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Conceptual survey of Generators and Power Electronics for Wind Turbines

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Risø National Laboratory, Roskilde, Denmark
December 2001

Abstract

This report presents a survey on generator concepts and power electronic concepts for wind turbines. The report is aimed as a tool for decision-makers and development people with respect to wind turbine manufactures, utilities, and independent system operators as well as manufactures of generators and power electronics.

The survey is focused on the electric development of wind turbines and it yields an overview on:

- State of the art on generators and power electronics.
- Future concepts and technologies within generators and power electronics.
- Market needs in the shape of requirements to the grid connection.

This survey on generator and power electronic concepts was carried out in cooperation between Aalborg University and Risø National Laboratory, in the scope of the joint research programme *Electric Design and Control*.

The report has been reviewed by:

__________________	__________________
Anca Daniela Hansen	Peter Hauge Madsen

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Preface

The present report is a result of the co-operation between Aalborg University and Risø National Laboratory within the scope of the research programme *Electric Design and Control* (EDS, alias Elektrisk Design og Styring).

The report has as an objective to compile and disseminate some of the knowledge on generators and power electronics for wind turbines, which now is at EDS' disposal. In this work, the following persons have contributed to the report writing:

- Birgitte Bak-Jensen.
- Henrik Bindner.
- Frede Blaabjerg.
- Lars Henrik Hansen.
- Lars Helle.
- Stig Munk-Nielsen.
- Ewen Ritchie.
- Poul Sørensen.

In order to focus the report towards the needs of the wind turbines manufactures a task group consisting of:

- NEG Micon: Niels Vilsbøll.
- Vestas: Michael Kinch.
- ABB: Hans Christian Christensen.
- Siemens: Kim Eskildsen and Ulf Lindhard.

have been asked to contribute to this report by valuable input – in specific on the concept evaluation criteria. Moreover, ABB and Siemens have kindly put pictures and drawings at disposal for this report.

Finally, the four largest wind turbine gearbox manufactures have been asked to supply specific gearbox data. The following two:

- Brook Hansen Transmission
- Lohmann & Solterfoht.

have contributed with data which are used to point out trends on gearboxes.

Frontpage picture has been supplied by Vestas

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Acronyms and abbreviations

AG	Asynchronous Generator
AHF	Active Harmonic Filters
ASVC	Advanced Static Var Compensator
CHP	Combined Heating Power
CUPS	Custom Power Systems
CSC	Current Source Converter
CSI	Current Source Inverter Current Stiff Inverter
DF	Doubly Fed
DPM	Discrete Pulse Modulation
DSFC	Double-Sided with Flux Concentration
DSPMG	Doubly Salient Permanent Magnet Gen.
DVR	Dynamic Voltage Restorer
FACTS	Flexible AC transmission systems
FEM	Finite Element Method
GTO	Gate Turn Off thyristor
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristors
IM	Induction Machine
LFPM	Longitudinal Flux Permanent Magnet
MCT	Mos Controlled Thyristors
NCC	Natural Clamped Converter
PCC	Point of Common Coupling
PE	Power Electronic
PMG	Permanent Magnet Generator
PWM	Pulse Width Modulation
SCIG	Squirrel Cage Induction Generator
SG	Synchronous Generator
SR	Switched Reluctance
SRG	Switched Reluctance Generator
SRM	Switched Reluctance Machine
SSSM	Single-Sided with Surface Magnets
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TF	Transversal Flux
TFPM	Transverse Flux Permanent Magnet
UPQC	Unified Power Quality Conditioner
UVC	Unified Voltage Controller
VSI	Voltage Source Inverter Voltage Stiff Inverter
WRSG	Wound Rotor Synchronous Generator

1 Introduction

1.1 Report outline

In recent years, the development in the area of electric machines and power electronics has been vigorous. Due to this development, the authors have a need for a survey on the present state of the art for generators and power electronics and a corresponding state of the art on wind turbines.

The survey presented in this report has the following objectives:

- to document state of the art for generators and power electronics with respect to wind turbines.
- to describe new concepts and technologies for generators and power electronics, which potentially could be used in wind turbines.
- to analyse market needs in terms of demands to the grid connection for wind turbines and wind farms.

The report is structured based on the philosophy sketched in Figure 1. When designing a new wind turbine, a number of function at demands are placed on e.g. the mode of operation etc., which is characteristic for a given wind turbine manufacture. It is foreseen that in the near future, these function at demands will be strongly influenced by customers desires, i.e. towards a more market demand oriented development. Therefore in this report, special emphasis is put on market needs – in particularly needs which shape demands to grid connection. Grid connection demands can be described objectively and simultaneously; they are important factors in the definitions of the function at demands.

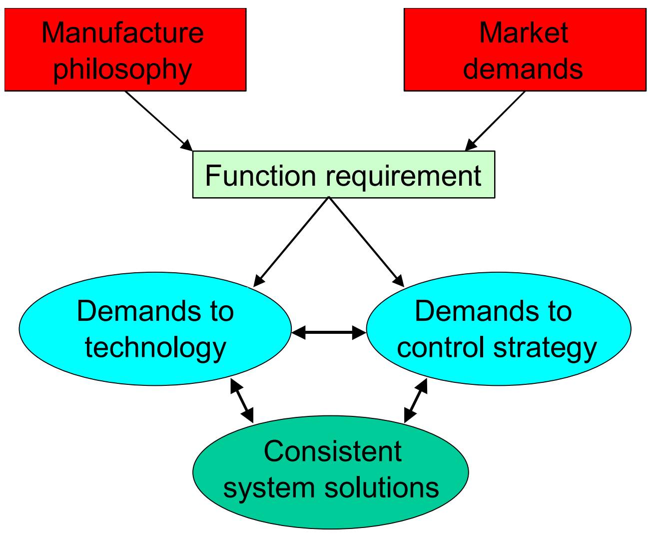


Figure 1.Philosophy of the report structure.

On basis of the function demands, it is a task of the designer to find a suitable technology, which combined with a matching control strategy, yields a consistent system solution. In the succeeding sections, the report presents examples of technological components for wind turbines in the form of concepts generator and power electronics. Control strategies will not be discussed further in this report, since implementation of this issue typically is specific for each manufacturer, i.e. each has his own characteristic approach.

By nature a large number of consistent system solutions exist. The electrical part of a wind turbine is becoming more and more important. Therefore, it is very important to have this system highly integrated into the overall wind turbine design. Thus, a successor to this report would be one, which describes and analyses consistent system solutions (including aspects of controls), combined with an assessment of these solutions seen in the light of market needs regarding the grid connection demands.

1.2 State of the art

Since the start of modern wind turbine development in 1957, marked by the innovative Gedser wind turbine (200 kW), the main aerodynamic concept has been a horizontal axis, three bladed, downwind wind turbine, connected to a three phase AC-grid. Many different concepts have been developed and tested since. Activities in this field were encouraged by the oil crisis in 1973. Twenty years ago the concept of the Riisager wind turbine (22 kW) initiated a new area. The concept was similar to the innovative Gedser wind turbine, but it was built using inexpensive standard components, e.g. spare parts from cars. It became a success with many private households and it was the kick-off for the Danish wind generator industry.

During the last two decades, the production of wind turbines has grown in size from 20 kW to 2 MW. Many different concepts have been developed and tested. Those, which have been successful, are more or less descendants of the Gedser wind turbine concept. One modification is variable pitch blades. The pitch control concept has been applied during the last fourteen years. Recently, the active stall concept has been utilised. Another modification is in the electric field, where alternative concepts have been introduced. Since 1993, a few manufacturers have replaced the "traditional" asynchronous generator in their wind turbine design by a synchronous generator, while other manufacturers have introduced the asynchronous generator with wound rotor. Electrical developments include the use of advanced power electronics in the wind generator system design, introducing a new control concept, namely variable speed.

Due to the rapid development of power electronics, offering both higher power handling capability and lower price/kW, see e.g. (Thøgersen & Blaabjerg, 2000), the application of power electronics in wind turbines will increase further. Another interesting issue is the efforts, which have been put into research and development of new motor/generator concepts for some years. A comparison of 7 new concepts is presented in (Dubois et al., 2000). Thus, it is evident that the development departments of the wind turbine manufacturers are active analysing and evaluating potential new wind turbine concepts.

The scope of this section is to describe the "state of the art" of wind turbines seen from an electrical point of view, using two approaches. The first approach describes the state of art from a technical point of view, while the second applies a market-based point of view. The following chapters will look deeper into old and new concepts of generators and power electronics.

1.2.1 Concepts and wind turbine configurations

The generator and power electronic configurations most commonly applied in wind turbines are displayed in Figure 2.

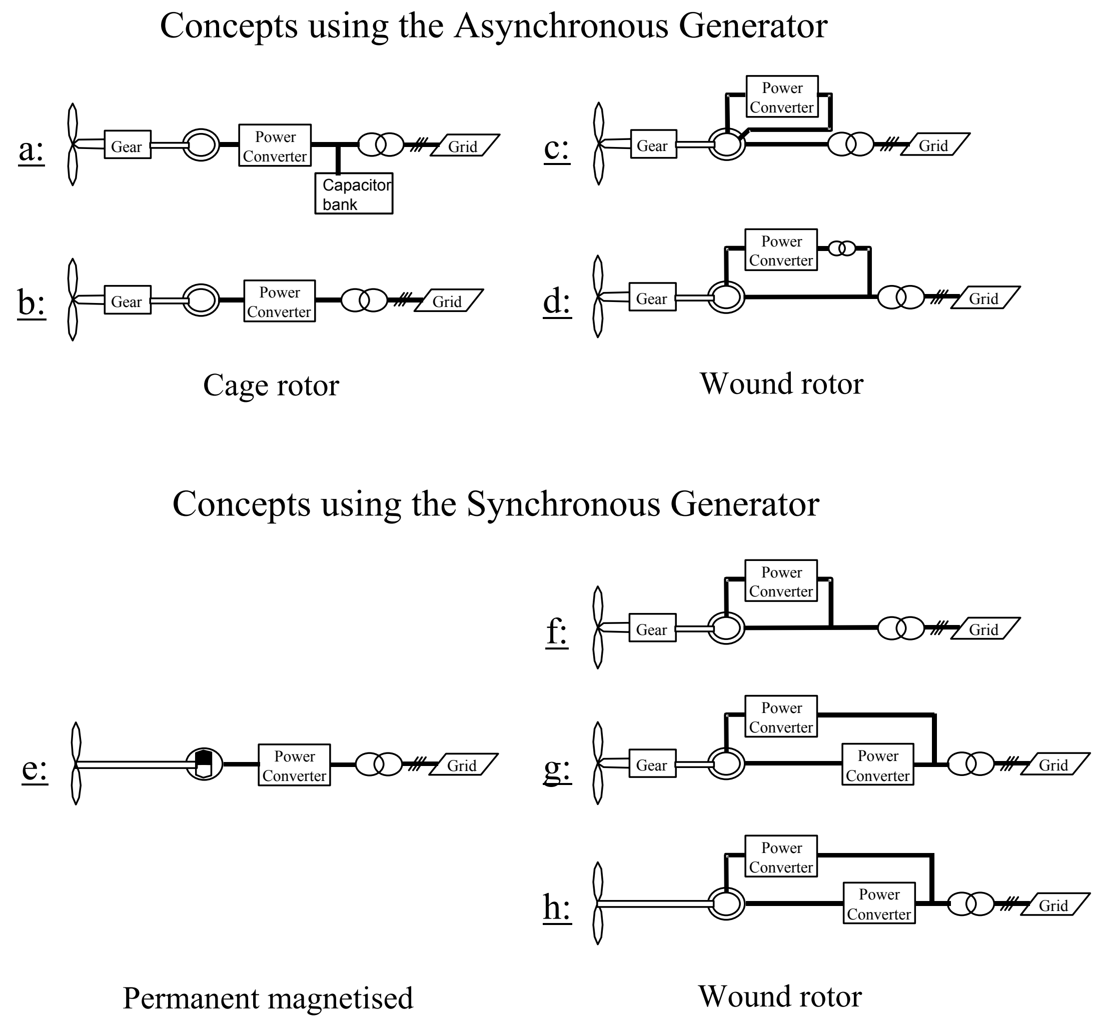


Figure 2. Standard wind turbine configurations using the asynchronous generator (AG) and the synchronous generator (SG). Depending on the particular configuration, the term Power Converter covers different types of power electronic components such as: a soft starter (part a), an external variable rotor resistance (part c), a rectifier (part e – stator connected or part f, g, h – rotor connected) and a frequency converter (part b, d, e, g and h).

The configurations depicted in Figure 2 present an outline of typical electrical topologies used in wind turbines. As listed in Table 1, these seven configurations cover a wide range of the applied power control concepts for wind turbines.

General comments on configurations in Figure 2:

a) This is the “conventional” concept applied by many Danish wind turbine manufacturers during the 1980’s and 1990’s, i.e. an upwind, stall regulated, three bladed wind turbine concept using an induction generator (cage rotor). During the 1980’s this concept was extended with a capacitor bank (for reactive power compensation) and a soft-starter (for smoother grid connection).

Table 1 . The generally applied control concepts for wind turbines (refer to Figure 2*).*

Con-fig.	Power Converter	Multipole or gearbox	Power control features	Comments
A	Soft starter	Gearbox	Stall or active stall	One or two speed machine
B	Frequency converter	Gearbox	Stall or active stall	Variable speed
C	PE converter or passive components	Gearbox	Pitch	Limited variable speed
D	Frequency converter	Gearbox	Pitch	Variable speed (doubly fed generator)
E	Frequency converter	Multipole	Stall, active stall or pitch	Variable speed
F	Rectifier	Gearbox	Stall or pitch	Variable speed
G	Rectifier and frequency converter	Gearbox	Pitch	Variable speed with gearbox
H	Rectifier and frequency converter	Multipole	Pitch	Variable speed without gearbox

b) In this configuration, the capacitor bank and soft-starter are replaced by either a full scale frequency converter or a “low wind” region sized frequency converter – used e.g. by Wind World - where the frequency converter is bypassed (implying fixed speed) and used only for reactive power compensation when the wind speed exceeds the design wind speed. This concept uses a smaller frequency converter (20-30% of nominal generator power) compared to the full-scale concept (approximately 120% of nominal generator power). On the other hand the full-scale concept enables variable speed operation at all wind speeds.

c) This configuration employs a wound rotor and it has been used by Vestas since the mid 1990’s – known as OptiSlip. The basic idea of this concept is to control the total rotor resistance using a variable external rotor resistance by means of a power electronic (PE) converter. With the power electronic converter mounted on the rotor shaft, it is possible to control the slip (by controlling the external rotor resistance) over a 10% range. Control of the slip implies control of the power output in the system. (Wallace & Oliver, 1998) describes an alternative concept using passive coponents instead of a PE converter, which also achieves a range of 10% slip variation. However, this concept does not support controllable slip.

d) An other configuration in wind turbines employs a doubly fed induction generator. A frequency converter directly controls the currents in the rotor windings. This enables control of the whole generator output, using a PE converter, rated at 20-30% of nominal generator power. Introduction of this concept is mainly motivated by two reasons: 1) variable speed in a wide speed range compared to the OptiSlip concept and 2) less expensive compared to the full power control concept.

e) A typical application of the full power control configuration is as a power source on sailing boats. A gearless two or three bladed upwind wind turbine using a PMG (typically less than 1kW) is used to charge a battery energy storage through a rectifier. This configuration is also applied in wind turbines for home wind systems and hybrid systems, i.e. wind turbines larger than 1kW and smaller than approximately 20kW. A future concept – the Windformer – using this configuration has been suggested in year 2000 by ABB, with the following specifications: multipole 3.5MW PMG which together with a diode-rectifier produces 21kV DC. It is proposed to combine this configuration with a HVDC-light based grid.

f) This configuration is not widely used in wind turbines. It is externally excited as shown in the figure using a rectifier (the "Power Converter"). The low utilisation compared to the previous configuration could be due to three reasons: 1) the need for an exciter circuit, 2) the need for slip rings and 3) a more complex wind turbine safely strategy; which makes this configuration less attractive. Note that also internally excited configurations exist.
g) Neither this configuration is widely used in wind turbines. Compared to the previous configuration, this one supports variable speed, if the grid power converter is a four-quadrant frequency converter.
h) In this configuration a multipole wound SG is used. In principle, it is the same as the previous configuration, but due to the multipole generator no gearbox is needed. The wind turbine companies Enercon and Lagerwey are examples of manufacturers using this configuration.

Configuration "a" is the only commonly applied control concept, which does not support variable speed operation. Excluding this configuration for a while, a road map for conversion of mechanical energy into electrical energy may be drawn, as presented in Figure 3. The focus in this figure is the applied generator concept used in the conversion of a mechanical torque input at variable speed to an electrical power output at fixed frequency. Thus, except for configuration "a", the other configurations in Figure 2 (alias Table 1) are classified in the road map.

As it may be observed in Figure 3, the doubly-fed induction generator has two possible implementations, where 1) the rotor is connected to the grid through a small frequency converter or 2) the rotor is connected to an external power conversion unit (PE converter or passive components). The energy coming from the external power conversion unit is dissipated as heat loss – e.g. as in the case of the OptiSlip concept of Vestas. In the last case no slip rings are necessary.

The term "Novel Machines" in Figure 3, is used here to cover e.g. the reluctance machine, the Windformer (from ABB) etc. In the case of the Windformer, the "Large PE converter" is a simple diode bridge and the grid is a HVDC-grid (refer to comments on configuration "e", Figure 2).

Until now, the main focus has been on generators and generator concepts, while power electronics mostly has been referred to by the general terms "Power Converter" or "PE converter", which in this context covers devices like soft starters (and capacitor banks), rectifiers, inverters and frequency converters. Quite a variety of different design philosophies exist, both for rectifiers, inverters and frequency converters. A short introduction is presented below, while a more detailed description is presented in Section 3. A thorough introduction to this subject may be found in (Novotny & Lipo, 1996).

The basic elements for these converters are diodes and electronic switches such as: thyristors, GTO's (gate turn off thyristor), IGCT's (Integrated Gate Commutated Thyristors), BJT's (bipolar junction transistor), MOSFET's (metal oxide semiconductor field effect transistor) or IGBT's (insulated gate bipolar transistor). A comparison of characteristics and ratings for five of these switches is presented in Table 2.

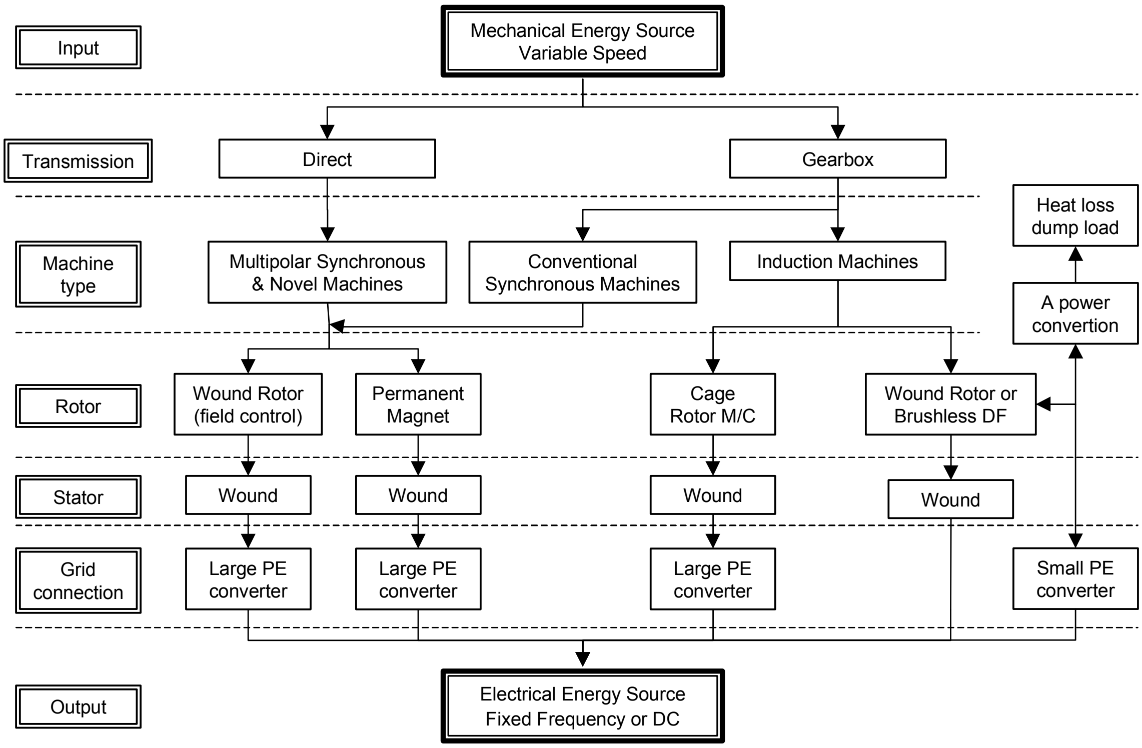


Figure 3. Road map: Conversion process of Mechanical Energy to Electrical Energy using power electronic converter (inspiried by (Wallace & Oliver, 1998)).

Table 2. Maximum ratings and characteristics. Source (Heier, 1998).

Switch type	**GTO**	**IGCT**	**BJT**	**MOSFET**	**IGBT**
Voltage (V)	6000	4500	1200	1000	3300
Current (A)	4000	2000	800	28	2000
Switched-off time (μs)	10-25	2-5	15-25	0.3-0.5	1-4
Pulse bandwidth (kHz)	0.2-1	1-3	0.5-5	5-100	2-20
Drive requirements	High	Low	Medium	Low	Low

In Table 2, voltage, current and output power are maximum ratings. The switch-off time is related to the circuit-commutated recovery time, while the pulse bandwidth defines the operational frequency range.

A traditional AC frequency converter (also called a drive), as seen from the grid, consists of: a rectifier (AC to DC unit), an energy storage, and an inverter (DC to AC with controllable frequency). Talking about motor drives the terms "semiconverter" and "full converter" are used to classify the type of drive. A semiconverter has single quadrant operation (only positive voltage and current rms-values), which utilises motor operation (or acceleration) in the forward direction. A full converter offers two-quadrant operation (i.e. positive/negative voltage and positive current rms-values), which utilises both motor operation in two directions and electrical braking. Since generators feed power back to the grid, it is necessary to use a "dual converter". A full dual converter offers four quadrant operation (i.e. positive/negative voltage and current rms-values), which utilises both motor and generator operation.

Inverters for variable speed operation, may in general be classified in two basic groups: VSI (voltage source inverter) or CSI (current source inverter) and CSC (current source converter). While the VSI creates a relatively well-defined, switched voltage waveform at the terminals of the electrical machine, the CSC produces a switched current waveform. In the case of a VSI, the voltage in the energy storage (the DC bus) is maintained stiff by a large capacitor or a DC source e.g. a battery (voltage source inverter) – while the resulting current is primarily formed by load and speed. In a CSC the opposite is the case, the current in the energy storage (the DC bus) is maintained stiff using a large inductor – while the resulting voltage is primarily formed by load and speed. Thus, VSI and CSI are dual. This duality is further investigated in (Novotny & Lipo, 1996). A diagram of the basic inverter concepts is shown in Figure 4. It must be stressed, that VSI and CSI are quite different concepts.

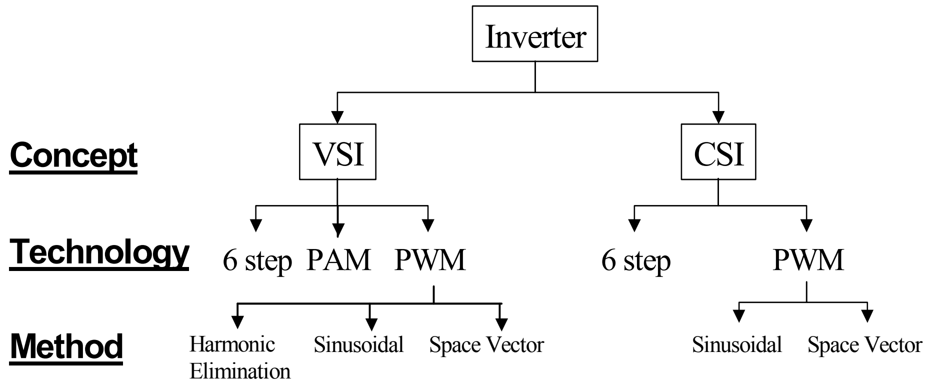


Figure 4. Diagram of basic inverter concepts for adjustable speed in wind turbines.

As indicated in Figure 4, the concepts of VSI and CSI may both be implemented in several ways, e.g. as: 1) six step inverter, 2) pulse amplitude modulated or 3) pulse width modulated inverter. Moreover, the implementation of a PWM inverter for a VSI e.g. may be realised by tree methods: 1) harmonic elimination 2) a “sinusoidal” PWM converter, or 3) a space vector strategy converter. The basic operation of these technologies is described further in Section 3.

A number of different strategies exist to combine a rectifier and an inverter to form a frequency converter. Table 3 serves as a short introduction to five drive topologies applicable for adjustable speed in a wind turbine.

Table 3. Comparison of five AC drives for adjustable speed.

Converter type	**Concept**	**Technology**	**Applicable configuration** (Figure 2)	**Comments**
Back to back	VSI	PWM	b,d,e,f,g and h	Mature technology
Tandem	CSC+VSI	6-step+PWM	b,d,e,g and h	Unproven technology
Matrix	VSI	PWM	b,d,e,f,g and h	Unproven technology
Multilevel	VSI	PWM	b,d,e,f,g and h	Mature technology
Resonant	VSI	PWM	b,c,d,e,f,g,h	Unproven technology

After this brief outline on generator and power electronics it would be appropriate to make a few comments on the grid performance of the various configurations of Figure 2. The performance depends of course on the applied frequency converter technology. In Table 4, some grid performance issues are presented for each configuration.

Table 4. Comments on grid performance of the various configurations in Figure 2 *using 1) a thyristor or 2) a pulse width based frequency converter.*

Con fig.	Voltage control	Reactive power control	Grid demand
a	No	No, reactive power consumer with step-wise compensation	Stiff
b	1) Yes 2) Yes	1) No, reactive power consumer 2) Yes, constant cos(φ) or constant reactive power	1) Stiff 2) Stiff or weak
c	2) Yes	2) Constant cos(φ) or constant reactive power could be made possible	2) Stiff or weak
d	1) Yes 2) Yes	1) No, reactive power consumer 2) Yes, constant cos(φ) or constant reactive power	1) Stiff or weak 2) Stiff or weak
e	1) Yes 2) Yes	1) No, reactive power consumer 2) Yes, constant cos(φ) or constant reactive power	1) Stiff 2) Stiff or weak
f	No	Yes, e.g. constant cos(φ) or constant reactive power	Stiff
g	1) Yes 2) Yes	1) No, reactive power consumer 2) Yes, constant cos(φ) or constant reactive power	1) Stiff 2) Stiff or weak
h	1) Yes 2) Yes	1) No, reactive power consumer 2) Yes, constant cos(φ) or constant reactive power	1) Stiff 2) Stiff or weak

1.2.2 Market aspects

One way of describing the "state of the art" of frequency converters applied to wind turbines is to survey the supply rates of the manufacturers – as presented in Table 5 – and then map the applied concept of each manufacturer with respect to Figure 2 and Table 1. Table 5 ranks the top 10 suppliers (BTM Consults Aps, 2000) with respect to sold MW of converters in 1999.

Table 5. The top-10 list of suppliers in 1999. Source (BTM Consults Aps, 2000).

