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By

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Theme

Application Of Magnetic Power-Split Device / CVT To Variable Speed Wind Turbine For Wind Power Generation

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ABSTRACT

For high power generation of future offshore wind turbine application, size and cost were the big challenge that must be overcome. Furthermore, the weight of lubrication system and the dimension of the mechanical gearbox must be taken into consideration. To overcome these problems, a new topology approach for wind power generation without mechanical gear is presented. Using magnetic gear coupled mechanically and magnetically with permanent magnet synchronous generator, even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached with this topology. For these, two original ideas have been presented. The first one, deals with magnetic gear generator which contains two rotors, the input rotor and the output rotor. The mechanical energy extracted from the wind turbine is transferred to the input rotor, which is transmitted magnetically to the output rotor. The permanent magnet of the output rotor interacts with the stator windings to produce electromagnetic torque. Thus, the power captured by the wind turbine is transmitted to the grid by the stator winding.

The second idea is the use of power-split magnetic gear. The power transmitted to the grid is split between the generated power by the permanent magnetic synchronous generator and the power produced or consumed by the magnetic gear generator. Thus, the dimension of the nacelle will be reduced and the mechanical gear box can be reduced or omitted.

Computer simulation results are given to verify the validity of the proposed machine. It appears that the disadvantages associated to future offshore wind turbine can be surmounted using magnetic gear generator.

Key Words: *Artificial neural network, magnetic gear, permanent magnet synchronous generator, wind turbine.*

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NOMENCLATURE

Symbols

A	Swept area of rotor
Br	Flux density
C_p	Power coefficient
dq	Park's reference frame
e	Voltage at the output inverter
G_r	gear ratio
i	Current
J_l	Inertia of the input rotor
J_s	Inertia of the output rotor
J_h	Inertia of the control rotor
L	Inductance
L_T	Overall inductance of the grid-side converter
n_s	Pole-pieces.
P	Active power
p	Pole-pairs
P_h	Pole-pairs of high speed rotor
P_l	Pole-pairs of low speed rotor
P_t	Wind turbine power
Q	Reactive power
R	Resistance
R_T	Overall resistance of the grid-side converter
s	Indicate the stator winding
T_e	Electromagnetic torque
T_l	Input torque
T_{lo}	Load torque
T_{max}	Maximum torque which can be produced by the magnetic gear
T_{mec1}, T_{mec2}	Mechanical torques

T_s	Output torque
$T_{turbine}$	Wind turbine torque
V	Wind speed
v	Stator voltage
v'	grid voltage
ω	Electrical angular velocity.
ω_r	Velocity of the permanent magnet
ω_h	Velocity of the high speed rotor
ω_l	Velocity of the low speed rotor
ω_s	Synchronous speed
ω_s	Velocity of ferromagnetic pole-pieces
θ_l,	Angular position of the input rotor
θ_h	Angular position of the control rotor
θ_s	Angular position of the output rotor
α	Angle of attack
β	Blade pitch angle
λ	Tip speed ratio
φ	Flux linkage
φ_{PM}	Flux of the permanent magnet
ρ	Air density
μr	Permeability

Abbreviations

ANN	Artificial neural network
CVT	Continuously variable transmission
DD	Direct-drive
DFIG	Doubly fed induction generator
EESG	Electrically excited synchronous generator
GWEC	Global Wind Energy Council
MPPT	Maximum power point tracking
MGG	Magnetic gear generator

PM	Permanent magnetic
PMSG	Permanent magnet synchronous generator
SCIG	Squirrel cage induction machine
SG	Synchronous generator
WRIG	Wound rotor induction generator

CHAPTER 1
INTRODUCTION

1.1. Background

The cost of electricity generated from wind turbines is no higher than that produced by fossil-fuel-generators. And there is good reason to think that the wind power will become a substantial source of electrical power throughout the world and could contribute to the reduction of CO2 emissions in the atmosphere [1].

International Greenpeace and the Global Wind Energy Council (GWEC) published their bi-annual report on the future of the wind industry. This shows that by the end of 2011, wind energy installations in the world would be raised to 240 GW, and that the industry is set to grow by at least another 40 GW in 2012. This means that wind power could supply up to 12% of the global electricity by the year 2020 [2].

Manufacturers have used a variety of generator concepts in their variable speed turbines. The doubly fed induction generator (DFIG), being the lightest, low-cost concepts and the rating of its power electronic converter is only 25-30% of the generator capacity, is used since 1990 and is still dominating the wind market. On the other hand, it needs a high-speed gearbox and extra maintenance. With the rapid development of wind turbine technologies, the future trends to the big size single wind turbine and to offshore wind energy [17]. This because turbine manufacturers have been looking for new directions. The permanent magnet synchronous generator (PMSG) concept seems to be the most promising [3].

Nowadays, the wind industry challenge is scaling up, cutting costs, and improving reliability. To fulfil that, some manufacturers replace the traditional gearboxes and high-speed generators with bigger low-speed generators which do not necessitate a geared transmission. Siemens company has begun selling a 3 MW turbine using direct-drive concept that replaces the conventional high-speed generator with a low-speed generator that eliminates the need for a gearbox [4].

Offshore wind turbine continues to be modest compared with onshore wind, with just 625 MW per annum between 2007 and 2011. This number has increased to just over 1 GW per year in the past two years. In parallel, the industry of onshore wind turbine has averaged over 30 GW globally in the same period. However, interest in the offshore sector continues to grow, with investors' commitments, policy support, and technological innovations [5].

Offshore wind is increasingly faced with pressure to deliver capacity on a large scale if it is able to reduce the costs in deeper waters. Installed offshore wind power capacity amounts to less than 2% of the total wind energy capacity installed worldwide. Currently, this amount reaches 4.62 GW, where offshore activations have become a regular and expanding contributor to wind power growth over the past decade. The share of offshore wind in Europe’s total wind additions peaked in 2010 at 9%, dropped off slightly in 2011 to 8%, and expected to jump to over 20% in 2012. The global offshore market is expected to reach 95 GW of installed wind energy capacity by 2025, which mean 13% of total global wind additions between 2012 and 2025 [5].

The wind turbine industry is continuously improving turbine designs to reduce the cost of wind energy. The most widely used method is to increase the power output of wind parks by increasing the power produced by each individual turbine. It is clear that by decreasing the number of machines per Mega-watt the operations and maintenance costs of the wind park could decrease [6].

1.2. Power System Worries

With rapid development of wind turbine technologies, the future of the wind turbine will be focused on huge single wind turbine to reduce the cost of placing wind turbine and offshore wind energy, due to higher wind speed and more space [6].

Bigger turbines reach higher in height above the earth's surface, where stronger winds blow. This allows them to extract more energy, and to work more efficiently. Using higher-capacity wind turbine reduces the number of turbines needed for a wind farm and results in dramatic reductions of the cost of wind energy [7].

Wind turbines have developed from an average of 700 kW to over 5 MW in the past decade. Due to reliable and efficient offshore wind energy, several offshore wind projects have been adopted. The offshore applications require lager turbine units, the sizes of wind turbine is about 7 MW at the present time and the largest turbines of the near future would be about 20MW [8].

This virtual 20 MW design is still impossible to manufacture and is uneconomic. Its weight would be about 880 tonnes standing on top of a tower, which means that the plan it not feasible; the support structures could not carry such a big generator, the lubrication system and the huge mechanical gearbox, elevated up to 153 metres in height [9, 12].

1.3. Purpose and Contributions

By removing the mechanical gearbox and the lubrication system, we reduce the nacelle size and weight. To achieve this goal, we used magnetic gear power-split.

The high-torque magnetic gear was invented and demonstrated by Pr. K. Atallah, University of Sheffield, in 2001 [13]. It uses permanent magnets to transmit torque between an input and output shaft without mechanical contact.

The mechanical gearbox is used extensively to increase the rotational speed of wind power generators. It is usually more costly and weights more when we use a high-speed electrical machine together with a gearbox to transform speed and torque. Too, mechanical gearbox requires lubrication and cooling, while noise, vibration and reliability can be significant issues. Magnetic gears offer several potential advantages over mechanical gears. For instance, a reduced acoustic noise and vibration, reduced maintenance and improved reliability, a precise peak torque transmission capability and physical isolation between input and output shafts [14].

The topology and high performance of magnetic gear have been presented [1] and it has been shown that by using rare-earth magnets, a high torque density can be achieved [15].

To overcome dimension problems of the nacelle, this work illustrates two new topologies using a magnetic power-split to a variable speed wind turbine. In the first one is used a magnetic gear with two rotors and without mechanical gearbox, the rated power is transmitted to the grid via the magnetic gear [16]. In the second method is used a magnetic gear with three rotors, the power transmitted to the grid is split between the generator and the power produced or consumed by the magnetic gear.

1.4. Thesis Layout

The main purpose of this thesis is the analysis of the application of the magnetic continuously variable transmission (CVT) in variable wind speed. To use the magnetic power-split, both the control and the modeling of the system is significant. The main contribution of this thesis is to give two new wind generator concepts without mechanical gearbox. Details are as follows:

Chapter 2 illustrates overview of different wind generator systems with comparisons. Chapter 3 describes the design and the performance of a magnetic gear that employs rare-earth magnets. Chapter 4 presents the first new topologies using magnetic gear generator for wind energy, even under low wind conditions often found inland, and without mechanical gear. High speed can be reached using this concept. Chapter 5 presents the second concept, this uses power-split magnetic gear to variable speed wind turbine, the rated power transmitted to the grid is split between the permanent magnetic synchronous generator and the power produced or consumed by the power-split magnetic gear. Chapter 6 conclusion and future work are presented.

CHAPTER 2

DIFFERENT WIND GENERATOR SYSTEMS

2.1. Introduction

As the use of wind power plants was increasing worldwide, various wind turbine concepts have been developed and different wind generators have been built. The wind energy conversion system is required to be as efficient and more cost-competitive as possible. So, comparisons of different wind generator systems are necessary.

Three main types of wind turbines are commonly being installed. The first one is a fixed-speed wind turbine system using a gearbox and a standard squirrel-cage induction generator directly connected to the grid. The second type is a variable speed wind turbine system with a gearbox and a doubly fed induction generator, in which the power electronic converter feeding the rotor winding has a power rating of 30% of the generator capacity and the stator winding is directly connected to the grid. The third type is also a variable speed wind turbine, but it is a gearless wind turbine system with a direct-drive synchronous and power electronic converter [17, 18, 19].

This chapter is arranged as follows: first, we give an overview of various wind turbine concepts with their advantage and disadvantage. Then follows quantitative comparisons of different wind generator systems are presented, including their market penetration. After that, the trends and developments of wind generator concepts are presented and comparison of different wind generator systems discussed. Finally, a challenge of future wind turbine is clarified.

2.2. Fixed Speed System

The first generating system is the oldest one. It consists of an induction generator, which is composed of a squirrel cage rotor and a stator with three distributed windings directly coupled to the grid through a transformer as illustrated in figure 2.1. The wind turbine rotor is coupled to the generator through a multiple-stage gearbox. This is the conventional concept applied by many wind turbine manufacturers during the 1980s and 1990s [17].

The fixed-speed wind turbine system often has two fixed speeds. This is accomplished by using two induction generators, one for low wind speeds (with lower synchronous speed) and the other for high wind speeds. One can also use a generator with two windings having different pairs. This leads to increased aerodynamic capture [20].

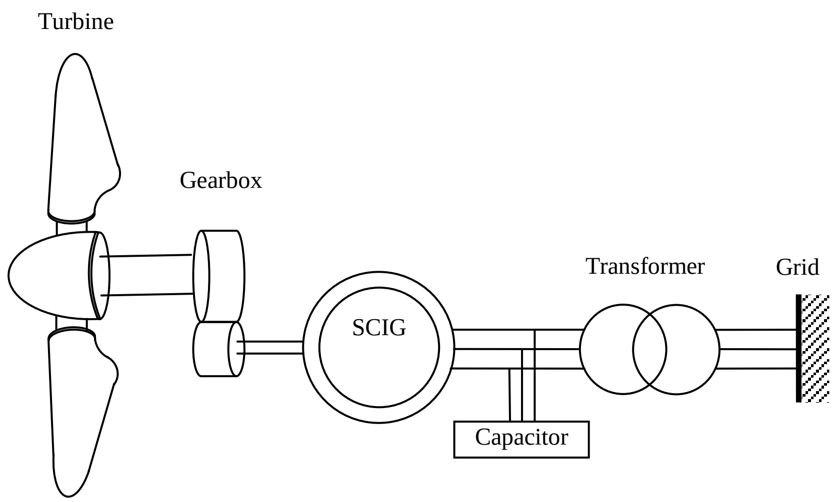


Fig. 2.1 Fixed speed concept with SCIG generator

The slip of a squirrel cage induction generator varies with the amount of power generated. Rotor speed variations are, however, very small, these are approximately 1 per cent [17, 21]. A squirrel cage induction generator always consumes reactive power, which is partly or fully compensated by capacitors in order to achieve one power factor.

The fixed-speed wind turbine has the advantage of being simple, robust and cheap. Although it allows stall-regulated generator when is connected to the grid, that is, stable frequency of the network. A simple pitch control method is generally combined with squirrel cage induction generator [17, 22].

There are several disadvantages of squirrel cage induction generator for the fixed speed wind turbine. The speed is not controllable and is variable only over a very narrow range, in which only speeds higher than synchronous speed are possible for generator operation. With high slip we get high dissipation of electrical energy in the rotor bars. Also, the fixed speed concept means that all fluctuation in the wind speed are transmitted as fluctuation in the mechanical torque followed by fluctuation in the electrical power on the grid. What results is large voltage fluctuations, which will result into significant line loses. This causes high mechanical and fatigue stresses on the system (turbine blades, gearbox and generator) and may result in swing oscillations between turbine and generator shaft. In addition, the turbine speed cannot be adjusted with the wind speed to optimise the aerodynamic efficiency. Although a pole-changeable squirrel cage induction generator has been used in some commercial wind turbines, it does not provide continuous speed variations. Moreover, a three-stage gearbox is necessary for this wind turbine concept, which makes the nacelle much heavier; this is also much more costly. And there is the reactive power consumption which is uncontrollable [17, 22].

2.3. Variable-Speed Systems

Due to the high wind turbines, the technology has switched from fixed speed to variable speed. To allow variable speed operation, the mechanical rotor speed and the electrical frequency of the grid must be decoupled. This means that the generator is partially or completely decoupled from the grid by a power electronics converter.

Currently the most common variable-speed wind turbine configurations are as follows [21, 23]:

- Limited variable speed concept,
- Variable speed concept with a partial-scale power converter,
- Variable speed direct-drive concept with a full-scale power converter.

2.3.1. Limited Speed Concept

The limited variable speed concept is known as the OptiSlip concept, which was applied by Vestas company since the mid 1990's [24]. In this concept, a wind turbine is connected to the wound rotor induction generator with variable resistance by means of a power electronic converter and pitch control method, as shown in figure 2.2. The stator is directly connected to the grid, while the rotor is connected in series with a controlled resistor. Variable-speed operation can be achieved by dissipating the energy collected by the rotor in the external resistor.

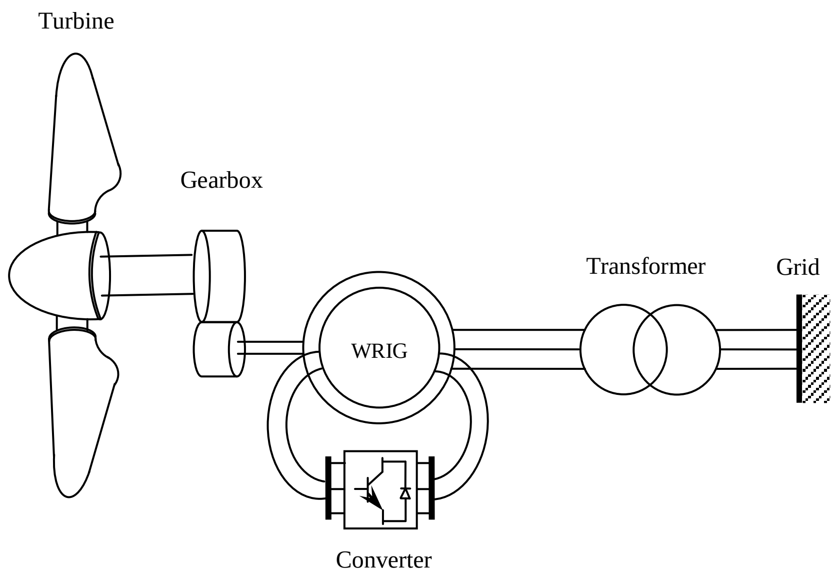


Fig. 2.2 Limited variable speed concept with WRIG.

Conversely, with the increase in variable speed range, means a high power dissipated in resistor, lower generator efficiency, and a higher rating resistor. A typical limited variable speed range is less than 10%. Moreover, reactive power compensation and a soft-starter are required for this concept [17, 24].

2.3.2. Variable Speed Concept with Multiple-Stage Gearbox.

Since wind speed varies, the mechanical power on the generator shaft cannot be kept constant when the rotor speed is fixed. With fixed speed concept we get mechanical oscillations in the drive train that contribute to variations in mechanical power and the major part of the mechanical power fluctuations will be transmitted into fluctuations in the electric output power. Because of that, and since 1990, most wind turbines over 1.5 MW output power have been changed to variable speed control concept. The variable speed control is necessary to get more efficiency of the turbine.

A wind turbine with variable speed pitch control has a multi-stage gearbox, a generator, a power electronic converter and a blade pitch system. The frequency of the generator is varied, for the grid connection we use the converter.

Between the cut-in wind speed and rated wind speed, the wind turbine of this concept is operated at fixed pitch with a variable rotor speed to maintain an optimal tip speed ratio. When the rated power is reached, the pitch control is used to maintain the rated power [24].

The advantages of this concept can be summarized as follows [24]:

- Improved output power quality, performed reactive power compensation and smooth grid connection.
- Increased energy capture.
- Reduced noise.
- Reduced mechanical stress of the drive train.

2.3.2.1. The Doubly Fed Induction Generator System

The doubly fed induction generator (DFIG) corresponds to a variable speed wind turbine with a wound rotor induction generator connected to the grid through the power electronic converter, as illustrated in figure 2.3. Since the rating of a power electronic converter could be reduced to 30% of rated power, it makes this generator more attractive and popular from an economic point of view. Typically, by controlling the rotor active power flow direction, a speed range of ± 30% around the synchronous speed can be obtained [24].

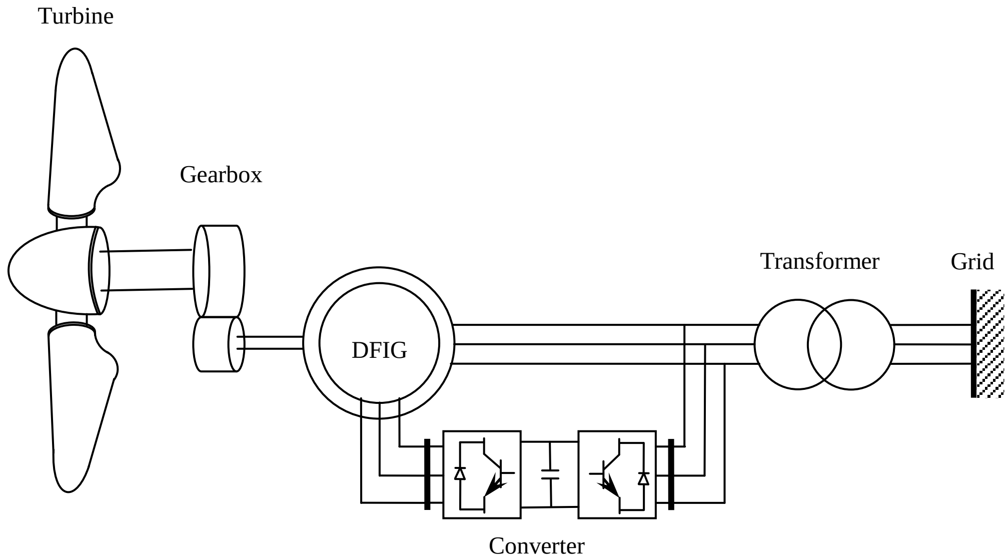


Fig. 2.3 Variable speed concept with DFIG.

Compared with the Optislip concept, the rotor energy is injected into the grid, instead of being dissipated into resistor. Also, the power converter system can perform reactive power compensation and smooth grid connection [17].

There are many manufacturers, such as Vestas, Gamesa, Repower, Nordex, using this DFIG in the market. The largest capacity for the commercial wind turbine product with DFIG has reached up to 5 MW from Repower [17].

However, the DFIG system has the following disadvantages [17, 24].

- Heat dissipation by friction of gearbox
- Regular maintenance of gearbox
- Audible noise from gearbox
- High torque peaks in the machine and large stator peak currents under grid fault conditions
- The slip ring is used to transfer the rotor power, which requires a regular maintenance, and maybe results in machine failures and electrical losses.
- Under grid fault conditions, on the one hand, the large stator currents result into large rotor currents. So, the power electronic converter needs to be protected

from being destroyed. On the other hand, large stator peak currents may cause high torque loads on the drive train of wind turbines.

- In case of grid disturbances, the control capability of DFIG is required which makes control strategies very complex. Detailed transient models and good knowledge of the DFIG parameters are needed to make a correct estimate of occurring torques and speeds.

2.3.2.2. Squirrel Cage Induction Generator System

A squirrel cage induction machine (SCIG), with a rotor connected to the grid via a power electronic converter, is also an alternative for variable speed. In this case, the capacitor bank is replaced by a full scale converter, which enables variable speed operation whatever the speed of the wind, as shown in figure 2.4.

Siemens is using this concept in the model of Bonus 107-3.6 MW on the market [24].

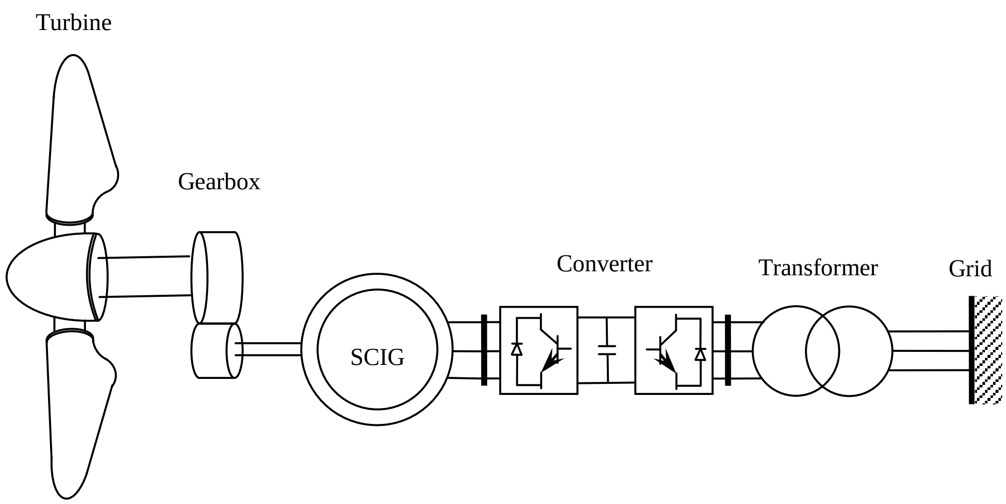


Fig. 2.4 Multiple-stage geared SCIG concept with full-scale converter.

2.3.2.3. Permanent Magnetic Synchronous Generator System

A permanent magnetic synchronous generator (PMSG) connected to the grid through a full scale converter is a possible configuration for a variable speed system. The converter converts the variable-frequency generator voltage into the grid frequency.

In recent years, the use of PMSG is more attractive than before because the performance of permanent magnetic (PM) is improving and the cost of PM has been decreasing. Currently, Harakosan and Mitsubishi are using this concept in 2 MW wind turbines in the market [17].

