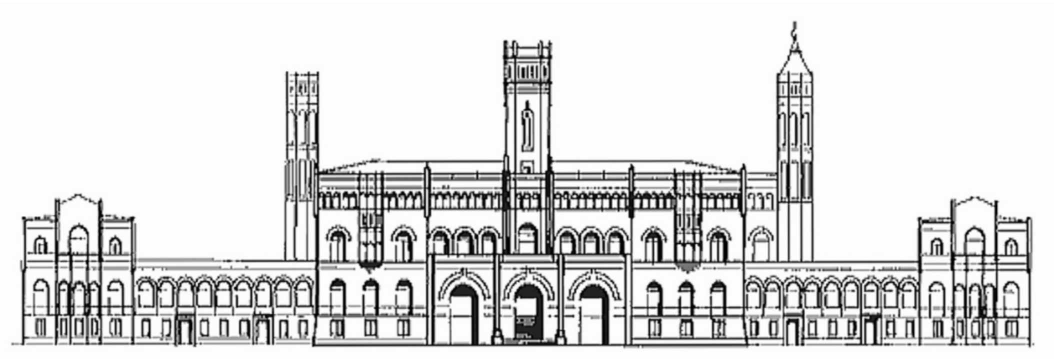

Leibniz University of Hanover, Germany
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Investigation of the Thermal Load of Power Semiconductors Used in Wind Turbines with Doubly Fed Induction Generator

Master Thesis

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Ich versichere, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Ort, Datum

Structure of the thesis

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NOMENCLATURE

*	This sign accompanying any of the following parameters defines the reference or desired value of that parameter
P_m	Mechanical power captured by the wind turbine and transmitted to the rotor
P_s	Stator active power output
P_r	Rotor active power output
Q_s	Stator reactive power output
Q_r	Rotor reactive power output
T_m	Mechanical torque applied to the rotor
T_e	Electromagnetic torque applied to the rotor by the generator
ω_s	The rotational speed of the stator flux (synchronous speed)
ω_r	The rotational speed of rotor flux
v_{ds},v_{qs}	The three-phase supply voltages in dq reference frame, respectively
i_{ds},i_{qs}	The three-phase currents in dq reference frame, respectively
λ_{ds}, λ_{qs}	The three-phase stator flux linkages in dq reference frame, respectively
v_{dr},v_{qr}	The three-phase rotor voltages in dq reference frame, respectively
i_{dr},i_{qr}	The three-phase rotor currents in dq reference frame, respectively
λ_{dr}, λ_{qr}	The three-phase rotor flux linkages in dq reference frame , respectively
R_s,R_r	The stator and rotor resistances of machine per phase, respectively
L_{ls},L_{lr}	The leakage inductances of stator and rotor windings, respectively
L_m	The mutual inductance between stator and rotor
θ_s, θ_r	The stator and rotor flux angle, respectively

J,D	The moment of inertia (Combined rotor and wind turbine) and the damping coefficient, respectively
z_p	Number of pole pairs
L,R	The inductance and resistance of the filter, respectively
P_{DC}	The DC-link active power

Motivation

Among many other reasons, but more importantly, as a consequence of oil price shock during 1970s, is that the global energy outlook is toward the renewable energy resources and in this field, wind energy -absorbed through wind turbines- has received great attention. For this, it is needed to set up wind farms -a field of wind turbines, producing large sum of electrical energy like a powerhouse- and due to change of wind speed we need to be able to control these turbines to adjust their operation with the wind velocity for the maximum power absorption.

Since the wind turbines are set up, the reliability of the system components plays a major role in the field of electrical energy supply. The failure of a wind turbine, for the investor, always means losses due to repair costs and loss of feed-in tariffs. Especially in the field of offshore wind farms, a failure is inevitably associated with a longer downtime, as repair is difficult and lasts longer because of the availability of the funds. For this reason, it is of interest to analyze the reliability of the electrical system of wind turbines.

This is to be mentioned that the following publication has been studied as a pre-requisite for getting an overview about the subject of this thesis:

- S.M. Bolik, institute of energy technology, Aalborg University, Modeling and Analysis of Variable Speed Wind Turbines with Induction Generator during Grid Faults, Oct.2004.