Top 10 list suppliers	Sold MW 1999	Share in %	Accu. MW 1999	Share in %
1. NEG Micon	761	18.9	3034	21.0
2. Vestas	652	16.2	2530	17.5
3. Gamesa	494	12.3	853	5.9
4. Enercon	488	12.1	1553	10.7
5. Enron (Zond/Tacke)	360	8.9	1153	8.0
6. Bonus	338	8.4	1197	8.3
7. Nordex	306	7.6	638	4.4
8. Made	218	5.4	450	3.1
9. Ecotecnia	59	1.5	136	0.9
10. Dewind	58	1.4	86	0.6
Others	298	7.4	2839	19.6
Total	**4032**	**100**	**14469**	**100**

The applied concept of each manufacturer listed in Table 5 has been evaluated using publicly available data obtained from the Internet. The result is presented in Table 6, where the two largest wind turbines of each top-10 manufacturer have been assessed by their configuration and control concept. As it may be observed from Table 6, there is a trend towards the configuration using a doubly fed, asynchronous generator with variable speed control, combined with variable pitch control. Of the top-10 suppliers, only NEG Micon and Bonus are still using configuration "a" in Figure 2 – the conventional solution – updated with active stall control. All the machines presented in Table 6 are 3 bladed, upwind wind turbines.

Table 6. Applied concept of each manufacturer based on information found on the internet August 8th 2000 concerning the two biggest (alias newest) wind turbines from each manufacture.

Manufacture (top 10 supp.)	**Wind turbine**	**Conf.** Figure 2	**Power control features**	**Comments**
NEG Micon	NM 2000/72	a	Active stall	Two speed
	NM 1500C/64	a	Stall	Two speed
Vestas	V80 – 2 MW	d	Pitch and variable speed	Range: 905 rpm. to 1915 rpm.
	V66 – 1.65 MW	c	Pitch and OptiSlip	Range: 1500 rpm. to 1650 rpm.
Gamesa	G52 – 850 kW	d	Pitch and variable speed	Range: 900 rpm. to 1650 rpm.
	G47 – 660 kW	d	Pitch and variable speed	Range: 1200 rpm. to 1626 rpm.
Enercon	E-66 – 1.8 MW	h	Pitch and variable speed	Gearless. Range: 10 rpm. to 22 rpm.
	E-58 – 1 MW	h	Pitch and variable speed	Gearless. Range: 10 rpm. to 24 rpm.
Enron Wind	1.5s – 1.5 MW	d	Pitch and variable speed	Range: 989 rpm. to 1798 rpm.
	900s – 900 kW	d	Pitch and variable speed	Range: 1000 rpm. to 2000 rpm.
Bonus	2 MW	a	Active stall	Two speed
	1.3 MW	a	Active stall	Two speed
Nordex	N80/2500 kW	d	Pitch and variable speed	Range: 700 rpm. to 1303 rpm.
	N60/1300 kW	a	Stall	Two speed
Made	No technical information was available on the internet			
Ecotecnia	No technical information was available on the internet			
Dewind	D4 – 600 kW	d	Pitch and variable speed	Range: 680 rpm. to 1327 rpm.
	D6 – 1.25 MW	d	Pitch and variable speed	Range: 700 rpm. to 1350 rpm.

The manufacturers applying configuration "d" and "h" all use IGBT based converters. Moreover, manufacturers of configuration "d" use 4 or 6 pole, doubly fed machines.

1 The technical information supplied by some manufactures was in some cases quite limited, which implies that caution should be exercised on some of the indicated configurations.

To obtain an overview of the wind turbine prices, the sales departments of the manufacturers listed in Table 6 were contacted to ascertain the standard price for one machine, on the Danish market (if possible), or alternatively the price on the German market. The result is presented in Table 7. It should be noted that these prices may not be absolutely comparable, since no standard exists on what is to be included in the wind turbine price. E.g. on the German market the step-up transformer is included, while in general it is not on the Danish market. Moreover, service contracts and other optional items may or may not be included. In this connection the price formation on these markets are also different. Nevertheless, the listed prices generally include the wind turbine price (with tubular tower) and installation and start-up costs. Foundation costs are excluded. The hub height is also an optional parameter, which has been selected here to be as close to the rotor diameter as possible.

Table 7. Nominal power, typical rotor diameter, typical hub height and wind turbine prices on the Danish market. The wind turbine price also includes installation and start-up and excludes foundation costs. Data were supplied by the sales departments of the manufacturers.(Year 2000)

Manufacture (top 10 supp.)	Wind turbine	Power kW	Rotor diameter	Hub height meters	Wind turbine price DDK
NEG Micon	NM 2000/72	2000	72	68	12.800.000
	NM 1500C/64	1500	64	60	8.500.000
Vestas	V80	2000	80	78	13.500.000
	V66	1650	66	67	10.000.000
Gamesa	G52	850	52	40-65	No info
	G47	660	47	40-55	No info
Enercon	E-66	1800	70	65	3.120.000*) DM
	E-58	1000	58	70	Not generally available
Enron Wind	1.5s	1500	70.5	80	2.770.000*) DM
	900s	900	55	60	Not yet for sale
Bonus	2 MW	2000	76	70	Not yet for sale
	1.3 MW	1300	62	60	6.800.000
Nordex	N80/2500	2500	80	80	3.750.000*) DM
	N60/1300	1300	60	60	6.600.000
Made	No information was available				
Ecotecnia	No information was available				
Dewind	D6	1250	62	56-91.5	No info
	D4	600	48	40-70	No info

*) This price is valid on the German market.

1.2.3 Trends in wind turbine design

Based on the previous subsection the present "state of the art" large wind turbine may be summarised as a 3-bladed upwind turbine (with tubular tower) using:

- Active stall with a two speed asynchronous generator or
- pitch control combined with variable speed. Moreover, the variable speed concept is mainly realised using configuration "d", i.e. a doubly-fed induction generator with a rotor connected IGBT based frequency converter.
- Only one of the top-10 manufacturers offers a gearless (variable speed) wind turbine.

Meanwhile, it should be mentioned that a number of alternative wind turbine designs exist. Lagerwey uses configuration “h”, but with a 6-phase synchronous generator. Nordic Windpower promotes configuration “a” in a two bladed up-wind version. Vergnet also uses configuration “a”, but in a two bladed upwind or downwind version. Scanwind has started to construct a wind turbine using configuration “e” based on the Windformer and a DC grid.

The trend in wind turbine prices is illustrated in Figure 5 and Figure 6, based on the data presented in Table 7. The specific wind turbine price on the Danish market has decreased from 12.000 DKK/kW for 20-30 kW machines down below 6.000 DKK/kW for 450-600 kW machines as reported e.g. in (Hansen & Andersen, 1999). Meanwhile, the Megawatt machines have an increasing specific price as it may be observed in Figure 5. This fact is partly explained by the development in offshore wind turbines, which are generally Megawatt turbines. It seems to be the technical performance, measured as the swept rotor area per nominal power, or the yearly energy production per unit swept rotor area, that is the optimising criterion – rather than the economic performance, measured as the cost per nominal power, or the cost per yearly energy unit production.

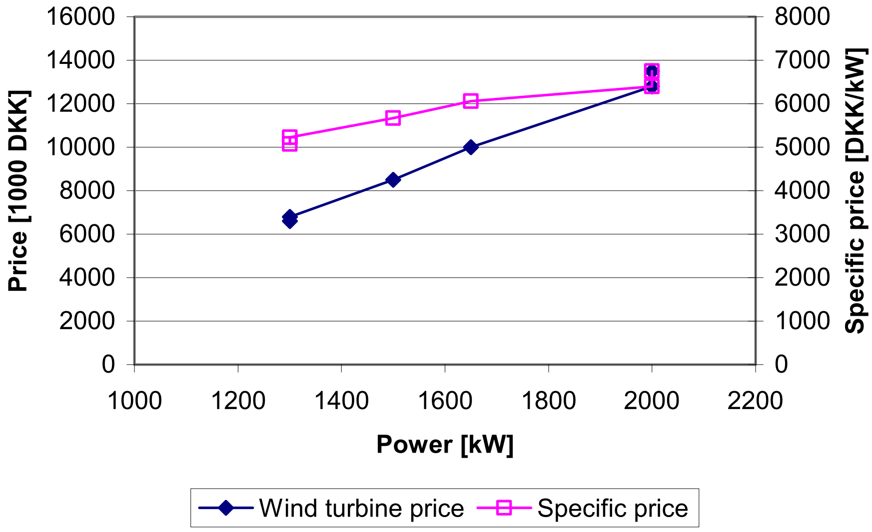


Figure 5. The trend on the Danish market in respect to wind turbine price and specific price (DKK/kW) as a function of wind turbine size.

On the German market, the specific wind turbine price from these limited data is continuously decreasing as shown in Figure 6.

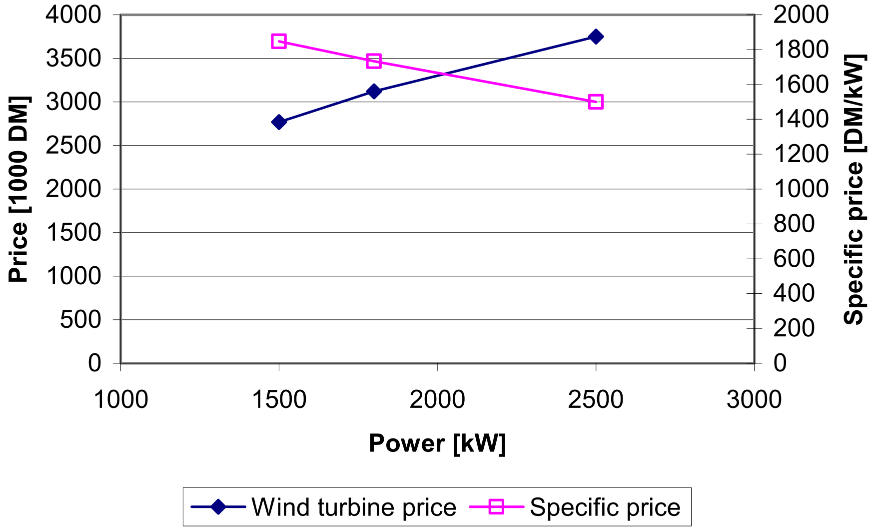


Figure 6. The trend on the German market in respect to wind turbine price and specific price (DKK/kW) as a function of wind turbine size.

The outline of this report is:

Chapter 2 will discuss different generator types, both the standard generators but also new generators, which may be a future solution.

Chapter 3 treats different power electronic concepts, which are possible for controlling the variable speed. It also includes a comparison of some topologies as well as it discusses some wind farm solutions.

In Chapter 4 the grid integration issues are discussed which include discussion of disturbances and standardized grids.

Finally, a summary of the report is done including a list of important research topologies in the area of electrical design and control of wind turbines.

2 Generic Generator Types

Several generic types of generator are possible candidates in wind turbines. Historically, the squirrel cage, induction generator has been frequently applied commercially. A second popular type is the induction generator with wound rotor, while a third is the current excited, synchronous generator. These types have been synchronised directly to the grid, providing a constant speed solution. This confines the choice of generator to a very few types, which exhibit inherently flexible behaviour, notably the induction machines, or where there is an established technology for control, for example, the separately excited synchronous generator.

The generator provides a means of energy conversion between the mechanical torque from the wind rotor turbine, as prime mover, and an electrical load. In this study, the electrical load is confined to the public utility supply grid system. Island operation is not considered, although islanding may be discussed in certain circumstances, e.g. during start-up.

Mechanical connection to the turbine rotor is through the main shaft. The connection may be by direct drive, or using a gearbox. The use of a gearbox allows matching of the generator speed to that of the turbine. This allows some optimisation of generator characteristics, but a disadvantage of the gearbox is that as a mechanical component it is subjected to wear and tear and in some cases has been relatively unreliable.

The ready availability of high power semiconductors for frequency converters has increased the interest in direct coupled, variable speed turbines and generators. The electrical converter thus acts as an electrical gearbox. This system is more flexible than the mechanical gearbox, and the converter may be mounted either in the nacelle, the tower, or elsewhere. Also new option and constraints for generator design are made available by the application of the semiconductor converter, as are new methods for control and protection.

The number of possible options is large. The selection of a final design thus becomes a very complicated process. The objective of this chapter is to illustrate the characteristics of some of the available candidate, generic generator types.

2.1 Criteria for Assessment of Generator Types

Criteria such as weight of active materials, operational characteristics, applicable type of semiconductor power converter, protection considerations, service and maintenance aspects, environmental considerations, and list price are all relevant for the assessment. It may however be difficult to derive some of this information from public literature, and other methods may have to be taken into use.

2.2 The Asynchronous Machine (Induction Machine)

Induction machines may generally be set in two categories, those with squirrel cage, and those with wound rotor. Both categories were considered, as each has some special features to offer. The search term 'Induction Generator' produced an immediate list of some 303 articles, and standards dating from 1990 and later. This was reduced to 133, by rejecting the majority of articles concerning island operation, and studies of the power electronics converter, and control system. The list of 133 is included in the references. Some 15 representative articles have been studied for inclusion in this report.

Induction machines have been proposed as generators in many research articles and are currently the predominant commercial wind turbine generator. Advantages include the asynchronous operation, which allows some flexibility when the wind speed is fluctuating. A major disadvantage is the need for excitation of the magnetic field via the supply terminals. Other applications are also considered in the literature, e.g. Hydroelectric Power Plants (Shibata & Taka, 1990), energy recovery scheme (McQuin, 1989), large steam turbine generator (McQuin, 1989; Hammons et al., 1996; Jiang et al., 1998). An overall description of the function of the Induction Generator is provided in e.g. (Pham, 1991).

2.2.1 Squirrel Cage Induction Generator

The Squirrel Cage Induction Generator (SCIG) is a very popular machine due to its mechanical simplicity and robust construction. The stator winding is connected to the load/excitation source, and is insulated. The rotor is provided with an uninsulated winding, which is very resistant to the effects of possible dirt ingress, and vibration. Maintenance is generally restricted to bearing lubrication only. A major problem is the necessity of obtaining the excitation current from the stator terminals (Shibata & Taka, 1990).

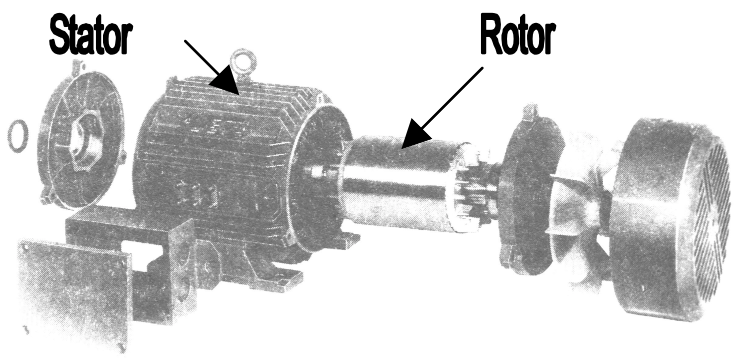


Figure 7. Exploded view of a Squirrel Cage Induction Machine.

Large machines are reported (16 MW (McQuin, 1989)) (several hundred MW (Hammons et al., 1996)). Applying a self-excited start, followed by a fully excited synchronisation, while generation is ensured (McQuin, 1989; Hammons et al., 1996; Jiang et al., 1998), may alleviate voltage dips during start-up. Shaft torques produced under fault conditions, are sometimes very high (Hammons et al., 1996).

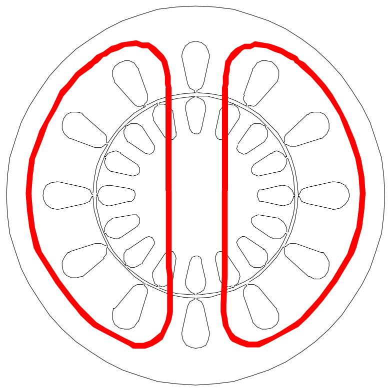


Figure 8. Cross section of a 2-pole squirrel cage induction machine showing main flux path.

Methods of control include full power frequency inverter, fixed capacitor, thyristor and static VAR controller (Abdin & Xu, 1998).

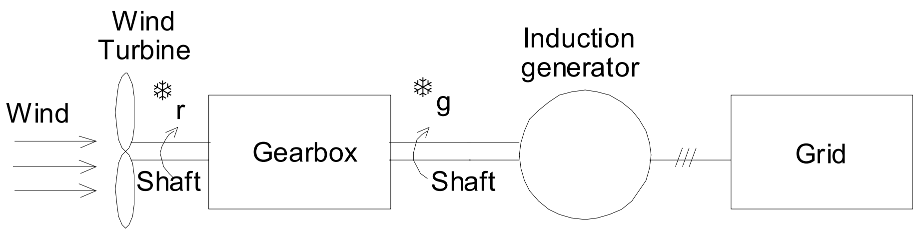


Figure 9. Diagram showing an uncontrolled, grid connected, Squirrel Cage Induction Generator, as a Wind turbine Generator.

At power frequencies, the SCIG is inherently stable, but when connected to a weak grid with an unbalanced, three-phase load, overheating and torque pulsations may occur in the SCIG (Muljadi et al., 1999).

2.2.2 Wound rotor Induction Generator

It has been found useful to apply the wound rotor Induction Machine as a Wind Power Generator. In this case, the rotor is provided with a three-phase insulated winding very similar to that of the stator. The rotating winding may be connected to the stationary supply circuits via a set of slip rings and brushes. This is the traditional manner. An alternative is to use a power electronic converter, which may or may not require slip rings.

The output of the generator may now be controlled, by controlling only the rotor losses. This is very convenient, as the alternative is to control the whole armature power on the stator. With the advent of power electronics it is possible to recover slip energy from the rotor circuit, and add this to the output of the stator. Vestas Wind Systems have made extensive use of this in their 'OptiSlip' system.

Although the inclusion of a wound rotor affords the advantage described above, the wound rotor is inevitably more expensive than a squirrel-cage rotor. The insulated winding on the rotor may be subject to stresses arising from the rotation and vibration, which may reduce the lifetime of the generator.

2.2.3 Principle of Operation

The Induction Generator is provided with two windings, one on the stator, and one on the rotor. The stator winding of the induction motor has two functions. It provides the excitation or magnetisation, and carries the armature or generated current. The rotor winding carries the armature current only. When AC excitation is present, the magnetic field created rotates at a speed determined jointly by the number of poles in the winding and the frequency of the current, the synchronous speed.

If the rotor rotates at a speed other than the synchronous speed, voltage is generated in the rotor winding at a frequency corresponding to the difference in the two frequencies, known as the slip frequency. This voltage drives the armature current, and provided the rotor speed is faster than the synchronous speed, the machine acts as a generator. The function is thus asynchronous.

2.2.4 Methods of Analysis

The magnetic circuit may be analysed using analytic methods, which are heavily dependent on the availability of test results for machines with the same internal geometry. A more modern method, which has become viable due to the increase in speed of computing, is the Finite Element Method, which may be used to predict the performance of magnetic circuits of which one has no previous experience.

Having solved the magnetic circuit, the machine performance is most conveniently predicted using electric circuit techniques.

For many purposes, the steady state equivalent circuit is adequate for analysis. In other cases, it is necessary to use dynamic simulation of the differential equations (Li & Ching, 1997). Some authors use a version of the step by step method used for analysis of synchronous machines (Hammons et al., 1996), or symmetrical component analysis (Jiang et al., 1998) to simulate dynamic conditions.

Losses are important to know, as they determine the self-heating, hence the machine lifetime, and the energy conversion efficiency. Generally, losses are determined from the steady state equivalent circuit model, or from the loss models.

2.2.5 Operational Characteristics – Normal Duty

In normal duty and directly connected to a stiff AC grid, the Induction Generator is very robust and stable. The slip varies, increasing with increasing load. The major problem is that, due to the magnetising current supplied from the grid to the stator winding, the full load power factor is relatively low. This is to be compared with the fact that most power distribution utilities penalise industrial loads with low power factors. Clearly generation at low power factor cannot be allowed either. When the power factor is too low, connecting capacitors in parallel with the generator may be used to compensate it.

Operating in this manner, the Induction Generator is uncontrolled. Any fluctuations in shaft power are passed on to the net, modified only by the internal impedance of the generator itself. This is to say that the damping is negligible. This is also a situation, which is difficult for the distribution utility to accept.

Some manufacturers seek to improve this situation by adding means of control. Modern power electronics converters have made this technically easier. One solution is to provide an insulated winding on the rotor, controlled by a power electronics converter. In this way, the power handled by the converter is restricted to the rotor power, in some cases the slip power only.

Another solution is to insert a power converter in series with the armature circuit. In this way, full control is obtained over the IG performance, by employing the somewhat cheaper SCIG, but at the cost of a converter capable of handling the full power of the generator.

Both the above controller solutions function well, smoothing the power supplied to the grid. Additional benefits may also be gained in special situations, such as start-up.

2.2.6 Operational Characteristics – Fault Conditions

Should external fault conditions occur, the fault current is reported to be sufficient to trip relays and operate protective relays.

Internal faults are more difficult to determine and isolate. Traditionally, they have been detected by excessive temperature being measured by embedded temperature detectors, or excessive vibrations being measured by accelerometers fitted at strategic positions. These methods detect only faults requiring immediate attention. It would be advantageous to be able to detect incipient faults, to enable maintenance to be planned on the basis of predicted actual necessity rather than predicted estimated necessity.

New methods are being researched and developed, enabled by the improvements to electronics, computing and signal processing techniques, where incipient faults may be detected and identified. The progress of these faults may be charted, and automatic predictions made regarding the seriousness of the fault, and the time remaining until maintenance attention becomes necessary. Such monitoring methods are studied by Aalborg University, Institute of Energy Technology, and Risø's Wind Energy Department, partly funded by the Danish Energy Agency.

2.2.7 Axial Flux Induction Machines

Because of the large numbers of slots on both the stator and the rotor, and the small air-gap, it has not been found practical to propose an axial air-gap induction generator.

2.2.8 Efficiency of Induction Generators as a Function of Load and Speed

The efficiency surface of a typical small induction motor is shown in Figure 10. Efficiency is shown plotted as a function of shaft speed and torque load. This motor was controlled to operate at the maximum efficiency for each working point tested. Scrutiny of this surface reveals that the efficiency may be controlled to give a reasonably flat plateau at a high efficiency for medium to high speeds, and over a wide torque range. However, when the speed drops below a critical level, it becomes impossible to obtain an acceptable efficiency.

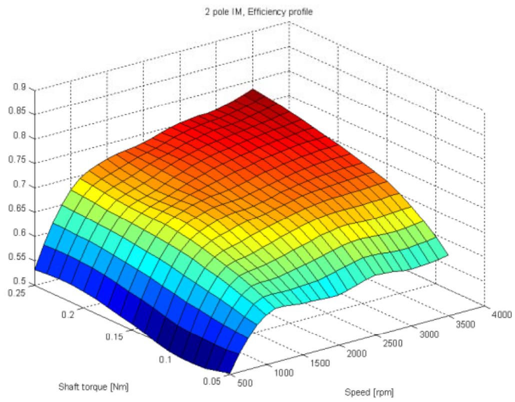


Figure 10. Tested efficiency surface of Induction Motor, controlled to operate at maximum possible efficiency for each working point.

The above figures were obtained by testing a small induction motor. It may be expected that a similar development of the efficiency would apply for a large induction generator, although in this case, the efficiency values would be higher

2.2.9 Well-Established or New Technology

The induction machine is a well-established technology, as is its application as a wind generator, using a gear drive to a generator with a low number of poles.

2.2.10 Gear or Direct Drive Multi-pole

In general, because of the small air-gap, the Induction Machine leakage flux increases to an unacceptable limit for machines with many poles. This causes the difficulty that the machine cannot use the current flowing to generate torque, but only leakage flux. Induction Machines with a large number of poles must be large enough to accommodate a sufficient number of slots per pole per phase, in order to prevent this situation from taking the upper hand. This means that induction machines with many poles will inevitably be oversized in relation to the rated output.

2.3 The Permanent Magnet Generator

Figure 11 shows the cross-section of a typical Permanent Magnet Generator (PMG). The PMG differs from the Induction Generator in that the magnetisation is provided by a Permanent Magnet Pole System on the rotor, instead of taking excitation current from the armature winding terminals, as it is the case with the Induction Generator. This means that the mode of operation is synchronous, as opposed to asynchronous. That is to say, in the PMG, the output frequency bears a fixed relationship to the shaft speed, whereas in the mains connected IG, the frequency is closely related to the network frequency, being related by the slip. These differences will be discussed at length. However, it must be recognised at the outset that the differences have a significant effect on the operating characteristics and performance of the two generator types.

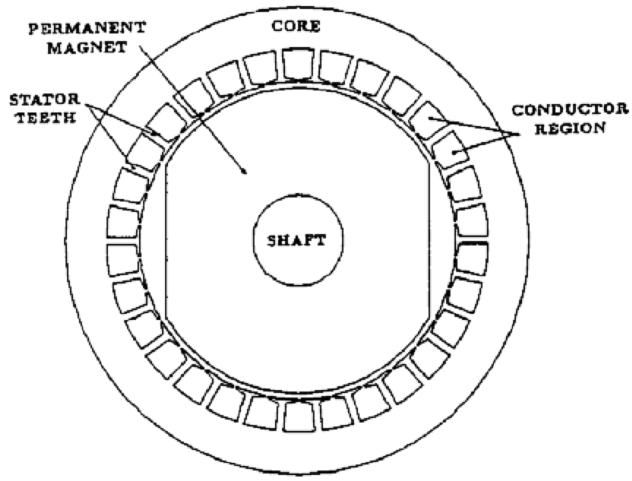


Figure 11. Cross-section of typical conventional Permanent Magnet Generator.

Permanent magnet machines may be set in several categories, those with surface mounted magnets, those with buried magnets, those with damper windings, etc., etc. All categories where data was found were considered, as each has some special features to offer. The search term 'Permanent Magnet Generator' produced an immediate list of some 50 articles, and standards dating from 1990 and later. In view of the small number of articles found, this was not reduced in any way, see Appendix A.2. Some 21 representative articles have actually been studied for this report. Other articles and references found have been included if they came to the notice of the author. This means that some significant articles may have been omitted from consideration. References [8, 9] in Appendix A.2 were ignored, as it concerned a high-speed, 400Hz generator, and cyclo converter. This combination was found interesting, but irrelevant to the case under consideration.

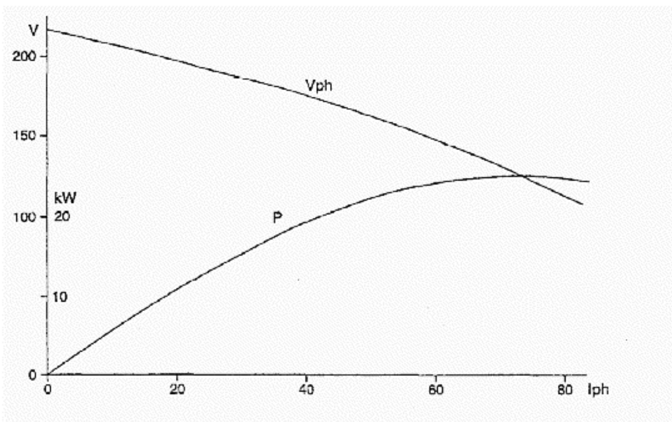


Figure 12. Voltage regulation of 12 pole, outer stator PMG with surface mounted magnets (Mitcham & Grum, 1998).

The PMG has been proposed as wind turbine generator in several research articles. Advantages include self-excitation, which allows operation at high power factor and efficiency. A disadvantage may be the synchronous operation, which causes a very stiff performance in the case of external short circuits, and when the wind speed is unsteady. This may lead to instabilities. Other applications are also considered in the literature, e.g. animal driven generators (Van Niekerk & Hancke, 1999). An overall description of the function of the PMG was not found in the literature search.

2.3.1 Permanent Magnet Generator

The PMG is proposed as a wind turbine generator due to its property of self-excitation. The stator winding is connected to the load, and is insulated. The rotor is provided with a permanent magnet pole system, which is resistant to the effects of possible dirt ingress. However, the permanent magnets will attract ferromagnetic swarf. They also call for special care when assembling, to avoid damage and accidents to personnel. Maintenance is generally restricted to bearing lubrication only. A major problem is the necessity of maintaining the rotor temperature below the maximum operating temperature of the magnet, which may be limited by the Curie point of the magnetic material, and also by the thermal properties of the binding material in the case of powder metallurgy composites.

Large machines are reported (17 MW motors), but most research papers describing generators consider machines with ratings less than 10 kW. The synchronous nature of the operation causes problems of start, synchronisation, and voltage regulation.

