Expanding the Operational Envelope of Modern Wind Turbine Induction Generators

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Energy Systems and the Environment

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ABSTRACT

Variable speed operation is becoming the standard in modern wind turbine design. The advantages offered by such systems are becoming increasingly important as the amount of wind energy on the network grows.

Doubly-Fed Induction Generators (D-FIGs) can be used to provide variable speed operation. This project is an exploration of the evolution from the simple squirrel cage induction generator to the D-FIG, with assessments and comparisons made of the characteristics and attributes of importance to the electricity industry.

A detailed theoretical analysis is supported by modelling and simulation in MATLAB Simulink to provide a thorough investigation.

Aknowledgements

I would like to thank Dr Andy Cruden for his help and guidance through this dissertation. I would also like to extend my gratitude to Janet Harbidge for her rapid organisational skills at the start of term.

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Section 4

Introduction

Aim

While the debate over future UK energy policy is ongoing, there have been some government commitments, driven by international agreements on climate change.

Renewable energies are set to play a larger part in meeting our energy demands, reducing CO_2 emissions and promoting the concept of sustainability.

The EU Renewables Directive states that 22.1% of electricity should be developed from renewable energies by 2010. As part of this goal, 10% of the UK's electricity demand is expected to come from renewables by 2010. The Scottish Executive has set targets of 18% of electricity from renewables and has introduced a further target of 40% by 2020.

Currently 13% of Scotland's generation portfolio is made up of renewables. To meet the 2020 target, based on predicted future demand, another 3000MW of renewable generation plant must be installed in addition to currently existing and consented plant.
Wind power is considered a mature technology, already being exploited significantly in other areas of Europe For this reason wind energy is expected to play the lead role in achieving the UK renewables targets of the near future.

As the amount of wind generation plant on the network increases, wind turbines have a greater responsibility to reliably provide a dependable source of power and perhaps take on some of the regulatory tasks of traditional plant.

Modern wind turbines favour a variable speed operating concept. This allows for smoother power output, less wear and tear and control of reactive power. Doubly-Fed Induction Generators can be used to provide variable speed operation.

This thesis aims to examine the expansion of the operating range of an induction generator, through manipulation of the rotor properties. Theoretical analysis will be fortified with software modelling in MATLAB Simulink allowing comparisons to be made between different machine concepts in terms of range of operation, efficiency and reactive power control.

Proposed Approach and Organisation of this Thesis

This thesis begins with a review of the current position wind energy plays in the UK electricity industry and looks at how that position is changing.

The potential for wind energy in the UK is discussed and reasons for the rate of expansion are highlighted.

The implications of increased wind generation including potential network and market constraints are considered and recent changes in trading regulations are explained.

The purpose of this section is to supply the reader with an up to date evaluation of wind energy in the UK.

The evolution of the modern utility scale wind turbine is then presented in brief. Wind resource evaluation, the aerodynamic conversion of wind and relevant operating concepts are outlined. This should provide the reader with an understanding of modern wind turbine operation.

An appreciation of modern wind turbine operation, in particular the relevance of variable speed operation is required to provide the context for the rest of this thesis.

The next section is an in depth examination of the induction machine, beginning with the simple squirrel cage rotor construction and leading, eventually to a wound rotor construction with a rotor connected voltage converter.

In this section the operational characteristics of the different machines are explained via an electrical and mechanical analysis, giving the reader a detailed comprehension of induction machine theory and the range of operation that can be expected from different machine concepts.

Models of the machines are then built and simulated in MATLAB Simulink. The purpose of this exercise is to produce models with real parameters that accurately demonstrate the behaviour of electrical machines. This allows further exploration of the performance characteristics of each system and for comparisons to be made between different configurations.

There follows a conclusion and discussion section where the thesis is reviewed and suggestions are made for further areas of research.

Section 1

Wind Energy and the UK Electricity Industry

The UK electricity industry is currently facing some tough decisions. Nuclear and coal power stations built in the 50s and 60s are nearing the end of their life spans, the UK is already a net gas importer and much of the network is in need of renewal. Concerns over CO_2 emissions, increasing oil and gas prices and a lack of a coherent nuclear waste disposal solution, mean that our future energy source is uncertain.

The renewable energy targets of the near future look set to be fulfilled using wind energy.

The UK is ideally situated for the capture of wind energy. The weather is dominated by low pressure systems that form in the North Atlantic and pass over the UK from the west. These systems are responsible for the changeable weather that is typical to the UK though also push up the average wind speed to 6-7m/s, around 2m/s higher than most of mainland Europe. In terms of energy content this is extremely significant, meaning that the UK can lay claim to around 40% of the exploitable wind resource of the whole of Europe.

The UK has been slow to take advantage of this huge energy resource. Other European countries, in particular Denmark and Germany have been the real pioneers.

Denmark has been growing a wind energy industry for more than 20 years. Wind energy now supplies 20% of Denmark’s electricity needs and is predicted to reach 25% by 2008. The wind industry has created 20,000 jobs in Denmark and 90% of manufactured plant is sold abroad.

The UK is slowly making ground, motivated by international commitments made on climate change. In 2004 1909GWh or 0.5% of the UK’s electricity demand was met with wind energy. This amounts to an increase of 51.6% in wind energy since 2003 [1]. During 2004, 250MW of wind farms were installed in the UK and a further 600MW are expected to be completed by the end of 2005. Presently the British Wind Energy Association estimates that there are around 5GW of proposed wind projects at various stages of planning and development in the UK.

Figure 1.1. Shows the locations of wind farms in the UK that are operational, planned, consented and under construction as of 08/05

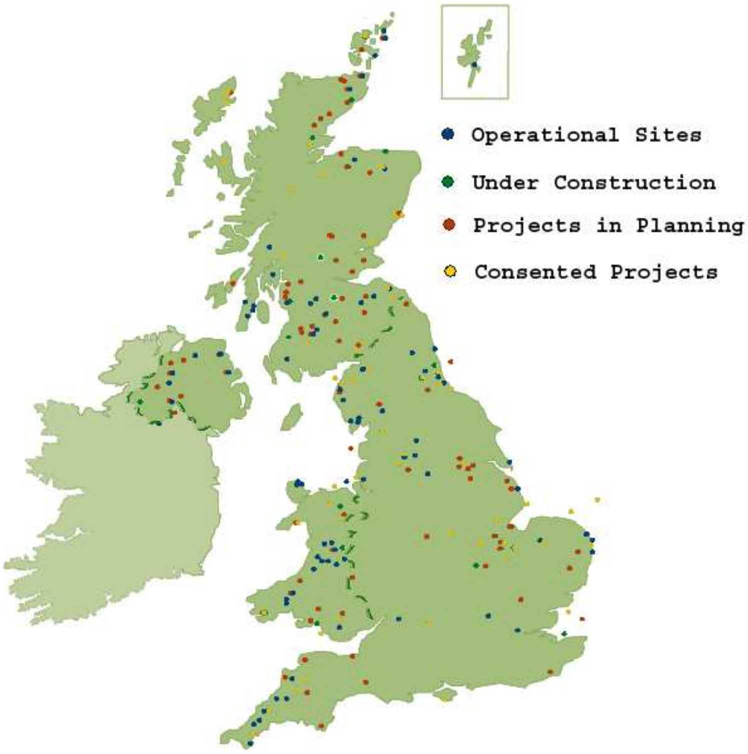


Figure 1.1

Offshore and Onshore Wind Farms

Wind farms are being constructed both onshore and offshore. The sites with the highest mean wind speed tend to be the hill tops of the north and west of the UK. This is a result of the air mass being compressed as it is forced to travel over or around the hill. Wind speed also increases with altitude. The proximity to the coast also is a factor as coastal winds have less exposure to the drag and turbulence effects encountered over land. Unfortunately the windiest onshore sights tend to be the most visually intrusive and developments can be met with protest.

Offshore wind farms tend to avoid the land use disputes and can have other advantages. Offshore sites offer large continuous areas suitable for large scale projects. Offshore winds are less turbulent which can mean the turbines harvest the energy more effectively and there is a reduction in fatigue on the constructions. Lower wind-shear (the boundary layer of slower moving wind close to the surface is thinner) means that tower height can be reduced.

The major disadvantage of building offshore is cost. Compared with onshore projects, costs associated with construction, operation and maintenance tend to be higher as a result of limited access, caused by adverse weather and the additional cost of marine foundations. Grid integration can also be more expensive as coastal connection points are often weak and require strengthening.

Network Constraints

Network constraints are a limiting factor in the rate at which wind energy can be developed in the UK. The Grid was essentially designed to take power from large nuclear or fuel burning power stations, transfer it to populated areas via a high voltage transmission network then distribute it to consumers through a medium and low voltage distribution network. Consequently control and protection systems were designed accordingly. Most renewable energy generation plant including wind farms produce significantly less power than conventional plant and in many cases are connected directly to the MV or LV distribution network, where the power is absorbed locally. Increasing the amount of generating plant on the distribution network, especially from stochastic power sources such as wind can create complications in protection and control systems.

When transporting electricity regionally, over long distances the voltage is boosted in order to minimize losses. This is the purpose of the High Voltage transmission network. The Geographical spread of planned and existing wind farm sites does not correspond with the existing network, especially in the north of Scotland where lack of transmission infrastructure has long been identified as a major constraint. This problem is now being addressed with a controversial 400kV transmission line to bring power from the Highlands and Islands down to customers in the central belt.

The electricity network in Scotland currently operates with an over-capacity of 70% (due largely to a decline in industry over recent years) with plans to increase generation. The export capacity via the inter-connection to access the English and Welsh network is currently limited to 2200MW. This means there is essentially a bottleneck in the system that can make the addition of new generation plant less enticing for potential developers in Scotland.

A major consideration in operating an electricity network with increasing levels of wind power is how to balance a 'live' system with a power source that is stochastic in nature and has limited predictability. Without any feasible storage facility, spinning reserve, from conventional plant is required to come on line in the event of a lull in the wind. Much is made of the amount of reserve required with numerous studies producing conflicting results. Data gathered from operational networks in Germany and Denmark show that the maximum power swings, occurring on average once a year are never above 20% of the installed wind capacity and for 90% of the time the power swing is less than 5% within the hour[2]. These figures amount to a spinning reserve demand similar to existing levels and suggest that though there may be a need for an increase it is likely to be manageable.

Market System

The UK Electricity Market is regulated by OFGEM (Office of the Gas and Electricity Markets). In April 05 OFGEM introduced the British Electricity Trading and Transmission Arrangements (BETTA) essentially to bring the whole of the UK under one market system and to revise various operating practices. The entire UK transmission system, including access to the Scotland-England inter-connection is now operated by NGC (National Grid Company). The system involves a new charging strategy for the transmission network that sees generators in remote areas paying the highest price for access, though on the whole, better access to larger markets should be beneficial to wind farm operators.

Financial Incentives

To provide a financial incentive and encourage investment in wind energy, some government initiatives were launched. Electricity generated from approved renewable sources is exempt from the Climate Change Levy (CCL). In recognition of companies fulfilling the Renewables Obligation, Renewable Obligation Certificates (ROCs) are issued accordingly. Companies have the option of meeting obligations or buying the requisite amount of certificates from companies with a surplus. Another option is to pay a 'buy-out' fee. The revenue raised from companies choosing this option is distributed amongst the more compliant customers providing further incentive to comply.

Section 2

Wind Energy Conversion

Introduction

In this section wind energy conversion systems shall be discussed. Whilst it is recognised that there has been significant development in small-scale technologies in recent years and progress in vertical axis systems, this thesis is concerned with modern, large utility-scale upwind, horizontal-axis turbines.

This chapter begins with a brief history of the evolution the modern utility-scale wind turbine. It then gives an overview of wind resource evaluation and summarises the aerodynamic conversion of wind energy and development of useful mechanical power. Finally, various operating concepts are presented and the differences between fixed speed and variable speed systems are discussed.

The purpose of this section is to supply the reader with a background that will provide the context necessary to appreciate the relevance of the detailed electrical analysis that follows in this thesis.

Evolution of the Modern Wind Turbine

The wind was identified as a useful energy source around five thousand of years ago when it was captured by sails and used to propel boats in Egypt. The earliest known example of a windmill is thought to have come from Persia (now Iran) where rudimentary devices were used to grind grain between 600-900BC. Wind Energy Conversion systems have been used ever since to grind grain and pump water.

The first electricity generating wind turbine was invented in 1888 by Charles F. Brush in Ohio. The system (pictured below) had a rotor diameter of 17m, and generated 12kW.

The machine worked for 20 years and even had a full electrical control system, based on solenoids which remained standard for a century.

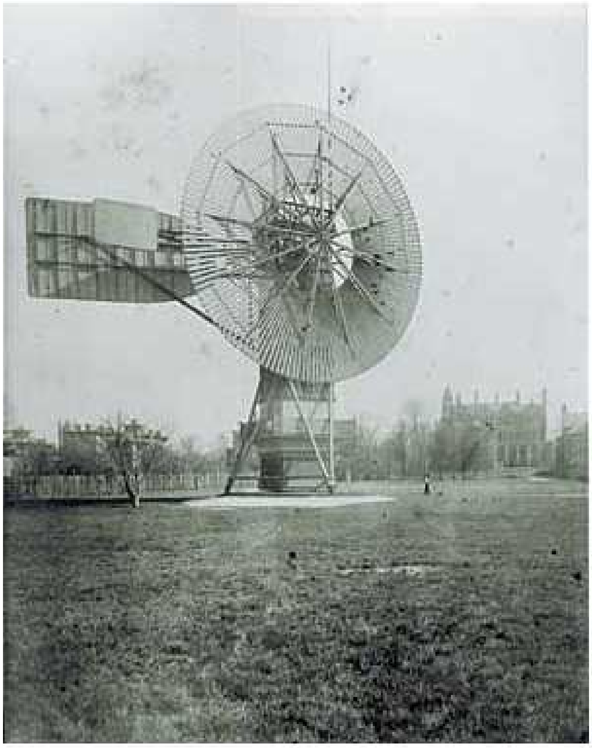


Figure 2.1 First Electricity Producing Turbine

Wind was being used to generate electricity in many European countries by 1910. The first widespread use of wind to generate electricity occurred in America in the 1930’s, when hundreds of thousands of small turbines were used to power farms and small settlements too remote for grid connection at the time. Their prime use was to charge batteries and power communications equipment.

The first utility scale turbine to generate a significant amount of power was invented in Russia in 1931. The Balaclava turbine could generate 100kW and operated in the Caspian sea for about two years.

The bold, American Smith-Putman machine (pictured below) was built in 1941 and was capable of generating 1.25MW, which, until even a few years ago, would have been ambitious. However, after just a few hundred hours of intermittent operation, one of the blades succumbed to the huge stresses it was under and broke off.

Figure 2.2 Smith-Putman Machine

Wind Turbine development continued after the war at a gentle pace until the 1970’s when wind received renewed interest, the catalyst being the Arab Oil Crisis of 1973.

Between 1974 and 1981 the American Government funded a huge research program with the intention of developing a multi-mega watt turbine that could be produced in large numbers so as to be attractive to utility companies. The program suffered several setbacks, for example, early attempts at building large double bladed downwind systems didn’t properly account for tower shadow (the period when the blade passes behind the tower) the problem took years to resolve.

The program eventually started to have some success, producing several effective vertical axis wind turbines, (pictured below), four large scale horizontal axis turbines and a selection of smaller systems. More importantly, the

Americans had gained a high level of experience and expertise through years of experiment.

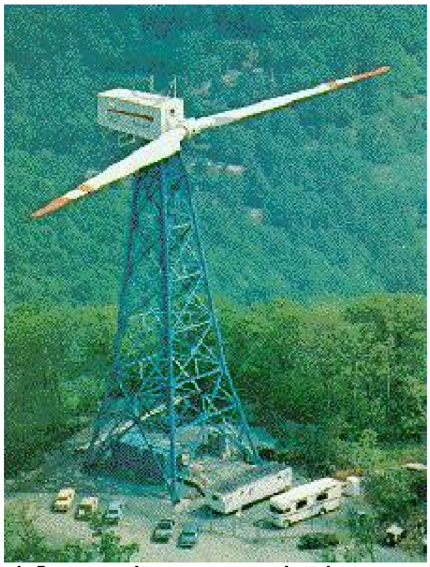


Figure 2.3 VAWT Figure 2.4 Problematic Downwind System

In 1981 the newly elected Reagan administration proposed energy tax credits to encourage investment in wind. This led to the Californian wind rush of the 80’s and the introduction of the first wind farms.

Unfortunately this created an over enthusiasm to install systems that were not fully developed. A lot of the lessons learned from the years of research were ignored and consequently there were inevitable design problems with the large immature machines. This over exuberance was encouraged by ignorance in congress who, not understanding the difference between installed capacity and produced energy, granted tax credit based on installed capacity.

Meanwhile in Europe, the Danes and Germans had developed their own systems, encouraged by the opportunities of exploiting the high wind speeds of northern Europe. The preferred European system was the horizontal axis up-wind, two or three bladed system that is becoming a common site around the UK.

The Danes were able to capitalise on the American situation and soon the troubled Californian Wind farms were filling up with Danish machines. American interest in wind eventually dwindled.

The Danes became world leaders in wind energy and have steadily developed their home market and created a huge export industry with 90% of the manufactured plant being sold abroad.

Recent years have seen another resurgence in wind energy, driven by environmental concerns over carbon emissions. This has brought about a subsequent development in technology.

The original American ‘bigger is better’ philosophy seems to have been proven and multi-megawatt turbines are now the trend. REpower in Germany, having recently introduced a 5MW Turbine with 61.5m blades (pictured below).

Figure 2.5 REpower 5MW Turbine

Wind Resource Evaluation

The wind is constantly changing, it is influenced by so many factors that it is impossible to model exactly. The annual average wind speed can give an indication of the potential power that can be developed from a particular site, though on a shorter time basis, the distribution of wind speeds around the mean is extremely important.

In order to characterise the wind resource for a particular site, statistical analysis techniques are employed.

It has been found that, for a general case, probability functions can be used to accurately describe the spread of predicted wind speeds around the mean. Weibull probability distribution functions are commonly used.

The Weibull probability density function:

$$f(w) = \frac{k}{c}\left(\frac{w}{c}\right)^{k-1} e^{-(w/c)^k} \qquad 2.1$$

where *k* is a shape parameter, *c* is a scale parameter, and w is the wind speed. Hence, the average wind speed (or the expected wind speed) is:

$$w_{\text{ave}} = \int_0^\infty w f(w) \mathrm{d}w = \frac{c}{k}\Gamma\left(\frac{1}{k}\right) \qquad 2.2$$

where _ is Euler's gamma function:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} \mathrm{d}t. \qquad 2.3$$

For a Rayleigh distribution, the shape parameter, k is 2. The scale factor can be found, given the average wind speed as $\Gamma(^1/_2) = \sqrt{\pi}$ giving:

$$c = \frac{2}{\sqrt{\pi}} w_{\text{ave}}. \qquad 2.4$$

The plot below shows a Rayleigh wind speed probability density function for average windspeeds of 5.4m/s.(solid), 6.8m/s(dashed), 8.2m/s (dots).

