(v) \, dv$$

(1)

It has here been assumed that the availability of the wind energy converter is 100 %. The turbine power as a function of wind speed for a constant-speed turbine is shown in Fig. 1.

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

$$\eta_{\text{av}} = 1 - \frac{P_{\text{av}}}{P_{\text{av}}_{\text{total}}}$$

(2)

The probability density of different wind speeds is approximated by a Weibull distribution. A typical wind speed probability density distribution and typical losses of a wind energy converter are shown in Fig. 2. In Fig. 3 the product of the probability density and the losses is shown. That function is the loss density and its integral is the average losses. It can be seen in Fig. 3 that the losses at wind speeds below 8 m/s are much more important for the average losses than the losses above rated wind speed, 13 m/s, because the loss density is much higher at low wind speed than above the rated wind speed.

The average losses are not necessarily the same for two similar wind energy converters at different sites because the probability density function depends on the wind conditions at the site. Therefore, the average losses must be calculated for a site with wind conditions similar to the ones at the site where the wind energy converter will be used. Since wind conditions differ considerably between different sites, both a low, a medium, and a high-wind speed site have been used as examples in this paper.

The probability density parameters and turbine performance are usually calculated from 10 minutes average values, while the time constant of the speed control of a variable-speed wind energy converter is only in the order of a few seconds. The average power of the variable-speed turbine calculated by the presented method will, therefore, have an error which is in the order of some percents or less. The input power of the variable-speed turbine may be slightly higher than predicted by the
method used. Therefore, the calculated average power should not be used to compare the energy production of a variable-speed and a constant-speed turbine. However, since the losses are a function of the input power and not of the wind speed, the losses will be calculated correctly for the slightly underestimated input power. Thus, the predicted average efficiency is right in relation to the calculated average input power. A variable-speed turbine may, however, reach that average power on a site with a little lower average wind speed than assumed here. This error is not a problem for the conclusions in this paper since the purpose is only to compare the generator system efficiency. The difference in energy production between variable-speed and constant-speed turbines is not included here and it must be calculated by means of a more detailed aerodynamic model.

III. THE COMPARED SYSTEMS

In this section the three compared 500 kW generator systems are presented. The systems represent three different concepts which are all interesting for future wind energy converters.

The first one is the conventional constant-speed generator system with a step up gear and a directly grid-connected four-pole induction generator.

The second system is a variable-speed synchronous generator equipped with a gear and a frequency converter. The synchronous generator is very interesting for variable-speed systems because it can be connected to a diode rectifier and, thereby, lead to a very efficient system. The generator has almost the same efficiency as the induction generator, only 0.4 % lower because of current harmonics from the diode rectifier. To maximize the generator and frequency converter efficiency the flux linkage is reduced at low power. The frequency converter has a diode rectifier, a dc step up converter and an IGBT inverter (Insulated Gate Bipolar Transistor), see Fig. 4. The rectifier is chosen for its low price and low losses and the inverter because it produces high quality power to the grid.

The third system is a directly-driven variable-speed permanent-magnet generator with a frequency converter of the same type as the one in system two. The generator has been designed by Chalmers University of Technology as a part of a EU Joule II project. It has a three-phase stator, NdFeB magnets, the air gap diameter is 3.8 meter, the stator length 0.35 m, the pole number 160 and the active weight 2800 kg.

The proposed diode/IGBT frequency converter has an efficiency at rated load of about 97 %. There are both more efficient converters, like the diode/thyristor converter (98 %), and less efficient converters, like the IGBT/IGBT converter (96 %). The more efficient converters have higher harmonic content in the grid current and are, like the proposed converter, only for generator operation. The less efficient converters can be used both for generator and motor operation and, if necessary, they can be used to start the turbine. Stall regulated turbines need motor start and pitch regulated turbines do not need motor start. However, the low efficiency and the high price of four-quadrant converters may make it better to use a separate small frequency converter for motor start rather than to use the main converter.