Chapter 1:

- ***Introduction To Wind Energy And Wind Turbines***

1 Introduction

As a general introduction to the topic of wind energy and wind turbines seems required but this generality is behind the scope of this thesis, the introduction in this chapter is based on [3].

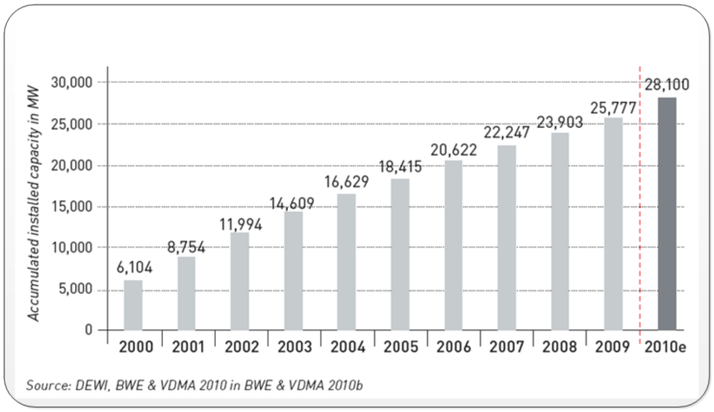
1.1 Overview

Some international statistics can show the global interest for huge utilization of wind power. Among these, the U.S. wind industry had 40,180 MW wind power capacity installed at the end of 2010 which is more than 20% of the world's installed wind power, with 5,115 MW installed in 2010 alone [1].

In addition to these international statistics, the cumulative installed capacity for Germany and the total global percentage installed capacity by continent are shown in Table 1.1 and Figure 1.1, respectively [2]. Along with these, fast progress in the field of generators, semiconductor devices, and solid materials, have established a strong basis for the huge, and more importantly cost-competitive wind turbines.

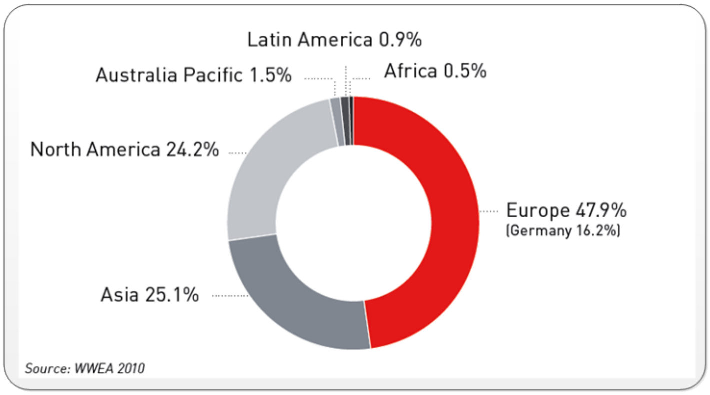
Table 1.1

The cumulative installed wind energy capacity in Germany



Source: DEWI, BWE & VDMA 2010 in BWE & VDMA 2010b

Figure 1.2 illustrates the general power conversion, beginning from power absorbed by turbine from wind, to electrical power delivered to the consumer. The power from the wind is converted into rotational power through the rotor of the wind turbine. This power conversion is in some turbine configurations, partly controllable. The rotational power is then transferred to the generator, either directly or through a gearbox to step up the rotor speed (optional here means that gearbox can either exist in the configuration or not).



Source: WWEA 2010

Figure 1.1

The total global percentage wind energy installed capacity, by continent

The mechanical power is then converted into electrical power by generator. From the generator, the electrical power is transferred to the supply grid either directly or through an electrical power converter (optional here means that either existing or not, and also different configurations are available for this stage when it is used in the system). From the supply grid, the power finally is delivered to the consumer. The main goal of this section is to show the different concepts for converting the mechanical power at rotor to electrical power available at the supply grid. However, to form a foundation to understand the problems related to different electrical concepts, a short description of the conversion of wind power to rotational power is provided.