Methods of control include full power frequency inverter, and cyclo-converter. Methods of improving voltage regulation include the application of full voltage, large capacitance capacitors.

2.3.1.1 Voltage Regulation

The main disadvantage of the permanent magnet generator is that it does not readily provide a constant voltage, when the shaft speed and the load current vary, (Mitcham & Grum, 1998). Voltage regulation is the term used to describe the variation of the terminal voltage, as a result of load variations, see Figure 12. In a synchronous machine with a wound field winding this regulation may be compensated by varying the magnetising current. In a 30 W generator, fitted with ferrite magnets, the regulation is reported to be too high (Naoe, 1997). It is also reported as high in an outer rotor, surface-mounted NdFeB 20 kW generator, but may be compensated for in each case, by means of a capacitor connection. Shunt connected capacitors give improved output voltage, when feeding an impedance (Ojo & Cox, 1996), i.e. in island duty. Voltage regulation may also be improved by fitting series capacitors (Naoe, 1995). Acceptable voltage regulation was reported when testing the 'Torus' generator (Chalmers et al., 1996). The synchronous reactance may be a problem, limiting the output of the PMG (Mitcham & Grum, 1998). This comprises mainly armature reaction and slot leakage, if the pole number is high, as would be the case with a many-pole generator, provided with surface mounted magnets of NdFeB or ferrite. Machines provided with soft iron pole shoes, or embedded magnets will also have a significant zigzag reactance.

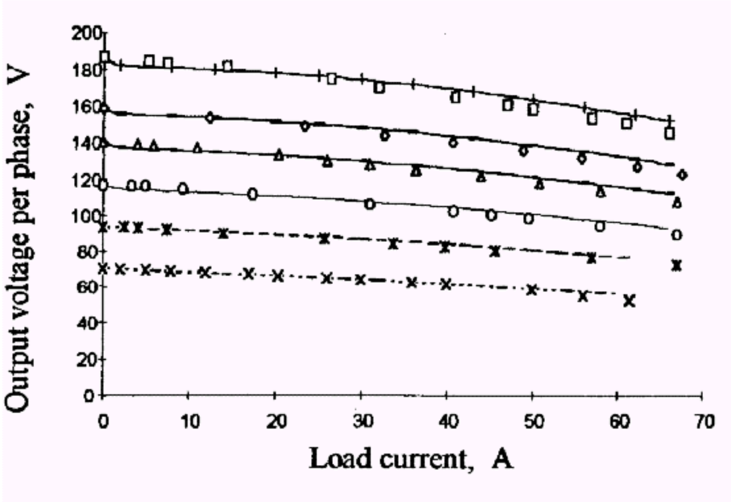


Figure 13 . Regulation of Outer Rotor PMG of (Chen & Nayar, 1998), on resistive load.

At power frequencies, the PMG is usually stable, but the response to fault situations is not well documented and will require some investigation.

2.3.2 Axial Flux Machines

Several authors promote the axial flux design as opposed to the radial flux design. Disadvantages include that it is difficult to manufacture an axial flux machine with a small mechanical air-gap, and that adequate stiffness must be provided in the mechanical design to maintain the air-gap during operation (Chalmers et al., 1996).

2.3.2.1 Torus

The Torus machine, see Figure 14, with a toroidal stator, wound without slots and employing an axial air-gap, has been proposed as a wind turbine generator (Chalmers et al., 1996; Spooner & Chalmers, 1992; Wu et al., 1995). Difficulty with assembly was overcome on a Torus machine. An axial force of 10 kN was experienced, with a 1.5 mm physical air-gap on a 5 kW generator (Chalmers et al., 1996). Use of a machine with a large diameter, a thick winding, and a low, air-gap flux density will reduce axial forces (Chalmers et al., 1996).

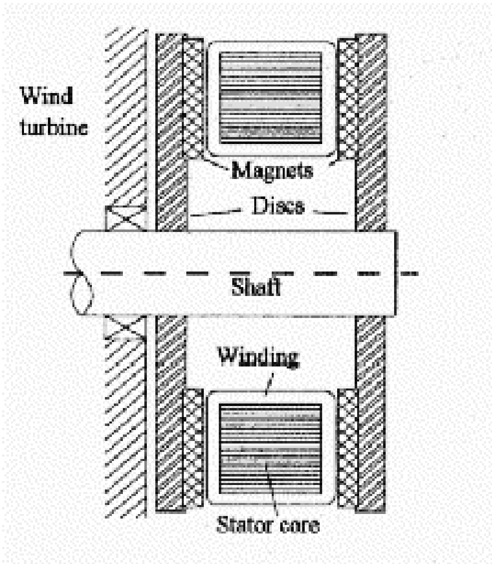


Figure 14. Cross-section of a TORUS generator (Chalmers et al., 1996; Spooner & Chalmers, 1992; Wu et al., 1995).

2.3.3 Hybrid Permanent Magnet machines

2.3.3.1 Doubly salient Permanent Magnet Generator (DSPMG)

The DSPMG in Figure 15 is described in (Sarlioglu & Lipo, 1998). No claims are made as to improvements in performance. It is expected that the DSPMG will improve the performance of an SRMG, by the addition of permanent magnets to bias the magnetic circuit. Alternatively, the performance of a surface mounted PMG is improved by the addition of saliency. This paper focuses on the modelling of the DSPMG, without comparing its performance with other types of generator.

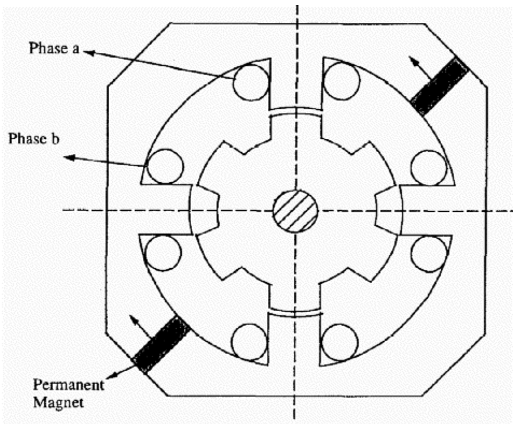


Figure 15. Cross-section of the Doubly Salient Permanent Magnet Generator (Sarlioglu & Lipo, 1998).

2.3.3.2 Axial Flux PMG with salient poles

The hybrid axial flux PMG with salient rotor poles is described in (Muljadi et al., 1998). This is a modular construction, which should make it easy to maintain. Like the transverse flux machines, for this design a complete rotor/stator unit is required for each phase. Poles may be added around the circumference to increase the torque.

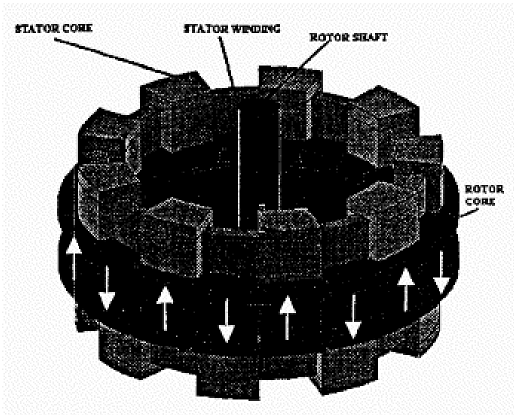


Figure 16. 3D representation of hybrid axial flux PMG with rotor saliency (Muljadi et al., 1998).

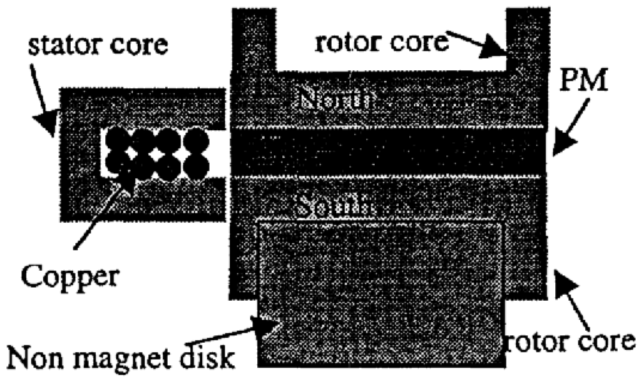


Figure 17. Cross section of hybrid axial flux PMG with rotor saliency (Muljadi et al., 1998).

2.3.4 Methods of Analysis of PMG

Models are reported, which are adjustable to allow for internal and surface mounted magnets, and for the current dependence of flux and inductance (Ojo & Cox, 1996). The model takes no account of current waveform and gives inaccurate results. (Lampola, 2000) reports extensive Finite Element modelling of surface mounted, NdFeB, cylindrical air-gap PMG. This may be supplemented by a linked circuit simulator. In (Polinder & Hoeijmakers, 1997) an analytic method is proposed, to determine the magnetic field distribution in a PMG. This is to ease the numerical problem of optimisation, as opposed to the Finite Element Method. It is also claimed that the method provides insight into the relationship between dimensions and equivalent circuit parameters.

2.3.5 Methods of loading the PMG

To apply the PMG as a wind turbine generator - Figure 18, it should be considered to take advantage of the self-excitation property and allow the machine to operate under variable speed conditions. This would necessitate the use of a line power converter, for the full power to be transmitted. Reasons for this are that variable speed of the PMG will give variable frequency and variable amplitude of the terminal output voltage.

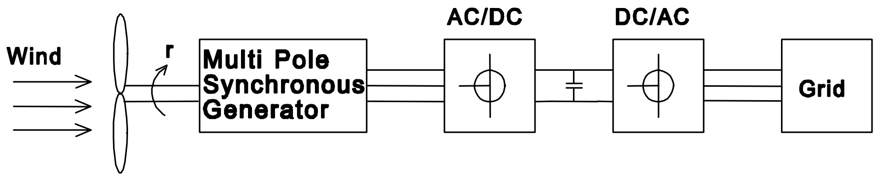


Figure 18. Typical arrangement of Wind turbine driving a PMG, loaded by a Power Converter and the Distibution Grid (Blaabjerg & Mohan, 1999).

Use of a diode bridge rectifier will cause harmonics in the current waveform, giving an exceptionally high peak current in relation to the RMS value of the load (Lampola, 2000). This will cause increased eddy current losses in the rotor, and also the danger of demagnetising the magnets at a relatively small load. This means that the PMG will give less output than it otherwise would, given a sinusoidal current. Additionally, the value of the DC link voltage is directly related to the shaft speed of the PMG. The use of a controlled rectifier allows several advantages. The current may be controlled to be sinusoidal, thus avoiding the above-mentioned problem. The amplitude of the voltage may be controlled to match the grid voltage, independent of shaft speed. Especially, the PMG is more isolated from the grid, making it possible to control fault currents in the PMG, arising from external faults in the grid. The use of the inverter effectively decouples the generator from the grid (Chen & Spooner, 1996). The inverter performance, such as voltage regulation, reactive power control, and power quality, depend mainly on the grid-side inverter. This also removes the need for special starting and synchronising equipment for the PMG. The system may operate at any power angle, without losing synchronism.

2.3.6 Design Considerations

Many authors promote a particular design of generator, where the basic version is possibly the cylindrical air-gap machine, with the stator on the outside and the rotor free to rotate inside it, see Figure 11. The basic magnet design must be NdFeB magnets, surface mounted, see Figure 11 and Figure 12. A problem with this design is that the magnets, which should be maintained at a low temperature, are in the hottest place.

2.3.6.1 Cylindrical air-gap with outer rotor

The outer rotor is proposed, as this gives good cooling conditions for the magnet poles (Chen & Nayar, 1998). An additional advantage is that the magnets are well supported by the drum outside them. For the same air-gap diameter, the outer diameter of the drum may be expected to be less than that of the equivalent outer stator, so a saving may be expected in the materials.

2.3.6.2 Cylindrical air-gap, outer stator

The machine with a cylindrical air-gap and outer stator is the conventional arrangement. It was chosen in (Lampola, 2000) for detailed optimisation studies. The surface mounted magnet, with magnets shaped to suit the radius of the rotor was found to be the best version. Fitting pole shoes was found to be a disadvantage, requiring more machine weight to give the same output, and giving reduced pull-out torque.

2.3.6.3 Modular design using E-cores

(Chen & Spooner, 1995) proposed a modular stator design using E-cores originally designed for the use in transformers, magnetised by ferrite magnets in a flux-amplifying magnetic circuit – see Figure 19. An advantage of this system is claimed to be that the modules may be combined to make a generator having any required number of poles. Tests were performed on a 26-pole unit, but results showing output power related to efficiency are not supplied. (Lampola, 2000) tested a similar arrangement, but with surface mounted NdFeB magnets, and concluded that it was inferior in performance and output/cost to the normal, slotted stator design.

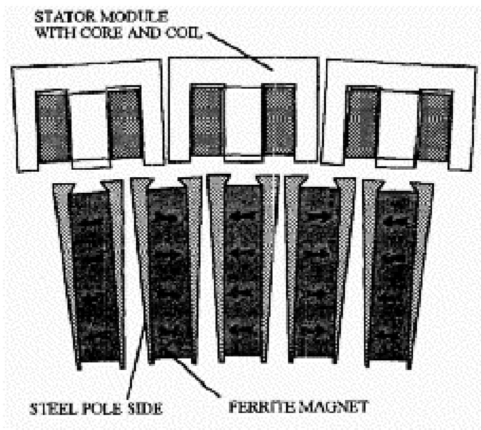


Figure 19. Cross-section of the modular design, using E-cores (Chen & Spooner, 1995).

2.3.6.4 Armature winding design

(Lampola, 2000) found that the conventional distributed winding gave more output from the same machine size than a winding wound around a single tooth.

2.3.6.5 Stator wound without teeth

A 2-pole version is reported, wound without teeth on the stator, (Vyas & Arkadan, 1994), see Figure 20. This was found to yield lower amplitudes of current harmonics on a diode rectifier load, but the total output power was reduced by about 15%.

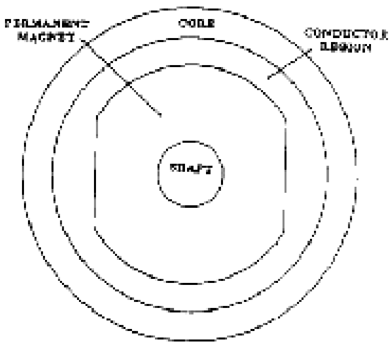


Figure 20. Showing a 2pole design with a toothless stator (Vyas & Arkadan, 1994).

2.3.6.6 Power Angle

(Muljadi et al., 1996) remarks that the power angle for maximum torque, of a PMG, feeding a rectifier, is 45°, instead of the 90°, one would expect of an excited synchronous machine. This means that a PMG will be relatively stiff and susceptible to the effects of sudden fault conditions, compared to the conventional, wound rotor synchronous machine. To obtain the best power characteristics, the DC bus voltage must be changed according to rotor speed. Compensation may be achieved by including a series capacitance in each phase. The DC bus may be used to optimise the output of the wind generator for any working condition.

2.3.7 Experimental Results

2.3.7.1 Efficiency

Efficiency of 83.9% was reported on a 5 kW Torus design (Chalmers et al., 1996). Efficiency of 86% was reported on a 20 kW outer rotor design (Arkadan et al., 1989).

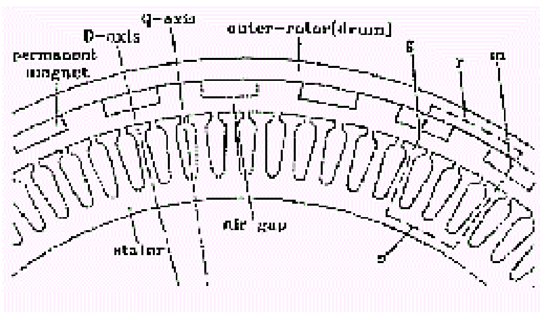


Figure 21. Cross section of PMG with outer rotor (Arkadan et al., 1989).

2.3.7.2 Magnetic Circuit

Efficient use of the magnetic circuit reduces the power to weight ratio (Wang, 1999).

2.3.7.3 Output Power

The fitting of a damper winding can increase the output power by about 4% (Arkadan et al., 1989). The specific power density is claimed to increase with increasing pole number, up to a maximum value (Wang, 1999).

2.3.7.4 Operational Characteristics – Normal Duty

The Permanent Magnet Generator is a form of synchronous machine. As such it will be very stiff in operation if directly connected to the grid. That is to say that all variations of load and power from the turbine must be accommodated at constant shaft speed. This situation is unlikely to produce robust stable operation.

The alternative is to use a power electronic controller between the generator and the grid. To compensate for the cost of the controller, the gearbox may be omitted. It may then be convenient to select a generator with many poles. The use of a full power line converter is expensive, but affords many advantages. E.g. the speed is no longer directly related to the frequency of the grid, energy may be stored locally in the system, as kinetic, electric or magnetic energy, to provide a cushion to even out the effects of wind gusting, etc. Power may be supplied to the grid over a speed range of the shaft.

2.3.7.5 Operational Characteristics – Fault Conditions

On external faults, the Permanent Magnet Generator will easily generate sufficient fault current to activate any type of protection system. The problem is more, if the fault will be cleared before the machine causes serious damage to itself, e.g. in the form of demagnetising the magnets.

Any overheating causing the magnets to achieve the Curie temperature will also cause demagnetisation of the magnets.

2.3.7.6 Efficiency of Permanent Magnet Generators as a Function of Load and Speed

The efficiency surface of a typical small permanent magnet motor is shown in Figure 22. This motor was controlled to operate at the maximum efficiency for each working point tested. Scrutiny of this surface reveals that the efficiency may be controlled to give a reasonably flat plateau at a high efficiency for medium to high torques, and over a wide speed range. However, when the torque drops below a critical level, it becomes impossible to obtain an acceptable efficiency.

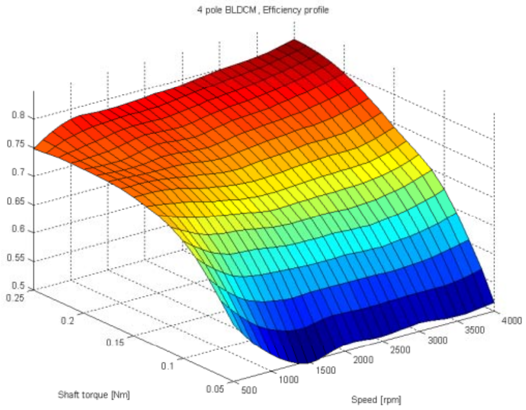


Figure 22. Tested efficiency surface of Permanent Magnet Motor, controlled to operate at maximum possible efficiency for each working point.

The above figures were obtained by testing a small permanent magnet motor. It may be expected that a similar development of the efficiency would apply for a large permanent magnet generator.

2.3.7.7 Well Established or New Technology

The permanent magnet machine is a newer technology than the induction machine, as an application as a wind turbine generator.

2.3.7.8 Gear or Direct Drive Multi-pole

In general, because of the relatively large air-gap, the Permanent magnet Machine leakage flux remains below an acceptable limit for machines with many poles. This means that the machine can use the current flowing to generate torque. Permanent magnet Machines with a large number of poles, may be designed with a reasonably small size compared to the output. This means that permanent magnet machines with many poles will have an acceptable size in relation to the rated output, and may be recommended.

2.3.7.9 One-Off Price

The price of a permanent magnet generator is unknown, as no permanent magnet wind turbine generator is in production. However, the permanent magnet material may be very expensive for NdFeB materials, or reasonably cheap for ferrite materials. The situation is complicated, as a machine provided with NdFeB will need less magnet and other materials than a corresponding machine provided with ferrite magnets. To obtain a reliable estimate, prototypes would have to be designed, built and tested extensively.

2.3.7.10 Other Comments

Acoustic Noise
The Torus machine is reported as having a low level of acoustic noise, (Chalmers et al., 1996).

2.3.8 Conclusion on PMG

The PMG seems attractive as a wind turbine generator. Advantages include self-excitation, high power factor, and high efficiency. Designs have been proposed in cylindrical and axial flux versions. In the PM machine, efficiency is higher than in the induction machine, as the excitation is provided without energy supply, by the Permanent Magnets. However, permanent magnet materials are expensive in initial purchase, and are difficult to handle in manufacture. Additionally, the use of permanent magnet excitation forces the use of a full power converter, to adjust the frequency of generation to the frequency of transmission. This is an added expense, but the benefits are that generation may be at any speed to suit the current conditions.

The internal voltage generated inside a PMG is directly dependent on the speed. This may be catered for by the power converter, to a certain extent, but the voltage may reach a dangerous level if the speed becomes high enough. Field weakening may be applied, but this requires a special mechanical design of the field system, providing a saliency effect, in addition to extra current being required to reduce the effective magnetic field. This has the effect of reducing the efficiency obtained. Voltage regulation as a function of varying load is a problem, which has received some research attention. Various solutions have been proposed, including the use of a parallel-connected capacitor.

Special attention must be paid to the physical properties of the permanent magnet materials used. Some materials are brittle, others are highly reactive, and rust readily. All magnetic materials are sensitive to temperature. They lose their magnetic qualities at a high temperature, called the Curie Point. This may be in the mid 250˚C, which is critical, as these temperatures may be reached during fault conditions.

The stator of a permanent magnet generator is wound in a similar manner to an Induction Generator, and as such, should present no special problems.

PMG with surface mounted magnets may be designed with a relatively large air-gap. This eases the mechanical problems encountered when building and operating a large generator. On the other hand, surface mounted magnets exacerbate the problems of high voltages at speeds above the base speed.

In general, the efficiency of a PMG may be expected to be relatively high, as long as the torque is high. At low torques, the efficiency will fall off rapidly.

2.3.8.1 Further work

Further work is necessary to determine and study the operating characteristics of the various designs of PMG, and to study and eliminate quasi-periodic oscillations of power angle. At the same time it is important in large scale generators to have the possibility to easily repair broken/destroyed magnets. Otherwise repair cost can be too high.

2.4 The Switched Reluctance Generator

The Switched Reluctance Generator has in the last decades been considered for Wind Power applications, but much of the available literature is focussed on aircraft generators. However, the two applications should have similar requirements, the main differences being a matter of scale. The rotor construction is particularly robust, being without windings. Excitation of the magnetic field is provided by the stator current in the same way as for the Induction Machine. The Switched Reluctance machine in Figure 23 operates on a Vernier principle, making it suitable for low speed operation. A total of 19 articles were located, dealing with Switched Reluctance Generators, and all 19 have been considered in this discussion.

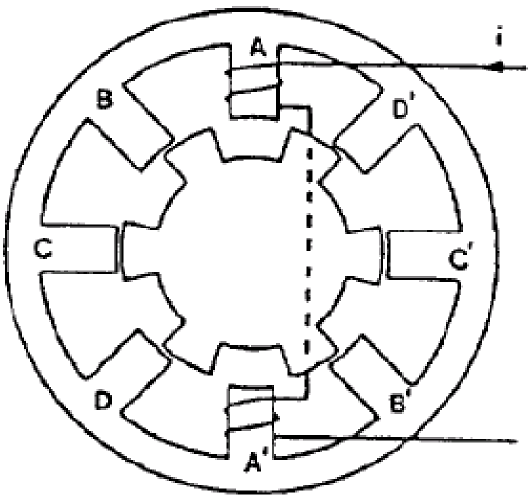


Figure 23. Cross-section of typical Switched Reluctance Generator (Cardenas et al., 1995).

2.4.1 Principle of operation

The SRG is a doubly salient construction, with salient poles on both the stator and the rotor (Mese et al., 2000). Phase windings are wound on the stator poles, each coil being wound around a single pole or tooth. The principle of operation is simple in concept, (Cardenas et al., 1995), but is easier to explain in the motoring mode. If the winding on poles D-D' be energised, the rotor will be pulled clockwise to align with the axis of the magnetic field produced. If now the winding on D-D' is de-energised, and the winding on poles A-A' be energised instead, the rotor will continue to move in the same direction. The machine is now acting as a motor, converting supplied electric energy into mechanical work. Movement in the direction of the torque produced tends to minimise the inductance of the winding (Mese et al., 2000). Generator action may be obtained simply by changing the angular position of the rotor at which current is supplied to the phase winding, to cause generating torque to be produced.

2.4.2 Operational Characteristics – Normal Duty

Generator operation is claimed to be characterised by single pulse operation, rather than chopping, the DC-link voltage being kept constant during operation. By arranging the switching timing to position current pulses where the inductance is decreasing, generating mode may be selected (Husain et al., 1999; Cardenas et al., 1995). The bulk of the generated current is carried by the diodes (Cardenas et al., 1995). The controlled switches mainly provide excitation current (Cardenas et al., 1995).

SRG is interesting for application as an aircraft generator because of its ability to continue operating at reduced output in the presence of faults on the generator itself (Sawata et al., 1997). For the same application, potential instability was reported in (Skvarenina et al., 1997). The SRG is suitable for gearless generation in aircraft applications, because it is capable of high-speed operation (Mitcham & Grum, 1998).

The SRG may be controlled to produce the best efficiency in a given working point (Mese et al., 2000).

Inverter output filtering of SRG current is necessary due to current ripple caused by the commutation (Heglund & Jones, 1997).

In a study (Abouzeid, 1998), the author studies the effects of the variable inductance of the SRG on the load characteristics, and concludes that the inductance/resistance ratio of the load is important to the operation. Otherwise, the SRG is judged to operate in a similar fashion to a separately excited DC generator, if loaded through a rectifier.

The SRG is inherently unstable and requires the firing angles to be adjusted to suit the load exactly (Sawata et al., 1999b). This applies to normal operation and fault conditions. Instability during faults may be controlled by proper detection of the conditions, and control (Sawata et al., 1999a).

A detailed design study (Mueller, 1999) presented an SRG for a 20 kW, 100 rpm wind generator. Torque densities of about 2 – 3.2 were achieved, the best being for a 12/16 design. A converter dimensioned for 80 kVA was predicted. The 12/8 version gives a somewhat lower torque/kg, 2.5, but has a reduced converter requirement, about 55 kVA. The specific torque may be increased, by increasing the iron saturation, at the expense of lower efficiency and increased converter requirement.

A high speed SRG (Ferreira et al., 1995) was successfully controlled, by fixing the turn-on and turn-off angles, and then controlling the output current by turning off both power switches when the current reached the threshold. This system was built and tested for military use. There was no current chopping when generating. Machine efficiency increases with increasing load, while the converter efficiency decreases.

A 30 kW SR-generator has been designed, built and tested (Heglund & Jones, 1997), operating in the speed range of 27,000 to 46,850 rpm. A 25 kW, 250 rpm, 100 Hz, 32/24 SR generator has been designed for a 250 V DC bus (Mitcham & Grum, 1998), the maximum speed was 3100 rpm, yielding 150 kW, 1240 Hz.

2.4.3 Comparison with other types of machine

The SRG is considered inferior to the PM machine, due to its lower power density, and the need for a sophisticated power converter (Mitcham & Grum, 1998). However, the rugged mechanical design and the concentrated coil design are attractive.

2.4.4 Axial Flux Machines

An axial design of 6/2 SRG is reported (Abou-Zaid et al., 1999), with the rating of 300 V, 4 A, where the test results are reported to give a 9% change in voltage, at a 2 A load, for a change of speed from 1500 rpm to 3000 rpm. Changes of load inductance can lead to large changes in output voltage at 2 A load. However, the test results are for voltages around 30 V only, the machine performance at a reasonable rating would be required to be established at a reasonable rating.

2.4.5 Methods for modelling and analysis

The SRG is inherently, extremely non-linear in the magnetic circuit, and in operation. For this reason, Finite Element Analysis is often used as an analysis method (Mese et al., 2000) for the magnetic circuit. Sophisticated simulation of the non-linear electro-mechanical normal duty is required to produce estimates of steady-state performance. Both of these may be effected using in-house software produced by AFEE, (Blaabjerg et al., 1999; Rasmussen et al., 1999).

(Husain et al., 1999) present a general modelling approach for a Switched Reluctance Generator. Modelling and tests were carried out on a 12/8, 250 kW, 22000 rpm machine, operating at 50 V DC. The model was found to be useful for investigating the response of the SRG to fault conditions.