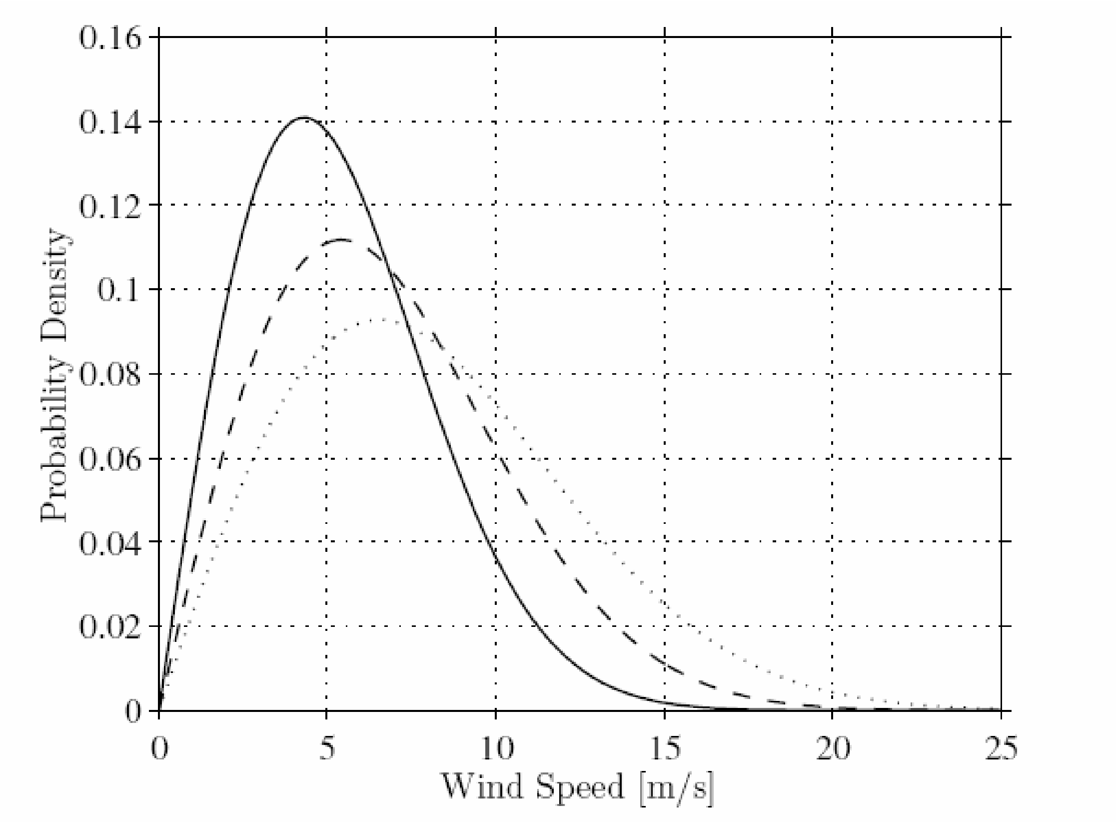


Figure 2.6 Probability Density Function

On a very short time scale, i.e. down to fractions of seconds, the variation of wind speed is referred to as turbulence.

To fully understand the wind currents that act on a turbine, a model of the turbulence must be developed. One commonly used function is the Kaimal spectral density function:

$$S(f) = \left(\frac{0.4}{\ln(z/z_0)}\right)^2 \frac{105 z w_0}{\left(1 + \frac{33fz}{w_0}\right)^{5/3}} \qquad 2.5$$

where S is the single-sided longitudinal velocity component spectrum, f is the frequency, z is height above ground, z_0 is the surface roughness coefficient, and ω_0 is the average wind velocity at hub height.

The wind speed also varies in space, meaning that different parts of the blade swept area will experience different wind speeds and directions. This is particularly relevant in modern large turbines where the diameter of the swept area can be 120m.

A full understanding of wind characteristics is vital for both design engineers who need to evaluate stress levels, and electricity wholesalers who need to know how much electricity can be produced.

Power in the Wind

The most common method for calculating the steady state mechanical power that can be extracted by a wind turbine is the $C_p(\lambda)$ curve. C_p is the power coefficient and λ is the tip-speed ratio. A typical $C_p(\lambda)$ curve can be seen below:

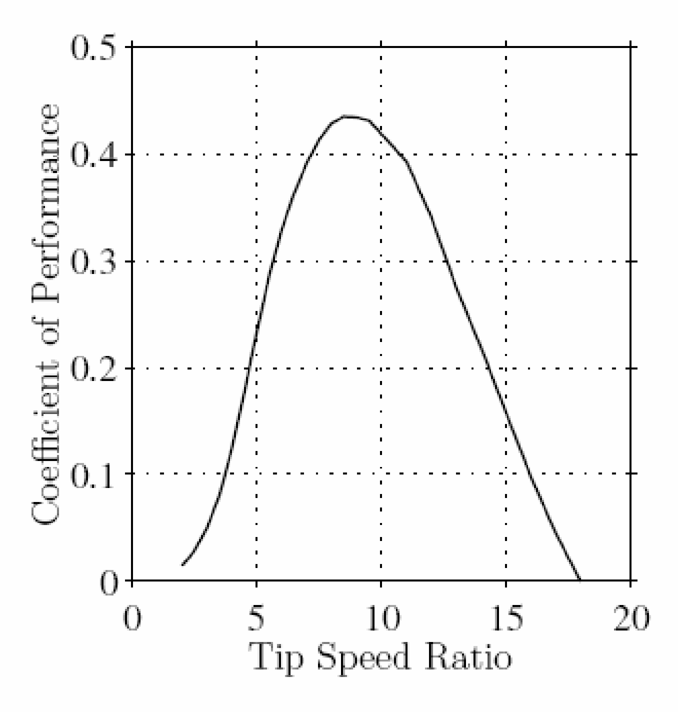


Figure 2.7 A typical $C_p(\lambda)$ curve

The power that can be drawn from a swept area A within an air flow is:

$$P_{mech} = \frac{1}{2} \rho A C_p \cdot V^3 \qquad 2.6$$

Where ρ is the air density and V is the wind velocity. The power coefficient is taken from the $C_p(\lambda)$ curve for the corresponding tip speed ratio, calculated by:

$$\lambda = \frac{\Omega R}{V} \qquad 2.7$$

where Ω is the rotor angular velocity (on low speed side of gear box) R is the radius at the blade tip.

It can be seen from equation () that the mechanical power is proportional to the cube of the wind velocity. This means that a slight increase in wind speed gives rise to a large increase in available energy.

The power coefficient C_p is not a measure of efficiency as it has an upper limit known as the Betz limit. This limit can be proven mathematically to be 0.593 or 16/27. It arises from the fact that not all of the energy from the wind can be extracted as there must be a flow of air behind the turbine. Therefore, energy that is not captured bypasses the blades and is not dissipated by the rotor.

A plot of power vs wind speed for a Danish 600kW turbine can be seen below:

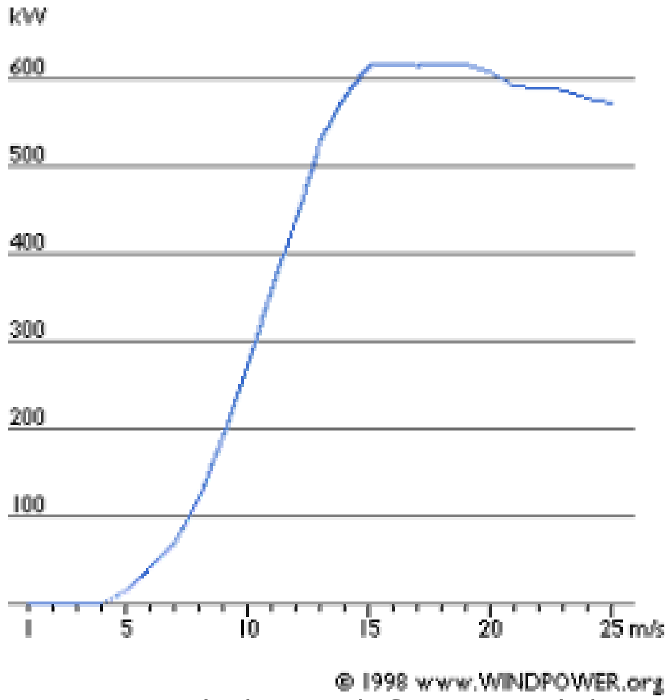


Figure 2.8 power vs wind speed for a Danish 600kW turbine

It is often desirable to tailor the power/speed characteristics of a wind turbine. A wind farm operator must be able to control the amount of power produced by the turbines or may wish to increase energy yield at low wind speeds. The power/speed characteristics can, to a certain extent be altered by changing the aerodynamic properties of the blades. The following section gives a brief overview of how turbine blades work and highlights the differences between various operating concepts.

Aerodynamic conversion

Wind turbine blades use an aerofoil to generate lift, the same way an aeroplane wing does.

Figure 2.9 shows the relevant forces and angles for a stationary aerofoil in an air flow:

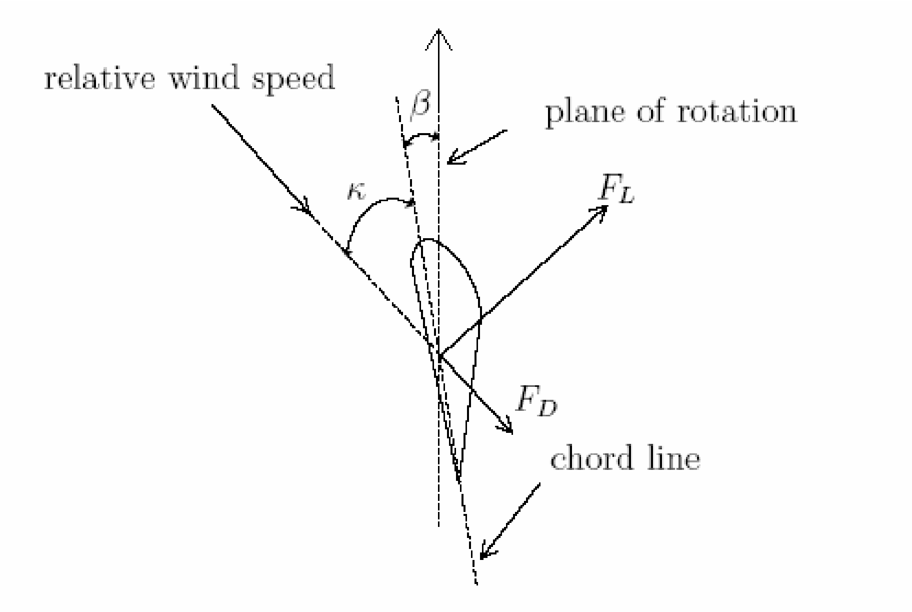


Figure 2.9 Stationary aerofoil in an air flow

The air flow causes a lift force F_L that is perpendicular to the direction of the air flow, and a drag force F_D that is in the same direction as the air flow. The blade will move in the direction indicated on the plane of rotation. The pitch angle, β, is the angle between the plane of rotation and the chord line. The angle of attack κ is the angle between the chord line of the blade and the relative wind direction.

The lift and drag forces can be manipulated by varying the angle of attack. If the angle of attack exceeds a certain value, a wake is created above the aerofoil which causes the blade to stall.

These principals form the basis of aerodynamic control.

Operating Concepts

Wind turbine operating concepts can be divided in to Fixed Speed Systems and Variable Speed Systems.

Fixed Speed Systems

Fixed speed systems use a squirrel cage induction generator directly connected to the grid. This type of generator needs to be turned at a fixed speed (or within 1% of rated speed). A gearbox is used between the generator and turbine shaft to adjust the speed appropriately. The original fixed speed system, popular in turbines built in Denmark during the 80s and 90s used stall control and is still the most common turbine in operation today. In a stall controlled, fixed speed system the blades are firmly bolted to the hub. The pitch angle is set so that the blade will stall and limit the power when the wind speed becomes too high. Often the blade will be slightly twisted so as to gradually stall the blade and ensure smoother transitions, reducing fatigue causing vibrations.

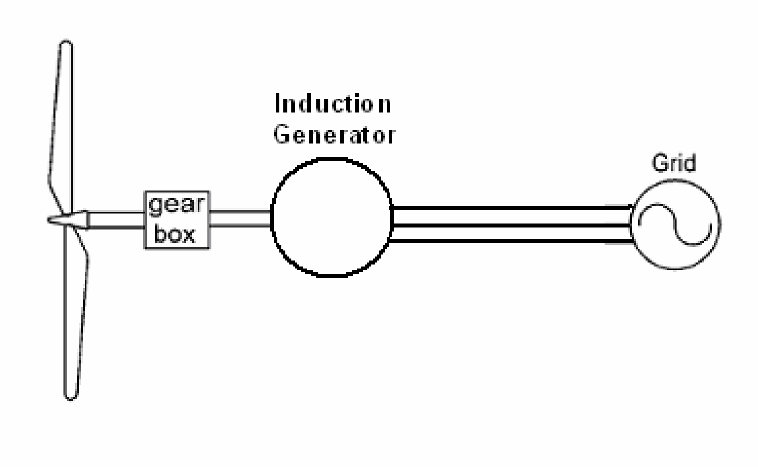


Figure 2.10 Fixed Speed System

In an active-stall, fixed-speed system, the stall angle of the blades can be controlled. This is usually employed in larger machines (>1MW). The attack angle can be set, using the stall effect to limit the power to a particular power output (normally rated power), thus flattening the power/ wind speed curve for wind speeds above nominal value. This is known as power limitation. The range of pitch variation is usually limited between 0 and 4 degrees for active stall.

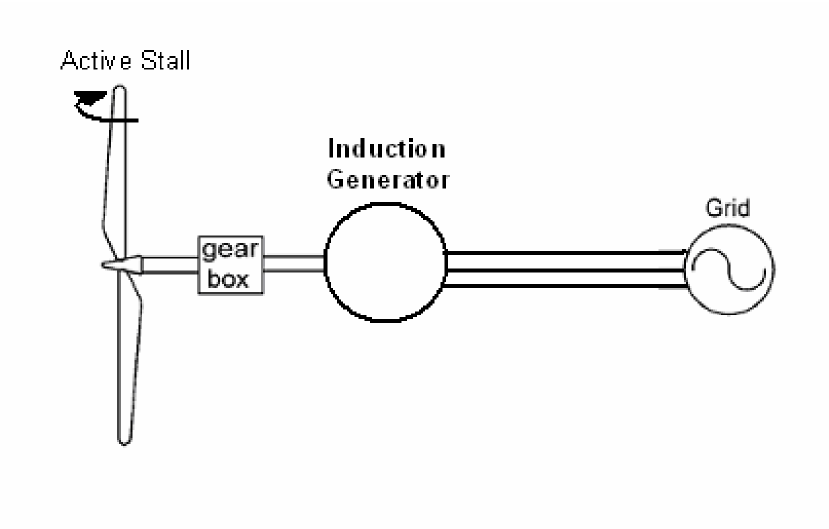


Figure 2.11 Active Stall System

In full pitch control the blade can be varied with a range of around 0 to 30 degrees. With pitch control, the blade angle can be adjusted to maximize the power at low wind speeds and to limit the power to its rated value at high wind speeds. Pitch control is used almost exclusively by modern variable-speed machines. There are some pitch controlled fixed speed systems, though they are uncommon and have undesirable properties such as gearbox wear and power fluctuations at high wind speeds. []

Figure 2.12 Shows how changing the pitch angle can affect the Power vs Wind Speed characteristics for a fixed speed turbine. The embedded values next to the individual plots refer to the pitch angle.

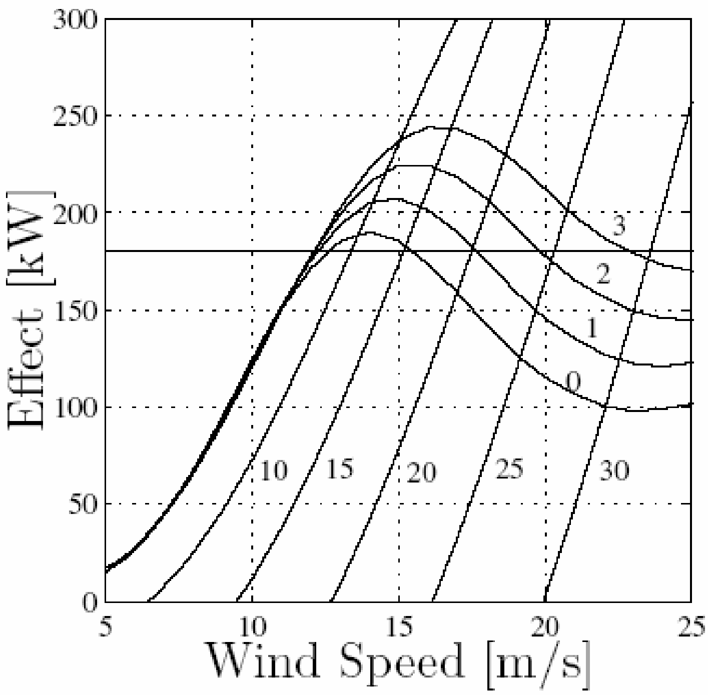


Figure 2.12 Effect of Changing Pitch Angle

The disadvantage of fixed speed systems is that, because the rotor speed must remain fixed, fluctuations in wind speed cause fluctuations in torque. This has the consequence of causing voltage fluctuations on the electrical grid, especially when connected to a weak grid. The shaft pulsations will also result in high stresses on the rotor, shaft, gearbox and generator.

Variable Speed Systems

In a variable speed system the generator rotor speed can be changed. By allowing the rotor speed to change, power fluctuations can be more or less absorbed by increasing the speed. Combined with full pitch aerodynamic control, this allows for smoother power output, and a reduction in fatigue on the gearbox and drive train. Variable speed, in some instances can allow for greater energy capture and more efficient operation.

Grid compatibility is achieved by the use of a voltage converter. The converter can be connected between the stator of a synchronous generator and the grid, or between the rotor of a Doubly-Fed Induction Generator (D-FIG) and the stator/grid.

Most modern systems will use a D-FIG as the power converter only has to convert the rotor power, which is a fraction of the power of the stator. The D-FIG will be discussed in detail later in this thesis.

In a fixed speed system with a squirrel cage generator, a capacitor bank is needed for power factor adjustment. In a D-FIG the use of a voltage converter allows for real and reactive power control. This feature may become more important as the amount of wind capacity on the grid increases. Wind farms may be called on to regulate reactive power. This is already underway in Spain.

Another advantage of variable speed operation is that noise levels can be reduced.

The diagrams below show the basic configuration of variable speed systems.