The advantages of PMSG can be summarized as follows[17]:

- Higher efficiency and energy yield,
- No additional power supply for the magnet field excitation,
- Absence of field losses,
- Lesser losses due to the absence of mechanical components such as slip rings,
- Lighter and therefore higher power to weight ratio.

However, PMSG have the following disadvantages [17]:

- High cost of PM material,
- Difficulties to handle in manufacture,
- Demagnetisation of PM at high temperature.

PM machines are not standard machines and they allow a great deal of flexibility in their geometry, therefore various topologies may be used. PM machines, based on the direction of flux penetration, can be classified into three types: radial flux, axial flux and transversal flux [16–28].

2.4. Variable Speed Direct-Drive Concept

Synchronous generators or permanent-magnet synchronous generators can be designed with multiple poles. This implies there is no need for a gearbox; see figure 2.5.The direct-drive generator rotates at low speed because the rotor of generator is directly connected on the hub of rotor blades. The direct-drive generator can be classified to two concepts: the electrically excited synchronous generator (EESG) and the permanent magnet synchronous one (PMSG).

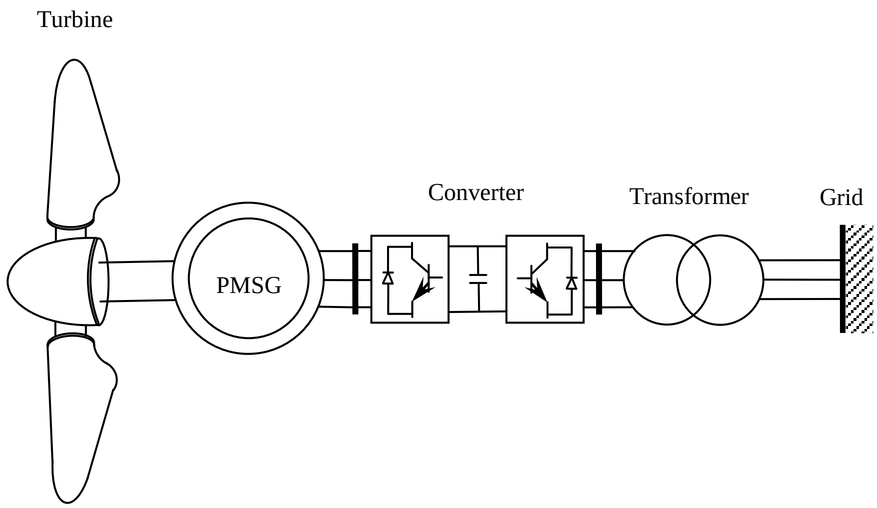


Fig. 2.5 Direct-drive PMSG concept.

The advantages of the direct-drive generator compared to the geared generator can be summarized as follows:

- Heavy and simple by omitting the gearbox
- High efficiency and reliability
- High availability
- Low noise

However direct-drive generators have the following disadvantages:

- Large weight and diameter of the generator
- High cost

While considering the energy yield and reliability, direct-drive systems seem to be more powerful than the geared ones, especially for the offshore [24].

2.4.1. Electrically Excited Synchronous Generator

The electrically excited synchronous generator (EESG) is directly driven by the turbine with a rotor carrying a DC field excitation system, figure 2.6. The control of the synchronous generators feeding the grid is indispensable to maintain the frequency and voltage constant at their rated values. The generator speed is fully controllable over a wide range, even to very low speeds [24, 25].

The main advantage of the EESG is that it can operate at any arbitrary power factor due to the independent control of the electrical excitation. Compared with geared generator it has normally a non-negligible manufacturing cost, generates some acoustic noise, requires regular maintenance (lubrication), and is also a potential cause of mechanical failure. The active and reactive power can be fully controlled in case of normal and disturbed grid conditions [24].

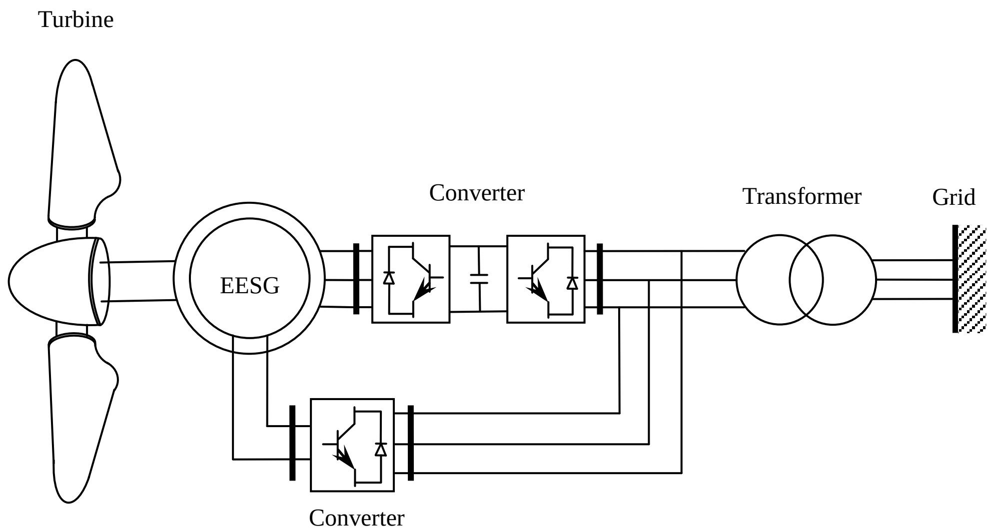


Fig. 2.6 Direct-drive EESG concept.

Some disadvantages of direct-drive EESG can be summarized as follows:

The cost of both generator and power electronic converter is considerably more expensive than a DFIG system. The converter has to process all the rated power which requires more expensive power electronic components and needs intensive cooling. Also, the generator needs a specific design and is very costly. Compared with normal electrical machines, it has to supply high electrical torques at low speeds. In addition, it is necessary to excite the rotor winding with DC, using slip rings and brushes, and in this case the field losses are inevitable [17, 24].

2.4.2. Permanent Magnetic Synchronous Generator

Direct-drive permanent magnetic generator system is more superior in terms of the energy yield, reliability, and maintenance problem [26]. That is why they are becoming more attractive; figure 2.5. The advantages of direct drive permanent magnetic synchronous machines can be summarized as follows [24, 26]:

- Higher efficiency and energy yield.
- No additional power supply for the magnet field excitation.
- Improvement in efficiency due to absence of field losses.
- Higher reliability due to absence of slip rings.
- Higher torque density.

The disadvantages of the direct-drive permanent magnetic synchronous generator are [26]:

- Relatively new technology for applications in larger MW-range
- Difficult assembly of the generator
- High costs of the permanent magnets
- Low material reliability in harsh atmospheric conditions (offshore)
- Demagnetization of PM at high temperature

Recently, the use of PM materials is more attractive, because the performance of PM materials is improving and the cost of PM materials is decreasing. The development makes PM machines with a full-scale power converter more attractive for direct-drive wind turbines. Currently, Zephyros (today's Harakosan) and Mitsubishi are using on the market this concept in 2 MW wind turbines [17].

2.5. Variable Speed Concept With Single-Stage Gearbox

In this scheme, a wind turbine is connected to a single-stage gearbox that increases the speed by a factor of roughly 10 and to low-speed permanent-magnet generator. This concept is shown in figure 2.7. This model has attracted attention because it has the advantages of a higher speed than the direct-drive concept and lower mechanical component than the multiple-stage gearbox one. Wind turbine manufacturers, such as Multibrid and Winwind, have products in the market based on this concept [17, 24].

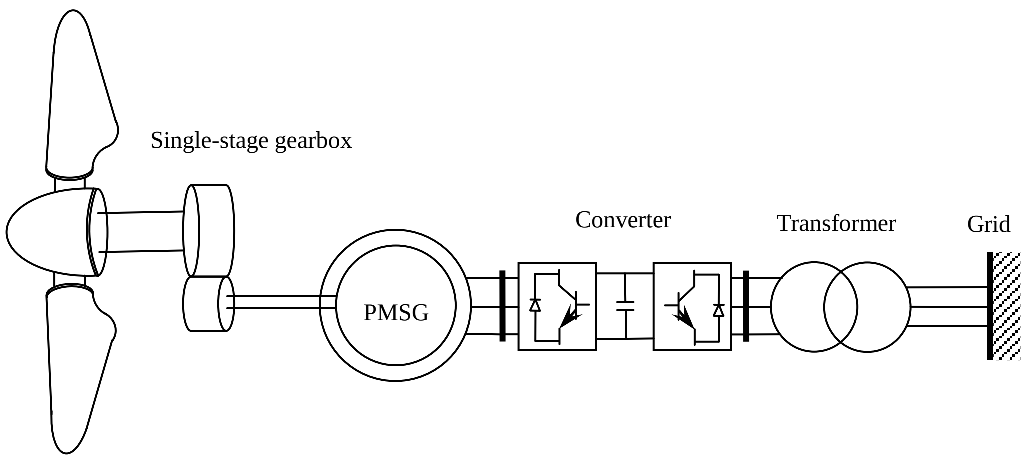


Fig. 2.7 Single-stage drive PMSG with full-scale coverter.

2.6. Variable Speed Concept With Hydraulic Gearbox System

Wind turbines that swap traditional mechanical gearbox for hydraulics could be lighter, more reliable, and less costly.

Instead of putting inside the nacelle the turbine blades, a multi-ton planetary gearbox, a synchronous generator and a cabinet full of electronics converts, why not just put a hydraulic pump there and let the hydraulic pressure spin a generator on the ground; figure 2.8.

Such hydraulic systems would eliminate the need for mechanical gearboxes. Consequently, the overall wind-turbine mechanics would be less complex. And a setup of this nature would decouple torsional vibrations generated in the rotor hub from the generator. Also, a hydraulic pump would have less inertia and thus would let the turbine begin generating power in lighter winds. So, such systems would have lower operating costs.

But there is some disadvantage to this concept. The hydraulic solution would be from 10 to 30% less efficient than the electromechanical system. There are line losses encountered in moving the hydraulic fluid up and down the length of the tower for a split system. And it is not easy to scale up multimegawatt turbines [27].

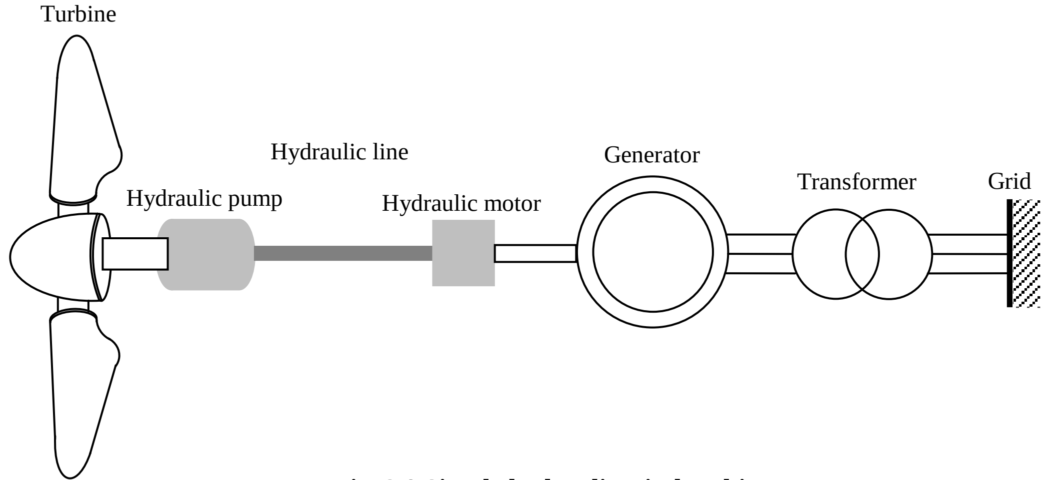


Fig. 2.8 Simple hydraulic wind turbine.

2.7. Performance Comparisons

Different generators concept of the wind turbines have been discussed by a number of authors [28-32].

According to [28, 17], the diameter of the direct drive PMSG is two times longer than that of geared-drive SCIG. But, the total length is two to three times shorter than that of SCIG. Also, the direct-drive PMSG system has its average efficiency of 2.3% and 1.6% higher than the fixed speed SCIG system at the 500 kW and 3 MW rated power, respectively. Furthermore, the direct-drive PMSG system can produce 5–10% more energy than the fixed two-speed concept, or 10–15% more than the fixed single-speed one. The detailed results are given in Table 2.1.

Table 2.1 Comparison of the direct-drive PMSG and the fixed-speed SCIG concepts [17]

Generators concepts	PMSG	SCIG	PMSG	SCIG
Rated power, KW	*500*	*500*	*3000*	*3000*
Outer diameter of generator, m	*2.7*	*1.5*	*5*	*2.5*
Length of system	*1.2*	*3*	*2*	*6*
Average efficiency, %	*90.7*	*88.4*	*91.6*	*90.0*

On the other hand, comparison between the direct-drive PMSG and the geared-drive SCIG of 500 kW wind turbines was shown in Table 2.2. The annual energy production of the direct-drive PMSG is higher than that of the geared-drive conventional SCIG. Although the wind turbine rotor diameter of the direct-drive PMSG is greater than that of the geared-drive SCIG, the total weight of the rotor and nacelle is lower [29, 17].

Table2. 2 Comparison of two 500 KW wind turbines with the direct-drive PMSG and fixed-speed SCIG system [17].

Generators concepts	PMSG	SCIG
Speed of wind turbines rotor, rpm	*18-38*	*30*
Speed of generator rotor, rpm	*18-38*	*1500*
Annual energy production at mean wind speed, KWh		
5 m/s	*615*	*525*
10 m/s	*2350*	*2189*
Wind turbine rotor diameter, m	*40.3*	*38.2*
Wind turbine weight, ton		
Rotor, including hub	*20.5*	*9.2*
Nacelle	*5.6*	*19.9*
Rotor + nacelle	*26.1*	*29.9*
Tower	*34.0*	*27.8*
Total	*60.1*	*56.9*

In [31, 32, 17], a 1.5 MW direct-drive wind turbine system with EESG is compared with the DFIG system having a multi-stage gearbox. It is mentioned that the direct-drive system would be more expensive and heavier than the DFIG wind turbines. Also, the comparison between the direct-drive PMSG and EESG shows the cost for active material of PMSG is lower.

In [30, 17] are presented comparison of five 3 MW different generator systems for variable speed wind turbine concepts. The dimensions and performances of the comparison are presented in Table 2.3. The outer diameter of the direct-drive wind generator is usually larger than the geared-drive generator, but the total length is shorter. It is clear that the DFIG3G is the lightest, low cost solution, explaining why it is most widely-used commercially. However, it has a low energy yield due to the high losses in the gearbox. For direct-drive wind turbine topologies, PMSG DD has the highest energy yield, EESG DD appears to be the heaviest and most expensive concept. PMSG 1G has a better performance than PMSG DD with respect to the energy yield per cost.

Table 2.3 Comparisons of five wind generator concept [17].

Generators concepts	DFIG 3G	EESG DD	PMSG DD	PMSG 1G	DFIG 1G
Stator air-gap diameter, m	*0.84*	*5*	*5*	*3.6*	*3.6*
Stack length, m	*0.75*	*1.2*	*1.2*	*0.4*	*0.6*
Active material weight, ton					
Iron	*4.03*	*32.5*	*18.1*	*4.37*	*8.65*
Copper	*1.21*	*12.6*	*4.3*	*1.33*	*2.72*
PM			*1.7*	*0.41*	
Total cost, KEuro	*5.25*	*45.1*	*24.1*	*6.11*	*11.37*
Generator active material	*30*	*287*	*162*	*43*	*67*
Generator construction	*30*	*160*	*150*	*50*	*60*
Gearbox	*220*			*120*	*120*
Converter	*40*	*120*	*120*	*120*	*40*
Sum of generator system cost	*320*	*567*	*432*	*333*	*287*
Total cost KWh/Euro	*1870*	*2117*	*1982*	*1883*	*1837*
Annual energy yield, MW h	*7690*	*7740*	*7890*	*7700*	*7760*
Annual energy yield / total cost, KW h/Euro	*4.11*	*3.67*	*3.98*	*4.09*	*4.22*

2.8. Market Status

Table 2.4 shows some wind turbines with a rated power over 2 MW from different manufactures, in which the concept, generator type, rated power and manufactures are summarized.

As it can be seen, most manufactures are using geared-drive wind turbine concepts. Also, it is clear that the wind market is still dominated by DFIG with a multiple-stage gearbox and the mostly used generator type is still the induction generator (DFIG, SCIG and WRIG).

Table 2.4 Wind turbine concepts on the market over 2 MW [17]

Wind turbine concept	Generator Type	Power / Rotor diameter / Speed	Manufacturer
Variable speed multiple-stage concept with partial-scale power converter	DFIG	*4.5 MW / 120 m / 14.9 rpm*	Vestas
		2 MW / 90 m / 19 rpm	Gamesa
		3.6 MW / 104 m / 15.3 rpm	GE Wind
		5 MW / 126 m / 12 rpm	Repower
		2.5 MW / 90 m / 14.85 rpm	Nordex
		3 MW / 100 m / 14.25 rpm	Ecotecnia
Limited variable speed with multiple-stage gearbox	WRIG	*2 MW / 88 m / 17 rpm*	Suzlon
Variable speed multiple-stage gearbox with full-scale power converter	SCIG	*3.6 MW / 107 m / 13 rpm*	Siemens Wind Power
	PMSG	*2 MW / 88 m / 16.5 rpm*	GE Wind
Variable speed single-stage gearbox with full-scale power converter	PMSG	*5 MW / 116 m / 14.8 rpm*	Multibrid
		3 MW / 90 m / 16 rpm	Winwind
		2.5 MW / 93 m / 15.5 rpm	Clipper Windpower
Variable speed direct-drive with full-scale power converter	EESG	*4.5 MW / 114 m / 13 rpm*	Enercon
	PMSG	*2 MW / 71 m / 23 rpm*	Zephyros

Figure 2.9 presents an overview of the market share for each wind turbine concept over the years 1995-2005. As it can be seen, the fixed-speed SCIG concept has decreased about threefold over 11 years, from almost 70% in 1995 to less than 20% in 2005. Market penetration of WRIG has declined since 1997 in favour of the more attractive variable speed concept DFIG. It is clear that WRIG is being phased out of the market. The DFIG has increased from 0% up to more than 60% of the yearly installed wind power over 11 years, becoming the most dominant concept by the end of 2005. Market penetration of SG concept (EESG or PMSG) has altered little over the years. During the analyzed years, SG concept has ranked third or fourth [33].

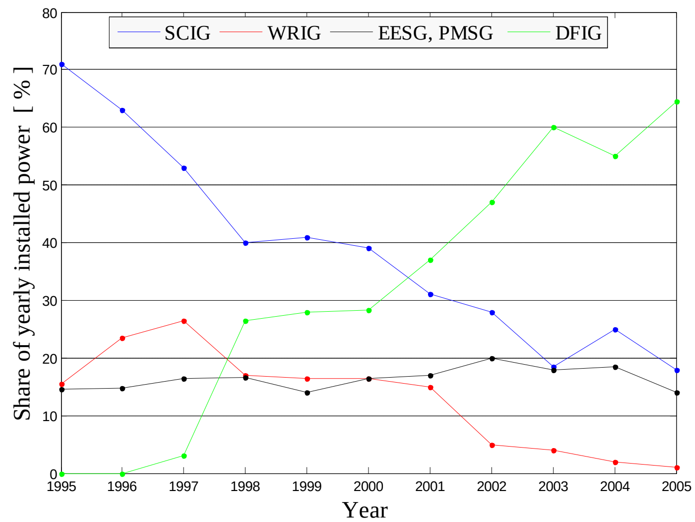


Fig. 2.9 World share of yearly installed power for different wind generator systems [33].

2.9. Technology Trends

With fast development of wind turbine technologies, future trends in the wind turbine industry will be focused on:

- Super-large wind turbine designs: since 2003, attention has been focused on 1.5 MW wind turbine and there is higher demand for these products. Today, only two real concepts in the MW size exist within the industry and the difference is limited to using a gearbox with an asynchronous generator or a synchronous ring one [17, 34]. On the engineering side, they focused on scaling-up wind turbines so as to improve mechanical strength for rotor blades. Up to now, the research works for super-large wind turbine designs in particular for offshore wind turbine power generators are rated at 10 MW to 20 MW [17, 35].
- Offshore site production: unlike offshore site production, few sites are available on land where the wind profile is appropriate for wind power generation. Out at sea there can be up to 40% more wind than on land. In addition, wind turbine sizes are increasing to more efficiently capture wind energy. With increasing sizes, the systems can be transported more easily via water than overland. For this reason, the offshore wind farms sites productions have been increasing, yet their technology has not yet been developed to its full potential. Everything

indicates that the future of offshore production projects will be more promoting [36, 39].

- Direct drive wind turbine: to cut costs and improve reliability, the industry is trying to scale up the equipments of wind energy system. The wind turbine market of direct drive is growing fast since the last years; it has a better efficiency and reliability. Direct drive technology is captured approximately up to 17.4% share in global wind turbine market for the year 2010 and it is expected to capture up to 24.3% of overall wind turbine installation by 2016 [40, 41]. Furthermore, the use of permanent magnetic PM machines is becoming more attractive than ever before because the performance of PM materials is improving and the cost of PM materials is decreasing during the recent years. These advantages make direct drive PM wind generator systems more attractive for wind turbine concepts, especially for offshore applications [26]. It is expected that larger low-speed generators that don't require geared transmission will replace traditional gearboxes and high-speed generators.

2.10. Large Turbine Challenge

The goal of a larger turbine is to increase efficiency by capturing more wind energy using longer blades. Thanks to reliable and efficient offshore wind energy, several offshore wind projects have been adopted. The offshore applications require larger turbine units, the sizes wind turbine is about 7 MW at the present time and the largest turbines in the near future would be about 20MW. Danish company Vestas was offered its 7 MW offshore giant in 2011, GE Global Research announced the development of generator to support large-scale wind turbines in the 10-15 MW range. Also, UpWind, starting with a reference 5 MW wind turbine, has initially extrapolated this reference design to upscale it to 10 MW, and then up to 20 MW [43, 45].

This virtual 20 MW design was impossible to manufacture and it is uneconomic. It would weigh 880 tonnes on top of a tower making it impossible to carry and support such a mass. The blade wall thickness would also exceed 30 cm, which puts constraints; the blade length would also require new types of fibres in order to resist the loads [45].

2.11. Conclusions

The development, configurations and characteristics of different wind generators concepts, with their advantages and disadvantages, have been reviewed. A detailed analysis has been presented with the quantitative comparison of different wind generator concepts as well as their market penetration. The developing trends of wind generator systems have been presented and some wind systems challenges exposed.

The multiple-stage geared drive DFIG concept is still dominant in the current market, due to the fact that it is the lightest and is a low cost solution. However, it has a low energy yield because of high losses in the gearbox.

Additionally, the market shows interest in the permanent magnet direct drive with a full-scale power electronic converter. The performance of permanent magnets PMs is improving and the cost of PMs is decreasing in the recent years. This makes variable speed direct-drive PM machines with full-scale power converter more attractive for offshore wind power generations. In one word, permanent magnet direct drive turbines are the future of wind energy generation.

Big MW-size turbines, due to the pressure of reducing the energy cost, have become the dominant machines in the commercial market. In the near future wind turbine rated power would attain 10 MW. Thus, the current developments of wind turbine concepts are more and more being directed to offshore wind energy.