IV. DIFFERENT TYPES OF LOSSES

In this section the losses for the different systems will be estimated and discussed. The losses of the generator systems 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 speed. The no load losses are bearing losses, oil churning losses and windage losses. They are independent of load but speed-dependent. The no load losses are at a conservative estimate proportional to the speed. The gear is here assumed to include the turbine bearing. The estimated losses at rated load of a 500 kW gear for wind turbines are shown in Table I. The losses have been estimated from the data of three different wind turbine gearboxes.

The generator losses are calculated according to the conventional electric machine theory. The losses are copper losses, hysteresis and eddy current core losses, windage and friction losses, and additional losses. The copper losses depend 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. The losses of the four-pole induction generator are based on data from a commercial induction generator and the losses of the directly driven generator are from a design study of a 500 kW generator. Since the directly driven generator has to include the turbine bearing and since large cooling fans are needed, the friction windage and cooling losses are high. The
losses of the four-pole synchronous generator are estimated for a generator with the same stator kVA rating as the induction generator and a salient pole rotor excited by a brushless exciter. The losses at rated load of the different 500 kW generators can be seen in Table II.

In the two variable-speed systems the losses of the frequency converter have to be included. The converter losses are copper losses, voltage drop losses and no load losses of the rectifier, the dc step-up converter, and the inverter. For a 500 kW diode/IGBT converter the losses at rated load are shown in Table III.

V. LOSSES AT DIFFERENT WIND SPEEDS

To be able to use the proposed method to calculate the average losses, the losses must be expressed as functions 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 parameters change differently for wind energy converters with different control of the generator speed and flux density.

In the constant-speed system the speed and flux linkage of the generator are approximately constant. The generator current decreases as the power captured by the turbine decreases. In the two variable-speed systems the speed increase linearly with the wind speed up to the rated speed, which in this case is reached at 9 m/s. Above that wind speed the turbine speed is kept constant. The flux linkage of the generator is approximately constant in the directly driven permanent magnet generator, but in the variable-speed four-pole generator it is reduced at low power to keep the efficiency high at low load. The currents in the two variable speed generators and converters are determined by the power captured by the turbine and the generator voltages.

In Fig. 5 the different losses are plotted separately for the three generators. It can be seen that the copper losses decrease in all the generators as the wind speed decreases. The core losses and friction losses are not reduced in the grid connected induction generator because the flux linkage and the speed remain approximately constant. In the two variable-speed systems the windage and friction losses decrease when the generator speed decreases, below 9 m/s. The core losses of the directly driven permanent magnet generator do not decrease before the speed is decreased, since the flux linkage is constant. The core losses of the conventional synchronous generator decrease when the wind speed is below 12 m/s, approximately, since the flux linkage is reduced by the excitation control. It can be seen that the core 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 the average losses than the copper losses, especially in a grid-connected generator but normally also in variable-speed generators. Even in the directly driven generator, which has three times higher copper losses than core losses at rated load, the average core losses are still somewhat higher than the average copper losses.

The various losses in the gearbox also change differently with the wind speed. The gear mesh losses are always a fixed percentage of the input power so their average losses are the same for the two systems equipped with a gear, but the average no load gear losses are much higher in the constant-speed system than in the variable-speed system.

The losses in the frequency converter are mainly voltage drop losses of the semiconductors and resistive losses and they are reduced as the current decreases. The no load losses of the frequency converter are rather small and, therefore, the frequency converters average efficiency is not much lower than its rated efficiency.
The total losses of the different generator systems at different wind speeds are shown in Fig. 6. It can be seen that the two variable-speed systems have the highest losses at rated wind speed because of the converter losses and the increased losses in the generator due to harmonics. At low wind speeds the losses of the variable-speed systems decrease much and at wind speeds below 7 to 8 m/s the constant-speed system has the highest losses because the generator and gear no load losses remain constant in that system. The losses of the directly driven generator system do not decrease as much as the losses of the synchronous generator system because the flux linkage of the permanent magnet generator can not be decreased. Fig. 6 illustrates why it may seem as variable-speed systems are less efficient than constant-speed systems. The large difference in losses at rated load looks so much more important than the small difference in losses at low load. However, as will be shown in the next section the high probability of the low wind speeds and the low probability of the high wind speeds lead to a high average efficiency of the variable-speed systems.