2.4.6 Operational Characteristics – Fault Conditions

Armature phase shorts and open circuits are internal faults, other faults occurring in converters or wiring are external faults (Husain et al., 1999). The SRG investigated was found to continue generating in the presence of single-phase internal faults and converter faults. The excitation required to feed external faults adequately, so that protection equipment would operate as required.

Any generator system must be able to clear load faults by blowing fuses or tripping circuit breakers (Husain et al., 1999). In the case of the SRG, sufficient DC link current must be produced to enable fault clearance by tripping a relay or other fault protection device (Heglund & Jones, 1997). For the SRG tested, the load fault voltage collapsed to 35 V from around 270 V, the phase current was 1400 A, peak value, compared to full-load current of 900 A. (Sawata et al., 1998) found that the 8/8, single phase SRG tested could continue generating in the presence of an internal fault. For certain faults, this was at half capacity only.

2.4.7 Efficiency of the SRG as a Function of Load and Speed

No direct claims to efficiency were found. The SRG may be controlled to produce the best efficiency in a given working point (Mese et al., 2000). The specific torque may be increased, by increasing the iron saturation, at the expense of lower efficiency and increased converter requirement (Mueller, 1999). Many claims have been made that the SR machine should have a higher efficiency than the Induction Machine. This has been shown to be true, if a new design of SRM is compared with a commercial standard IM. However many commercial standard IM’s have basic designs which were laid out in the 1950’s, with no subsequent changes to lamination geometry. The difference would not be so large, and may even disappear, were the comparison to be made with a completely new design of IM.

Because the SRG is excited from the stator current, as opposed to being excited from a permanent magnet, the controlled best efficiency as a function of torque and speed may be expected to take the same form as for the Induction Motor. This is illustrated by test results obtained on a 100 W induction motor. Note that as the values shown correspond to a 100 W machine, only the form may be interesting here.

2.4.8 Well Established or New Technology

The SRG is a new technology. As a motor, the SRM has attracted a great deal of research interest. However, the number of available commercial suppliers of motors is very small and the even fewer suppliers of SRG are all aiming at the aerospace market, and are building very small, high-speed generators for aircraft duty. It is doubtful whether any real series production of SR machines is currently in manufacture, despite the amount of advertising.

2.4.9 One off Price

The SRG should be reasonably cheap in manufacturing cost, as there are no permanent magnets, and special inter-coil insulation is not required. The air-gap is relatively small, due to the excitation being provided via stator current, which will make the mechanical construction relatively expensive. By using a high number of phases, which will be expensive in wiring and converter costs, an improvement in fault tolerance may be possible.

2.4.10 Gear versus Multi-pole

Due to the Vernier action of the SR machine, it should be easy to manufacture slow running versions. However, the performance characteristics of such a machine are unknown.

2.4.11 Other Comments

(Cardenas et al., 1996) treated a PMG system, and merely mentioned the SRG as a possible solution for further investigation. (Skvarenina et al., 1997) treated the application of a particular commercial graphic modelling language to the solution of problems involving SRG. Only a very simple problem of resistive switching was tested, in order to demonstrate the language. (Wiegele, 1996) treated the detailed design problems of a micro-SRG, considering mostly problems of the impulse-turbine used. (Cardenas et al., 1995) contains a discussion on how to control a DC motor in order to emulate the behaviour of a wind-turbine in the laboratory. (Ke Liu & Striebler, 1998), treated a fuzzy logic controller, suitable for an SRG. (Ferreira & Richter, 1996) treated the subject of channel independence for an SRG feeding two separate bus-bar systems for aircraft use.

2.4.12 Conclusion on SRG

The SRG is a possible candidate for a Wind Turbine Generator. However, the literature is not substantial, and much investigative work remains to be done before the SRG is well prepared for application.

The SRG will require a full power converter in order to function as a grid connected generator, but will otherwise perform in a similar manner to the Induction Generator, as the excitation is provided from the grid.

2.5 The Transverse Flux machine

The Transverse Flux (TF) machine topology is new, but appears to be interesting. The high values of torque per kilogram of active materials reported make it seem very attractive. The transverse flux principle may be applied to a range of machine types, e.g. both permanent magnet and reluctance machines could be made. The machine will inherently behave as the generic type applied, but will have characteristics, influenced by the TF design. Here, the Transverse Flux Permanent Magnet Machine will be discussed. Most of the researchers have treated motors, but here, we are interested in generators. In principle, the generator is very similar to the motor, except that the windings are subject to severe loads due to short circuits on the generator. This means that the windings need to be strengthened, to cope with the resulting stresses.

2.5.1 Reported machine type designs

Different designs of TFPM will be considered here:

- Double-sided and single-sided.
- Flat magnets and embedded magnets.
- Flux concentrated and not flux concentrated.

In the double-sided design, stator poles are sited on both sides of the rotor and in the single-sided design; only one side is provided with stator poles. Flat magnets are surface mounted magnets and embedded magnets are internal in the rotor structure. Finally, flux concentration means that soft iron pole pieces are fitted to the permanent magnets.

A comparison of several reported TFPM machines was undertaken by Harris, Pajooman and Sharkh, Southampton University (Harris et al., 1997). The various topologies are referred to by the city/university where they were developed;

- Southampton: Single-Sided with Surface Magnets (SSSM)
- Aachen: SSSM with non-conducting stator bridges
- Braunschweig/Newcastle: Double-Sided with Flux Concentration (DSFC)

The findings of this study are that the SSSM machines from Southampton and Aachen can deliver approximately the same torque: circa T_{spec} = 30 kNm/m^3. The DSFC types are superior in specific torque with up to T_{spec} = 52 kNm/m^3. This compares to about 15 kNm/m3 for a standard Induction Motor, and is a dramatic improvement.

According to Harris et al, the larger specific torque of the DSFC machine is caused by the better utilisation of both the stator excited flux and the magnet flux. The power factor of DSFC machines is also higher than SSSM machines - typically 0.53 versus 0.35-0.40. Disadvantages are a more complex and less robust construction - more parts to manufacture and assemble with small tolerances requiring greater accuracy. This construction could be improved by using powder core technology instead of a laminated steel core. Powder metallurgy offers high utilisation of the material and the ability to form and produce complex shapes. This would ease the manufacture and assembly of the motors. However, both material costs and tools will be increased by this solution.

Several attempts have been made to use powdered iron as a direct replacement for laminated steel, but with poor result. According to (Jack et al., 1999) this is because the designs were unsuited for the use of powder cores, where the advantages are three-dimensional flux distribution, lower component count, and, as mentioned, new methods of manufacture and assembly. Hence, designing a wheel motor with powdered core or cores offers new challenges to the designer. To benefit properly from the material, the designer has to have exact knowledge of the material at hand, moulding techniques and assembly methods. Although reported in the literature, the application of powder technology to cores of electric machines is in its infancy, and requires much more study and material characterisation before application is advisable.

These factors, set limitations for the choice of machine type. The double-sided, transverse-flux, permanent magnet generator seems very attractive for further work, due to its high torque-density and low leakage inductance.

2.5.2 TFPM technology

The TFPM machine has its origins in the SR machine, and it is found to be a promising new design of a linear SR machine. The SR machine is named after its ability to exploit the change in air gap reluctance. This means it produces force by moving according to the maximum inductance of the excited winding. The motion may be rotary or linear, and the rotor may be interior or exterior (Miller, 1989).

In a TFPM machine the flux path in the core back iron is perpendicular (transverse) to the direction of movement – see Figure 24. The opposite, a core back flux path parallel to the direction of movement, is found in the Longitudinal Flux Permanent Magnet machine (LFPM). The LFPM machines are claimed to have inferior performance than the TFPM machines because of their larger rotor mass and difficulties in design, due to unwanted magnetic coupling. All in all LFPM machines do not exhibit results as promising as those of the TFPM machines.

An SR machine consists of a number of separate electromagnets, which are excited in turn. The position of the rotor determines the exact timing of the excitation of each phase. Because of this, the machine will always need to be supplied by a converter and a controller and provided with an accurate position indicator for the rotor position. The excitation of TFPM machine is produced by the permanent magnets instead of by current flowing in rotor windings. The machine must be controlled via current flowing in the stator windings, which like the SR machine must be fed by a converter, preferably a simple converter. The requirement for a simple converter feeding the wheel motors, leads to the proposal of a three-phase motor design. However, a final decision on this point must be the result of a careful study of cost and performance analysis.

The control of the SR machine or TFPM machine is difficult; the air gap flux is non-sinusoidal, and the magnetic circuit of the machine changes continuously and is non-linear when the rotor moves. Also, there is strong local saturation at the edges of the overlapping stator and rotor poles, which means the machine constantly operates in a more or less saturated condition. As a result, the design of a TFPM motor must contain some modelling by use of numerical methods and/or prototyping followed by measurements.

2.5.3 TFPM basic design

The magnetic circuit of the TFPM is complex due to stray flux and the constantly changing saturation of the iron. This means that analytical analysis of the magnetic circuit is difficult. Therefore, numerical methods are attractive. A well-known and documented method is the Finite Element Method (FEM), where the problem is defined inside a boundary and solved by division into small segments with knowledge of the surrounding boundary conditions.

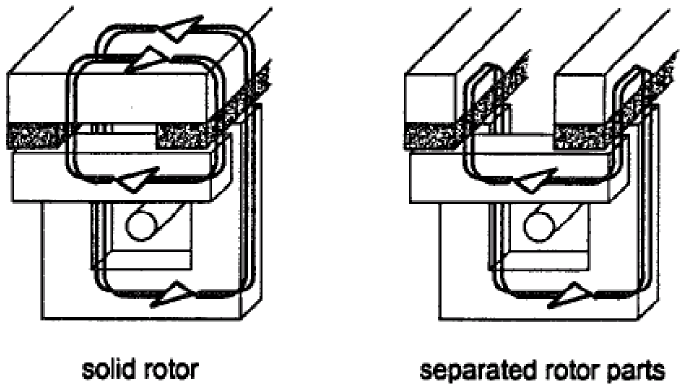


Figure 24. Sketch of the flux path in a transverse flux design. Source (Henneberger & Bork, 1997).

FEM calculations may be used to determine the steady state performance of the non-linear TFPM machine magnetic circuit. According to (Salo et al., 1999) an FEM analysis of only the basic pole-pair will be adequate to determine the traction force and the flux linkage. These are functions of the current and the position of the machine but of course the physical dimensions, the pole number, the air gap length, etc. and the properties of the magnetic material will determine the torque and flux linkage supplied by a pole pair. The torque and inductance for a whole motor may then be found by multiplying by the number of pole pairs of the motor and the number of phases.

The design steps are as follows:

- Decide traction force
- Decide cross-sectional area of pole leg face
- Total mmf is chosen from calculated database or analytical expressions
- Current density is chosen by cooling method. Table in (Hendershot, 1994).

Some dimensional constraints common for SR machines are listed in (Salo et al., 1999):

- Width of the stator poles and the rotor poles is equal
- Distance between two stator poles is equal to the pole width.
- Minimum length of the whole motor is an electric length determined by the number of phases
- Stray flux . 0 and may be ignored in the dimensioning equations
- Pole width is chosen so that it together with the pole length gives the minimum mass of the rotor.

The ultimate *simplicity in design* is obtained with one-pole-pair per phase and then choosing a three, four- or five-phased motor. A three-phase design will lead to a simple converter. The design process uses analysis of the simple basic pole-pair concept.

After determining the basic dimensions i.e. geometric properties, the performance of the magnetic circuit may be predicted by using a numerical method such as FEM. After design and construction of the FEM model, it may be used to calculate the forces on a plane in the air gap. It must be remembered that the steady-state performance represents ideal conditions. Electric, magnetic and friction losses impair the performance of the real machine and should be taken into account. This must be done using separate calculations, as they are not considered in the FEM environment. When the magnetic design is finished, the weight of materials used may be calculated, and the circuit parameters estimated, to enable system calculations, etc.

2.5.4 Force production and calculation

The linear SR motor produces a traction force when that pole pair which has an increasing inductance in the direction of movement is excited. Force is produced to oppose the change in inductance i.e. to attempt to minimize the field energy in the SR motor, and not by induced current as in the case of induction machines. The mechanism is the same as for the production of reluctance torque in the salient pole synchronous machine. The magnetic flux and the torque producing current must be perpendicular to each other. The magnetic flux must cross the air gap in the normal direction to produce a tangential force component. The magnetic flux is excited by current flowing in the stator winding.

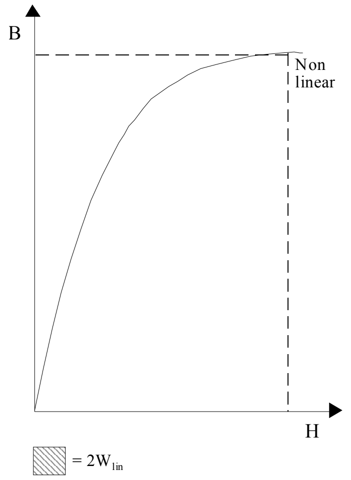


Figure 25. B,H-curve for a ferromagnetic material.

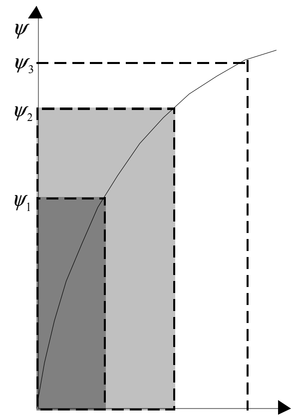


Figure 26. Magnetisation curve for a transverse flux machine.

The magnetic circuit is very complex for analytical calculation due to the effects of stray flux and saturation in the soft iron flux paths. This complex magnetic circuit and the relative unfamiliarity of the construction make it necessary to use a general numerical method for modelling and solution of magnetic problems. A suitable and available method is the Finite Element Method (FEM). After the FEM model is built, and solved, a force determining method is applied to calculate forces on a plane in the air gap. Because the force is strongly dependent on the rotor position, it is necessary to calculate it for a number of different rotor positions and then determine the average traction force. In order to explore saturation effects, the calculations may be repeated with various values of armature current. A suitable modelling tool is Opera-2D a commercially available FEM platform, by Vector Fields Ltd. of Oxford, UK.

The force calculation method used in Opera-2D is the Maxwell Stress Tensor Method. This method is provided for two-dimensional (2D) modelling, because here the closed surface integral is modelled by a line integral around a closed path. This eases the calculation. It is important to note, that the integration path must be completely in air and not pass through elements, which touch the surface of any iron or dielectric. This would give large errors due to abrupt changes flux in the tangential direction in those positions [Opera-2D, pp 3-127]. Another precaution to take is to draw the integration path, avoiding nodes of the FEM model, preferably in the centre of elements.

2.5.5 Flux linkage calculation

Magnetic flux induced by the armature coil penetrates all the physical objects of the TFPM and thereby creates the armature field of the machine. The flux linkage is an expression of the electrical properties of the motor, and a flux linkage calculation may be used to design the motor windings. However, the flux linkage is strongly dependent on the eddy current losses of the motor cores and the skin effect and proximity effect losses in the windings. Therefore, the flux linkage cannot be accurately determined from a static solution of the motor magnetic circuit. If these losses are very small, their influence on the flux linkage may be neglected and a static magnetic solution used to determine the flux linkages of the motor.

Figure 25 shows the B/H-curve of a non-linear material. The region above the curve is the stored field energy and the region below the curve is the co-energy. The static magnetic field energy and co-energy must be obtained from the FEM solution - like the force performance. The static flux linkages may be calculated by summing their energies and dividing by the current flowing in each calculation when the rotor position is kept constant.

$$\lambda(i,x) = \frac{W_f(i,x) + W_{CO}(i,x)}{i}$$

where i is the armature current and x is the rotor position. A magnetisation curve is plotted for each rotor position, which is changed by altering the size of the air gap in the model.

2.5.6 Conclusion on TFPM Machine

The TFPM machine seems suitable for application as a wind power generator. The nature of its operation is that of a synchronous machine, and it will function in principle in a similar manner to any other permanent magnet machine. It can be made with a very large number of poles, which may make it suitable for direct drive, gearless applications. The TFPM has however, a relatively large leakage inductance. In the reluctance version, this may cause problems that the power factor becomes very low in normal operation, and the short circuit current may be insufficient to trip normal protection. Similar problems exist for the permanent magnet version, but because of the PM, they will not be so severe.

A disadvantage of the TFPM is the large number of individual parts required to produce it, using lamination technology. This may be alleviated, if powder technology becomes viable.

More research study will be required, before it is clear that the TFPM machine is suitable for application as a wind power generator.

2.6 The Wound Rotor Generator

The wound rotor synchronous generator is the workhorse of the electrical power supply industry. As such, it has been described in a multitude of research papers over the years. Both the steady state performance and the fault performance are well documented. Versions are found with cylindrical rotor, (steam turbine, high speed machines), and with salient poles (diesel driven, and water turbine driven machines). Extremely large machine have been built, up to about 1200 MW. Very slow running machines have been built as water turbine generators. This machine type could be applied as a wind turbine generator, as it could be built with a suitable pole number for direct drive applications, and in suitably large sizes. Enercon and Lagerwey are examples of wind turbine manufacturers that have selected this type of machine.

As a synchronous machine, it is probably most suited for full power control, using a power electronics converter. This would enable variable speed operation. Otherwise, the synchronous machine is strictly fixed speed operation, and is unforgiving if affected by transient and sub-transient loads. The load characteristics may be further controlled, by controlling the magnetising current in the rotor winding.

The operational characteristics should be excellent in all respects, due to the many years of research, design, development and operational experience.

The construction, with an insulated wound rotor makes the machine vulnerable to vibration, which could degrade the rotor insulation. In addition, the rotor current must be supplied, either by using a brushless exciter, and rotating rectifiers, or by using slip rings and brushes. The brushless exciter design adds another rotating winding, and the rotating rectifiers. The slip ring design has the disadvantage of brush losses, and brush wear, requiring maintenance attention. Both of these designs have the potential of regular maintenance and low reliability.

2.6.1 Description

The synchronous machine is usually built with a rotor carrying the field system, provided with a winding excited by DC. The stator carries a three-phase winding quite similar to that of the induction machine. The rotor may have salient poles, or may be cylindrical - Figure 27. Salient poles are more usual in slow speed machines, and may be the most useful version for application to wind turbine generators. The saliency gives added torque, and a stiffer machine operation.

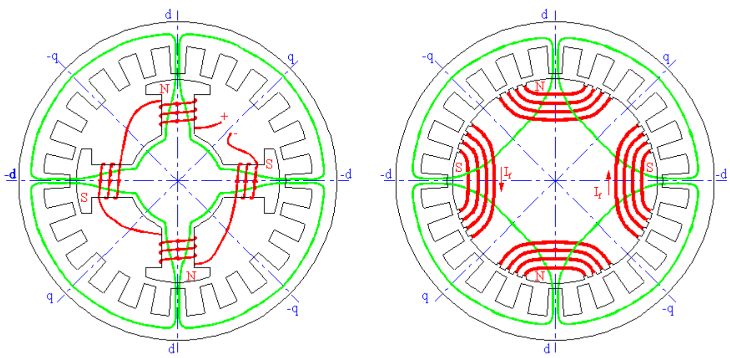


Figure 27. Cross-section diagram of typical salient pole and cylindrical synchronous machines.

Figure 28 illustrates the torque characteristics of salient pole synchronous machine as functions of load angle.

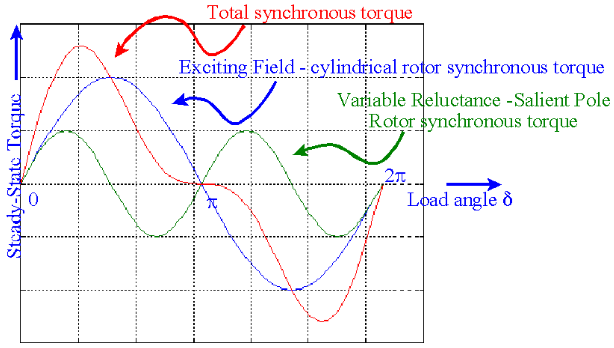


Figure 28. Typical synchronous torque characteristics of salient pole synchronous machine.

Typical low speed synchronous machines are of the salient pole type, with many poles. A typical multi-pole, salient pole, synchronous machine rotor is shown in Figure 29. A typical low-speed, high voltage stator is shown in Figure 30.

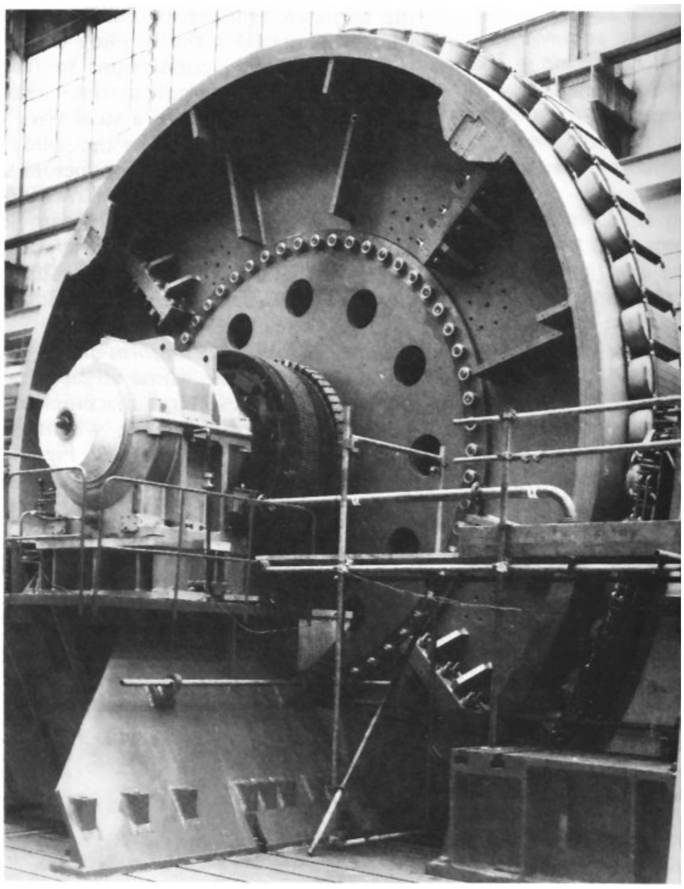


Figure 29. Photograph of a multi-pole, salient pole, synchronous machine rotor.

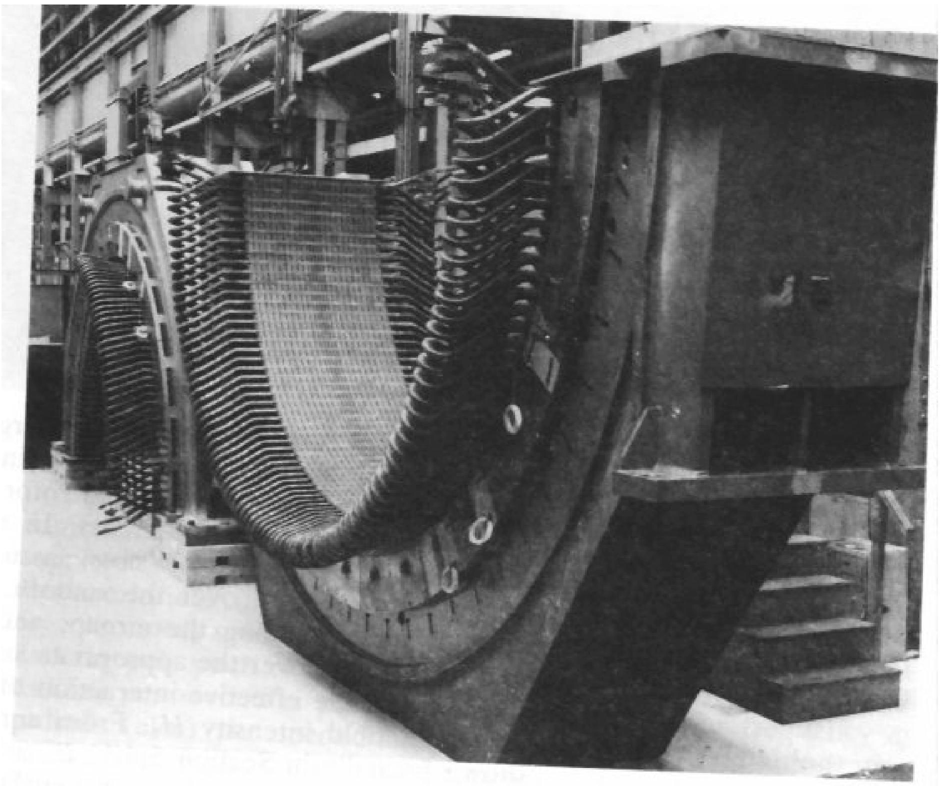


Figure 30. Typical high voltage, low speed, synchronous machine stator with three-phase winding.

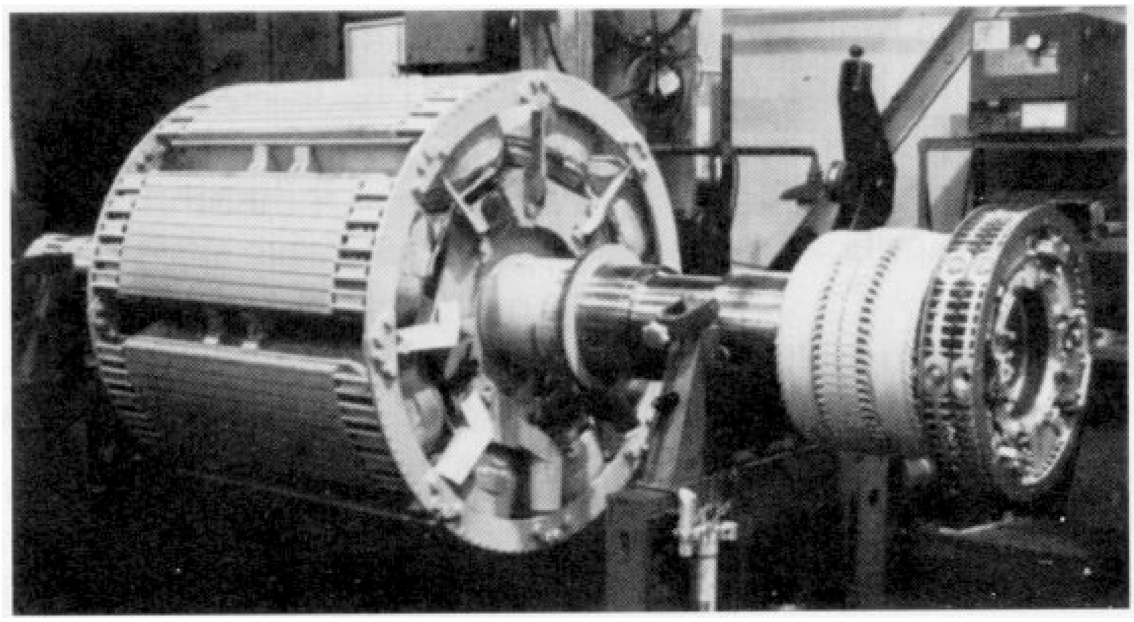


Figure 31. 8 pole, salient pole rotor, fitted with brushless exciter and damper winding.

2.6.2 Operation

To operate as a wind turbine generator, it will be preferable to feed the power through a power electronics converter, carrying the full output power. The system will act as storage for the power fluctuations, which are inevitable with a synchronous generator, driven by an inherently gusting wind. It will also buffer transients coming from the net side, and enable variable speed operation of the wind turbine.

2.6.3 Conclusion on Wound Rotor Synchronous Generator

The Wound Rotor Synchronous Generator is already in application as a wind power generator. The large number of parts and windings probably make it an expensive solution.

It may be supplied in high voltage and industrial voltage versions, and it is widely used as a generator in connection with other forms of prime mover. It may be used, at constant speed, and fixed to the net frequency with consideration of the drive train dependencies and synchronization at start-up. There is a massive amount of research and technical literature. The WRSG may also be applied using a full power inverter, with the option of variable speed operation. In all cases, it is necessary to excite the rotor winding with DC, using slip rings and brushes, or a brush less exciter, employing a rotating rectifier.