CHAPTER 3

MAGNETIC POWER-SPLIT CONTINUOUSLY VARIABLE TRANSMISSION CVT

3.1. Introduction

Mechanical gearboxes are used extensively both for increasing and decreasing the rotational speed. However, they cause vibration, wear and noise by reason of direct contact. Also, the more we employ a high-speed electrical machine together with a gearbox to transform speed and torque, the more it is costly and heavier. Not to mention that lubrication is needed for practical use. A magnetic gear having no direct contact solves all these problems. In 2001, the high-torque magnetic gear was invented and demonstrated by Dr Kais Atallah, University of Sheffield, U.K [46]. A magnetic gear uses permanent magnets to transmit torque between an input and output shaft without mechanical contact. This means no wear and lubrication is required. Magnetic gears offer several advantages, such as lubricant-free operation, reduced maintenance costs, quiet operation between the input and output shafts, physical isolation between input and output shafts, and inherent overload protection [47, 52]. The topology and a high performance of magnetic has been presented in [50], simulation and experimental studies have shown that this gear has a transmitted torque density capability comparable with three-stage helical gearboxes, viz. 50-150 KNm/m^3 [15]. They also can be used as magnetic torque-limiter; the gear will harmlessly slip when a torque reaches the reference torque [51].

This chapter describes the design and performance of a magnetic gear topology employing rare-earth magnets. Its principle of operation was introduced in [50]. Such a magnetic gearbox could offer significant advantages in applications like wind power generation.

3.2. Topologies Of Magnetic Gearbox

The magnetic gear topology shown in figure 3.1, whose principle of operation was introduced in [50]. It consist of three components; an inner permanent magnet rotor with p_h pole-pairs, an outer permanent magnet rotor with p_l pole-pair and ferromagnetic pole-pieces n_s between the two rotors.

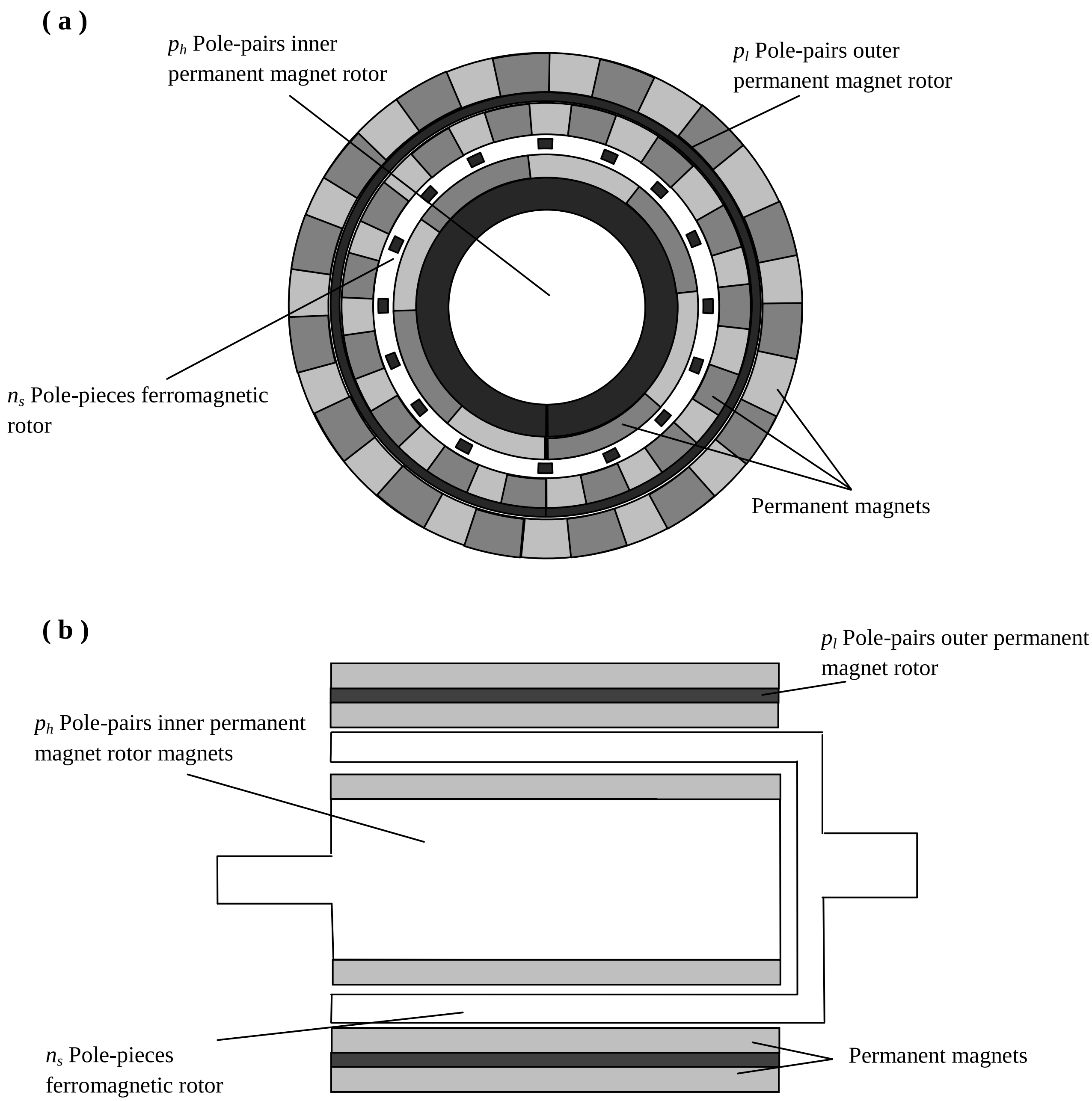


Fig. 3.1 The magnetic gear.
(a) Radial cross section. (b) Axial cross section.

3.3. Principle Of Operation

The number of pole-pairs in the space harmonic flux density distribution produced by either the high or low speed rotor permanent magnets is given by [50]:

$$p_{m,k} = |mp + kn_s|$$
$$m = 1, 3, 5, 7, \dots, \infty \qquad (3.1)$$
$$k = 0,\ \pm 1,\ \pm 2,\ \pm 3, \dots,\ \pm\infty$$

p is the number of pole-pairs on permanent magnet rotor, and n_s the number of stationary steel pole-pieces.

The rotational velocity of the flux density space harmonics is given by [4]:

$$\omega_{m,k} = \frac{mp}{mp + kn_s}\omega_r + \frac{kn_s}{mp + kn_s}\omega_s \qquad (2.3)$$

ω_r and ω_s are the rotational velocity of the permanent magnet rotor and ferromagnetic pole-pieces respectively. To transmit torque at a different rotational speed, the number of pole-pairs of the other permanent magnet rotor must be equal to the number of pole-pairs of a space harmonic for which $k \neq 0$ [15].

The gear ratio is given by [50]:

$$G_r = \frac{|mp + kn_s|}{mp} \qquad (3.3)$$

Since the combination m = 1, k = -1, results in the highest asynchronous space harmonic and the gear ratio is then given [15]:

$$G_r = \frac{n_s - p}{p} \qquad (3.4)$$

To illustrate the variation of flux density distribution of magnetic gear, we take the simulation studies in [50]. Table 3.1 gives the parameters of the magnetic gear, shown in figure 3.1.

Table 3.1
Parameters of magnetic gear [50]

Parameter	
Number of pole-pairs on high speed rotor	$p_h = 4$
Number of pole-pairs on low speed rotor	$p_l = 22$
Number of stationary steel pole-pieces	$n_s = 26$
Air gap length	*1 mm*
Outside diameter	*140 mm*
Remanence of sintered NdFeB	$Br = 125\ T$
Relative recoil permeability of sintered NdFeB	$\mu r = 1.05$

3.3.1. Flux Density Waveforms

[15, 50, 54, 55] have shown the variation of the radial component of flux density. The modulation of the magnetic fields produced by each of the permanent magnet rotors by the ferromagnetic pole-pieces, such that appropriate space harmonics having the requisite number of poles as the associated permanent magnet rotor result. The flux density distribution at a radial distance r produced by either permanent magnet rotor is given in [15].

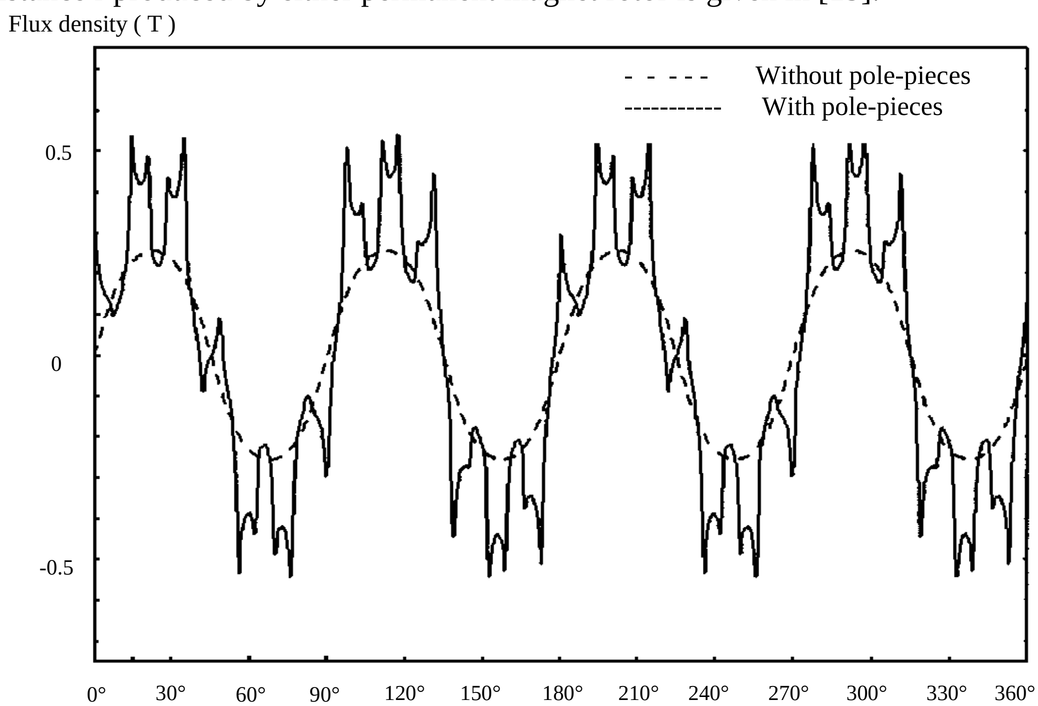


Fig. 3.2 Variation of radial flux density due to high speed rotor adjacent to low speed rotor [50].

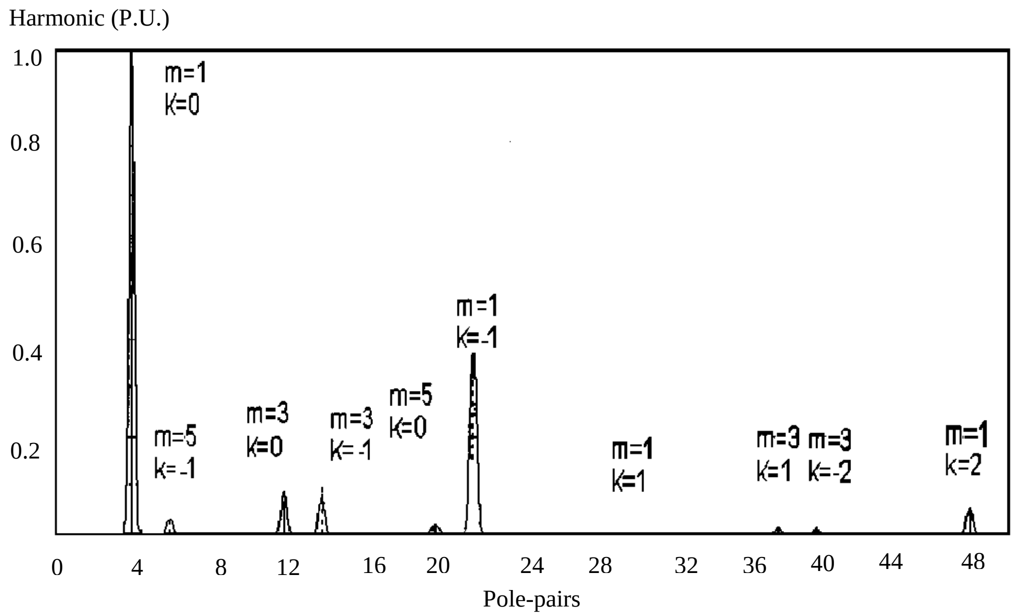


Fig. 3.3 Space harmonic spectrum of radial flux density due to high speed rotor adjacent to low speed rotor [50].

Figure 3.2 shows the variation of the radial component of flux density due to the high speed rotor permanent magnets in the airgap adjacent to the low speed rotor, while the ferromagnetic pole-pieces are stationary, i.e. $\omega_s = 0$. And figure 3.3 shows the corresponding space harmonic spectrum. It can be seen that the presence of the steel pole-pieces results in a number of asynchronous, *viz.* $k \neq 1$, space harmonics, the largest of which is the 22 pole-pair space harmonic, (m = 1, k = -1), which interacts with the 22 pole-pair low speed rotor permanent magnets to transmit a torque at a rotational velocity [50, 56]:

$$\omega_l = \frac{p_h}{p_h - n_s}\omega_h = -\frac{1}{5.5}\omega_h \qquad (3.5)$$

ω_h and ω_l are the rotational velocities of the high and low speed rotors respectively.

In the same way, figure 3.4 shows the variation of the radial component of flux density due to the low speed rotor permanent magnets in the airgap adjacent to the high speed rotor, while the ferromagnetic pole-pieces are stationary, i.e. $\omega_s = 0$.

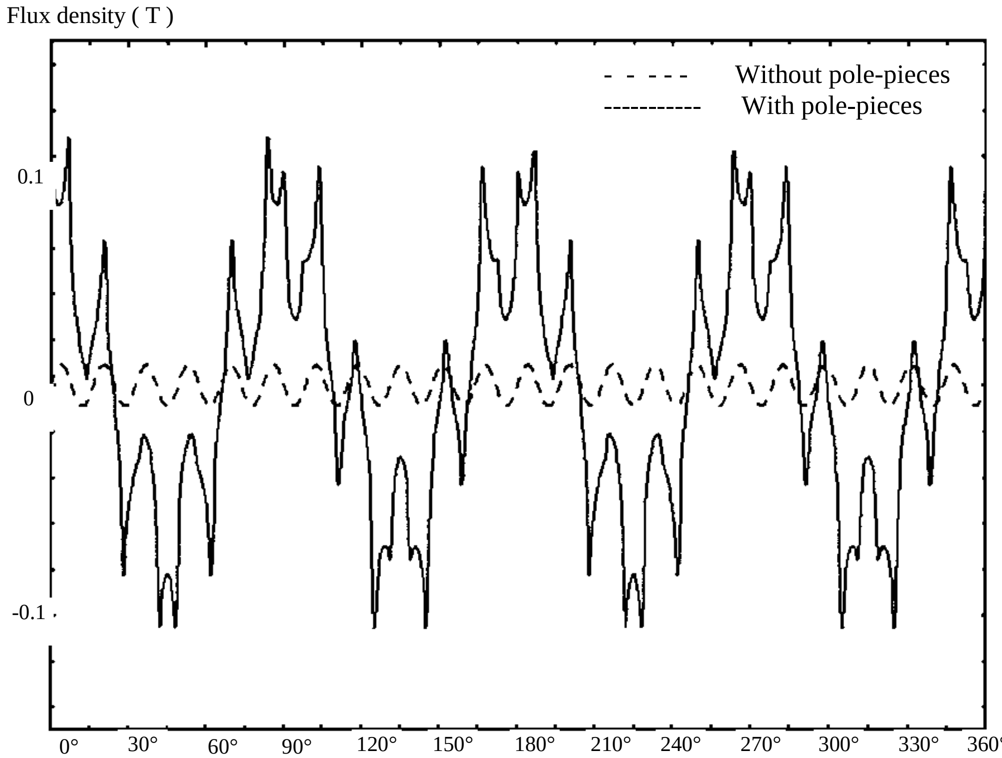


Fig. 3.4 Variation of radial flux density due to low speed rotor adjacent to high speed rotor [50].

And figure 3.5 shows the corresponding space harmonic spectrum. It can be seen that the presence of the steel pole-pieces results in a dominant 4 pole-pair asynchronous space harmonic, (m = 1, k = -1), which interacts with the 4 pole-pair high speed rotor permanent magnets to transmit torque at a rotational velocity [50, 56]:

$$\omega_h = \frac{p_l}{p_l - n_s}\omega_l = -5.5\omega_l \tag{3.6}$$

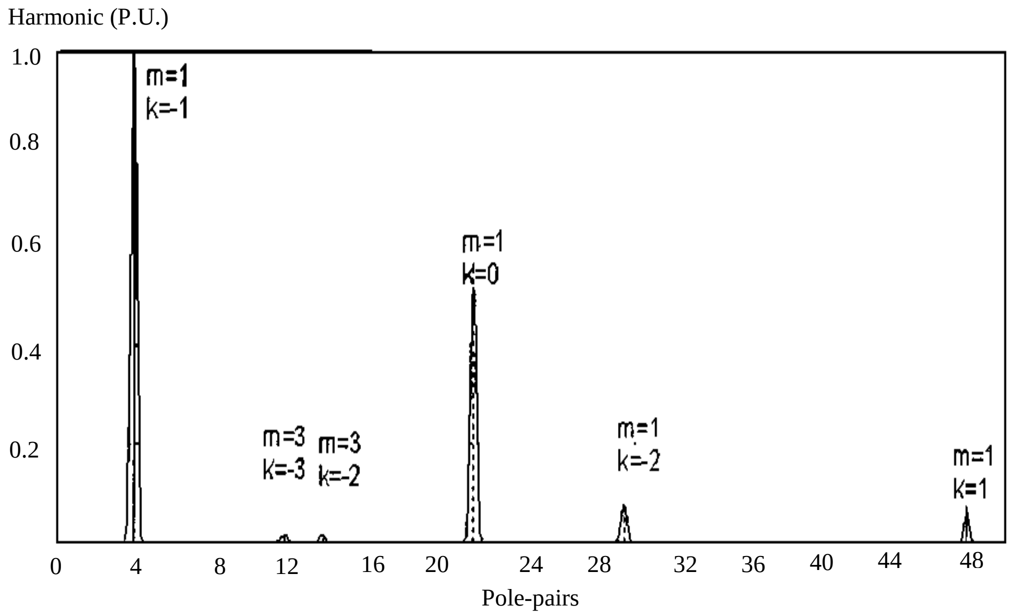


Fig. 3.5 Space harmonic spectrum of radial flux density due to low speed rotor adjacent to high speed rotor [50].

3.3.2. Torque Transmission

Figure 3.6 and figure 3.7 illustrate the variation of the maximum torque which is exerted on the high and low speed rotors as they rotate. As can be seen, a transmitted torque density can be reach high value [50, 57, 58]. As well, it had demonstrated in [15] that the maximum torque varies with the radial thickness of the pole-pieces which mean that an optimum thickness for the pole-pieces exists that result in the maximum torque transmission capability. Also the choice of the combination of the number of pole-pairs on the input and output rotors and number of pole-pieces has a significant influence on the maximum torque transmission.

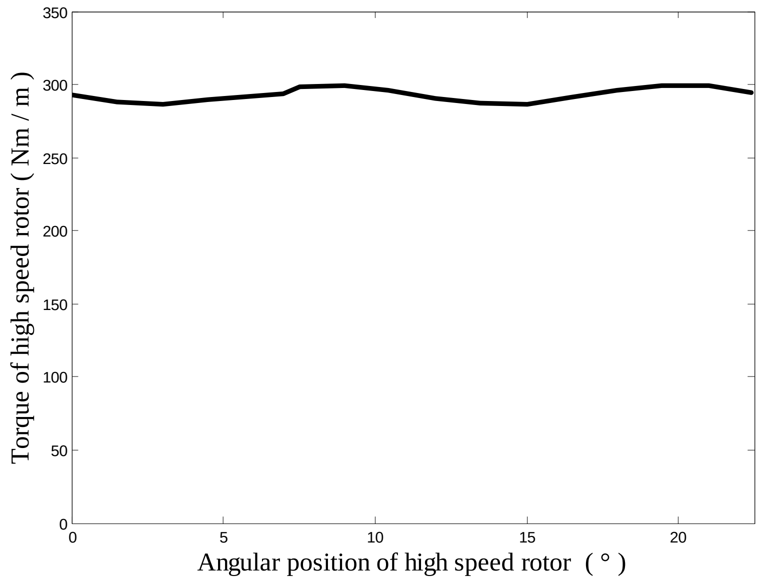


Fig. 3.6 Variation of maximum torque on high speed rotor [50]

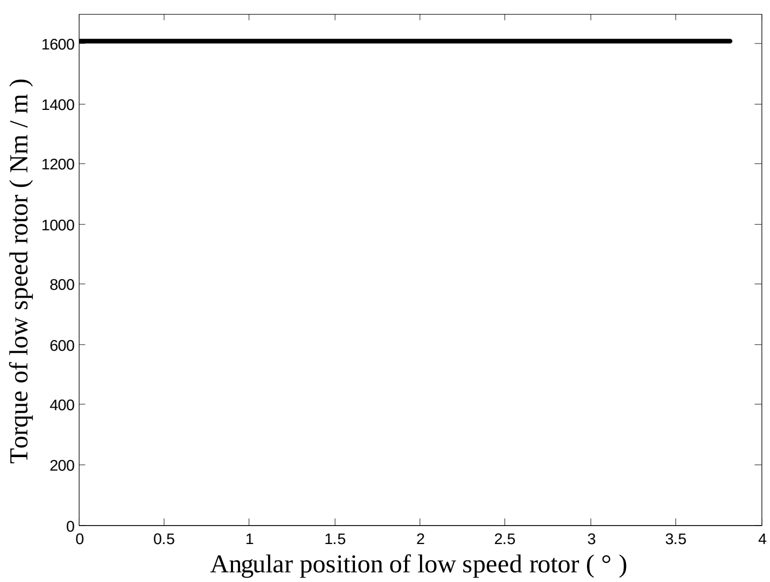


Fig. 3.7 Variation of maximum torque on low speed rotor [50].

3.3.3. Cogging Torque

It is important to consider the cogging torque since this may be detrimental to the performance of the magnetic gear. The cogging torque results from interaction between the ferromagnetic pole-pieces and both the input rotor and the output rotor, qualitatively, the cogging torque is determined by the cogging torque factor, $2p\, n_s / N_c$, where N_c is the smallest common multiple between the number of poles *2p* (*2p_h* or *2p_l*) and the of ferromagnetic pole-pieces n_s [54, 59]. For the magnetic gear, table 3.1, p_h = 4, p_l = 22, n_s = 26, the cogging torque factor is 2.

3.3.4. Equation Of Motions

The equation relating the motions of the different components of the gear is given by [50]:

$$p_h \omega_h + p_l \omega_l = n_s \omega_s \qquad (3.7)$$

To have a fixed-ratio magnetic gear, one of the three components of the gear is held stationary, while the other components are connected, so we have three cases:

- **Stationary pole-piece array ($\boldsymbol{\omega}_\mathbf{s}$ = 0)**

According to the equation 3.7, the gear ratio is:

$$G_r = -\frac{p_l}{p_h} \qquad (3.8)$$

- **Stationary outer magnet array ($\boldsymbol{\omega}_\mathbf{h}$ = 0)**

According to the equation 3.7, the gear ration is:

$$G_r = \frac{n_s}{p_l} \qquad (3.9)$$

- **Stationary inner magnet array ($\boldsymbol{\omega}_\mathbf{l}$ = 0)**

From the equation 3.7, the gear ration is:

$$G_r = \frac{n_s}{p_h} \qquad (3.10)$$

According to the equation 3.7, if the input shaft is connected to the inner magnet array and the output shaft is connected to the pole-piece array, the speed of the output shaft can be written as follows:

$$\omega_s = \frac{p_l}{n_s}\omega_l + \frac{p_h}{n_s}\omega_h \qquad (3.11)$$

And the output torque T_s is related to the input torque T_l as follows:

$$T_s = \frac{n_s}{p_l} T_l \qquad (3.12)$$

From equation 3.7, it can be seen that even if the input speed $\boldsymbol{\omega}_l$ varies, the output speed $\boldsymbol{\omega}_s$ can be kept constant by controlling $\boldsymbol{\omega}_h$.