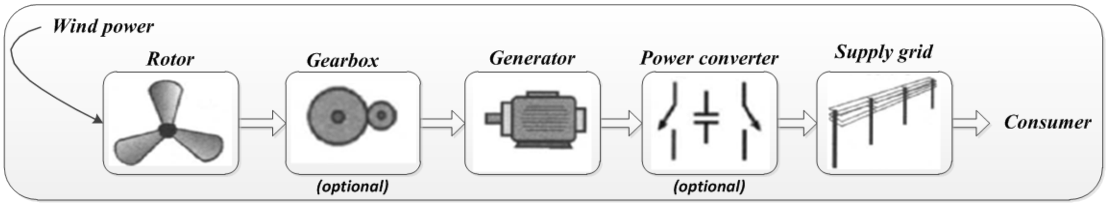


Figure 1.2

General wind power conversion

1.1.1 Wind energy

When wind is considered as a source of energy for the supply grid, two main problems have to be noticed:

- Unpredictability in the macro-scale airflow, *i.e.*, average wind speed
- Problems caused by the micro-scale air flow, *i.e.*, rapid wind speed changes such as wind gusts

The macro-scale airflow is due to the weather in the area and is imposed by local low- and high-pressure zones and is known by slowly varying conditions. Thus, the macro-scale airflow represents the average wind speed. However, because of the movements of these low -and high-pressure zones, the long-term prediction of wind power is impossible.

Another problem in the utilization of the wind energy is the micro-scale airflow. This micro-scale airflow causes rapid fluctuations in the wind speed at a given site and hence fast transients in the generated power.

The instantaneous power, P_{wind}, available in the wind flowing in the area A_v, can be described by:

$$P_{wind} = \frac{1}{2}\,\rho_{air} \cdot\ A_v\ \cdot v_w^3 \tag{1.1}$$

where ρ_{air} is the air density and v_w is the wind velocity.

Absorbing all the power carried by the wind moving with this speed requires the wind speed to be zero after passing the turbine, therefore full utilization of the power described by (1.1) is impossible. Actually, the theoretical maximum power extraction ratio, the so-called betz limit, is 59%. In practice the actual wind extraction ratio, described by the power performance coefficient C_p will be below the *betz* limit and it is influenced by several factors, among these, the blade design and the ratio between wind speed and rotor tip speed. The power transmitted to the hub of the wind turbine (P_{tur}) can be expressed as:

$$P_{tur} = \frac{1}{2} C_p(\lambda) \cdot \rho_{air} \cdot A_v \cdot v_w^3 \tag{1.2}$$

The power performance coefficient varies considerably for various designs, but in general it is a function of the blade tip speed ratio λ and β the pitch angle which is not considered in this thesis.

The blade tip speed ratio (T.S.R) is defined as performance coefficient varies considerably for various designs, but in general for a constant value of β it is [4]:

$$\lambda = \frac{v_{trip}}{v_w} = \frac{r_{rt} \cdot \omega_{rt}}{v_w} \tag{1.3}$$

where v_{trip} is the blade tip speed, r_{rt} is the radius of the propeller, and ω_{rt} is the angular velocity of the propeller. It can be shown that λ must be constant to be able to absorb the maximum power from the wind. Then we can see that v_w and ω_{rt} are inversely proportional which means that turbines rotational speed must increase when the wind speed increases, to keep λ constant. The relation between λ and C_p for the rotor of wind turbine investigated here can be expressed though equation 1.4 [5]:

$$C_p = 0.244 \left(\frac{130}{\lambda} - 6.56 \right) e^{\frac{-13.3}{\lambda}} \tag{1.4}$$

This equation is plotted for $\lambda = 0$ to 22 and the result is illustrated in Figure 1.3.

A typical value for the maximum power performance coefficient in C_p is 0.45 for $\lambda = 8$. It should be noted that C_p depends on pitch angle which is out of the scope of this thesis and here pitch angle is considered zero.