VI. THE AVERAGE EFFICIENCY

In this section the average efficiency of the different generator systems are compared. This is done for three different wind energy converter sites. The first site is a low-wind speed site (average wind speed 5.3 m/s), the second site is a typical Swedish wind turbine site (6.6 m/s), and the third site is a high-wind speed site (7.8 m/s). The capacity factors for the wind turbine, average power divided by the rated power, are 15%, 25%, and 35% for the three sites.

In Fig. 7 the loss densities of the different systems at a medium-wind speed site have been calculated from the losses in Fig. 6. The loss densities above 8 m/s are higher for the two variable-speed systems, while the loss densities at wind speeds below 8 m/s are higher for the constant-speed system.

The calculated average efficiency at different sites and
the efficiency at rated load for the three systems are compared in Table IV. The comparison shows that the variable-speed gear and generator system can be about as efficient as the constant-speed system even though the efficiency at rated load is 3.2 % 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 site 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 generators equipped with a gear both at low and high-wind speed sites. The difference in average efficiency between the proposed directly driven generator system and the grid-connected generator system is 1.5 % at a medium-wind speed site. This shows that the high losses of the directly driven generator are not a big disadvantage. There are two reasons for that: the gearbox losses are eliminated, and a large part of the losses in the directly driven generator are copper losses which cause rather low average losses.

The difference in efficiency between constant-speed and variable-speed systems is, of course, depending on how efficient the frequency converter is. If a higher harmonic content is acceptable in the grid current a thyristor inverter can be used and the efficiency of the variable-speed system will be higher. If a four quadrant converter is used the efficiency will, instead, be lower.

There are two important reasons for why the converter-speed system can be as efficient as the directly grid-connected generator in applications with a low average generator utilization. Both the generator and the gearbox no load losses are reduced in the variable-speed system. In other applications than wind energy converters, where there are no gearbox or the average utilization is higher, a constant-speed system will probably always be more efficient than a variable-speed system.

VIII. REFERENCES


Anders Grauers was born in Gothenburg, Sweden, in 1966. He received the MSc (E1.Eng) and Lic (E1.Eng) degrees from Chalmers University of Technology, Gothenburg, Sweden, in 1990 and 1994, respectively. Since 1990 he is studying for the PhD degree at the Department of Electric Power Engineering at Chalmers University of Technology, Sweden. His research interests are in the area of electrical systems for wind power applications, especially variable-speed generator systems and directly driven generators.
DISCUSSION

Lambert Pierrat (SM IEEE, Electricité de France, General Technical Division, 37 Rue Diderot, 38040 Grenoble Cedex, France):

This study is very interesting because it allows to compare the energy efficiency of various electromechanical converters taking into account the expected operating conditions of the wind turbine. I wish to thank the author for the answers and the comments to the following questions:

1. Losses in the generators at related load: Table II summarize the losses of 3 generators having the same rated power (500 kW). In my opinion, the total losses of the 3 generators are practically equal and the rated losses of induction generator and of the synchronous generator cover the range between 5 and 6% (the values are related to 4-6 poles machines). Can the author provide more information about the values shown in Table II (estimated or measured values)?

2. Input average power and energy production: the author rightly remark that these two parameters cannot be used to compare constant and variable speed turbines. As far as the variable speed turbine is concerned, the input power has to be increased in order to take into account the high dynamic response of the frequency static converter. This energy increase depends, on one hand on the ratio between the observed wind speed time and the response time of the system (~200), and on the other hand on the maximum operating speed and on the spectral density of the wind speed. Considering the values shown in Table IV (average mean speed) and the Figs. 6, 7 (maximum wind speed), the increase will be in the range of 0 to 5%. Can the author evaluate this increase for the 3 sites defined in Table IV?

3. Average efficiency: the relation (2) includes the ratio between the mean losses (Pdav) and the mean input power (Ptav). These mean values are defined considering the probabilistic density function of the wind speed (cfr equation (1) and loss density). The speed does not influence in the same way the power and the losses, so the average efficiency has to be lightly increased when variable speed generators are considered in order to take into account the previous considerations. What is the magnitude of this correction?