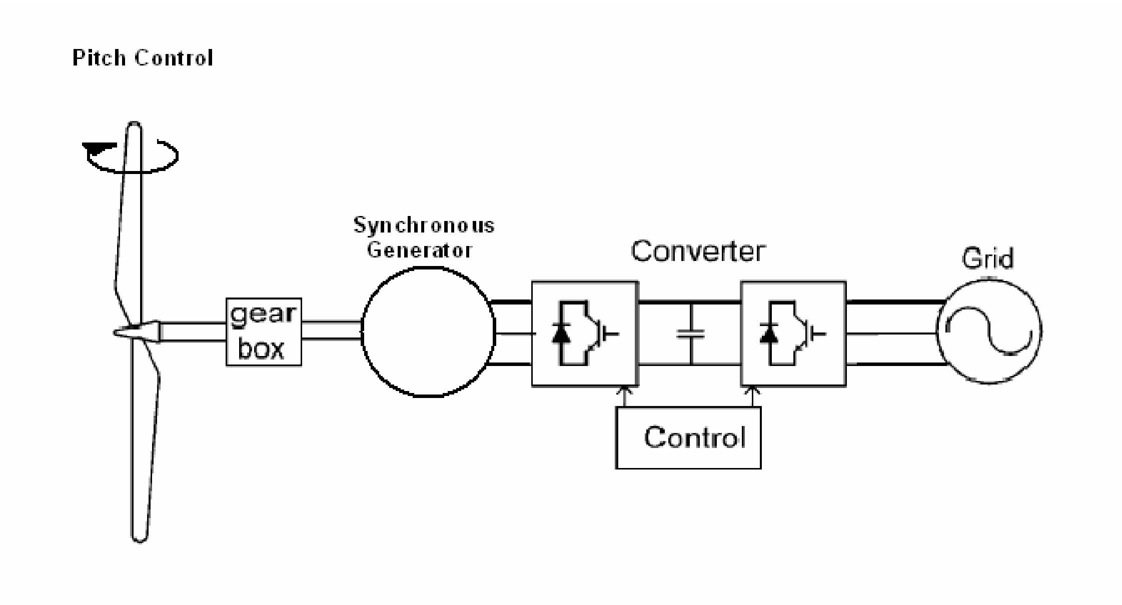


Figure 2.13 Variable Speed with Synchronous Generator

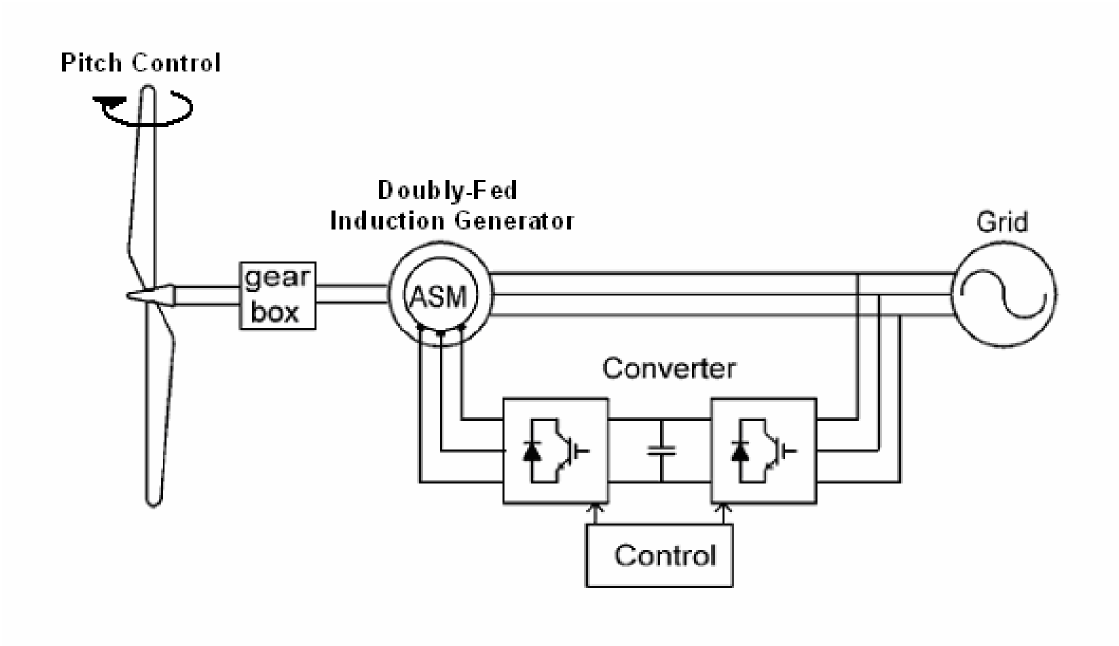


Figure 2.14 Variable Speed with D-FIG

The effects of variable speed operation are well demonstrated by the following graphs taken from the technical specifications of a 2MW Vestas variable speed wind turbine, equipped with a 'Optispeed' Doubly-Fed Induction Generator. It can be seen that pitch adjustment and rotor speed adjustment are combined to produce a smooth, constant power output.

The power vs wind speed curve is also plotted for different noise levels.

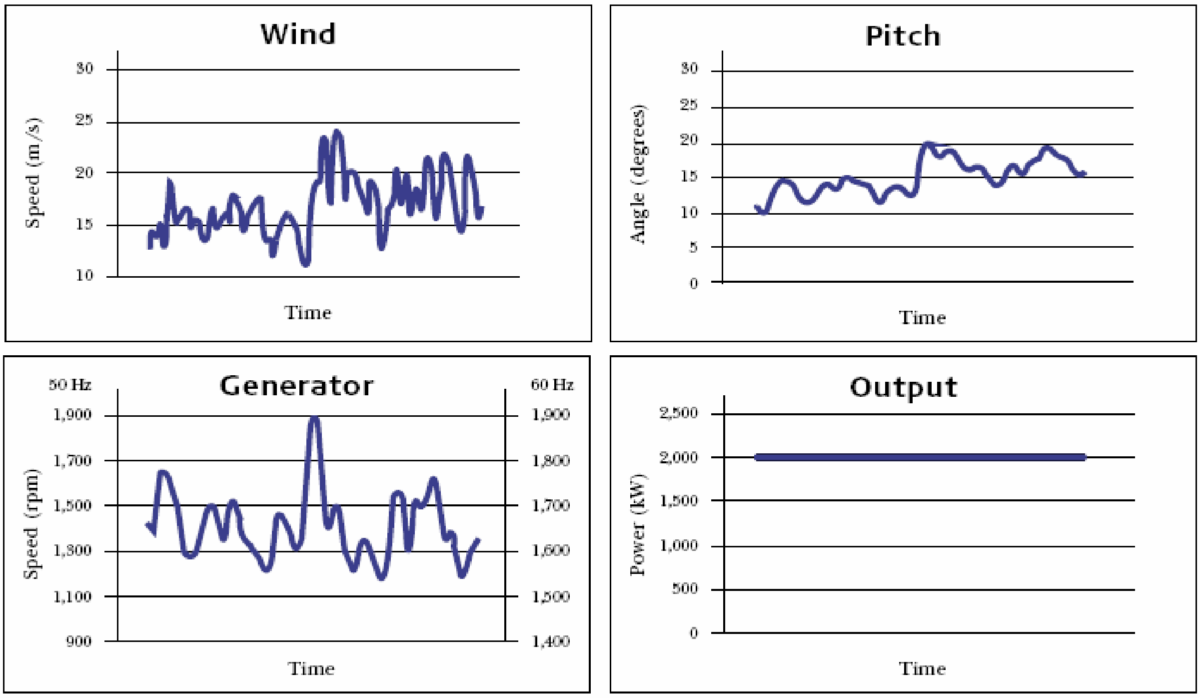


Figure 2.15 Technical specifications of a 2MW Vestas variable speed wind turbine

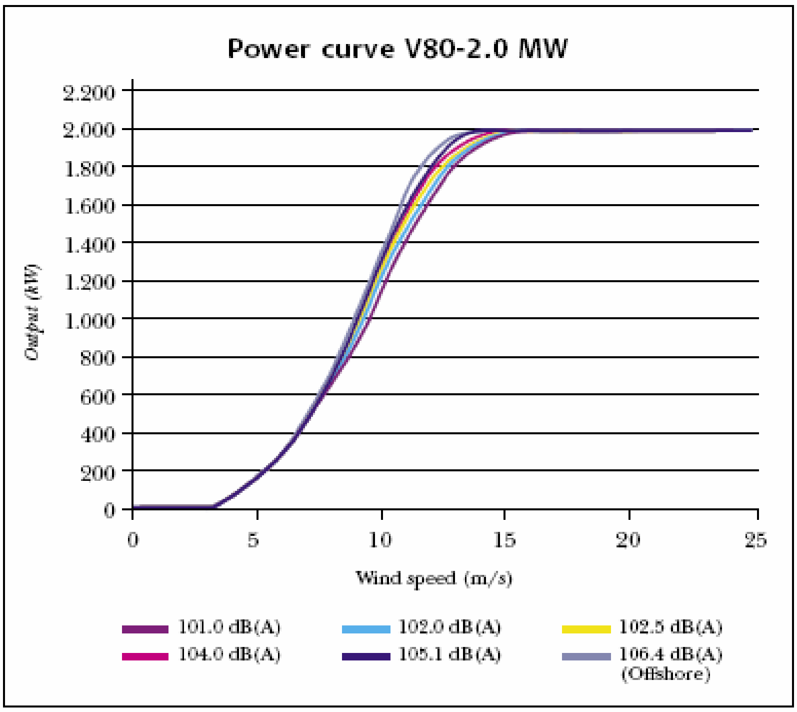


Figure 2.16 Power Curve Vestas 2MW

Section 3

Machine Analysis

Introduction

There are a variety of generator technologies that can be used in wind turbines. Factors which determine the suitability of a particular generator type include; the scale of the machine, the intended use for the generated power, complexity and cost. For example, small systems (often used for battery charging) may use permanent magnet generators for simplicity and low cost. Some variable speed systems use a synchronous generator with a voltage converter connected between the stator and grid. Though the most common machine type, found in large wind turbines is, by far an induction machine.

Induction machines are particularly suitable for use in wind turbines as they can produce grid compatible power without the need for frequency adjustment or phase synchronisation. In their simplest forms they offer a robust and relatively low cost, low maintenance construction, compared with synchronous machines.

This chapter shall present analysis of the induction machine, beginning with a simple squirrel cage assembly and progressing to a wound rotor construction. It will then show how, with the addition of external resistance and eventually a rotor connected voltage converter, the performance envelope can be broadened to give the range of control that is desirable in modern wind turbines.

Induction Machines

Rotating Magnetic Field

An Induction Machine relies on a rotating magnetic field, produced by the stator windings. This is achieved using a three phase winding arrangement, with either a star or delta connection. The stator, or armature windings are arranged as shown in figure 3.1

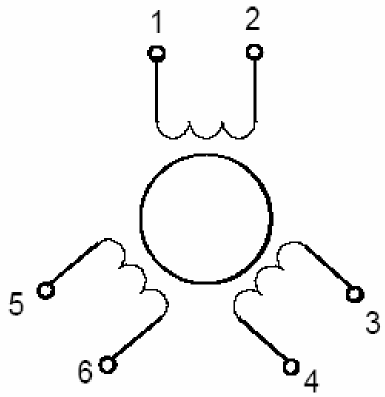


Figure 3.1 Armature windings arrangement

The spatial and electrical separation of 120 degrees causes the rotating magnetic field in the stator. figure 3.2 shows the resultant magnetic field produced by the three stator windings at instants a,b,c,d demonstrating 180^o rotation in clockwise direction. The speed of the rotating field is equal to the supply frequency and referred to as the *Synchronous Speed* (ω_1).

$$\omega_1 = 2\pi f_1 \ rad/sec \qquad 3.1$$

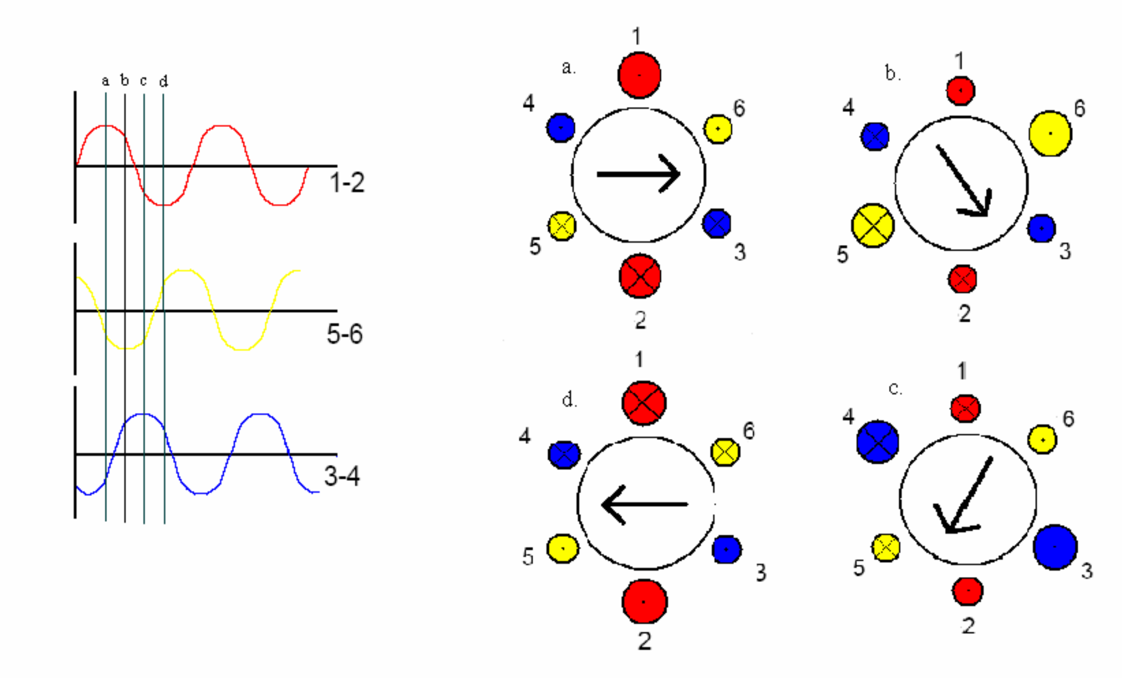


Figure 3.2 Resultant magnetic field produced by three stator windings

Induction machines require an external voltage supply to set up the rotating magnetic field, in a wind turbine the three-phase supply comes from the grid. Therefore a power system must be regulated by a primary, synchronous machine that sets the frequency and phase for the whole system, wind turbines act as secondary generators. Three phases are chosen as constant mean instantaneous power can be achieved. Three phase power can also be transmitted along three conductors (no need for neutral line) therefore is more economical.

Squirrel Cage Rotor

A traditional induction machine employs a squirrel cage rotor that is placed within the stator.
A diagram of a squirrel cage can be seen in figure 3.3.

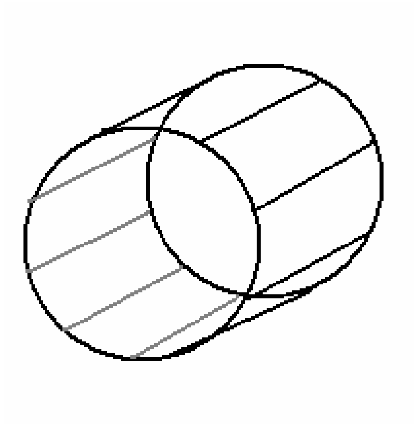


Figure 3.3 Diagram of a squirrel cage

The bars that make up the squirrel cage are connected together and can in effect be considered as a series of closed circuits, or single turn coils.

Induction Machine Operation

First consider the Induction machine working as a motor.
If the stator supply is switched on, with the rotor stationary, then the rotor will experience the rotating magnetic field. EMFs are therefore induced in the squirrel cage ‘coils’, and since these are closed circuits, ac currents will flow in the rotor. With the rotor stationary the system will act like a transformer and the rotor currents will be at the same frequency as the stator (ω_1). The rotor currents will give rise to mmfs (magneto-motive forces) which, by Lenz’s Law will attempt to counter the source of the rotor currents i.e. the rotating magnetic field produced by the stator. If the rotor is free to move the stator and rotor mmfs will react such that the rotor will turn in the same direction as the rotating magnetic field. The relative speed of the rotating field, from the perspective of the rotor, will decrease as the rotor mechanical speed increases, consequently the induced rotor current frequency will also decrease. If the rotor speed reaches the synchronous speed it will no longer experience a changing magnetic field and the rotor emfs and currents will no longer be induced. During motoring operation this is an impossible situation as there will a shaft load and losses that prevent the rotor reaching synchronous speed. Consequently there will always be a difference between rotor mechanical speed and synchronous speed. This speed

differential is known as the *slip.* The concept of slip is fundamental to the understanding of induction machines.
Slip (s) is defined by:

$$s = \frac{n_s - n_r}{n_s} \qquad 3.2$$

Where n_s is synchronous speed and n_r is rotor speed in rev/sec.

If the rotor frequency f_2 is now considered:
In an a.c. motor, the frequency is a product of the speed of rotation and the number of poles p. The stator frequency f_1 defines the synchronous speed n_s. From the reference point of the rotor in an induction machine, the relative speed is the difference between the synchronous speed and the rotor speed. Hence:

$$f_1 = n_s p \qquad 3.3$$

$$f_2 = \left(n_s - n_r\right) p \qquad 3.4$$

Equations 3.2,3.3 &3.4 can be combined to show that rotor frequency f_2 is a product of the slip and f_1*:*

$$f_2 = sf_1 \qquad 3.5$$

f_2 is often referred to as the slip frequency.

Consider now the rotor mmf. This is the rotating magneto-motive force that results from the rotor currents. Relative to the rotor, the speed of this mmf is:

$$n_{mmf} = \frac{f_2}{p} = \frac{sf_1}{p} = sn_s \qquad 3.6$$

However since the rotor is already turning at speed n_r, the actual speed of the rotor mmf is: $sn_s + n_r$. By rearranging equation 3 it can be seen that the rotor mmf rotates at synchronous speed irrespective of rotor speed:

$$sn_s + n_r = n_s \qquad 3.7$$

During motor operation the stator rotating mmf leads the rotor mmf and can be considered to be dragging the rotor mmf with power flow going from stator to rotor.

Generator Operation

Consider an external torque, for example from a wind turbine drive shaft, applied to the rotor causing the rotor speed to reach synchronous speed and increase beyond.

From the perspective of the rotor, as it reaches synchronous speed the relative speed of the stator mmf becomes zero ($n_s = n_r$, $s = 0$).

As the rotor speed increases further the rotor will again experience the rotating stator mmf, though this time from the rotor perspective it will be rotating in the opposite direction. The machine is now operating at negative slip ($n_s < n_r$, $s < 0$). AC Currents will once again flow in the rotor though now the phase has been reversed. The rotor mmf will still turn at synchronous speed though now the rotor mmf is leading the stator mmf. The rotor mmf can be considered to be dragging the stator mmf. Power flow is now going from rotor to stator.