3.4. Wind Energy Application

This work describes approach to creating a machine by combining a magnetic gear and permanent magnet synchronous machine both mechanically and magnetically [54].

Figure 3.8 shows a schematic of the proposed magnetically and mechanically coupled magnetic gear and synchronous machine. For a given input speed, which is governed by the turbine speed, the output speed is maintained at the synchronous speed by controlling the speed of the control rotor of the magnetic gear.

3.4.1. Electromechanical Modelling

For the magnetic gear machine shown in figure 3.8, the input shaft is connected to the inner magnet rotor, the output shaft is connected to the pole-piece rotor and the outer magnet rotor is used like controller rotor

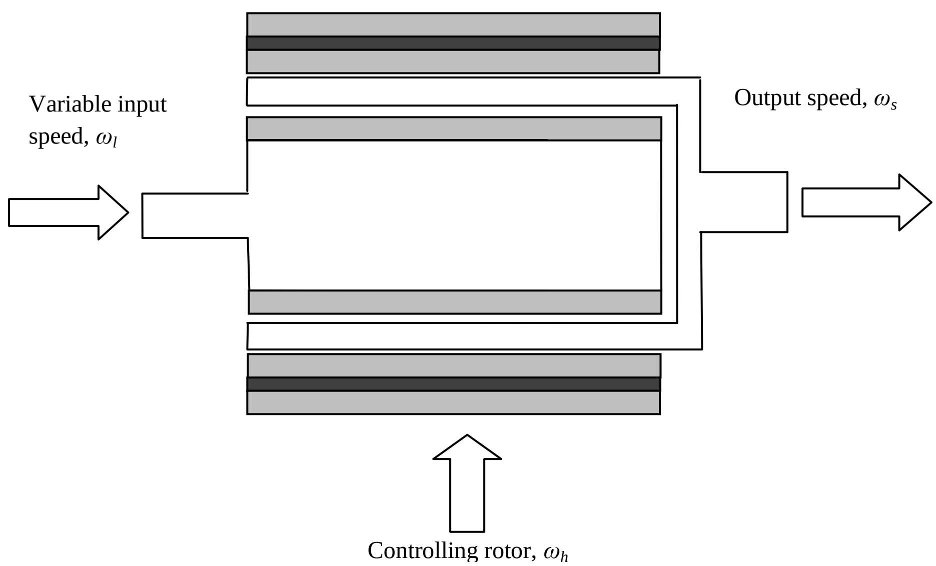


Fig. 3.8 Magnetic gear under variable speed.

To see the behaviour of the magnetic gear, the input shaft is connected to the variable speed, the output shaft is connected to variable load and we used the controlling rotor to kept the output shaft to a reference speed ω_s^*.

Since the torque is transmitted magnetically from the input rotor to the output rotor, the equations which govern the motion of the input rotor, output rotor and the ferromagnetic rotor are [51, 53, 54, 59]:

$$J_l \frac{d\omega_l}{dt} = T_{mec\,1} - T_{max}\,\frac{p_l}{n_s}\sin(p_l\theta_l + p_h\theta_h - n_s\theta_s) \tag{3.13}$$

$$J_h \frac{d\omega_h}{dt} = T_{mec\,2} - T_{max}\,\frac{p_h}{n_s}\sin(p_h\theta_h + p_l\theta_l - n_s\theta_s) \tag{3.14}$$

$$J_s \frac{d\omega_s}{dt} = -T_{lo} - T_{max}\,\sin(n_s\theta_s - p_h\theta_h - p_l\theta_l) \tag{3.15}$$

Where θ_l, θ_s and θ_h are the angular position of the input rotor, the output rotor and the control rotor respectively, T_{max} is the maximum torque which can be produced by the magnetic gear, J_l, J_s and J_h are the inertia of the input rotor, the output rotor and the control rotor respectively, T_{mec1}, T_{mec2} are the mechanical torques and T_{lo} is the load torque.

3.5. Simulation Studies

A control scheme of the magnetic gear is represented in figure 3.9.

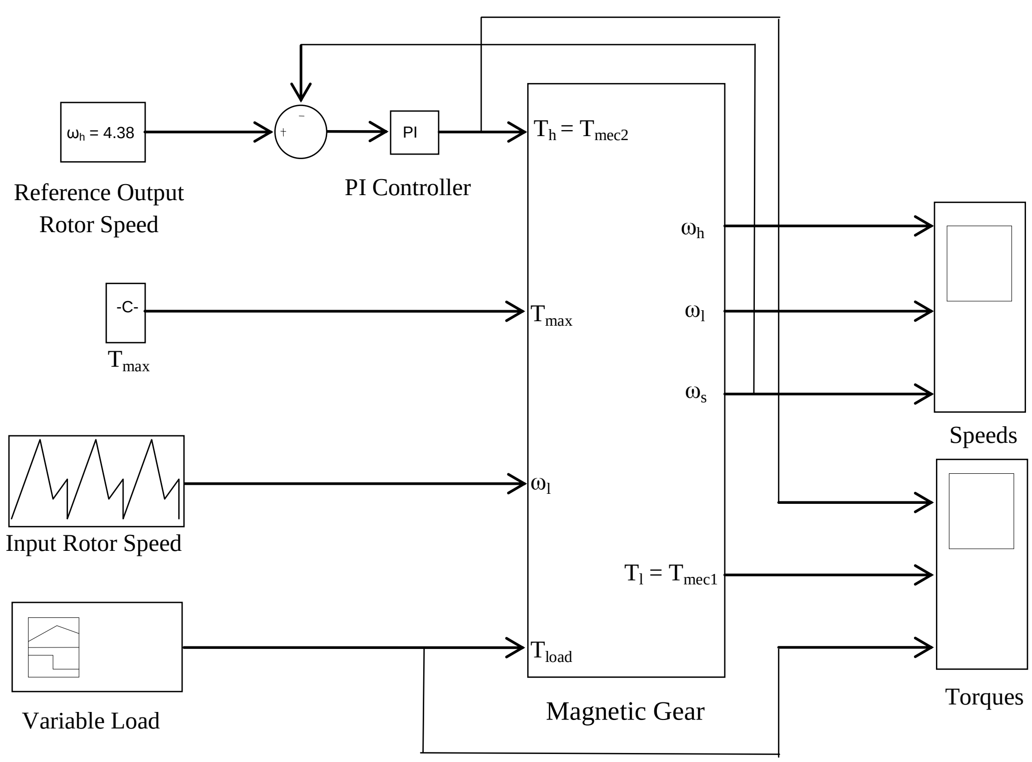


Fig. 3.9 A control scheme of magnetic gear

To check the behaviour of the magnetic gear, a dynamic simulation is implemented using variable speed in the input shaft figure 3.10 and variable load in the output shaft figure 3.11.

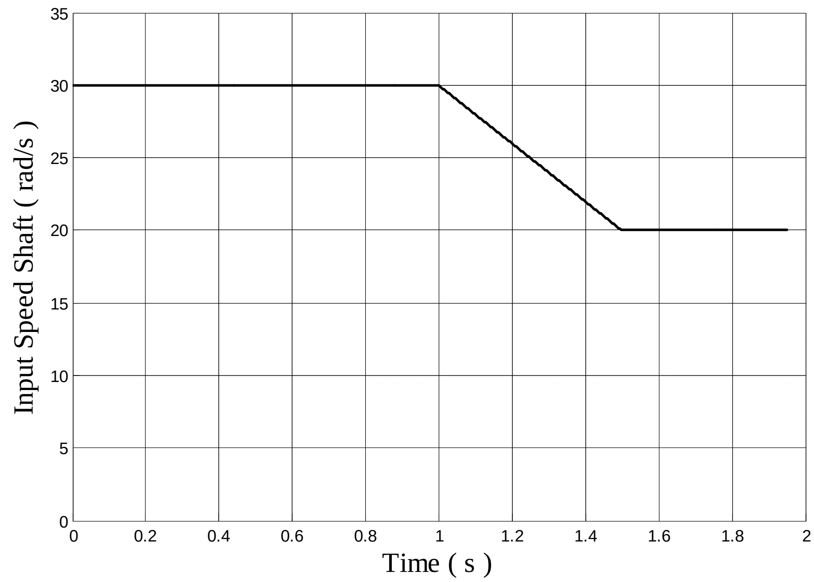


Fig. 3.10 Variable speed of the input rotor.

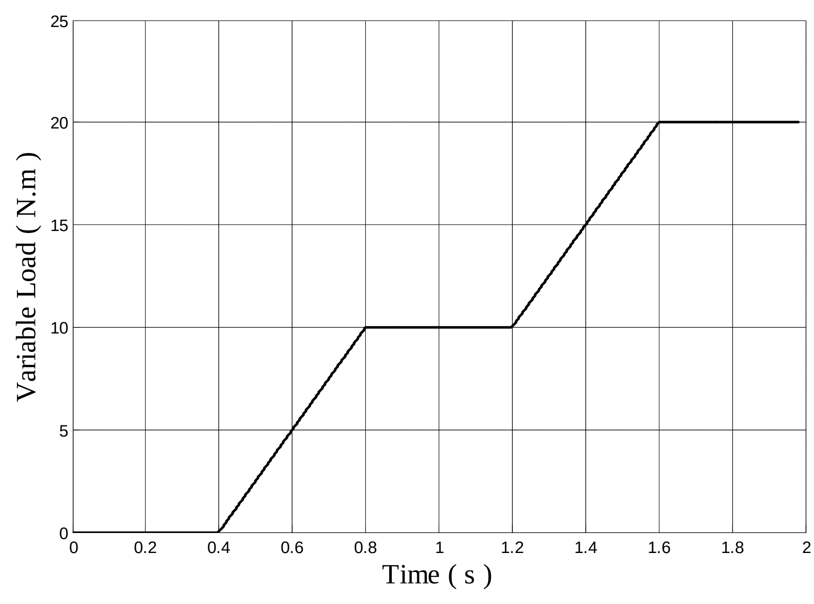


Fig. 3.11 Variable load of the output rotor.

Table 3.2 gives the parameters of magnetic gear which have a topology shown in figure 3.8.

Table 3.2 Parameters of magnetic gear

Number of pole-pairs inner rotor, p_l	*4*
Number of pole-pairs outer rotor, p_h	*21*
Number of pole-pieces, n_s	*23*
Moment of inertia of inner rotor, J_l	*0.0001 Kg.m*^{2}
Moment of inertia of outer rotor, J_h	*0.0001 Kg.m*^{2}
Moment of inertia of pole-pieces rotor, J_s	*0.0001 Kg.m*^{2}

From figure 3.12 and figure 3.13, it can be seen that even though the input speed ω_l varies, the output speed ω_s can be kept constant by controlling ω_h (ω_s = 4.38 rad/s). Now, it is confirmed that the three rotors of the magnetic gear are linked by the equation 3.11.

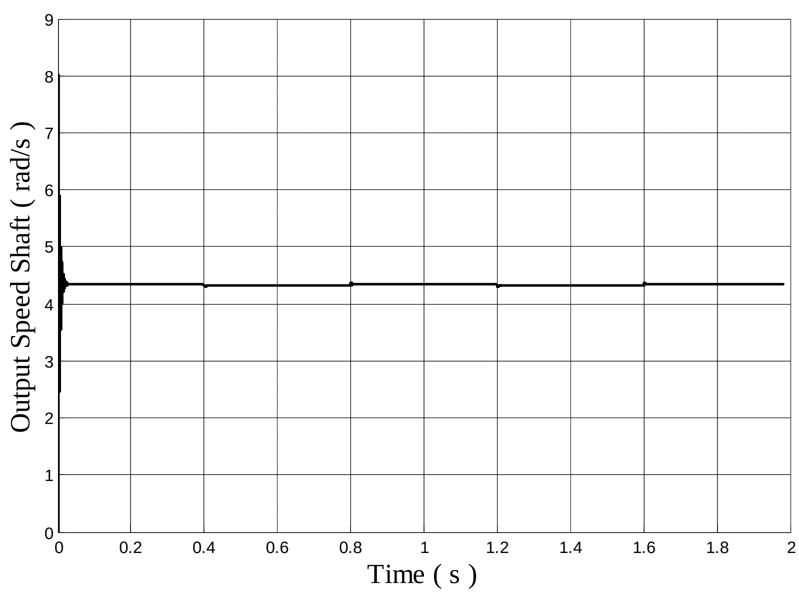


Fig. 3.12 The output speed ω_s

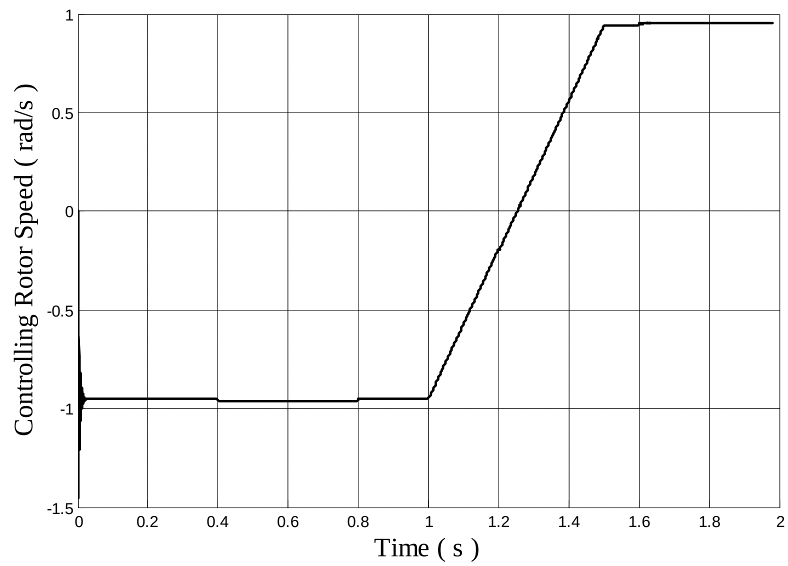


Fig. 3.13: The Controlling rotor speed ω_h.

According to the figure 3.12, figure 3.14 and figure 3.15, the torque which needs to be applied to the controlling rotor is independent of the speeds of the rotors, and is a function of the applied input torque and gear ratio of the magnetic gear.

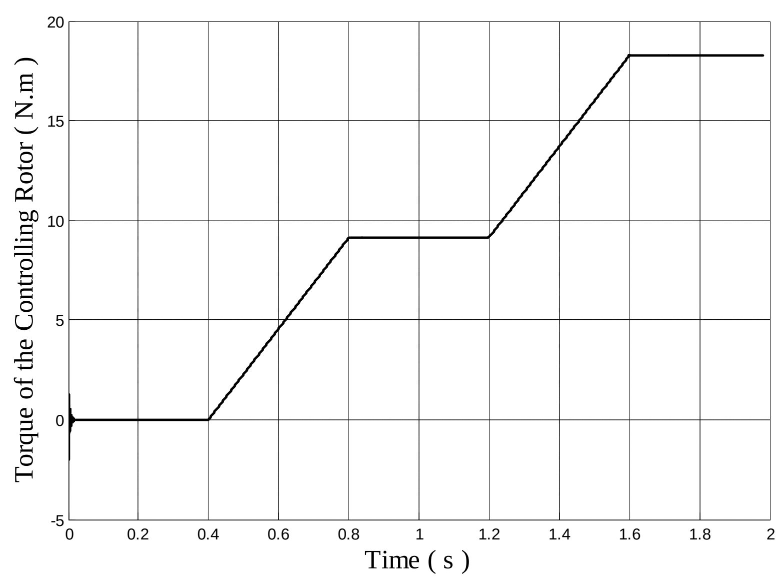


Fig. 3.14: The torque of the controlling rotor T_h.

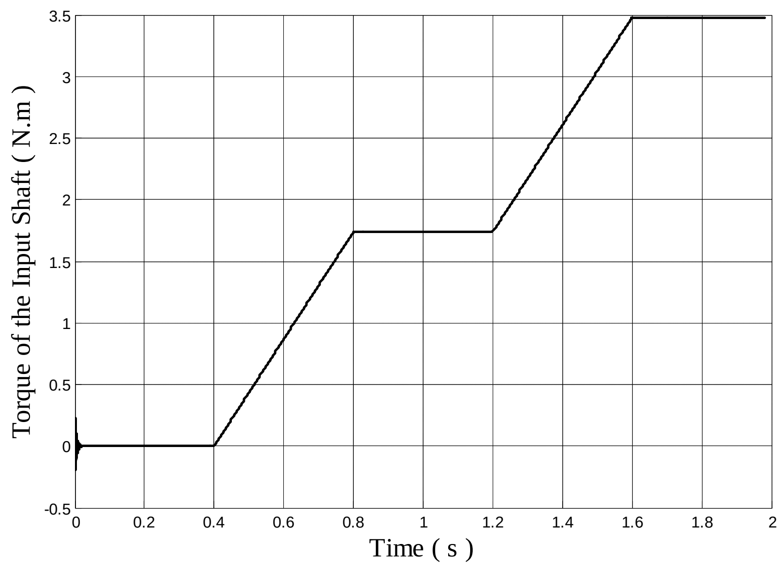


Fig. 3.15: The torque of the input rotor T_I.

3.6. Conclusion

A new topology for magnetic gear has been presented. It offers significant advantages compared with mechanical gear, i.e. reduced maintenance, free lubrication and cooling system, inherent overload protection, and physical isolation between the input and output shaft. It has be seen that the choice of the combination of the number of pole-pairs on the input rotor and output rotor and the number of ferromagnetic pole-pieces has a significant influence on the maximum torque transmission and output speed.

CHAPTER 4

2.5 MW DIRECT-DRIVE MAGNETIC GEAR FOR WIND ENERGY

4. 1. Introduction

As seen in chapter 3, magnetic gears offer several advantages, such as lubricant-free operation, reduced maintenance costs, quiet operation between the input and output shafts, physical isolation between input and output shafts, and inherent overload protection [60, 15]. The topology and a high performance of magnetic has been presented in [50], simulation and experimental studies have shown that this gear has a transmitted torque density capability comparable with three-stage helical gearboxes, viz. 50-150 KNm/m^3 [15]. Several magnetic gear topology with combined structure have been simulated and constructed [62, 65], this has shown that the magnetic gear has a better efficiency than the mechanical one. We conclude that this will help to initiate a shift from mechanical gears to the magnetic one.

This chapter illustrates a different approach to generate electricity. We use a proposed magnetic gear generator to a variable speed wind turbine. A description of the system will be presented and it will be described how to collect maximum power to be injected to the grid. Simulation results will be presented and we show the performance of the 2.5MW magnetic gear generator in the wind system.

4. 2. Principle Operation

The topology of the proposed coupling magnetic gear and permanent magnet synchronous generator is illustrated in figure 4.1. Two permanent magnetic rotors and between the two rotors there are a ferromagnetic pole-pieces rotor, one of the two permanent magnet rotors held stationary. The numbers $n_s = 166$, $p_l = 168$ and $p_h = 5$, present the pole-pieces low-speed ferromagnetic rotor (input rotor), pole-pairs stationary permanent magnet, and pole-poles high-speed permanent magnetic rotor (output rotor) respectively.

A wind turbine extracts kinetic energy from the swept area of the blades, the mechanical energy is transferred to the shaft of the input rotor, which is transmitted magnetically from the input rotor to the output rotor. The permanent magnet of the output rotor interacts with the stator windings to produce electromagnetic torque. Thus, the power captured by the wind turbine is transmitted to the grid by the stator winding.

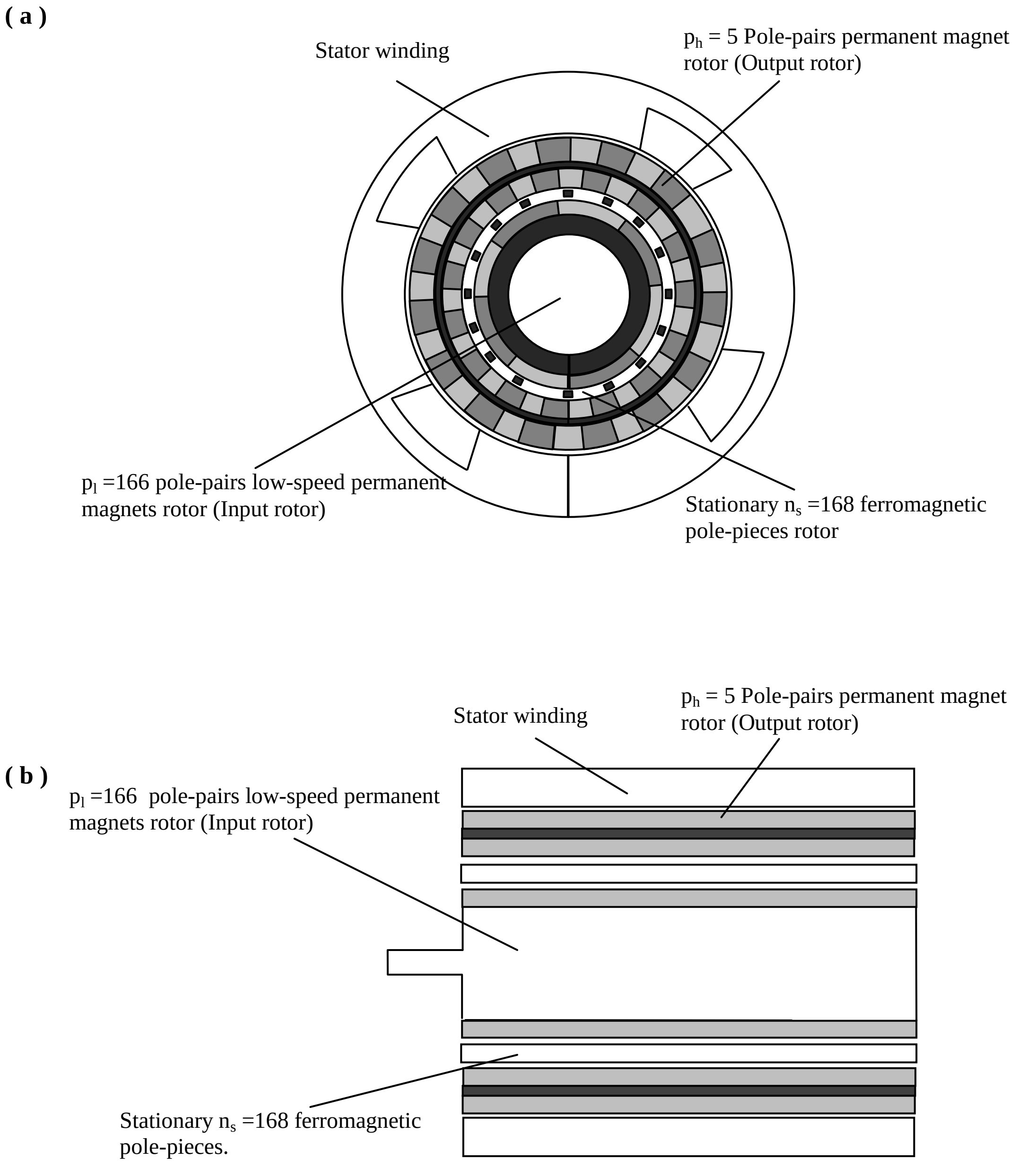


Fig.4 1. Magnetic gear generator.
(a) Radial cross section. (b) Axial cross section.

The magnetic gear ratio of proposed machine is:

$$G_r = \frac{p_l}{p_h} = 33.2 \qquad (4.1)$$

The speed which needs to be applied to the output rotor is independent of the torques of the rotors, and is a function of the applied input speed and gear ratio.

The equation relating the motions of the magnetic gear is given by [50]:

$$p_h \omega_h = p_l \omega_l \tag{4.2}$$

Where ω_h, and ω_l are the speed of the output and input rotors respectively.

The torque is transmitted magnetically from the input rotor T_l to the output rotor T_h according to the equation [59]:

$$T_h = -\frac{1}{G_r} T_l \tag{4.3}$$

The torque which needs to be applied to the output rotor is independent of the speeds of the rotors, and is a function of the applied input torque and gear ratio.