2.7 The High Voltage Machine

High voltage machines are manufactured both as synchronous machines and as asynchronous machines. They have been used in applications where high power is needed. They have especially been used for power generation in large power stations, but also for large loads such as large pumps, cement mills and fans. The main motivations for using high voltage machines are the reduction in current, leading to lower copper losses and possible direct connection to the grid without the need for a transformer.

So far only very few wind turbines are provided with high voltage generators. These have been prototype wind turbines, usually designed by utilities or large manufacturers of electric equipment e.g. Tjæreborg 2 MW, applying an induction generator, and Growian 3 MW, applying a doubly fed induction generator. So far, commercially available wind turbines have not applied high voltage machines.

The choice of generator, including the voltage level, should be part of the overall design of the wind farm, from the wind turbine to the point of common coupling of the total wind farm to the grid. Issues that have to be taken into consideration include cost and availability of components, grid connection and control properties, maintenance requirements, required skills of the maintenance workers, safety requirements, etc.

The main motivation for increasing the voltage of the generator is to reduce the current and by that to reduce the copper losses and therefore the amount of heat that has to be dissipated. This can lead to a reduction in the size of the generator and to an increased efficiency of the wind turbine, especially at higher loads. The grid connection and control requirements are the same for the low voltage equivalent generators.

High voltage machines are potentially an interesting alternative for wind turbines from 3 MW and upward. This size limit is mainly due to the high cost of the machine and to the high cost of the auxiliary equipment, such as switchgear. The manufacturing costs may be reduced if a number of wind turbines applying high voltage generators becomes significant. Power electronics are more expensive at these high voltages and there are very few suppliers. The application of high voltage generators means that the requirements regarding safety etc. according to international standards are very different from the requirements applying at low voltage (<1000Vac). These requirements include increased requirements on the level of training of maintenance crew, and different rules of safety. The need for service and maintenance are similar to the equivalent type of system at low voltage. It depends on the type of machine and if gearbox is included, see above.

Recently ABB have announced the WINDFORMER - a high voltage multi-pole permanent magnet synchronous generator, specially developed for application in wind turbines. The WINDFORMER is based on ABB's POWERFORMER concept in which the windings of the stator are made from high voltage cables. This makes a robust construction that is directly connected to the high voltage grid. The utilisation of permanent magnets in a multi-pole rotor also reduces the rotor losses significantly and makes it possible to eliminate the gearbox. The idea of ABB is to combine the WINDFORMER technology with their HVDC-light technology in order to provide a complete concept for the electrical design of not only the wind turbine but of the whole wind farm including the grid connection. The main ideas of the WINDFORMER concept are:

- To provide a simple mechanical construction, without a gearbox, simple power electronics at the wind turbine (diode rectifier) in order to reduce maintenance and increase availability.
- To provide an efficient drive train by having an efficient generator, no gearbox, and a low loss diode rectifier.
- To exploit the features of the HVDC-light technology to have a simple internal grid in the wind farm and to have a high quality grid interface.

ABB is currently testing a prototype of the generator and will later test a complete wind turbine together with Scanwind A/S.

The major disadvantages involved are the cost of the total system and the uncertainty of the long-term performance of the equipment since it uses all new concepts.

2.8 Trends and perspectives

In the previous subsections, the focus has been on technical issues, whereas trends and perspectives are more the subject of this section. The present situation for seven types of generators regarding specific weight and specific price are illustrated in Figure 32 and Figure 33, respectively. These figures present the case of five asynchronous machines – i.e. three cage rotor machines with 4, 6 and 4/6 poles and two slip ring machines 4 and 6 poles, and two synchronous machines 4 and 6 poles, with wound rotor. The two synchronous machines are not relevant for application in wind turbines. They were included solely for comparison purposes. The origin of the data from ABB or Siemens have not been specified, since the purpose of Figure 32 and Figure 33 is to indicate trends rather than to benchmark products from these companies.

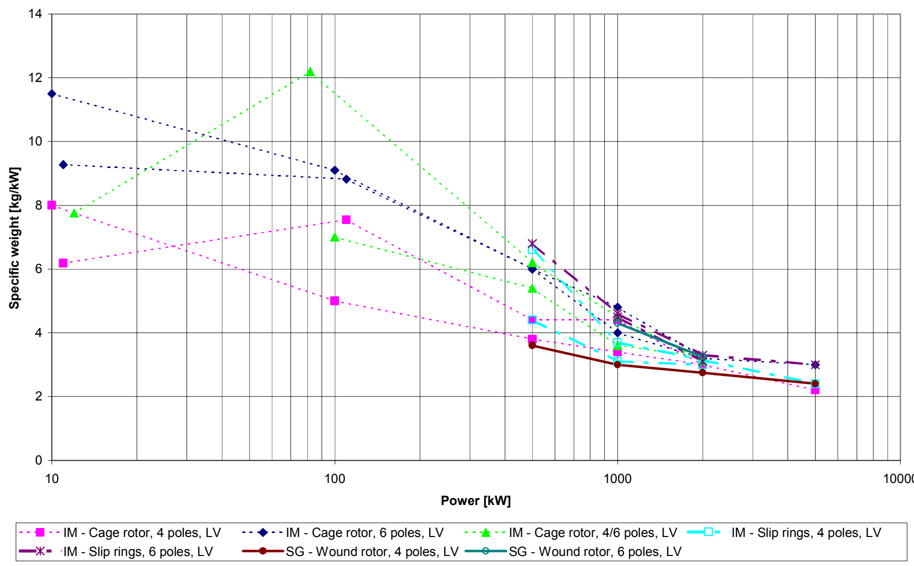


Figure 32. Specific weight for five relevant types of induction generators (IM) and two synchronous generators (SG). Estimated data supplied by ABB and Siemens.

As may be observed in Figure 32, the general trend of specific generator weight approximates to 3 kg/kW in the case of the Megawatt machines. The deviation is quite small in this area.

Regarding the specific price in Figure 33, larger machines may be expected to have an improved price-power ratio. The classical 4-pole cage rotor machine is the most cost efficient of the selected designs, while the slip ring machines turn out to have the poorest price performance.

It should be noted that the machines discussed in Figure 32 and Figure 33 are low voltage machines. The increasing nominal wind turbine power size may lead to application of medium or high voltage machines. This is highly likely, as the machines are getting more compact and the currents are increasing, i.e. higher losses will occur, and higher demands to cooling may be expected.

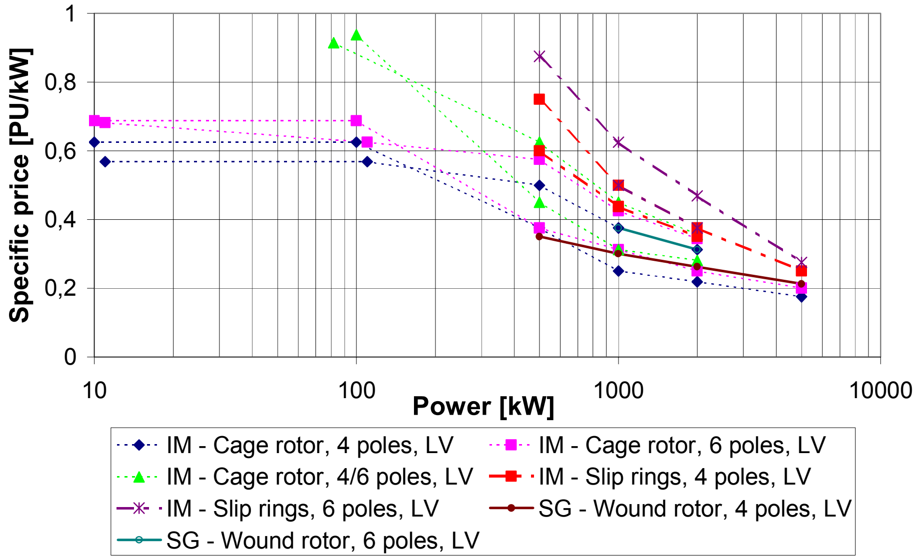


Figure 33. Specific price for five relevant types of induction generators (IM) and two equivalent synchronous generators (SG). Estimated data supplied by ABB and Siemens.

An equivalent analysis of multi-pole machines would be of interest. At present, it seems that this market is quite sensitive, and data is not easy to obtain. Nevertheless, in order to analyse and forecast trends on this aspect a number of gear manufactures have been asked to supply this report with gear data.

Based on the previous analysis of generators, it may be stated that an increasing size will both give a better specific weight and specific price. Therefore, the trend will move against still bigger wind turbines. Further on, consideration on solutions with gear versus without gear becomes still more important because the development in power electronics make it more feasible to use gearless solutions. Important solutions are the synchronous generator with field winding, the switched reluctance generator and the transverse flux machine. Also generators with permanent magnets become still more interesting, due to the lower price of the magnets. It can therefore be recommended that more research is conducted in this area. However, new generator concepts in Mega watt scale are very expensive to prototype. Further on, making a new production line also include huge investments.

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. Related to this it is also at interest to investigate gearboxes and drive train loads using variable speed. The mechanical stress may be reduced using variable speed. The doubly fed induction generator is now widely used but still research is needed in diagnosis, control and even more optimized design in order to reduce the losses to a minimum but also to reduce the overall prices of the generator system. New solutions with a gearbox (low gearing) together with a multi-pole generator may also be an interesting solution both in respect to cost but also in respect to weight.

An indirect way to shed some light on the gear versus gearless machine concept is to take a closer look on the gearbox. The most interesting factor is probably the weight of the gearbox. Data on this parameter is shown in Figure 34. The origin of the data from Brook Hansen Transmission and Lohmann & Solterfoht is not directly specified, since the purpose of Figure 34 and the following 3 figures it is to indicate trends rather than benchmark products from these companies.

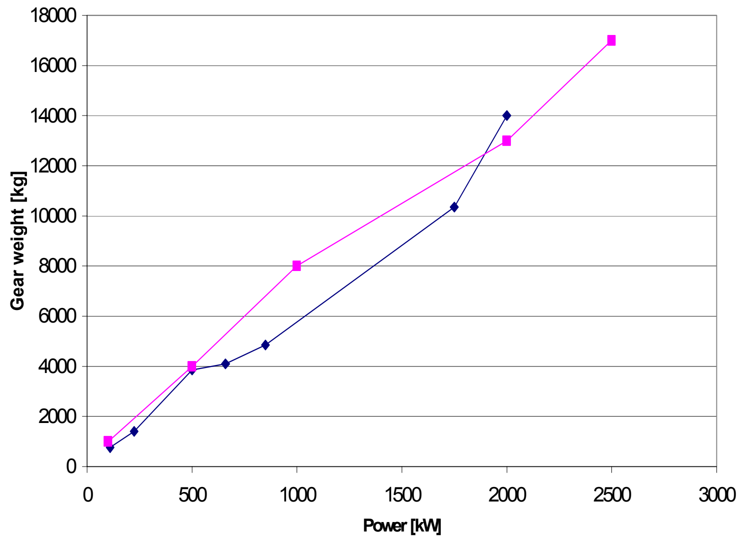


Figure 34: Weight data on gearboxes. Estimated data from Brook Hansen Transmission and Lohmann & Solterfoht.

As it can be observed in Figure 34, the weight of the gearbox is approximately a linear function of the power of the wind turbine. In Figure 35 the specific weight is presented.

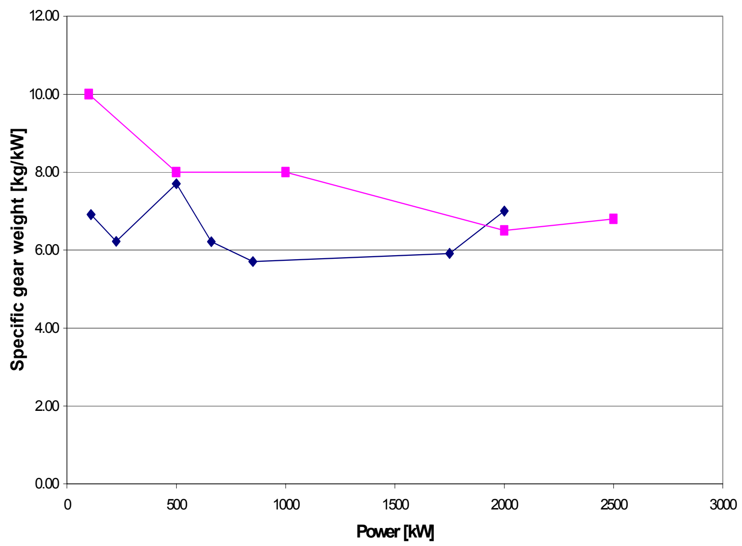


Figure 35: Specific gear weight. Estimated data from Brook Hansen Transmission and Lohmann & Solterfoht.

The trend presented in Figure 35 converges to a specific gear weight of 6-7 kg/kW. The specific weight of the gearbox and e.g. a 4 pole cage rotor machine is approximately 10 kg/kW. The corresponding number of a synchronous multipole generator is in the range of 20-30 kg/kW (Søndergaard & Bindner, 1995). Thus the gearless concept is more than twice as heavy.

Another interesting gearbox parameter is the oil volume. This is shown in Figure 36, based on the same setup as above.

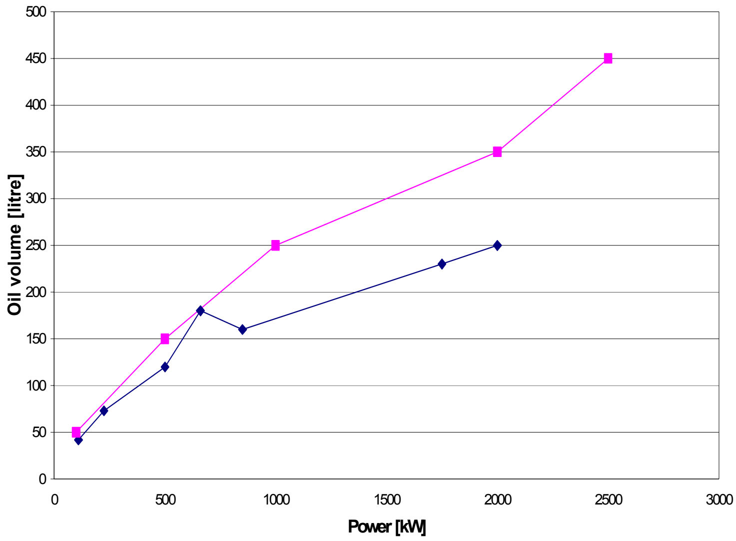


Figure 36: Oil volume of gearboxes. Estimated data from Brook Hansen Transmission and Lohmann & Solterfoht.

The trend in Figure 36 is clear – higher power of course implies more oil. Looking at the specific oil volume a surprising fact is revealed. The specific oil volume decreases exponentially with the power – see Figure 37. This clearly indicates an intensive optimization of the gearbox.

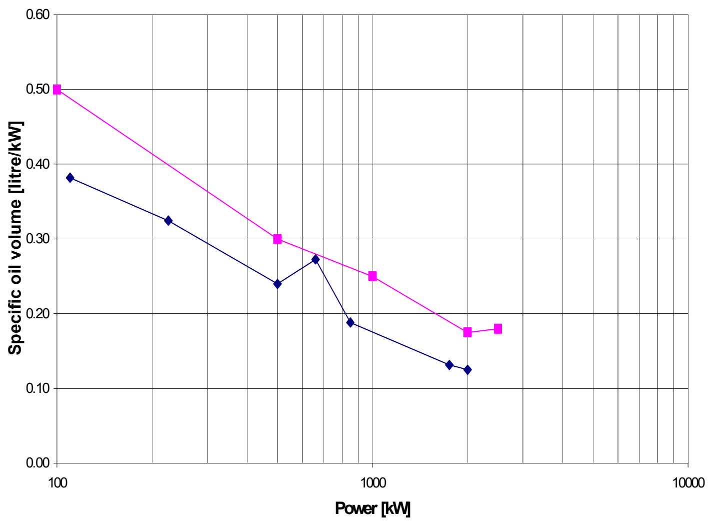


Figure 37: Specific oil volume of gearboxes. Estimated data from Brook Hansen Transmission and Lohmann & Solterfoht.

3 Power Electronic Concepts

Power electronics is a rapidly developing technology. Components are getting higher current and voltage ratings, the power losses decrease and the devices become more reliable. The devices are also very easy to control with a mega scale power amplification. The prices are still going down pr. kVA and power converters are becoming attractive as a mean to improve the performance of a wind turbine. This chapter will discuss the standard power converter topologies from the simplest converters for starting up the turbine to advanced power converter topologies, where the whole power is flowing through the converter. Further, different park solutions using power electronics are also discussed.

3.1 Criteria for concept evaluation

The most common topologies are selected and discussed in respect to advantages and drawbacks. Very advanced power converters, where many extra devices are necessary in order to get a proper operation, are omitted.

3.2 Power converters

Many different power converters can be used in wind turbine applications. In the case of using an induction generator, the power converter has to convert from a fixed voltage and frequency to a variable voltage and frequency. This may be implemented in many different ways, as it will be seen in the next section. Other generator types can demand other complex protection. However, the most used topology so far is a soft-starter, which is used during start up in order to limit the in-rush current and thereby reduce the disturbances to the grid.

3.2.1 Soft starter

The soft starter is a power converter, which has been introduced to fixed speed wind turbines to reduce the transient current during connection or disconnection of the generator to the grid. When the generator speed exceeds the synchronous speed, the soft-starter is connected. Using firing angle control of the thyristors in the soft starter the generator is smoothly connected to the grid over a predefined number of grid periods. An example of connection diagram for the soft-starter with a generator is presented in Figure 34.

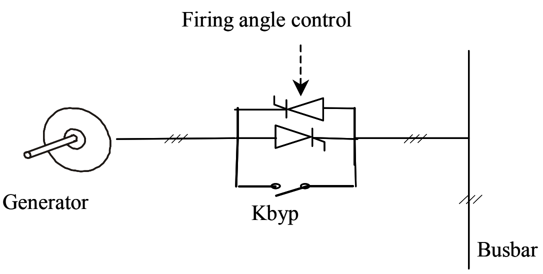


Figure 38. Connection diagram of soft starter with generators.

The commutating devices are two thyristors for each phase. These are connected in anti-parallel. The relationship between the firing angle (α) and the resulting amplification of the soft starter is non-linear and depends additionally on the power factor of the connected element. In the case of a resistive load, α may vary between 0 (full on) and 90 (full off) degrees, in the case of a purely inductive load between 90 (full on) and 180 (full off) degrees. For any power factor between 0 and 90 degrees, α will be somewhere between the limits sketched in Figure 39.

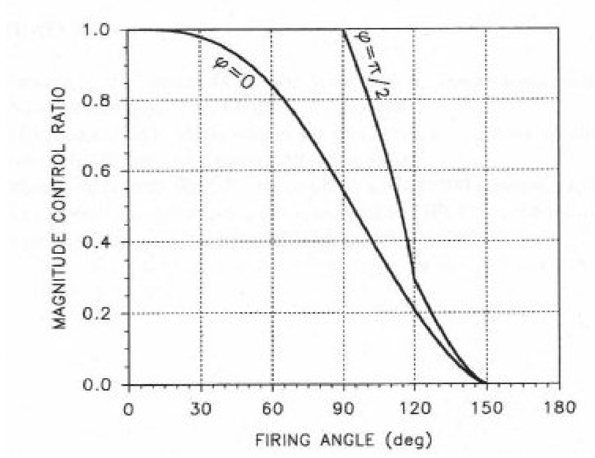


Figure 39. Control characteristic for a fully controlled soft starter.

When the generator is completely connected to the grid a contactor (Kbyp) bypass the soft-starter in order to reduce the losses during normal operation. The soft-starter is very cheap and it is a standard converter in many wind turbines.

3.2.2 Capacitor bank

For the power factor compensation of the reactive power in the generator, AC-capacitor banks are used, as shown in Figure 36. The generators are normally compensated into whole power range. The switching of capacitors is done as a function of the average value of measured reactive power during a certain period.

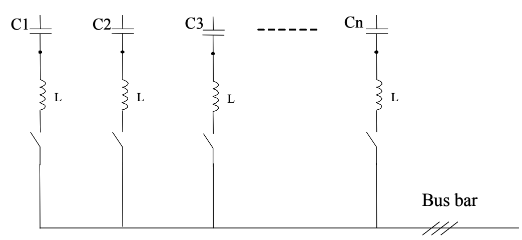


Figure 40. Capacitor bank configuration for power factor compensation in a wind turbine.

The capacitor banks are usually mounted in the bottom of the tower or in the nacelle. In order to reduce the current at connection/disconnection of capacitors a coil (L) can be connected in series. The capacitors may be heavy loaded and damaged in the case of over-voltages to the grid and thereby they may increase the maintenance cost.

3.2.3 Diode rectifier

The diode rectifier is the most common used topology in power electronic applications. For a three-phase system it consists of six diodes. It is shown in Figure 36a.

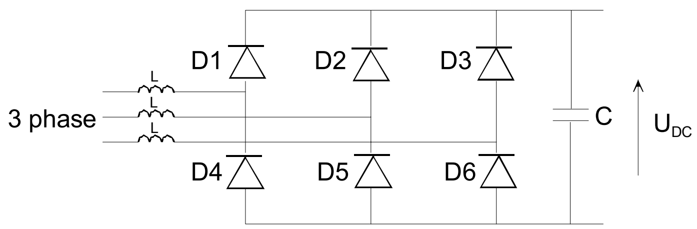


Figure 36a. Diode rectifier for three-phase ac/dc conversion

The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It could be used in some applications with a dc-bus.

3.2.4 The back-to-back PWM-VSI

The back-to-back PWM-VSI is a bi-directional power converter consisting of two conventional PWM-VSI. The topology is shown in Figure 41.

To achieve full control of the grid current, the DC-link voltage must be boosted to a level higher than the amplitude of the grid line-line voltage. The power flow of the grid side converter is controlled in order to keep the DC-link voltage constant, while the control of the generator side is set to suit the magnetization demand and the reference speed. The control of the back-to-back PWM-VSI in the wind turbine application is described in several papers (Bogalecka, 1993), (Knowles-Spittle et al., 1998), (Pena et al., 1996), (Yifan & Longya, 1992), (Yifan & Longya, 1995).

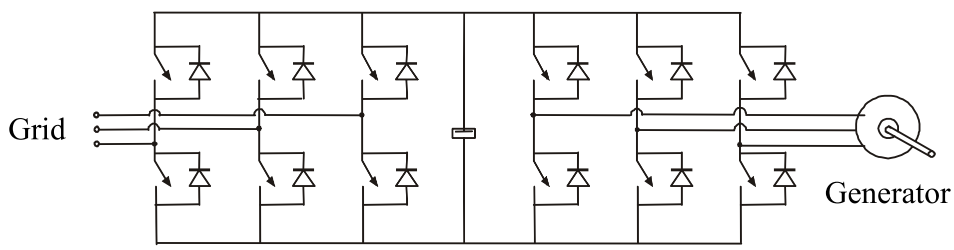


Figure 41. The back-to-back PWM-VSI converter topology.

3.2.4.1 Advantages related to the use of the back-to-back PWM-VSI

The PWM-VSI is the most frequently used three-phase frequency converter. As a consequence of this, the knowledge available in the field is extensive and well established. The literature and the available documentation exceed that for any of the other converters considered in this survey. Furthermore, many manufacturers produce components especially designed for use in this type of converter (e.g., a transistor-pack comprising six bridge coupled transistors and anti paralleled diodes). Due to this, the component costs can be low compared to converters requiring components designed for a niche production.

A technical advantage of the PWM-VSI is the capacitor decoupling between the grid inverter and the generator inverter. Besides affording some protection, this decoupling offers separate control of the two inverters, allowing compensation of asymmetry both on the generator side and on the grid side, independently.

The inclusion of a boost inductance in the DC-link circuit increases the component count, but a positive effect is that the boost inductance reduces the demands on the performance of the grid side harmonic filter, and offers some protection of the converter against abnormal conditions on the grid.

3.2.4.2 Disadvantages of applying the back-to-back PWM-VSI

This section highlights some of the reported disadvantages of the back-to-back PWM-VSI which justify the search for a more suitable alternative converter:

In several papers concerning adjustable speed drives, the presence of the DC-link capacitor is mentioned as a drawback, since it is heavy and bulky, it increases the costs and maybe of most importance, - it reduces the overall lifetime of the system. (Wen-Song & Ying-Yu, 1998); (Kim & Sul, 1993); (Siyoung Kim et al., 1998).

Another important drawback of the back-to-back PWM-VSI is the switching losses. Every commutation in both the grid inverter and the generator inverter between the upper and lower DC-link branch is associated with a hard switching and a natural commutation. Since the back-to-back PWM-VSI consists of two inverters, the switching losses might be even more pronounced. The high switching speed to the grid may also require extra EMI-filters.

To prevent high stresses on the generator insulation and to avoid bearing current problems (Salo & Tuusa, 1999), the voltage gradient may have to be limited by applying an output filter.

3.2.5 Tandem converter

The tandem converter is quite a new topology and a few papers only have treated it up till now ((Marques & Verdelho, 1998); (Trzynadlowski et al., 1998a); (Trzynadlowski et al., 1998b)). However, the idea behind the converter is similar to those presented in ((Zhang et al., 1998b)), where the PWM-VSI is used as an active harmonic filter to compensate harmonic distortion. The topology of the tandem converter is shown in Figure 42.

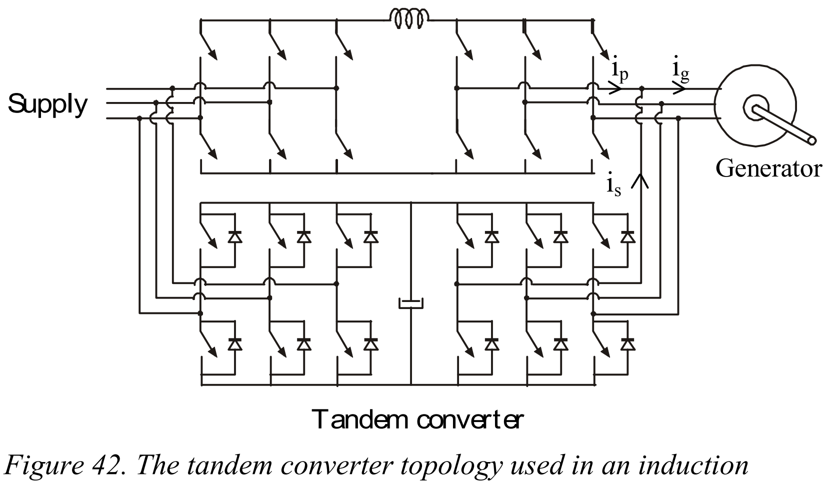


Figure 42. The tandem converter topology used in an induction generator wind turbine system.

The tandem converter consists of a current source converter, CSC, in the following designated the primary converter, and a back-to-back PWM-VSI, designated the secondary converter. Since the tandem converter consists of four controllable inverters, several degrees of freedom exist which enable sinusoidal input and sinusoidal output currents. However, in this context it is believed that the most advantageous control of the inverters is to control the primary converter to operate in square-wave current mode. Here, the switches in the CSC are turned on and off only once per fundamental period of the input- and output current respectively. In square wave current mode, the switches in the primary converter may either be GTO's, or a series connection of an IGBT and a diode.

Unlike the primary converter, the secondary converter has to operate at a high switching frequency, but the switched current is only a small fraction of the total load current. Figure 43 illustrates the current waveform for the primary converter, i_p, the secondary converter, i_s, and the total load current i_l.

In order to achieve full control of the current to/from the back-to-back PWM-VSI, the DC-link voltage is boosted to a level above the grid voltage. As mentioned, the control of the tandem converter is treated in only a few papers. However, the independent control of the CSC and the back-to-back PWM-VSI are both well established, (Mutschler & Meinhardt, 1998); (Nikolic & Jeftenic, 1998); (Salo & Tuusa, 1997); (Salo & Tuusa, 1999).