Equivalent Circuit

In order to fully understand the power flows in an induction machine an equivalent circuit must be developed. The equivalent circuit begins with recognition of the parallels between the induction machine and a transformer.

The stator coils will experience a back emf E_1 as a result of the rotating flux. For balance, this back emf will completely oppose V_1 (supply voltage):

$$E_1 = -V_1 \qquad 3.8$$

When the rotor is stationary the induction machine behaves just like a transformer with ratio between rotor emf E_2 and stator emf E_1 more or less the rotor/stator turns ratio i.e.

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \qquad 3.9$$

Different winding factors mean that this is not exact, but nonetheless a close approximation.

To further explore these emfs, note that any point in the air gap between stator and rotor will experience a sinusoidal flux φ. This flux will induce an emf by Faradays Law:

$$\phi = \Phi cos(\omega t)$$

$$e = -N \cdot \frac{d\phi}{dt} = -N\left(\omega \Phi sin(\omega t)\right)$$

$$e_{rms} = \frac{(2\pi f N \Phi)}{\sqrt{2}} = 4.44 f N \Phi \qquad 3.10$$

From this series of equations it can be seen that the induced emf is proportional to the frequency of the flux and hence the speed of revolution (synchronous speed).

When the rotor is turning, the relative frequency of the flux is proportional to the slip s. Therefore the rotor emf is as follows:

$$E_r = sE_2 = 4.44 f_2 N_2 \Phi \qquad 3.11$$

Stator Equivalent Circuit

The stator can be represented in an equivalent circuit by considering the physical parameters and their magnetisation characteristics:

If an ac voltage is applied to a coil wound around a circular core or toroid (as per induction machine stator construction) the current can be observed to take on a non-sinusoidal shape. This is a result of the magnetic parameters of the stator, i.e. the permeability of the core material, the dimensions and the number turns on the coil.

The magnetising characteristics of a core are non linear. As the current increases the flux density saturates, as the current falls the core retains some magnetism, still remaining magnetised when the current in the coil is zero. After a few current cycles the alternating flux cycle, when observed against the current, will form a loop known as a hysteresis loop. A hysteresis loop is specific to the physical parameters of the core, windings and applied voltage and describes how these parameters influence the current.

The resulting current, known as the *excitation current,* can be considered as having two constituents. The first, i_c is in phase with the applied voltage and represents the real core power losses, this can be modelled in an equivalent circuit by a resistor R_c in parallel with the voltage source. The second, i_m ,reduced to a sinusoidal fundamental by a Fourier transform, lags the applied voltage by 90^o and can be represented in an equivalent circuit by an inductor L_m ,(often referred to as the magnetising or mutual inductance) in parallel with the applied voltage.

The losses modelled by R_c are a result of eddy currents in the core and hysterisis losses. Eddy currents are currents that occur in the cross section in the core and can be reduced by using cores made from thin insulated laminations as opposed to solid iron. Hysterisis losses are a result of energy being held in the core by the residual magnetism.

A stator equivalent circuit can now be built:

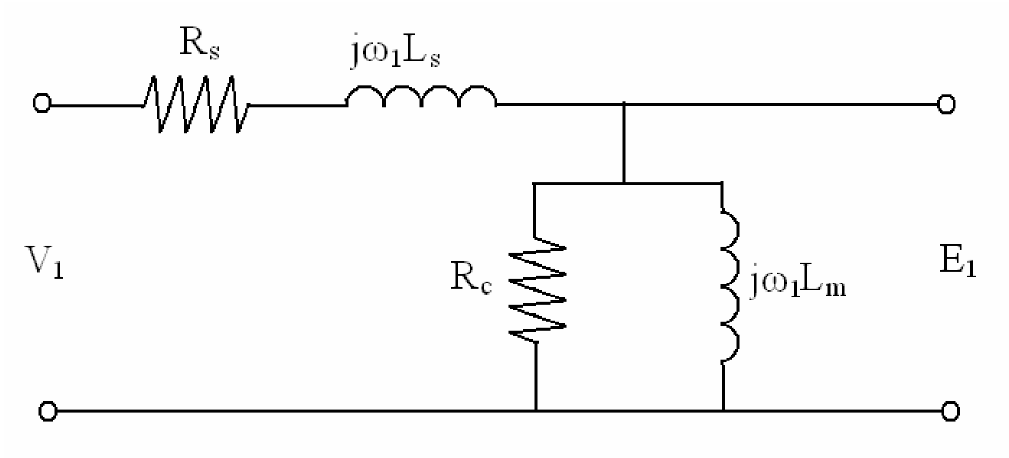


Figure 3.4 Stator equivalent circuit

R_S and L_S represent the winding resistance and leakage reactance that can be intuitively expected.

Rotor Equivalent Circuit

The rotor equivalent circuit can be considered to have some resistance R_r and some leakage inductance L_r. From equation %, the rotor emf is sE_2.

This analysis is from the rotor perspective i.e. at the slip frequency f_2. The leakage reactance from L_r will therefore be $j\omega_2 L_r$ or $js\omega_1 L_r$.

The rotor equivalent circuit is therefore:

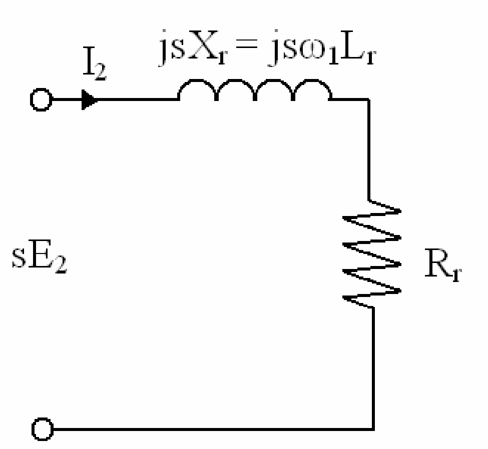


Figure 3.5 Rotor equivalent circuit

I_2 can be easily derived from this circuit as:

$$I_2 = \frac{sE_2}{R_r + jsX_r} \qquad 3.12$$

The rotor circuit can be considered from the stator perspective i.e. at synchronous frequency f_1, if the above equation is simplified by dividing top and bottom by s. It can now be seen that from the reference point of the stator, the rotor resistance varies with speed:

$$I_2 = \frac{E_2}{\frac{R_r}{s} + jX_r} \qquad 3.13$$

The rotor equivalent circuit, from the stator perspective now becomes:

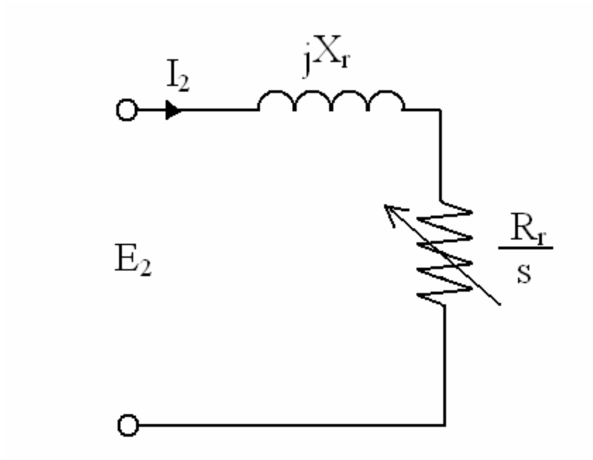


Figure 3.6 Rotor equivalent / stator perspective

Rotor and stator equivalent circuits can now be combined.

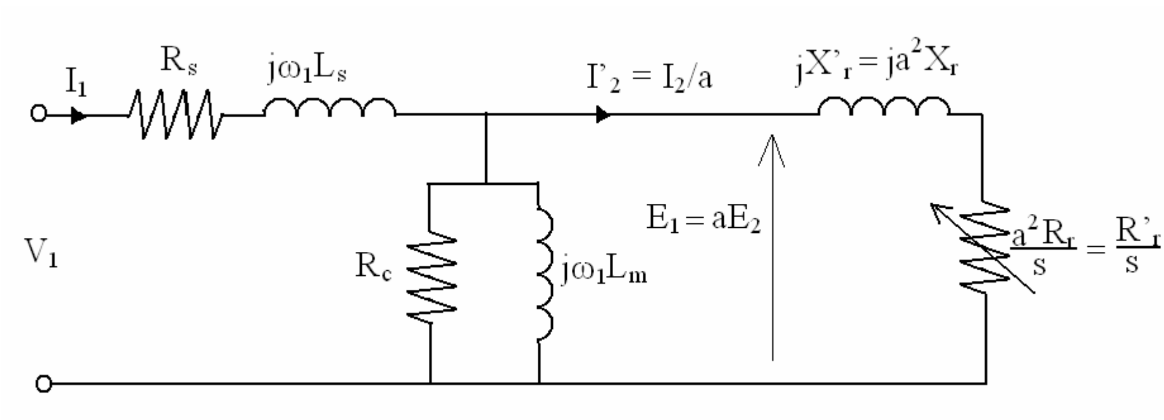


Figure 3.7 Rotor and stator equivalent circuits combined

The above circuit is a complete equivalent circuit for an induction machine with the rotor components expressed from the stator perspective. The term ‘a’ represents the stator/rotor turns ratio N_1/N_2 as per equation $.

If the machine is operated from a constant voltage, constant frequency supply, as in a grid connected wind turbine, the core losses can be assumed constant at all operating speeds. R_C can in this case be included in the copper losses (R_S).

The IEEE equivalent circuit, and the one most commonly found in literature is:

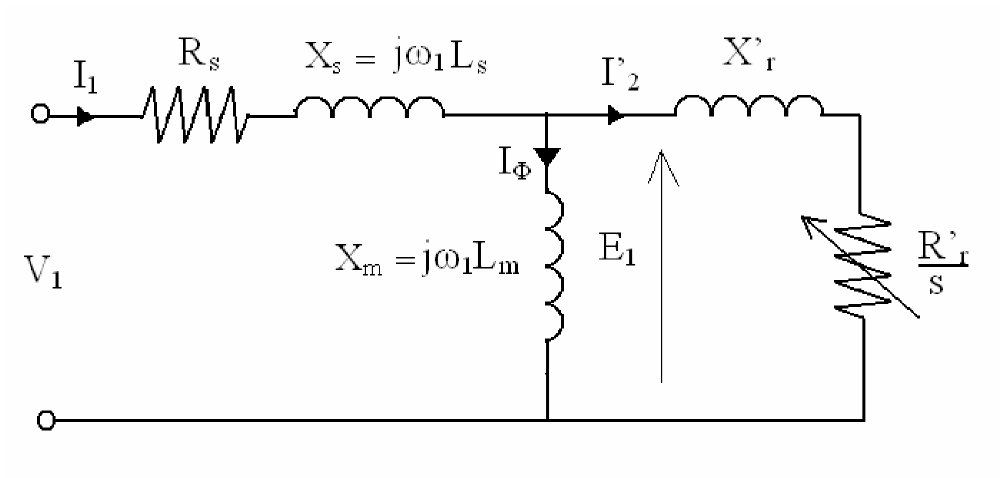


Figure 3.8 IEEE Equivalent Circuit

These circuits can now be used to analyse the power flows and to study the performance characteristics of an induction machine.

First consider the rotor circuit as viewed from the rotor (figure 3.5), at slip frequency f_2.
The power in this circuit is:

$$P_2 = I_2^2 R_r \tag{3.14}$$

This is the power lost due to the actual physical rotor resistance, this resistance is unaffected by the slip and is referred to as the copper loss.

If the rotor circuit is now considered from the stator perspective (figure 3.6), the effects of rotation are now taken in to account. It was shown previously that from the view point of the stator the rotor resistance varies with slip. The power in this circuit is therefore:

$$P = I_2^2 \frac{R_r}{s} = \frac{P_2}{s} \tag{3.15}$$

This is the total power that crosses the air-gap between the stator and rotor. This power is made up of the mechanical power P_{mech} developed by the rotor and the copper losses P_2. The mechanical power can be drawn from this equation by the following expansion.

$$P = P_2 + P_{mech} = I_2^{\,2}\left(R_r + \frac{R_r(1-s)}{s}\right) \tag{3.16}$$

$$P_{mech} = I_2^{\,2}\frac{R_r(1-s)}{s} \tag{3.17}$$

This mechanical power is subject to frictional and other losses and does not represent the actual mechanical power developed by the machine.

The mechanical torque can now be investigated. The mechanical torque either drawn from or applied to an induction machine is one of the most important commodities when it comes to studying machine characteristics.

The mechanical torque defined as:

$$T_{mech} = \frac{P_{mech}}{\omega_{mech}}$$

where:

$$\omega_{mech} = (1-s)\,\omega_{synch} \tag{3.18}$$

Substituting for P_{mech} gives:

$$T_{mech} = \frac{1}{\omega_1} \cdot I_2^{\,2} \cdot \frac{R_r}{s} \tag{3.19}$$

Recognising that the turns ratio a is generally 1. T_{mech} can be expressed in stator equivalent rotor quantities:

$$T_{mech} = \frac{1}{\omega_1} \cdot I'^{2}_{2} \cdot \frac{R'_r}{s}$$

3.20

I'_2 can be found by analysing figure$ and the use of its Thevinin Equivalent:

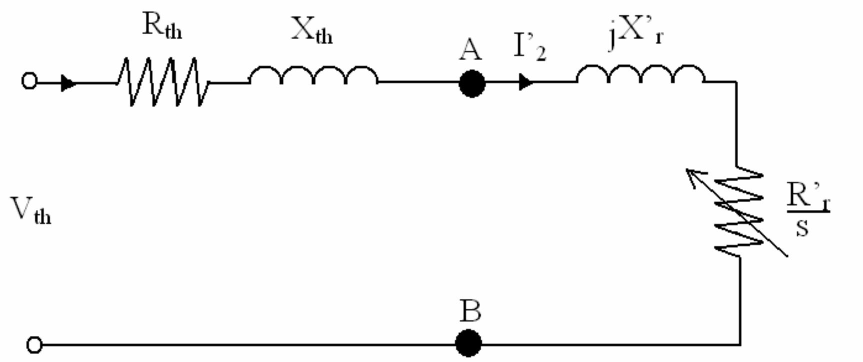


Figure 3.9 Thevinin Equivalent

The Thevenin Equivalent circuit involves separating the circuit at the rotor terminals AB. The original voltage source and impedance network can be replaced by looking back from these terminals, recognising that the stator circuit is now a voltage divider, with $V_{AB} = V_{th}$, the voltage over the magnetising reactance X_m. The impedance network can then be reduced to a series equivalent by short circuiting V_1 and calculating the equivalent impedance. The rotor can then be reconnected back to the equivalent series circuit.

Analysis of this simplified circuit gives an expression for I'_2 in terms of known electrical parameters allowing the mechanical torque to be investigated.

$$T_{mech} = \frac{1}{\omega_1} \cdot \frac{V_{th}^2}{\left[\left(R_{th} + \frac{R'_r}{s}\right)^2 + \left(X_{th} + X'_r\right)^2\right]} \cdot \frac{R'_r}{s}$$

3.21

The following graph shows the Torque vs speed plot for an induction machine:

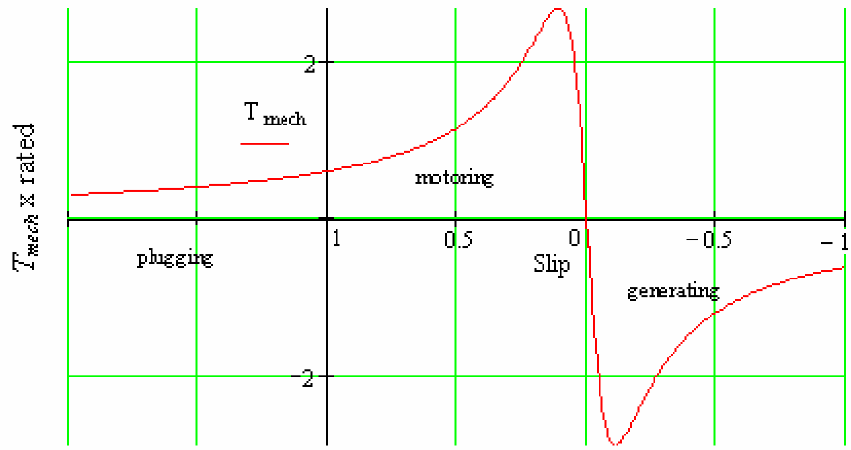


Figure 3.10 Torque vs speed plot

T_{mech} is expressed as a ratio of the rated value. The speed is expressed as the corresponding slip values. This graph is also based on the idealised mechanical power obtained from the equivalent circuits and does not account for frictional losses etc.

The Torque vs speed graph demonstrates the operating modes of an induction machine. When the slip is between 1 and 0, the torque is positive, indicating the torque is being produced by the machine and the system is motoring.
When the slip is negative, the torque is negative, indicating that a torque is being applied to the machine and it is generating. The plugging mode refers to a change in direction of rotor, i.e. switching two of the stator phases. This is a method that can be used to brake the machine quickly.

It can be seen from the graph that the torque vs slip relationship is linear for low values of slip and eventually tails of after reaching a maximum.

The maximum possible torque can be found differentiating equation$ w.r.t. s and setting it to zero this results in the following expression:

$$s_{Tmax} = \frac{R_r}{\sqrt{R_{th}^2 + \left(X_{th} + X_r\right)^2}} \qquad 3.22$$

Giving a maximum Torque value:

$$T_{max} = \frac{1}{2\omega_1} \cdot \frac{V_{th}^2}{\left[R_{th} + \sqrt{R_{th}^2 + \left(X_{th} + X'_r\right)^2}\right]} \qquad 3.23$$

Efficiency

The ideal efficiency of the induction motor can be calculated if the ‘Power in’ is considered to be the power that crosses the air-gap and the ideal mechanical power is taken as ‘power out’.

From equation ($$$) an expression for ideal efficiency can be found:

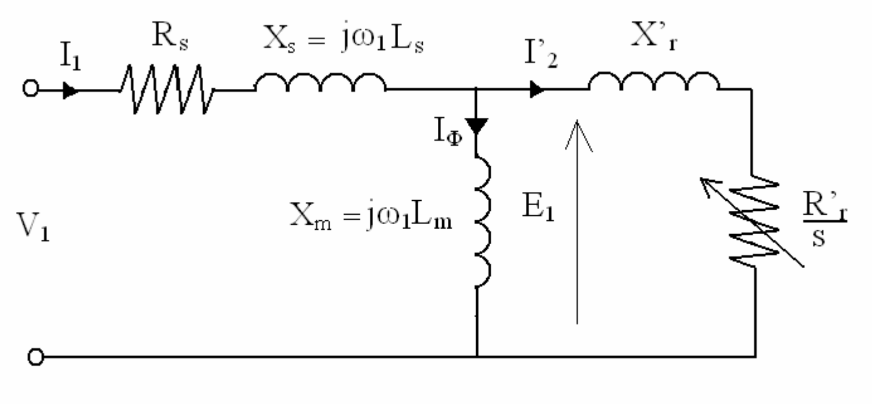
$$P = \frac{P_2}{s} = P_2 + P_{mech}$$

$$Eff_{ideal} = \frac{P}{P_{mech}} = (1 - s) \qquad 3.24$$

From this expression it is clear that the efficiency increases as slip decreases. This expression does not include all real losses, though demonstrates a trend.