4. Economic aspects: the increase of the average efficiency is a technical and economic target. The comparative study of the 3 wind sites points out the need to consider the operating aspects and the interest for a specific solution. Even if the study regards only the conversion efficiency, can the author evaluate the relative costs of the 3 solutions?

Clearly the points of this discussion do not affect the validity of the author conclusions.

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A Grauers: L Pierrat has several interesting questions about the comparison of different generator systems. Some of them are difficult for me to answer fully at the moment, since they include aerodynamical and economic aspects. I hope the following answers will make the comparison clearer.

1) The efficiency of the induction generator, IG, is based on a manufacturer's data for a 500 kW four-pole machine with a shaft height of 400 mm. Similar efficiency can be found for other standard IGs as well. The efficiency of the synchronous generator, SG, is based on estimations and it is, therefore, a little uncertain. The reason that data for existing SGs are not used directly is that standard SGs are of an open design, IP 23, while IGs are enclosed, IP 54. The open generator is smaller and cheaper, but because it produces the same torque in a smaller frame size it has a lower efficiency. The efficiency of an IP 54 SG has been estimated by assuming that the SG has the same stator dimensions as the IG. For sinusoidal currents and voltages the SG will have about the same efficiency as the IG. The diode rectifier, however, increases the additional losses by approximately 0.4%. It can be noted, that the estimated efficiency of the SG, 96.1%, is only slightly higher than the efficiency of a standard SG with a shaft height of 400 mm and a reduced rated current (Marine class) at a comparable power factor.

Directly driven generators will generally have lower efficiency than four-pole generators because of the high rated torque. The reason that the efficiency is not even lower than 94.3% is that the generator diameter is large and that it is a permanent magnet, PM, generator. The efficiency can be further increased by optimizing the design. However, there is a trade-off between efficiency and diameter and I believe it is more likely that improvements will be used to decrease the diameter rather than increase the efficiency. The efficiency used in my calculations is almost the same as for a generator without flux concentration found in reference [2] of the paper.

2) The increase in energy captured by a turbine using variable speed instead of constant speed will be 6.2% for the low wind speed site. For the medium wind speed site the increase will be 2.9% and for the high wind speed site 1.6%. These figures are based on the 10 min average values and will, therefore, be under-estimations. There is, unfortunately, no simple way to calculate the exact increase accurately, since not only the probability density function changes if the calculations are made on a time scale of seconds. On this shorter time scale also the control system will influence the amount of energy captured and the aerodynamic behaviour of the turbine will, perhaps, have to be described by a dynamic model instead of the static power coefficient function used in my calculations.

3) The difference in generator speed is included in the comparison of the systems. For the variable speed system, the speed has been defined as a function of wind speed and the speed variations are also included in the calculations of Ptav and Pdav. Thus, Ptav is not the same for the constant speed and the variable speed systems.

4) Today, a 500 kW IGBT frequency converter system is very expensive. However, the cost will be reduced. In a near future, I believe, it is reasonable to assume that the frequency converter, in large series, will cost less than 10% of the complete wind energy converter, WEC. Compared with the increased energy production this will lead to approximately the same or slightly higher cost of the produced electricity. However, the reason to use variable speed and frequency converter is not only the increased energy production, but also the possibility to limit mechanical loads in the WEC and to allow reduction of the grid disturbances caused by the WEC. Reducing the mechanical load may decrease the cost of the WEC.

The cost of directly driven generators cannot be estimated yet since the technology is still immature. Based on the studies I have made I would guess that a directly driven PM generator of the type described in this paper is today likely to cost as much as or even more than a conventional gear plus generator. However,
directly driven generators have a large development potential. Several new generator concepts have been proposed and if the generator size can be reduced, without increasing the weight too much, directly driven PM generators will be competitive in the future.

Finally I would like to add that the questions of using variable speed or directly driven generators, of course, will be determined mostly by other aspects than the system efficiency. One of the aims of my paper is to show that the low efficiency at rated load of such systems should not be considered as a drawback.

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