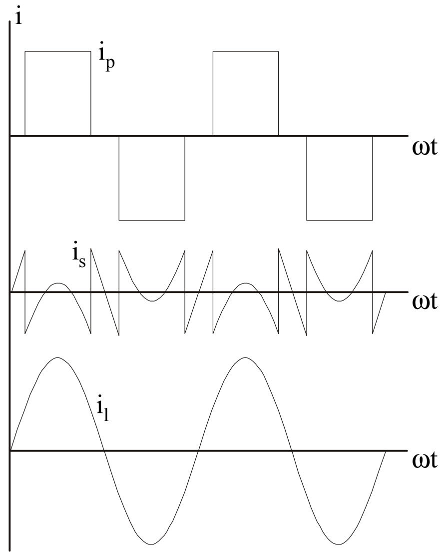


Figure 43. Current waveform for the primary converter, i_p, the secondary converter, is, and the total load current i_l.

3.2.5.1 Advantages in the use of the Tandem Converter

The investigation of new converter topologies is commonly justified by the search for higher converter efficiency. Advantages of the tandem converter are the low switching frequency of the primary converter, and the low level of the switched current in the secondary converter. It is stated that the switching losses of a tandem inverter may be reduced by 70%, (Trzynadlowski et al., 1998a) in comparison with those of an equivalent VSI, and even though the conduction losses are higher for the tandem converter, the overall converter efficiency may be increased.

Compared to the CSI, the voltage across the terminals of the tandem converter contains no voltage spikes since the DC-link capacitor of the secondary converter is always connected between each pair of input- and output lines (Trzynadlowski et al., 1998b).

Concerning the dynamic properties, (Trzynadlowski et al., 1998a) states that the overall performance of the tandem converter is superior to both the CSC and the VSI. This is because current magnitude commands are handled by the voltage source converter, while phase-shift current commands are handled by the current source converter (Zhang et al., 1998b).

Besides the main function, which is to compensate the current distortion introduced by the primary converter, the secondary converter may also act like an active resistor, providing damping of the primary inverter in light load conditions (Zhang et al., 1998b).

3.2.5.2 Disadvantages of using the Tandem Converter

An inherent obstacle to applying the tandem converter is the high number of components and sensors required. This increases the costs and complexity of both hardware and software. The complexity is justified by the redundancy of the system (Trzynadlowski et al., 1998a), however the system is only truly redundant if a reduction in power capability and performance is acceptable.

Since the voltage across the generator terminals is set by the secondary inverter, the voltage stresses at the converter are high. Therefore the demands on the output filter are comparable to those when applying the back-to-back PWM-VSI.

In the system shown in Figure 38, a problem for the tandem converter in comparison with the back-to-back PWM-VSI is the reduced generator voltage. By applying the CSI as the primary converter, only 0.866% of the grid voltage can be utilized. This means that the generator currents (and also the current through the switches) for the tandem converter must be higher in order to achieve the same power.

3.2.6 Matrix converter

Ideally, the matrix converter should be an all silicon solution with no passive components in the power circuit. The ideal conventional matrix converter topology is shown in Figure 44.

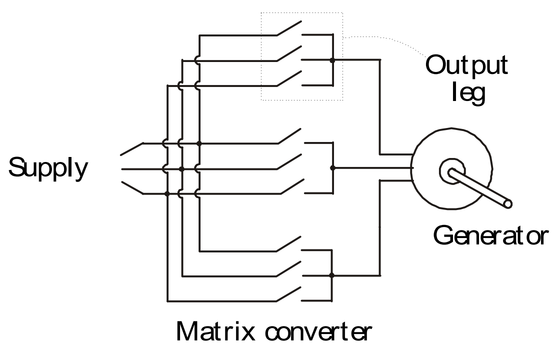


Figure 44. The conventional matrix converter topology.

The basic idea of the matrix converter is that a desired input current (to/from the supply), a desired output voltage and a desired output frequency may be obtained by properly connecting the output terminals of the converter to the input terminals of the converter. In order to protect the converter, the following two control rules must be complied with: Two (or three) switches in an output leg are never allowed to be on at the same time. All of the three output phases must be connected to an input phase at any instant of time. The actual combination of the switches depends on the modulation strategy.

3.2.6.1 Advantages of using the Matrix Converter

This section summarises some of the advantages of using the matrix converter in the control of an induction wind turbine generator.

For a low output frequency of the converter the thermal stresses of the semiconductors in a conventional inverter are higher than those in a matrix converter. This arises from the fact that the semiconductors in a matrix converter are equally stressed, at least during every period of the grid voltage, while the period for the conventional inverter equals the output frequency. This reduces the thermal design problems for the matrix converter.

Although the matrix converter includes six additional power switches compared to the back-to-back PWM-VSI, the absence of the DC-link capacitor may increase the efficiency and the lifetime for the converter (Schuster, 1998).

Depending on the realization of the bi-directional switches, the switching losses of the matrix inverter may be less than those of the PWM-VSI, because the half of the switchings become natural commutations (soft switchings) (Wheeler & Grant, 1993).

Compared to converters with constant DC-link voltage and only two output levels, the output harmonic content of the matrix converter is lower, due to the fact that the output voltage of the matrix converter is composed of three voltage levels.

3.2.6.2 Disadvantages and problems of the matrix converter

A disadvantage of the matrix converter is the intrinsic limitation of the output voltage. Without entering the over-modulation range, the maximum output voltage of the matrix converter is 0.866 times the input voltage. To achieve the same output power as the back-to-back PWM-VSI, the output current of the matrix converter has to be 1.15 times higher, giving rise to higher conducting losses in the converter (Wheeler & Grant, 1993).

In many of the papers concerning the matrix converter, the unavailability of a true bi-directional switch is mentioned as one of the major obstacles for the propagation of the matrix converter. In the literature, three proposals for realizing a bi-directional switch exists. The diode embedded switch (Neft & Schauder, 1988) which acts like a true bi-directional switch, the common emitter switch and the common collector switch (Beasant et al., 1989). The latter two are able to control the current direction, which is preferable in the phase commutations.

Since real switches do not have infinitesimal switching times (which is not desirable either) the commutation between two input phases constitutes a contradiction between the two basic control rules of the matrix converter. In the literature at least six different commutation strategies are reported, (Beasant et al., 1990); (Burany, 1989); (Jung & Gyu, 1991); (Hey et al., 1995); (Kwon et al., 1998); (Neft & Schauder, 1988). The most simple of the commutation strategies are those reported in (Beasant et al., 1990) and (Neft & Schauder, 1988), but neither of these strategies complies with the basic control rules. The most used commutation strategies are those reported in (Burany, 1989) and (Kwon et al., 1998). In either of (Burany, 1989) or (Kwon et al., 1998), half of the switchings become soft switchings, thereby reducing the switching losses. The solutions in (Jung & Gyu, 1991) and (Hey et al., 1995) require a more complex hardware structure of the converter.

Due to the absence of the DC-link, there is no decoupling between the input and output of the converter. In ideal terms, this is not a problem but in the case of unbalanced or distorted input voltages, or unbalanced load, the input current and the output voltage also become distorted. Several papers have dealt with the problems of unbalanced input voltages and various solutions have been proposed (Casadei et al., 1994); (Casadei et al., 1995a); (Casadei et al., 1995b); (Casadei et al., 1996); (Enjeti & Wang, 1990); (Nielsen, 1996); (Nielsen et al., 1996); (Oyama et al., 1997); (Zhang et al., 1998a). Each of the solutions has superiorities and drawbacks, and the choice of solution depends on which performance indicator has the highest priority (input disturbance, line losses, controllability of the input power factor etc.).

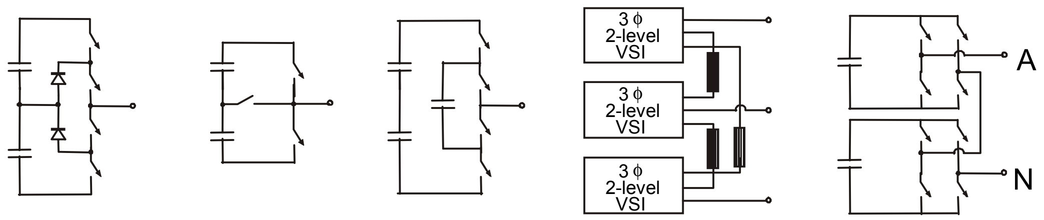
Finally, the protection of the matrix converter in a fault situation presents a problem. The protection of the matrix converter is treated in (Nielsen, 1996). This protection circuit adds an extra 12 diodes and a DC-link capacitor to the component list, although these components are rated much smaller than the components in the power part of the matrix converter.

3.2.7 Multilevel Converter

Since the development of the neutral-point clamped three-level converter (Nabae et al., 1981), several alternative multilevel converter topologies have been reported in the literature. The general idea behind the multilevel converter technology is to create a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The different proposed multilevel converter topologies can be classified in the following five categories (Lai & Peng, 1996); (Lai & Peng, 1995); (Manjrekar & Venkataramanan, 1996); (Marchesoni & Mazzucchelli, 1993); (Suh et al., 1998):

- Multilevel configurations with diode clamps (Nam et al., 1991); (Sun-Kyoung Lim et al., 1999); (Nabae et al., 1981); (Lixiang & Fahai, 1999).
- Multilevel configurations with bi-directional switch interconnection (Brumsickle et al., 1998); (Nabae et al., 1981).
- Multilevel configurations with flying capacitors (Xiaoming et al., 1999).
- Multilevel configurations with multiple three-phase inverters (Cengelci et al., 1998).
- Multilevel configurations with cascaded single phase H-bridge inverters (Peng et al., 1997).

A common feature of the five different multilevel converter concepts is, that in theory, all the topologies may be constructed to have an arbitrary number of voltage levels, although in practice some topologies are easier to realize than others. The principle of the five topologies is illustrated in Figure 45.



(a) (b) (c) (d) (e)

Figure 45. Multilevel topologies. a) One inverter leg of a three-level diode clamped multilevel converter. b) One inverter leg of a three-level multilevel converter with bi-directional switch interconnection. c) One inverter leg of a three level flying capacitor multilevel converter. d) Schematic presentation of a three-level converter consisting of three three-phase inverters. e) One inverter leg of a three-level converter consisting of H-bridge inverters.

Below is a brief comment on the different multi-level converter topologies:

a) Despite the more complex structure, the diode clamped multilevel converter is very similar to the well known back-to-back PWM-VSI. Unlike the multilevel topologies shown in Figure 45d and Figure 45e, the diode clamped multilevel converter may be coupled directly to the grid without transformers. For a converter based on the diode clamped multilevel converter a voltage-balancing problem occurs for levels higher than three, but for a three level converter this is only a minor problem.

b) For a three level structure, the topology of the multilevel converter with bi-directional switch interconnection requires the same number of switches as the diode clamped three-level converter and the three-level flying capacitor converter. However, half of the switches have to block the full DC-link voltage.

c) The topology of the flying capacitor multilevel converter is very similar to that of the diode clamped multilevel converter shown in Figure 45a. In the literature it is stated, that the voltage-balancing problem is relatively easy to solve, compared to the diode clamped converter. The difference in component count between the diode clamped multilevel converter and the flying capacitor multilevel converter is, that two diodes per phase may be substituted by one capacitor.

d) The number of switches (and other components) required realizing a three level converter is very high compared to the concepts a-c, but the converter can be realized from the well-proven VSI technology.

e) The multilevel converter based on multiple H-bridge inverters is heavy, bulky and complex (Nam et al., 1991), and maybe of most importance, - connecting separated DC-sources between two converters in a back-to-back fashion is very difficult because a short circuit will occur when two back-to-back converters are not switching synchronously (Lai & Peng, 1996), (Suh et al., 1998).

3.2.7.1 Advantages in the use of the multilevel converter

Initially, the main purpose of the multilevel converter was to achieve a higher voltage capability of the converters. As the ratings of the components increases and the switching- and conducting properties improve, the secondary effects of applying multilevel converters become more and more advantageous. In recent papers, the reduced content of harmonics in the input and output voltage is highlighted, together with the reduced EMI (Tolbert & Peng, 1999). The multilevel converter distinguishes itself by being that converter in this survey with the lowest demands to the input filters. (or alternatively reduced number of switchings) (Rodriguez et al., 1999).

The switching losses of the multilevel converter are another feature, which is often accentuated. In (Marchesoni & Mazzucchelli, 1993), it is stated, that for the same harmonic performance the switching frequency can be reduced to 25% of the switching frequency of a two-level converter. Even though the conducting losses are higher for the multilevel converter, it is stated in (Tolbert & Peng, 1999) that the overall efficiency for the diode clamped multilevel converter is higher than the efficiency for a comparable two-level converter. Of course, the truth in this assertion depends on the ratio between the switching losses and the conducting losses.

3.2.7.2 Disadvantages concerning the multilevel converter

The most commonly reported disadvantage of the three level converters with split DC-link is the voltage imbalance between the upper and the lower DC-link capacitor. However, for a three-level converter this problem is not very serious, and the problem in the three-level converter is mainly caused by differences in the real capacitance of each capacitor, inaccuracies in the dead-time implementation or an unbalanced load (Shen & Butterworth, 1997). By a proper modulation control of the switches, the imbalance problem can be solved (Sun-Kyoung Lim et al., 1999). In (Shen & Butterworth, 1997), the voltage balancing problem is solved by hardware, while (Newton & Sumner, 1997) and (Peng et al., 1995) proposed solutions based on modulation control. However, whether the voltage-balancing problem is solved by hardware or software, it is necessary to measure the voltage across the capacitors in the DC-link.

For converters based on the topology in Figure 45a to Figure 45c, another problem is the unequal current stress on the semiconductors. It appears that the upper and lower switches in an inverter branch might be derated compared to the switches in the middle. For an appropriate design of the converter, different devices are required (Lai & Peng, 1996). For the topology in Figure 45b it appears that both the unequal current stress and the unequal voltage stress might constitute a design problem.

From the topologies in Figure 45, it is evident that the number of semiconductors in the conducting path is higher than for the other converters treated in this survey, this might increase the conduction losses of the converter. On the other hand, each of the semiconductors need only block half the total DC-link voltage and for lower voltage ratings, the on-state losses per switch decreases, which to a certain extent might justify the higher number of semiconductors in the conducting path.

3.2.8 Resonant converter

In the efforts towards reducing the switching losses in power converters, several resonant converter topologies have been proposed. A common drawback of these converter topologies is that they suffer from one or more of the following properties.

- Complex hardware structure and complex control.
- High peak voltage in the DC-link and across the load.
- High power flow through the resonant circuit.

The only resonant converter treated in this section is a topology, which does not suffer from the disadvantages mentioned above. The converter topology is termed *Natural Clamped Converter* (NCC). The NCC topology is shown in Figure 46.

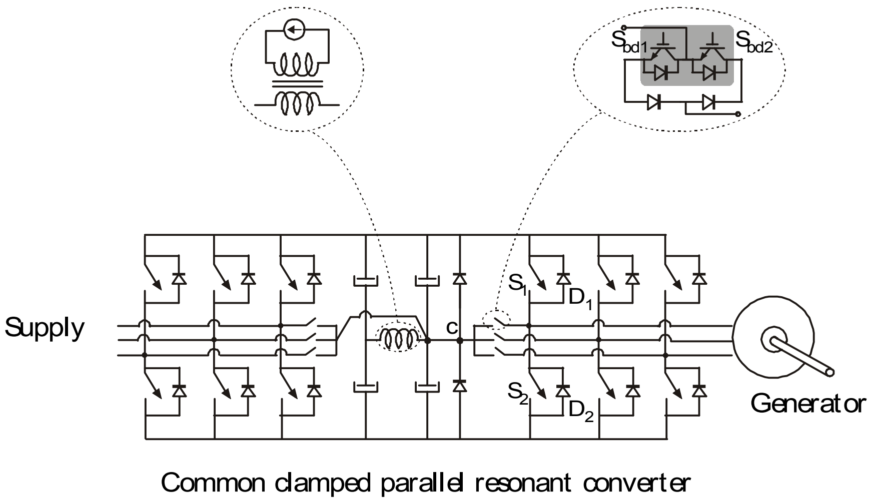


Figure 46. The natural clamped converter topology used in the induction generator wind turbine system.

The NCC consists of the conventional back-to-back PWM-VSI and in addition a circuit to obtain the resonance. To start and to maintain the resonance an inductive energy transfer is used. In order to control the current to/from the supply grid, the DC-link voltage is boosted. Like for the back-to-back PWM-VSI, it is assumed that the voltage is boosted to 800 V. In Figure 46, the boost inductances are shown as a part of the line filter. The used switches in the resonance circuit are bi-directional switches and as in the case of the matrix converter, these have to be built from several discrete devices. The bi-directional switch shown in Figure 46 is made from a standard two-pack transistor module and additional two diodes, but may as well be constructed as a common-emitter, a common-collector or a diode-embedded switch.

3.2.8.1 The commutation process for the NCC.

To explain the operating mode of the NCC, assume that the load current is flowing through diode D_2, resulting from a positive load current. At a given time, the controller demands turn off of S_2. To achieve the commutation, both switches S_{bd1} and S_{bd2} in the bi-directional switch are first turned on when the voltage at point c is equal to $u_{DC}/2$. Then S_2 is turned off at zero voltage (and zero current because D_2 was conducting). During the following half period of the resonance, the load current is supplied through S_{bd1} and the voltage across S_1 decreases. When the voltage at point c reaches $u_{DC}/2$, the voltage across S_1 is zero. Then, first S_{bd2} is turned off, then S_1 is turned on and finally S_{bd1} may be turned off. The commutation process is depicted in Figure 47.

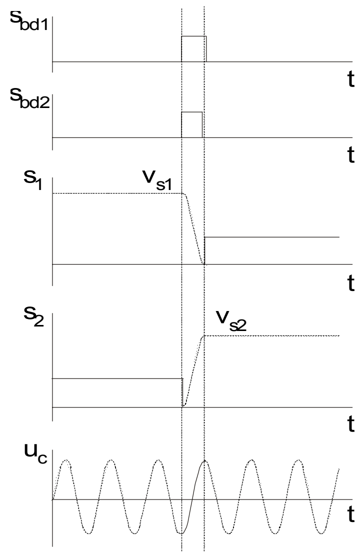


Figure 47. Illustration of the commutation procedure for the NCC.

The NCC is suitable both for discrete pulse modulation (DPM), and pulse width modulation (PWM). Both techniques are described in several papers concerning different resonant converters and a brief survey is given in (Munk-Nielsen, 1997).

3.2.8.2 Advantages in the use of the NCC

Compared to other resonant converters, the NCC possesses the advantageous properties of the different resonant converters while the unsuitable properties are avoided. The advantageous properties of the NCC are: the resonant voltage is clamped and never exceeds the DC-link voltage, the resonant circuit is not in the power part of the converter, and only one resonant circuit is needed for the entire converter.

By inspection of the topology of Figure 46, it appears that the NCC also supports three level operations. This implies however, that the bi-directional switches must be rated for a higher power level. In comparison with the back-to-back PWM-VSI, the main advantage of the NCC is the reduced switching losses, which in applications where the switching losses dominate might increase the overall converter efficiency. Furthermore, due to the lower du/dt, the radiated EMI is reduced, and the demands to the output filter inductance might be reduced. The conduction losses of the NCC are similar to those of the back-to-back PWM-VSI.

The modulation of the NCC may be either PWM or DPM (Direct Pulse Modulation). It may also be possible to use a different modulation strategy in the machine inverter and in the grid inverter. The use of DPM makes the response of the converter very fast, while the use of PWM more or less gives a harmonic spectrum comparable to that of a back-to-back PWM-VSI.

3.2.8.3 Disadvantages of the NCC

Although the complexity is less than the pole commutated resonant converter (Pickert & Johnson, 1998); (Teichmann & Bernet, 1998), the converter is still more complex (hardware and control) than the back-to-back PWM-VSI and several additional components are needed. Furthermore sensors are needed to detect the zero voltage events and to determine the energy needed to maintain the resonance.

As mentioned above, the use of the DPM technique yields fast response time, but a consequence of the DPM is that the switching harmonics are distributed over a broader spectrum (Dehmlow et al., 1993). The broad switching harmonic spectrum makes the grid filter design procedure a quite difficult task since the harmonics may coincide with the resonant frequency of the filters. However, this increases the complexity of the converter.

The voltage imbalance of the two main capacitors may constitute a problem for the NCC. For every commutation, only one of the main capacitors is discharged. In the case of asymmetrical commutations due to small differences in the switch characteristics, the voltage unbalance has to be compensated actively.

3.2.9 Comparison of the five frequency converters

The five converters presented above: the back-to-back PWM VSI, the tandem converter, the matrix converter, the multilevel converter and the NCC, may be evaluated in terms of their applicability to wind turbine systems. For each converter, a presentation of the topology and the working principles has been presented, combined with a discussion of advantages and disadvantages.

It is evident that the back-to-back converter is highly relevant, as this converter is the one used in wind turbines today. Therefore, this converter type may be used as a reference in a benchmark of the other converter topologies:

- <u>Components and ratings.</u> Considering the number of used components, the matrix converter differs from the other converters, because it consists only of active components in the power part. The back-to-back converter includes a moderate number of passive components, while it has the least number of active components. The latter three converters all include a high number of both active and passive components.
- <u>Auxiliary components.</u> Two converters distinguish themselves, namely the matrix converter and the multilevel converter. The main reason for this statement is that in both the transformer may be omitted, without requiring excessively high voltage ratings for the components. On the other hand, the tandem converter and the NCC both require a greater number of transducers than the other three converters.
- <u>Efficiency.</u> Assessment of the efficiency of the five converters is based on the literature and includes the reported conducting losses and switching losses. The NCC is assessed to have potentially the highest efficiency of the five converters – followed by the multilevel converter and the tandem converter.
- <u>Harmonic performance.</u> Considering the harmonic performance, and the requirements for filters, the multilevel converter shows the best spectra on both the grid side and the generator side. The only converter that really seems to constitute a problem for the filter design is the DPM modulated NCC. Due to a broad switching spectrum, the filter design may be complicated.

- Implementation. Because the back-to-back converter and the multilevel converter are the most used commercial converters of the five, it is believed that these two converters are the least troublesome converters to implement, while the three latter all are quite undiscovered in a commercial sense.

Summarising the findings on the converters presented it is concluded that the back-to-back converter, the matrix converter and the multilevel converter are to be recommended for further studies in different generator topologies.

3.3 Park solutions

Wind power installations with blade angle control and/or power converters are able to control the active power supply to the power system. Moreover, wind power installations with power converters are able also to control the reactive power supply to the power system. The active power control in these wind power installations normally serve to obtain maximum production, and limit the power to avoid only overloading and stress of the wind turbine components, whereas the reactive power control serves to obtain a constant, high power factor, e.g. at unity.

Other types of active control of power plants in the power system contribute to the frequency control by regulation of the active power, and to the voltage control by regulation of the reactive power. Such control capabilities can also be obtained in wind power installations fitted with power converters, but have only been practised in a few cases. The main reason for this is caution because the impact on the stability of the power system becomes a concern when thousands of wind turbines were to regulate the voltage on the local terminals independently. However, in the future such performance is expected from the parks.

For power systems with a large amount of wind energy, the ability of the wind power installations to contribute to the regulation of the voltage and frequency of the power system becomes an important issue, because it influences the ability of the wind power installations to replace other power plants strongly. Thus, both the capacity credit of the wind power installation and the fuel savings at other power plants are influenced by the control capabilities of the wind power installations.

To provide the wind power installations with power system control capabilities and to improve the influence on the power system stability, central power electronic units in large wind farms are a promising technical solution. Central units may be connected to the power system at the wind farm connection point, and consequently could contribute to the control of the voltage and frequency at that point. In this respect, wind farms with central power electronic units can act more like a regular power plant. Also, the application of central units is likely to be the most cost effective way to provide control capabilities for large wind farms.

3.3.1 Reactive power compensation units

Reactive power compensation units are widely used in power systems to provide the reactive power balance and improve the voltage stability. These compensation units are used to supply both inductive and capacitive power. Typically, capacitive power is supplied to compensate for reactive loads while inductive power is supplied to compensate for capacitive consumption in cables.

The most used units to compensate for reactive power in the power systems are either synchronous condensers or shunt capacitors, the latter either with mechanical switches or with thyristor switches, as in Static Var Compensators (SVC). The disadvantage of using shunt capacitors is that the reactive power supplied is proportional to the square of the voltage. Consequently, the reactive power supplied from the capacitors decreases rapidly when the voltage decreases. The reactive power is needed to maintain voltage stability.

STATCOMs or ASVCs are inverters based on forced-commutated switches, i.e. with full, continuous control of the reactive power. The maximum available reactive power from a STATCOM is proportional to the voltage, and consequently the available maximum reactive power decreases more slowly for STATCOMs than SVCs, when the voltage decreases.

The transmission system operator ELTRA in the western half of Denmark has installed a 2×4 MVA ASVC (Stöber et al., 1998) on the 24 MW wind farm at Rejsby Hede, to demonstrate and test this concept. The Rejsby Hede wind farm consists of forty, 600 kW, NEG-Micon wind turbines with directly connected induction generators. The no-load consumption of reactive power in the induction generators is compensated by shunt capacitors on the 700 V level, in the individual wind turbines.

The ASVC at Rejsby Hede compensates for the load-dependent reactive power consumption in the wind farm by a fast, continuous reactive power regulation at the wind farm connection point. Thus, the ASVC runs in the power factor control mode, i.e. controls the power factor to be unity at the wind farm connection point.

The ASVC may in principle also run in a voltage regulation mode, i.e. participate in the voltage regulation on the grid. However, the grid is very strong at the wind farm connection point of the Rejsby Hede wind farm. Therefore, the ASVC has not been designed to participate in the voltage regulation, and it has also not been tested in that mode.

Further issues on these compensation units may be found in Table 10 and Table 11 in the next section.

3.3.2 Power regulation and storage units

The normal power regulation strategy of a wind turbine is designed to combine optimisation of operation and limitation of the power to protect the wind turbine. Overall wind farm regulation of the power to meet the requirements of the grid is not so common, but some examples of voltage dependent power regulation are known. At Cronalaght wind farm in Ireland (Bindner, 1999a), the blade angle control is used to limit the power. At Bockstigen wind farm in Sweden, dump loads and disconnection of wind turbines are used (Lange et al., 1999) as control options.

When wind energy penetration in the power system becomes high, the use of storage units becomes interesting, because the limitation of power required by the power system may lead to substantial loss of available energy from the wind turbines. At the same time, storage units may ensure power delivery from the wind farm, even when the wind speed is low. Consequently, storage units can provide large wind farms with power regulation capabilities, which can enable wind farms to replace, and not just to supplement, other power plants. Besides a capacity reduction of other power plants, such regulation capabilities may further reduce the requirement for spinning reserve and thus reduce the total fuel costs in the power system. Therefore, the development of storage technologies is very important to the development of wind energy.

When the natural resources are available, pumped storage may be competitive to grid reinforcement today (Bindner, 1999b). However, in many places, pumped storage is not an option. Therefore, the development of batteries, fuel cells and other storage technologies is very important. The main drawback of batteries today is the relatively high cost. An additional cost item for battery storage systems is the conversion from the AC grid to a DC. That cost could be avoided if the batteries were connected to an existing DC voltage, e.g. the DC link in an ASVC, or an HVDC transmission.

3.3.3 HVDC

One of the most widely discussed concepts for grid connection of large (offshore) wind farms is HVDC. This is due to a combination of the rapid development of this technology and the advantages that this technology can give for system operation as well as wind turbine operation.

An HVDC link consists of a minimum of two AC/DC converter stations and a DC cable to link the stations. The latest semiconductor technology development, combined with advanced control of series connected semiconductors has provided modern HVDC transmission systems, like ABBs HVDC Light, with fully controllable converters, based on forced commutated semiconductors.

HVDC technologies are mainly interesting for power transmission over longer distances. The DC cable is less expensive than an AC transmission cable with the same capacity, but the costs of the converter stations make the complete HVDC link more expensive than the corresponding AC link, if the transmission distance is below a certain threshold. The exact threshold distance for HVDC Light today is not public because of commercial interests (Asplund, 2000), but it is very long. Still, the threshold distance is expected to decrease rapidly with the technology development of power electronics, which reduces the cost of the converter stations.