Power Factor

The last characteristic to be examined is the power factor. This can be assessed by considering the impedance of the equivalent circuit (figure 3.8) from the input terminals.



The impedance of the above circuit is:

$$Z_s = R_s + jX_s + \frac{jX_m\left(jX_r + \frac{R'_r}{s}\right)}{\frac{R'_r}{s} + j\left(X_m + X'_r\right)} = \left|Z_s\right| \angle \theta_s \quad 3.25$$

The power factor is the cosine of the impedance angle θ_s.

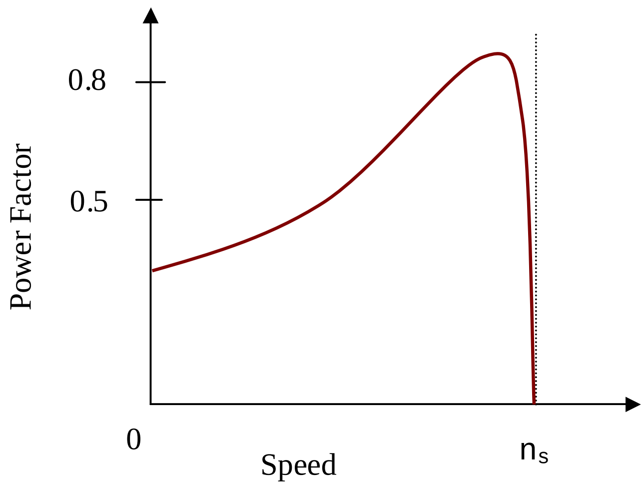


Figure 3.11 Power Factor

Figure 3.11 shows how the power factor varies with rotational speed for a typical induction machine. It shows that to achieve values close to unity the slip needs to be small.

Wind turbines equipped with a squirrel cage induction generator, often have a capacitor bank to adjust the power factor.

Induction Machine with Wound Rotor

The performance characteristics of an induction machine with a squirrel cage rotor are set by the physical parameters of the construction. In many applications it is desirable to be able to alter these characteristics. In a grid connected wind turbine the stator frequency is fixed to the grid frequency, the synchronous speed is therefore set. The operating speed is consequently fixed for a particular torque. The induction generator relies on the mechanical systems in the wind turbine to regulate speed and torque i.e. the blade stall angle and gear box.

If the squirrel cage rotor is replaced with a wound rotor, similar to that found in a synchronous generator with connected slip rings, the rotor properties can be altered externally.

Recall equations 3.22 &3.33

$$s_{Tmax} = \frac{R_r}{\sqrt{R_{th}^2 + \left(X_{th} + X_r\right)^2}}$$

$$T_{max} = \frac{1}{2\ \omega_1} \cdot \frac{V_{th}^2}{\left[R_{th} + \sqrt{R_{th}^2 + \left(X_{th} + X'_r\right)^2}\right]}$$

From these equations it can be seen that the value of maximum torque does not depend on the rotor resistance, however the value of slip where maximum torque occurs does. Intuitively, the value of slip that corresponds to a value of torque can be varied by changing the rotor resistance.

This can be achieved by connecting resistors to the slip rings of a wound rotor.

The following plot shows the Torque vs Speed characteristics as the rotor resistance is increased.

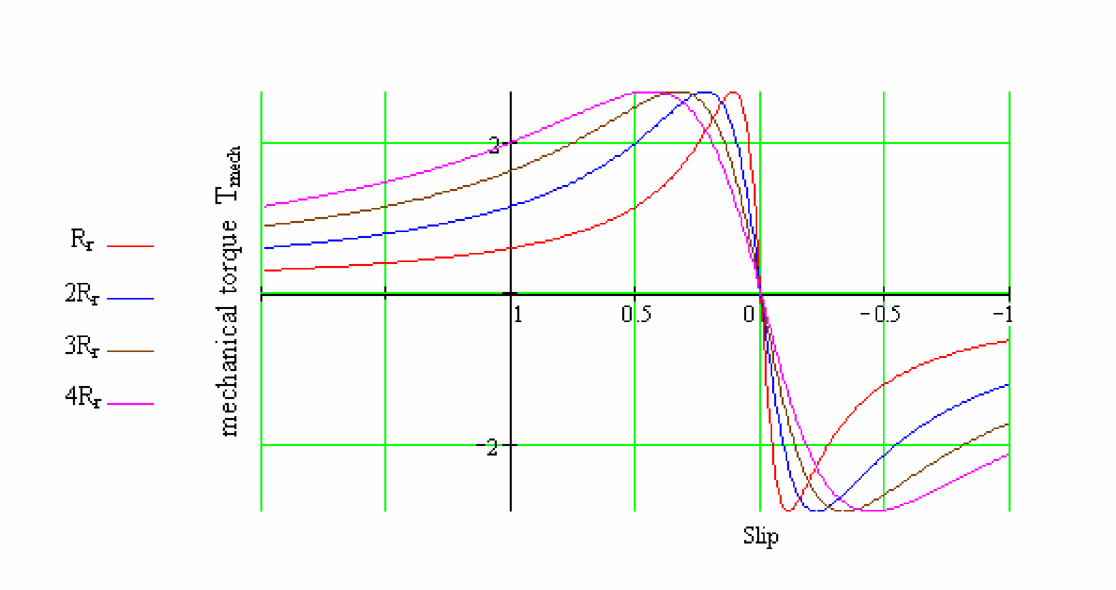


Figure 3.12 Increased rotor resistance

Aside from changing the speed at which maximum torque occurs, increasing the rotor resistance also boosts the output torque at low speed levels during motoring operation. During generator operation the advantage of external resistance is that it gives the machine the option of different operating speeds for a particular torque, however power will be consumed by the increased resistive load and efficiency will be decreased.

By using external resistance and a wound rotor it can be seen how manipulating rotor parameters can vary the machine characteristics, though the operating range is still limited. The full exploitation of the potential range of requires a voltage converter. This arrangement is known as a Doubly-Fed Induction Machine (D-FIG)

Doubly-Fed Induction Generator

Doubly-Fed Induction Generators were introduced in Section 2, when the significance of variable-speed operation was explained.

To Recap, D-FIGs are the preferred method of providing variable speed operation as the converter needs only to handle the rotor power. Variable speed operation of a wind turbine allows turbulence to be absorbed, reducing the strain on the gearbox and drive train and smoothing the power output. Having the ability to select an operating speed for a particular torque can also reduced noise levels and avoid resonance.

A Doubly-Fed Induction Generator uses a wound rotor with slip rings, though instead of connecting a passive load, (resistors), an active source is used in order to give full control of the electrical behaviour of the rotor. This active source is a bi-directional voltage converter, connected between the rotor and the grid.

A System diagram for wind turbine utilising a D-FIG can be seen below:

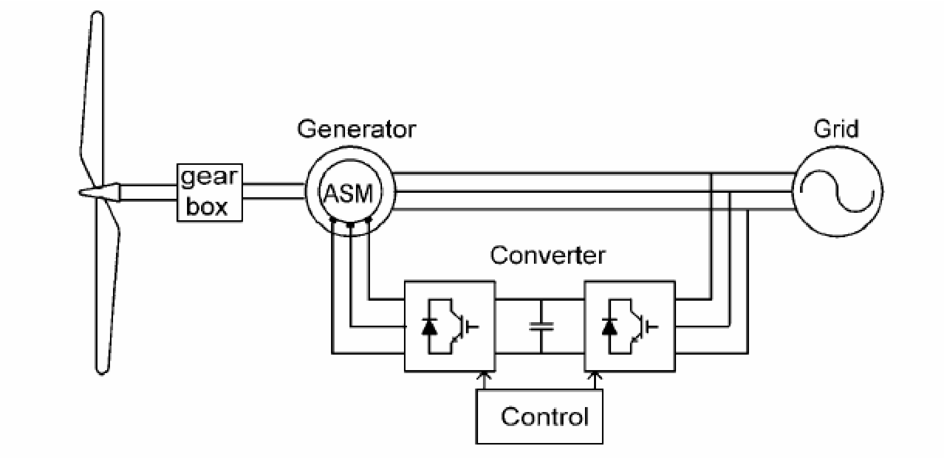


Figure 3.13 System diagram for wind turbine with D-FIG

The converter injects the rotor with a voltage at a particular frequency as set by the controller. The rotor electrical frequency is therefore independent of the mechanical speed. The relationship between stator and rotor mmfs are, however, maintained. The D-FIG allows for rotor speeds both above and below synchronous speed.

The equivalent per-phase circuit for a D-FIG is shown below:

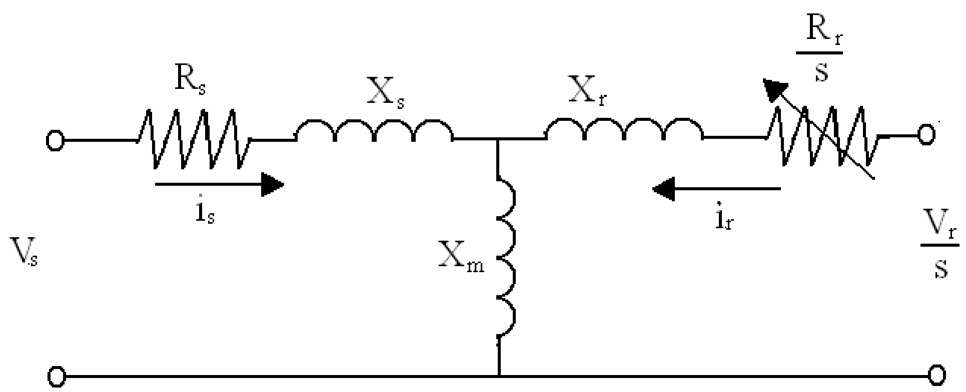


Figure 3.14 Equivalent per-phase circuit for a D-FIG

The mechanical power in a D-FIG can be found as:

$$P_{mech} = 3|I_r|^2 R_r \frac{1-s}{s} - 3\mathrm{Re}[V_r I^*_r] \frac{1-s}{s} \qquad 3.26$$

Power losses and electrical torque can be found as:

$$P_{loss} = 3R_s |I_s|^2 + 3R_r |I_r|^2$$

$$T_e = P_{mech} \frac{p}{(1-s)\omega_1} \qquad 3.27$$

The multiplication by 3 accounts for three phases. Notice that the mechanical power is now influenced by V_r, which is of course supplied by the converter. This allows the electrical torque to be manipulated externally.

The rotor mechanical speed is determined by the frequency of the applied voltage V_r. The rotor and stator mmfs will still turn at the same speed so the relationship between rotor electrical frequency and synchronous frequency remains;

$$f_2 = sf_1$$

Now, since f_1 is fixed, the rotor electrical frequency f_2 can be controlled to give a desired value of slip and hence rotor speed.

In a Doubly-Fed Induction Generator the rotor voltage can be adjusted to give the desired slip or torque.

Power flow in a D-FIG

The voltage converter in a D-FIG is connected to the grid. Neglecting losses the power flows in a D-FIG can be approximated by the following diagram:

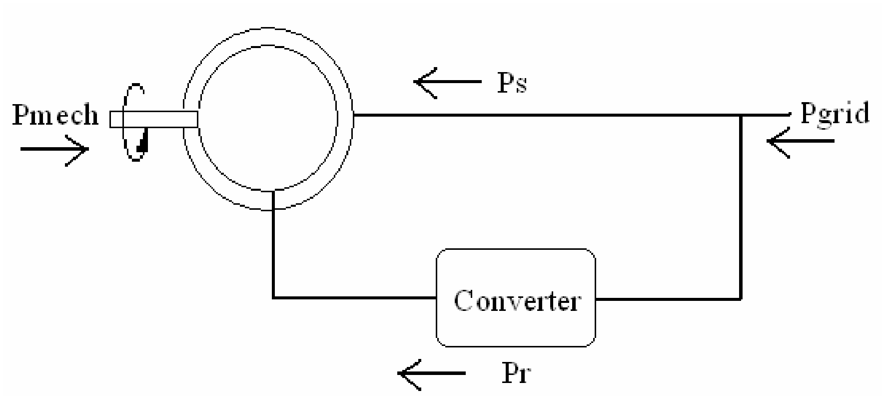


Figure 3.15 Power flow in a D-FIG

If an ideal situation is considered, where losses are neglected the following relationship is apparent:

$$\text{Pgrid} \approx \text{Ps} + \text{Pr} \qquad 3.28$$

Rotor Power P_r is the slip power, and can be defined as: $\mathbf{-sP_s}$

This gives the approximation:

$$Pgrid \approx (1 - s)\ Ps \qquad 3.29$$

These relationships can be used to show an idealised plot for the variation of grid power, stator power and rotor power as slip changes. The plots below show how the power varies over a typical range of slip values for a fixed torque.

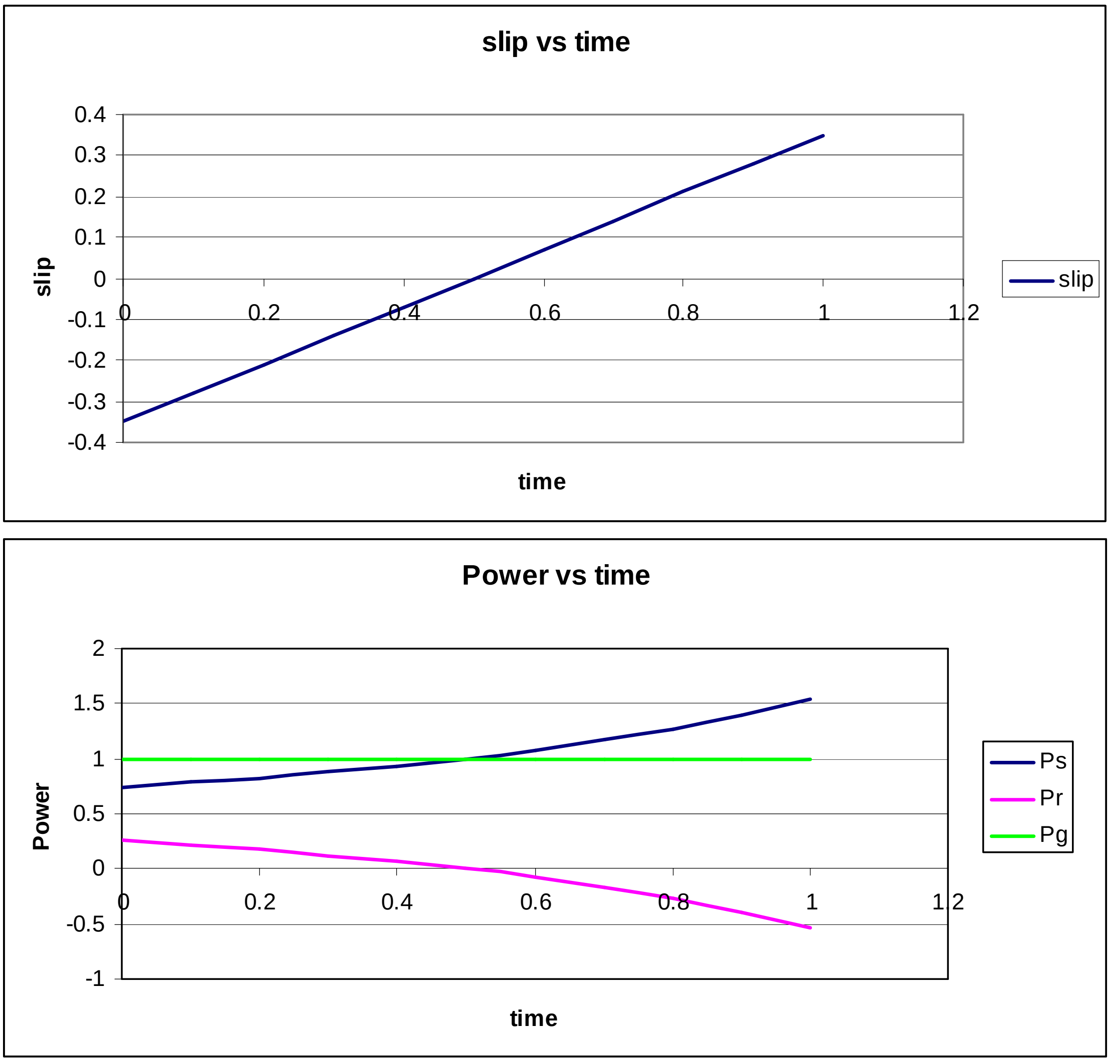


Figure 3.16 Power variation with slip

The plots show that rotor power must travel in both directions. In these plots positive power refers to power coming from the machine. At subsynchronous speed, (positive slip), the rotor is supplying power to the machine, at supersynchronous speeds, the power flow is in the opposite direction.

Real and Reactive Power Control

The real and reactive power can be controlled via the voltage converter. The bi-directional power converter consists of a stator/grid connected inverter and a rotor connected inverter linked via a DC bus and a capacitor.
A block diagram of the converter is shown below.

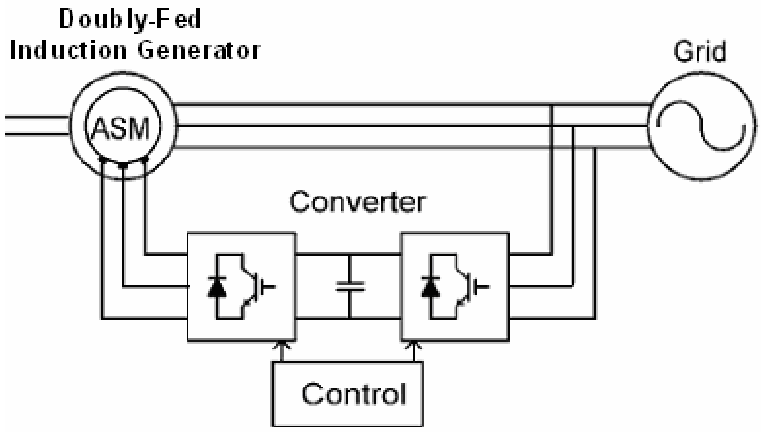


Figure 3.18 block diagram of the converter

The rotor side inverter can supply the real and reactive power necessary to meet the control objectives of the system. This can include altering the stator terminal power factor. This is done by drawing current from or supplying current to the capacitor that links each inverter. The main objective of the stator side converter is to maintain the voltage level on the DC bus capacitor by exchanging reactive power with the grid.

The controller for a D-FIG governs the behaviour of the generator. The controller must monitor slow mechanical, speed and torque levels as well as fast electrical properties. It must react to changes in rotor speed and other influencing factors, including power factor requirements. There is a wealth of proposed control methods available in literature, though this thesis is concerned with the physical range of capabilities offered by a D-FIG.

Section 4

Modelling and Simulation in MATLAB Simulink

Introduction

In this section a software model of a simple induction machine is built and then developed in to a doubly-fed induction machine.

The models are built using the MATLAB SimPowerSystems toolbox and Simulink package.

This chapter begins with a brief overview of MATLAB, and Simulink, explaining how they work and why they are suitable for the task at hand.

The relevant SimPowerSystem blocks are then explained and a squirrel cage induction machine is built and simulated. The effects of increasing rotor resistance are then investigated. The model is then extended to a wound rotor configuration and a voltage source is used to supply the rotor to imitate a D-FIG with a voltage converter. The results are then compared and discussed

The purpose of this exercise is to produce models with real parameters that accurately demonstrate the behaviour of electrical machines. This allows further exploration of the performance characteristics of each system and for comparisons to be made between different configurations.

MATLAB

MATLAB stands for Matrix Laboratory, it is an interactive computation and visualisation package, whose basic data element is an array.
The use of arrays and an interactive operating system is particularly suitable for technical computations involving vectors or matrices, meaning systems can be built much quicker in MATLAB than in conventional scalar languages such as C.

MATLAB is widely used in industry and in universities for research and development as well as education. It has evolved over many years with input from a number of sources.

MATLAB is made up of a ‘Development Environment’, i.e. a set of tools that allows the use of functions and files. The development environment includes the editor, debugger etc.

It has a ‘Mathematical Function Library’ that houses a collection of algorithms that can be employed in a project and a graphics package for displaying vectors and matrices as graphs.

The MATLAB Application Program Interface (API) allows C and Fortran programs to interact with MATLAB. There is also a MATLAB Language that is a high level matrix/array language with object oriented programming features.

There is a selection of add-ons to MATLAB, known as toolboxes. Toolboxes are application specific libraries of MATLAB functions. Toolboxes are compatible and can be used alongside normal and custom built MATLAB functions.

Simulink

Simulink is a software package that facilitates the simulation and analysis of dynamic systems. Models are first constructed in the Simulink model editor. Models are built from blocks either taken from MATLAB or Simulink libraries or can be custom designed. The toolbox of interest in this project is called SimPowerSystems, and contains preconstructed blocks, systems and measuring tools that can be used to model power systems.

The model depicts the time-dependent mathematical relationships among the system’s inputs, states and outputs. Simulink can be used to set the model parameters and initial conditions and to study the behaviour of the system over a defined time period.

Simulink Blocks

Asynchronous Machine

The SimPowerSystems ‘Asynchronous Machine’ block will form the foundation of the models in this project. The block is a three-phase machine that can either be operated as a motor or a generator. The electrical side of the machine is represented by a fourth-order space-vector model and the mechanical part is modelled by a second-order system.

The electrical model follows from the steady state, per-phase analysis of an induction machine presented in section$. This time however, the three-phase quantities are graphed on to an arbitrary two axis reference frame (dq frame). This is referred to as space-vector notation and is the preferred method used in dynamic analysis, it is found frequently in literature.

The dq reference frame is based on the principal that a three-phase rotating magnetic field can be reproduced by two adjusted phases.

As the three (abc) phases have an inherent relationship amongst themselves i.e. equal phase displacement and magnitude, there is only two independent variables in (abc). The other is a dependent variable. Three phase quantities can therefore be transformed in to two (dq) quantities and vice versa without loss of information.

The abc dq transfer works as follows:

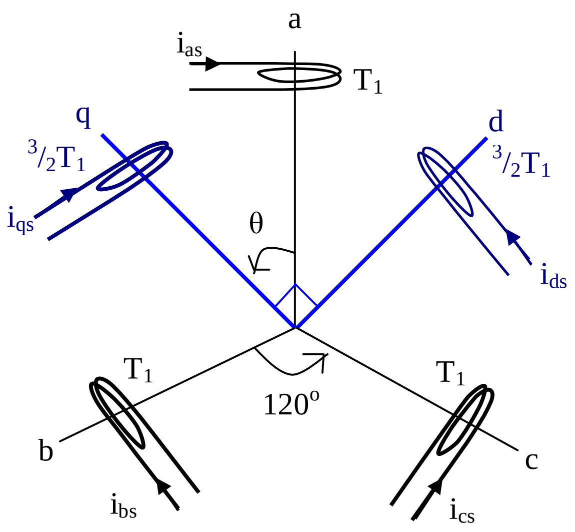


Figure 4.1 abc dq transfer

The three-phase stator mmf can be replaced with a two-phase equivalent with $3T_1/2$ turns per phase.

The dq reference frame can be fixed to either the stator (synchronous), the rotor or can be stationary. This allows for phase and speed to be expressed from the point of view of each rotating part.

The relationship between each reference frame is described in the following table where: θ is the angular position of the reference frame and $\beta = \theta - \theta_r$ is the difference between the position of the reference frame and the electrical position of the rotor.

Reference Frame	θ	β
Rotor	θ_r	0
Stationary	0	$-\theta_r$
Synchronous	θ_e	$\theta_e - \theta_r$

Figure 4.2 Reference Frames

θ_e is the position of the synchronous reference frame.

The transfer functions between abc currents and voltages and the dq equivalents are as follows:

(Remember; **V'$_r$** represents a rotor voltage from the stator perspective)

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2\cos\theta & \cos\theta + \sqrt{3}\sin\theta \\ 2\sin\theta & \sin\theta - \sqrt{3}\cos\theta \end{bmatrix} \begin{bmatrix} V_{abs} \\ V_{bcs} \end{bmatrix}$$

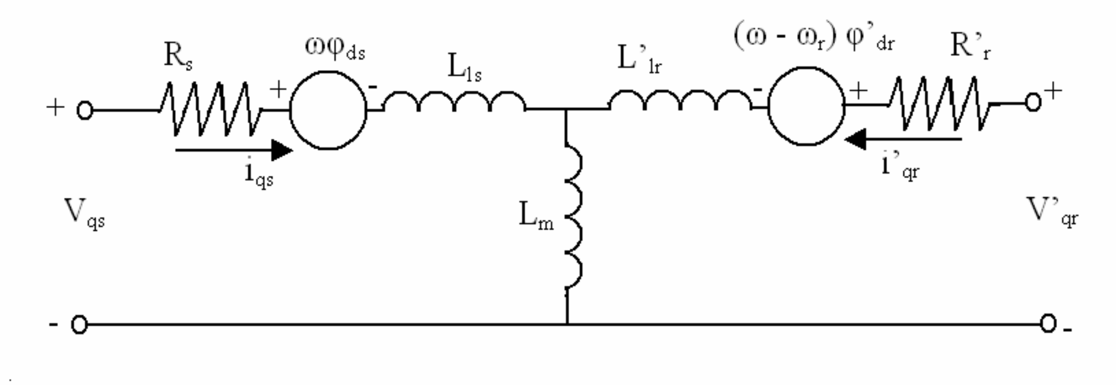
$$\begin{bmatrix} V'_{qr} \\ V'_{dr} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2\cos\beta & \cos\beta + \sqrt{3}\sin\beta \\ 2\sin\beta & \sin\beta - \sqrt{3}\cos\beta \end{bmatrix} \begin{bmatrix} V'_{abr} \\ V'_{bcr} \end{bmatrix}$$

$$\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \dfrac{-\cos\theta + \sqrt{3}\sin\theta}{2} & \dfrac{-\sqrt{3}\cos\theta - \sin\theta}{2} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}$$

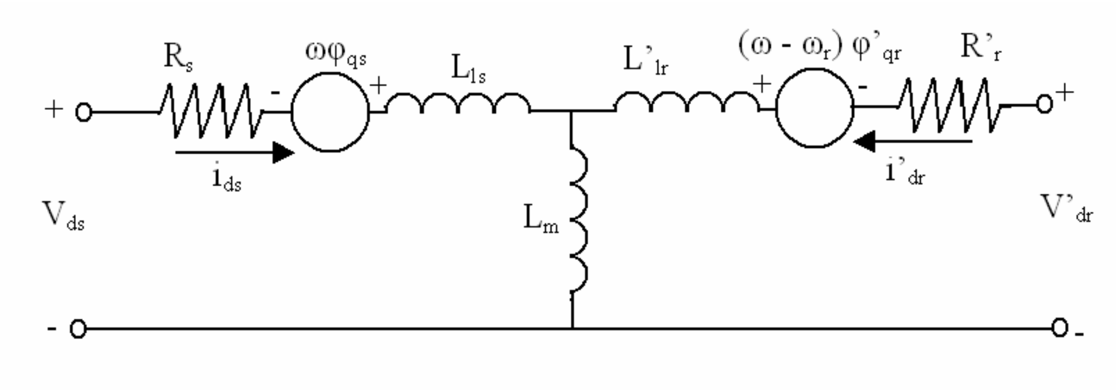
$$\begin{bmatrix} i'_{ar} \\ i'_{br} \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta \\ \dfrac{-\cos\beta + \sqrt{3}\sin\beta}{2} & \dfrac{-\sqrt{3}\cos\beta - \sin\beta}{2} \end{bmatrix} \begin{bmatrix} i'_{qr} \\ i'_{dr} \end{bmatrix}$$

$$i_{cs} = -i_{as} - i_{bs}$$
$$i'_{cr} = -i_{ar} - i_{br} \qquad 4.1$$

The equivalent circuit used for dynamic modelling by the SimPowerSystems Asynchronous Machine block, with all components stated in dq equivalent form is:



q axis



d axis

Figure 4.3 Equivalent Circuits

The equivalent circuits are based on the T-model circuit for a doubly-fed induction machine as shown in the previous section. The above circuits are referred to a synchronous reference frame.

The equivalent circuits can be described by the following equations:

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega\varphi_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega\varphi_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt}\varphi'_{qr} + (\omega - \omega_r)\varphi'_{dr}$$

$$V'_{dr} = R'_r i'_{qr} + \frac{d}{dt}\varphi'_{dr} - (\omega - \omega_r)\varphi'_{qr}$$

$$T_e = 1.5p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds})$$

where

$$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\varphi_{ds} = L_s i_{ds} + L_m i'_{qr}$$

$$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$\varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L'_{1s} + L_m$$

$$L'_r = L'_{1r} + L_m$$

4.2

The mechanical system is described by the following equations:

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m)$$

$$\frac{d}{dt}\theta_m = \omega_m$$

4.3

The Asynchronous block parameters are as follows:

Figure 4.4 Table of Parameters

The parameters are set by opening the ‘block parameters’ window of the Asynchronous machine:

Parameter	Definition
R_s, L_{ls}	Stator Resistance and Leakage Inductance
R'_r, L'_{lr}	Rotor Resistance and Leakage Inductance
L_m	Magnetising Inductance
L_s, L'_r	Total stator and rotor inductances
V_{qs}, i_{qs}	q axis stator voltage and current
V'_{qr}, i'_{qr}	q axis rotor voltage and current
V_{ds}, i_{ds}	d axis stator voltage and current
V'_{dr}, i'_{dr}	d axis rotor voltage and current
φ_{qs}, φ_{ds}	Stator q and d fluxes
φ'_{qr}, φ'_{dr}	Rotor q and d fluxes
ω_m	Angular velocity of rotor
θ_m	Rotor angular position
p	Number of pole pairs
ω_r	Electrical angular velocity
θ_r	Electrical rotor angular position
T_e	Electromagnetic torque
T_m	Shaft Mechanical Torque
J	Combined rotor and load inertia coefficient
H	Combined rotor and load inertia constant
F	Combined rotor and load viscous friction coefficient

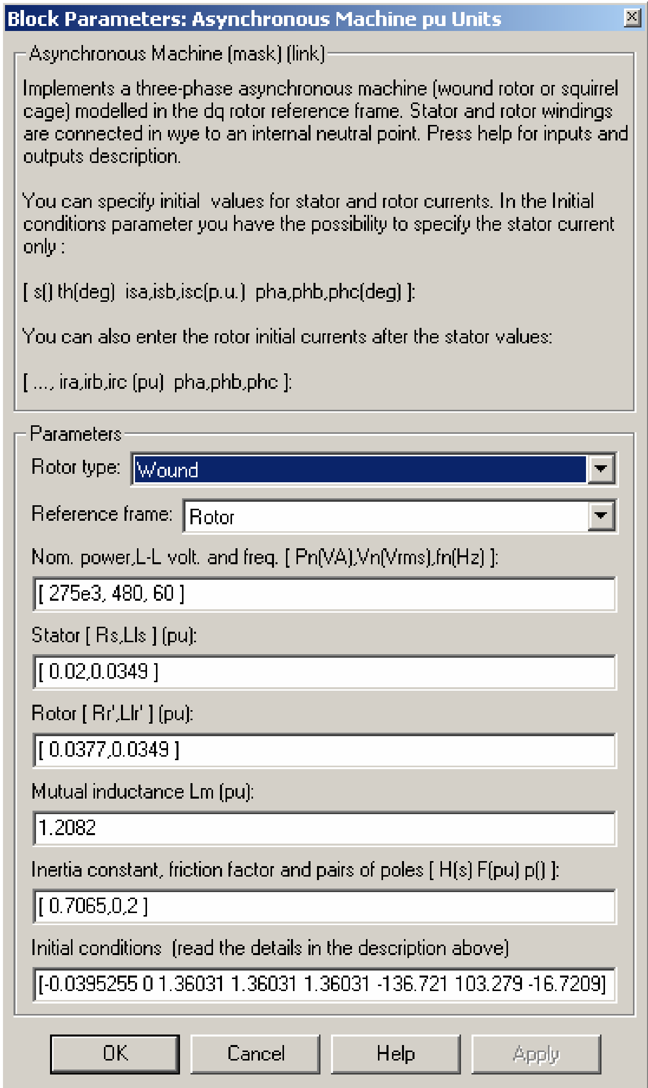


Figure 4.5 Block Parameters

The parameters can either be entered as per unit quantities (p.u.) or in SI units. Most machine parameters are expressed in p.u. quantities and Simulink converts them accordingly.

The rotor type can be either a squirrel cage or a wound rotor configuration.

The reference frame can be set to either rotor, synchronous or stationary. This defines the transfer from abc to dq variables as explained previously.

The choice of reference frame affects the waveforms of the dq variables and can also affect the simulation speed and accuracy of results.

It is suggested that stationary or synchronous reference is used if all voltages are balanced and continuous, rotor reference should be used if rotor voltages are unbalanced and stator reference should be used if stator voltages are unbalanced.

Inputs and Outputs

The following diagram shows the asynchronous machine block as it appears on the Simulink Model Editor:

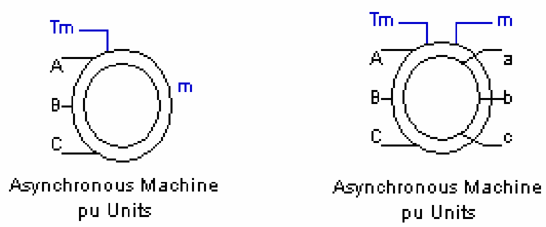


Figure 4.6 Asynchronous machine blocks

The diagram on the left is a squirrel cage construction and the diagram on the right is a wound rotor.

A,B,C represent the stator terminals, the rotor terminals on the wound rotor machine are identified a,b,c.

T_m is the mechanical torque. For generator operation a negative torque should be applied, for motor operation the torque should be positive.

The output ‘m’ of the block is a vector containing 21 signals. These outputs include: the rotor and stator currents in abc and dq representations, the d and q rotor and stator fluxes and voltages, the mechanical angular velocity of the rotor, the electromagnetic torque and the angular rotor position.

The signals can be demultiplexed using the Machine Measurements Demux block in the machines library.

Squirrel Cage Model

The first model to be built involves an asynchronous generator with a squirrel cage rotor.

The system diagram for the model is shown below:

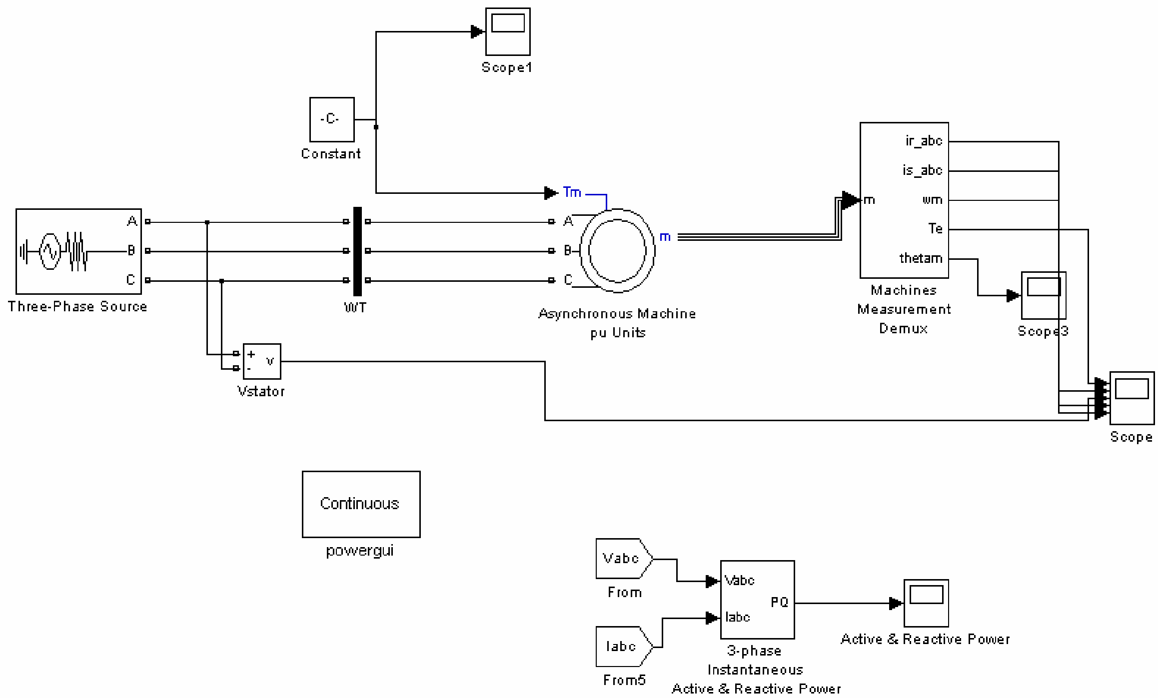


Figure 4.7 Squirrel cage system diagram

The Asynchronous Machine block stator terminals are connected to a three-phase source. The output from the machine is demultiplexed and the desired outputs are monitored on a scope.

A sub-system is set up to monitor the three-phase active and reactive power on the stator.

The parameters are taken from a 275kW, 480V, 60Hz machine and are expressed in per unit quantities:

Parameter	Value
Nominal Power	275kW
Nominal Voltage	480Vrms
Frequency	60Hz
Stator Resistance	0.02pu
Stator Leakage Inductance	0.0349pu
Rotor Resistance	0.0377pu
Rotor Leakage Inductance	0.0349pu
Mutual Inductance	1.2082pu
Inertia Constant	0.7065s

Figure 4.8 Parameters

The model was originally built with parameters from a 2MW machine, which would be more representative of the scale of modern wind turbines, though the high inertia of the large generator prevented the machine from stabilizing quickly, meaning that simulations had to last a long time. In order to reduce the simulation time, a 275kW machine was chosen throughout the modeling process.

Since the purpose of this exercise is to investigate and demonstrate the behavior of a generic machine, a 275kW generator was deemed appropriate.

The initial conditions and load flow are handled by the Powergui.

The Powergui block provides graphical user interface tools for the analysis of SimPowerSystem models. The functions of interest in this exercise are; the ability to display ‘Steady State Voltages and Currents’ and ‘Load flow and Machine Initialisation’.

A value of mechanical power, to drive the machine can be specified in the powergui. This is then converted to a torque that is sent to the T_m terminal of the machine. Alternatively a Mathematical function, such as a ramp, step or exponential increase or decrease can be attached to the T_m terminal to vary the torque in a specific way.

The Load flow can be calculated by the powergui and it returns steady state values.

The machine can be initialized to start from a steady state.

To view the time variant properties of the system, a simulation must be performed.

The areas of interest in these simulations are; the Torque vs. Speed characteristics, the efficiency over a range of applied torques, and the power factor.

The squirrel cage model was simulated over a range of mechanical torques. This was done by ramping the torque from zero to -3 * the rated value of the generator and sending the mechanical torque and rotor speed measurements to an XY plot. The system diagram is shown below:

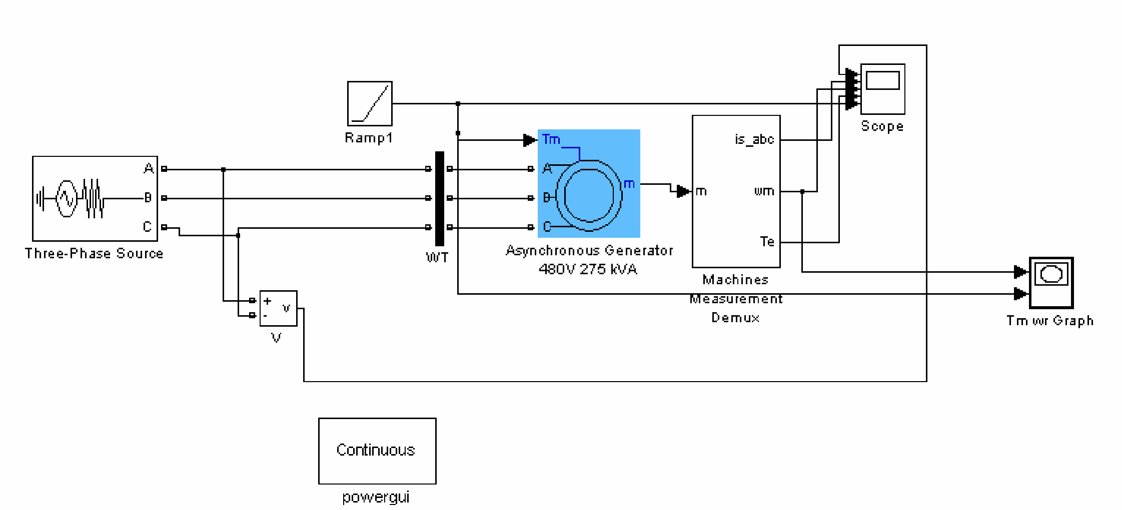


Figure 4.9 Ramped Torque

The Torque vs rotor speed plot for the 275kW squirrel cage generator is shown below:

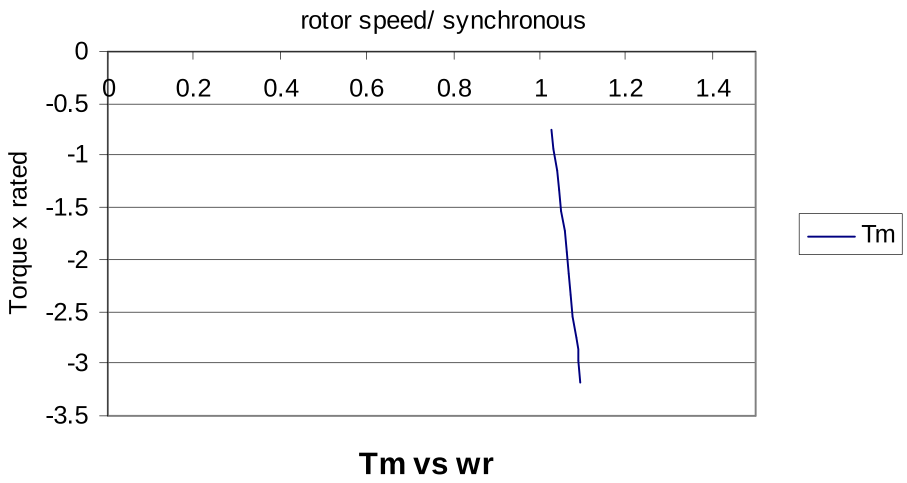


Figure 4.10 T_m vs ω_r

The plot shows the linear relationship between torque and speed for a range of torques above and below rated value.

The following plot shows the efficiency dropping as applied mechanical power is increased beyond rated value:

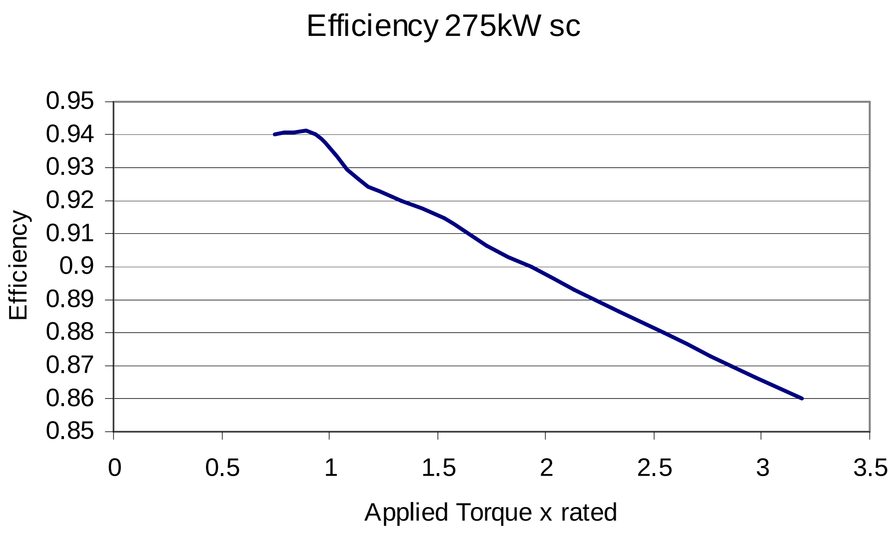


Figure 4.11 Efficiency

The power factor was measured by reading the P and Q values at the stator terminals:

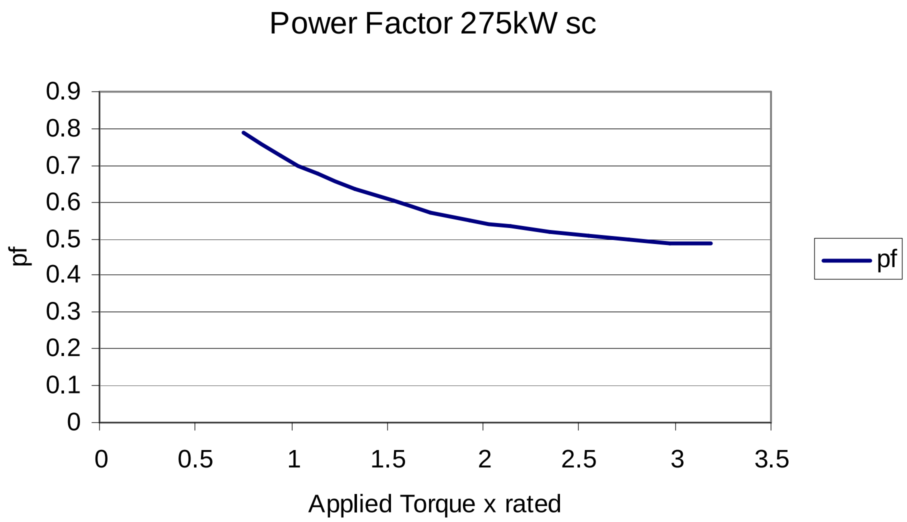


Figure 4.12 Power Factor

The plot shows the power factor decreasing then leveling off as the applied torque is increased. At nominal power the power factor is 0.7. If this generator was used in a wind turbine a capacitor bank would be required to achieve a power factor of 1.

These results can now be used as a basis for comparison with the other configurations discussed in this thesis.

Wound rotor with variable Resistance

Now the effects of increasing rotor resistance are investigated.

This can be done simply by changing the parameters of the squirrel cage block. Alternatively a three-phase resistor block could be attached to the terminals of a wound rotor machine, though this would give the same result.

The rotor resistance was increased to 2x, 3x and 4x the original value and the simulation was repeated.

The Tm vs ω_r plot shows the effects of varying rotor resistance.

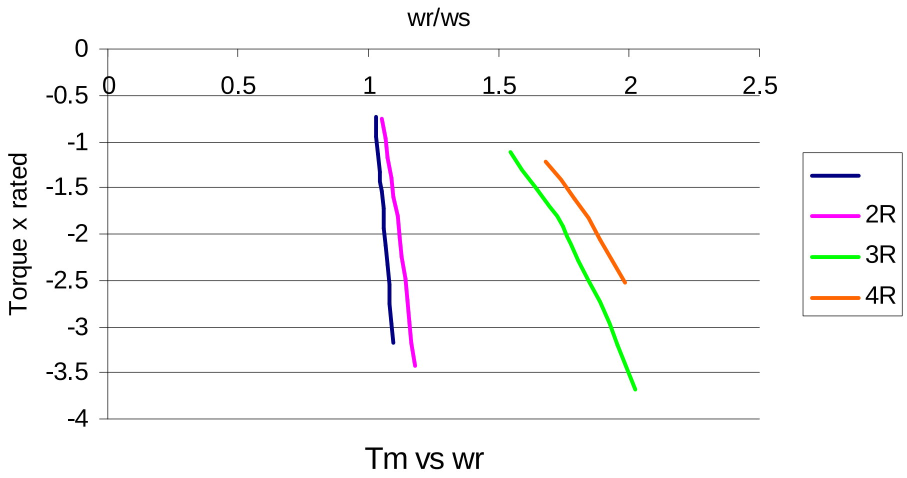


Figure 4.13 T_m vs ω_r increased rotor resistance

It can be seen that the rotor speed can be increased by adding rotor resistance. The machine was able to operate at nearly four times the nominal torque value at twice the synchronous speed.

It is intuitive to expect the efficiency to be reduced as the rotor resistance is increased, since the extra resistance will have associated power losses.

This is demonstrated by the following plot.

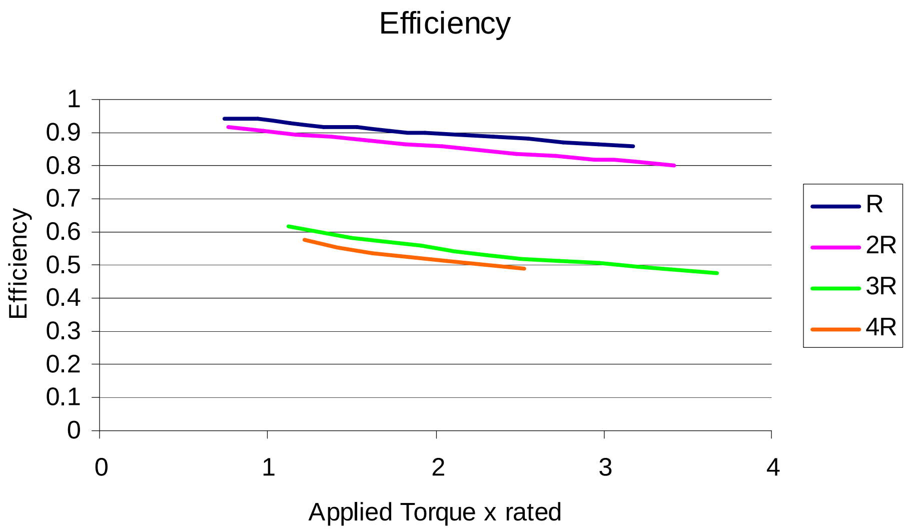


Figure 4.14 Efficiency

Finally the implications of varying rotor resistance on the power factor are investigated.

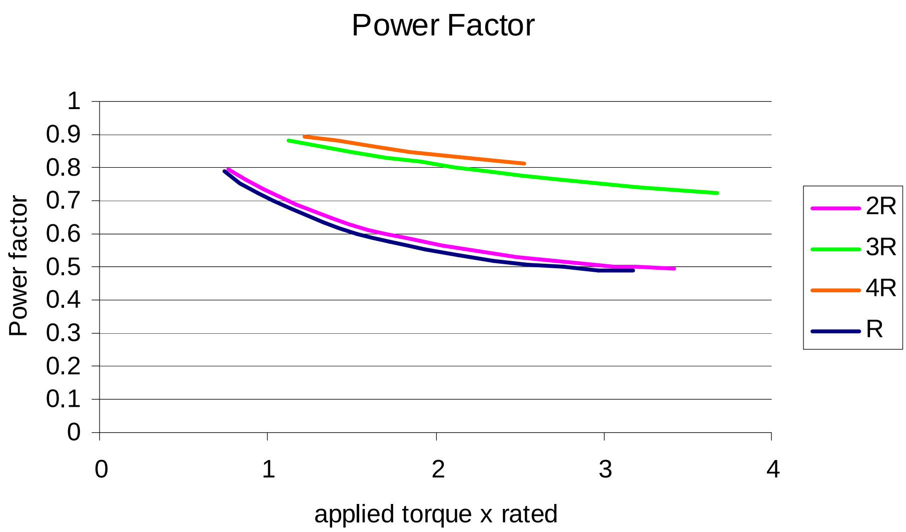


Figure 4.15 Power Factor

It can be seen from the plot that the power factor increases as the rotor resistance is increased. If the impedance of the machine is considered from the rotor terminals, a higher rotor resistance would reduce the impedance angle.

Doubly-Fed Induction Generator

The Doubly-Fed Induction Generator is modeled by changing the rotor configuration in the machine parameters window to a wound rotor and connecting a voltage source to the rotor terminals.

In an actual D-FIG the rotor is fed from the stator via a voltage converter. In this exercise the rotor supply is independent. This arrangement is suitable for the task of investigating the characteristics of interest in this thesis.

The machine is built with the same parameters as the 275kW squirrel cage machine, to allow for comparison.

A diagram of the D-FIG system is shown below:

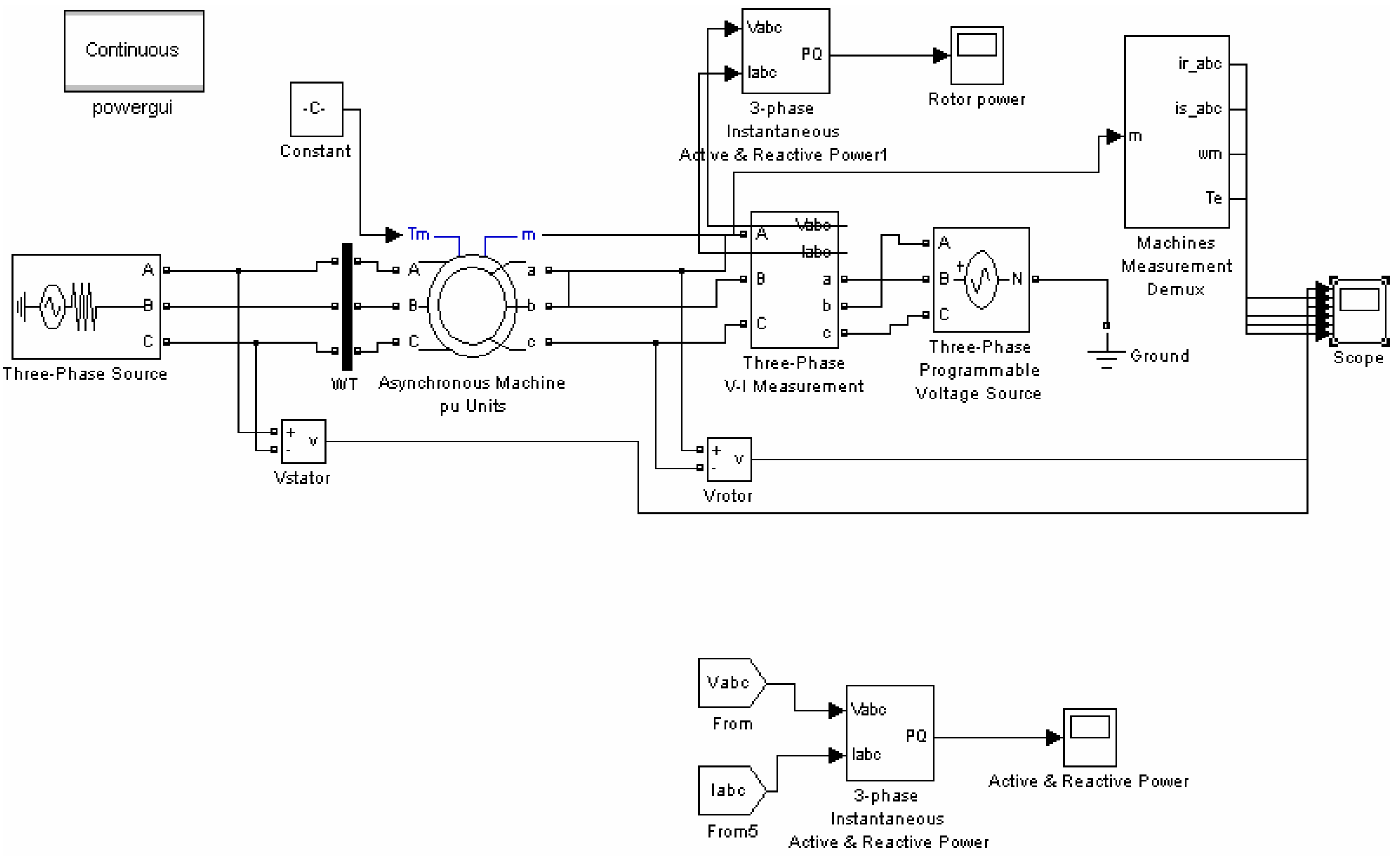


Figure 4.16 diagram of the D-FIG system

The rotor is fed from a three-phase programmable voltage source, allowing voltage magnitude and frequency to be altered or ramped as desired.

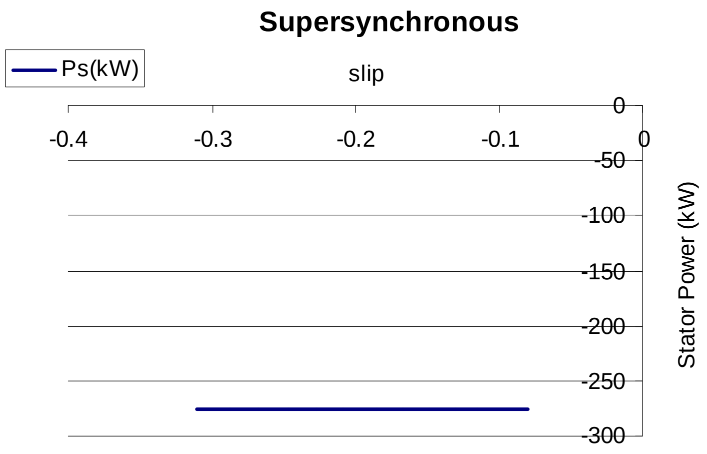
There are some additional measurement blocks to monitor rotor active and reactive power.

To operate the machine in sub and supersynchronous modes, the phase of the rotor supply must be reversed. This can be achieved by switching two of the terminals. The arrangement shown is for super synchronous operation.

A variety of simulations were carried out to verify that the machine behaves like a D-FIG. It was originally found that during transients the machine would become unstable and the rotor speed would oscillate and sometimes never settle. This effect was made worse by the use of a 2MW machine with a 3.5sec inertia constant. It was for this reason that a 275kW machine was chosen.

By initializing the machine appropriately and slowly ramping the rotor frequency and voltage, a wide range of operation could be achieved.

By varying the rotor voltage and frequency, the stator power could be held constant over a range of rotor speeds +/- 32% of synchronous speed as shown in the following plot. During this simulation the applied mechanical power was held at 300kW.



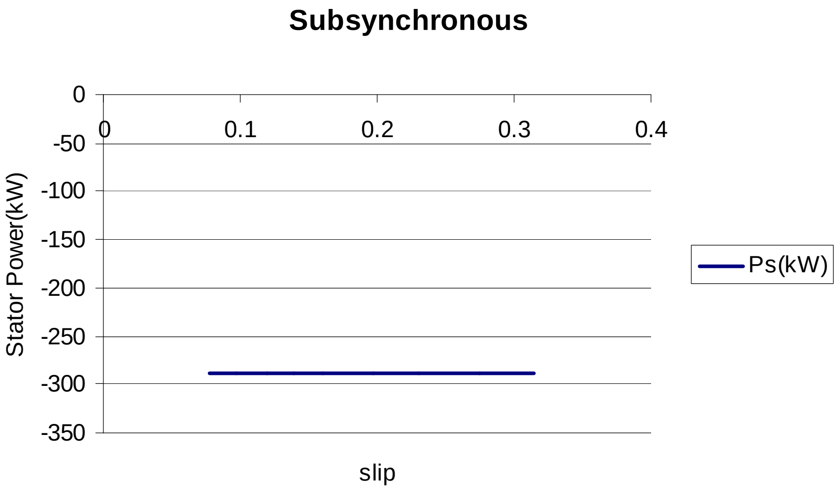
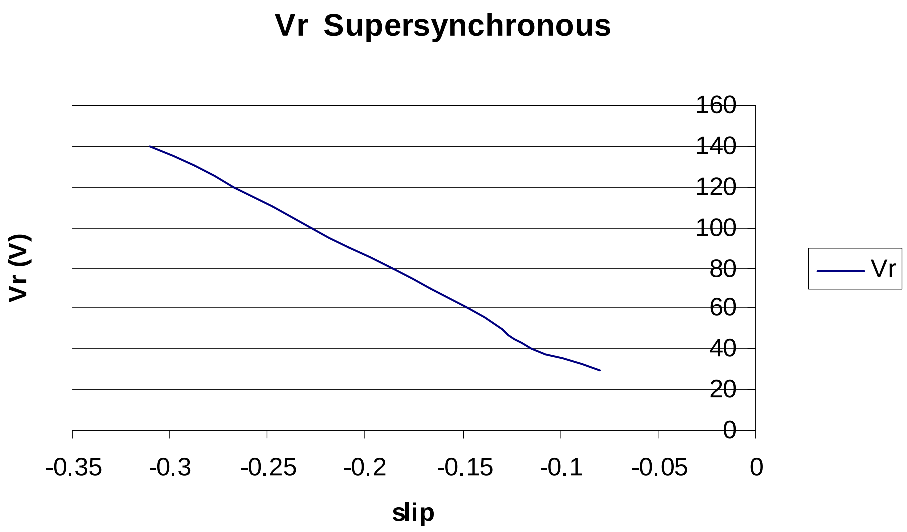


Figure 4.17 Constant Power

The rotor voltages across the range of speeds can be seen below:



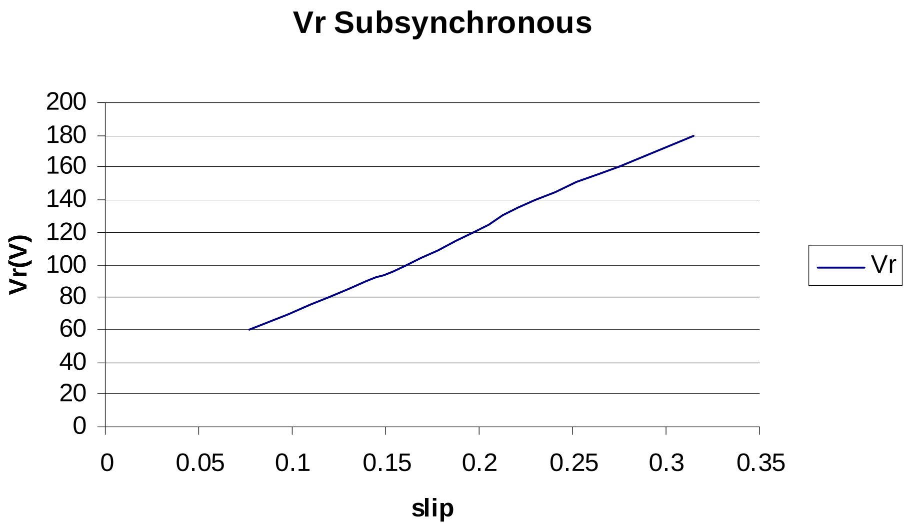


Figure 4.18 Vr vs slip

It can be seen that there is a linear relationship between slip and hence frequency and the rotor voltage for steady operation of the generator.

By keeping the rotor voltage constant and varying the frequency or vice versa, it is possible to vary the stator reactive power while the active power remains fixed.

An example of the stator P and Q output can be seen below. During this simulation the rotor voltage is held at 60V and the frequency ramps between 5 and 11Hz, translating to slip change of -0.0833 to -0.1833.

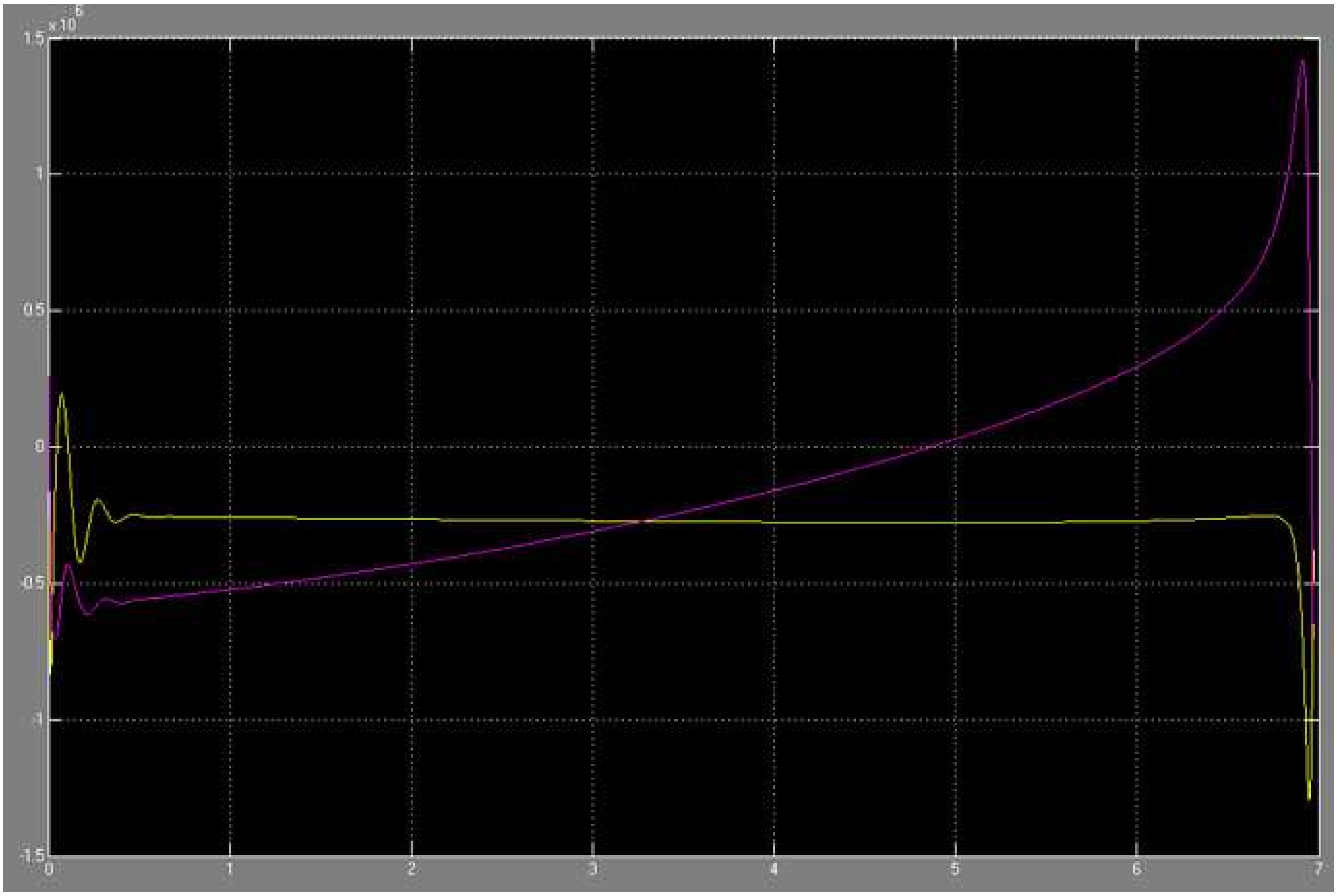


Figure 4.19 Stator P & Q

The yellow trace is the active power and the purple line is the reactive power. In this plot negative readings refer to power coming from the generator. During the period of stability it can be seen that the stator power remains constant while the reactive power goes from a leading to a lagging reactance.

If the corresponding rotor plot is now considered:

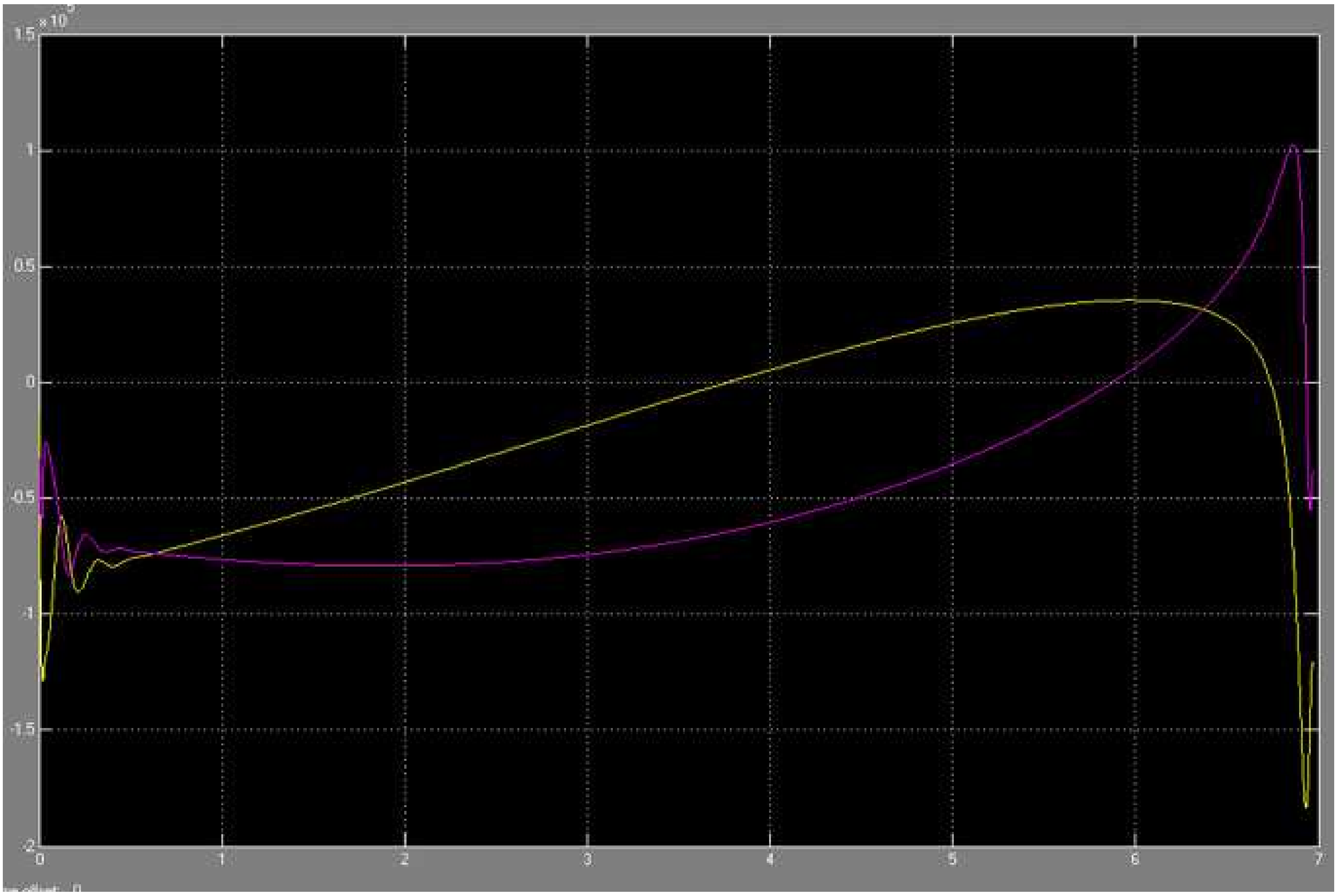


Figure 4.20 Rotor P&Q

It can be seen from this plot that the rotor power varies with slip, as would be expected. The rotor power begins flowing from the rotor, reaches a point where there is no active power flowing and then flows in to the rotor.

The efficiency of the modeled machine will obviously vary with the direction and magnitude of the rotor power since the rotor is supplied by an independent voltage source and not connected back to the stator.

From the simulations it can be seen that there is an operating condition where there is no real power flowing in the rotor. This is the case for the range of rotor speeds. At this point the efficiency can be considered to be the stator power divided by the supplied mechanical power.

With 300kW mechanical power supplied to the generator, the efficiency is 0.92 for supersynchronous operation and 0.96 for subsynchronous.

For the squirrel cage model operating with the same applied mechanical power, the efficiency is also 0.92.

Discussion and Comparison

From the simulated models the operating range and characteristics can be acknowledged and compared. The squirrel cage, being the most basic configuration can be treated as a benchmark for comparison.

The simulations show that the squirrel cage machine has a specific operating speed that corresponds to a value of torque.

Adding resistance to the rotor allows for different operating speeds, though to be useful in a wind turbine, the resistance would have to be dynamically controlled if it were to allow speed variation. Changing the rotor resistance does not allow subsynchronous operation and speed variation is limited at low torques.

The D-FIG was shown to have a good range of operating speeds (+/- 32%). The operating range spans a good range of torques. Sub synchronous speeds are achievable through adjusting the model, though the phase change would be performed by the voltage converter in an actual system.

In terms of efficiency the squirrel cage performs well. The efficiency only drops slightly at very high torques. There will also be a drop in efficiency at torque values lower than presented in this exercise. The efficiency values returned from the model are idealistic as there will be other losses from climate variations etc. Also the Asynchronous Machine block does not include a representation of iron losses and saturation.

The major disadvantage of the increased rotor resistance is the loss of efficiency. The simulations saw a drop below 50%. This is the price of extending the range of speed.

The D-FIG efficiency was found to be similar or better than the squirrel cage. In this model, however the losses in the converter are obviously not accounted for.

The power factor was shown to be quite high for the squirrel cage, though it drops as the torque increases. At nominal power the power factor is around 0.7 for the machine simulated. A capacitor bank could be used to correct this as the squirrel cage offers no reactive power control.

Increasing the rotor resistance was found to increase the power factor. This is a result of the impedance angle of the machine, from the stator terminals, reducing as resistance is added.

The simulation of the D-FIG showed that the reactive power on the stator could be manipulated by varying the rotor voltage around a fixed rotor frequency, or varying the rotor frequency around a fixed voltage, though at the cost of efficiency.

Overall the range of operation displayed by the D-FIG far outstrips the other constructions.

The D-FIG model presented, though adequate for this exercise has many limitations. In order to develop a model that can demonstrate the reaction to sudden increases in torque or speed, or fault situations a controller must be developed. MATLAB is an ideal package in which to develop a control system and there are various designs to be found in literature.

Conclusions and Discussion

The purpose of this thesis was to evaluate the potential for improved wind turbine performance through variable-speed operation, specifically looking at the evolution from squirrel cage generators to modern Doubly-Fed Induction Generators. The value of improved performance and increased operating range was shown to be born from the impending mass exploitation of wind energy in the UK and the subsequent responsibilities that will be placed on wind generation plant.

The origins and development of modern wind turbines were presented and an overview of wind energy conversion was given. This set the scene for an in depth analysis of wind turbine induction generators. It was shown how the operating characteristics of induction generators could be enhanced by manipulation of the rotor properties. The importance of these characteristics was explained in terms of desired wind turbine capabilities.

Software models of induction generators were built and simulated to further explore the properties of each construction.

The simulations allowed comparisons to be made between the generator types in terms of their range of operation, efficiency and power factors.

The Doubly-Fed Induction Generator was shown to demonstrate the desired operating range, to meet the requirements of modern wind turbines.

Suggestions for Further work

The D-FIG model built in this project had limited capabilities. The model could be extended with the addition of a control system that could allow simulations of sudden increases or decreases in torque or speed. Real and reactive power control could also be incorporated in the control system. The comparison between generator types could also be extended to cover field operation, reliability, maintenance issues and product life span.

List of Figures

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