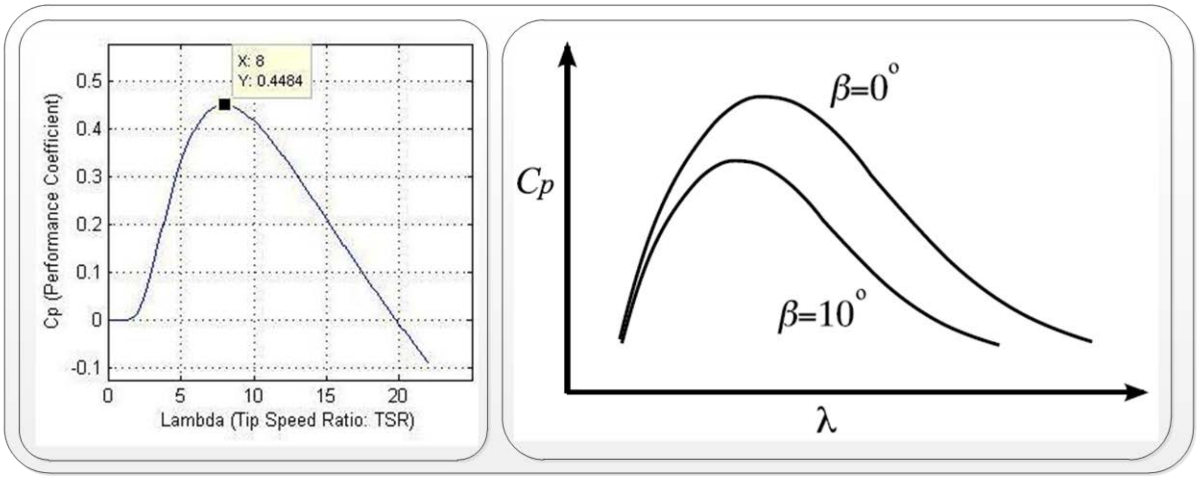


Figure 1.3 [4]

The relation between λ and Cp and dependency to pitch angle

1.1.2 Power control

Wind turbines are designed to produce electrical energy as cheaply as possible and therefore they are generally designed to yield maximum output at wind speeds around 15 meters per second. In the case of stronger winds it is necessary to waste a part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of power control. The control of the power extracted from the wind can be done in several ways; although stall and pitch control (or a combination) seems to be the prevalent methods in modern wind turbines (both constant speed solutions and variable speed solutions). However, for completeness, a short description of known power limiting methods is provided:

- *Ailerons:* some earlier wind turbines use ailerons (flaps) to control the power. Ailerons are moveable flaps along the blade trailing edge-as existing in the airplanes.
- *Twistable tip:* Some turbines, instead of moveable flaps, use a method which the tip of the turbine blades can turn and change the aerodynamic performance of the blade and therefore increasing the friction in the rotational direction.
- *Yaw control:* To yaw the rotor partly out of the wind to decrease power is another possibility. This method of yaw control in practice, is used only for very small wind

turbines (class of 1 kW or less), as it subjects the rotor to cyclically varying stress that can damage the structure.

- *Pitch:* basically, the operation of a pitch-controlled wind turbine is related to its ability to change the power performance coefficient ***Cp*** by turning the rotor blades around their longitudinal axis. On a pitch-controlled wind turbine, the turbine's controller checks the output power and whenever the output power is too high, the rotor blades are moved (pitched) slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops. During normal operation, the blades will pitch a fraction of a degree at a time and the rotor will be turning at the same time. Although pitch control seems to be a simple operation, its practical realization needs some serious efforts in order to make sure that the blades pitch the desired angle and that all blades are in angle synchronously. The pitch mechanism can be operated either by the use of electrical or hydraulic actuators where the latter seems to be the common method.
- *Stall:* a simpler power control method is the passive stall regulation (or just stalls regulation). In a stall-regulated wind turbine, the rotor blades have a fixed angle, contrary to the pitch-controlled turbine. Therefore, it is the aerodynamic performance of the blades that provides the power control. The blades are designed in such a way that at the moment the output power reaches the nominal power, turbulence at the back of the blades occurs, thus reducing the power extracted from the wind. To ensure a gradually occurring stall rather than an abrupt stall, the blades of a stall-regulated turbine are slightly twisted along their longitudinal axis, thereby providing stall to occur gradually. The basic advantage of stall control method is that one avoids moving parts in the rotor itself and a complex control system. On the other hand as a disadvantage, stall control includes a very complex aerodynamic design problem. Compared with the pitch controlled wind turbine, it appears that at low wind speeds, their performance is almost the same. In the power-limiting zone, i.e., wind speeds above nominal wind speed; the stall- regulated turbine shows a small power overshoot with a decreasing output power as wind speed increases. The pitch-controlled turbine has almost constant power extraction at high wind speeds.
- *Active stall: an* increasing number of new and larger wind turbines include an active-stall power control mechanism. The active stall machines resemble pitch-controlled machines, since they have the ability to pitch their blades. At low wind speeds, the active stall controlled turbine will typically be programmed to pitch the blades like a common pitch-