For offshore applications, HVDC links may also be viable when the critical cable length for AC transmission is reached. In that case, a compensation unit is required on the AC transmission system, which is also very costly in the case of offshore transmission.

The world's first HVDC Light installation is operating today on Gotland. It was installed to increase the transmission capacity from the many wind turbines installed in the south of the island to the consumers in the town in the north of the island (Castro, 2000). At the same time, it serves to feed reactive power into the AC grid, particularly to the wind turbines in the south, and to ensure voltage stability. ELTRA has also installed an HVDC Light connection in Tjæreborg to test the use of it for large wind turbines. This is because HVDC Light is a candidate for connection to some of the large offshore wind farms, which are targets in "Energi 21", the Danish government action plan for energy.

Because of the advantages for the power system, HVDC Light will probably be installed for transmission of power over long distance from a number of large wind farms, both offshore and on land. This will open up new possibilities for variable speed control of wind turbines, because the frequency (or frequencies) of the grid(s) at the wind turbines can be controlled independently of the power system frequency.

The simplest HVDC Light configuration for connection of a wind farm is the group connection shown in Figure 48. The HVDC link is connected to the power system in one end and to the wind farm AC grid in the other end.

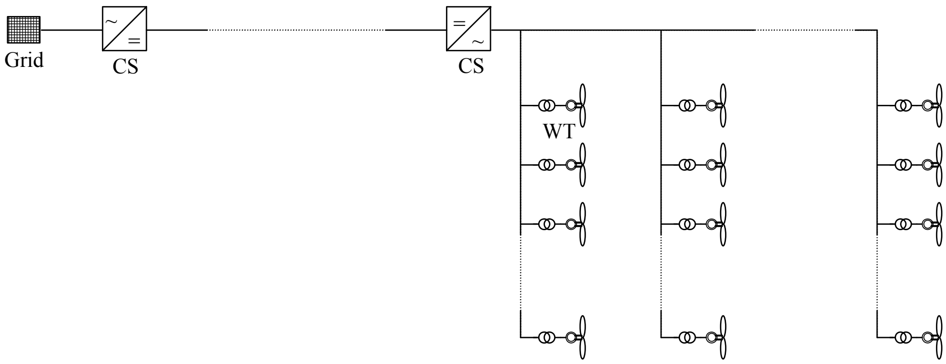


Figure 48. Group connection of a wind farm to an HVDC link.

In principle, all wind turbines designed for connection to AC grid may be connected to the wind farm AC grid in Figure 48, but many of the advantages in using power converters in the wind turbines are reduced. It is therefore most obvious to use wind turbines with directly connected induction generators. With such a concept, the converter at the wind farm will supply the wind turbines with reactive power, and in that way make the wind farm grid more robust to grid faults.

HVDC connection also makes it possible to control the frequency of the wind farm grid in order to improve the aerodynamic efficiency in the same way as for wind turbines with individual power converters. The frequency control must set the frequency as a compromise between the optimum frequency for all the individual wind turbines in the wind farm, because the wind speed and consequently the optimum frequency is different from wind turbine to wind turbine. Therefore, the aerodynamic efficiency is reduced slightly compared to wind turbines with individual power converters.

Another aspect of the group connection concept, which is probably more important is that the common frequency control cannot be used to reduce mechanical loads on the drive train like individual power converters in the wind turbines can. This is important for stall controlled wind turbines and in particular for pitch controlled wind turbines where it may be necessary to have additional speed control of the individual wind turbine, e.g. Optislip.

Another configuration, which appears to have all the technical advantages of wind turbines with individual power converters is shown in Figure 49. The wind turbines are provided with their own AC/DC converter.

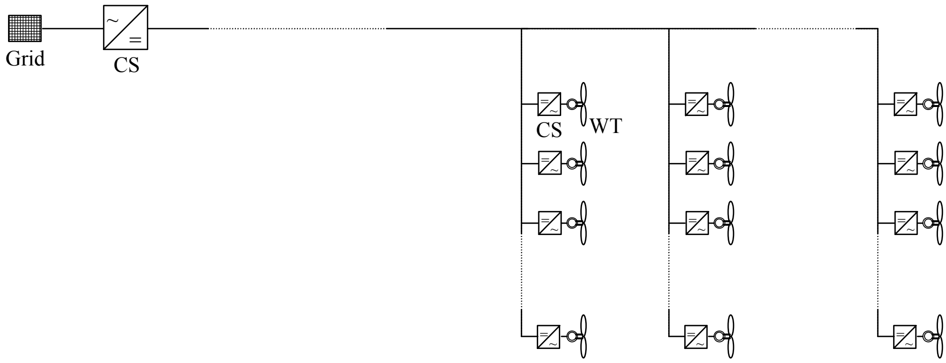


Figure 49. Individual connection of wind turbines to HVDC link.

If the AC/DC converters in the individual wind turbines are based on forced-commutated semiconductors, the frequency and consequently the speed of the wind turbines can be controlled individually. In that case, the frequency control may be used to reduce mechanical loads on the drive train, effectively using the rotor moment of inertia to absorb the fastest fluctuations in the aerodynamic loads.

ABB has proposed a new Windformer concept with individual AC/DC converters as shown in Figure 49, but using diode rectifiers in the converters (Nielsen, 2000). The generators are of synchronous type, because they must provide the magnetic field themselves. ABB proposes a multipole (gearless), high voltage permanent magnet generator, which can be connected directly to the rectifier without a transformer. The wind turbine in the Windformer concept will be pitch controlled.

The Windformer concept removes the ability to use the frequency control to reduce mechanical loads on the drive trains, because the speed control is based on control of the DC voltage at the converter at the power system connection point, which is common for all the wind turbines. The mechanical drive train loads are, however, not so critical for the Windformer concept, because the wind turbines are gearless.

A more critical aspect of the Windformer concept is whether it will be stable with the required blade pitch angles. Both the steady state stability and the dynamic stability must be studied. The system is very complicated, with speed dependent aerodynamic loads and generator AC impedances in the individual wind turbines, and only one common DC voltage, which must be controlled with compromise between all the wind turbines.

3.4 Trends and perspectives

As in Section 2, this final subsection is dedicated to a discussion on trends and perspectives. The rapid development of power electronics, as described in e.g. (Thøgersen & Blaabjerg, 2000), is already reflected in commercial converters. The present situation for two types of converters regarding specific weight and normalised specific price (per unit price) are illustrated in Figure 50 and Figure 51, respectively. The depicted data are related to back-to-back PWM VSI converters using a vector control strategy. The low voltage converters are air cooled, while the medium voltage converters are water-cooled. Again, the origin of data from the ABB or Siemens has not been specified, since the purpose of Figure 50 and Figure 51 is to indicate trends rather than to benchmark products from these companies.

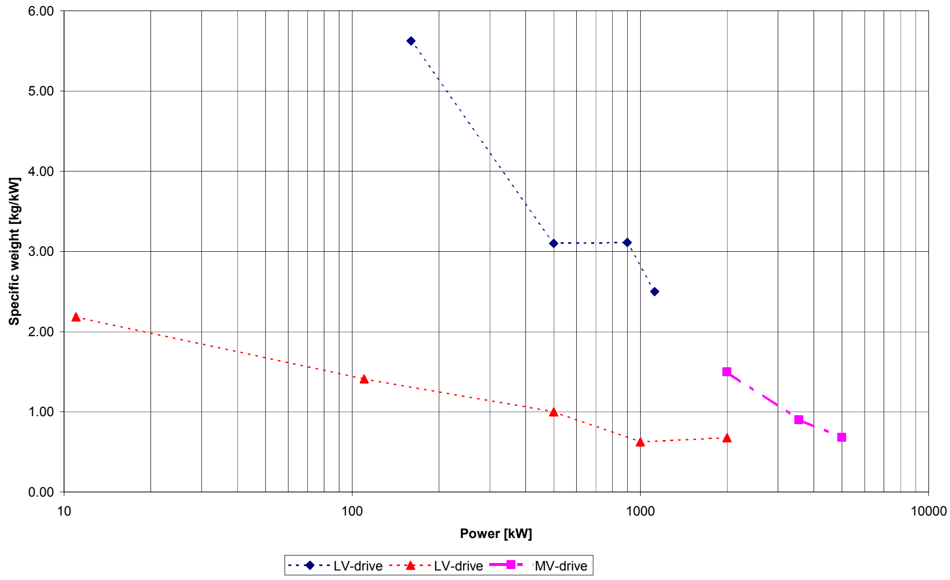


Figure 50. Specific weight of LV and MV converters. Estimated data supplied by ABB and Siemens.

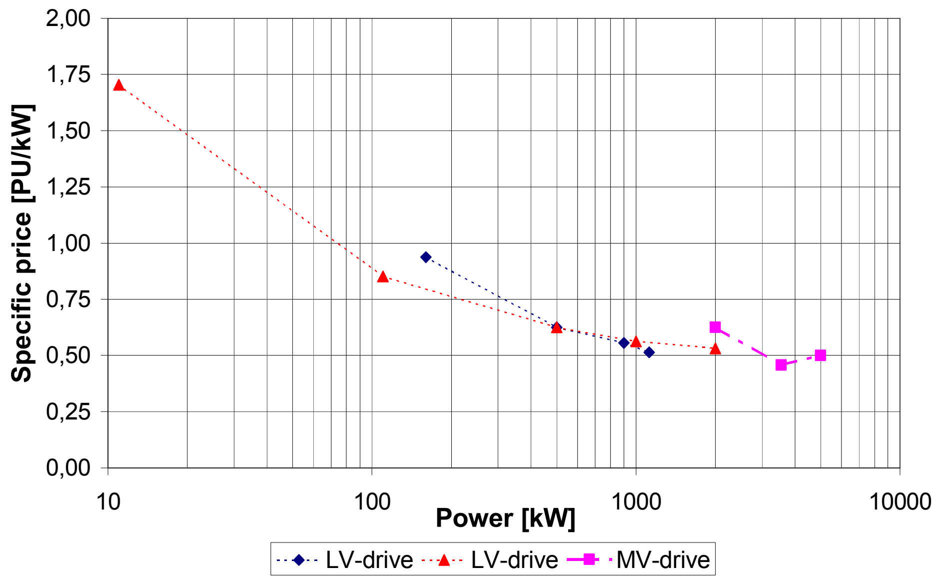


Figure 51. Specific price of LV and MV converters. Estimated data supplied by ABB and Siemens.

In Figure 50, the specific weight of the LV-converters indicates two different implementations, while Figure 51 states that this is not important for the price. The specific weight of the converters in the Megawatt range is approximately half the specific weight of the generators presented in section 2 – and still decreasing. Meanwhile, the specific price of the converters in this area is only twice the specific price of the generators presented.

4 Grid Integration Issues

This section describes the grid integration issues. The first part of this section is generic grid issues. The second part is mainly concerned with the influence of wind turbines on the power quality of the grid. Moreover, power equipment to enhance or control power quality is discussed. The third part presents different types of grids. Each of these standardised grids defines a number of demands and characteristics for a specific wind turbine design. Therefore, each grid presents different market demands. The last part of the chapter focus on integration issues on large amounts of wind power in the power system.

4.1 Grid Generics and Main Focus

A power supply system consists of three main components: 1) power generation units, 2) a grid and 3) loads, which are the customers. The primary aim of a power supply system is to meet the demands for energy imposed by the customers. The function of the grid depends on the size of the power supply system. If the amount of generated, distributed and consumed energy is of considerable size, the grid is divided in a transmission grid (high voltage) and a distribution network (medium and low voltage).

The activities related to "large", deregulated, power supply systems, i.e. generation, transmission and distribution, are in general widely different. Therefore, these activities are (or may be) covered by different supply organisations, e.g. power generation companies, transmission system operators and distribution system operators. The function of the transmission grid is to transmit energy from large power generation plants to the distribution networks, whereas the distribution networks distribute the energy from the transmission grid or from small/local power generation plants to the customers. The main objective of the power generator companies is to produce power at a cost efficient price. Meanwhile the two other organisations have a number of objectives to pursue, which may be summarised by the following goals: to achieve an acceptable level of reliability, quality and safety for the power supply at an economic price – since the price a customer has to pay is determined by the costs of the associated generation, transmission and distribution. Moreover, the transmission system operators are responsible for the overall energy production planning in their own area.

To be able to fulfil the objectives of reliability, quality and safety for the power supply at an economic price, the system operator of the transmission grid has to attend to a number of tasks, e.g.:

- To form and specify Power Station Specifications.
- To plan further development of the transmission grid.
- To contribute to optimal allocation of resources, including balancing of the requirements on various types of plants.
- To ensure the properties essential for the power system operation as regards reliability, power quality and security of supply in the short term as well as in the long run.

On a distribution network level, the same tasks are valid for the system operator of the distribution network.

The key issues for the last task are: power system control and power system specifications. The purpose of power system specifications is to ensure certain abilities and characteristics in the power input for use in the operation and control of the power system. In this way, it becomes possible to operate and control the power system under various load conditions and disturbances. Thus, the main control aspects are power system stability and power quality.

In the rest of the report, focus will be on power quality. Other important issues, which will not be discussed, are various economic items.

4.2 Power Quality and other Demands to Grid Connection

The used term 'Power Quality' is usually considered to include two aspects of power supply, namely Voltage Quality and Supply Reliability (CIGRE WG14-31, 1999). The Voltage Quality part includes different disturbances such as: rapid changes, harmonics, interharmonics, flicker, unbalance and transients, whereas the reliability part involves phenomena with a longer duration, like interruptions, voltage dips and sags, over and under voltages and frequency deviations. Figure 52 gives a simplified view of the characterisation of Power Quality.

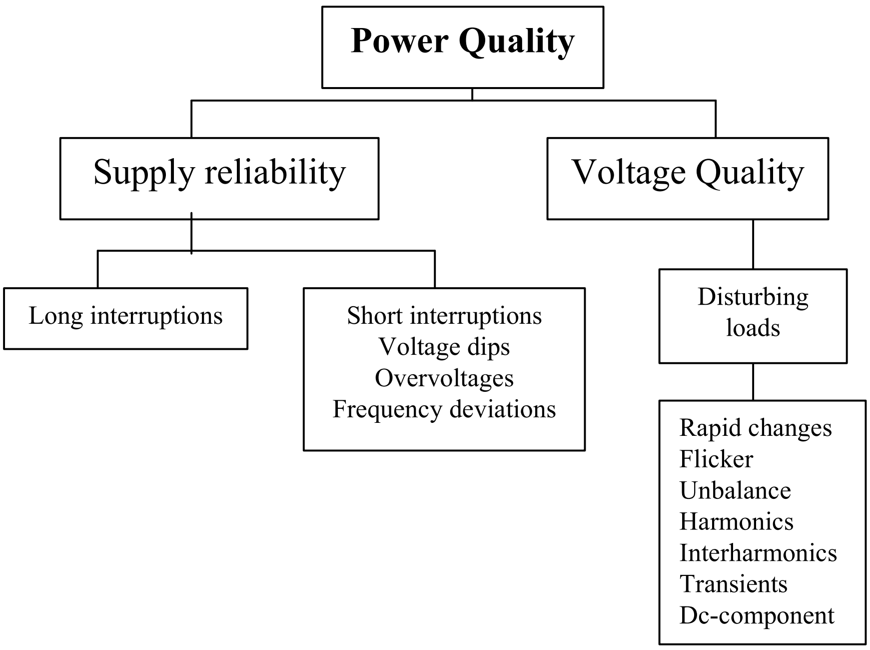


Figure 52. Simplified characterisation of Power Quality.

To give a complete idea of Power Quality, also a third phenomenon may be introduced, i.e. information (Thomsen, 1999). Information about planned outages and information after faults and disturbances, give the customer a better impression of the quality of supply, and of the supplier. So as to complete the term Power Quality a figure like Figure 53 can be drawn.

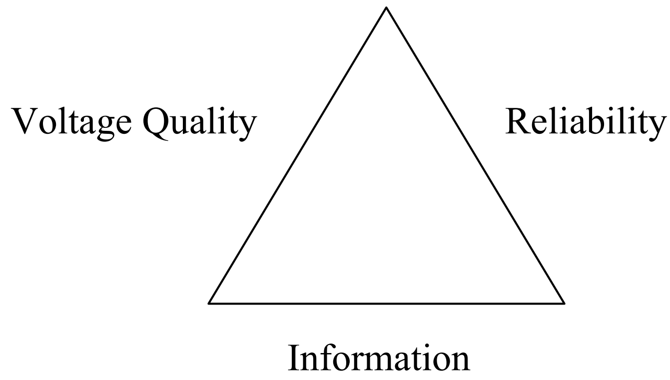


Figure 53. Three important factors for Power Quality.

With the emergence of computers, a high level of automation with sensitive loads and modern communication, reliable electricity supply with a good voltage quality has become a necessity. Electricity is fundamental to economic activity, to the standard of living and quality of life. Over the last ten years the customers perception of reliability has changed. Outage times of a few cumulative hours per year are no longer considered as an characteristic of an extremely reliable supply for an increasing number of sensitive customers, in particular industrial and commercial customers. A few cycles interruption or a voltage reduction to less than 90 % may cause serious problems for industrial customers. The number of voltage dips and swells and their duration becomes more important than the cumulative outage time per year (CIGRE WG14-31, 1999).

The variety of disturbances that may affect customers' equipment are the parameters that describe Voltage Quality and Reliability, and these parameters, and equipment to compensate for their influence, will be described in the following.

4.2.1 Categorisation and characterisation of disturbances in the grid

According to (Dugan et al., 1996) and (Thomsen, 1999) the different disturbances may be classified as in Table 8.

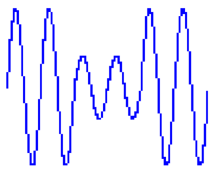
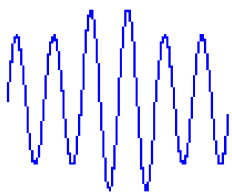
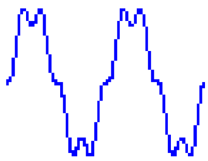
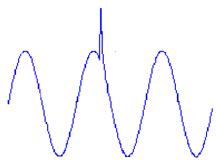
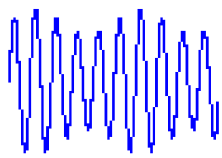
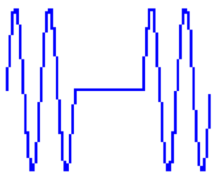
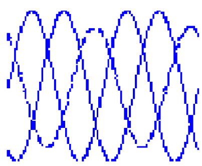
Table 8. Categories and typical characteristics (Low-Voltage grid) for variations in the supply voltage with given voltage quality parameters. EN for chapters in EN 50160 (Thomsen, 1999).

Category	Typical characteristics Spectrum	duration	magnitude	Voltage quality parameters	EN
1.0 Transients					9
1.1 Impulsive	5 ns - 0.1 ms	50 ns - > 1ms	< 6 kV		
1.2 Oscillatory	<5 kHz-5 MHz	5µs – 0.3 ms	0 - 4 pu		
2.0 Short duration variations					
2.1 Interruptions		10 ms - 3 min.	< 1 %	Short duration interruption	6
2.2 Sag		10 ms - 1 min.	1 - 90 %	Voltage sag	5
2.3 Swell		10 ms - 1 min.	110 - 180 %	Voltage swell	8
2.4 Rapid voltage changes		not defined	> +- 5 %	Rapid voltage changes	41
3.0 Long duration variations		stationary	< 106 % > 90 %	Supply voltage	3
3.1 Under voltages		> 1 min.	80 - 90 %		
3.2 Over voltages		> 1 min.	106 - 120 %		
4.0 Voltage unbalance		stationary	0.5 - 2 %	Voltage Unbalance	10
5.0 Curve distortion					
5.1 DC offset	n=0	stationary	0 - 0.1 %		
5.2 Harmonics	n=2 - 40	stationary	0 - 20 %	Harmonics	11
5.3 Interharmonics	0 - 6 kHz	stationary	0 - 2 %	Interharmonics	12
5.4 Notches		stationary			
5.5 Noise	Broadband	stationary	0 - 1 %		
5.6 Signal transmis-sion	< 148 kHz	stationary	0.09	Signal transmis-sion	13
6.0 Voltage - fluctuations	< 25 Hz	intermittent	0.2 - 7% Plt< 1	Voltage Fluctuations (flicker)	4.2
7.0 Net frequency-variations	50 Hz	< 10 s	1 %	Net frequency	1

These categories and the description of the different disturbances in Table 8 are important to classify measurement results and to describe the actual phenomena, which may cause the Power Quality problem. These disturbances are not all new, and the utilities are aware of them. However, they have to take a new look because of the rapidly changing customers' needs and the nature of loads (CIGRE WG14-31, 1999). This may force the utilities to be able to provide value-added options to industrial and commercial customers relating to their specific needs. The way to give some customers better service than others is by using Custom Power equipment to secure better reliability and improved voltage quality.

Another way to categorise the different disturbances is to look at possible causes for each kind of disturbance and to look at the consequences they might give. They are summarised in Table 9.

Table 9. Voltage disturbances their origin and their consequences (Thomsen, 1999; CIGRE WG14-31, 1999).

Disturbance		Origin	Consequences
Voltage sag undervoltage 2.2		Short circuits in the network grid passing or on another radial. Start up of large motors	Disconnection of sensitive loads Fail functions.
Voltage swell Overvoltages 2.3		Earth fault on another phase Shut down of large loads Lightning strike on network structure Incorrect setting in substations	Ageing of insolation Disconnection of equipment May harm equipment with inadequate design margins
Harmonic distortion 5.2-5.3		Nonlinear loads Resonance-phenomena Transformer saturation Notches	Extended heating . Fail function of electronic equipment
Transients 1.1-1.2		Lightning strike Switching event	Insulation failure Reduced lifetime of transformers, motors etc.
Voltage-fluctuations/ flicker 6.0		Arc furnaces Sawmill, crushing mill Welding Wind turbines Start up of large motors	Ageing of insulation Fail functions Flicker
Short duration interruptions 2.1		Direct short circuit Disconnection False tripping Load shedding	Disconnection Disconnection
Unbalanced 4.0		One phase loads Weak connections in the network	Voltage quality for overloaded phase Overload and noise from 3-phase equipment

In Table 9, the distortion caused by DC-offset is not taken into account. This is not considered by IEC. The DC-offset may occur from geomagnetic disturbance or due to the effects of half-wave rectification. Also voltage setting on equipment with iron cores, or short circuits close to the generators can give DC-offset in the voltage. The consequence of a DC-offset is that transformer cores may be biased, so they can saturate in normal operation, leading to heating and loss of transformer life. DC-current can also cause electrolytic erosion of grounding electrodes and other connectors (Dugan et al., 1996).

Also interharmonics are not mentioned in Table 9. Interharmonics are sinusoidal voltages and currents having a frequency that are not an integer multiple of the frequency of the supply voltage. Depending on the source of the interharmonics, they appear as discrete frequencies or as a wideband spectrum. The main source of interharmonics is static frequency converters, cycloconverters and arcing devices. Interharmonics may affect power line carrier signalling, and can induce flicker in display devices such as cathode ray tubes (Dugan et al., 1996).

Finally, power frequency variations are not mentioned in Table 9. The frequency of the power system is directly related to the rotational speed of the generators supplying the network. Frequency variations occur when the dynamic balance between load and generators change, the size and duration depending on the load characteristics and the response of the generation control. Large frequency deviations may be caused by faults on the bulk power transmission system, disconnection of large blocks of load, or a large source of generation going off-line. On modern interconnected power systems, this kind of frequency variation is rare, but the phenomenon may occur on isolated systems.

All the different Power Quality terms are now defined and the origin of the different disturbances is also mentioned. One could also claim that reactive power should be a Power Quality parameter, but in the literature, it is not defined as an independent Power Quality parameter, since the voltage is chosen here as the Power Quality parameter. It may be relevant to take the reactive power into consideration, since the magnitude of the losses in the network and the sizes of transformers and generators may be increased, due to the reactive power in the network. The losses in the network result in large voltage drops, giving rise to poorer Voltage Quality. With the above terms of Power Quality, the effect of the reactive power must be considered under the term voltage fluctuation, and the effect of reactive power must then be compensated with regard to this term (Thomsen, 1999).

4.2.2 Equipment used to enhance the Power Quality.

In this section, the focus will primarily be on the distribution level (up to 60 kV), where equipment used to enhance the Power Quality is called Custom Power Systems (CUPS), as opposed to equipment used on the transmission level, which is called Flexible AC-systems (FACTS). Anyway for some of the apparatus used on the distribution level, corresponding apparatus exists on the transmission level, and this relationship is shown in a later table.

There are many different types of apparatus, which may be used to enhance the Power Quality, and these may be divided into three groups:

- On/off apparatus, switches
- Stepwise controllable apparatus
- Continuously controllable apparatus

4.2.3 On/off apparatus, switches

On/off apparatus is installed typically at industrial or commercial facilities, with a dual, medium voltage supply, to switch between service from one source to the other. Electromechanical switches normally take from 1 to 10 seconds to switch. Such electromechanical switches are too slow to protect sensitive electronic devices, which are sensitive to, for instance, voltage sags and swells. Here solid-state switches based on GTO thyristor technologies are emerging in transfer switch, fault current limiter, and breaker applications (CIGRE WG14-31, 1999). At 600V level and below the Voltage Static Transfer Switch, which uses low voltage power electronic devices, is being used. The use for medium-voltage power electronics for similar applications has evolved in the recent past. In the case of local generation or in case where a transfer between asynchronous sources is needed, solid state breakers may be useful. These are able to interrupt current and they use GTO's or equivalent. Solid state circuit breakers are often used in connection fault current limiters to reduce the fault current, and thereby reduce the voltage sags on the unfaulted system segments.

4.2.4 Stepwise controllable apparatus

Stepwise controllable apparatus may either regulate the voltage by use of an electronic controlled voltage tap changer, or by the use of stepwise-coupled capacitors as in Static Var Compensators or in Thyristor Switched Capacitors. Such apparatus may also be used for compensation of reactive power. In smaller systems, the electronic switches may be replaced by mechanical switches.

4.2.5 Continuously controllable apparatus

This group of apparatus will normally include a voltage source converter, controlled by various control strategies. The connection to the network grid is usually done by use of transformers. New power electronic devices such as Insulated Gate Bipolar Transistors (IGBT), Insulated Gate Commutated Thyristors (IGCT), and MOS controlled Thyristors (MCT) are used in the converters. Depending on the topology used for the converters they are split up into two groups:

1) Shunt converters.
2) Series converters.

The shunt converter injects current into the network at its coupling point. This current injection may then be used to compensate for different disturbances. Typical shunt connected apparatus may be the following: Static Var Compensator SVC, Static Synchronous Compensator (STATCOM) and for harmonic compensation Active Harmonic Filters (AHF).

The series converter injects a voltage with a certain phase lag or lead to the line between the supply and load. The resulting power flow in the circuit where the voltage is injected will be changed, dependent on the resulting voltage and phase-shift across the load. The most frequently used series apparatus is the Dynamic Voltage Restorer (DVR).

Shunt connected compensators are useful for cancelling out disturbances in the network current, whereas the series compensators are useful for cancelling out voltage disturbances at the load side.

The two kinds of apparatus may also be combined. The apparatus is then called a Unified apparatus, for instance a Unified Power Quality Conditioner (UPQC).

Finally, the active compensator may be combined with passive filter elements. Then the apparatus is called hybrid apparatus. Some of the compensators also have an energy storage device connected, to be able to deliver active power, and not only reactive power. In this way also voltage dips and voltage fluctuations may be compensated. Depending on the amount of energy stored, different sizes and duration of the dips can be compensated. On some occasions a shunt apparatus in connection with a series apparatus can replace the energy storage device. A Unified Voltage Controller (UVC) is an example of such an apparatus.

An overview of the different kind of apparatus used at the distribution level (CUPS) and at the transmission level (FACTS) is shown in Table 10.

Table 10. Different CUPS and FACTS apparatus (Thomsen, 1999).