Torque production and torque transmission are coupled. Thus, the equations which govern the rotors motion are given by [59]:

$$\begin{cases} J_l \frac{d^2\theta_l}{dt^2} = T_{turbine} - T_{max} \frac{p_l}{n_s} sin(p_l\theta_l - p_h\theta_h) \\ J_h \frac{d^2\theta_h}{dt^2} = T_e - T_{max} \frac{p_h}{n_s} sin(p_h\theta_h - p_l\theta_l) \\ T_e = \frac{3}{2} p_h \left(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}\right) \end{cases} \tag{4.5}$$

Where θ_h and θ_l are the angular position of the output rotor and the input rotor respectively, φ is flux linkage, *i* is the current, *s* indicate the stator winding, $T_{turbine}$ is the wind turbine torque, T_e is the electromagnetic torque which results from the interaction between the permanent magnets on output rotor and the stator winding, T_{max} is the maximum torque which can be produced by the magnetic gear and J_h and J_l are the inertias of the output rotor and the input rotor respectively.

Figure 4.2 illustrates representation of three magnetic gears, having gear ratios of 5.75, 13.5 and 15.5, which have been selected.

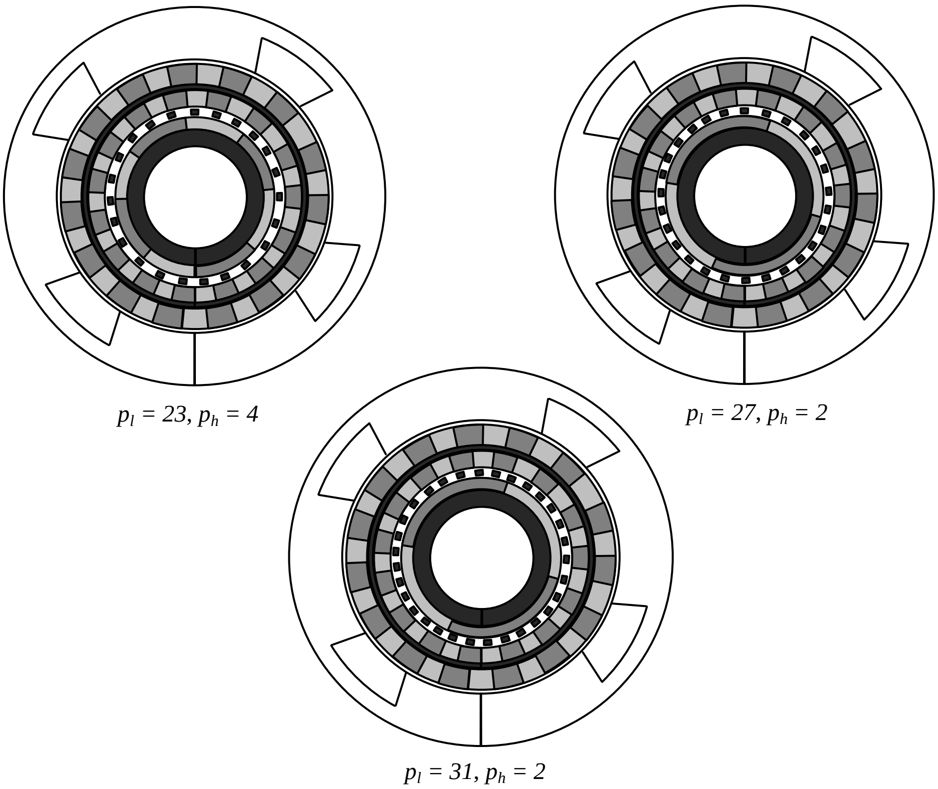
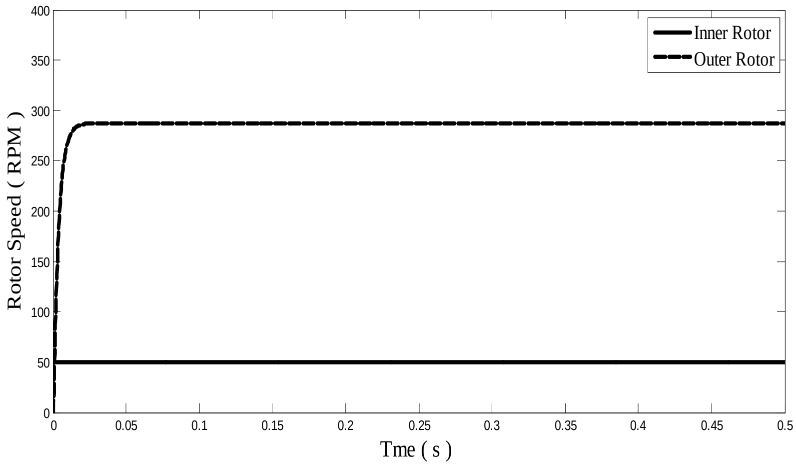


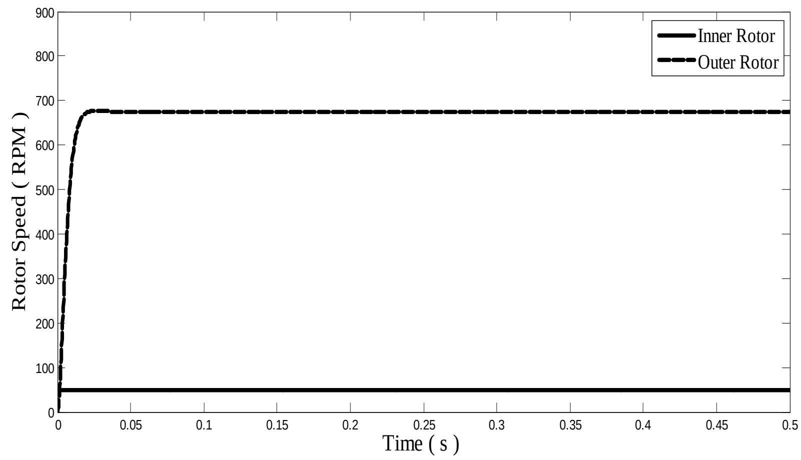
Fig. 4.2. Schematics of magnetic gears.

For standard step response tests, the representations relating the mentions of the inner rotor and the outer rotor of previous gears ratios are given by figure 4.3.

(a)



(b)



(c)

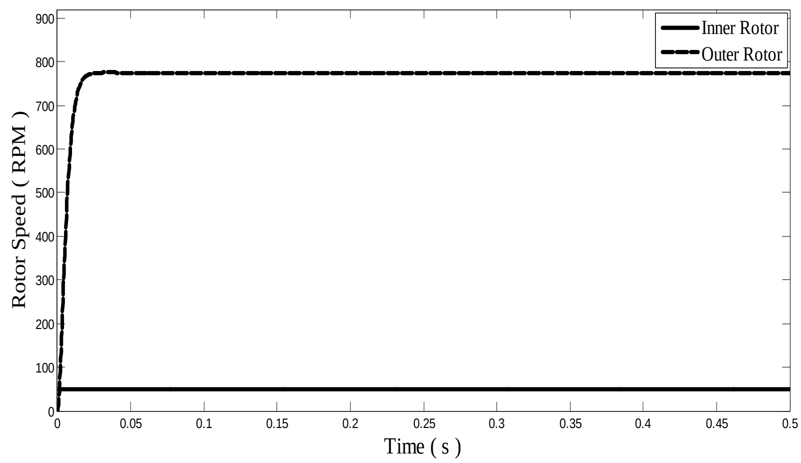


Fig. 4.3. Standard step response of magnetic gear.
(a) For 5.75 gear ratio. (b) For 13.5 gear ration. (c) For 15.5 gear ratio.

For a given input speed, which is governed by the turbine speed figure 4.3, it can clearly seen that the output rotor speed is a function of the applied input speed and the gear ratio of the magnetic gear, $\omega_h = G_r \, \omega_l$. It can be seen that the choice of the combination of the number of pole-pairs p_l et p_h has a significant influence the maximum speed and torque transmission capability. Using magnetic gear with wind power system, even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached with this topology**.**

4. 3. Control Strategy

Figure 4.4 shows the proposed control topology of wind power generation system, which used a magnetic gear generator (MGG) connected to the grid through a back-to-back converter [66]. It includes a two converters connected by a capacitor, the converter connected to the MGG is used as a rectifier, while the converter connected to the grid is used as an inverter. The advantage of this topology is the capacitor decoupling between the two converters, which offers separate control of the converters [67].

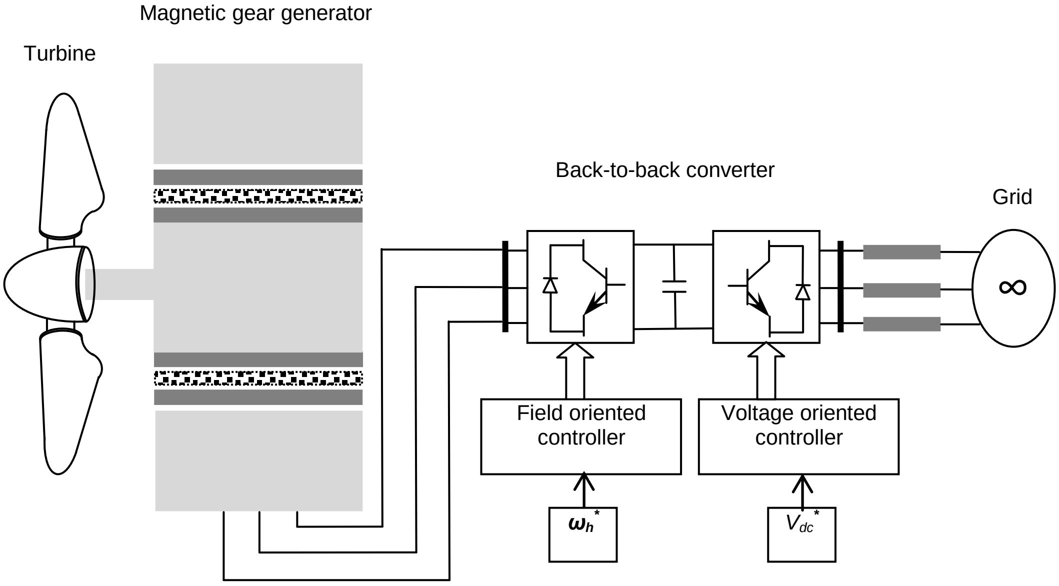


Fig. 4.4 Magnetic gear generation topology.

4.3.1. Magnetic Gear Generator Side Control

The MGG side converter is controlled the input rotor to the reference speed ω_s^* or using maximum power tracking algorithm to extract maximum power from wind turbine [69, 72].

A wind turbine extracts kinetic energy from the swept area of the blades, the power transferred to the wind turbine rotor is [68]:

$$P_t = \frac{1}{2} C_p(\beta, \alpha)\rho A V^3 \tag{4.6}$$

Where P_t is wind turbine power, C_p the power coefficient, ρ the air density, A the swept area of rotor, V the wind speed, β the blade pitch angle and α the angle of attack.

The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed V [68]:

$$\lambda = \omega \frac{R}{V} \tag{4.7}$$

Where ω is the turbine rotor speed and R the radius of the wind turbine blade.

The stator winding of the MGG is modeled in the rotor reference frame *dq-axes* by:

$$\begin{cases} V_{sd} = \frac{d\varphi_{sd}}{dt} - R_s i_{sd} - \omega_h \varphi_{sq} \\ V_{sq} = \frac{d\varphi_{sq}}{dt} - R_s i_{sq} + \omega_h \varphi_{sd} \end{cases} \tag{4.8}$$

Where v is the stator voltage, ω_h electrical speed, R resistance and the indices s indicate the stator winding.

The flux linkages are:

$$\begin{cases}\varphi_{sd} = L_s i_{sd} - \varphi_{PM} \\ \varphi_{sq} = L_s i_{sq}\end{cases} \tag{4.9}$$

φ_{PM} is the flux of the permanent magnets and L the inductance.

The electromagnetic torque is:

$$T_e = \frac{3}{2} p_h \left(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}\right) \tag{4.10}$$

From the equation (4.10), due to the cross-related flux terms, it is not easy to control the electromagnetic torque. So, we chose the reference frame *dq* figure 4.5 in such a way that :

$$I_{sd} = 0 \text{ and } I_{sq} = I_s \tag{4.11}$$

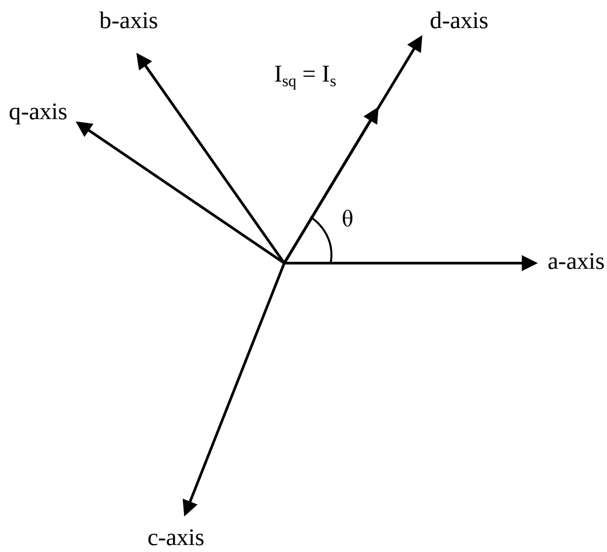


Fig. 4.5 Rotating reference frame.

Now, the electromagnetic torque can be simplified into:

$$T_e = \frac{3}{2} p_{\text{h}} \varphi_{PM} i_{sq} \tag{4.12}$$

Thus, the electromagnetic torque can be controlled through i_{sq}. The i_{sd} and i_{sq} errors can be tuning by a *PI* controller. The controller is based on two loops, the inner loop is a current controller and the outer loop is a torque controller.

From the equations (4.2), (4.5), (4.8), (4.9) and (4.12), the general structure of control strategy for MGG inverter can be represented by the figure 4.6.

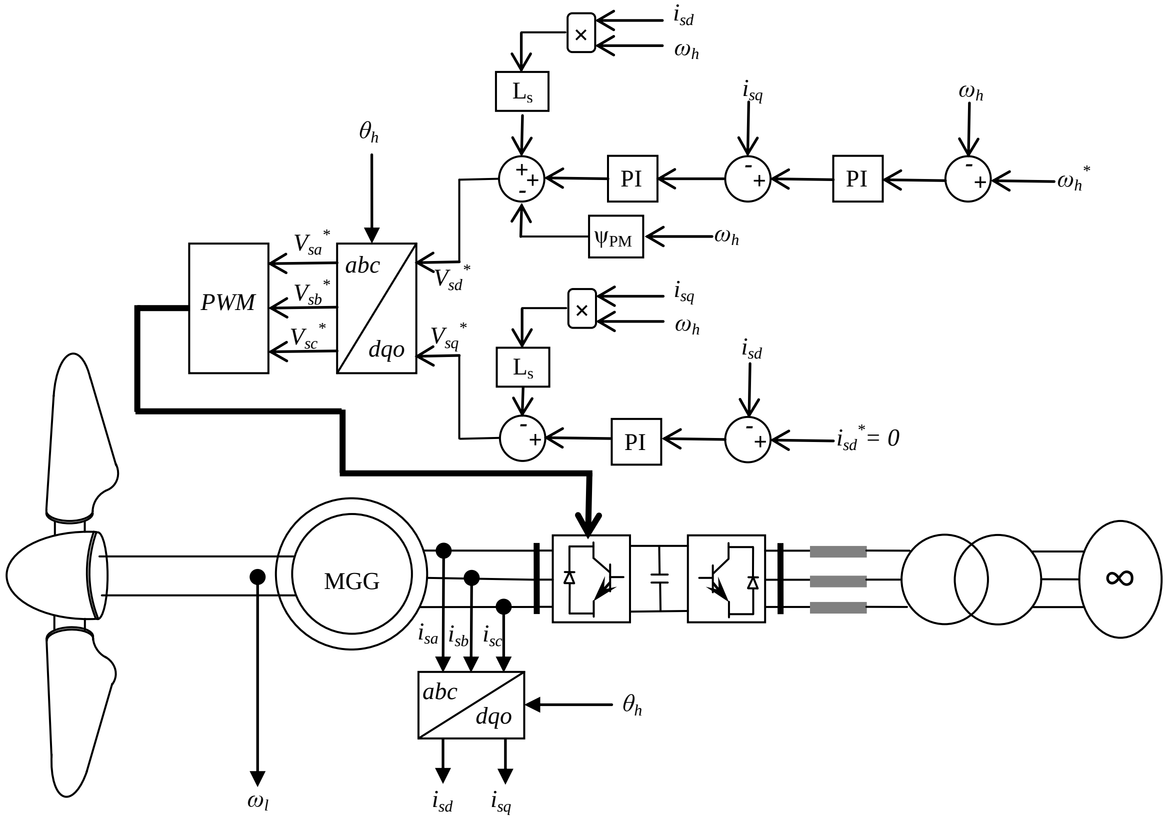


Fig. 4.6 General structure of MGG-side control

4.3.2. Grid-Side Control

The grid side inverter controls the active and reactive power flowing between the inverter and the grid [73].

The active and reactive powers produced by the MGG are:

$$\begin{cases} P = \frac{3}{2}\left(e_d i_d + e_q i_q\right) \\ Q = \frac{3}{2}\left(e_q i_d - e_d i_q\right) \end{cases} \tag{4.13}$$

Where *e* is the voltage at the output inverter and *i* the line current.

To overcome the problem of cross-related voltage terms in equation (4.13), the *dq* reference frame figure 4.7, is chosen in such a way that:

$$v'_q = 0 \text{ and } v'_d = \left| v' \right| \tag{4.14}$$

v' is the grid voltage.

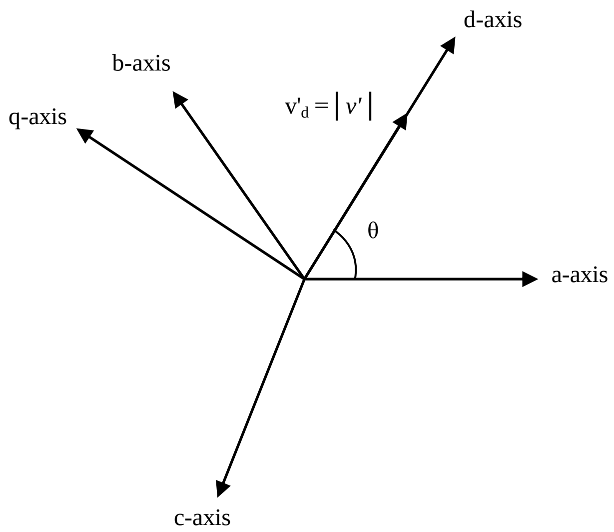


Fig. 4.7 Rotating reference frame

So the active and the reactive power will be proportional to i_d and i_q respectively:

$$\begin{cases} P = \frac{3}{2} e_d i_d \\ Q = -\frac{3}{2} e_d i_q \end{cases} \tag{4.15}$$

Now the active power can be controlled via i_d and the reactive power can be controlled via i_q. The i_q is usually set to zero in order to achieved unit power factor [67].

The voltage equations of grid side inverter can be defined by:

$$\begin{cases} e_d = R_T i_d + L_T \frac{di_d}{dt} - \omega L_T i_q + v'_d \\ e_q = R_T i_q + L_T \frac{di_q}{dt} - \omega L_T i_d \end{cases} \tag{4.16}$$

Where e the voltage at the output inverter, R_T and L_T are the overall resistance and inductance of the grid-side converter and ω is the electrical angular velocity.

From to the equations (4.15) and (4.16), the general structure of control strategy for grid-side inverter can be represented by the figure 4.8. The inverter is based on two loops, the inner loop is a current controller, and the outer loop is a dc-link and reactive power controllers.

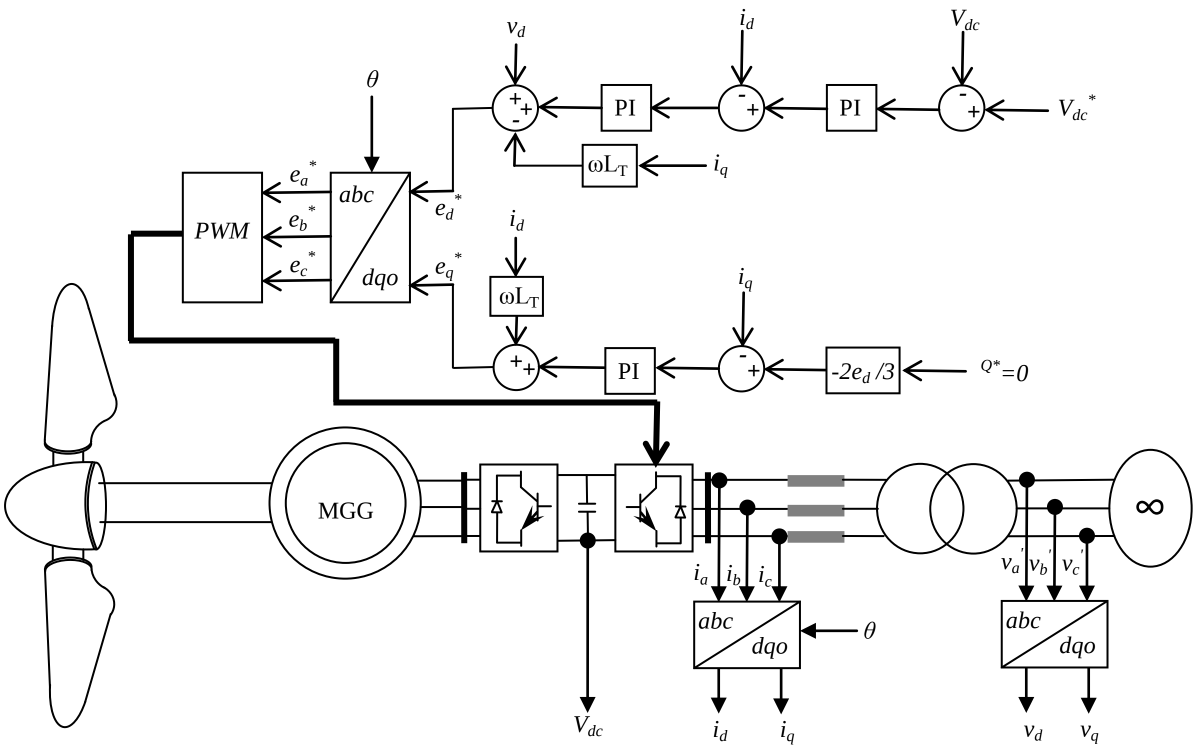


Fig. 4.8 General structure of grid side control

4. 4. Simulation Results

The simulation was presented to evaluate the high performance of 2.5 MW magnetic gear generator. The dynamic simulation is performed with variable wind speed. Table 4.1 shows the parameters of the magnetic gear generator.

Table 4.1 Parameters of magnetic gear generator.

Magnetic gear generator	values
Rated Power	*2.5 MW*
Rated Voltage	*900 V*
Stator Phase Resistance	*0.001*Ω
Inductance L_d	*0.0007 H*
Inductance L_q	*0.0007 H*
Number Of Pole-Pairs Inner-Rotors	*166*
Number Of Pole-Pairs Outer-Rotors	*5*

To show the impact of the variable wind speed against the proposed magnetic gear generator, the wind speed variation is chosen figure 4.9.

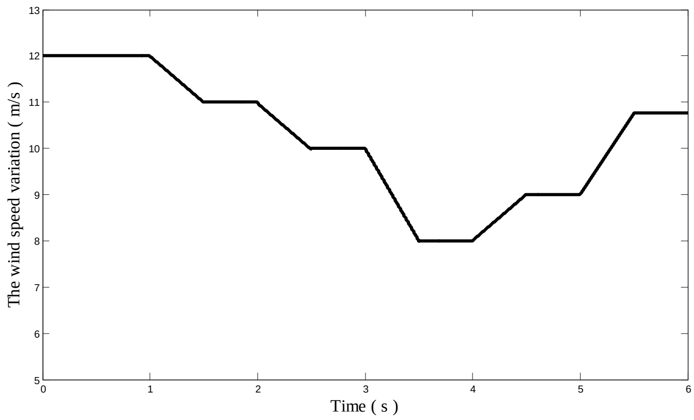


Fig. 4.9 The wind speed variation.

The simulation results of the torque on the outer rotor and of the inner rotor are depicted in figure 4.10. The gear ratio can be verified between any of the rotors using these wavelength torque curves. We can see that, the electromagnetic torque which needs to be applied is independent of the speed of the rotors, and is a function of the applied input rotor torque and the gear ratio.

(a)

(b)

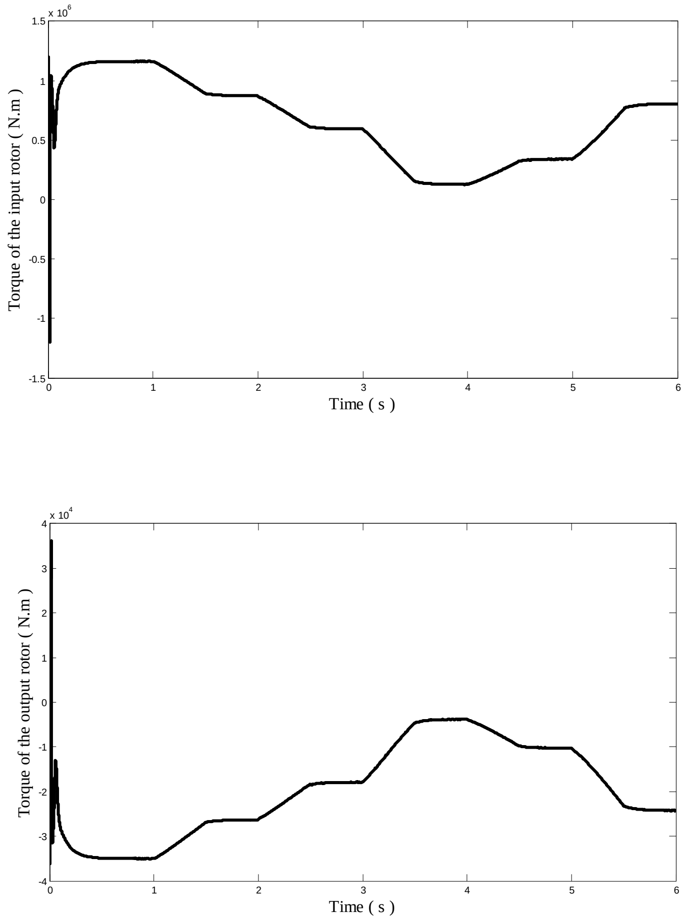
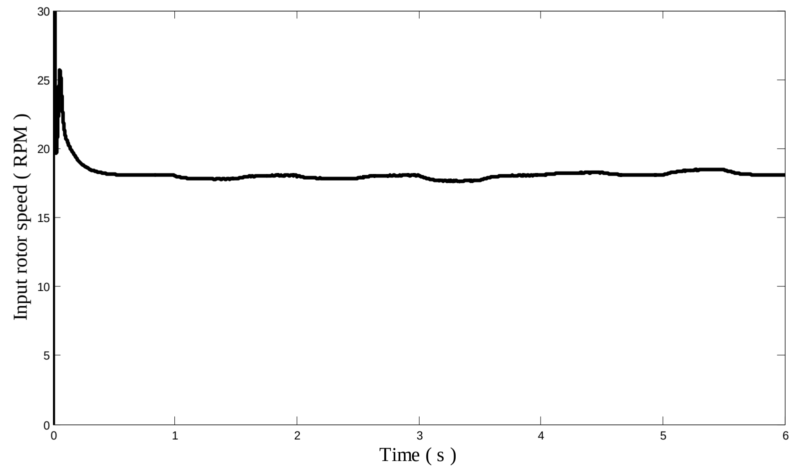


Fig. 4.10 Torque of the magnetic gear generator.
(a) Torque of input rotor. (b) Torque of output rotor.

The magnetic gear side converter is controlled to maintain the output rotor to the rated speed *600 rpm*. Figure 4.11 shows the output and input rotors variation, it is clear that: $\omega_h = G_r\ \omega_s$, that mean even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached using magnetic gear generator.

(a)



(b)

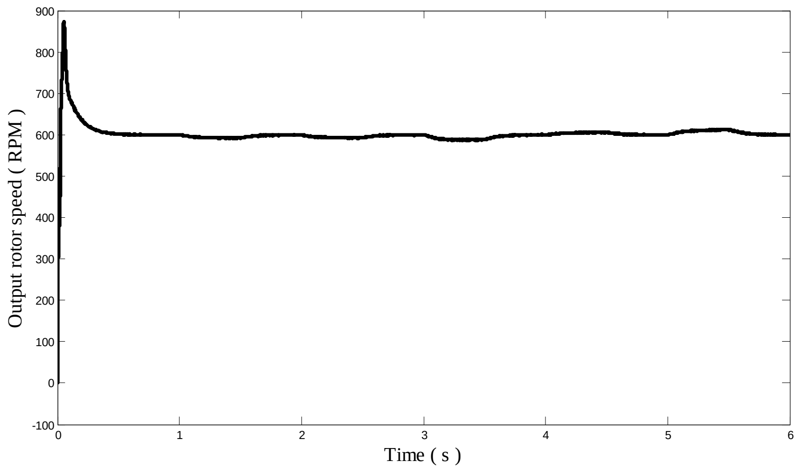


Fig. 4.11. Rotors speed of the magnetic gear generator (a) Input rotor. (b) Output rotor.

To collect the maximum power produce by the magnetic gear generator, the dc-link voltage is adjusted to a high level than the amplitude of the grid voltage. From figure 4.12, we can see the dc-link voltage is kept constant to the reference value that means, the dc-link controller reacts fast enough to control the voltage.

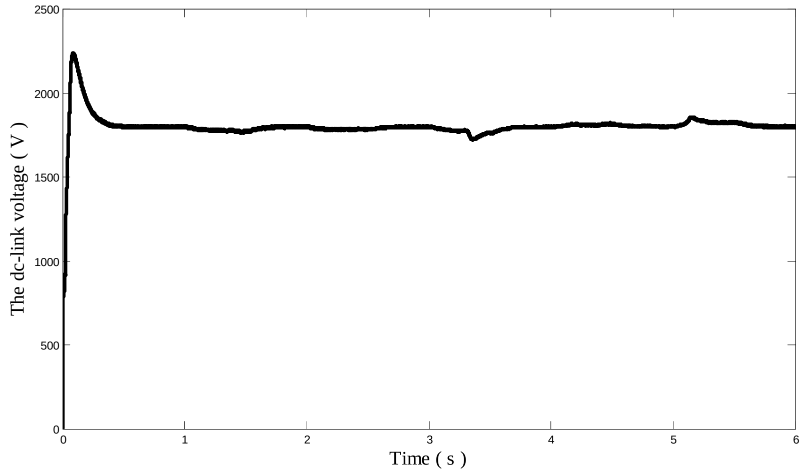


Fig. 4.12. The dc-link voltage.

Figure 4.13 shows the variation of the active power produce by the magnetic gear generator witch transmitted to the grid, the nominal power injected to the grid is about 2.5 MW.

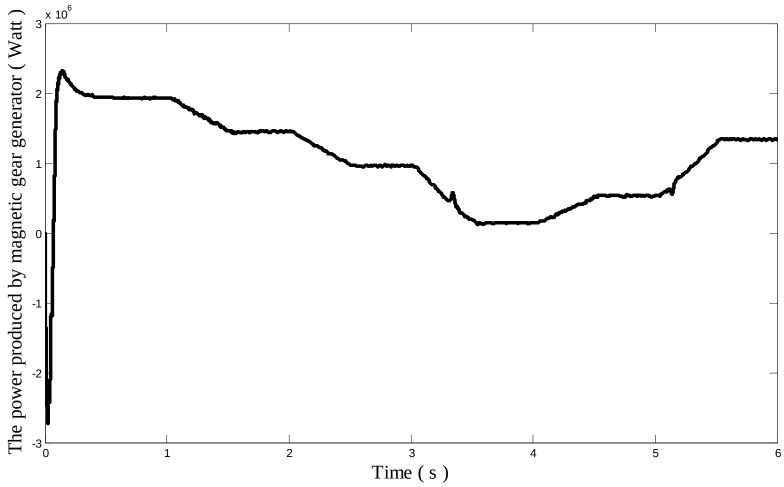


Fig. 4.13 The power produced by magnetic gear generator.

4. 5. MPPT for Magnetic Gear Generator

The output power of a wind turbine at various wind speeds is conventionally described by its power curve figure 4.14, the mechanical power converted from the turbine blade is a function of the rotational speed, and the converted power is maximized at the particular rotational speed for various wind speed.

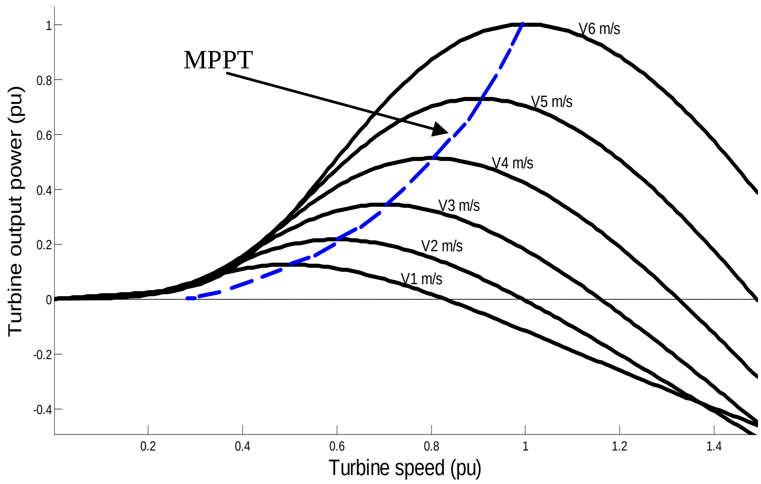


Fig. 4.14 Mechanical power versus rotor speed

So, it is clear that when instantaneous wind speed varies, the maximum energy also changes. To determine the optimal generator speed that ensures maximum energy, we should include a controller that can track the maximum peak regardless of wind speed.
Many maximum power point tracking (MPPT) studies has been proposed, such as, [74, 75, 76, 77, 78], etc. Since the wind energy system is a nonlinear form, the artificial neural network (ANN) can be used to solve this kind of problem.

4.5.1 ANN Controlling Model

The MPPT controller adopts back-propagation artificial neural network and its structure is multilayer feedforward network. The study uses the learning method to estimate speed of magnetic gear generator, the proposed training scheme is shown in figure 4.15. The rpm samples are used as targets to train a 3-layer network, with 1 linear neuron in the input layer, 7 tan-sigmoid neurons in the first hidden layer, and 1 linear neuron in the output layer. The input network parameter wind speed is n (m/s) and the output network parameter is a speed of magnetic gear (rpm). The training operation is made in a few cycles using 06 input-output patterns.

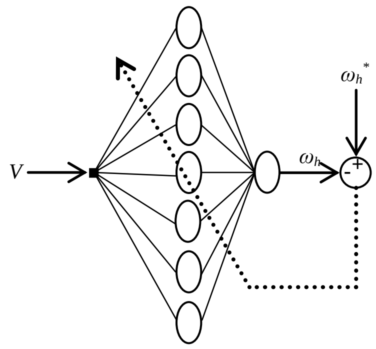


Fig. 4.15 Training scheme using ANN controller

4. 5.2 The Structure of MPPT Control

The structure of MPPT control system is shown in figure 4.16.

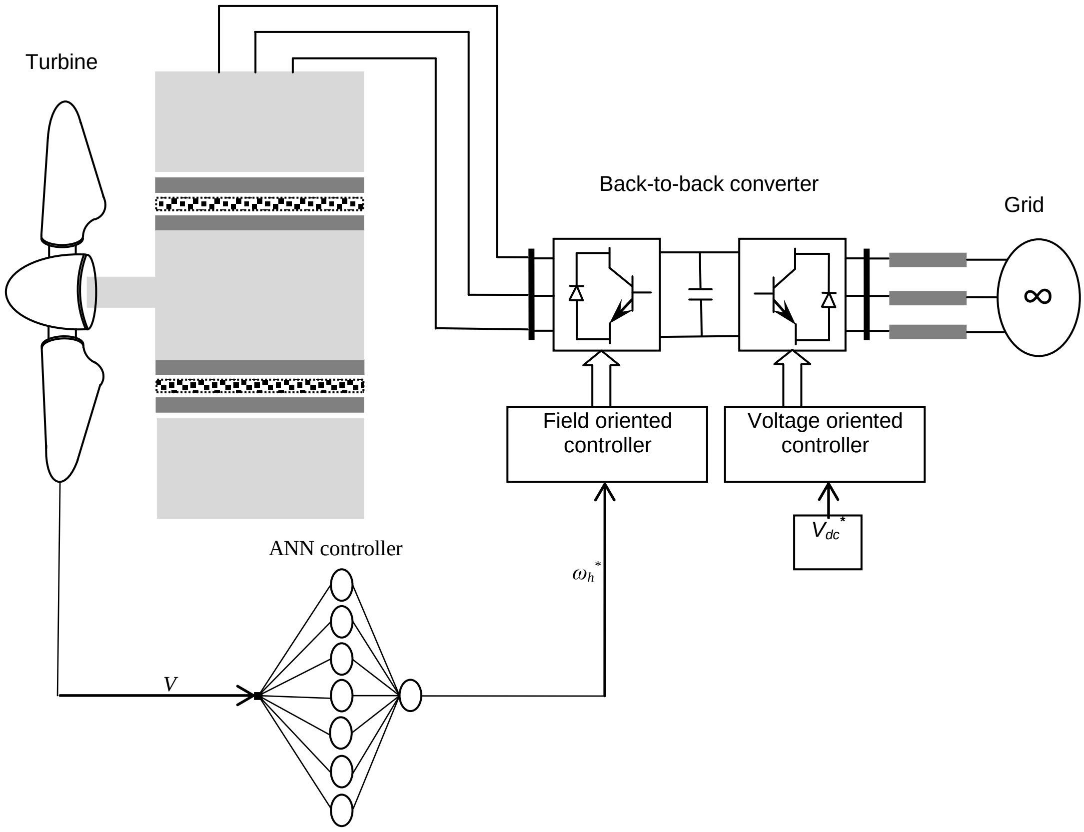


Fig.4.16 Block diagram of the MPPT control system.

The MPPT control system is accomplished by Matlab/Simulink, and is shown in figure 4.17.

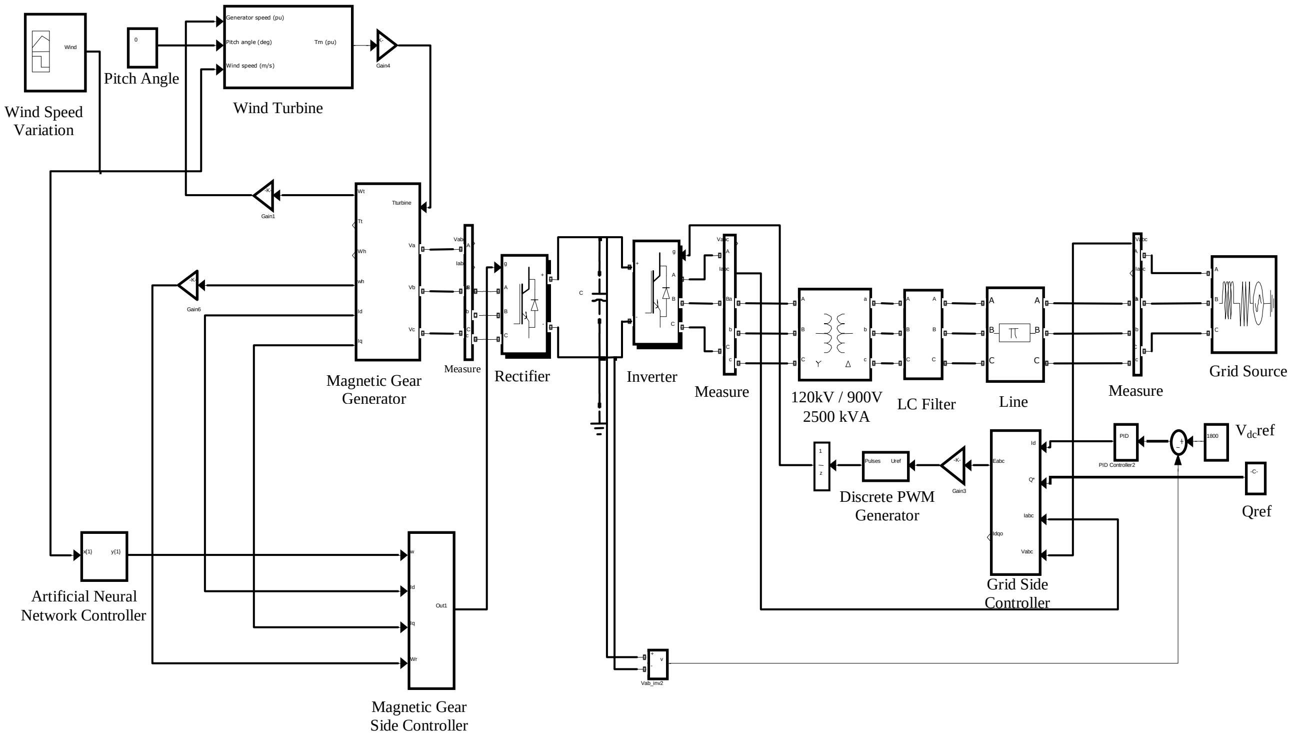
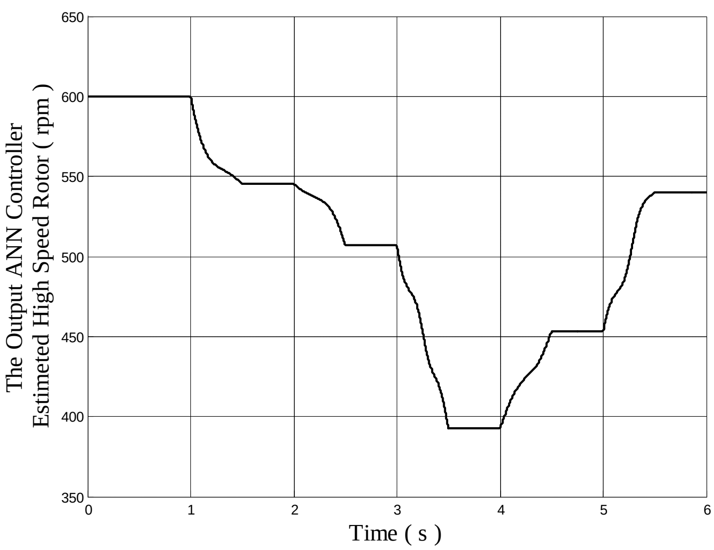


Fig.4.17 Simulink structure of MPPT control.

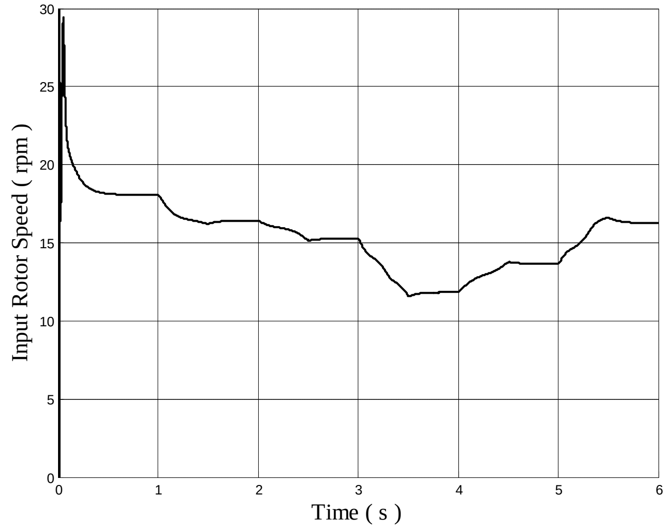
4. 5.3 Simulation Results

The simulation was presented to evaluate the performance of 2.5 MW magnetic gear generator using ANN controller for maximum power point tracking. Table 4.1 shows the parameters of the magnetic gear generator. To show the impact of the variable wind speed against the proposed magnetic gear generator, the wind speed variation is chosen figure 4.9.

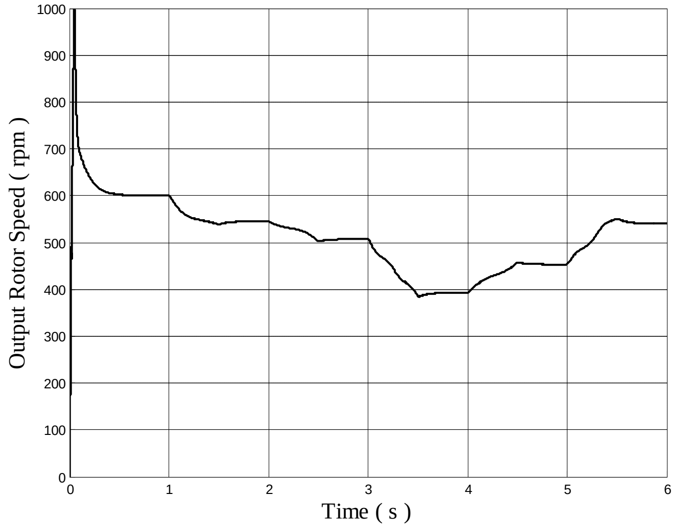
(a)



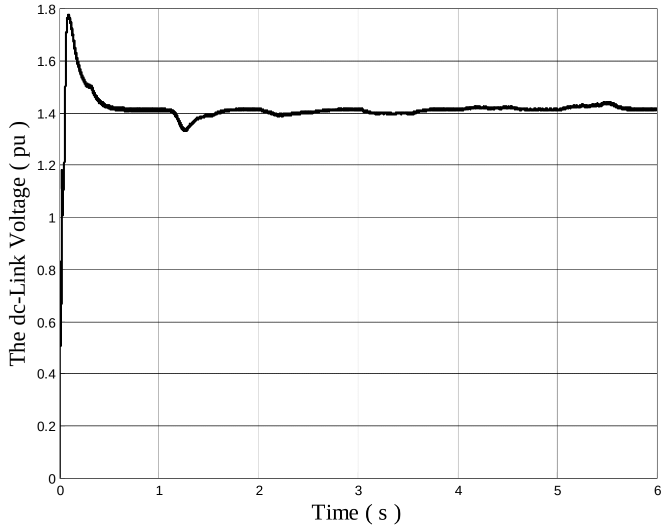
(b)


Input Rotor Speed (rpm)
Time (s)
0
5
10
15
20
25
30
0
1
2
3
4
5
6

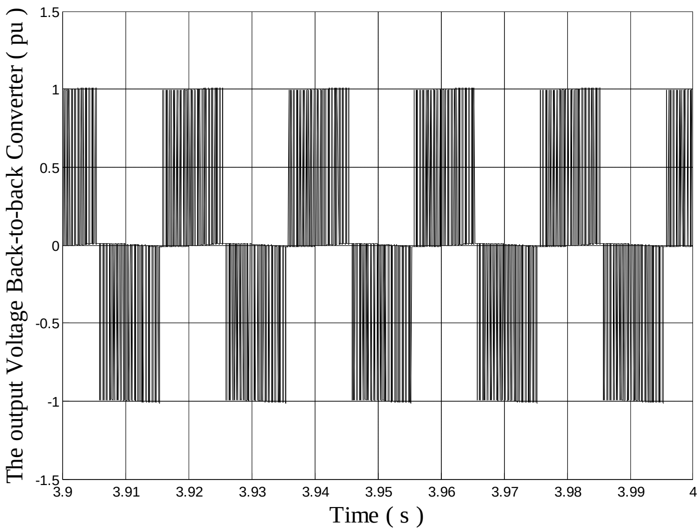
(c)


Output Rotor Speed (rpm)
Time (s)
0
100
200
300
400
500
600
700
800
900
1000
0
1
2
3
4
5
6

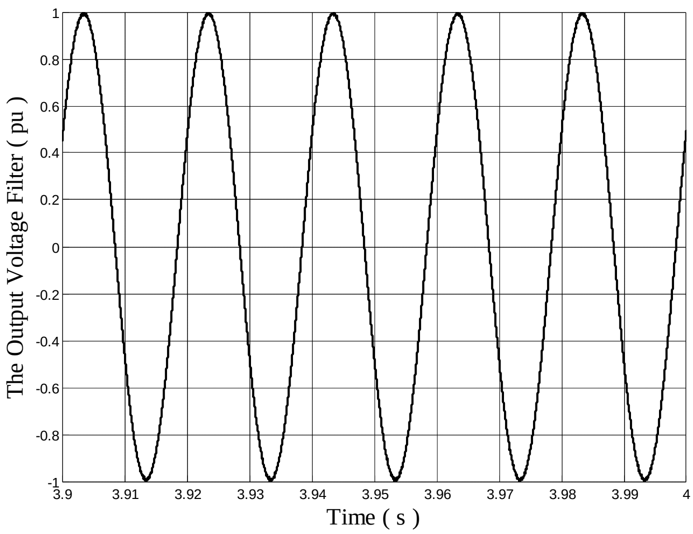
(d)


The dc-Link Voltage (pu)
Time (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
1
2
3
4
5
6

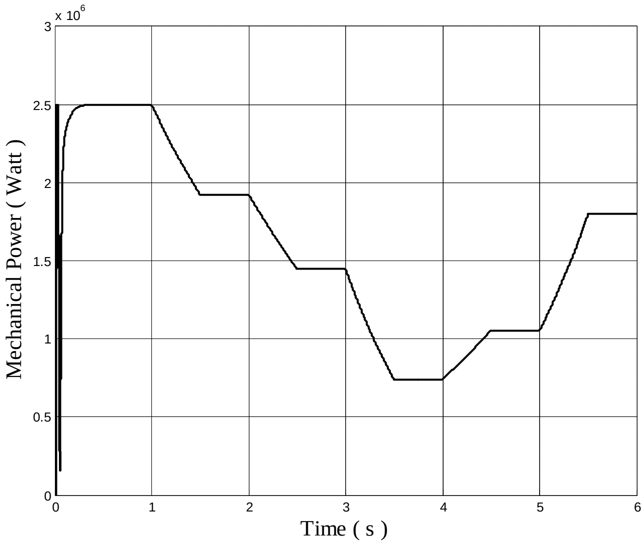
(e)


The output Voltage Back-to-back Converter (pu)
1.5
1
0.5
0
-0.5
-1
-1.5
3.9
3.91
3.92
3.93
3.94
3.95
3.96
3.97
3.98
3.99
4
Time (s)

(f)


The Output Voltage Filter (pu)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
3.9
3.91
3.92
3.93
3.94
3.95
3.96
3.97
3.98
3.99
4
Time (s)

(g)


x 10^6
Mechanical Power (Watt)
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
Time (s)

(h)

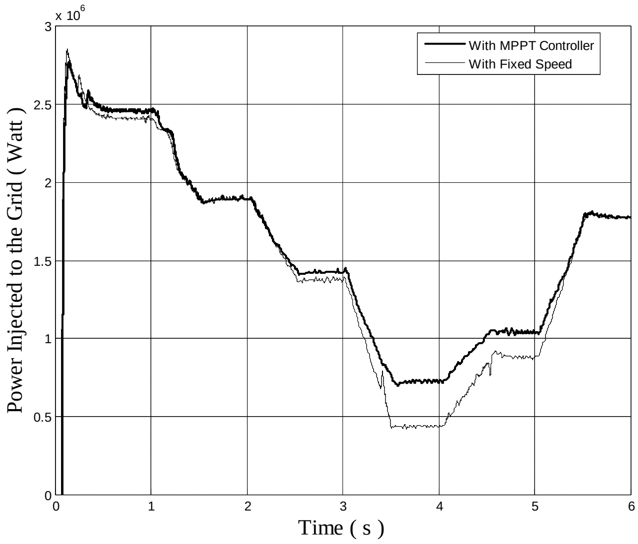


Fig.4.18 MPPT results under wind speed variation.
(a) The output of ANN controller. (b) Speed of the input rotor.
(c) Speed of the output rotor. (d) dc-Link voltage. (e) Output voltage of back-to-back converter.
(f) Output voltage of filter. (g) Mechanical turbine power. (h) Power injected to the grid.

The magnetic gear side converter is controlled via ANN controller to maintain the output rotor to the rated speed to collect maximum power. As shown in figure 4.18 (a) and figure 4.18 (c), there is a good agreement between reference values of the estimated high speed rotor and of output rotor speed. As revealed in figure 4.10 and figure 4.18 (g), when the wind speed increases, the input mechanical power also increases and thus the electrical power produced by the generator increases.

Figure 4.18 (b) and figure 4.18 (c), show the output and input rotors variation. For example, we can see that, from 18 rpm of the inner rotor and without mechanical gear, the output rotor reached 600 rpm. That mean even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached using magnetic gear generator. Performance of the proposed ANN controller was compared with a fixed rated speed figure 4.18 (h) and figure 4.18 (g). The ANN controller provides superior performance, as it derives the maximum possible power from the wind at different wind speeds. To realize the feasibility of the grid side controller, figure 4.18 (d) presents the dc link voltage variation. The controller gives good agreement between the actual and reference values of the dc link voltage thus the actual dc voltage is almost constant over the whole period.

4. 6. Conclusion

This chapter presents a coupling magnetic gear with permanent magnet synchronous generator for 2.5 MW wind turbine. We have described the different gear ratio of magnetic gear. We have seen that, with low wind conditions often found inland, one can achieve high speed variation using the proposed magnetic gear generator. Also, we do no more require huge mechanical gear and system of lubrication. By way of such topology, we can overcome the dimension problem of the nacelle and allow more space to work safely. The dynamic behaviour of the magnetic gear generator with variable speed was explored and the simulation results confirm the benefits of the proposed magnetic gear generator.

CHAPTER 5

POWER-SPLIT MAGNETIC GEAR FOR WIND POWER

5.1. Introduction

With the development of offshore wind power huge wind turbines emerged. According to the assessment, by the year 2020 the size of a wind turbine would be 20 MW offshore. However, construction of offshore wind projects is still a challenge. Offshore wind turbines require more space for a big generator, a system lubrication, and massive gear box in the same place within the nacelle. Also, the controllers involve power electronic to be rated at the rated power of the turbine. To overcome this problems, we used magnetic gear power-split. The rated power transmitted to the grid is split between the generated power by the permanent magnetic synchronous generator and the power produced or consumed by the power-split magnetic gear. Thus, the dimension of the generator will be greatly reduced and the mechanic gearbox can be reduced or omitted.

This chapter illustrates the application of a magnetic power-split to a variable speed wind turbine. A description of the system will be presented and it will be described how to keep a permanent magnet synchronous generator at the synchronous speed and to extract a maximum power from the magnetic power-split. Simulation results will be presented to show the performance of the magnetic power-split in the system [79, 17].

5.2. Magnetic Gearbox

Figure 5.1 shows a schematic of the proposed magnetically and mechanically coupled magnetic gear and permanent magnetic synchronous generator, contains numbers p_l, p_h and n_s of pole-pairs of inner rotor, output rotor and ferromagnetic rotor respectively. The torque is transmitted magnetically from the inner rotor to the output rotor and pole-pieces rotor. The equations which govern the motion are given by [59]:

$$\begin{cases} J_l \frac{d^2\theta_l}{dt^2} = T_{turbine} - T_{max} \frac{p_i}{n_s} \sin(p_l\theta_l + p_h\theta_h - n_s\theta_s) \\ J_h \frac{d^2\theta_h}{dt^2} = T_e - T_{max} \frac{p_h}{n_s} \sin(p_h\theta_h + p_l\theta_l - n_s\theta_s) \\ J_s \frac{d^2\theta_s}{dt^2} = T_s - T_{max} \sin(n_s\theta_s - p_l\theta_l - p_h\theta_h) \end{cases} \quad (5.1)$$

Where θ_l, θ_h and θ_s are the angular position of the inner rotor, output rotor and the pole-pieces rotor respectively, $T_{turbine}$ is the wind turbine torque, T_e is the electromagnetic torque, T_s is the output torque, T_{max} is the maximum torque which can be produced by the magnetic gear and J_l, J_h and J_s are the inertias of the inner rotor, output rotor and pole-pieces rotor respectively.

The equation relating the motions of the different components of the magnetic gear is given by:

$$p_l\omega_l + p_h\omega_h = n_s\omega_s \quad (5.2)$$

Where, ω_l, ω_h and ω_s are the speeds of the inner rotor, the output rotor and pole-pieces rotor respectively.

The torque transmitted to the permanent magnetic generator T_s is related to the wind turbine torque $T_{turbine}$ as follows [59]:

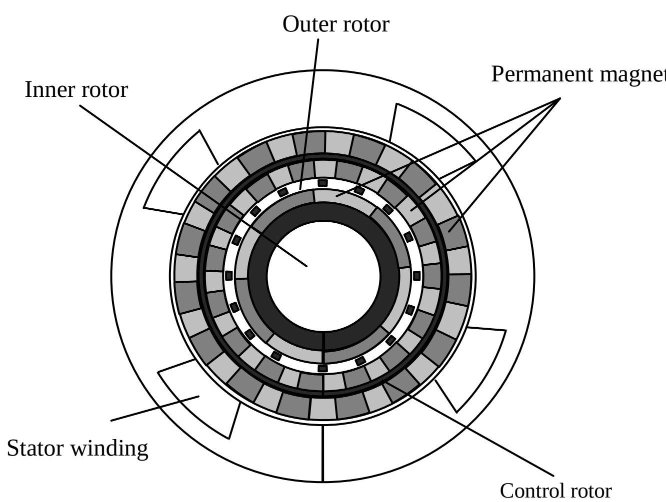
$$T_s = \frac{n_s}{p_l} T_{turbine} \quad (5.3)$$

And the torque which needs to be applied to the controlling rotor Te is [59]:

$$T_e = \frac{p_h}{p_l} T_{turbine} \quad (5.4)$$

From (5.3) and (5.4), it can be seen that the torques which be applied to the permanent magnetic synchronous generator and the controlling rotor are independent of the speeds of the rotors, and is a function of the wind turbine torque and the gear ratio of the magnetic gear.

(a)



(b)

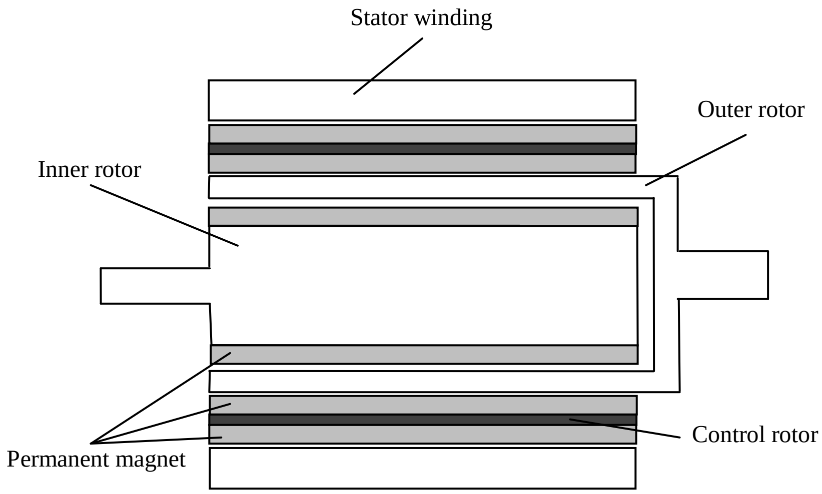


Fig. 5.1 Magnetic gear for wind turbine generator.
(a) Radial cross section. (b) Axial cross section.

5.3. Wind Turbine System with Proposed Magnetic Gear

The main system is divided in two parts; the magnetic gear and the permanent magnet synchronous generator, the scheme of the system is shown in figure 5.2.

Up to now the back-to-back converter is usually used in wind power control. It is a bidirectional power converter, it consists of two converters connected by a capacitor. A vector-control approach is used for the converters, the converter connected to the magnetic gear is used as a rectifier and the converter connected to the grid is used as an inverter. The aim of the grid side controller is to keep the dc-link voltage constant while the magnetic gear side controller is controlled the permanent magnet synchronous generator speed to specific value ω_s^*. The advantage of this control technique is the capacitor decoupling between the grid converter and the magnetic gear converter [82].

From equation (5.4), even though the wind speed varies ω_l, the permanent magnet synchronous generator speed ω_s can be kept constant by controlling the ω_h.

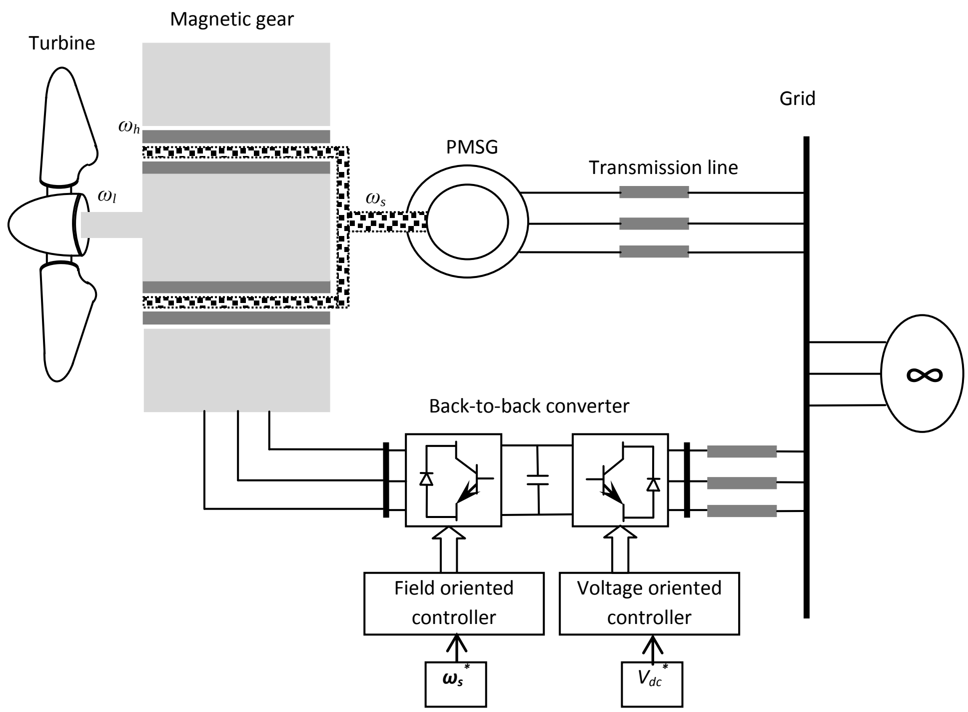


Figure 5.2 Wind turbine with a magnetic gear, permanent magnet synchronous generator and back-to-back converter.

5.3.1. Magnetic Gear Controller

The magnetic gear, the generator side converter is controlled the permanent magnetic synchronous generator to a synchronous speed ω_s^*, with:

$$\omega_s = \frac{p_l}{n_s}\omega_l + \frac{p_h}{n_s}\omega_h \tag{5.5}$$

The stator winding of the magnetic gear is modeled in the rotor reference frame *dq-axes* by:

$$\begin{cases} V_{sd} = \frac{d\varphi_{sd}}{dt} - R_s i_{sd} - \omega_h \varphi_{sq} \\ V_{sq} = \frac{d\varphi_{sq}}{dt} - R_s i_{sq} + \omega_h \varphi_{sd} \end{cases} \tag{5.6}$$

Where *v* the stator voltage, *R* resistance, *i* the current, ω_h electrical angular velocity and φ are flux linkage. The indices *d* and *q* indicate the direct and quadrature axis components and the indices *s* indicate the stator winding.

The flux linkages:

$$\begin{cases} \varphi_{sd} = L_s i_{sd} - \varphi_{PM} \\ \varphi_{sq} = L_s i_{sq} \end{cases} \tag{5.7}$$

φ_{PM} is the flux of the permanent magnets and *L* the inductance.

The electromagnetic torque is:

$$T_e = \frac{3}{2} p_h \left(\varphi_{sd} i_{sd} - \varphi_{sq} i_{sd}\right) \quad (5.8)$$

We can see from the equation (5.8) that is not easy to control the electromagnetic torque due to the cross-related flux terms. To overcome this problem; figure 5.3, we choose the reference frame *dq* in such a way that:

$$I_{sd} = 0 \text{ and } I_{sq} = I_s \quad (5.9)$$

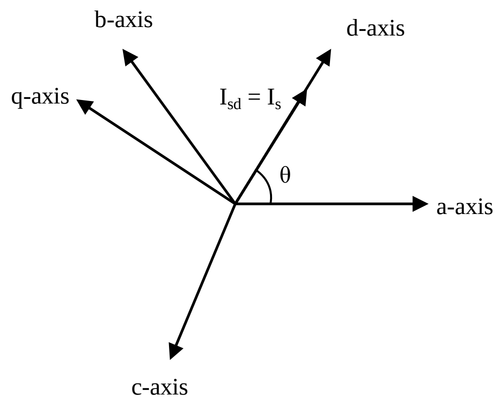


Fig. 5.3 Rotating reference frame.

Now the output torque can be simplified as:

$$T_h = \frac{3}{2} p_h \, \varphi_{PM} i_{sq} \quad (5.10)$$

As can see from equation (5.10), the electromagnetic torque can be controlled through i_{sq}. The i_d and i_q errors can be tuning by a PI controller. The controller is based on two loops, the inner loop is a current controller and the outer loop is a torque controller. A suitable choice will be to make the inner loop as fast as the closed-loop system [83].

According to the equations (5.5), (5.6), (5.7) and (5.10), the general structure of control strategy for magnetic gear inverter can be represented by the figure 5.4.

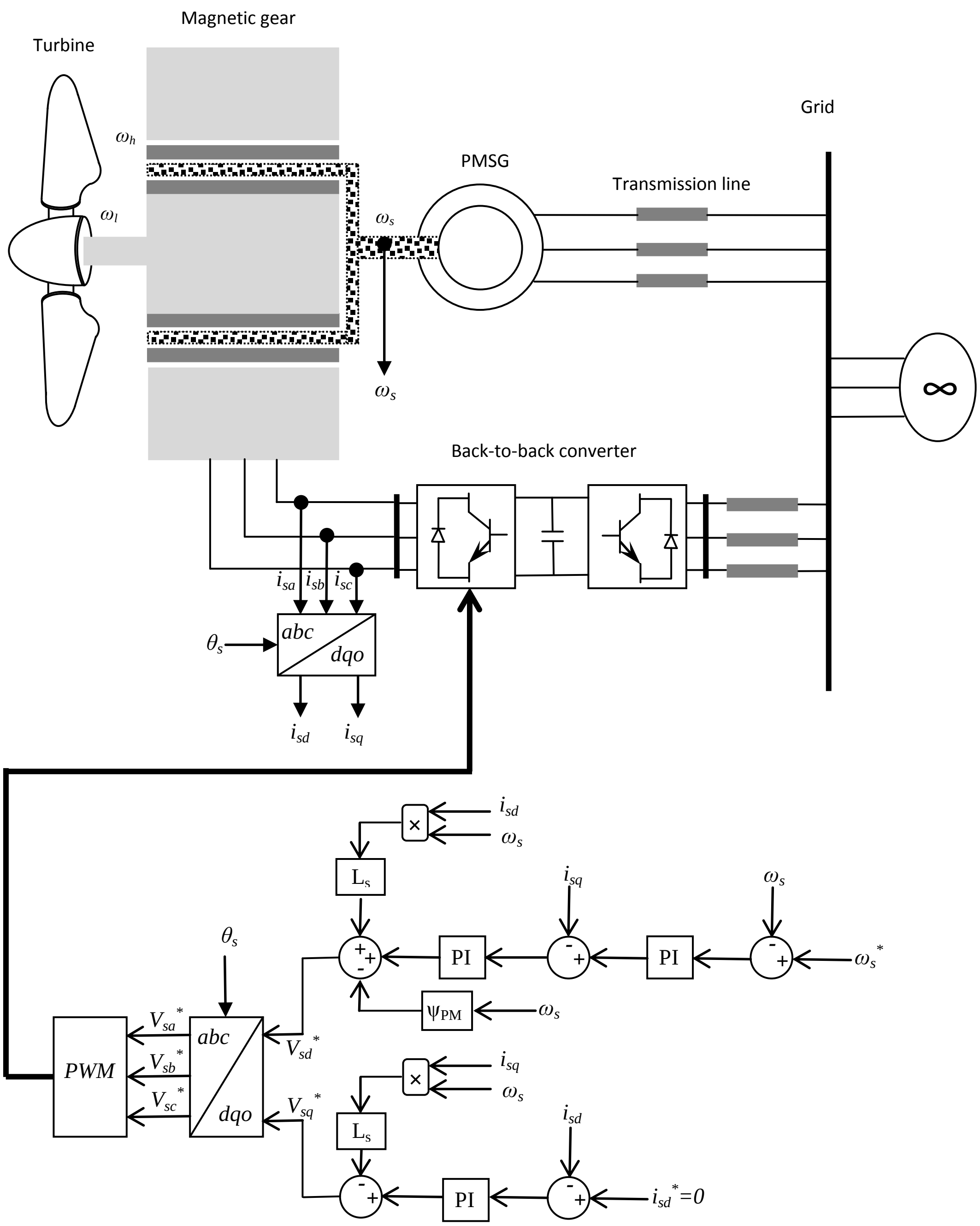


Figure 5.4 General structure of magnetic gear controller.

5.3.2. Grid Side Control

The active and reactive powers produced by the magnetic gear are:

$$\begin{cases} P = \frac{3}{2}\left(e_d i_d + e_q i_q\right) \\ Q = \frac{3}{2}\left(e_q i_d - e_d i_q\right) \end{cases} \tag{5.11}$$

Where, *e* the voltage at the output inverter and *i* the transmission line current.

To overcome the problem of cross-related voltage terms in equation (5.11), the *dq* reference frame; figure 5.5, is chosen in such a way that:

$$v'_q = 0 \text{ and } v'_d = |v'| \tag{5.12}$$

Where, v' is the grid voltage.

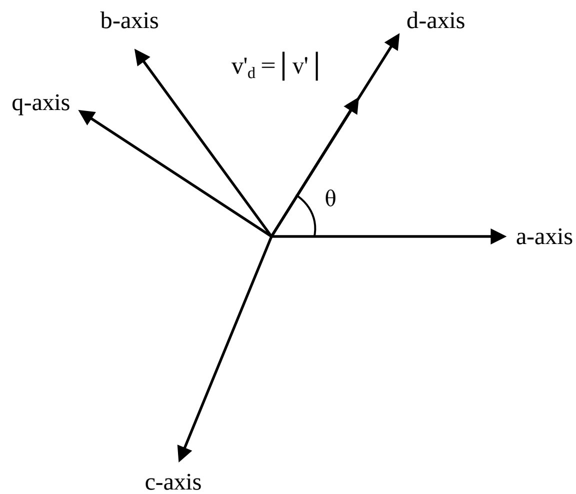


Fig. 5.5 Rotating reference frame

So the active and the reactive power will be proportional to i_d and i_q respectively:

$$\begin{cases} P = \frac{3}{2} e_d i_d \\ Q = -\frac{3}{2} e_d i_q \end{cases} \tag{5.13}$$

Now, it can be seen that the active power can be controlled via i_d and the reactive power can be controlled via i_q. The i_q is usually set to zero in order to achieved unit power factor [82].

The voltage equations of grid side inverter can be defined by:

$$\begin{cases} e_d = R_T i_d + L_T \frac{di_d}{dt} - \omega_s L_T i_q + v_d \\ e_q = R_T i_q + L_T \frac{di_q}{dt} - \omega_s L_T i_d \end{cases} \tag{5.14}$$

Where, R_T and L_T are the overall resistance and inductance of the grid-side converter.

According to the equations (5.13) and (5.14), the general structure of control strategy for grid-side inverter can be represented by the figure 5.6. The inverter is based on two loops, the inner loop is a current controller and the outer loop is a dc-link and reactive power controllers. The parameters of PI controllers can be defined as [69].

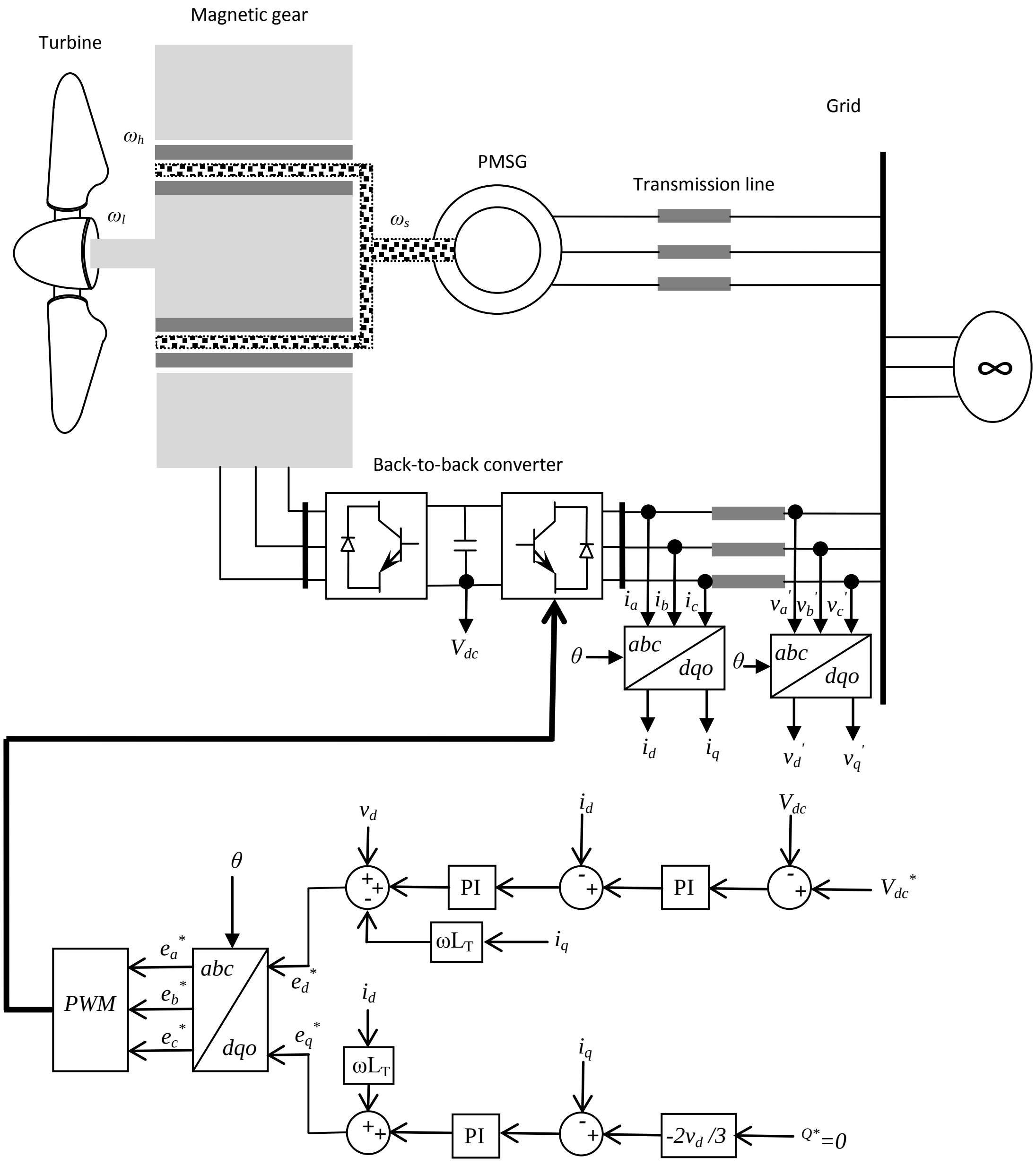


Fig. 5.6 General structure of control strategy

5.4. Simulation Results

The permanent magnetic synchronous generator rated power is 2 MKA, the power-split magnetic gear rated power is 500 kVA and the transmission line 7 KM. Table 5.1 shows the parameters of the system.

Table 5.1
The parameters of the system

Permanent magnetic synchronous generator	
Rated power	*2 MVA*
Rated voltage	*380 V*
Number of rotor poles	*23*
Stator phase resistor	*0.0025* Ω
Inductance L_d	*0.00004 H*
Inductance L_q	*0.00004 H*
Magnetic gear	
Rated power	*500 KVA*
Rated voltage	*380 V*
Winding resistor	*0.0004* Ω
Inductance L_d	*0.00019 H*
Inductance L_q	*0.00019 H*
Number of pole-pairs inner rotor	*21*
Number of pole-pairs outer rotor	*4*
Number of pole-pieces	*23*
Transmission line	
Resistance	*0.01273* Ω*/KM*
Inductance	*0.0009337 H/KM*
Distance	*7 Km*

For studying the dynamic behaviour of proposed magnetic power-split in the system, the wind speed variation is chosen, figure 5.7. The inner rotor kept constant to *20 rad/s*, decreases linearly from *20 rad/s* to *14 rad/s*, kept constant to *14 rad/s*, decreases again from *14 rad/s* to *10 rad/s*, kept constant to *10 rad/s*, increases from *10 rad/s* to *12 rad/s*, kept constant to *12 rad/s*, increases again from *12 rad/s* to *17 rad/s* and finally kept constant to *17 rad/s*, knowing that the nominal power is reached at *20 rad/s*.

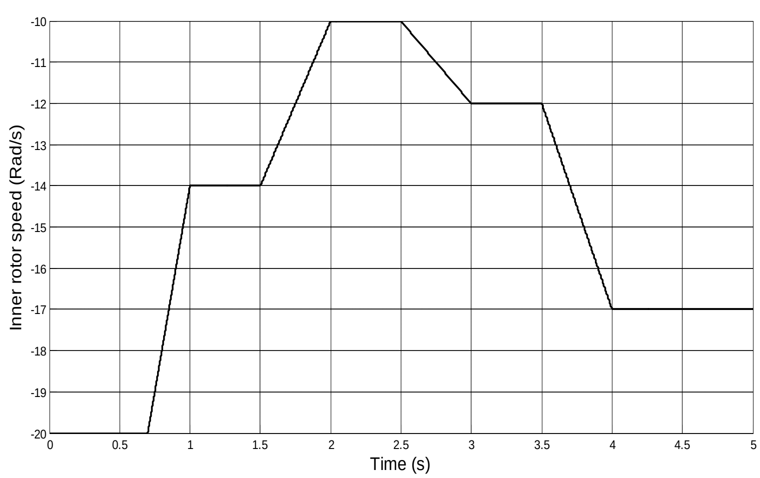


Fig. 5.7 The inner rotor speed variation.

Through the converter, the generator speed ω_s is kept constant to the synchronous speed *13.66 rad/s* by controlling the high speed ω_h. We can see from the figure 5.8 the parmanent magnetic synchronous generator speed still constant even though the variation of the wind turbine.

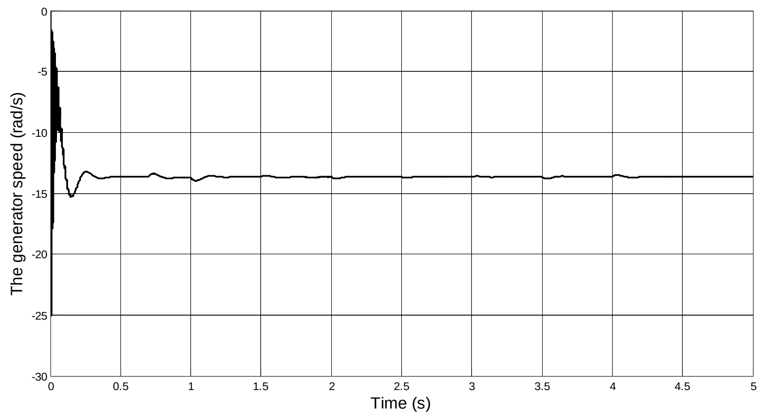


Fig. 5.8 The generator speed variation.

By controlling the speed of the control rotor of the magnetic gear figure 5.9, we can maintain the generator speed to the synchronous speed.

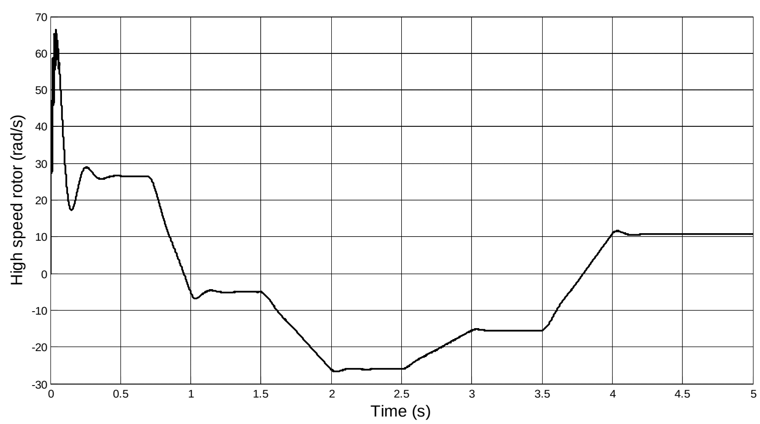


Fig. 5.9 The variation of high rotor speed of magnetic gear.

In order to collect the maximum power produce by the power-split magnetic gear by using the grid side inverter, the dc-link voltage is adjusted to the maximum voltage. We can see from figure 5.10 the dc-link voltage kept constant to the reference value *1300 V*.

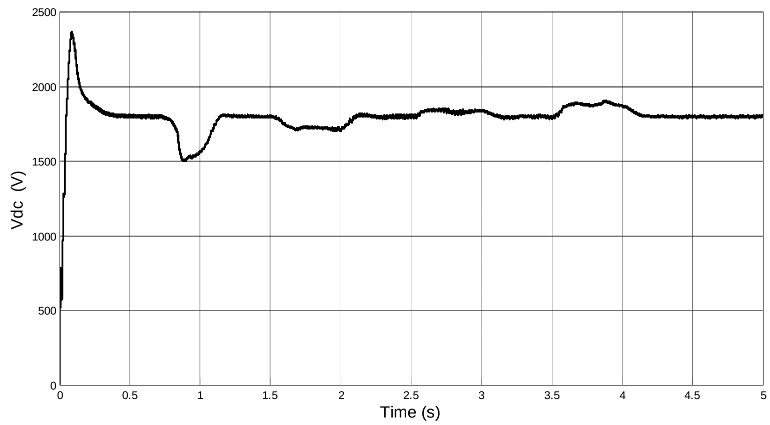


Fig. 5.10 The dc-link voltage.

From figure 5.11, we have the variation of the active power produce by the wind turbine and transmitted to the inner rotor of magnetic gear, the nominal value is about *2 MW*.

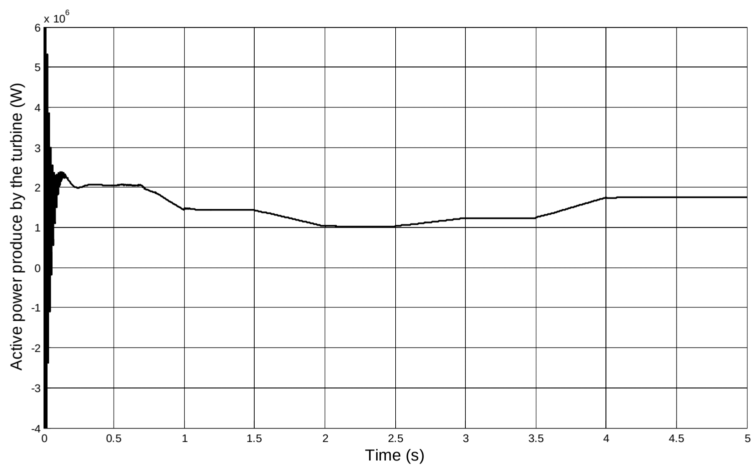


Fig. 5.11 The power transmitted to the inner rotor of the magnetic gear.

The demanded power of the output generator is fixed at *1.5 MW*; it is clear from figure 5.12 that the output power of the permanent magnet synchronous generator tracked the asked power. And the power injected to the grid through the generator is about *1.5 MW*.

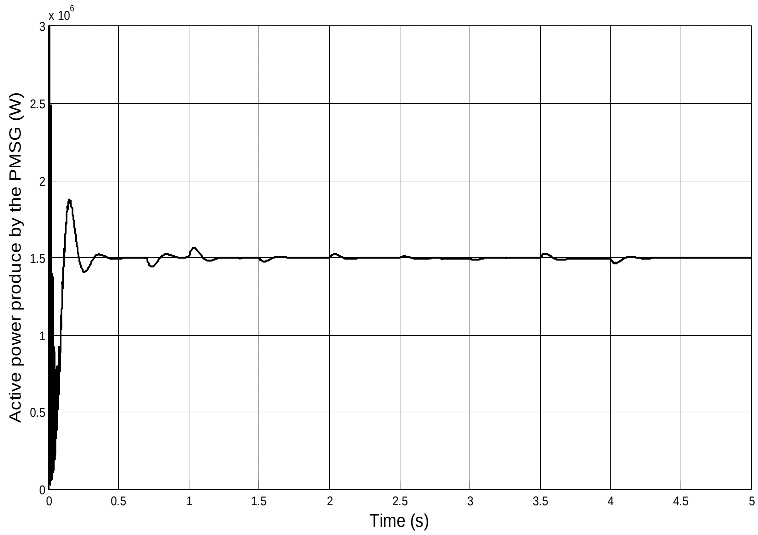


Fig. 5.12 The power produces by the PMSG.

From the figure 5.13, the total power produce by the turbine, split between the permanent magnetic synchronous generator and the magnetic gear, and that is the big advantage of the magnetic gear. We can see for example that from *0.5s* to *0.7s*; the total power is about *2 MW* Figure 5.11, the power produce by the PMSG is about *1.5 MW* figure 5.12 and the power produce by the magnetic gear is about *0.5 MW* figure 5.13.

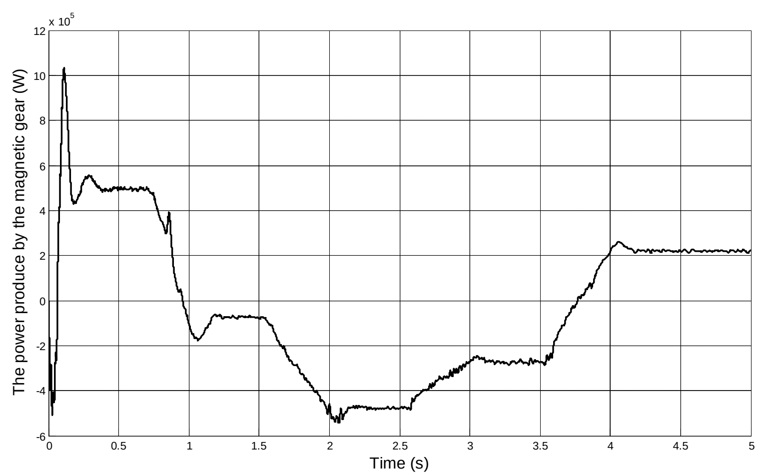


Fig. 5.13 The power produces by the power-split magnetic gear.

5.5. Conclusion

We have seen that with the magnetic gear power-split the dimensional problem of the nacelle can be overcome. With the magnetic gear, the power transmitted to the grid is split between the power generated by the permanent magnetic synchronous generator and the power produced or consumed by the magnetic gear. Also, with the power-split magnetic gear, controllers and the required power electronics can be reduce under the rated power.

CHAPTER 6

CONCLUSION

6.1. Summary

To reduce the cost and the weight of the future wind turbine, mechanical gearbox is replaced by magnetic gear generator. Using magnetic gear coupled mechanically and magnetically with permanent magnet synchronous generator, even under low wind conditions often found inland, and without mechanical gear, high speed can be reached with this topology. Two original wind generator concepts have been presented; the first concept consists of a magnetic gear that employs rare-earth magnets, coupled with conventional permanent magnet synchronous generator. The second new concept is a magnetic gear power-split, the power transmitted to the grid is split between the power generated by the permanent magnetic synchronous generator and the power produced or consumed by the magnetic gear. This means that the generator, the controllers and the required power electronics can be reduced under the rated power.

In this work we also find the development, configurations and characteristics of different wind generators concepts with their advantages and disadvantages. A detailed analysis has been presented with the comparison of different wind generator concepts as well as their market penetration. The developing trends of wind generator systems have been presented, some wind systems challenge have also been exposed.

The DFIG concept is still dominant in the current market. However, it seems that the permanent magnet direct drive turbines will be the future of wind energy generation. In the recent years, the market shows more interest in the permanent magnet direct drive with full-scale power electronic converter. The performance of permanent magnets PMs is improving and the cost of PMs have been decreasing in the recent years, which makes variable speed direct-drive PM machines with full-scale power converter more attractive for offshore wind power generations.

Big MW-size turbines, due to the pressure of reducing the energy cost, have become the dominant machines in the commercial market. In the near future wind turbine rated power would attain 10 MW. Thus, the current developments of wind turbine concepts are more and more being directed to offshore wind energy.

To decrease the cost and the weight of the future offshore wind turbine, a novel topology for magnetic gear has been presented. The first concept presents a coupling magnetic gear with permanent magnet synchronous generator for 2.5 MW wind turbine. I have described the different gear ratio of magnetic gear. It has been shown that, with low wind conditions often found inland, one can achieve high speed variation using the proposed magnetic gear generator. Also, we do no more require the huge mechanical gearbox and the system of lubrication. By way of such topology, we can overcome the dimension problem of the nacelle and allow more space to work safely. The dynamic behaviour of the magnetic gear generator with variable speed was explored and the simulation results confirm the benefits of the proposed magnetic gear generator.

With the second concept, we have seen that with the magnetic gear power-split, the dimensional problem of the nacelle can be overcome. With the magnetic gear, the power transmitted to the grid is split between the power generated by permanent magnetic synchronous generator and the power produced or consumed by the magnetic gear. Also, with the power-split magnetic gear, controllers and the required power electronics can be reduced under the rated power.

6.2. Future Research

The following applicant topics are proposed for future research:

- Analysis the performance of magnetic gear to show a variation of flux density and variation of a torque.
- A transient characteristic of magnetic gear.
- Design magnetic gear prototype.

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ملخص

في المستقبل القريب تواجه تطبيقات تربينات الرياح البحرية لتوليد الطاقة العالية تحديات كبيرة يجب التغلب عليها، هذه التحديات تتجلى في الحجم الكبير والتكلفة المرتفعة. علاوة على ذلك، يجب أن نؤخذ بعين الاعتبار وزن نظام التزييت وحجم مضاعف السرعة الميكانيكية. للتغلب على هذه المشاكل نقدم في هذه الرسالة نهجا جديدا لتبولوجيا توليد طاقة الرياح من دون معدات ميكانيكية باستخدام مضاعف السرعة المغناطيسي، حتى في ظل ظروف الرياح المنخفضة و دون ومضاعف السرعة الميكانيكي يمكن الوصول إلى سرعة عالية. لهذا قدمت فكرتين. الفكرة الأولى عبارة عن مولد كهربائي يتكون من دوارين مغناطيسيين، دوار المدخل والذي يتصل بالتربين، و دوار المخرج المقترن مغناطيسيا مع الشبكة الكهربائية لتوليد الطاقة الكهربائية. الفكرة الثانية هي استخدام مضاعف السرعة المغناطيسي، يحتوي هذا الأخير على ثلاثة دوارات. يتم تقسيم الطاقة المنتجة بين المولد الكهربائي و مضاعف السرعة المغناطيسي. بهذه الطريقة سيتم تخفيض كتلة التربين و حذف مضاعف السرعة الميكانيكي.

نقدم نتائج المحاكاة للتحقق من صلاحية الجهاز المقترح و يبدو أن العيوب المرتبطة بالتربينات الرياح البحرية يمكن التغلب عليها باستخدام مضاعف السرعة المغناطيسي.

الكلمات الرئيسية: مولد متزامن مغناطيسي، المضاعف المغناطيسي، الشبكات العصبية الاصطناعية، تربينات الرياح.

RÉSUMÉ

Pour les futures applications du générateur éolien offshore de grande puissance, la taille et le coût sont les grands défis qui doivent être surmontés. En outre, le poids du système de lubrification et la dimension du multiplicateur de vitesses mécanique doit être aussi pris en considération. Pour surmonter ces problèmes, une nouvelle approche pour la production d'énergie éolienne sans multiplicateur de vitesse mécanique est présentée, utilisant un multiplicateur magnétique, couplé mécaniquement et magnétiquement avec un générateur synchrone à aimants permanents. Avec cette nouvelle topologie, même dans des conditions de vent faible, et sans équipements mécaniques supplémentaires, la vitesse nominale peut être atteinte. En saisissant cette opportunité, deux idées ingénieuses ont été présentées. La première présente un générateur avec multiplicateur magnétique qui comporte deux rotors. L'énergie mécanique extraite par la turbine éolienne est transmise au rotor d'entrée, qui est transmis magnétiquement au rotor de sortie. A son tour, le rotor de sortie produit un couple électromagnétique et, de ce fait, une puissance engendrée par l'enroulement du stator va être injectée dans le réseau électrique. Le deuxième concept consiste à diviser la puissance transmise au réseau, entre la puissance produite par le générateur synchrone à aimants permanents et la puissance produite ou consommée par le multiplicateur magnétique. Ainsi, la dimension de la nacelle sera réduite et le multiplicateur de vitesse mécanique peut être réduite ou supprimée.

Les résultats de la simulation sont donnés pour vérifier la validité de la génératrice proposée. Il semble que les inconvénients liés à la future éolienne offshore peuvent être surmontés en utilisant ces nouvelles topologies.

Mot Clés: Générateur synchrone à aimants permanents, multiplicateur magnétique, réseaux de neurones artificiels, turbine éolienne.

ABSTRACT

For high power generation of future offshore wind turbine application, size and cost were the big challenge that must be overcome. Furthermore, the weight of lubrication system and the dimension of the mechanical gearbox must be taken into consideration. To overcome these problems, a new topology approach for wind power generation without mechanical gear is presented. Using magnetic gear coupled mechanically and magnetically with permanent magnet synchronous generator, even under low wind conditions often found inland, and without mechanical gear, the high speed can be reached with this topology. For these, two original ideas have been presented. The first one, deals with magnetic gear generator which contains two rotors, the input rotor and the output rotor. The mechanical energy extracted from the wind turbine is transferred to the input rotor, which is transmitted magnetically to the output rotor. The permanent magnet of the output rotor interacts with the stator windings to produce electromagnetic torque. Thus, the power captured by the wind turbine is transmitted to the grid by the stator winding. The second idea is the use of power-split magnetic gear. The power transmitted to the grid is split between the generated power by the permanent magnetic synchronous generator and the power produced or consumed by the magnetic gear generator. Thus, the dimension of the nacelle will be reduced and the mechanical gear box can be reduced or omitted.

Computer simulation results are given to verify the validity of the proposed machine. It appears that the disadvantages associated to future offshore wind turbine can be surmounted using magnetic gear generator.

Key Words: Artificial neural network, magnetic gear, permanent magnet synchronous generator, wind turbine.