controlled machine, in order to maximize the power extracted from the wind. At and above rated wind speed, i.e., rated power, the active stall regulated turbine behaves in a different and we can say an opposite way as the pitch-controlled turbine. Instead of pitching the blades out of the wind, the attack angle of the blades is increased, thus provoking a stall situation. Compared to passive stall control, the active stall-controlled wind turbine shows the same power performance as the pitch-controlled turbine. Moreover, because of the pitch-controlled blades, the rated power level can be adjusted precisely, eliminating effects of differences in air density, blade-surface contamination, etc. In this way, the uncertainties in the rated power level (typical for passive stall control) can be avoided. As a result, active stall control ensures maximum power output for all environmental conditions without overloading the drive system of the turbine. The pitch mechanism is usually operated using either hydraulics or electric actuators.

At this point, it should be noted that none of the discussed power control principles can be made fast enough to track the fast power transients from wind gusts.

1.1.3 General structure of a wind turbine

Nowadays, the horizontal three-blade turbine is the most popular topology, although principles described in the remaining part of this chapter can be applied to any wind turbine configuration. Figure 1.4 shows the general structure of the nacelle for a horizontal three-blade grid-connected wind turbine (it should be noted that the structure may differ for the different concepts; using the gear box in the structure and the size of the generator especially depend on the considered subject).

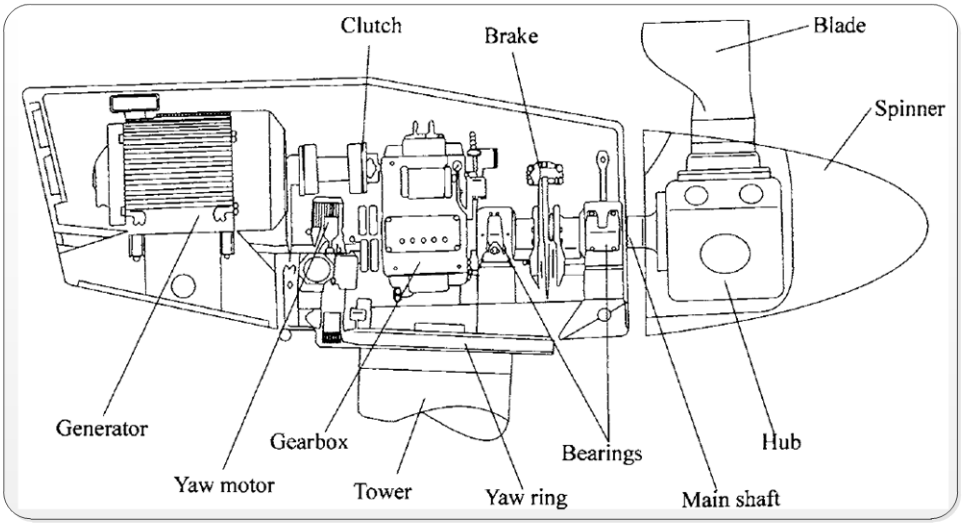


Figure 1.4

Typical structure of a horizontal three-blade grid-connected wind turbine

1.2 Constant-speed wind turbines

One group of presently installed but due to their problems, no more produced wind turbines operate as constant (or near constant) speed systems. This means that no matter what the wind speed is, the angular velocity of the rotor, ω_r, is fixed and determined by other factors, like the frequency at the supply grid, the gear box ratio, and the generator structure (Synchronous, Wound rotor, or Induction generators can be named here). In general, constant-speed solutions are known with the characteristic of simplicity and reliability in construction on the electrical parts, but in this configuration higher stresses are introduced to mechanical parts and additional safety factors must be considered in the mechanical design. Furthermore, constant-speed wind turbines have a certain negative effect on the supply grid, especially in the areas with weak supply grids and a high penetration of wind velocity.