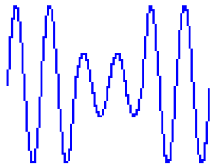
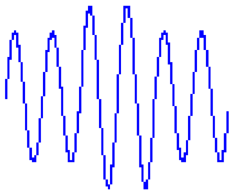
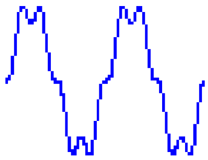
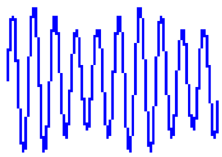
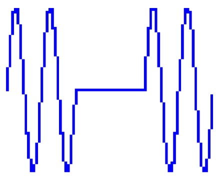
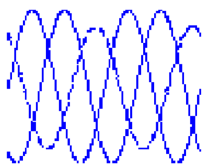
Generation group 1 is the first generation converters and is based on thyristors and current source line- commutated converters

Generation group 2 is second generation converters and is based on self-commutated converters with either GTO's or IGBT's in voltage source converters.

Generation - Group	CUPS	FACTS
1 – shunt		SVC Static Var Compensator
1 – series		TCSC Thyristor Controlled Series Capacitor
On/off apparatus		
1-2 – on/off	SSB Solid State circuit Breaker SSTS Solid State Transfer Switch or STS Static TS BTS Bus Transfer Switch	
1-2 – on/off	FCL Fault Current Limiter	
Stepwise controllable apparatus		
1-2	SVR Static Voltage Regulator SSLTC Solid State Load Tap Changer	
1-2	ASVC Advanced Static Var Compensator AVC Adaptive Var Compensator	
Continuous controllable apparatus		
2 – shunt	STATCOM STATic COMpensator or STATCON STATic CONditioner AHF Active Harmonic Filter	STATCON STATic CONdenser or ASVC Advanced SVC
2 – series	DVR Dynamic Voltage Restorer SABF Series Active Blocking Filter	SSSC Static Synchronous Series Compensator PAR Phase Angle Regulator or PAC Phase Angle Controller
2 – Combined	UPQC Unified Power Quality Conditioner APLC Active Power Line Conditioner UVC Unified Voltage Controller PQM PQ-Manager, Hybrid	UPFC Unified Power Flow Controller

Oscillating transients generated by coupling of capacitors must be eliminated at the generation point by use of coupling resistors or techniques, such as synchronised coupling or passive filters have to be used because of the high frequency (Thomsen, 1999).

Table 11. Compensation apparatus for different disturbances (Thomsen, 1999).

Distortions		Apparatus	Effect
Voltage dip and sags 2.2		StatCom. DVR UPQC	Moderate Good Good
Voltage swell 2.3		StatCom DVR UPQC	Moderate Good Good
Harmonic distortion 5.2 - 5.3		AHF SABF APLC, UPQC	Filtering, good Does not block alone Good, efficient
Voltage-fluctuations 6.0		StatCom □ASVC□ DVR UPQC	Good questionable Best
Short duration interruptions 2.1		StatCom DVR UPQC	UPS -function Hardly, but possible with UPS-function UPS - function
Unbalance 4.0		StatCom DVR UPQC, UVC	Moderate, problematic Good Good, difficult

4.2.6 Measures and indicators

Different types of disturbances have been described in this section. Measurements and indicators are needed to identify the nature of these phenomena. In connection with wind turbines, methods for measurement and assessment of the influence of wind turbines on the power quality are specified in (IEC 61400-21, 2000). This standard includes measures for maximum power, reactive power, voltage fluctuations and harmonics.

The following three measures related to voltage fluctuations and flicker are used:

- Flicker coefficient $c_f(\psi_k,v_a)$ – is used to characterise the flicker emission from the wind turbine in continuous operation e.g. in the PCC (Point of common coupling) without generator couplings. The flicker emission for continuous operation is defined to be:

$$P_{st} = P_{lt} = c_f\left(\psi_k, v_a\right)\frac{S_n}{S_k}$$

where ψ_k is the grid short circuit angle and v_a is the annual mean wind speed, while S_n denotes the nominal apparent power of the wind turbine and S_k is the apparent short circuit power e.g. in the PCC. According to the standard, $c_f(\psi_k,v_a)$ is given in a table with four values of ψ_k and v_a respectively, and the value in an actual case is obtained by interpolation of ψ_k and v_a.

- Flicker step factor $k_f(\psi_k)$ – is used to characterise the flicker emission from the wind turbine arising from generator switching operations. The short term flicker emission is defined to be:

$$P_{st} = 18\cdot\left(N_{10}\right)^{0.31}\cdot k_f\left(\psi_k\right)\cdot\frac{S_n}{S_k}$$

where N_{10} is the number of switching operations occurring during ten minutes. The long-term emission is defined to be:

$$P_{lt} = 8\cdot\left(N_{120}\right)^{0.31}\cdot k_f\left(\psi_k\right)\cdot\frac{S_n}{S_k}$$

where N_{120} is the number of switching operations occurring during 120 minutes.

- Voltage change factor $k_u(\psi_k)$ – is used to characterise the voltage changes, which occur on switching. The relative voltage change in %, d, is defined as:

$$d = 100\cdot k_u\left(\psi_k\right)\cdot\frac{S_n}{S_k}$$

The above formulas for assessment of the influence of a wind turbine on the power quality are valid for a single wind turbine. (IEC 61400-21, 2000) also specifies methods for summation of the effect of wind turbines in a cluster, or a wind farm, taking into account the smoothing effect of the contributions from the individual wind turbines.

Another basic characteristic measure, which has been used in earlier standards, is the cut-in current factor k_i:

$$k_i = \frac{I_{max}}{I_r}$$

where I_{max} denotes the maximum current during one half period and I_r denotes reference current of the wind turbine/farm (both are rms. values). The cut-in current factor is usually used to specify an upper limit for the current at cut-in of a load (passive as well as active). The cut-in current factor k_i has been used to predict the maximum voltage change substituting $k_u(\psi_k)$ in the above equation. However, this method is conservative, because it does not take into account the influence of the impedance angle of the grid. This is particularly relevant for the cut-in of induction generators on grids with high values of short circuit impedance angle, because typically I_{max} is due to reactive power, and therefore $k_i > k_u(\psi_k)$

A widely used technique in signal analysis is to analyse a signal by its Fourier transform. This technique is especially relevant in connection to wind turbines provided with power electronic, due to the harmonics produced by the switching patterns of the applied power electronic device.

The ideal case is a sinusoidal voltage and a sinusoidal current, with a frequency of 50 Hz. In order to be able to describe deviations from the ideal case three different measures have been defined as presented below (Arrillaga et al., 2000):

- Total harmonic voltage distortion is given by:

$$THD_{U\%} = \sqrt{\sum_{h=2}^{40}\left(\frac{U_h}{U_1}\right)^2} \cdot 100\%$$

  where U_h denotes the amplitude of the h'th harmonic. A small THD_U value indicates a signal close to the ideal case. Thus, THD_U is a normalised measure of the harmonic content due to over harmonics up to and including the 40th harmonic.

- Total voltage distortion factor is given by:

$$TDF_{U\%} = \frac{\sqrt{U_{rms}^2 - U_1^2}}{U_1} \cdot 100\%$$

  This includes all kinds of distortion. A small TDF_U value indicates a signal approaching the ideal case. TDF_U can be seen as a normalised measure of the energy of the sinusoidal signal content at frequencies other than 50 Hz.

- The weighted distortion factor is given by:

$$THD_w = \sqrt{\sum_{h=2}^{N}\left(h \cdot \frac{U_h}{U_1}\right)^2}$$

  The weighted distortion factor is dedicated to systems employing shunt capacitors, as it weights the higher frequencies in a manner corresponding to the frequency dependence of the current in a shunt capacitor.

4.3 Standardised Grids

The economic viability of a wind turbine investment is judged e.g. by its pay-back time. The energy production at a given site is a key parameter for this calculation – in other words, the focus is on the power curve of the wind turbine. Here the type of grid and type of wind turbine are of great importance.

In this section, standardised grids are discussed and reviewed. The focus is on how to characterise a particular grid and differentiate between it and other grids. The generic type of a grid will impose certain demands on the grid connection of a wind turbine and/or wind farm. These demands are usually defined at the point of common coupling.

4.3.1 Basic grid properties

A simple way to analyse or to characterise a grid/network is to approximate it by a first order equivalent as shown in Figure 54. If the load Z_l is displaced by a short circuit, the apparent short circuit power may be calculated as:

$$S_k = \sqrt{3} \cdot U_n \cdot I_k$$

in the case of a three phase system.

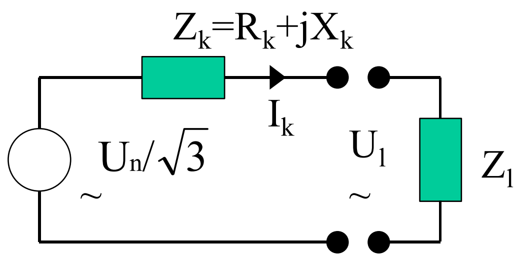


Figure 54. Simple grid equivalent.

A basic characteristic measure of a grid is the short circuit ratio (KR 111, 1998):

$$R_{sc} = \frac{S_k}{S_r}$$

where S_k denotes the short circuit power and S_r the apparent power reference of the wind turbine/farm. This ratio reflects the stiffness of a grid, i.e. a higher value of R_{sc} indicates a stiffer grid. In a sense the short circuit ratio describes the capacity of a grid compared to applied load.

Another characteristic grid measure is the short circuit angle (IEC 61400-21, 2000):

$$\psi_k = \mathrm{Arctan}\left(\frac{X_k}{R_k}\right)$$

where R_k and X_k denote the short circuit resistance and the short circuit reactance of the grid respectively, as indicated in Figure 54.

A simplified description of the load voltage at steady state conditions may be obtained by:

$$U_l = U_n - \frac{R_k \cdot P_l + X_k \cdot Q_l}{U_n}$$

where P_l is the active power production and Q_l the reactive power consumption of the load, respectively. Thus given knowledge of the grid and the load, it is possible to estimate whether or not the load voltage is within specified limits.

4.3.2 Various grid types

One way to describe a grid is by referring to a number of characteristic grid parameters. The first and most important parameters are the voltage level and the kind of source, i.e. either DC or AC. Two other characteristic parameters are the apparent short circuit power and the short circuit angle. Another way is to characterise a grid by certain properties. Examples of terms in use are:

- transmission grid
- distribution grid
- AC or DC grid
- stiff grid
- weak grid
- isolated grid

The first two properties are related to the voltage level. Issues concerning these properties were discussed in Section 4.1.

4.3.2.1 Stiff or weak grid

The properties stiff and weak are more difficult to handle in a short and precise definition. A stiff or a weak grid is not just a stiff or a weak grid, independently, since a grid could be characterised e.g. as frequency stiff and voltage weak. A frequency weak grid would influence the energy production of a fixed speed wind turbine in a less desirable manner. This has been studied in e.g. (Sørensen et al., 2000). Another problem related to the stiff/weak property is that, while a grid with a few connected wind turbines is stiff, the same grid might be characterised as weak at a higher number of connected wind turbines.

In order to assure a proper operating condition for the wind turbine and acceptable reliability and power quality for the grid, recommendations and standards have been developed for connection of wind turbine to the distribution grid. In Denmark, (KR 111, 1998) specifies the requirements for grid connection of wind turbines to the distribution system, based on the characteristics and methods specified in (IEC 61400-21, 2000).

Power quality and other issues related to grid-connected wind turbines are highlighted in a simulation study contained in three reports:

- (Jørgensen et al., 1996) with the focus on steady state voltage conditions. The influence of wind turbines on three different grids is analysed.
- (Sørensen & Kledal, 1996) with the focus on flicker. The flicker impact from both stall regulated and pitch controlled wind turbines is analysed on two different grids.

- (Vikkelsø et al., 1996) with the focus on harmonics and operating conditions of variable speed wind turbines. The distribution of harmonics is analysed for six different configurations of wind turbines on one grid.

If a project aims at installation of a wind power (or any other renewable source) on a weak grid, three options should be considered:

1. Appropriate reactive power compensation etc. of fixed speed wind turbines.
2. Use of wind turbines with controllable power output.
3. Reinforcement of the grid.

Which of these options is the right choice depends on the economics of the three options and the local planning.

4.3.2.2 Isolated grid

An isolated grid is a very ambiguous term. There are no well-defined upper or lower power limits. The term covers a variety of system types, e.g.: wind-diesel, hybrid power, stand-alone etc. The characteristics of an isolated grid are typically equivalent to those of a weak grid. (EN 50160, 1999) is the only identified standard with recommendations for isolated grids.

4.3.3 Off-shore wind farms on the transmission grid

As mentioned in Section 3.3.3, energy planning of the Danish Government has scheduled a number of offshore wind farms. According to the plan, the first two will be ready for operation in 2002 – each rated at 150 MW. By the year 2030, 50 % of the electrical energy consumption in Denmark will be supplied by wind energy.

The Danish power system operators Elkraft System and Eltra are responsible for the integration of these wind farms. Due to their rated power, they will be connected directly to the transmission grid. The specifications for connecting these wind farms are presented (Eltra, 2000).

As usual, specifications for frequencies, voltages, reactive power compensation, voltage quality and fault protection are presented. As a new item, requirements production control has been introduced (Eltra, 2000). Moreover, more stringent stability requirements and requirements for operation during grid faults have been incorporated.

In this context the requirements for production control are of great interest. Referring to (Eltra, 2000), it shall be possible to:

- control the production from the wind farm so that it does not exceed a certain MW-value, i.e. a production limit
- control the production limit by a single central signal
- control individually each wind farm
- have the control to act on the individual wind turbine
- control the production quickly, i.e. a reduction from 100% to below 20% of maximum power in less than two seconds.

Furthermore, high wind speed may not cause all the turbines to stop simultaneously.

These specifications impose new and challenging demands on the art of wind turbine design. As a new task the manufacturers must gain knowledge on how to construct and operate the local wind farm grid. This will imply development of new control strategies for park control, which can take account of the external power production demand, and of internal dispatching of wind turbines.

4.4 Power system integration

So far in the report the focus has been on single wind turbines with their drive train/power conversion system and their internal electrical layout and grid connection. In this section the focus is the integration of large amounts of wind power in a power system and the implications of that on both the wind farm and the rest of the system (transmission, generation, consumption).

In power systems with a high level of wind energy penetration it is necessary to adapt the wind turbines (or the wind farm) and the rest of the power system in order to ensure optimal operation of the combined system. Optimal operation in this context means the lowest operating cost of the complete system as well as maximum utilization of the wind energy.

The fast installation of wind turbine capacity is not the only change with a large impact on the power system. The power system and its organization is currently undergoing rapid changes as a result of both technological development and the political requirement to have a liberalized sector and a more sustainable system.

The technological development takes place in many areas such as micro combined heat and power plants (fuel cells, microturbines etc.) and pv-systems for distributed generation. Also the large development effort in hydrogen and energy storage technologies will have a large impact on the power system in the next 10-15-20 years. In this time frame the information technology will also be widely applied for control and automation of production, transmission and consumption.

Integration of wind energy therefore has to be seen both in the light of the current power system and in view of the opportunities which the future technology will open as it will be developed and implemented.

The fast implementation of wind energy in certain regions results in large regional power systems with very high wind energy penetration levels. This leads to problems for the Transmission System Operator (TSO). These problems include unit commitment, scheduling and dispatch, problems of the controllable power plants, transmission bottlenecks, voltage, angle and transient stability, large power exchanges with neighboring systems, trading problems on the power exchange and other similar problems. These problems off course exist in any power system but the impact from the wind turbines changes many of the well-known problems and therefore requires new solutions to planning, design and operation of the power system.

In order to mitigate these problems it is necessary to view the system as a whole, to exploit the possibilities that already exist in the system and to focus development activities on solutions that combine many different technologies.

Some of the main problems are the voltage control of the system, the need to be able to follow the load and the robustness of the system to faults and trips of both generation and transmission capacity.

As mentioned in Section 3.3, the connection of a wind farm to the grid has a large impact on the voltage at the point of common coupling and in an area close to that. It can also have large impact on the voltage stability due to the reactive power consumption if directly connected induction machines are used in the wind turbines (and there is no extra compensations apart from no-load consumption).

The fluctuating nature of wind power implies that wind power only in a limited way can contribute to the load following capability of the system and since the amount of power produced from more dispatchable sources is reduced there is a trade off between reduction in spinning capacity and the need to be able to cover the load given the fluctuation in the wind power production.

Arguments along the same line are valid regarding the need for the system to be able to pick up load in the case of faults in generators or the grid. In high penetration systems there is a need for the wind turbines (or wind farms) to be able to stay connected during some faults and to find (economic) solutions that enable the system to withstand such perturbations.

Many technical options exist that can be used in combination with wind energy to ease integration and to improve the value of wind energy.

One of the immediate technologies that can be utilized is implementation of wind power production prediction systems [Nielsen et al., 2001], [Giebel et al., 2001]. These have been under development for several years and they have also been installed in load dispatch centers in e.g. Denmark and Ireland, [www.predictor.dk]. The methods that are applied are both statistical and based on physical models like weather forecasts. The systems are used to predict the wind power production that will be fed into the system in the next 24-48 hours and thus to reduce the uncertainty associated with the production. The other types of generation can therefore be committed, scheduled and dispatched in a more economic way. The prediction of wind power production also improves the trading at the power exchange. Both these elements improve the value of wind power in the system.

In order to further improve the integration of wind energy by reducing the power fluctuations the recent development of large-scale power and energy storage has shown much promise. Power and energy storage in the system give many improvements to the way the power system can be operated. These possibilities are also attractive in a general power system perspective and are not linked exclusively to integration of wind power. The four main features are the buffering of energy, the peak shaving ability, the ability to contribute to black start of the grid and the improved utilization of the transmission grid. In this context, the wind power storage systems can reduce or eliminate the short-term fluctuations making it possible to reduce spinning reserve of the system. It will also make it possible to have the wind farms to contribute to the frequency control of the grid and to reduce the stress on the links in and out of the control area.

Until recently the main form of energy storage was lead-acid batteries. However, these batteries are not suited for large-scale storage applications. The main reasons are the investment costs, the maintenance requirements and the limited and uncertain lifetime of the system, [Drouilhet & Johnson, 1997]. New types of batteries have been developed recently, and some of the most promising types are the so-called redox flow or reversible fuel cell types of storage. These types of batteries have some very desirable features. The first and foremost is the ability to independently size the power and the energy capacity of the storage. This is due to the way the system works. The power exchange happens in a cell stack in which the two electrolytes are flowing separated by a membrane that permit ions to travel from one side to the other. The electrolyte is pumped through the cell stack and is stored in tanks outside the cell stack. The power capacity of the battery is determined by the area of the membrane while the energy capacity is determined by the volume of the tanks (or rather by the volume of the electrolyte stored in the tanks). Further is the self discharge practically zero, the efficiency is high (above 80%) and the lifetime can be very long, [Hawkins, 1998]. The cost of the systems is also relatively competitive even at this stage of development and further reductions are foreseen. Commercial products already exist (from Regenesys Technologies Ltd., UK), [www.regenesys.com]. Vanadium based system are in the final development phase.

In Section 3.3 it was shown how power electronics can be used in combination with wind farms to improve the integration by reducing the impact on voltage level and fluctuations in the grid close to the wind farm. Power electronics can also be installed in central places in the grid in order to improve the capacity of the grid by dynamically controlling the voltage (Flexible AC Transmission Systems, FACTS, such as STATCOMs, DVRs, UPQCs and HVDC). Combined control of these devices will contribute to the improved integration of wind power and it will also improve the utilization of already existing transmission systems.

The predicted development of distributed power production technology will have a large impact on the operation of the system. It can be expected that a very large number of small (5-10kW) systems will be installed in houses for combined power and heat production. There will also in some areas be a rapid increase in the installed capacity of pv-systems as these systems come down in price. This will be in contrast to the trend in wind energy, where the new capacity will be very concentrated in the areas with the highest wind resources. The control of this distributed generation system will be a big challenge, but there will be many control options that eventually could utilize also in the view of integrating wind power. One of the fuels in such a system could be hydrogen.

Utilization of hydrogen also has a large perspective. Hydrogen could be produced by electrolysers that are operated during off-peak hours or in situations with a large wind power production and a low consumption. The hydrogen can then be stored until consumption rises or during peak hours to produce power to the grid. It could also be used, as mentioned above, in a system with micro CHP plants in individual houses or it can be used in transportation. In this way renewable energy can be used to produce fuel and thus contribute to a more sustainable transport sector. The scheduling of the electrolysers can significantly increase the amount of wind energy that can be integrated in the power system.

It is evident from the above, that control of the system is a crucial aspect. If the possibilities mentioned above are to be realized, it is necessary to develop the control technology and the systems, which are used to control the power system. Application of new possibilities coming from the rapid development information technology is a prerequisite if this is to be realized.

5 Summary

This report presents a survey on electrical machines and power electronic concepts for wind turbines as well as the grid integration aspects of them.

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.

The chapter on generator presents the electrical machines used in wind energy conversion and identifies potential new types of machines. Starting with the classical and commercially agreed induction machine in both types, squirrel cage and wound rotor, the report focus in synchronous machines (permanent magnet and wound rotor), switched reluctance machine and transverse flux machine. Another considered candidate is the high voltage machine for power from 3MW and upward. Each machine has advantages and drawbacks.

- The squirrel cage induction machine has a very simple and reliable construction and there are no needs of special maintenance, however it has to be supplied with reactive power via the supply terminals although it.
- The wound rotor induction machine has a weak spot in the presence of the slip rings and brushes, it is more expensive than the squirrel cage machine and requires special maintenance. However, the presence of slip rings makes possible to control from outside the electrical characteristics of the rotor, by means of electric equipment.
- The synchronous machine is very attractive for direct drive applications although involve synchronous operation. The wound rotor machine is vulnerable to vibrations and the slip rings and brushes require special maintenance. The permanent magnet machine eliminates some disadvantages of the wound rotor machine, however it raises problems concerning the temperature and weight of the magnets and the fault capability.
- The switched reluctance machine and the transverse flux machine have not yet implemented in wind energy conversion systems. The switched reluctance machine has the advantages of squirrel cage induction machine regarding the simplicity and robustness of the rotor and it is suitable for low speed operation. However it requires a sophisticated power converter and control.
- The transverse flux machine offers high-values of specific torque and it is suitable for direct drive applications, although it has a large number of individual parts and special methods of manufacturing and assembly.
- Finally, the high-voltage machines manufactured currently as induction and synchronous machine offers a reduction in current, leading to lower copper losses and a possible direct connection to the grid.

The chapter on power electronics deals with two issues: power converter components for wind turbines and power electronic units for wind turbines. The first issue comprises the soft-starter, the capacitor bank, the diode rectifier and five frequency converter topologies (back-to-back PWM-VS converter, tandem converter, matrix converter, multilevel converter and resonant converter). A comparison of these converters is carried out with advantages and drawbacks for each one. As the back-to-back converter is state-of-the-art today in wind turbines 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 auxiliary components, the efficiency, the harmonic performances and implementation. Nevertheless, the comparison concludes and recommends further studies on back-to-back converter, the matrix converter and the multilevel converter. Wind farms and wind power plants connected to the grid requires full control of the active- and reactive power transferred with the grid. This demand can be done by means of reactive power compensations units, power regulation and power storage unit. Examples of reactive power compensation units are SVC, ASVC and STACOM inverters. Pitch angle control is a simple and direct example of power regulation as well as dump loads and disconnection of wind turbines. Pumped storage may be an option, although further developments of batteries, fuel cells and other storage technologies must be done. HVDC could be in the future a solution for transmission of power over long distance from a number of wind power plants, both offshore and on-land. This will open new possibilities for variable speed control of wind turbines.

The chapter on grid integration presents two main aspects: power quality and demands to grid connection, and the grid classification. The disturbances in the grid are classified and described using different criteria, as typical characteristics and origin of them, in order to classify measurements results and to describe globally the Power Quality. Then, the apparatus, which may be used to enhance the Power Quality both at the distribution level and transmission level, are presented (on/off apparatus, switches, step-wise controllable apparatus, continuously controllable apparatus). Finally, standardized grids are discussed and reviewed. The focus is on how to characterize a particular grid and differentiate between it and other grids. Each generic type of a grid will impose particularly demands on the grid connection of a wind turbine, wind farm and/or wind power plant.

The report highlights a very important issue. The energy conversion system between the wind turbine and grid has to be treated in an unified way and must satisfy the grid connection demands. Since the electrical machine candidates have advantages and drawbacks as well as the power converters, it is necessary to analysis this assembly based upon some indicators as:

- Overall efficiency.
- Power flow capability.
- Range of speed operation.
- Machine weight.
- Reliability and maintenance.

Trends and further research

At present, the Danish power grid holds more than 2 GW installed wind power as well as small Combined Heat and Power Plants with a capacity of more than 1.5 GW. Both types of plants are independently controlled and do not take part in the voltage and frequency control. Furthermore, a huge expansion of wind power is planned. The power system stability limit in power systems with a high penetration of wind energy is important to identify and to improve in order to obtain the maximum value of the wind energy in the grid system.

The major investment of wind turbines will in the future be done in wind farms with hundreds of MW power capacity. In order to maintain system stability it is important that each wind farm can provide voltage and frequency control by means of power electronic systems. Furthermore, a high penetration of wind power in a power grid structure may test the limits of power stability in the grid system as well as cause power overflow in certain areas.

During the last years the wind turbines have grown in size up to 2 MW and more, and this trend in size up scaling is expected to continue.

Hence, the main challenges related to technology development are then 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 (power regulations shared responsibility for power system stability etc.), develop the wind turbine technology for future applications, e.g. large highly reliable machines for offshore applications in shallow or deep waters, silent, "invisible" machines for distributed installations on land or simple, easily maintained hybrid systems for smaller, isolated communities, and to develop technology that facilitates the integration of a variable energy source into the energy system such as HVDC transmission system, energy storage technologies, power flow control, compensations units (voltage, frequency, power factor, phase imbalance etc) and production forecasting and control of the wind power plants.

Issues discussed in this report are essential for meeting these challenges. In particular the rapid development of power electronics, which offers high power handling capability at lower price per kW, can benefit both the turbine development and the integration of wind farms into the power system. Hence it is expected that the application of power electronics in wind turbine will increase further. As recommendation for further research in this area it can be mentioned:

- Study and analysis of switched reluctance machine for high-power applications in wind turbines;
- Study and analysis of transverse flux machine for high-power applications in wind turbines;
- Study and analysis of double-fed induction machine and converter optimization;
- High-voltage machine design for wind turbines;
- Optimization of back-to-back PWM-VS converter;
- Study and analysis of matrix and multilevel converter for wind turbine application;
- Identification and analysis of new power converter topologies.

As medium term recommendations for research regarding wind farms and/or wind power plants:

- Infrastructure design studies;
- Dynamic interaction between wind farm / wind power plant and grid for:
    - Normal operation;
    - Fault or transient events.
- Control concepts for wind power plant characteristics;
- Energy storage;
- HVDC connection
    - Control concepts;
    - Study of steady-state and dynamic stability.

As long-term research areas it can be mentioned:

- Grid stability;
- System optimization for wind turbine, wind farm and wind power plant;
- Global optimization based on system model;
- Standardization / committee work regarding parks and grid.

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Conceptual survey of Generators and Power Electronics for Wind Turbines

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Abstract (max. 2000 characters)

This report presents a survey on generator concepts and power electronic concepts for wind turbines. The report is aimed as a tool for decision-makers and development people with respect to wind turbine manufactures, utilities, and independent system operators as well as manufactures of generators and power electronics.

The survey is focused on the electric development of wind turbines and it yields an overview on:

- State of the art on generators and power electronics.
- future concepts and technologies within generators and power electronics.
- market needs in the shape of requirements to the grid connection, and
- consistent system solutions, plus an evaluation of these seen in the prospect of market needs.

This survey on of generator and power electronic concepts was carried out in co-operation between Aalborg University and Risø National Laboratory in the scope of the research programme *Electric Design and Control*.

Descriptors INIS/EDB

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