1.2.1 Problems related to the constant-speed operation

Among others, a reason for the earlier common and popular use of fixed-speed wind turbines is the simple and reliable generator construction, which for small wind turbines seems to be the most competitive characteristic in terms of cost per kilowatt-hour. In large wind turbines and particularly in wind farms, the problems with fixed-speed operation become more and more important. As shown in the previous sections, to deal with these problems several parameters like stronger mechanical design have to be considered, which can definitely reduce the reliability and cost-competitiveness of the fixed-speed wind turbine generator systems. Some of the drawbacks related to the fixed-speed configuration are summarized here:

- *Energy capture:* one problem concerning the design of a constant-speed wind turbine is choosing a nominal wind speed at which the wind turbine can deliver its rated power. This problem is related to the fact that the energy capture of the wind is a nonlinear function depending on the ratio between wind speed and rotor tip speed (C_p). Because of the more complicated structure of a variable-speed wind turbine, the power losses from mechanical power to electrical power might be higher, thereby wasting some of the gained power.
- *Mechanical stress:* another problem concerning the fixed-speed wind turbine is the problem related to the design of the mechanical system. Because of the almost fixed speed of the wind turbine, fluctuations in the wind power are converted to torque pulsations, which result in mechanical stress. To avoid breakdowns, the drive train and gearbox of a fixed-speed wind turbine must be able to withstand the absolute peak loading conditions, and consequently additional safety factors need to be incorporated into the design [6].
- *Power quality:* the power generated from a fixed-speed wind turbine is sensitive to fluctuations in the wind. Because of the sharp speed-torque characteristics of an induction generator, any change in the wind speed is transmitted through the drive train on to the grid [6]. An improvement of the power quality is the pitch control that to a certain extent compensates slow variations in the wind by moving (pitching) the rotor blades and then changing the power performance coefficient Cp. The pitch control is not able to compensate for gusts and the fast periodic torque pulsations that occur at a frequency at

which the blades pass the tower. The rapidly changing wind speed and thereby wind power, may create an objectionable transient voltage which causes in the form of spark. Another power quality problem of the fixed-speed wind turbine (with the induction generators configuration) is the reactive power consumption. Many of the electrical networks to which wind farms are connected have high source impedances and are generally weak. The output power of a constant-speed wind turbine changes related to the wind condition, resulting in voltage fluctuations at the point of connection. Due to these voltage fluctuations, the constant-speed wind turbine receives varying amounts of reactive power from the supply grid, which increases the voltage fluctuations and also the line losses. To improve the power quality of wind turbines, large reactive compensation components, actively controlled as well as passive, must be used to compensate the reactive power consumption. To get an impression of the size of the compensation installation, [7] treats a static VAR compensator for a 24 MW wind turbine farm and it is found that the necessary installation amounts to 8.8 MVAR.

1.3 Variable-speed wind turbines

As the size of wind turbines becomes larger and the penetration of wind energy in certain areas increases, the problems related to the constant speed wind turbines become more and more annoying to the system, especially in areas with relatively weak supply grids. To conquer these problems, the trend in modern wind turbine technology is doubtless toward variable-speed generation. However, the introduction of variable-speed wind turbines increases the number of applicable generator types and further introduces several degrees of freedom in the combination of generator type and power converter type. Although, presently no variable-speed wind turbine configuration seems to be able to occupy the standard position as the induction generator does in the constant-speed generation systems. This section surveys the most reliable concepts, which includes the induction generator system and doubly-fed induction generator (*DFIG*) and highlights their respective features. To summarize the common feature of all the variable-speed wind turbines, the power equation for a variable speed wind turbine is written: