An Analytical Study of a Grid Connected Direct Drive Permanent Magnet Generator Wind Turbine: Modeling and Simulation

by

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Abstract

Wind is clean, free and a readily available energy source. Around the world, every day, wind turbines are capturing the wind's power and converting it to electricity. There is considerable interest in wind power as a contributor to reducing our dependence on fossil fuel power. The number of wind turbines is growing rapidly at a rate of 29% per year. Off-shore wind turbines produce large amounts of power because of powerful ocean winds.

Within the last few years, several wind turbine manufacturers have offered off-shore wind turbines with direct drive permanent magnet generators (PMG) and electronic power converters to tie-in to the electric power grid. As opposed to previous designs, the direct drive PMG eliminates the high speed gearbox.

The **focus** of this paper is to provide an analytical study of a grid connected off-shore direct drive PMG wind turbine. The topics to be studied include the mathematical model from the moving air cylinder to the grid, the power as a function of wind speed and temperature, converter power electronics for optimal performance and wind turbine controls. Matlab is used to implement the mathematical model for analysis and simulation models using Simulink yield dynamic analyses of the wind turbine with varying wind speeds, operation of the converter and other real situations.

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List of Abbreviations

Symbol	Description	Unit
I_S	Stator Current	Ampere (A)
P_{wind}	Power of the Wind	Megawatt (MW)
P_t	Power of the Wind Turbine	Megawatt (MW)
s	Wind Speed	meters per second (m/s)
n	Rotor Speed	revolutions per minute (rpm)
ω_r	Rotor Speed	radians per second (r/s)
f	Frequency	Hertz (Hz)
E	Electrical Energy	kilowatt-hours (kWh)
T	Temperature	degrees centigrade (degC)
L	Length of rotor blade	meter (m)
A	Cross section area swept by rotor	square meters (m^2)
v	Wind Speed	meters per second (m/s)
K	constant related to generator physical properties	
Φ	phi – field flux	
δ	Angle of Complex Induced Stator Voltage	degrees (deg)
η	Efficiency	in percent (%)
ρ	Air density	kilogram/cubic meter(kg/m^3)
E_a	Complex Induced Stator Voltage	Volts or kilovolts (V or kV)
WT	Wind Turbine	
R_S	Stator Resistance	ohms (Ω)
L_S	Stator Inductance	millihenry (mH)
X_S	Stator Reactance	ohms (Ω)
SWL	Stator Winding Loss	kilowatts (kW)
$S_{3\Phi}$	Three Phase Apparent Power	Megavolt-Amps (MVA)

Symbol	Description	Unit
V_t	Terminal Volts	volts or kilovolts
AEP	The annual energy produced	Megawatt-hours (MWh)
CP	Capacity factor	Percent (%)
PP	Percent Power	Percent (%)
RFPM	Radial Flux Permanent Magnet Machine	
P	Number of Poles	
3ΦSM	Three Phase Synchronous Machine	
W	Watt – Measure of Power	joules / s
SI	International System of Units	
J	Joule	N-m
kWh	kilowatt-hour	1kW for 1hr
HAWT	horizontal axis wind turbine	
m	meter	SI basic unit of measure
TPES	Total World Primary Energy Supply	
NIMBY	not in my backyard	
GRP	glass fiber reinforced polyester	
WPD	wind power density	
USDOE	United States Department of Energy	
3Φ	three phase	
PMG	permanent magnet generator	
NREL	National Renewable Energy Laboratory	

1. Introduction

This research presents an analytical study of a grid connected off-shore direct drive PMG wind turbine. The topics to be studied are the mathematical model from the air cylinder to the grid [10], equivalent circuit model [10], SC and OC values, stator resistance and reactance [10] and power electronics for optimal performance [9]. Matlab is used to implement the mathematical model for analysis and a simulation model using Simulink yields dynamic models of the wind turbine with varying wind speeds, CPs and other variables. This research is introduced by three concepts: Renewable Energy, Power vs. Energy and Wind Energy.

1.1 Renewable Energy

We want energy because of what it can do for us; for its ability to do work. Major categories of end users are residential, commercial, industrial and transportation. Most end uses are for heat, mechanical work or electricity [13].

The International Energy Agency (IEA) – an international organization that tracks statistics on energy usage and energy sources defines Renewable Energy as the energy that is derived from natural processes that are replenished constantly; time to replenish the energy is less than the time for us to use that energy.

In its various forms, it (usually) derives directly or indirectly from the sun, or from heat generated deep within the earth. Renewable energy is energy that is derived from natural processes that are replenished constantly. In its various forms, it (usually) derives directly or indirectly from the sun, or from heat generated deep within the earth [13].

The IEA defines renewable energy as that generated from [13]:

- Wind
- Solar
- Biomass
- Geothermal
- Hydropower
- Biofuels
- Ocean power (tidal energy)

In 2012, renewable energy was only about 12% of the total energy supply in the US, dominated by hydro power. Key Points for renewables in the US [13]:

- Hydropower predominates, but non-hydro is growing.
- Wind is growing fast and now is the highest energy source other than hydro.
- Solar is still very small, but growing.
- Geothermal is significant.
- Waste burning is typically municipal waste.
- Energy storage, one of the largest challenges with renewables, due to its variability such as the lack of solar when the sun goes down.

Renewable Energy Sources are: [13]

1. Wind Energy for electric power generation is the energy from wind turbines. Air movements are primarily driven by thermal differences as air moves from high pressure to low pressure. This is wind caused primarily by solar heating. Wind complements Solar Energy as wind provides energy when solar may not, such as in the evening and night time, cloudy days and in northern regions. Wind adds diversity to the energy supply. Wind variability; wind varies in speed and direction over the day and over the year and geographically. Wind is “intermittent”, coming and going over time, not continuous [22].

2. Solar Energy is energy from the sun. The two types are solar thermal, where solar heat is concentrated to produce steam for a turbine to produce power and

solar photo-voltaics, where the photons from sun light impinging on solar cells create power. There is more than 89 PW solar power available on earth's surface, the equivalent of 89 million nuclear power plants   There is much more sun energy than we can imagine using [21].

3. Biomass and Biofuels – biomass was the first fuel primitive man used, including wood, straw, dung and charcoal (only 20% of energy in original wood). Biomass is organic material that comes from plants and animals and it is a renewable source of energy.

Biomass contains stored energy from the sun. Plants absorb the sun's energy in a process called photosynthesis. When biomass is burned, the chemical energy in biomass is released as heat. Biomass can be burned directly or converted to liquid biofuels or biogas that can be burned as fuels.

Examples of biomass and their uses for energy:

- wood and wood processing wastes - burned to heat buildings, to produce process heat in industry and to generate electricity
- agricultural crops and waste materials - burned as a fuel or converted to liquid biofuels
- food, yard, and wood waste in garbage - burned to generate electricity in power plants or converted to biogas in landfills
- animal manure and human sewage - converted to biogas, which can be burned as a fuel

Burning is only one way to release the energy in biomass. Biomass can be converted to other useable forms of energy such as methane gas or transportation fuels such as ethanol and biodiesel. Methane gas is a component of landfill gas or biogas that forms when garbage, agricultural waste, and human waste decompose in landfills or in special containers called digesters. Crops such as corn and sugar cane are fermented to produce fuel ethanol for use in vehicles. Biodiesel, another transportation fuel, is produced from vegetable oils and animal fats. Adapted from The National Energy Education Project (public domain) [42]

4. Geothermal is heat from the earth. The best places for Geothermal Energy are hot spots on the earth's crust such as near volcanos or on the ring of fire on the rim of the Pacific Ocean.

Geothermal Energy includes:

- Direct geothermal; use of heat in the ground directly for heating
- Geothermal heat pumps; use of the ground as an energy sink / source. Ground temperature is relatively constant – doesn't fluctuate with season. Geothermal systems comparable to home heat pump or air conditioner – fluid is circulated in pipes in earth, and heat pump then exchanges heat with the fluid instead of air.

Geothermal Electricity includes these types of plants:

- Dry steam – uses steam from the ground directly drives turbine
- Flash stem – pressurized water from a well, vaporizes and drives a turbine
- Binary cycle – uses heat exchanger and secondary fluid with a lower boiling point, such as pentane or butane.

Geothermal is not intermittent. Iceland receives 30% of their national energy from geothermal, for electricity and hot water for heating. Iceland has 5 major geothermal plants [18].

5. Hydropower is the converting of the kinetic energy of moving water into electricity. The efficiency of a hydropower plant is very good, ranging from 85% to 95%. Hydropower produces 7% of US electricity. Types of Hydropower include:

- conventional; "impoundment" – uses dams to create large reservoirs
- run-of-river; "diversion" – no large created reservoir
- Pumped storage

In the US, there are many dams build for flood control or navigation that do not have hydropower. There are estimated to be over 600 existing dams without hydro power, each with a potential capacity for over 1MW. It is estimated that the one hundred largest of these could generate 8GW of power [19].

6. Ocean Power is the emerging technology of capturing of wave energy. The advantages of ocean power are:

- Low environmental impact
- Low aesthetic impact (NIMBY concern)
- Predictability
- High power density

There is good potential for wave energy around Northern Europe and Australia – many demonstration projects have been in these areas.

Categories of wave energy harvesting methods:

- Point absorber - point absorbers and oscillating wave surge converters; the Seatows system and the Archimedes Wave Swing
  Captures movement of device in water (Oyster)
- Oscillating water column (Oceanlinx) - waves compressing air
- Overtopping device (Wave Dragon) - waves creating hydroelectric water reservoir
- Surface attenuator (Pelamis) - waves flexing device on surface
- The Sihwa Tidal Power Plant in Yellow Sea in Korea – the world's largest tidal power plant – 5.5 billion KWh in annual electricity production [20].

1.1.1 Non-Renewable Energy

Non-renewable energy comes from fossil fuels. In the Total World Primary Energy Supply (TPES): [13]

- Fossil: 81.7%
- Nuclear: 4.8%
- Renewables: 13.5%

World electricity production:

- Renewables 21.2%
- Fossil: 67.9%
- Nuclear 10.9%

Fossil fuels include coal, oil and natural gas. Fossil fuels are not renewable because the time frame to replenish is too long. Fossil fuels result from biological matter such as algae, plankton and plants that grew millions of years ago. These alga, plankton and plants we can think of as being biomass or biofuels, and under the right combination of temperature and pressure through geological processes these became the fossil fuels that we depend on today [13].

1.1.2 Advantages and Disadvantages of Renewable Energy

One major advantage with the use of renewable energy is that since it is renewable, it is therefore sustainable and so will never run out. Renewable energy facilities generally require less maintenance than traditional generators. Their fuel being derived from natural and available resources reduces the costs of operation. Even more importantly, renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so has minimal impact on the environment.

Renewable energy projects can also bring economic benefits to many regional areas, as most projects are located away from large urban centers and suburbs of large cities. These economic benefits may be from the increased use of local services as well as tourism. It is easy to recognize the environmental advantages of utilizing the alternative and renewable forms of energy but we must also be aware of the disadvantages.

Among the disadvantages of Renewable Energy is that it is difficult to generate the quantities of electricity that are as large as those produced by traditional fossil fuel generators. This may mean that we need to reduce the amount of energy we use or simply build more energy facilities. It also indicates that the best solution to our energy problems may be to have a balance of many different power sources.

Another disadvantage of renewable energy is the reliability of supply. Renewable energy often relies on the weather for its source of power. Hydro generators need rain to fill dams to supply flowing water. Wind turbines need wind to turn the blades and solar collectors need clear skies and sunshine to collect heat and make electricity. When these resources are unavailable so is the capacity to make energy from them. This can be unpredictable and inconsistent. The current cost of renewable energy technology is also far in excess of traditional fossil fuel generation. This is because it is a new technology and as such has extremely large capital cost [43].

1.2 Power vs. Energy

Energy is the "capacity for doing work" while work is force X distance. The SI unit of work is the joule (J), which is defined as the work expended by a force of one newton through a displacement of one meter [14].

Mechanical Energy includes kinetic energy and gravitational potential energy.

Forms of energy are:

- Thermal
- Kinetic
- Chemical
- Electrical
- Nuclear
- Electromagnetic (e.g. light)

Key point; we can convert from one energy source to another

- Photosynthesis
- Combustion
- Expansion
- Generator

- Motor

The law of conservation of energy (1st law of thermodynamics): energy can be neither created nor destroyed. Losses represent energy converted to forms that are not contributing towards our end goal (not useful), the goal of work. Many of the losses represent low quality heat where the temperature is not high enough or the source is not concentrated enough to make the energy worth capturing for further use [14].

The ratio of useful energy out of a system to the energy put into the system is the concept of efficiency.

The SI unit for energy is the Joule, which equals Newton (force) X meter (distance) = N-m

Scaling to larger units:

- kilo k 10^3
- mega M 10^6
- giga G 10^9
- tera T 10^{12}

For example, 1kWh = 1 kilowatt for 1 hour

A barrel of oil has the energy of ~ 6.1×10^9 joules [14]

1.2.1 Power Units Defined

Power = work/time = energy/time

Power is the rate at which work is done; power is work / time

Watts (W) = joules/sec (the SI unit for power)

Some examples of power generation include:

- large power generating plants: 500 – 800MW
- nuclear plants: ~1GW
- hydro plants: ~2GW
- wind farm: ~ 100MW

1.2.2 Energy affects

Energy affects economies and economic development, international relations and politics.

According to Energy Issues: 3.2 Energy and Society, humanity's top ten problems are [16]:

1. Energy
2. Water
3. Food
4. Environment
5. poverty
6. Terrorism & war
7. Disease
8. Education
9. Democracy
10. Population

By mid-century, it is expected that the population of the world will be 10 billion people. If we gave all people around the world some energy level comparable to what we experience in the developed world today, we would need the equivalent energy of about 60TW average power generation during the year. This is about 4X the world average power use in 2004.

The key points are that Energy is the world's top problem and it is critical to modern society. This is the major motivation for developing renewable energy [16].

1.3 Wind Energy for Electric Power Generation

The causes of wind:

- air movements are primarily driven by thermal differences.
- warmer air expands and rises, creating low pressure areas.
- air from cooler higher pressure areas moves in to replace the warmer air.
- Air moves from high pressure to low pressure; this is wind.
- Wind is caused primarily by solar heating

Wind is variable and intermittent, coming and going over time, not continuous.

- Speed and direction
- Over the day and over the year
- Geographically
- Turbines have operating regions with no power output (either wind speeds too slow or too fast)
- Even when turbines are generating power, they may be operating at less than full power

The wind turbines that are being studied in this research are called horizontal axis wind turbines (HAWT). These WTs have three fiberglass blades (38m long or more) attached to a horizontal axis hub at a vertical height (80m or more) from the turbine base. The hub is connected to the wind turbine main shaft. A cylinder of air moves across the aerodynamic surface of the blades causing them to rotate and create a torque on the WT main shaft. This mechanical power created by the kinetic energy of the wind is converted to electrical power by the WT generator. Every WT has a rated power in kW or MW.

For a given wind speed, maximum turbine efficiency can be achieved only at a specific rotor speed, pitch angle, and with laminar flow (no turbulence) perpendicular to the plane of rotation of the rotor. In real applications, wind speed and direction is continuously variable, so a HAWT must be direction-controlled and variable pitch, both which add complexity of design and introduce losses. Hence, even with the best designs, a maximum achievable efficiency is around 42%, and this is before gearing and generator losses are considered [10].

The capacity factor (CP) of a wind turbine is determined by its location. CP is calculated by taking its actual power produced divided by its maximum power it could produce over a period of time. Typical CPs of wind turbines: 20% - 40%, with ~25% actual average.

Wind complements Solar Energy; wind provides energy when solar may not, such as in the evening and night time, cloudy days and in northern regions. Wind adds diversity to the energy supply [22].

1.3.1 History of Wind Turbines

- Sail boat – 5000 years ago in Egypt
- Grain grinding – several thousand years later, vertical axis wind mills in Persia
- In Western Europe - wind mill evolved into more efficient horizontal axis
- The Dutch – modified the windmill to pump water and reclaim much of Holland from the sea
- Farm windmills – multi-vane farm windmills to pump ground water for livestock water tanks, during latter part of 19th century
- Farm wind turbines – in the 1930's and 1940's electricity producing wind turbines were built in the US to provide electricity to farms beyond the reach of power lines
- By the early 1950's, the extension of the central power grid to nearly every American household made these wind turbines unnecessary
- A new market for wind systems or wind farms began in the early1980's. As climbing oil prices in the 70's and a new federal law encouraged the use of alternative power sources [23].

1.3.3 Wind Farms

As the cost of wind technology becomes less expensive, areas such as the Great Plains, Midwest, pacific NW and NE are now starting to see greater wind farm development.

Wind farms typically have dozens of wind turbines. Since a single wind turbine needs about one half acre of land on which to operate and approximately 40 acres of wind space, a wind farm may spread out over thousands of acres [23].

2. Wind Turbines

Wind turbines allow us to harness the power of the wind and turn it into energy. When the wind blows, the turbine's blades spin clockwise, capturing energy. This causes the main shaft, connected to a gearbox within the nacelle, to spin. The gearbox sends that energy to a generator, converting it to electricity. Electricity then travels down the tower to a transformer, where it is converted again to AC or DC voltage depending on the grid [39].

The components needed to convert wind energy to electric energy include blades, bearings, high speed gear (in most models), generator, power converter, control systems (blade pitch, yaw drive) and emergency brake. [22]

The power available in the wind is expressed as:

T = temperature of the wind, in degC

$$\rho = \text{air density} = -(0.00425T) + 1.2922 \text{kg/m}^3 \qquad (2.1)$$

L = length of rotor blade in meters (includes ½ of nose cone diameter)

$$A = \text{cross section area swept by rotor } (\text{m}^2) = \pi L^2 \qquad (2.2)$$

v = wind speed (m/s)

Power in the Wind = (Dynamic pressure) x (Area) x (Wind speed) in kW or MW

$$P_{wind} = (½)\rho A v^3 \qquad (2.3)$$

This information and the following diagrams were taken from a Wind Energy Lecture by Gary Pawlas from a course co-developed w/ENREL, created by Pat Moriarty and Sandy Butterfield. The National Renewable Energy Laboratory (NREL), located in Golden, Colorado, is the United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is a government-owned, contractor-operated facility, and is funded through the United States Department of Energy (DOE) [24].

2.1 Wind Turbine Operation

The wind turbine nacelle is the large structure which encloses the main shaft, bearings, gear box, generator, power converter and controls. It is mounted at the top of the tower. Access to the nacelle is provided by ladders attached to the inside walls of the tower.

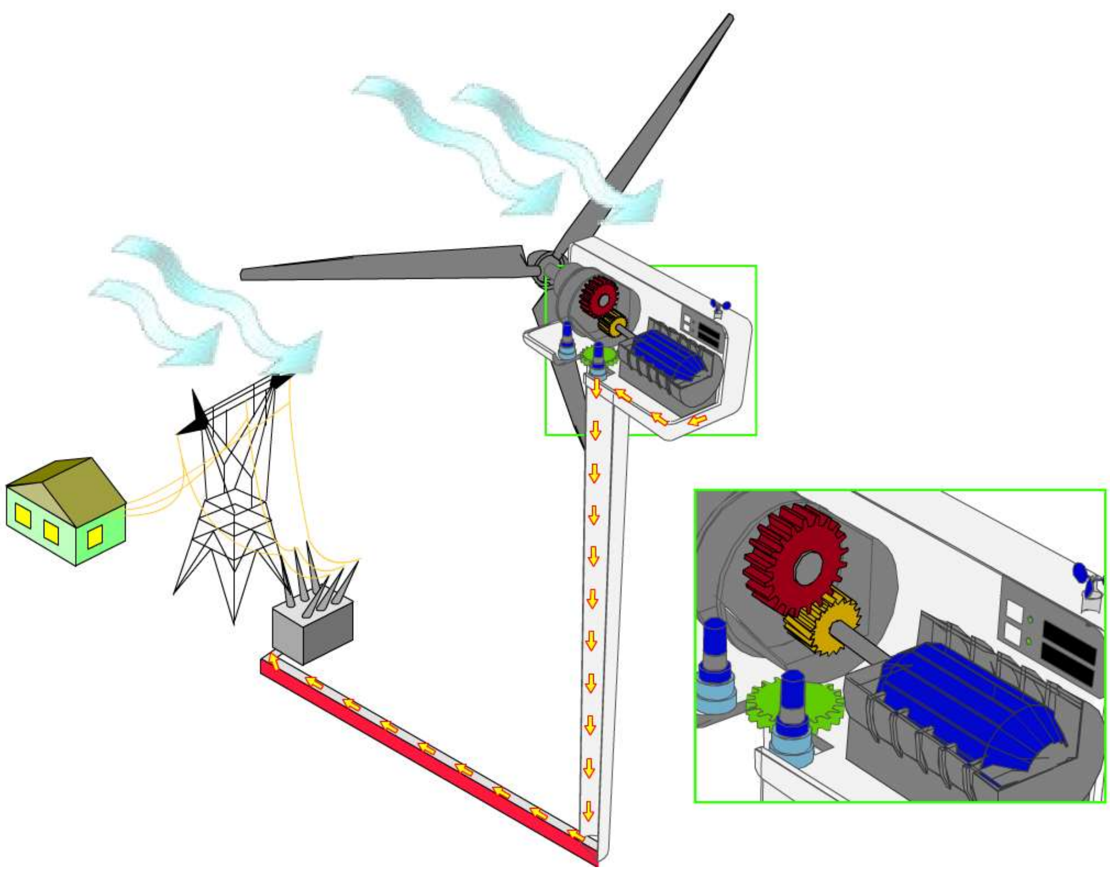


Fig. 2.1: Wind Turbine Operation [47]

Fig. 2.2 depicts a more detailed view of the wind turbine parts.

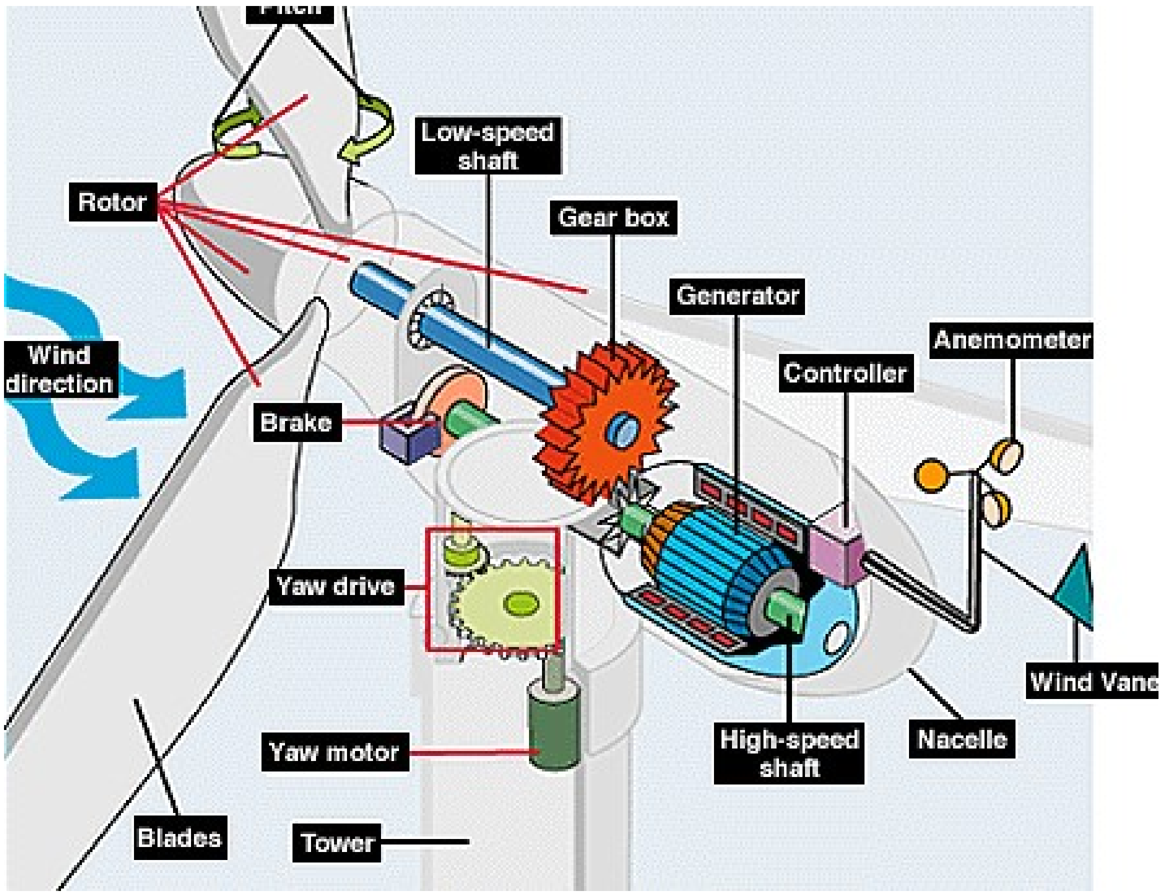


Fig. 2.2: Wind Turbine Details [24]

(Source: NREL)

The rotor includes the three blades attached to the hub. The blades and hub are assembled onto the main shaft, which rotates in the main bearing and gearbox bearing. The brake is used to stop the rotor if the wind speed exceeds the cut-out speed. The anemometer provides the wind speed to the controls and the wind vane indicates to the controller that the yaw motor must turn the rotor into the wind. The controller adjusts the blade pitch using the pitch motor.

The generator power converter output current is transmitted on electric cables down the inside of the tower and then to the step-up transformer for connection to the electric grid.

2.2 Wind Turbine Components

1. Wind Turbine Blades

Wind Turbine Blades lifts and rotate when wind is blown over them, causing the rotor to spin. Most modern rotor blades on large wind turbines are made of glass fiber reinforced plastics, (GRP), i.e. glass fiber reinforced polyester or epoxy [30]. Rotor blades for large wind turbines are always twisted.

Seen from the rotor blade, the wind will be coming from a much steeper angle as you move towards the root of the blade, and the center of the rotor. A stall occurs when a rotor blade stops giving lift; the blade is hit at an angle of attack which is too steep. Therefore, the rotor blade has to be twisted so as to achieve an optimal angle of attack throughout the length of the blade. It is important that the blade is built so that it will stall gradually from the blade root and outwards at high wind speeds [30].

The blade lift is perpendicular to the direction of the wind. The lift pulls the blade in the direction required and it also bends the rotor blade somewhat. Wind turbine rotor blades look a lot like the wings of an aircraft. Rotor blade designers often use classical aircraft wing profiles as cross sections in the outermost part of the blade.

The thick profiles in the innermost part of the blade, however, are usually designed specifically for wind turbines. Choosing profiles for rotor blades involves a number of compromises including reliable lift, stall characteristics and the profile's ability to perform well even if there is some dirt on the surface [30].

Fig. 2.3: A 40-meter wind turbine blade (photo taken by C. Bugg)

2. Wind Turbine Tower

Made from tubular steel, the wind turbine tower supports the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. The tower supports the nacelle and the rotor. Most large wind turbines with tubular towers are delivered in sections of 20 – 30 meters, with flanges at both ends, and bolted together on site [3].

The towers are conical, with their diameter increasing towards the base, in order to increase their strength and to save materials at the same time. Tower height is a major factor in production capacity. The higher the turbine, the more energy it can capture because wind speeds increase with elevation increase; ground friction and ground-level objects interrupt the flow of the wind. Scientists estimate a 12 percent increase in wind speed with each doubling of elevation [37].

The price of a tower for a wind turbine is generally around 20 per cent of the total price of the turbine. For a tower around 50 meters in height, the additional cost of another 10 meters of tower is about $15,000. It is therefore quite important for the final cost of energy to build towers as optimally as possible [3]. A 1.5 MW wind turbine of a type frequently seen in the United States has a tower 80 meters (260 ft.) high [38].

3. Wind Turbine Nacelle

The nacelle is a cover-housing that houses all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly.

A notable feature now found on some off-shore wind turbines is a large sturdy helicopter-hoisting platform built on top of the nacelle, capable of supporting service personnel and their tools, winched down to the platform from a helicopter hovering above it. Wind turbine rotors are stopped, feathered and locked before personnel are dropped down to or picked up from the platforms. [33] .

The nacelle may look impressive from a distance, installed on top of its tall steel tower. Up close, the nacelle is massive, stretching to over 50-ft long and weighing up to 300 tons and more, depending on the manufacturer and power rating.

Nacelles have common components, such as a hub, rotor, gearbox, generator, inverters, hydraulics, and bearings. More than 1,500 small and large components and subsystems are housed in the nacelle. [34].

4. Wind Turbine Hub

The hub consists of the hub housing and the blade pitch system. The blade mount of the hub housing is reinforced to enhance structural strength, thereby making the equipment lighter in terms of total weight. The pitch control mechanism is electrically driven to ensure accurate control; it features three-axis independent control [35]. The round base of the blade is bolted to the pitch mechanism, which adjusts their angle of attack according to the wind speed to control their rotational speed. The pitch mechanism is itself bolted to the hub. The hub is fixed to the rotor shaft which drives the generator directly or through a gearbox [36].

5. Wind Turbine Gearbox

The gearbox connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30-60 rpm to about 1,000-1,800 rpm; the rotational speed required by most generators to produce electricity. The gear box is a costly and heavy part of the wind turbine and engineers are exploring "direct-drive" generators that operate at lower rotational speeds and don't need gear boxes [36].

6. Wind Turbine Rotor

The wind-turbine rotor shaft is bolted to the center of the hub. When the blades and hub spin, the rotor transfers its mechanical-rotational energy to the gearbox coupling. The rotor is machined from an alloy steel forging.

7. Wind Turbine Generator

A wind turbine generator can be either an induction machine or a synchronous machine. It uses the properties of electromagnetic induction to produce AC electrical current. The generator consists of a stator (armature) and a rotor (field). A generator with a permanent magnet rotor is sometimes used. In electromagnetic induction, the rotor spins, rotating relative to the stator. This relative movement induces voltage in the stator conductors. With torque applied to the rotor and if current flows from the stator conductors, there is an induced voltage created that opposes the stator current. Large wind turbines generate three phase voltage and currents.

8. Wind Turbine Controls

- Rotor Brake - the most commonly activated safety system in a turbine is the braking system, which is triggered by above-threshold wind speeds.

Large wind turbines use a power-control system that applies the brakes when wind speeds get too high and then release the brakes when the wind speed decreases to below the wind turbine cut-out speed. There are several types of brakes used in large wind turbines [37].

- Yaw control – For assuring that maximum power is generated, the wind turbine must point directly upwind; the wind must be blowing through the blades perpendicularly. The turbine's electronic controller monitors the angle of the wind vane; if the angle is either positive or negative, then the yaw motor is energized to return the wind vane angle to zero.
- Pitch control - The turbine's electronic controller monitors the turbine's power output. At wind speeds over the rated speed, the power output would be too high, at which point the controller commands the blades to alter their pitch so that they become unaligned with the wind. This slows the blades' rotation. Pitch-controlled systems require the blades' mounting angle (on the rotor) to be adjustable [37].
- The electronic controller contains a computer which continuously monitors the condition of the wind turbine and controls the mechanical mechanisms. In case of any malfunction, (i.e. overheating of the gearbox or the generator), it automatically stops the wind turbine and notifies the turbine operator via a wireless internet connection [3].

2.3 Wind Speeds

What is the wind class of a wind turbine? According to *Renewables First*, some sites are windier than others. A lowland site in the middle of southern England might have an average wind speed of 6 m/s, whereas an exposed site on the top of a hill on the west coast of Wales or Scotland might have an average wind speed of 9 m/s. Because the “power in the wind” is proportional to the cube of the velocity, this means that the wind turbine on the 9 m/s site would on average be exposed to well over three-times the loads compared to the 6 m/s site.

Clearly this means that the more exposed wind turbine will have a tougher life and will be subjected to greater wear and tear. To avoid having to make over-engineered wind turbines that could all operate reliably on all sites, no matter how windy they were, manufacturers design their wind turbines for a specific wind class [41].

There are 3 steady wind speeds of importance:

The cut-in speed is the wind speed at which the brake releases and the WT blades begin to rotate. At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the cut-in speed and is typically between 3 and 4 meters per second [3].

The rotor speed is controlled by the pitch of the WT blades. The pitch motor turns the blades to the maximum power angle to accelerate the rotor between cut-in speed and rated speed. Once rated speed is obtained, the blade angle is continuously adjusted by the pitch motor to maintain a constant output power, the rated power.

The rated output speed is the wind speed at which the WT blades rotate to produce rated output power. As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly. However, typically between 12 and 17 meters per second, the power output reaches the limit of the generator power capacity. This limit to the generator output is called the rated power output and this wind speed is called the rated output wind speed. At higher wind speeds, the turbine controls will adjust the blade pitch angles to keep the power at a constant level [3].

The cut-out speed is the wind speed that is too high for safe operation of the WT. Above this speed, the blades are completely feathered and the brake is applied. As the wind speed increases above the cut-out wind speed, the forces on the turbine structure continue to rise and there is a risk of damage to the rotor. The cut-out speed is usually around 25 meters per second [3].

A quantitative measure of wind energy available at any location is called the Wind Power Density (WPD). It is a calculation of the mean annual power available per square meter of swept area of a turbine and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Color-coded maps are prepared for a particular area described, for example, as "Mean Annual Power Density at 50 Meters". In the United States, the results of the above calculation are included in an index developed by the National Renewable Energy Laboratory and referred to as "NREL CLASS". The larger the WPD, the higher it is rated by class. Classes range from Class 1 (200 watts per square meter or less at 50 m altitude) to Class 7 (800 to 2000 watts per square m). Wind turbines generally are sited in Class 3 or higher areas, although isolated points in an otherwise Class 1 area may be practical to exploit.

There is also a second dimension that affects wind class; turbulence intensity, which is a measure of how turbulent the wind is at a site. This is important because complex topography can cause turbulence. Turbulence can cause varying loads on wind turbines which causes them to wear more quickly. In extreme cases, if a site is just too turbulent, the wind turbine manufacturer will refuse to supply a wind turbine because they will know that the turbine will not operate reliably for the full design life at such a site.

Wind turbines are classified by the wind speed they are designed for, from class I to class IV, with A or B referring to the turbulence [38].

Table 3.1: Wind Speed Classes

IA	10m/s	18% turbulence
IB	10m/s	16% turbulence
IIA	8.5m/s	18% turbulence
IIB	8.5m/s	16% turbulence
IIIA	7.5m/s	18% turbulence
IIIB	7.5m/s	16% turbulence
IVA	6m/s	18% turbulence
IVA	6m/s	18% turbulence
IVB	6m/s	16% turbulence

Data provided by the Power and Energy Institute of the University of Kentucky indicates that:

~12% of the time – wind is less than cut-in speed ~5m/s

~58% of the time – wind is less than full power ~12 to 14m/s

~42% of the time – wind is at or above rated power [22]

2.4 Capacity Factor

The capacity factor (CP) of a wind turbine is the ratio of actual power generated to the maximum power it could generate over a period of time. Wind affects CP, depending on location. Consistently windy locations will have a higher CP [15]. Even when turbines are generating power, they may be operating at less than full power. Typical CPs of wind turbines are 20% - 40%, with ~25% the actual average. European averages are 24% for onshore and 41% for offshore (2012 data) [22].

According to Wind-Works.org by Paul Gipe, Annual Energy Production (AEP) is the annual energy, in kWh or MWh, produced by a wind turbine in one year. CP affects AEP [40].

2.5 Wind Farms

As in most other areas of power production, when it comes to capturing energy from the wind, efficiency comes in large numbers. Groups of large turbines, called wind farms or wind plants, are the most cost-efficient use of wind-energy capacity. The most common utility-scale wind turbines have power capacities between 700 KW and 1.8 MW and they're grouped together to get the most electricity out of the wind resources available. They are typically spaced far apart in rural areas with high wind speeds, and the small footprint of HAWTs means that agricultural use of the land in nearly unaffected. Wind farms have capacities ranging anywhere from a few MW to hundreds of MW.

The cost of utility-scale wind power has come down dramatically in the last two decades due to technological and design advancements in turbine production and installation. In the early 1980s, wind power cost about 30 cents per kWh. In 2006, wind power costs as little as 3 to 5 cents per kWh where wind is especially abundant. The higher the wind speed over time in a given turbine area, the lower the cost of the electricity that turbine produces. On average, the cost of wind power is about 4 to 10 cents per kWh in the United States [37].

2.6 Advantages and Disadvantages of Wind Power

Advantages - Wind turbines are generally inexpensive. They will cost between two and six cents per kilowatt hour, which is one of the lowest-priced renewable energy sources in today's world. And as technology needed for wind turbines continues to improve, the prices will decrease as well. In addition, there is no competitive market for wind energy, as it does not cost money to capture the wind. The main cost of wind turbines is the installation process. The average cost is between $48,000 and $65,000 to install a wind turbine. However, the energy harvested from the turbine will offset the installation cost, as well as provide virtually free energy for years after. Wind turbines provide a clean energy source, emitting no greenhouse gases and no waste product. Over 1,500 tons of carbon dioxide per year can be eliminated by using a one megawatt turbine instead of one megawatt of energy from a fossil fuel. Being environmentally friendly and green is a large advantage of wind turbines.

Wind turbines are also quite efficient. Wind farms can generate between 17 and 39 times as much power as they consume, and in the United States alone, wind turbines have produced about 16 billion kilowatt-hours of energy per year.

Disadvantages - Wind turbines can be very large, reaching over 400 feet tall and with blades 50 yards long; people have often complained about their visual impact. Their size can also make them harmful to surrounding wildlife. Thousands of birds, including rare species, have been killed by the blades of wind turbines.

Energy harnessed by wind turbines can be unreliable at times. Wind is often not available when needed, as wind can fluctuate. Turbines can be placed on ridges or bluffs to maximize the access to wind, but this also limits the locations where they can be placed. In this way, wind energy is not a particularly reliable source of energy [38].

2.7 Off-Shore Wind Turbines

Off-shore wind turbines operate in winds that are more consistent and powerful and typically have a higher rated power and a higher CP compared to on-shore locations. The USDOE states that there is enough offshore wind energy potential to meet 4 X the US's current generating capacity [22].

Off-shore winds are caused by solar heating, which during the day, create high pressure cooler air off-shore and low pressure warmer air on-shore. This causes consistent wind to blow from over the ocean to the shore. During the night, the opposite conditions cause consistent wind to blow from over the shore to over the ocean. Wind higher off the surface is a more consistent and powerful wind [22]. Off-shore wind turbines can capture this wind, both day and night, and convert the kinetic energy of the wind into mechanical power which is then converted to electric power. Off-shore wind turbines must be rugged and reliable in harsh conditions [11].

However, there are issues affecting the growth of off-shore wind energy. Part of the delay in tapping the offshore wind resources in the US has been due to the technical challenges installing WTs offshore in different depths of water, and then linking them to provide power to land. However, these challenges can be overcome, as they have been in much of Europe, but they do make offshore more expensive. Almost all offshore areas average over 7 m/s vs only a few select spots in onshore areas [11].

2.8 The Direct Drive Wind Turbine

The Wind Turbine diagram depicts the turbine blades (WT) connected to the main shaft. When the wind causes the blades to rotate, the shaft develops torque which rotates the rotor in the Three Phase Synchronous Machine (3ΦSM).

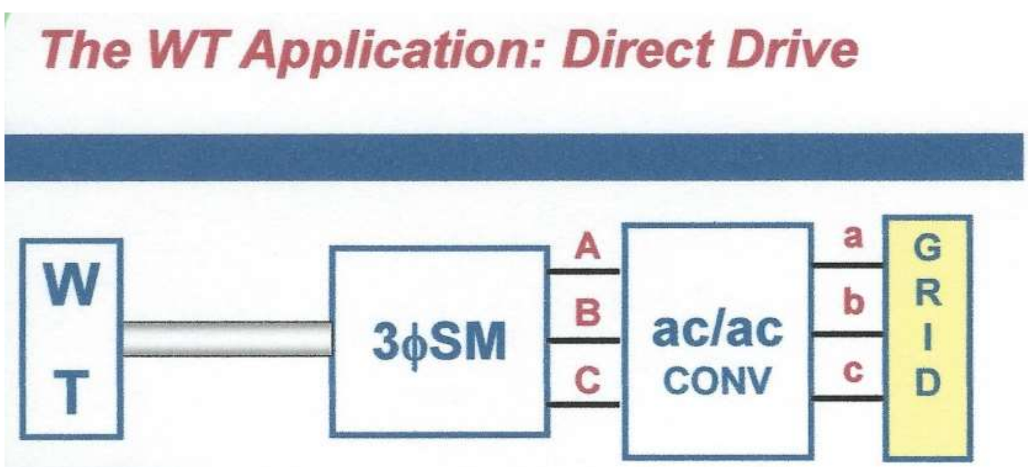


Fig. 2.4: Direct Drive Wind Turbine [10]

The 3ΦSM output is a variable frequency, 3Φ AC current, which must be converted by the ac/ac converter, to a 60Hz 3Φ AC Voltage that matches the requirement of the electrical grid. Usually, this involves the use of a HV step-up transformer to match the grid transmission voltage.

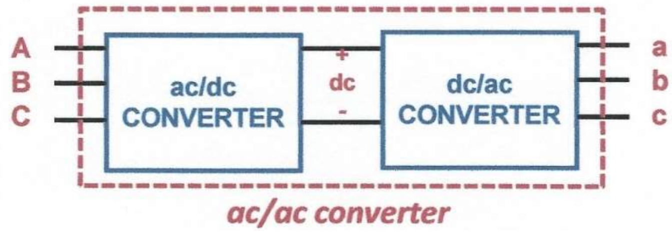


Fig. 2.5: The AC to AC Converter [10]

2.9 The Direct Drive Permanent Magnet Generator (PMG)

The Direct Drive PMG is a synchronous machine. Among wind turbines, the most common type of PM machine is the Radial flux permanent magnet machine with surface mounted magnets (RFPM). The RFPM, where the rotor spins on the outside of the stator is called the inverted rotor [8].

Since it does not have rotor windings, the RFPM has a higher efficiency than an induction machine and it also has higher torque and power density [6]. The PMG has several advantages over the conventional excited synchronous generator. The PMG is small and light. In large MW wind turbine applications, they are preferred [8].

The only electrical data needed to analyze this machine are [11]:

- The real and reactive power output
- The terminal currents
- The maximum power capability

The frequency of the stator voltages depends only on the number of poles and the speed of the rotor.

$$\omega = 2\pi f \quad \text{or} \quad f = \omega / 2\pi \qquad (2.4)$$

and

$$f = (P/2)(n/60) \quad \text{or} \quad n = 120 f / P \qquad (2.5)$$

or

$$f = (P/4)(\omega/\pi) \qquad (2.6)$$

where P = # of poles, f = frequency of stator currents (Hz) and

ω = rotor speed (r/s)

also,

$$n = 30\,\omega / \pi \qquad (2.7)$$

where n = rotor speed in rpm.

The stator voltage magnitude depends on the rate of change of the flux linking the stator windings which is related to the rotor speed, the strength of the rotor field (which is constant for a PMG) and the number of stator turns (which is fixed). **So, the important concept is that the stator voltage depends only on the rotor speed.**

The rotating field induces "internal" voltages in the stator ($Ea/\_\delta$). Because the stator windings are connected to a load, currents will flow. These currents produce a 2nd field which opposes the motion of the rotor. Torque from the WT is required to overcome this opposition and turn the rotor at speed n. These stator currents flow through the highly inductive stator windings, causing a voltage drop in the stator [11].

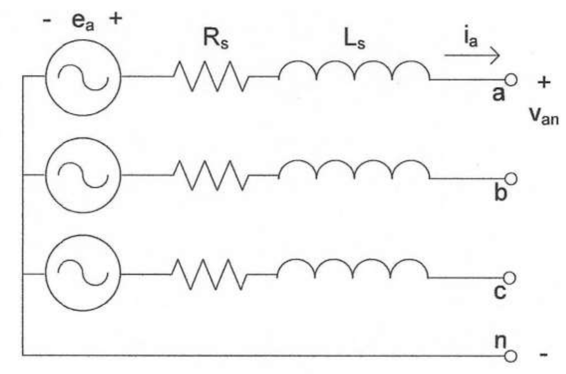


Fig. 2.6: Circuit Diagram for a Synchronous Machine [11]

Equations for this circuit:

Stator resistance:

$$R_s$$

Stator reactance:

$$X_s = 2\pi f L_s \qquad (2.8)$$

Induced stator voltage:

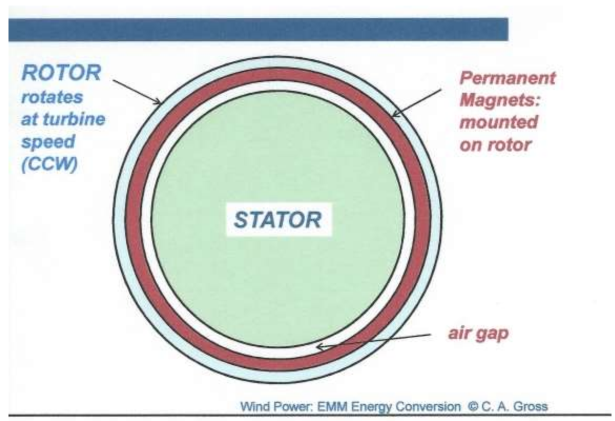
$$\mathbf{Ea}/\_\delta = i_a (R_s + jX_s) + v_{an}/\_\theta \qquad (2.9)$$

Stator winding losses:

$$SWL = 3 R_s I_a^2 \qquad (2.10)$$

The wind turbine rotor, in this example, rotates outside of the stator. This rotor permanent magnet configuration is called a Radial Flux Permanent Magnet Machine (RFPM).

Fig. 2.7: PMG Rotor & Stator [10]



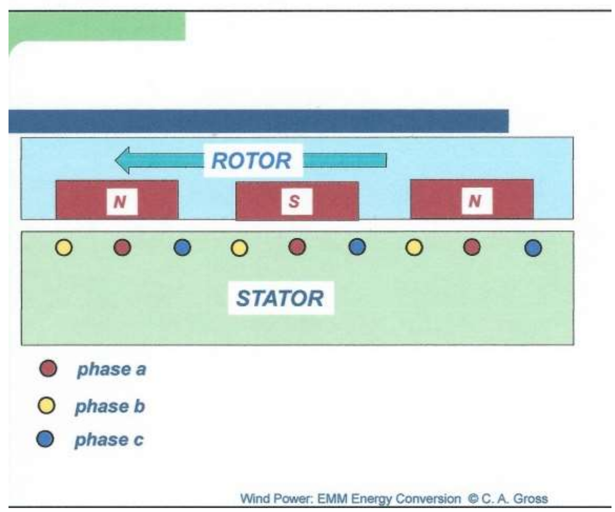


Fig 2.8: PMG Rotor & Stator (planar view) [10]

3. Specifying the Target Wind Turbine Model

To begin the Wind Turbine analytic study and research, specifications for the target model are chosen. The model will be an off-shore WT with a rating of 3MW. The model is a Radial Flux PMG (RFPM) with a large diameter 72 pole rotor, containing the permanent magnets, spinning around the 3 phase stator. The generator output is the input to an AC to AC converter. The rated converter output is 3-phase, 60Hz, 13.8kV, 126A, which is routed via submarine cable to an on-shore sub-station, where there is a connection to the power grid.

Wind specifications are 14m/s rated and 25m/s cut-out. These wind speeds correspond to WT speeds of 12rpm rated and 18rpm cut-out. At 12rpm, the generator produces 9.2kV and 188A at 7.2Hz. At 18rpm, the generator produces 13.8kV and 126A at 10.8Hz [10].

3.1 The Target Wind Turbine RFPM

A Matlab scripts yields the following data:

DIRECT DRIVE, SYNCHRONOUS GENERATOR
72 POLE, 3000kW, RFPM
AT RATED SPEED:

WIND SPEEDS AND TURBINE SPEEDS

srated = 14m/s

ωrated = 12rpm

CALCULATE WIND POWER PASSING THRU A CIRCLE with AREA = BLADE SWEPT AREA

T = 15degC

$\rho = -(0.00425T) + 1.2922 kg/m^3 = 1.225 kg/m^3$

L = 40m blade length

v = 14m/s wind speed

$A = \pi * L^2 = 5026.5 m^2$

WIND POWER IN MW

Pwind = $(\rho * A * v^3)/2$ = 8.445MW

EFFICIENCY

η = .355 = 35.5%

TURBINE POWER IN MW

Pt = η*Pwind = 3.00MW

ROTOR SPEED in rpm

n = 12rpm

CALCULATE ROTOR SPEED in r/s

ωr = n*pi/30 = 1.2566r/s

TURBINE TORQUE in kNm

Tt = (Pt/ωr)/1000 = 2386.6kNm

GENERATOR TORQUE IN kNm

Tg = Tt = 2386.6kNm

GENERATOR POWER in MW

P2 = Tg*ωr/10^3 = 3.00MW

CALCULATE FREQUENCY of STATOR VOLTAGES

P = 72 no. of poles

f = (n/60)*(P/2) = 7.20Hz

CALCULATE VOLTAGES

V_{LL} = 9.200kV RMS

V_{LN} = V_{LL}/sqrt(3) = 5.312kV

V_{LN} pk = V_{LN}*sqrt(2) = 7.512kV

CALCULATE CURRENTS

Ia = Pt*sqrt(3)/(3*V) = 188.21A RMS

Ipk = Ia*sqrt(2) = 266.17A

DIRECT DRIVE, SYNCHRONOUS GENERATOR
72 POLE, 3000kW, RFPM
AT CUT-OUT SPEED:

WIND SPEEDS AND TURBINE SPEEDS

scut = 25m/s

ωcut = 18rpm

CALCULATE WIND POWER PASSING THRU A CIRCLE with AREA = BLADE SWEPT AREA

T = 15degC

$\rho = -(0.00425T) + 1.2922 kg/m^3 = 1.225 kg/m^3$

L = 40m blade length

v = 25m/s wind speed

$A = \pi * L^2 = 5026.5 m^2$

WIND POWER IN MW

$Pwind = (\rho * A * v^3)/2 = 48.11 MW$

EFFICIENCY

η = .06236 = 6.24%

TURBINE POWER IN MW

Pt = η*Pwind = 3.00MW

ROTOR SPEED in rpm

n = 18rpm

CALCULATE ROTOR SPEED in r/s

wr = n*pi/30 = 1.885r/s

TURBINE TORQUE in kNm

Tt = (Pt/wr)/1000 = 1590.9kNm

GENERATOR TORQUE IN kNm

Tg = Tt = 1590.9kNm

GENERATOR POWER in MW

P2 = Tg*wr/10^3 = 3.00MW

CALCULATE FREQUENCY of STATOR VOLTAGES

P = 72 no. of poles

f = (n/60)*(P/2) = 10.8Hz

CALCULATE VOLTAGES

V_{LL} = 13.800kV RMS

$V_{LN} = V_{LL}$/sqrt(3) = 7.967kV

V_{LN} pk = V_{LN}*sqrt(2) = 11.267kV

CALCULATE CURRENTS

Ia = Pt*sqrt(3)/(3*VLL) = 126A RMS

Ipk = Ia*sqrt(2) = 177.426A

Table 3.1: The Wind Turbine PMG – Summary of Results

	Rated	Cut-out	
v	14	25	m/s
ω	12	18	rpm
T	15	15	degC
ρ	1.225	1.225	kg/m^3
A	5026.5	5026.5	m^2
Pw	8.45	48.11	MW
η	35.5	6.24	%
Pt	3	3	MW
n	12	18	rpm
ωr	1.257	1.885	r/s
Tt	663	1590.9	kN-m
fr	7.2	10.8	Hz
V_{LL}	9.2	13.8	kV RMS
V_{LN}	5.312	7.967	kV
V_{LN} pk	7.512	11.267	kV
Ia	188	126	A RMS
Ipk	266.17	177.43	A

3.2 The Target Wind Turbine Power Converter

A full power converter is required when using a PM Generator. A full power converter has a number of benefits over other generator types [5]. There are two power converter technologies that are commonly used with PMGs. Since a PMG does not need reactive power, a cost effective power converter is a diode rectifier with a DC boost converter and a 60Hz inverter [9]. These three units, the rectifier, the boost converter and the inverter make up the AC to AC power converter [8].

4.0 The Barrow Wind Farm

Located in the UK, this offshore wind farm is about 8 kilometers southwest from Barrow-in-Furness in the Irish Sea [1]. It consists of 30 Vestas V90-3MW wind turbines arranged in four rows with alternating 7 or 8 turbines per row [2]. With a hub height of 75m and rotor diameter 120m, these are large wind turbines [1].

The long-term mean wind speed at the site is 9.2 meters/second. The turbines suffered from significant reliability problems in the first two years of operation and, of the 720 monthly energy output figures, only 56 of the outputs arose from turbines that had 100% availability for the whole month. However, 351 of the monthly figures arose from turbines that had availability figures of 90% or more and the figure below shows a comparison between these monthly average power figures and the predictions of the *WindPower* program. The results show five monthly data points for mean wind speeds above 11 meters/s. The scatter on the data is such that there is no clear best fit against the wind speed standard deviation - although the wind speed data at mean wind speeds above 10 meters/second does seem to fit the 42% standard deviation curve better than the 52% and 62% curves [3].

The WindPower and UK Wind Speed Database will be utilized to provide statistical data for the target model. The UK Wind Speed Database presents the data from the UK Department of Energy and Climate Change in a user-friendly form. The data can be found at http://www.wind-power-program.com.

WindPower provides field data for large wind turbines obtained from reports on the performance of four UK offshore wind farms. It discusses the general performance of offshore wind farms based on a series of reports that are available from the Department for Energy and Climate Change [3].

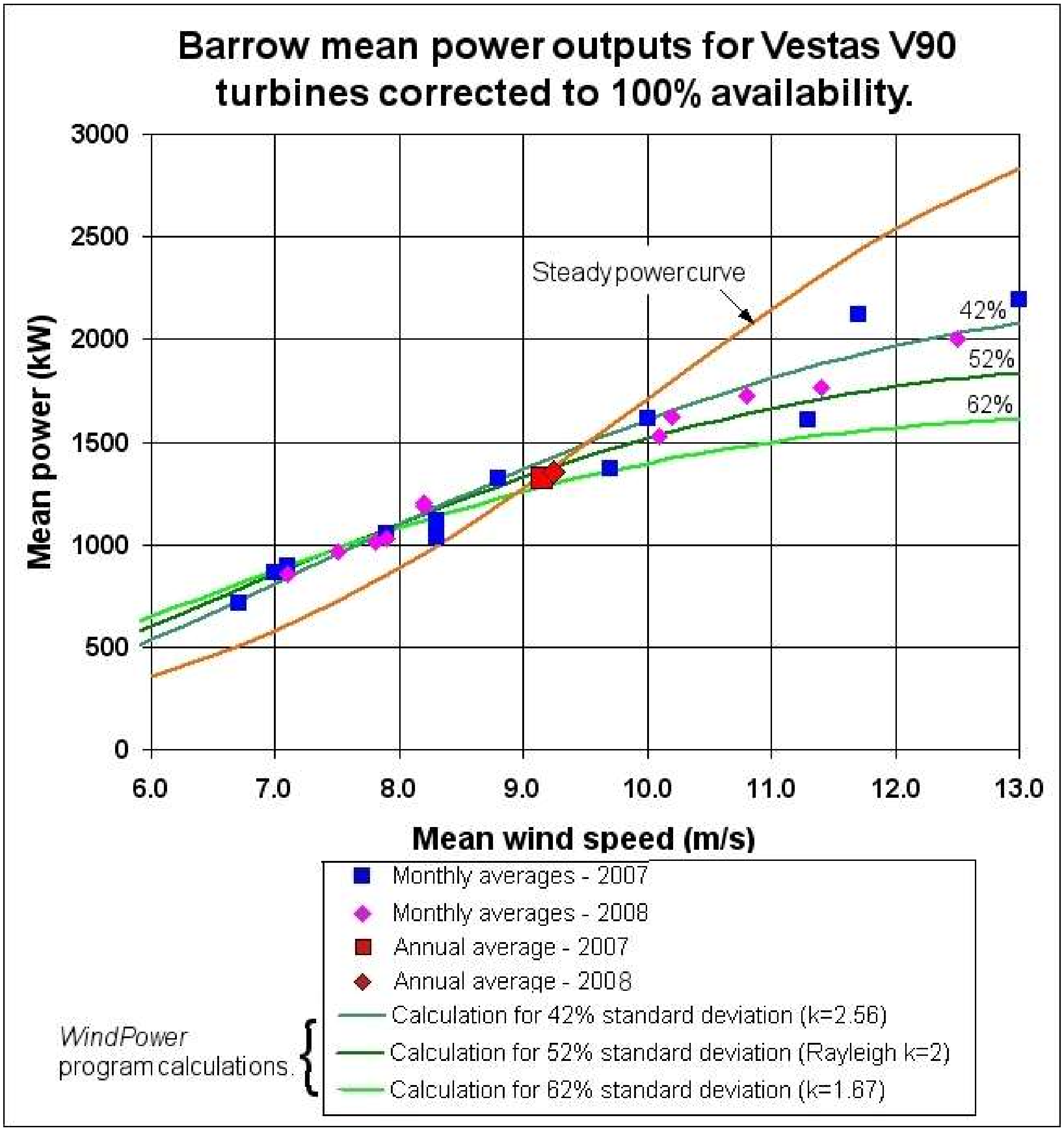


Fig. 4.1: Mean power vs Mean wind speed

Fig. 4.1, indicates the Mean Wind Speed = 9.3m/s.

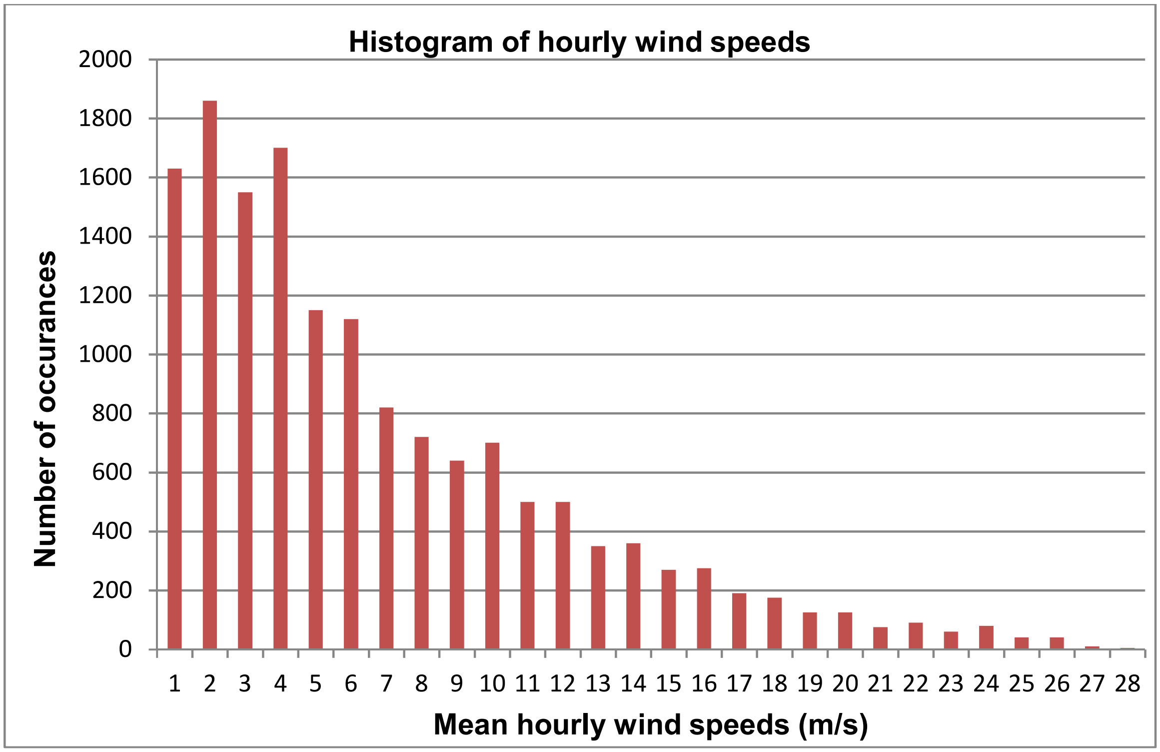


Fig. 4.2: Histogram of hourly wind speeds

5. Functions and Graphs for the Target Wind Turbine Model

Continuing the Wind Turbine analytic study and research, functions and graphs will be developed for the target model. Statistics developed from the Barrow Wind Farm will be used for the Target Wind Turbine Model.

5.1 The Wind Power

The formula given previously for determining wind power is:

$$P_{wind} = (½)\rho A v^3 \qquad (2.3)$$

where

$$\rho = \text{air density} = - (0.00425T) + 1.2922 \text{ kg/m}^3 \qquad (2.1)$$

T = temperature in degC and v = wind speed (m/s).

The cross section area swept by rotor in m^2

$$A = \pi L^2 \qquad (2.2)$$

L = length of rotor blade in meters (includes ½ of nose cone diameter)

In summary, Power in the Wind = (Dynamic pressure) x (Area) x $(\text{Wind speed})^3$ expressed in kW or MW.

Using these formulas, the power in the wind vs wind speed is calculated (at 15degC) and plotted on the graph in Fig. 5.1. Note the maximum wind power at a wind speed of 25m/s is 48MW. (wind speeds of 3.5m/s to 25m/s)

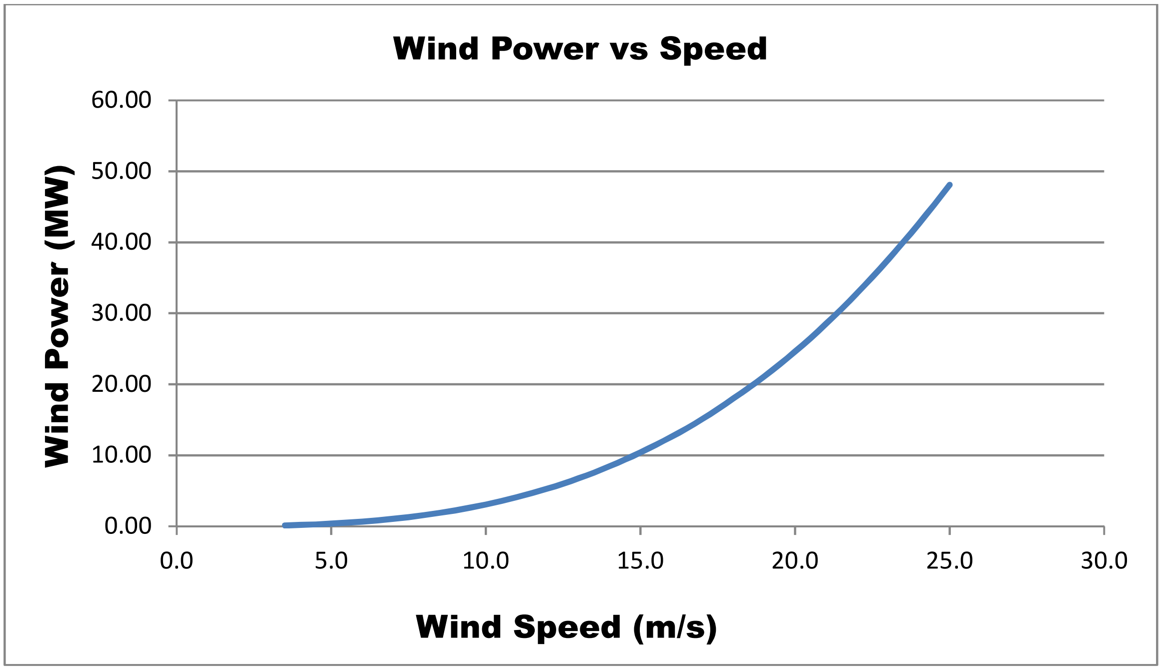


Fig. 5.1: Wind Power vs Wind Speed

Using formula (2.1), the air density vs air temperature is calculated and plotted on the graph in Fig. 5.2. (for air temperatures of -25degC to 35degC)

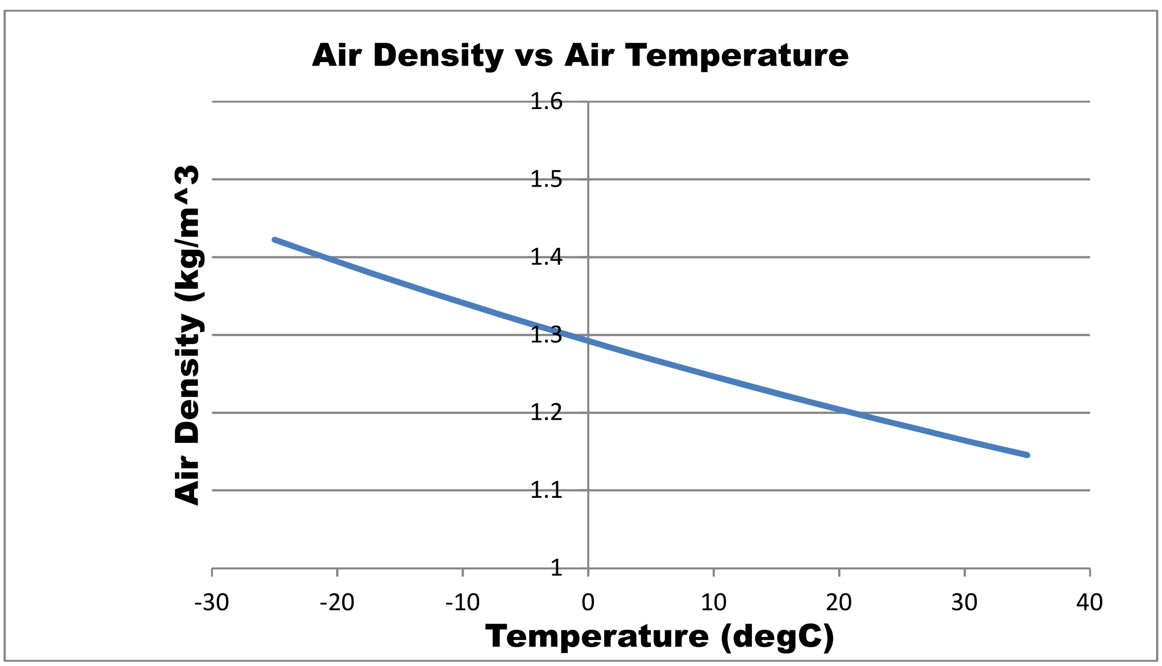


Fig. 5.2: Air Density vs Air Temperature

For wind temperatures of -25degC to +35degC, at a wind speed of 14m/s, the wind power vs temperature is calculated and plotted on the graph in Fig. 5.3.

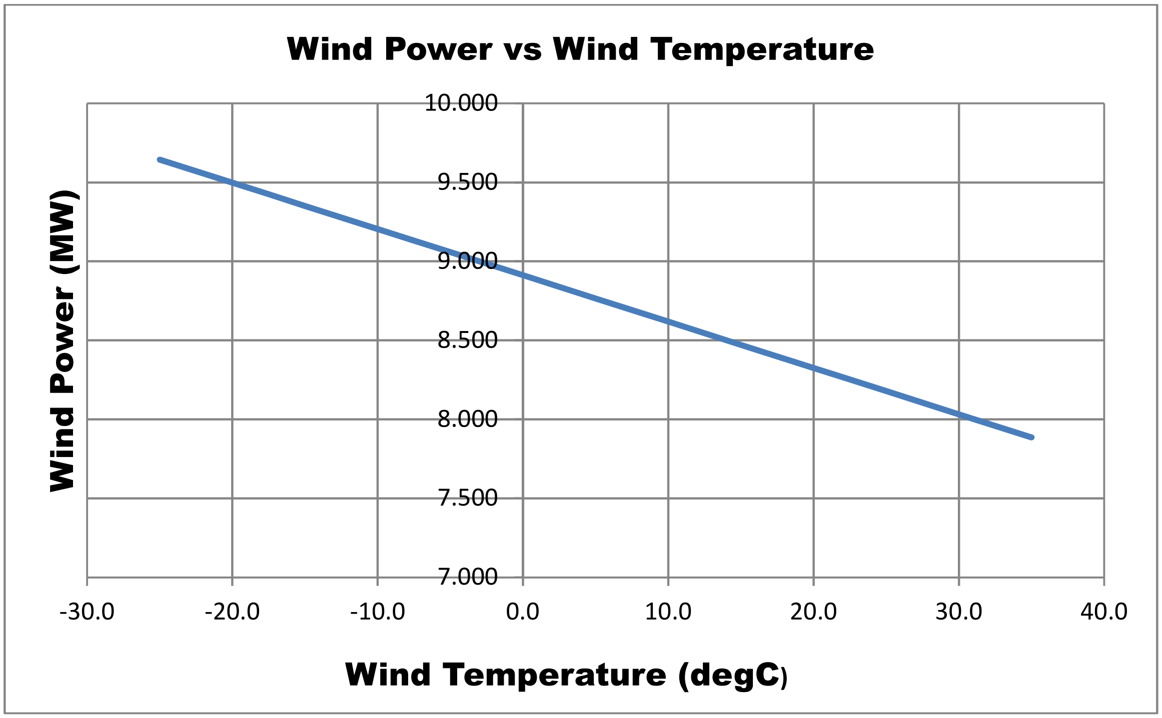


Fig. 5.3: Wind Power vs Wind Temperature

Fig. 5.1 shows that the wind power increases as a 3rd order polynomial function of wind speed. This is an incentive for off-shore wind farms due to the stronger and consistent off-shore winds.

Because the wind density decreases linearly vs the wind temperature, wind power also decreases linearly vs wind temperature. This increases the wind power available when the temperature drops, i.e. during the night. A wind power of 8.5MW at 15degC will increase 12%, to 9.5MW at -20 degC. However, during the warmer months, a wind power of 10MW at 10degC at night will decrease 15%, to 8.2MW at a daytime high of 25 degC.

5.2 The Wind Turbine Power

Using the Matlab script from 3.1, the wind turbine power vs steady wind speed is calculated and plotted on the graph in Fig. 5.4. (for steady wind speeds of 3.5m/s to 25m/s)

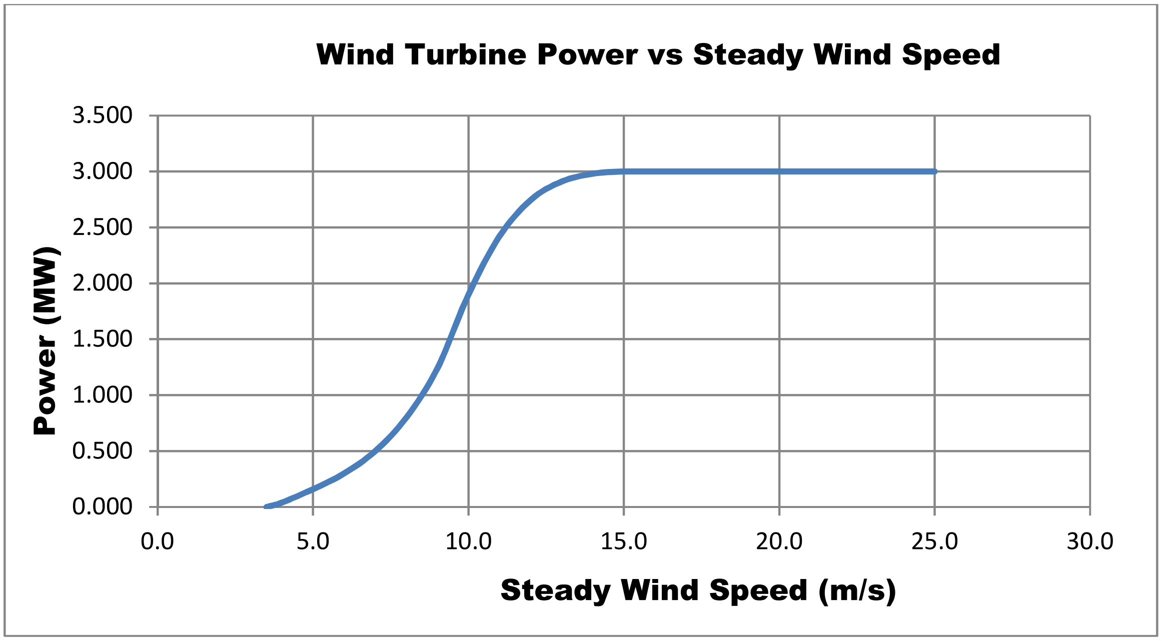


Fig. 5.4: Wind Turbine Power Output with Steady Wind Speed

The specifications for the target WT cut-in wind speed is 3.5m/s, the rated output wind speed is 14m/s and the cut-out wind speed is 25m/s.

The formula for Percent Rated Power vs Wind Speed (for wind speeds of 4 to 14m/s:

$$PP = 46.25 - 24.19v + 3.711v^2 - 0.1218v^3 \qquad (5.1)$$

where v = wind speed in m/s and PP = percent of rated power [3]. This formula is a 3rd order polynomial curve fit to the calculated data.

Recalling equation (2.6);

$$f = (P/4)(\omega/\pi) = (18/\pi)\omega \qquad (2.6)$$

the frequency of stator voltages depends only on the Rotor Speed. For the full range of Rotor Speeds, expressed as Stator Frequencies, the WT Power is calculated and plotted on the graph in Fig. 5.5.

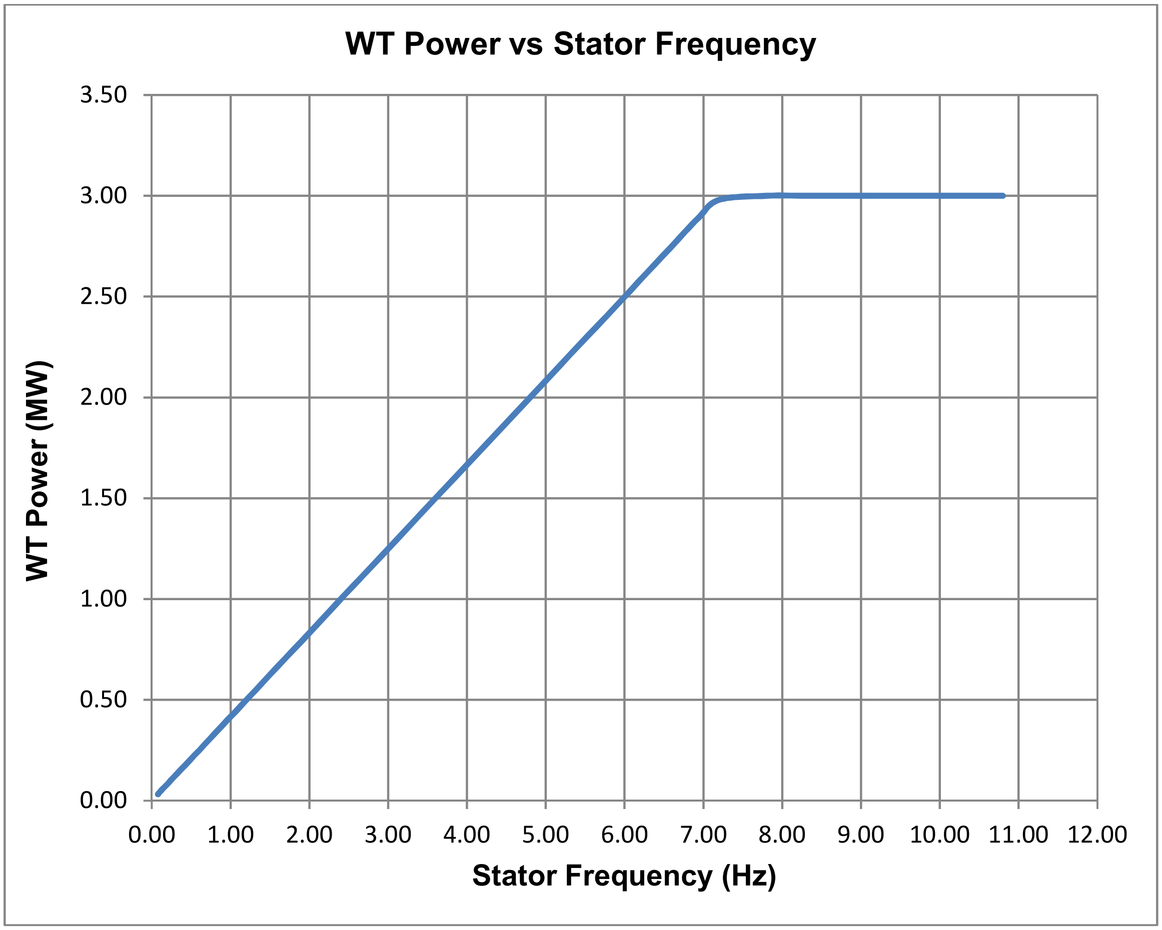


Fig. 5.5: Wind Turbine Power vs Stator Frequency

For a steady wind speed of 14m/s, the wind turbine power vs wind temperature is calculated and plotted on the graph in Fig. 5.6.

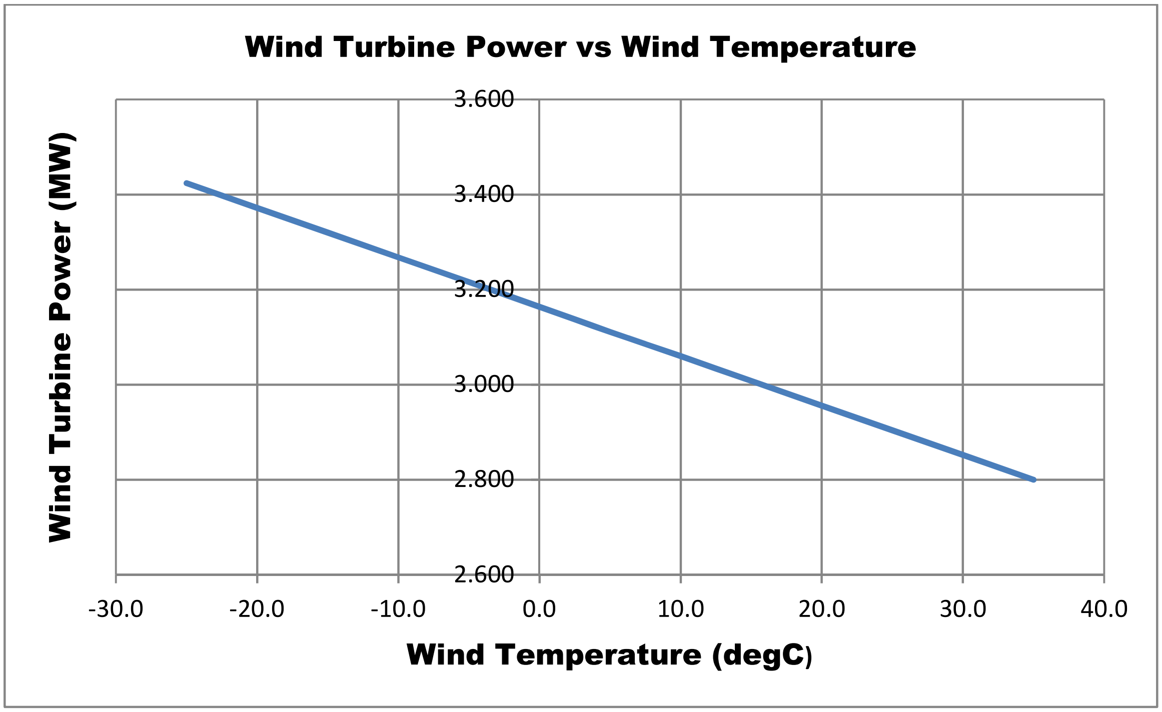


Fig. 5.6: Wind Turbine Power vs Wind Temperature

This graph similarly shows the Target Wind Turbine Power also decreases linearly vs increasing wind temperature and increases with decreasing wind temperature.

5.3 The Wind Turbine Voltage, Current and Stator Frequency

For the Target Model, using

$$f = (P/2)(n/60) \qquad (2.5)$$

the stator frequency is

$$f = (3/5)n \qquad (5.2)$$

or

$$n = (5/3)f \qquad (5.3)$$

where n = rotor speed in rpm

From (3), the Target Model PMG produces rated power of 3.00MW, 9.2kV (V_{LL}) and 188A at 12rpm. Using equation (5.2), the rated stator frequency = 7.20Hz.

Recall from (2), the stator voltage depends only on the rotor speed (stator frequency).

Therefore, the relationship between stator voltage and frequency:

$$Kvf = 9.2/7.2 = 1.2778 kv/Hz \qquad (5.4)$$

Also,

$$V_{LN} = (1/\sqrt{3})\, V_{LL\text{-}RMS} \qquad (5.5)$$

And

$$V_{LN}\ pk = \sqrt{2}\, V_{LN\text{-}RMS} \qquad (5.6)$$

Since the power can be expressed as

$$P = 3\, V_{LN\text{-}RMS}\, I_{A\text{-}RMS} \qquad (5.7)$$

Then the current is

$$I_{A\text{-}RMS} = P / 3\, V_{LN\text{-}RMS} \qquad (5.8)$$

and

$$I_{PK} = I_{A\text{-}RMS}\sqrt{2} \qquad (5.9)$$

Using these equations in a Matlab Script, Table 5.1 is produced.

Table 5.1: Target PMG Power, Frequency, Voltage and Current

	EIGHTH POWER	**QUARTER POWER**	**HALF POWER**	**RATED POWER**	**CUT-OUT POWER**	
P	0.375	0.75	1.50	3.00	3.00	MW
n	1.5	3	6	12	18	rpm
f	0.9	1.8	3.6	7.2	10.8	Hz
V_{LL}	1.15	2.3	4.6	9.2	13.8	kV RMS
V_{LN}	0.664	1.328	2.656	5.312	7.967	kV RMS
V_{LN} pk	0.939	1.878	3.756	7.512	11.268	kV
Ia	188	188	188	188	126	A RMS
Ipk	266.25	266.25	266.25	266.25	178.19	A

5.4 The Mean Wind Speed

For steady wind speeds of 4m/s to 14m/s, the wind turbine speed vs wind speed is calculated and plotted on the graph in Fig. 5.7.

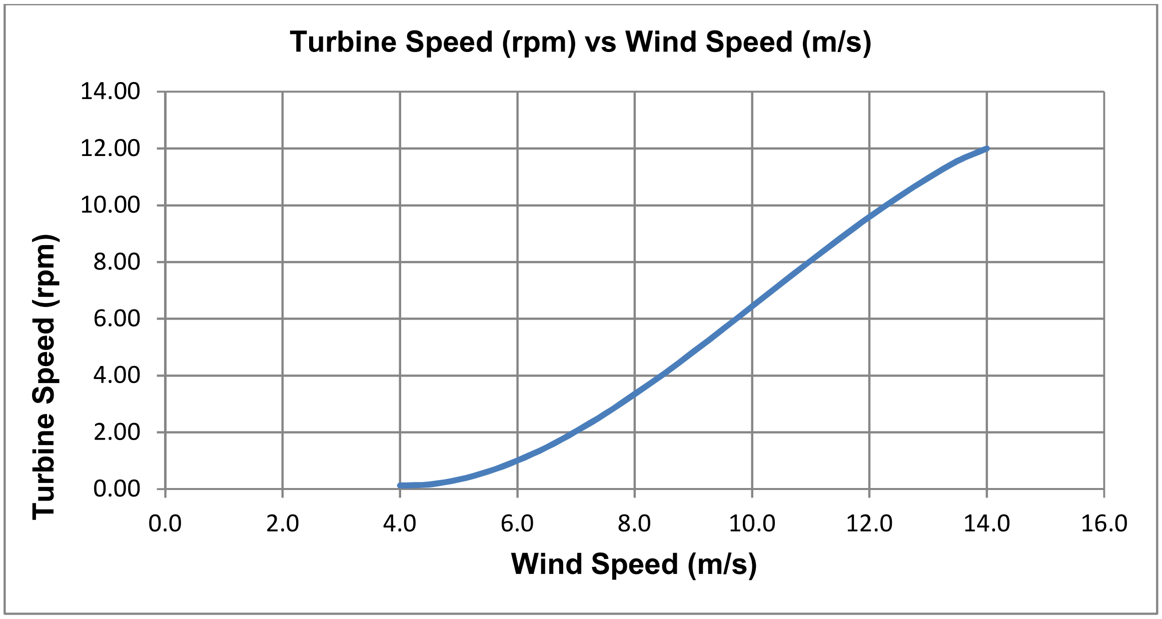


Fig. 5.7: Wind Turbine Speed vs Wind Speed (for speeds < rated)

Using the Barrow Wind Farm as a reference, the Target WT Mean Wind Speed = 9.3m/s.

5.5 The Mean WT Power, Capacity Factor and Annual Energy Production

A Matlab script calculates the mean turbine power, CP and AEP.

MEAN WIND SPEED

v = 9.3m/s

CALCULATE PERCENT WT POWER

PP = 46.25-(24.19*v)+(3.711*v^2)-(0.1218*v^3) = 44.28%   Using (5.1)

CALCULATE TURBINE POWER

Pt = 3*PP/100 = <u>1.328MW</u>   **Mean WT Power**

CALCULATE CP

Prated = 3.0MW

Erated = 365.25*24*Prated = 26,298MWh

Eactual = 365.25*24*Pt = 11,644MWh

CP = Eactual/Erated = 0.4428 = <u>44.3%</u> **Capacity Factor**

CALCULATE AEP

Eactual = <u>11,644MWh</u>   **Annual Energy Production**

5.6 The WT Model Equivalent Circuit

The rotating PM field induces voltages in the stator which are called "internal" voltages. Because the stator windings are terminated in a load (the electrical grid), there will be stator currents. These currents produce a 2nd field which opposes the rotor motion. Torque from the WT is required to overcome this opposition and turn the rotor. These stator currents flow through the predominately inductive stator windings, creating a voltage drop in the stator windings. The internal voltage is always greater than the terminal voltage [11].

Three quantities must be determined in order to describe the generator model [25]:

1. The relationship between field flux (Φ) and the internal generated voltage E_a

$$E_a = K\Phi\omega \qquad (5.10)$$

where KΦ is a constant related to the generator physical properties and ω is the rotor angular velocity in radians per second.

2. The synchronous reactance, X_S in ohms

3. The armature resistance, R_S in ohms

The equations which are used to calculate the induced armature (stator) voltage include [25]:

The armature reactance effect,

$$\mathbf{E_{STAT}} = -jXI_a \qquad (5.11)$$

where X is the armature reaction in ohms and $\mathbf{I_a}$ is the armature current in amps.

The armature self-inductance is L_a, in Henrys.

The reactance resulting from the self-inductance is X_S

$$X_S = 2\pi f L_a \qquad (5.12)$$

where f is the stator frequency in Hz.

The terminal voltage, VΦ

$$V\Phi = \mathbf{E_a} \angle \delta - jXI_a - jX_aI_a - R_aI_a \qquad (5.13)$$

and

$$X_S = X + X_a \qquad (5.14)$$

therefore

$$V\Phi = \mathbf{E_a} \angle \delta - I_a (R_a + jX_S) \qquad (5.15)$$

and

$$E_a \angle \delta = V\Phi + I_a (R_a + jX_S) \quad (5.16)$$

The frequency of stator voltages

$$f = = (n/60)*(P/2) \quad (5.17)$$

where n = rotor speed in rpm and P = number of rotor poles.

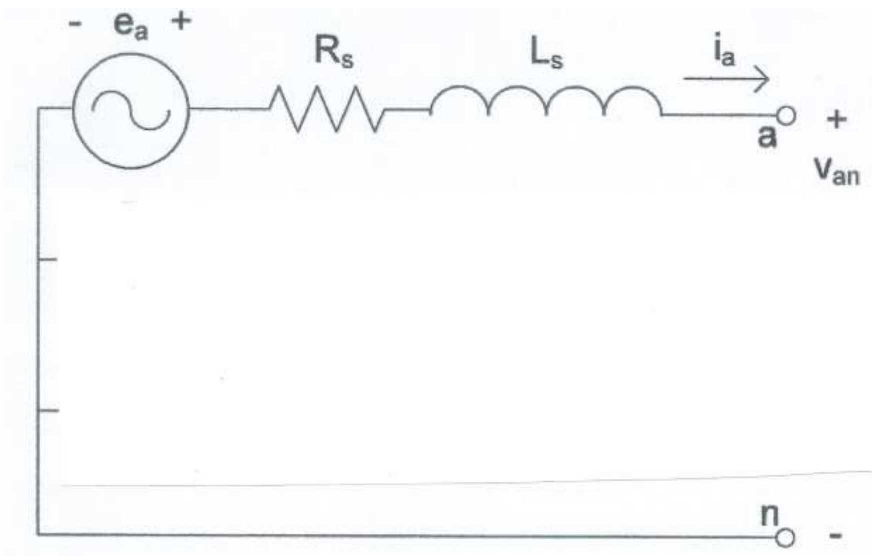


Fig. 5.8: The equivalent positive sequence circuit [11]

$\mathbf{V_{an}}$ = terminal volts @ /_0deg

$\mathbf{I_a}$ = terminal current in amps

R_S = stator winding resistance

L_S = stator winding inductance

$\mathbf{E_a}$ = induced stator voltage at an angle δ

5.6.1 WT Model Stator Quantities

Continuing the Wind Turbine analytic study and research, specifications for the target stator quantities are chosen.

L_S = 300mH and R_S = 100mΩ

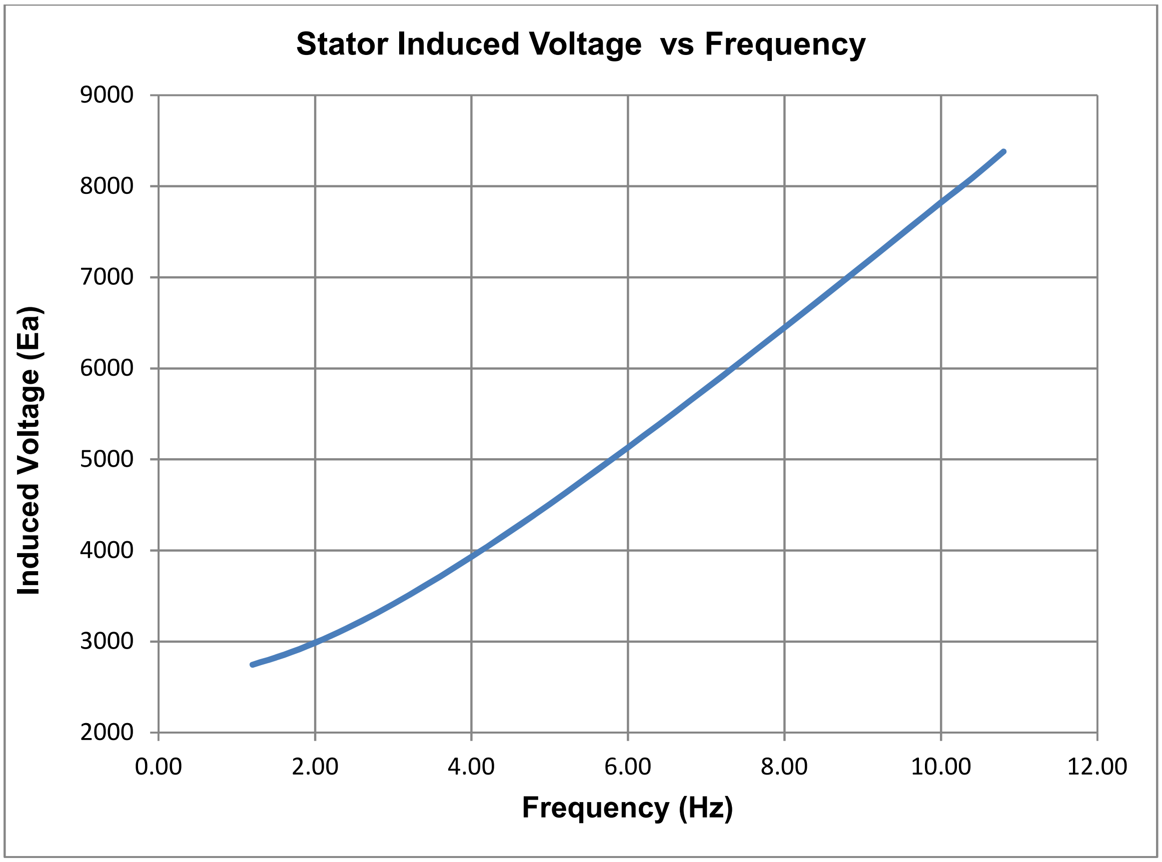


Fig. 5.9: The Stator Induced Voltage vs Stator Frequency

A Matlab script is used to calculate and plot the graph in Fig. 5.9 and Fig. 5.10.

The formula for E_a is a 3rd order polynomial curve fit to the plotted data:

$$E_a = -2.2558\ f^3 + 58.789\ f^2 + 177.6\ f + 2426.1 \quad (5.18)$$

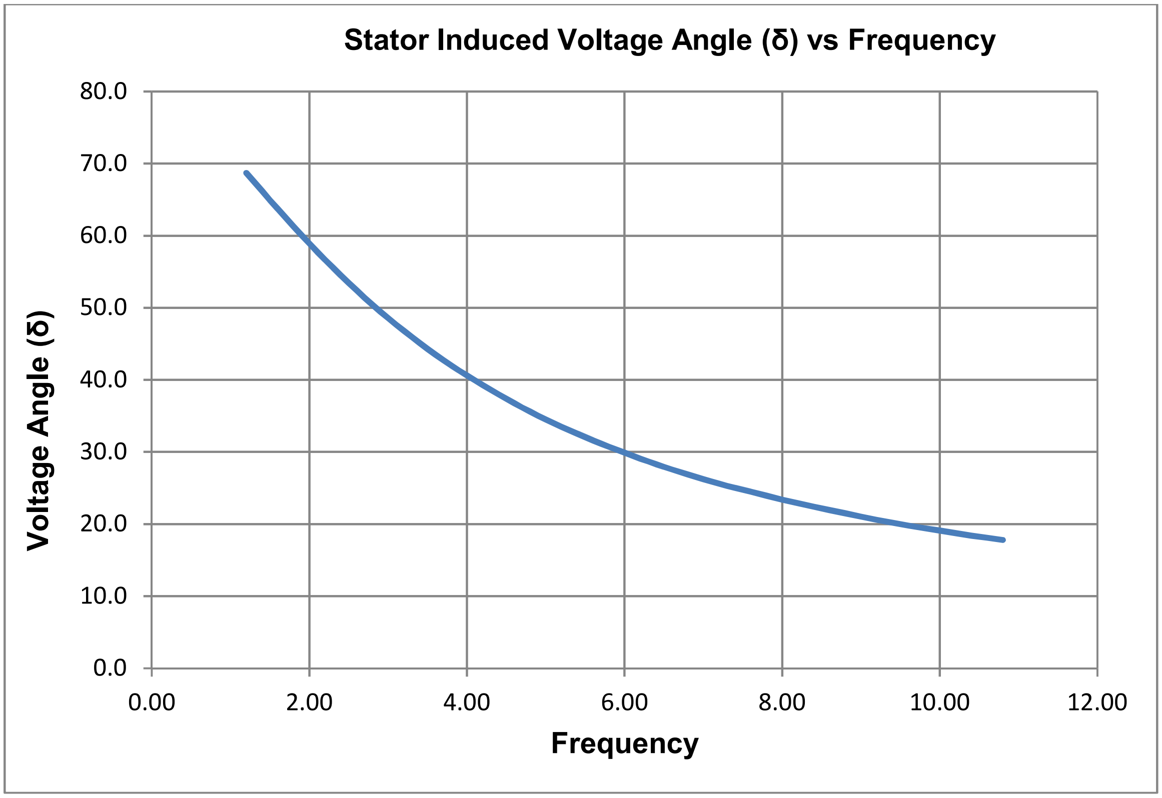


Fig. 5.10: The Stator Induced Voltage Angle vs Stator Frequency

The formula for δ_a is a 3rd order polynomial curve fit to the calculated data:

$$\delta_a = -0.0528\, f^3 + 1.5297\, f^2 - 16.771\, f + 86.683 \qquad (5.19)$$

Table 5.2: Stator Induced Voltage and Phase Angle vs Frequency (Hz)

STATOR FREQUENCY Hz	INDUCED VOLTAGE VOLTS	VOLTAGE ANGLE DEGREES
10.80	8380	17.8
10.40	8090	18.4
10.00	7821	19.1
9.60	7543	19.8
9.20	7267	20.6
8.80	6992	21.5
8.40	6719	22.4
8.00	6448	23.4
7.60	6179	24.5
7.20	5912	25.6
6.80	5649	26.9
6.40	5388	28.3
6.00	5132	29.9
5.60	4880	31.6
5.20	4632	33.5
4.80	4391	35.6
4.40	4157	38.0
4.00	3931	40.6
3.60	3715	43.5
3.20	3510	46.8
2.80	3318	50.4
2.40	3143	54.5
2.00	2987	58.9
1.60	2854	63.7
1.20	2746	68.7

5.6.2 WT Model OC Voltage and SC Current

A Matlab script calculates the OC voltage and SC current at rated speed:

CALCULATE OPEN CIRCUIT VOLTAGE

f = 7.2Hz

Ea = -2.2558*f^3+58.789*f^2+177.6*f+2427.6

Vt_{OC} = 5.912/_0kV

CALCULATE SHORT CIRCUIT CURRENT

f = 7.2Hz

Vt =0 SC

L = 300mH

Ra = 100mΩ

Xs = 2*pi*f*L = 13.57Ω

Ea = 5912*(cos(25.6)+jsin(25.6))

Ea = 5.912/_25.6kV

Ia_{SC} = Ea/(Ra+jXs) = 435.6/_-64A

5.6.3 WT Model Stator Winding Loss

A Matlab script calculates the SWL

CALCULATE STATOR WINDING LOSSES

AT RATED SPEED

f = 7.2Hz

Irated = 188A

Ra = 0.1Ω

P_{LOSS} = 3*(Ia^2)*Ra = 10.6kW

6. The Target Wind Turbine Power Converter

As stated in (3.2), a Full Power Converter is required for a synchronous PM Generator [5]. A PMG does not need reactive power [9], so for the target model, an AC to AC converter using a 3 phase diode rectifier with boost converter and PWM inverter will be used. This type of converter is [8]:

- cost effective
- more reliable than other converters
- commonly used today in large wind turbines

The diagram of Fig. 6.1 depicts the direct drive WT providing torque at a variable speed to the 3ΦPMG, whose 3Φ outputs are the inputs to the power converter. The 3Φ 60Hz outputs of the converter then provide power to the electrical grid.

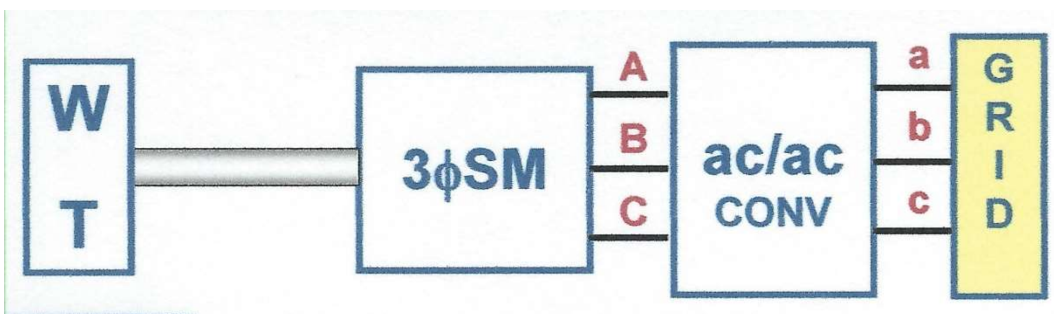


Fig 6.1: WT to Grid Diagram [10]

There are four major components needed to implement this design:

- 3Φ diode bridge rectifier
- DC boost converter
- 3Φ inverter
- control unit

6.1 WT PMG Power, Voltage, Current and Frequency

In Fig. 5.5: Wind Turbine Power vs Stator Frequency, the 3ΦPMG power was shown as a function of the stator frequency, or rotor speed, from cut-in speed up to rated speed. (Target Model; rotor speed = 5/3 of stator frequency.) Then from rated speed (f = 7.2Hz) to cutout speed (f = 10.8Hz), the WT control maintains a constant WT power of 3.0MW. Table 5.1 provides the data needed to model and simulate the Full Power Converter.

Table 5.1: Target PMG Power, Frequency, Voltage and Current

	EIGHTH POWER	**QUARTER POWER**	**HALF POWER**	**RATED POWER**	**CUT-OUT POWER**	
P	0.375	0.75	1.50	3.00	3.00	MW
n	1.5	3	6	12	18	rpm
f	0.9	1.8	3.6	7.2	10.8	Hz
V_{LL}	1.15	2.3	4.6	9.2	13.8	kV RMS
V_{LN}	0.664	1.328	2.656	5.312	7.967	kV RMS
V_{LN} pk	0.939	1.878	3.756	7.512	11.268	kV
Ia	188	188	188	188	126	A RMS
Ipk	266.25	266.25	266.25	266.25	178.19	A

The function of the Target Full Power Converter is to deliver 13.8kVLL, 60Hz power at the converter output for all the PMG frequencies and voltages shown in Table 5.1. Simulink models and simulations will be used to demonstrate this capability.

6.2 Converting Sequence Voltages to 3 Phase Voltages

The positive sequence voltage (Van) is a function of stator frequency, from cut-in speed to cut-out speed. The equations for phase to phase voltages in the balanced 3Φ PMG:

$$\mathbf{V_{AB}} \angle 0 = \sqrt{3}\ Vt \qquad (6.1)$$

$$\mathbf{V_{BC}} \angle -120 = \sqrt{3}\ Vt \qquad (6.2)$$

$$\mathbf{V_{CA}} \angle 120 = \sqrt{3}\ Vt \qquad (6.3)$$

Therefore, the rated voltage $V_{RATED} = \sqrt{3}$ (5.313) = <u>9.2kV RMS</u>

and the cut-out voltage $V_{CUT\text{-}OUT} = \sqrt{3}$ (7.967) = <u>13.8kV RMS</u>

6.3 Three Phase Diode Bridge Rectifier

Fig. 6.2 depicts the circuit diagram of a three phase diode bridge rectifier that will convert the AC voltage inputs to a DC voltage across the load. The PMG terminal voltages are 3Φ balanced sinusoidal RMS voltages, V_{AN}, V_{BN} and V_{CN}. The equation for the peak voltage is:

$$V_{PK} = V_{LNRMS}\sqrt{2} \qquad (6.4)$$

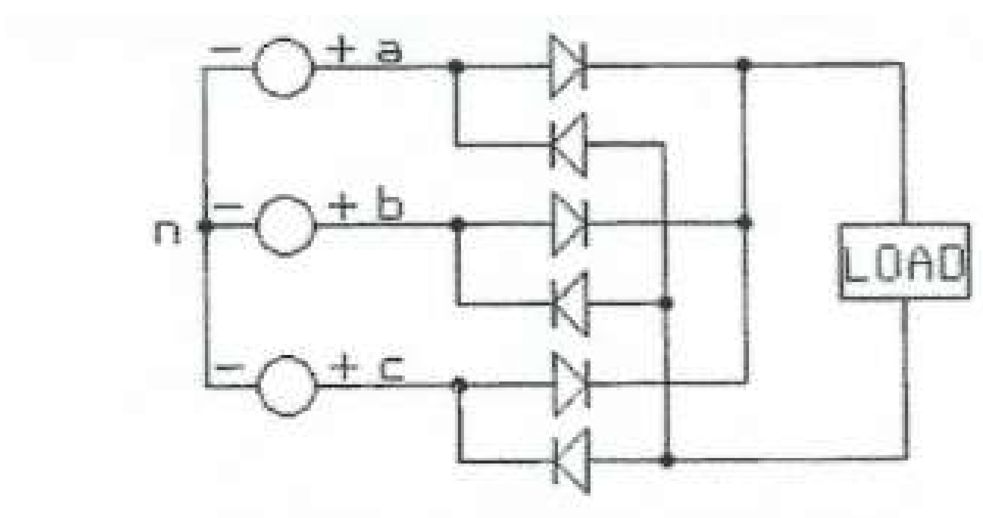


Fig. 6.2: 3Φ Diode Bridge Rectifier [10]

In the time domain, equations for the phase (line-neutral) voltages are:

$$V_{an}(t) = V_{PK} \cos(\omega_0 t) \qquad (6.5)$$

$$V_{bn}(t) = V_{PK} \cos(\omega_0 t - 2\pi/3) \qquad (6.6)$$

$$V_{cn}(t) = V_{PK} \cos(\omega_0 t - 4\pi/3) \qquad (6.7)$$

where

$$\omega_0 = 2\,\pi\, f \qquad (3.4)$$

Using a Matlab script:

```
THREE_PHASE_RECTIFIER
THREE PHASE DIODE BRIDGE RECTIFIER
CALCULATE THE RATED PHASE (LINE – NEUTRAL) VOLTAGES
Vrms = 9.2/sqrt(3) = 5.312kV
Vpk =  Vrms*sqrt(2) = 7.512kV
f = 7.2Hz
w0 = 2*pi*f = 45.24r/s
t =0sec
Van = Vpk*cos(w0*t) = 7.512kV
Vbn = Vpk*cos((w0*t)-(2*pi/3)) = -3.756kV
Vcn = Vpk*cos((w0*t)-(4*pi/3)) = -3.756kV
CALCULATE THE RECTIFIER OUTPUT VOLTAGE
VDC = maximum[abs(Van),abs(Vbn),abs(Vcn)] = 7.512kV
```

Fig. 6.3 and 6.4 depict Van, Vbn, Vcn and V_{DC} vs time.

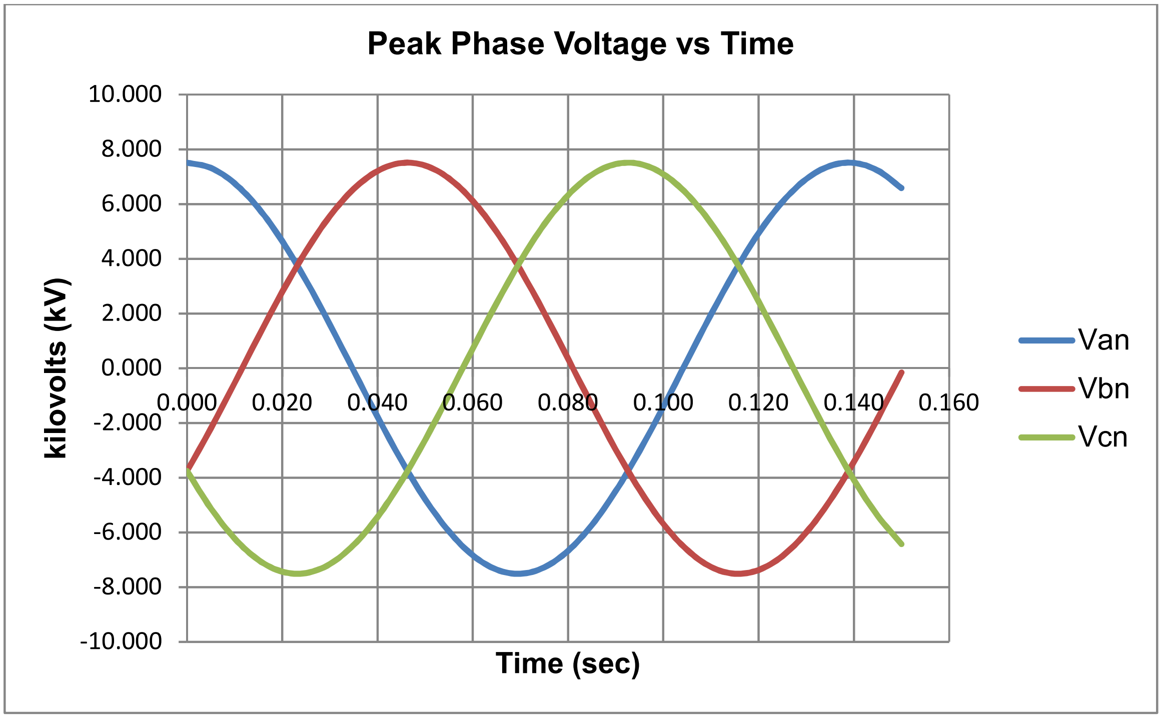


Fig. 6.3: Phase Voltages at Rated Power vs Time

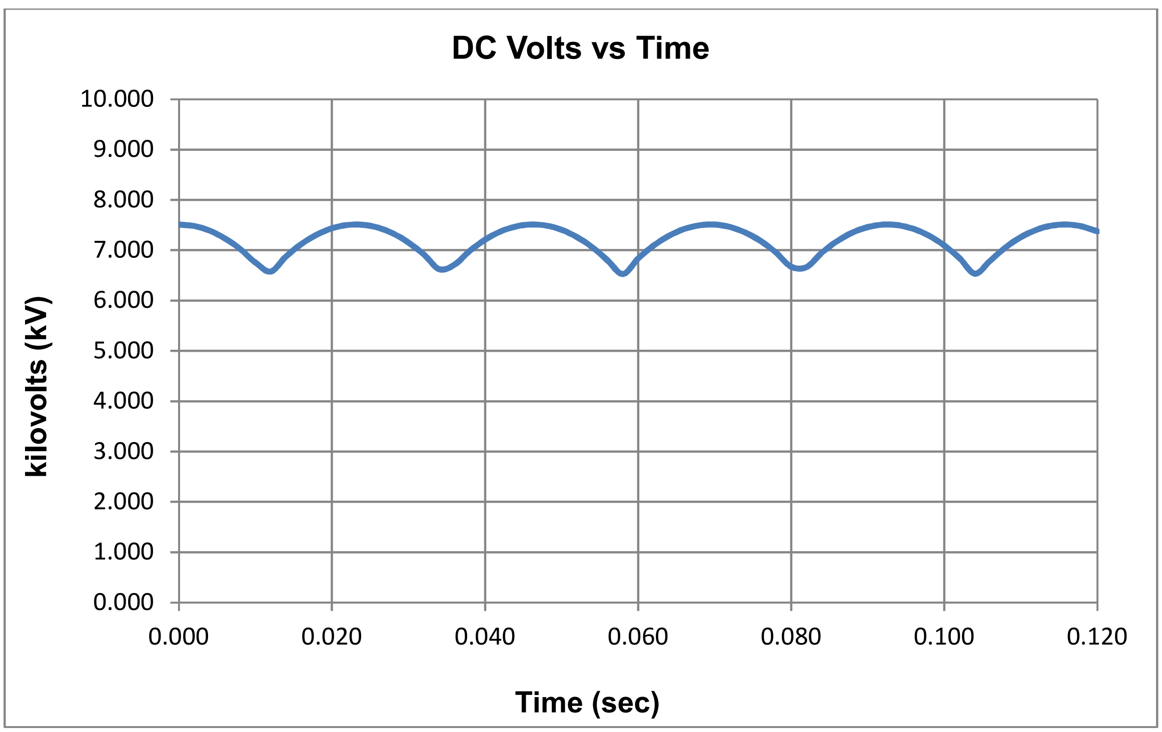


Fig. 6.4: Rated Voltage across Load (DC with Ripple)

6.4 Three Phase Target PMG

The frequency, voltage and current relationships for the Target PMG were all presented in table 5.1. The applicable equations have been shown in previous sections. Fig. 6.5 depicts the Simulink Model of the Target PMG.

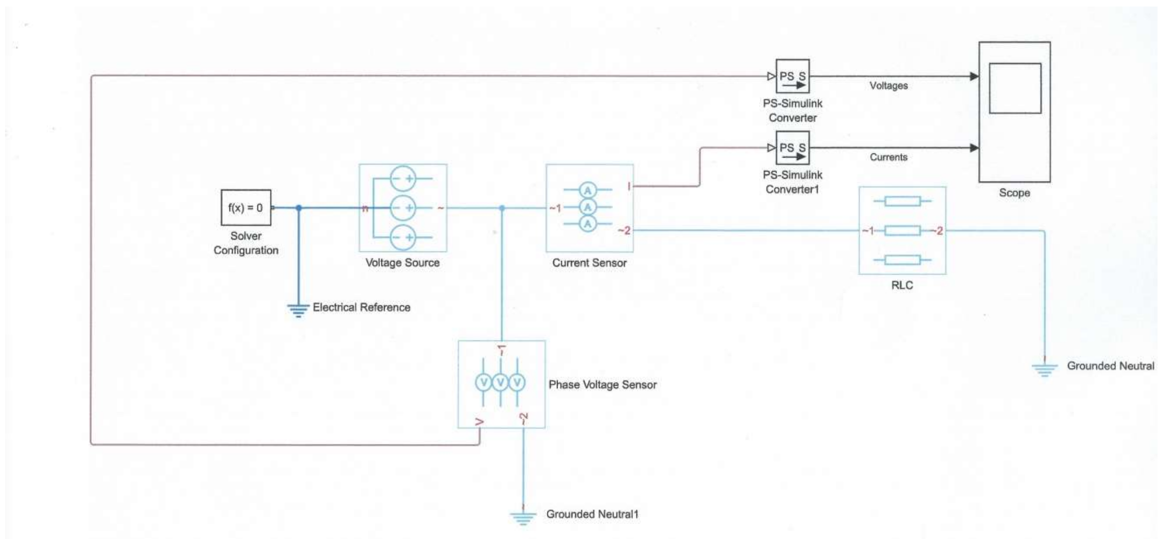


Fig. 6.5: Simulink Model of 3Φ PMG

The Simulink Model includes:

1. 3Φ AC voltage source (ideal voltage sources)
2. 3 Phase voltage sensor
3. 3 Phase current Sensor
4. 3 Phase load resistors
5. Scope to display voltages and currents

The 3Φ Voltage Source is the model for the PMG all at stator frequencies.

6.4.1 Simulink Simulation of the Target PMG

Several simulations were run to confirm the voltages and frequencies of the Target PMG model. Fig. 6.6 shows the scope trace at PMG rated power.

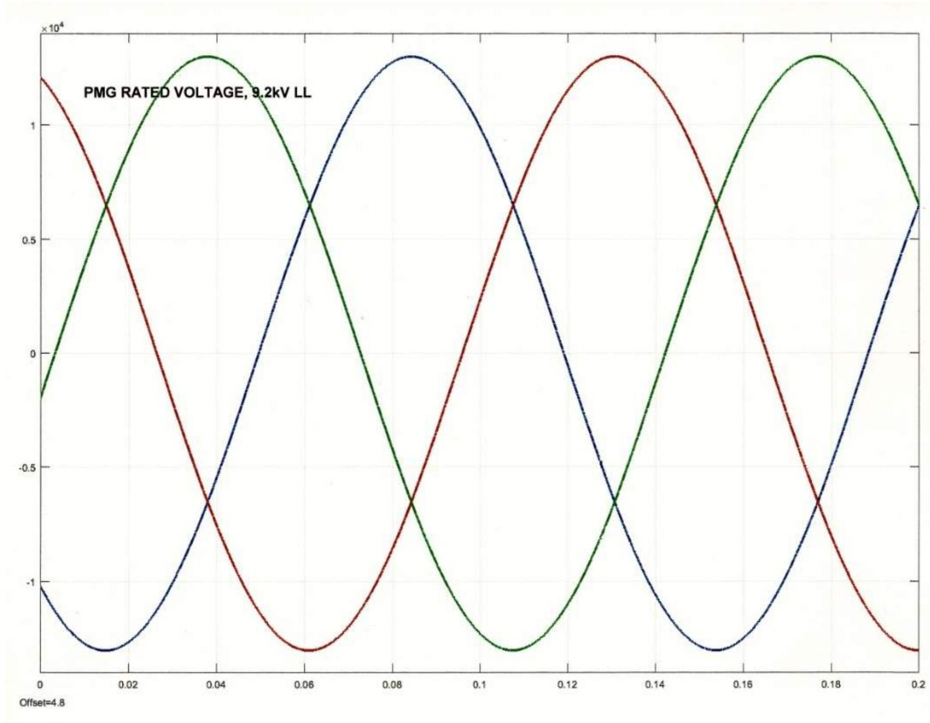


Fig. 6.6: PMG voltage at rated power, $9.2kV_{LL}$

$$V_{PK} = V_{RMS}\sqrt{2} \qquad (6.4)$$

Fig. 6.6. depicts Vpk = 9.2kV $\sqrt{2}$ = 13.01kV

6.5 Three Phase Diode Rectifier

A 3Φ Diode Rectifier is utilized in the Target Full Power Converter. The input to the Rectifier is the 3Φ V_{LL} from the PMG. The output is DC power, the input to the DC boost converter. Fig. 6.7 depicts the model of the diode rectifier with a 3Φ AC voltage source.

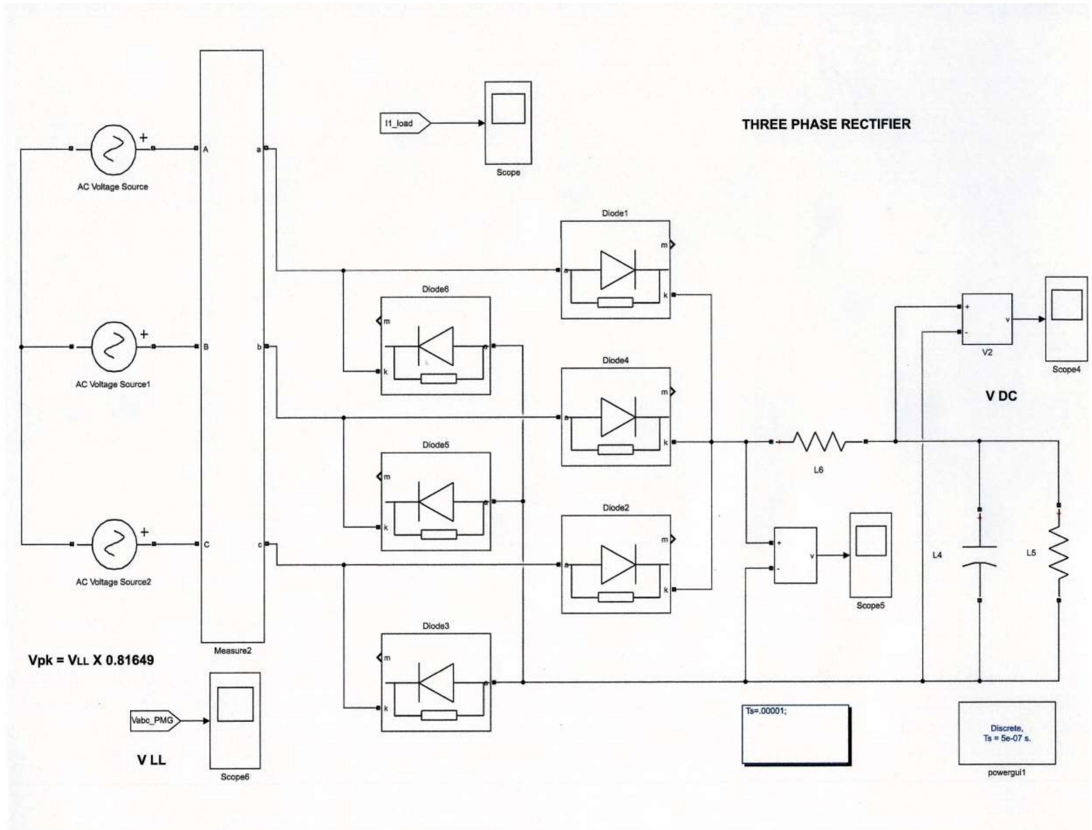


Fig. 6.7: Simulink Model of the 3Φ Diode Rectifier

The Simulink Model includes:

1. AC Voltage Sources (ideal voltage sources w/same amplitudes and phase angles of 0, -120, 120 degs)
2. 3 Phase Diode Bridge using 6 high power diodes
3. Current limiting resistor (1Ω)
4. Filter capacitor (4700μF)
5. Load resistor (300Ω); arbitrarily selected
6. Scopes to display voltages and currents

6.5.1 Simulink Simulation of the 3Φ Diode Rectifier

Several simulations were run to determine the HVDC output voltage as a function of the 3Φ PMG voltage and frequency. The results are summarized in Table 6.1.

Table 6.1: 3Φ Diode Rectifier DC output vs PMG voltage and frequency

	EIGHTH POWER	QUARTER POWER	HALF POWER	RATED POWER	CUT-OUT POWER	
P	0.375	0.75	1.50	3.00	3.00	MW
f	0.9	1.8	3.6	7.2	10.8	Hz
V_{LL}	1.15	2.3	4.6	9.2	13.8	kV RMS
Rectifier Output	0.925	1.85	3.7	7.4	11.1	kV_{DC}

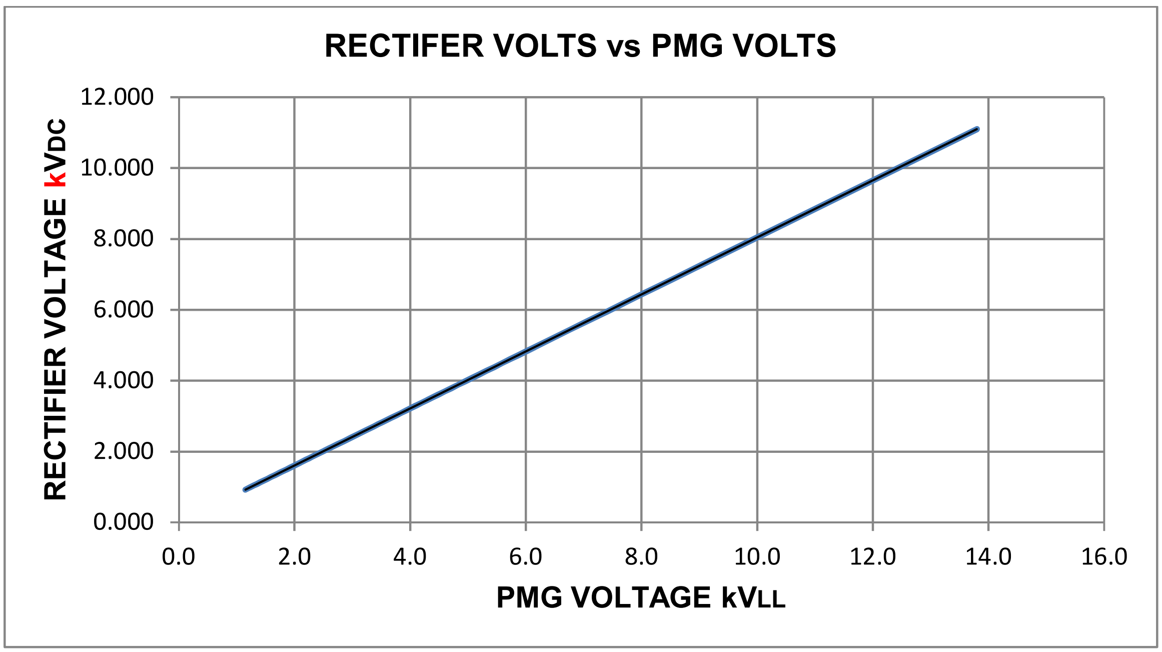


Fig. 6.8: Rectifier DC Voltage vs PMG Output Voltage

From (Fig. 6.8) the equation for the DC output voltage is

$$V_{DC} = 0.8043V_{LL} \qquad (6.8)$$

The transient response of the rectifier depicted in Fig. 6.9 is the DC voltage response to a step input voltage from 0 to rated V.

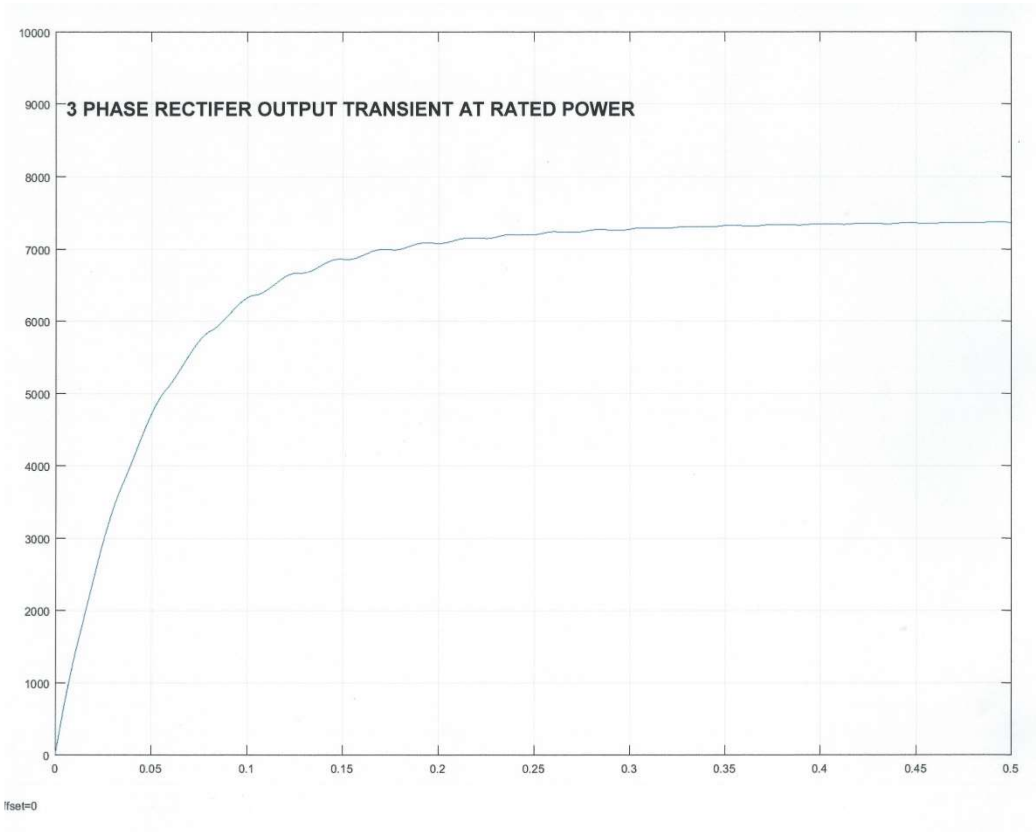


Fig 6.9: Transient response of rectifier to a 9.2kV$_{LL}$ step from 0V$_{LL}$; V$_{DC}$ (volts) vs Time (secs)

As the graph shows, the voltage becomes steady state after approximately 0.5 seconds.

6.6. DC to DC Pulse Width Modulation Boost Converter

A DC to DC PWM Boost Converter is utilized in the Target Full Power Converter. The input to this converter is HVDC from the 3Φ Rectifier; the output is an HVDC input to the PWM Inverter. Table (6.1) indicates the HVDC input varies from approximately 1kV$_{DC}$ to 11kV$_{DC}$.

The period of the PWM is

$$Ts = 1/fs \qquad (6.8)$$

where fs is the frequency of the pulse generator.

The term duty cycle (D), as applied to a PWM converter, is the ratio of pulse on-time (Ton) to the pulse time period (Ts). The formula for the duty cycle is [48]

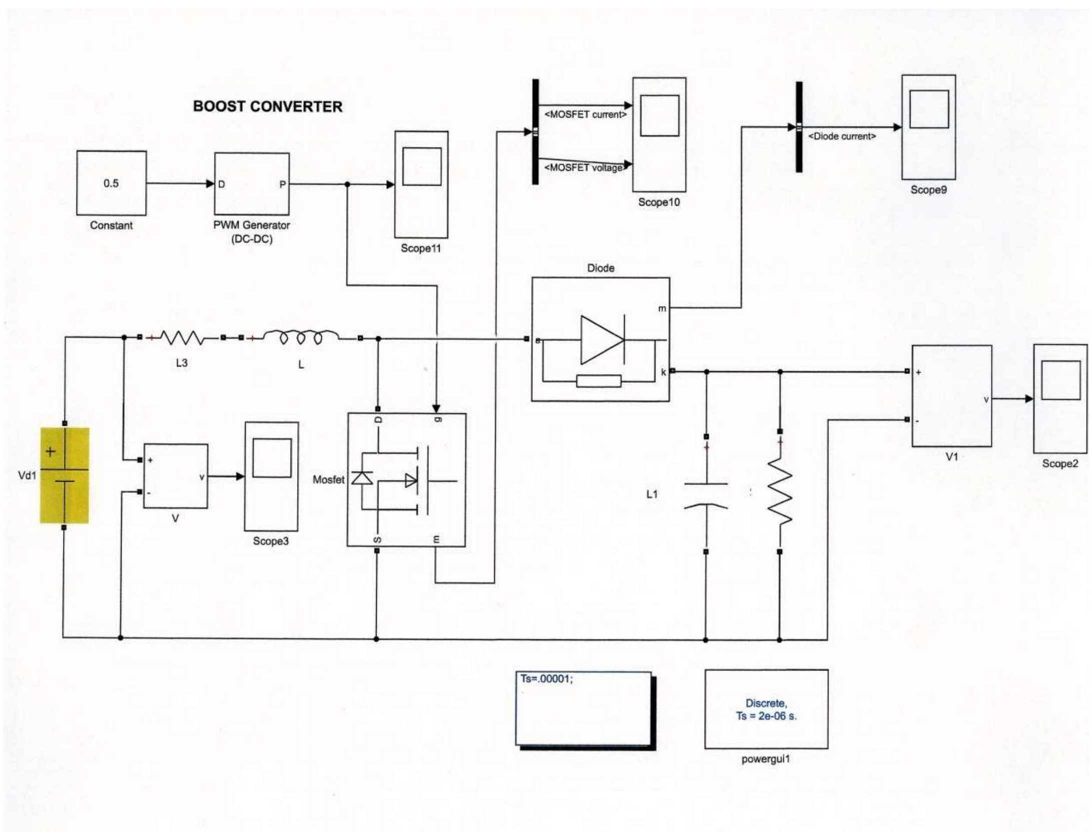
$$D = 1-1/(V0/Vin) \qquad (6.9)$$

Also

$$V0 = Vin / (1-D) \qquad (6.10)$$

Fig. 6.10 depicts the Simulink model of the PMW boost converter.

Fig. 6.10: Simulink Model of the PWM Boost Converter



The Simulink Model includes:

1. DC Voltage Source (ideal voltage source)
2. Current limiting resistor (1Ω)
3. Inductor (300mH)
4. MOSFET for PWM of the input current

5. PWM generator to control the MOSFET switching (f = 5kHz)
6. Duty cycle constant
7. Diode
8. Capacitor to store the output voltage (470μF)
9. Load Resistor (500Ω)
10. Scopes to display voltages and currents

6.6.1 Simulink Simulation of the PWM Boost Converter

Several simulations were run to determine the HVDC output voltage as a function of the Duty Cycle. The results are summarized in Table 6.2.

Table 6.2: Boost Converter Voltage as a function of Duty Cycle

Vin	10	10	10	10	10	kVDC
Duty Cycle	0.1	0.3	0.5	0.7	0.9	
Vout	11.204	14.416	20.187	33.465	86.675	kVDC

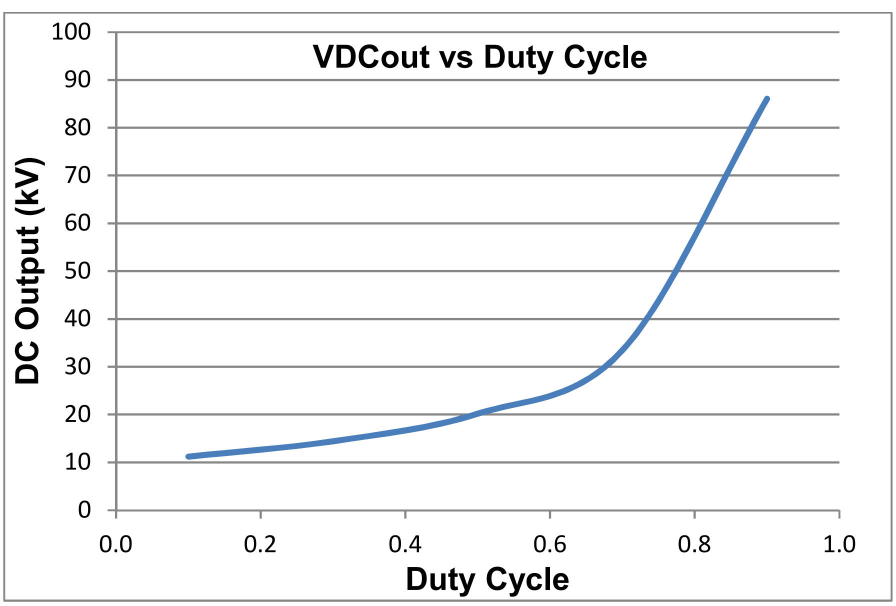


Fig. 6.11: Boost Converter Output Voltage vs Duty Cycle

The transient response of the Boost Converter is the output voltage response to a step input voltage from 0 to 10kV DC.

Fig. 6.12 depicts the transient response of the boost converter while Fig. 6.13 depicts the steady state response.

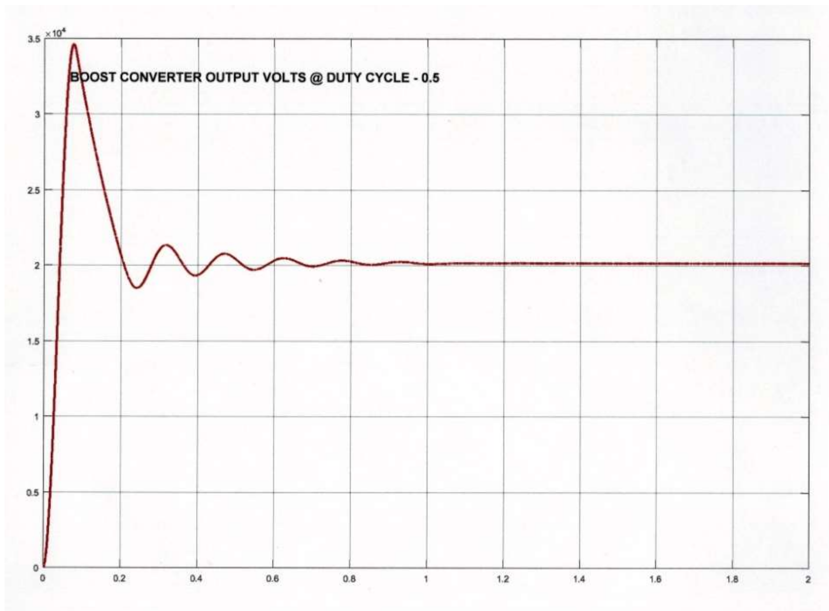


Fig. 6.12: Transient Response of DC Boost Converter @ D = 0.5

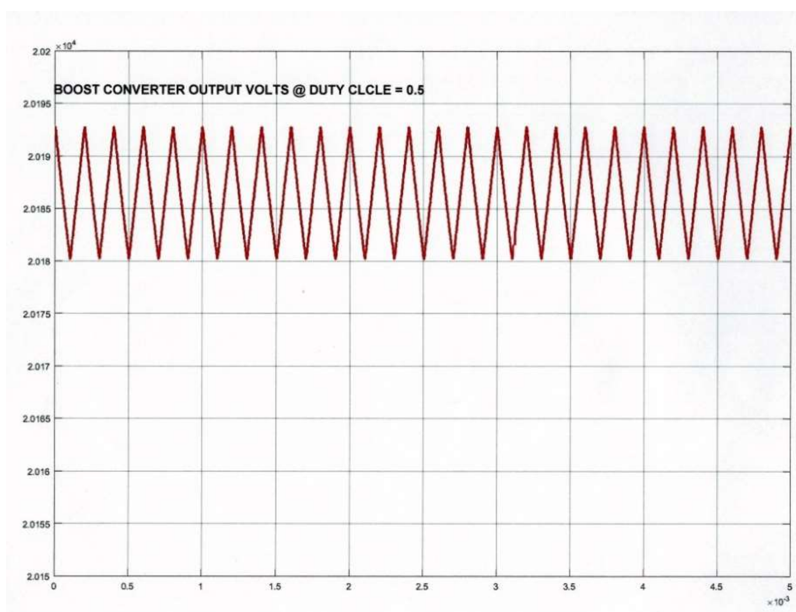


Fig. 6.13: Steady State Output of DC Boost Converter @ D = 0.5

Note the steady state response includes sawtooth signal of 1.3V riding on the boost converter output of 20.2kV$_{DC}$.

6.7 Three Phase Pulse Width Modulation Inverter

A 3Φ PWM Inverter is utilized in the Target Full Power Converter. The input to the Inverter is HVDC from the Boost Converter; the output is 3Φ V_{LL} = 13.8kV. The output is connected to the electrical grid via the generator breaker. The generator breaker is closed by a signal from the control unit while the breaker is tripped by the generator protective relays or control unit. Fig. 6.14 depicts the Simulink model of the PMW inverter.

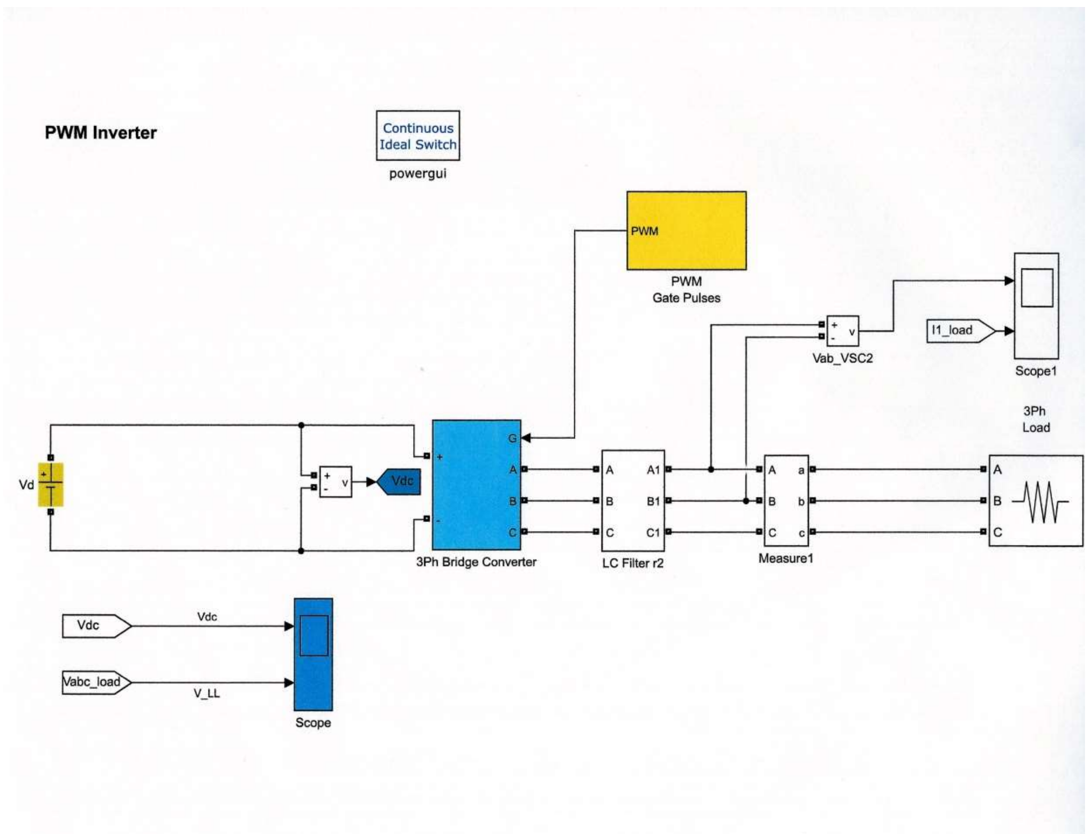


Fig. 6.14: Simulink Model of the PWM Inverter

The Simulink Model includes:

1. DC Voltage Source (ideal voltage source)
2. 3 Phase Bridge Converter using 6 MOSFETs

3. PWM Gate Pulses with 60Hz control signal and 20kHz switching frequency
4. 3Φ LC Filter with 10mΩ inductance and 20μF capacitance
5. 3Φ VI Measurement Block
6. 3Φ Parallel Resistive Load with adjustable Active Power
7. Scopes to display voltages and currents

6.7.1 Simulink Simulation of the PWM Inverter

Several simulations were run to determine the HVDC input voltage as a function of 3Φ output power and current. The results are summarized in Table 6.3.

Table 6.3: HVDC Input at several values of Inverter Output Power & Current

	EIGHTH POWER	**QUARTER POWER**	**HALF POWER**	**RATED POWER**	**CUT-OUT POWER**	
V_{IN}	22.14	22.13	22.55	22.41	22.41	kVDC
P	0.375	0.75	1.50	3.00	3.00	MW
V_{LL}	13.8	13.8	13.8	13.8	13.8	kV RMS
V_{LL}pk	19.5161	19.5161	19.5161	19.5161	19.5161	kV
V_{LN}	7.967	7.967	7.967	7.967	7.967	kV
I	16	31	63	126	126	A RMS
Ipk	22	44	89	177	177	A

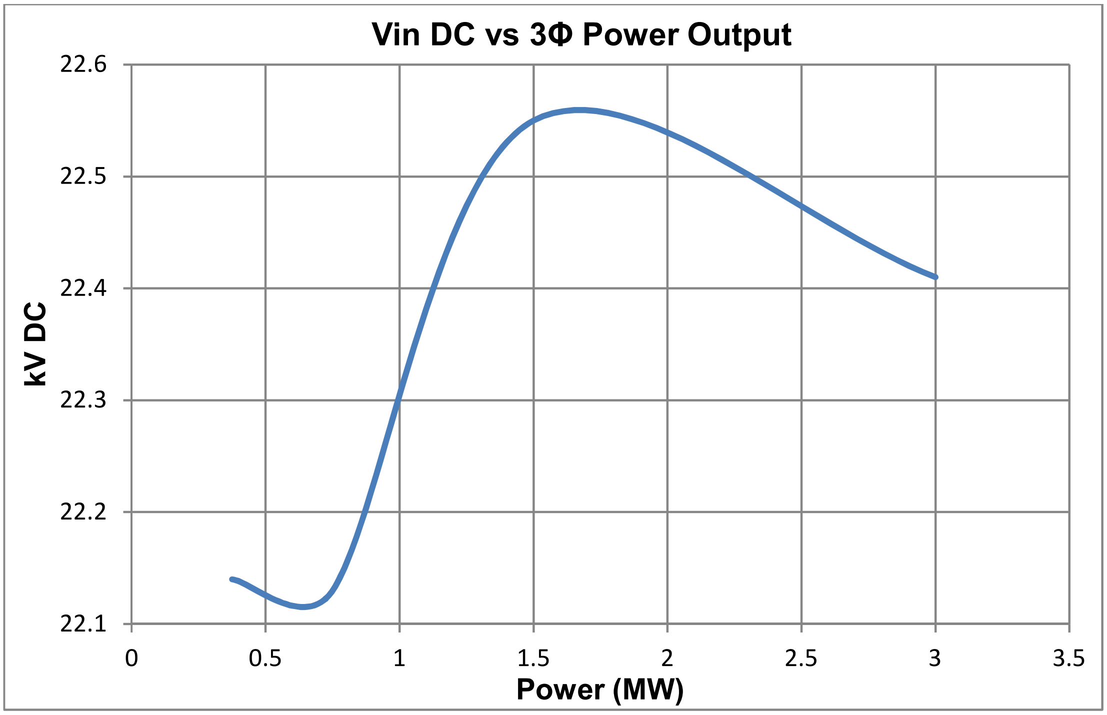


Fig. 6.15: Vin (DCV) vs Output Power (MW)

Fig. 6.15 shows that the required DC voltage input to the PMW inverter varies by about 2% over the WT power range.

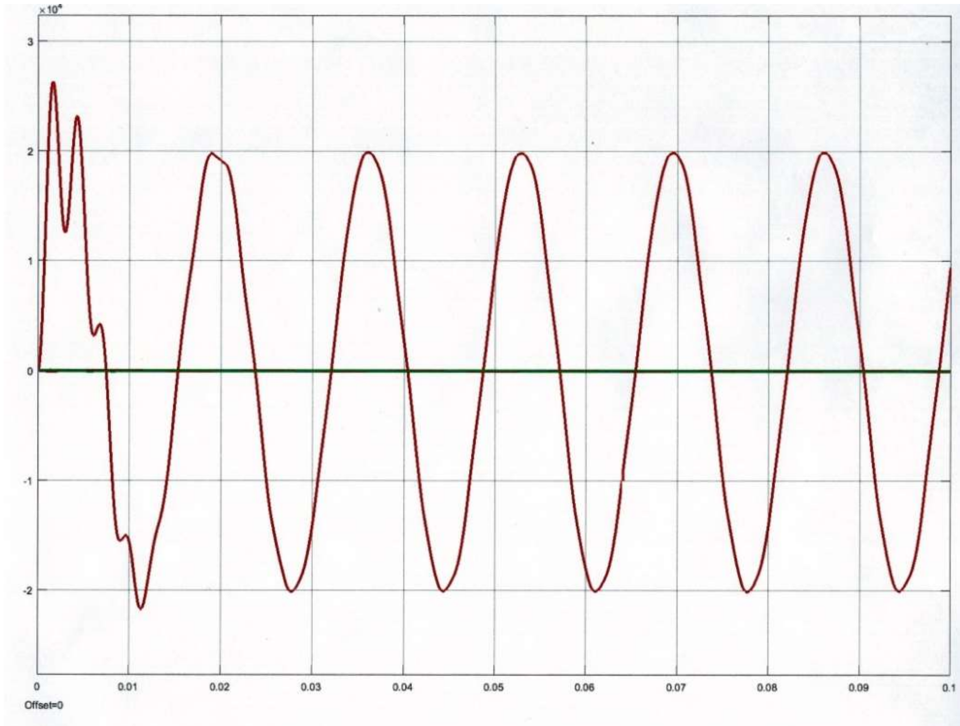


Fig. 6.16: 13.8kVLL (Vab) Inverter Output at 3.00MW

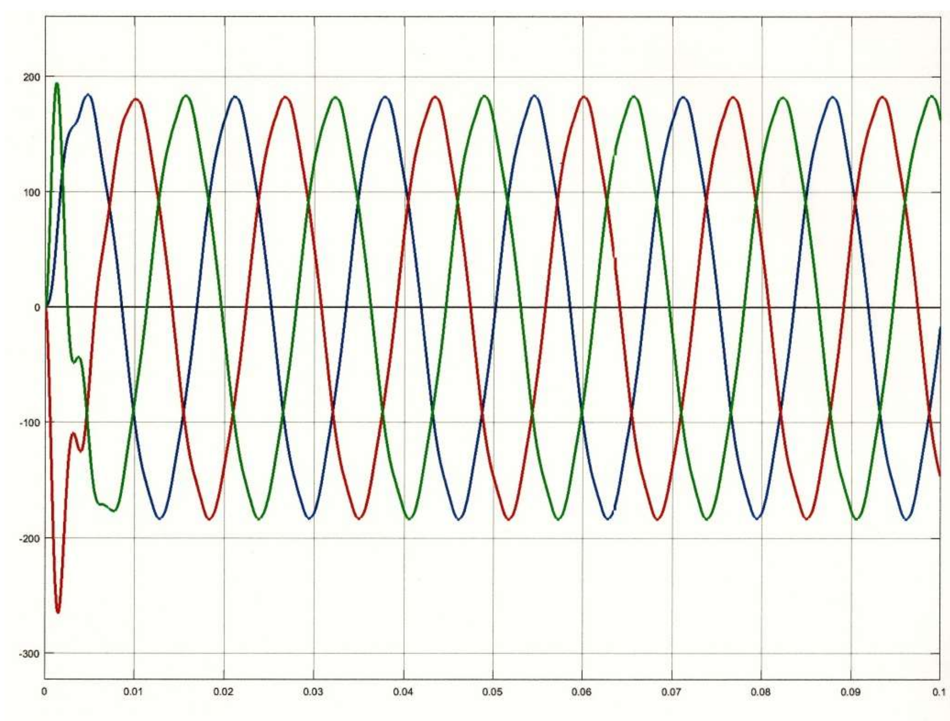


Fig. 6.17: 126A Phase Current Inverter Output at 3.00MW

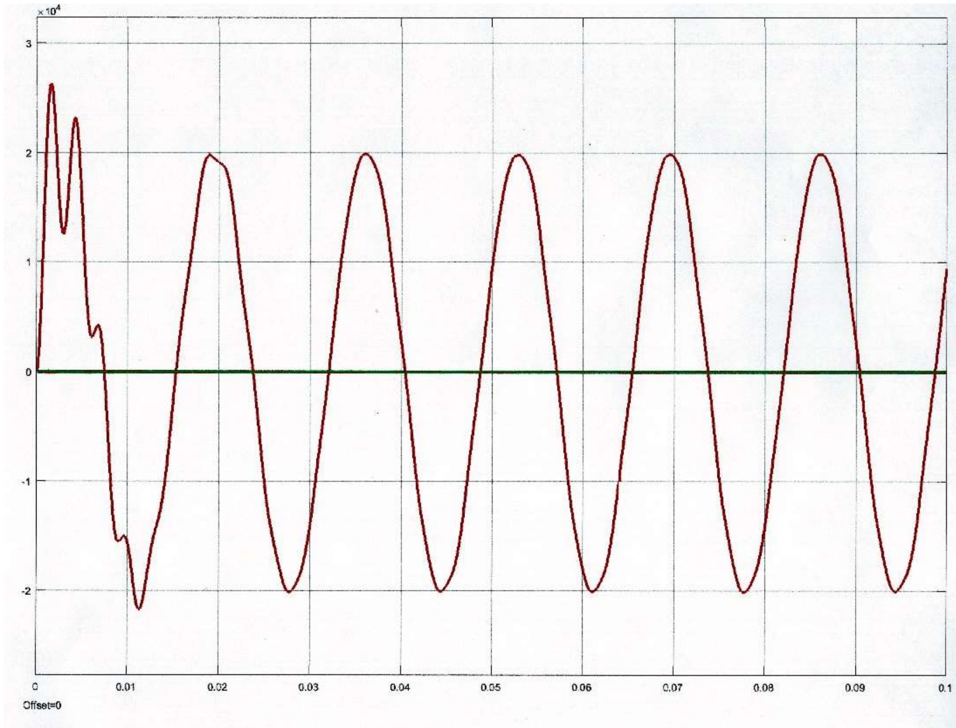


Fig. 6.18: 13.8kVLL (Vab) Inverter Output at 750kW

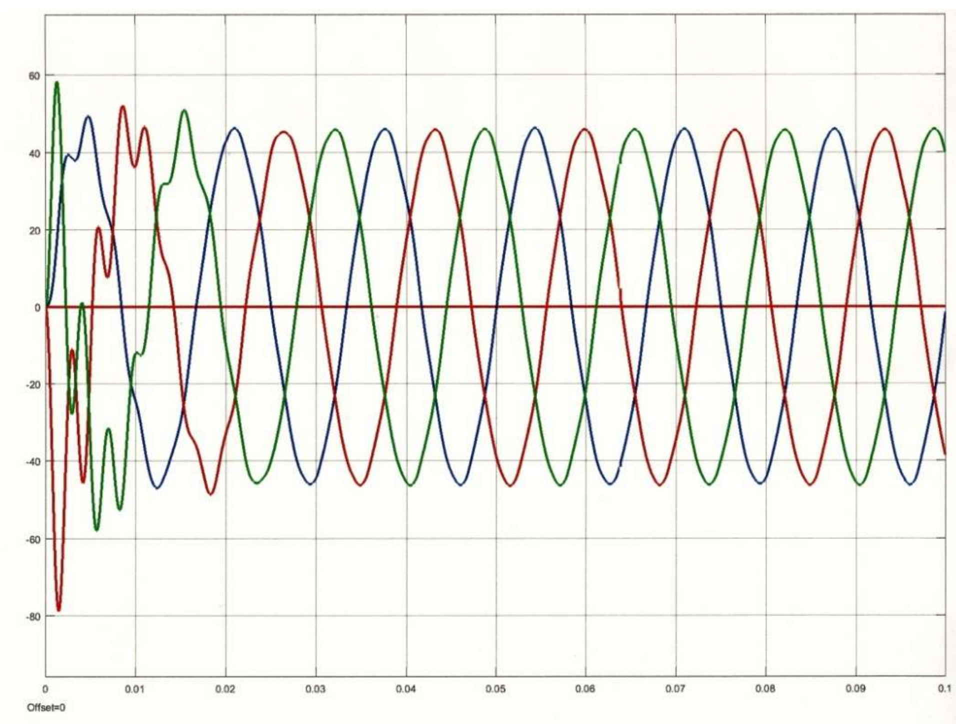


Fig. 6.19: Phase Current, Inverter Output at 750kW

6.8 AC to AC Full Power Converter

The target model includes a Full Power AC to AC converter using a 3 phase diode rectifier with a PWM boost converter and PWM inverter. The only control needed for this Full Power Converter is a voltage regulator signal to the Duty Cycle for the Boost Converter. Fig. 6.20 depicts Simulink Model of the complete AC to AC Full Power Converter.

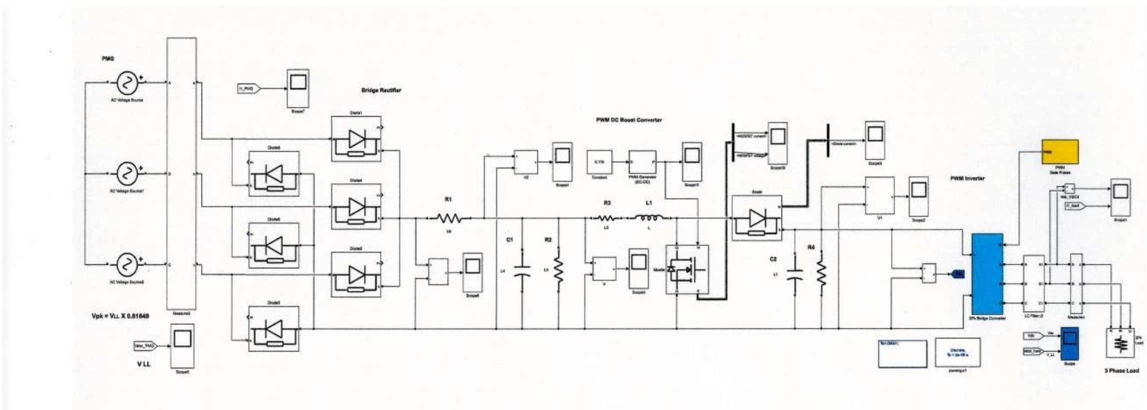


Fig. 6.20: Simulink Model of the AC to AC Converter

The Simulink Model includes:

1. PMG 3Φ Voltage Source (ideal voltage source)
2. 3 Phase Bridge Rectifier using high power diodes
3. Current limiting resistor (0.1Ω)
4. Filter capacitor (4700μF)
5. Inductor (300mH)
6. PWM Boost Converter using a MOSFET
7. PWM generator (5 kHz)
8. Duty cycle block
9. High power diode
10. Capacitor (470μF)
11. 3Φ PWM bridge inverter
12. PWM gate pulses (20kHz)
13. 3Φ LC filter
14. 3Φ measurement block

15. 3Φ Parallel Resistive Load with adjustable Active Power
16. Scopes to display voltages and currents

6.8.1 Simulink Simulation of the Converter

Several simulations were run to determine the Duty Cycle of the PWM Boost Converter as a function of 3Φ PMG Voltage. The results are summarized in Table 6.4.

Table 6.4: AC to AC Converter Data

	EIGHTH POWER	**QUARTER POWER**	**HALF POWER**	**RATED POWER**	**CUT-OUT POWER**	
P_{PMG}	0.375	0.75	1.50	3.00	3.00	MW
f_{PMG}	0.9	1.8	3.6	7.2	10.8	Hz
V_{LLPMG}	1.15	2.3	4.6	9.2	13.8	kV RMS
V_{LNPMG}	0.939	1.878	3.756	7.512	11.268	kV
Rectifier Output	0.925	1.85	3.7	7.4	11.1	kV_{DC}
Duty Cycle	0.96	0.92	0.83	0.66	0.50	
Boost Conv Output	22.0	22.0	22.0	22.0	22.0	kV_{DC}
Inverter Output	13.8	13.8	13.8	13.8	13.8	kV RMS

From

$$V0 = Vin / (1-D) \qquad (6.10)$$

and since V0 = 22kV,

$$Vin = 22.0kV(1-D) \quad (6.11)$$

where Vin = boost converter input voltage.

Simulations were also run to demonstrate converter output volts and currents at different stator frequencies.

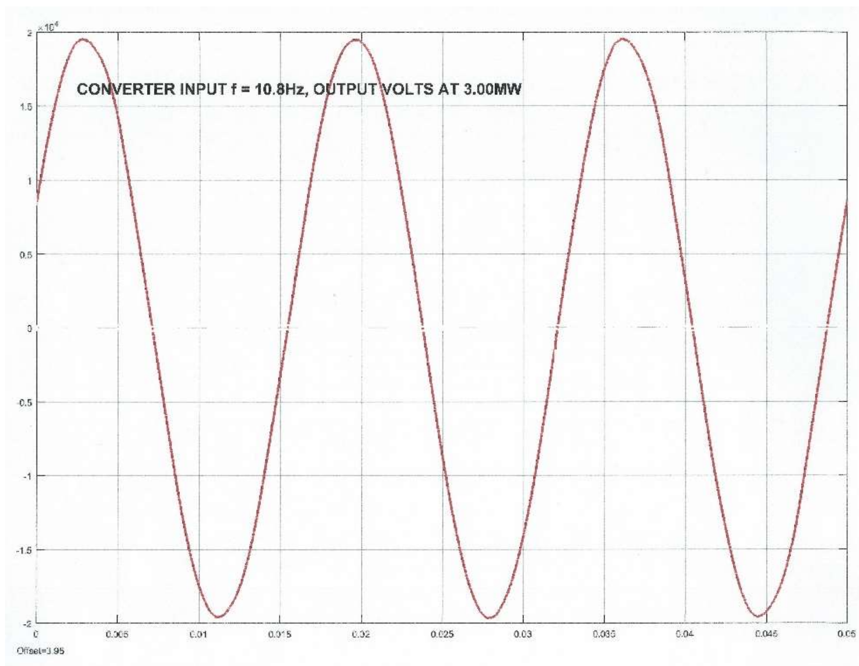


Fig. 6.22: Converter input f = 10.8Hz. output volts at 3.00MW

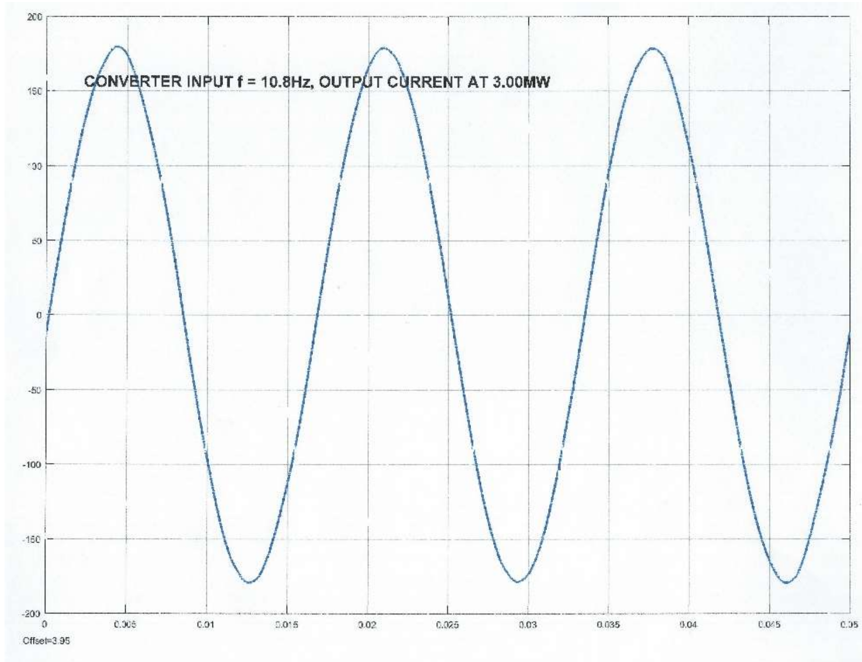


Fig. 6.23: Converter input f = 10.8Hz. output current at 3.00MW

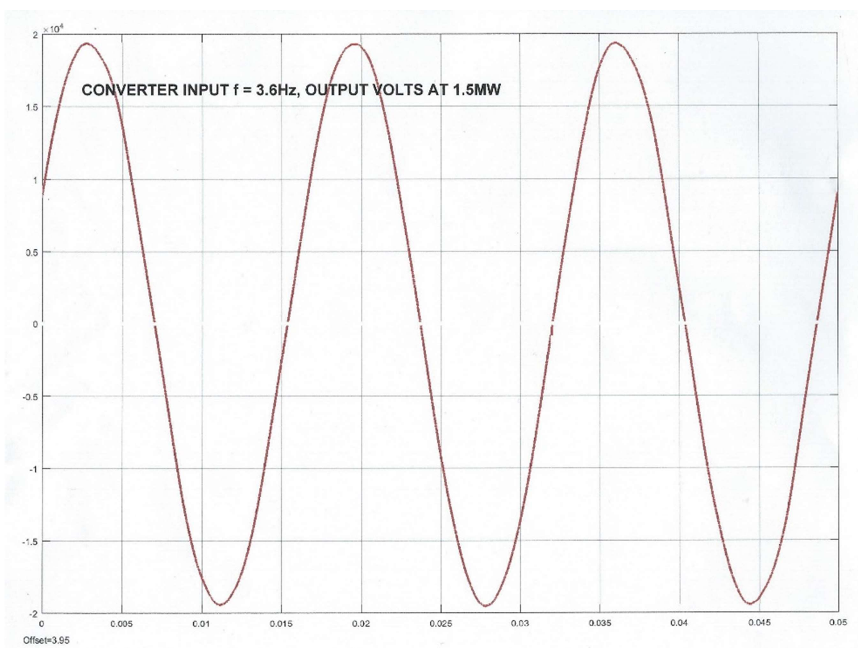


Fig. 6.24: Converter input f = 3.6Hz. output volts at 1.5MW

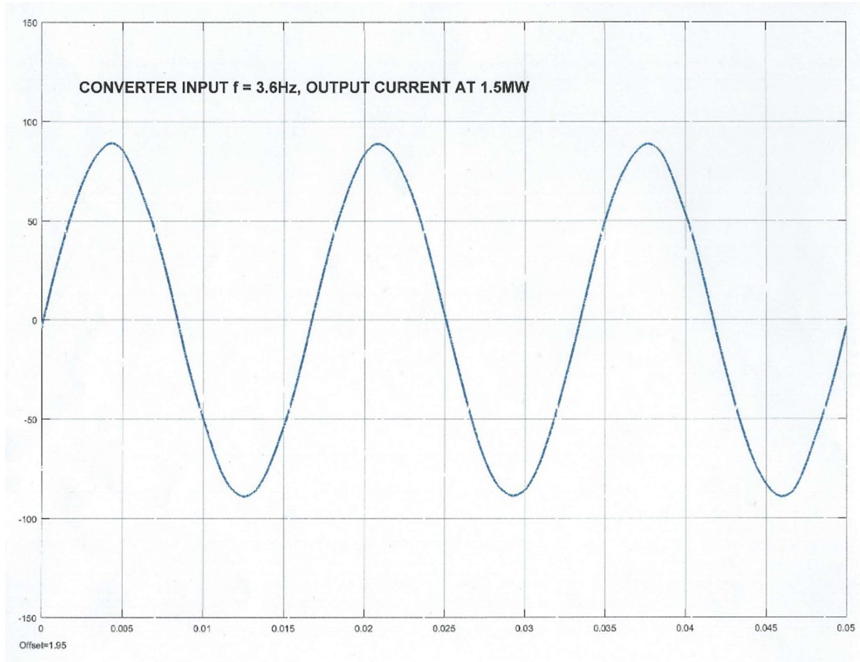


Fig. 6.25: Converter input f = 3.6Hz. output current at 1.5MW

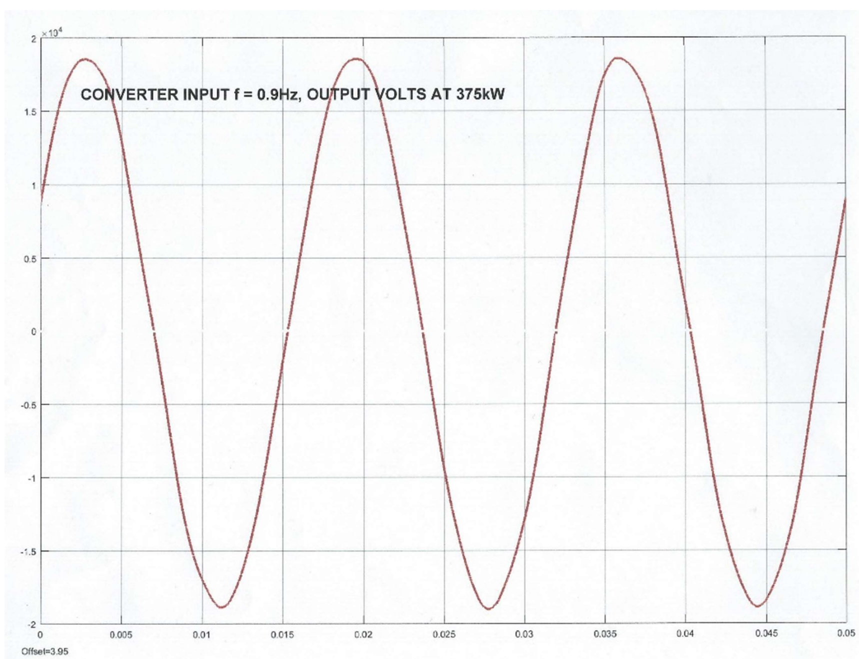


Fig. 6.26: Converter input f = 0.9Hz. output volts at 375kW

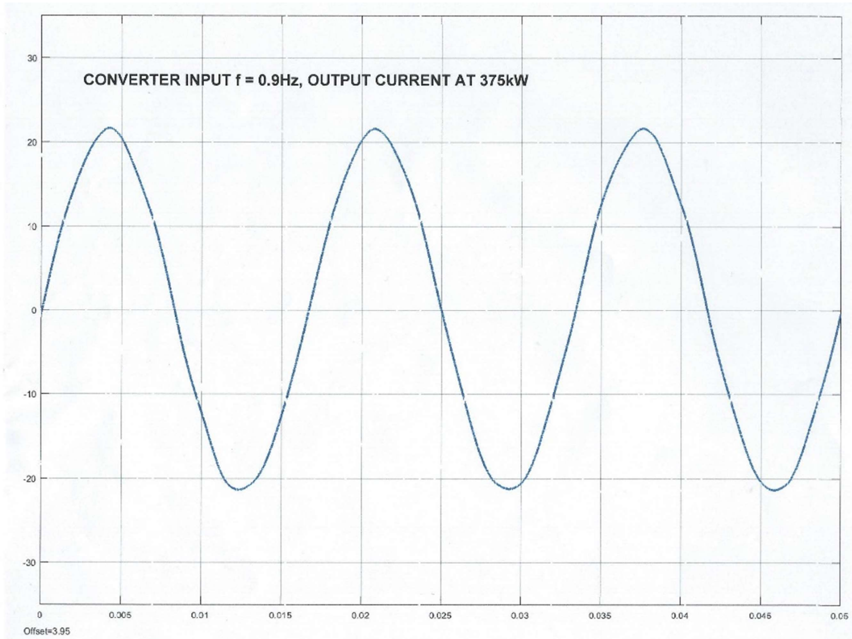


Fig. 6.27: Converter input f = 0.9Hz. output current at 375kW

7. **The Target Wind Turbine Control System**

A description of a control system relates the system inputs to the system outputs without taking into account the internal workings of the system. The control system description is often referred to as the input-output description, because it only deals with the inputs and the outputs [27].

Once the description has been completed, then it must be modeled, where the mathematical relationships between inputs and outputs are determined. These relationships are often referred to as transfer functions. Once a system is modeled, the system needs to be analyzed [27]. Matlab scripts and Simulink models are excellent tools to analyze and model the transfer functions.

When the system is successfully modeled and simulated with various inputs and found to satisfy the input-output description and also found to be stable, the design process moves to the last step, the physical implementation of the control system. Since microprocessors are so cheap, it's very common to implement control systems, including feedback loops, with computers. The computer makes continuous measurements of the inputs and then calculates the appropriate output signals. The I/O is implemented with power electronic devices.

The computer emulates logic devices, making measurements from switch inputs and electro-mechanical transducers, calculating a logic function from these measurements and then sending the resulting signals to electronically controlled switches, motor controllers and electrohydraulic valves [28].

7.1 The WT Control System Input-Output Description

The control system inputs include:

1. Wind anemometer – a signal proportional to wind speed; a 3 cup anemometer uses a reed switch to generate pulses proportional to wind speed. The range is from 0 to 45m/s wind speed. The pulses are counted by a signal conditioner that provides a standard process output of 4 to 20 mA.
2. Wind vane - the wind vane always positions itself according to the wind direction. There is a sensor in the wind vane that provides a 4 – 20mA output signal that is an input to the wind turbine control designating the wind direction.
3. Wind temperature – A bayonet style thermocouple, mounted outside the nacelle, measures the wind temperature with a range from -40degC to +40degC. A thermocouple signal conditioner provides a standard process output of 4 to 20 mA, proportional to wind temperature.
4. PMG stator steady state voltages - measured at the PMG output terminals, these signals are proportional to stator voltages (V_{LN}). Potential transformers (PTs) are used (ratio = 8400:120) to reduce the signal voltages. Signal conditioners provide a standard process output of 4 to 20 mA, proportional to V_{LN}.
5. PMG stator steady state currents - measured at the PMG output terminals, proportional to stator currents (Ia). Current transformers (CTs) are used (ratio = 200:5) to reduce signal currents. Signal conditioners provide a standard process output of 4 to 20 mA, proportional to Ia.
6. PMG stator frequency – a voltage proportional to PMG V_{LN}, measured by one of the PMG stator steady state voltage PTs, is the input to a frequency signal conditioner. The signal conditioner provides a voltage divider and standard process output of 4 to 20 mA, equal to 0 to 12Hz.
7. Generator breaker steady state voltages - V_{LN} measured at the converter side and the grid side of the generator breaker. Potential transformers (PTs) are used (ratio = 8400:120) to reduce signal voltages applied to the phase frequency detector (PFD).

8. Cable twist counter limit switches – there is a small enclosed gear mechanism (3:1 ratio) that trips limit switches if the wind turbine makes three full revolutions CW or CCW.

The control system outputs include:

1. Boost Converter Voltage Regulation
2. Rotor brake control – apply or release the rotor brake
3. Yaw motor control – drive the yaw motor CW or CCW
4. Blade pitch motor control - drive the blade pitch motors to a new position
5. Generator breaker control - close and trip the generator breaker

Inside the rear of the WT nacelle, there is a motor control center (MCC) which is an assembly of several enclosed sections having a common power bus and containing motor control units and the generator breaker control unit. The motor controllers provide a means for starting and stopping the yaw motor and for selecting forward or reverse rotation. [31].

7.2 The WT Remote Control and Monitoring

The wind turbine controls have a wireless interconnect used by the utility company's Energy Control Center and by technicians who service the WT [29]. All functions of control and monitoring can be performed from any location having an internet connection. For instance, the generator breaker can be tripped remotely. The WT power can be scaled back by adjusting the blade pitch angle.

7.3 Boost Converter Voltage Regulation

The boost converter voltage regulator assures that the boost converter output = 22kVDC, which in turn assures an inverter output phase voltage of 13.8kV The voltage at the input to the boost converter is used to calculate the duty cycle (D) of the pulse generator.

The equation used by the controller is

$$D = 1-(Vin/22k) \qquad (7.1)$$

calculates D required to maintain V0 = 22kV. The phase voltage output of the inverter is a function of the boost converter output DC voltage which is a function of the duty cycle of the boost converter as shown in table 6.4. From equation (6.12), the duty cycle required depends on the input voltage to the boost converter, Vin. The boost converter voltage regulator must compute D for all Vin voltages.

Fig. 7.1 depicts the Simulink Model of the boost converter voltage regulator interconnected to the boost converter.

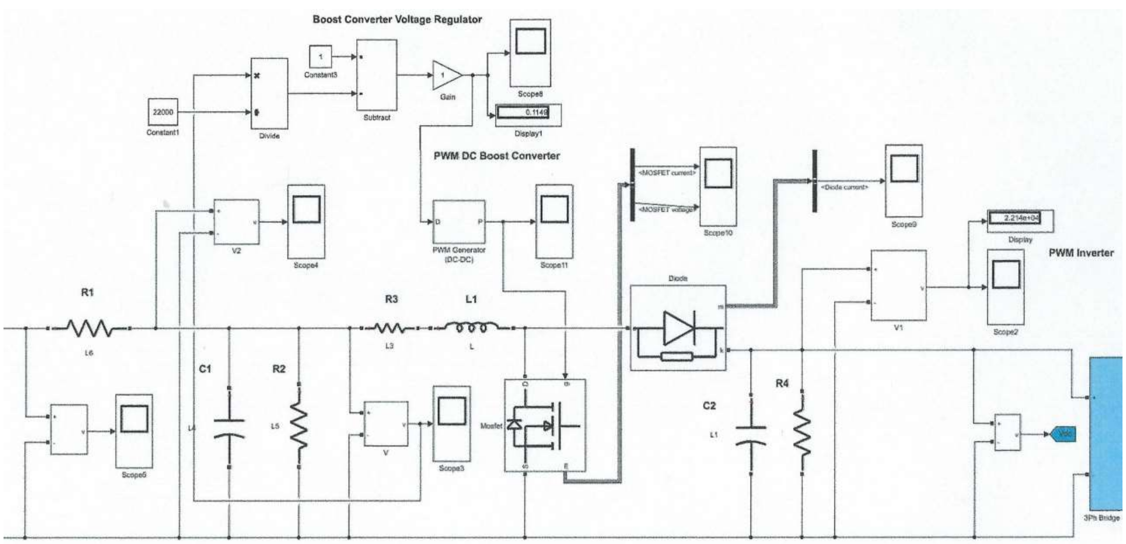


Fig. 7.1: Simulink Model of the boost converter voltage regulator

The Simulink Model includes:

1. a constant of 22,000
2. a divider to calculate Vin / 22,000
3. a constant of 1
4. a subtractor to calculate D = 1 - Vin / 22,000
5. a scope and a display to monitor the duty cycle, D

The 2nd input to the divider is the boost converter input voltage (Vin). The duty cycle is the input to the Pulse Generator, part of the DC PWM boost converter. In summary, the model computes the duty cycle (D) needed for the input voltage (Vin) and applies it to the boost converter pulse control.

7.3.1 The Boost Converter voltage regulator simulation

Three simulations were run on this model, at different stator frequencies, to demonstrate the transient and steady state boost converter output voltage responses.

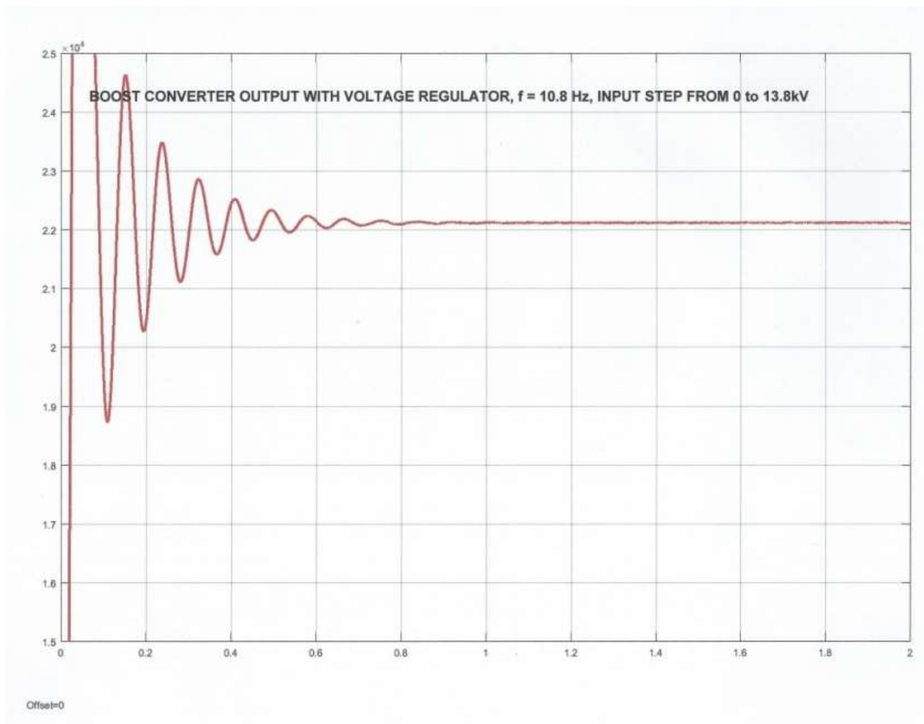


Fig. 7.2: Boost Converter Output at 10.8Hz

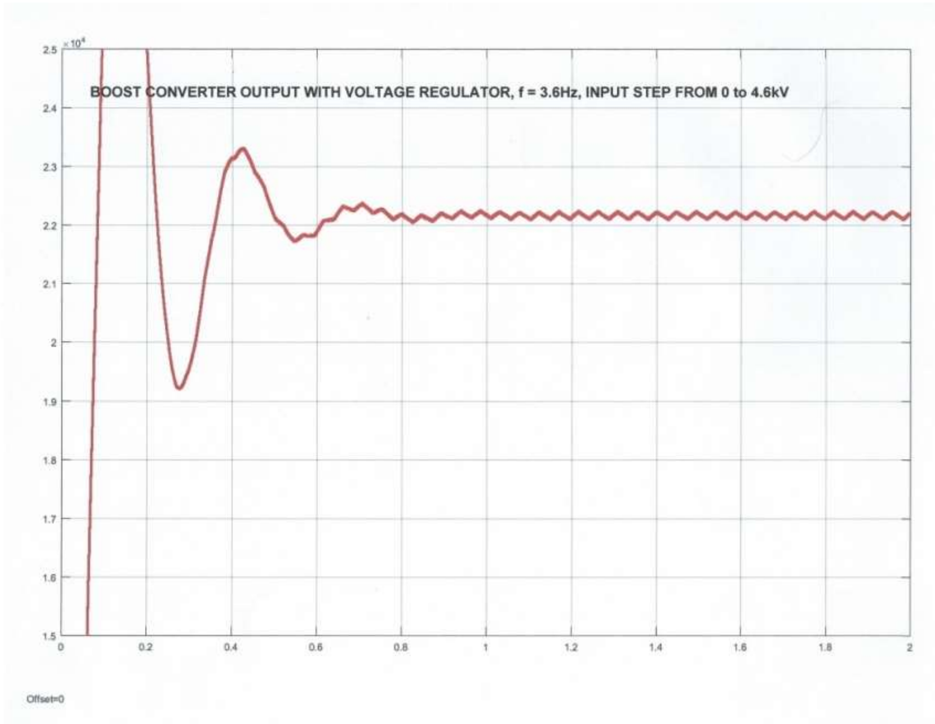


Fig. 7.3: Boost Converter Output at 3.6Hz

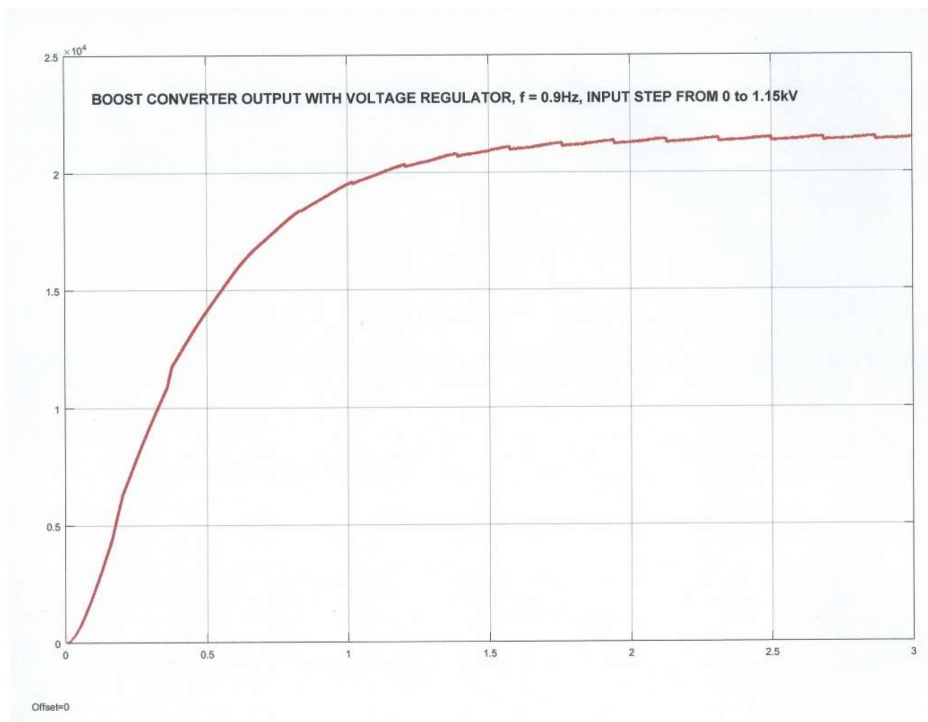


Fig. 7.4: Boost Converter Output at 0.9Hz

Note that in each simulation, the voltage regulator controls the boost converter steady state output voltage at 22kVDC. The transients are well damped; however this simulates a situation which could not exist in the real WT. The WT shaft speed and stator frequency changes with the wind velocity, perhaps enduring some wind gusts, but the shaft speed would never change as a step function.

7.4 Wind Temperature

A bayonet style thermocouple, mounted outside the nacelle, measures the wind temperature with a range from -40degC to +40degC. A thermocouple signal conditioner provides an output of 4 to 20 mA, where 12mA = 0degC and 16mA = 20degC. Fig. 7.5 depicts the Simulink Model of the wind temperature measurement. The temperature of the wind is a significant factor in determining the WT power generated.

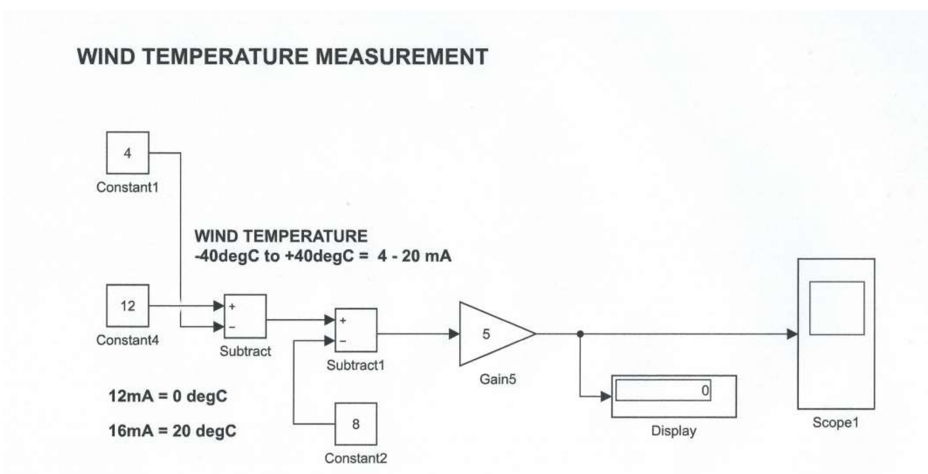


Fig. 7.5: Wind temperature Simulink model

The Simulink Model includes:

1. a subtractor to linearize the input signal
2. a subtractor to decrease the temperature signal so that 12mA = 0degC
3. a gain of 5 to adjust temperature so that 16mA = 20degC

4. a display and scope to observe simulation results

7.4.1 The Wind Temperature Measurement simulation

Simulations were run on this model, at different input currents to demonstrate the resulting temperature indications.

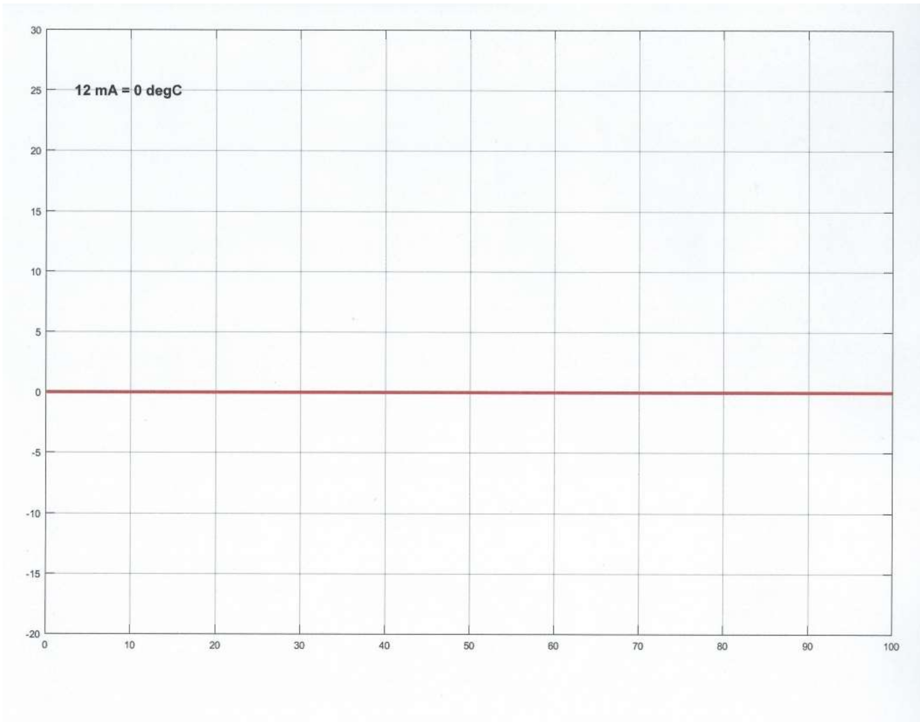


Fig. 7.6: Wind temperature, 12mA = 0degC

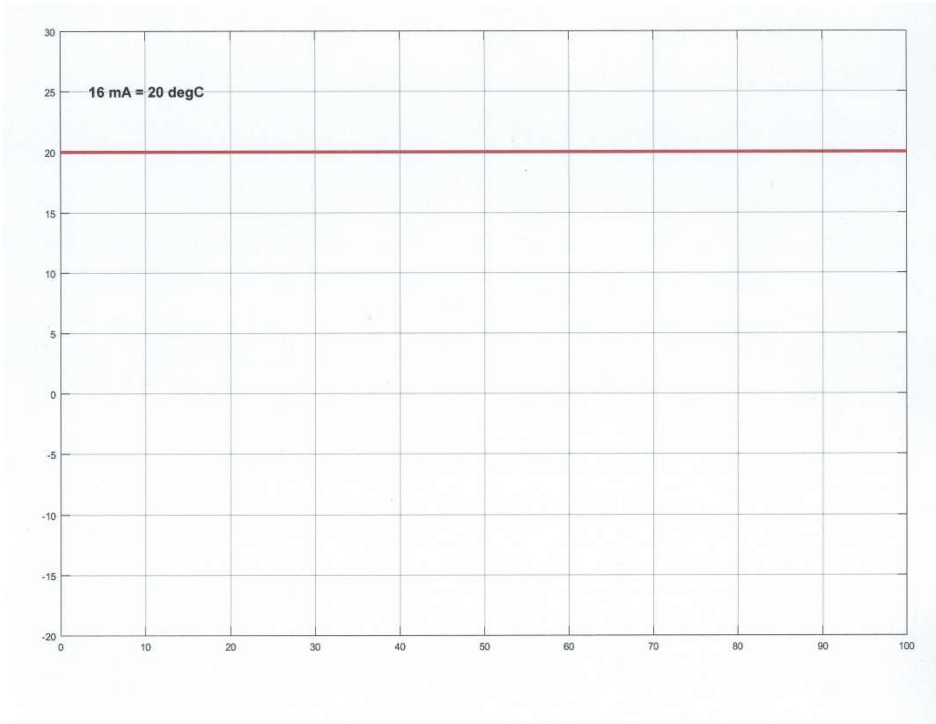


Fig. 7.7: Wind temperature, 16mA = 20degC

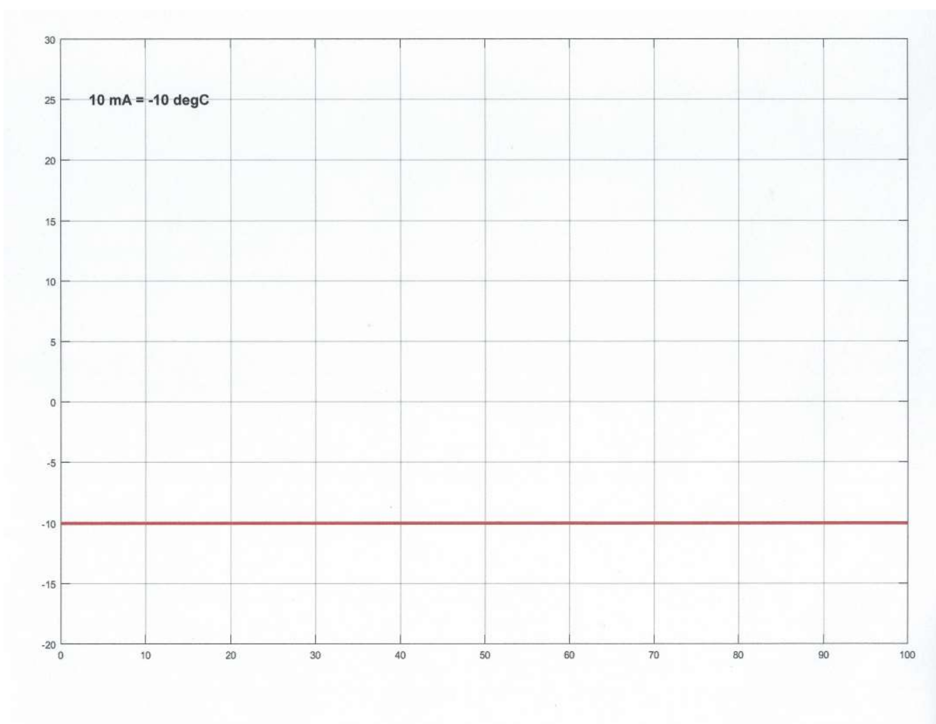


Fig. 7.8: Wind temperature, 10mA = -10degC

7.5 Rotor Speed and Stator Frequency

A voltage proportional to PMG V_{LN}, measured by one of the PMG stator steady state voltage PTs, is the input to a frequency signal conditioner. The signal conditioner provides a voltage divider and standard process output of 4 to 20 mA, equal to 0 to 12Hz. The resistor divider (ratio = 50:1) is the input to a frequency signal conditioner. The voltage divider is made with a 49kΩ resistor in series with a 1kΩ resistor; the current in the divider is less than 160ma. Fig. 7.9 depicts the Simulink model.

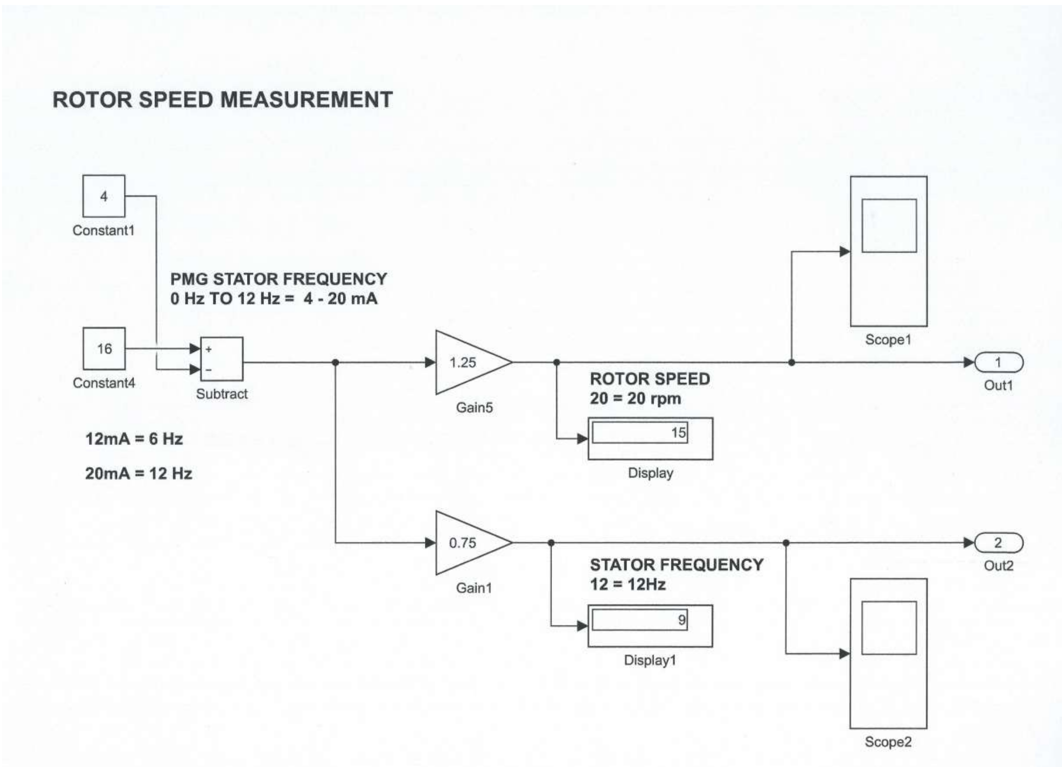


Fig. 7.9: The Simulink model for rotor speed and stator frequency

The Simulink Model includes:

1. a subtractor to linearize the input signal
2. a gain to increase the rotor speed signal so that 20 = 20rpm
3. a gain to decrease the stator frequency signal so that 12 = 12Hz
4. displays and scopes to observe simulation results

7.5.1 The Rotor Speed and Stator Frequency Measurement simulation

Simulations were run on this model, at different input currents to demonstrate the resulting speed and frequency indications.

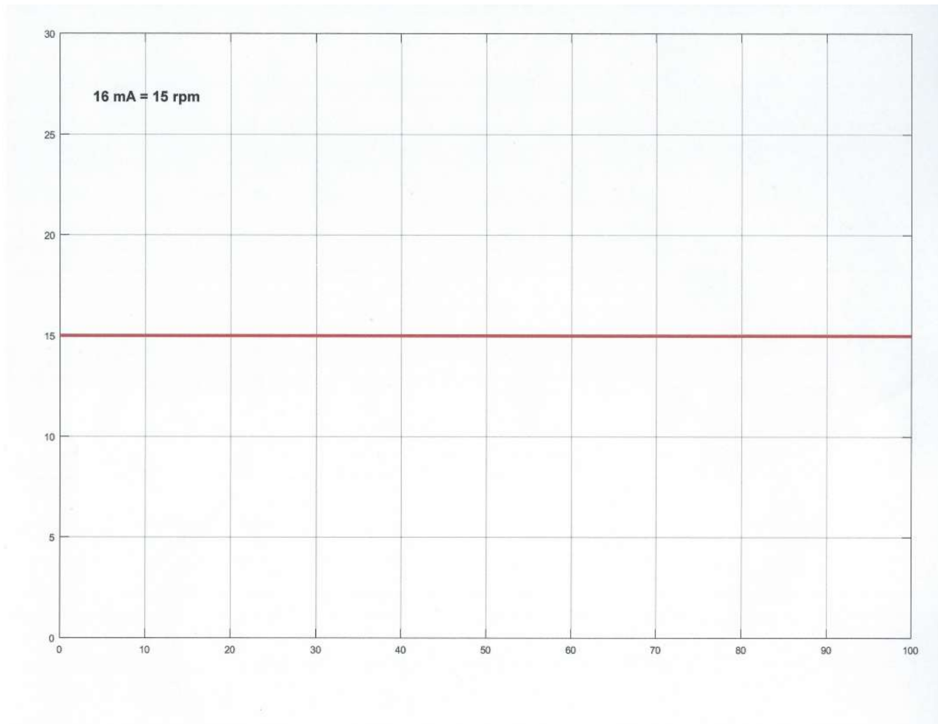


Fig. 7.10: Rotor speed, 16mA = 15rpm

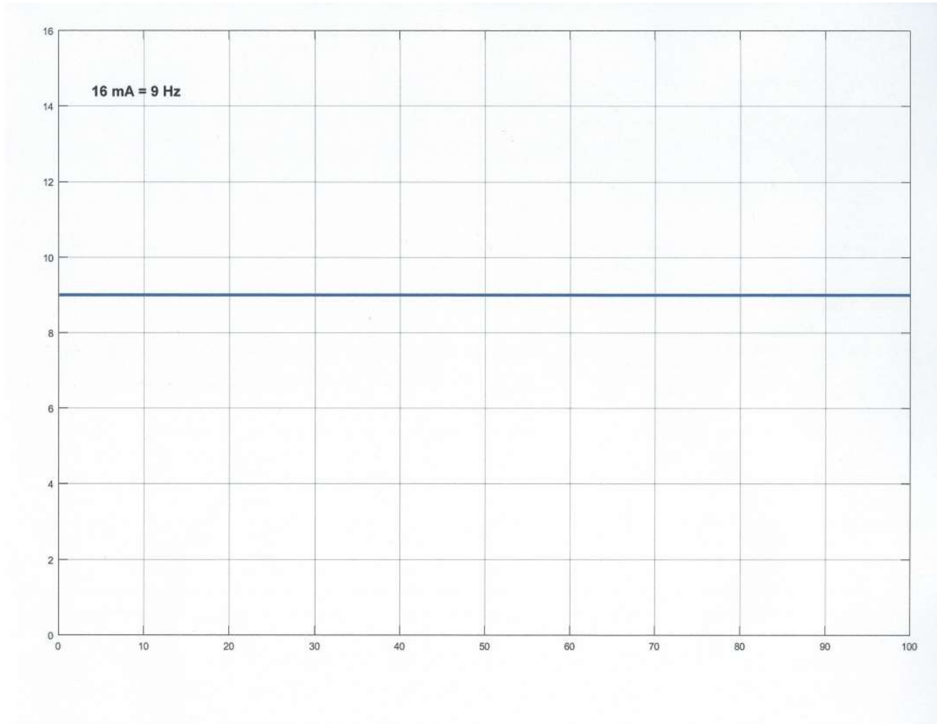


Fig. 7.11: Stator frequency, 16mA = 9Hz

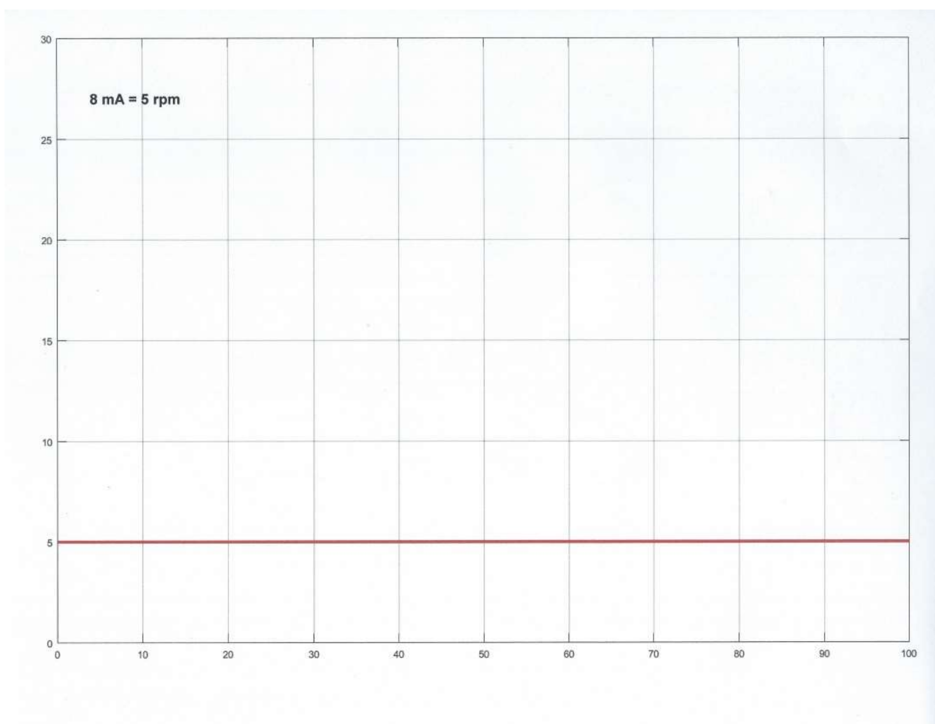


Fig. 7.12: Rotor speed, 8mA = 5rpm

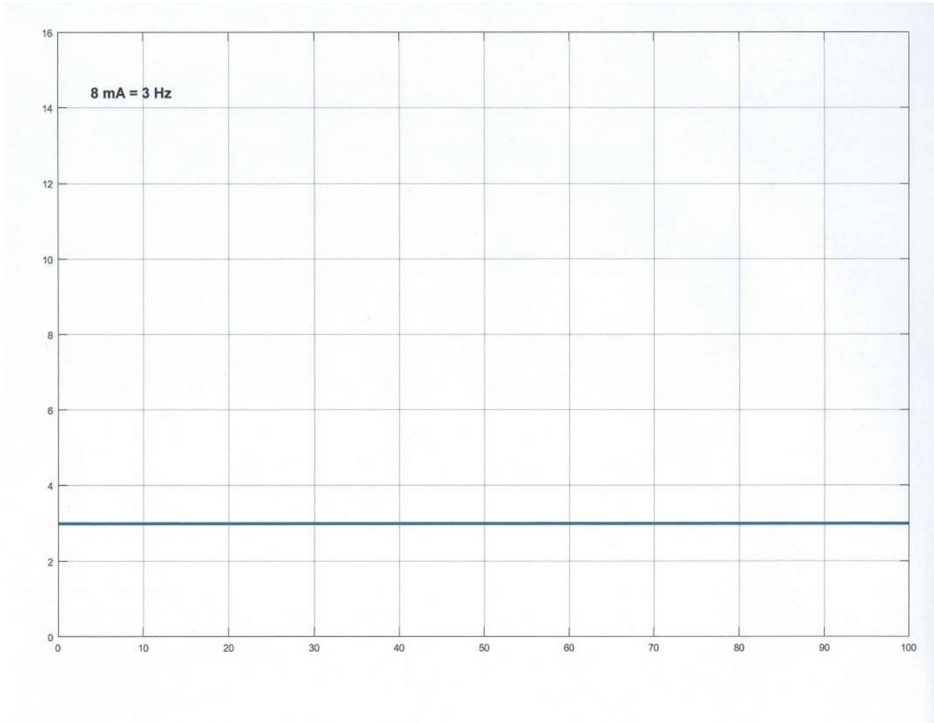


Fig. 7.13: Stator frequency, 8mA = 3Hz

7.6 The Rotor Brake Control

The rotor brake is similar to a large disk brake. A flange on the rotor forging is machined into a disk and multiple hydraulic cylinders compress disk brake calipers on both sides of the rotor disk, pressing the large brake pads onto the disk. A machined fabrication attached to the WT structure supports the calipers. There is a sealed and vented brake fluid reservoir.

A 24V signal from the brake control actuates an electro-hydraulic servo valve which compresses the brake fluid in the caliper cylinders to apply the rotor brake. When the brake control signal returns to 0V, the servo valve releases the pressure and removes the force applied to the calipers [32].

The rotor brake is applied whenever the wind speed is less than cut-in speed or greater than cut-out speed. The brake is also applied if the cable twist counter commands the yaw control to untwist the tower cables.
Fig. 7.14 depicts the Simulink model.

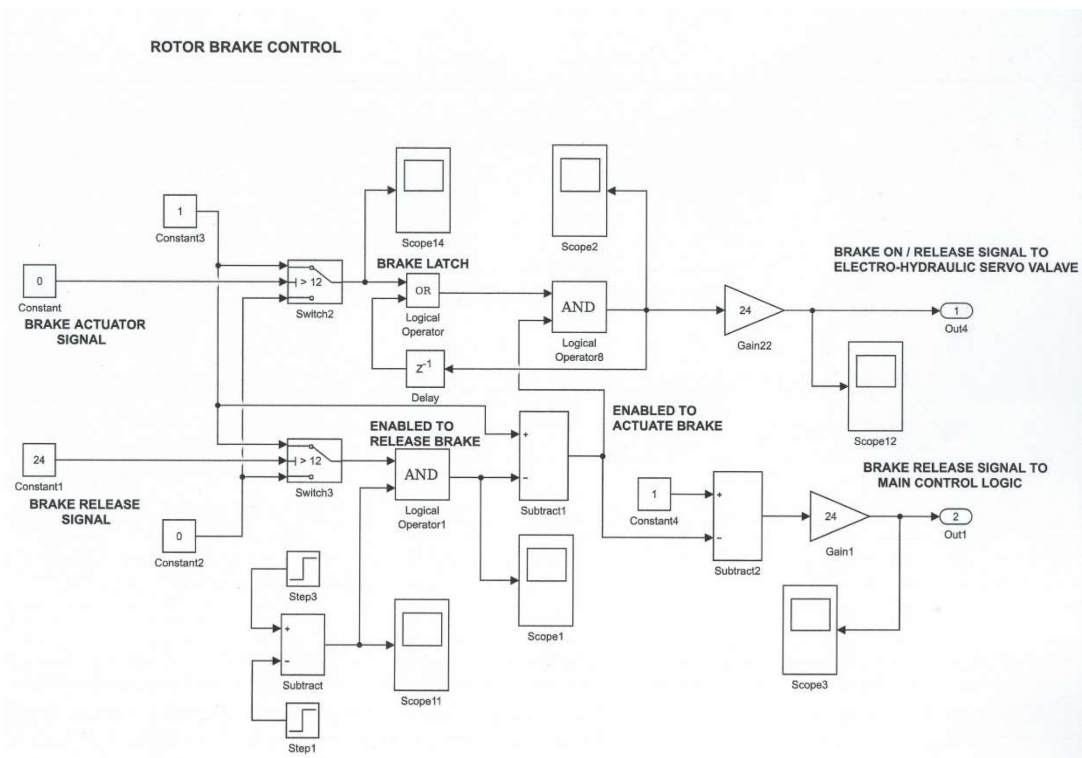
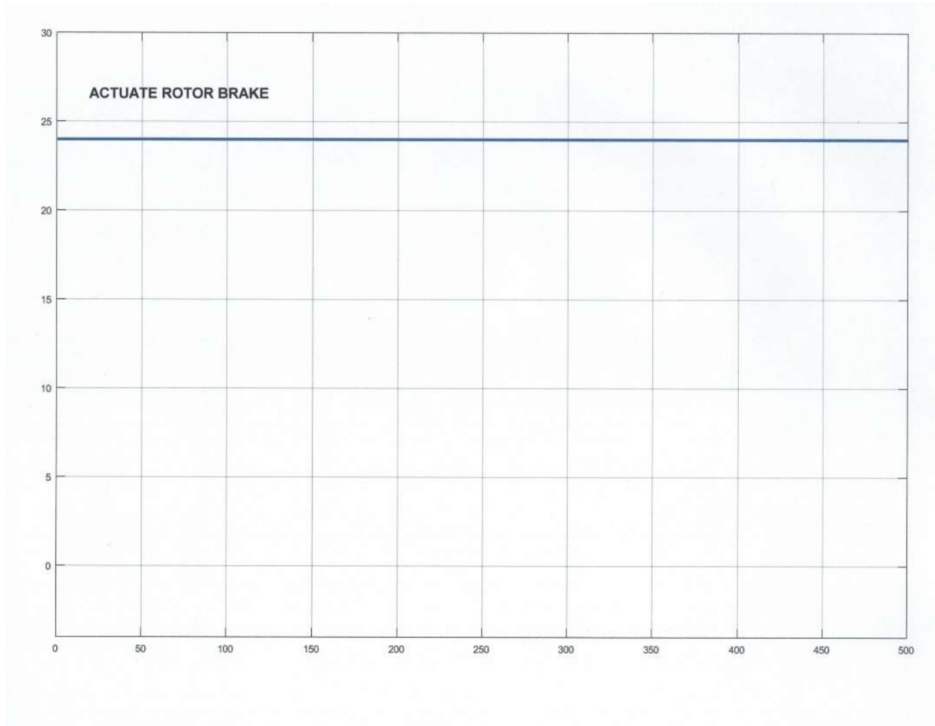


Fig. 7.14: The Simulink model of the rotor brake control

The



Simulink Model includes:

1. switches to apply or release the brake
2. a brake latch to hold the brake on (actuated)
3. a delayed 24V pulse to release the brake
4. logic including two subtractors and two and gates
5. a gain to create the 24V signal to the servo valve
6. scopes to observe simulation results

The brake actuator and release signal originate in the main logic control.

7.6.1 The Rotor Brake simulation

Simulations were run on this model, to demonstrate actuating and releasing the brake.

Fig. 7.15: The signal to the servo valve to actuate the rotor brake

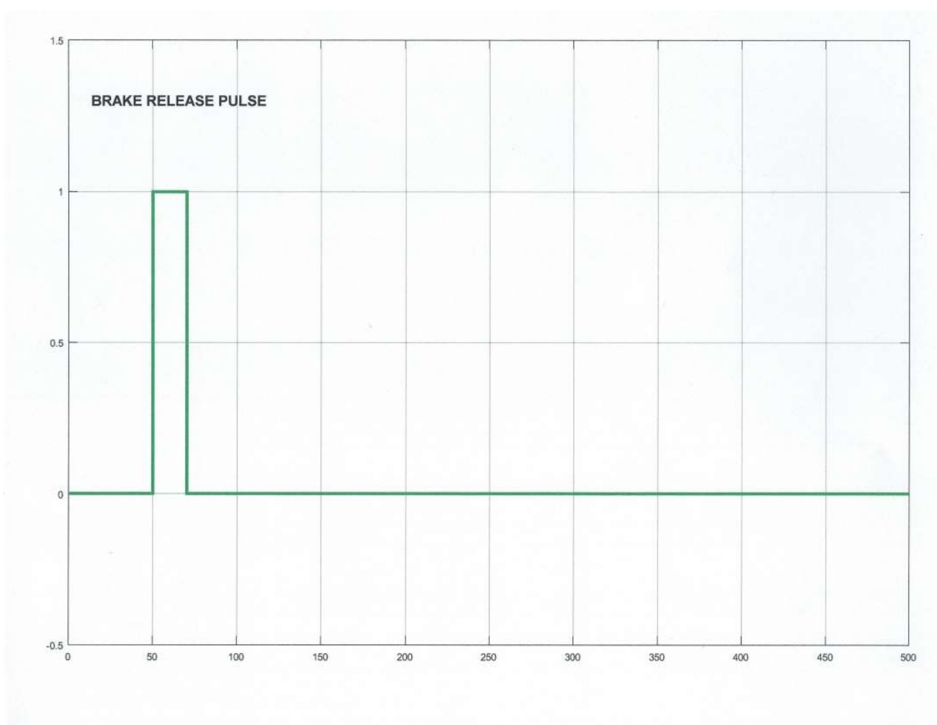


Fig. 7.16: The rotor brake release pulse (10sec.)

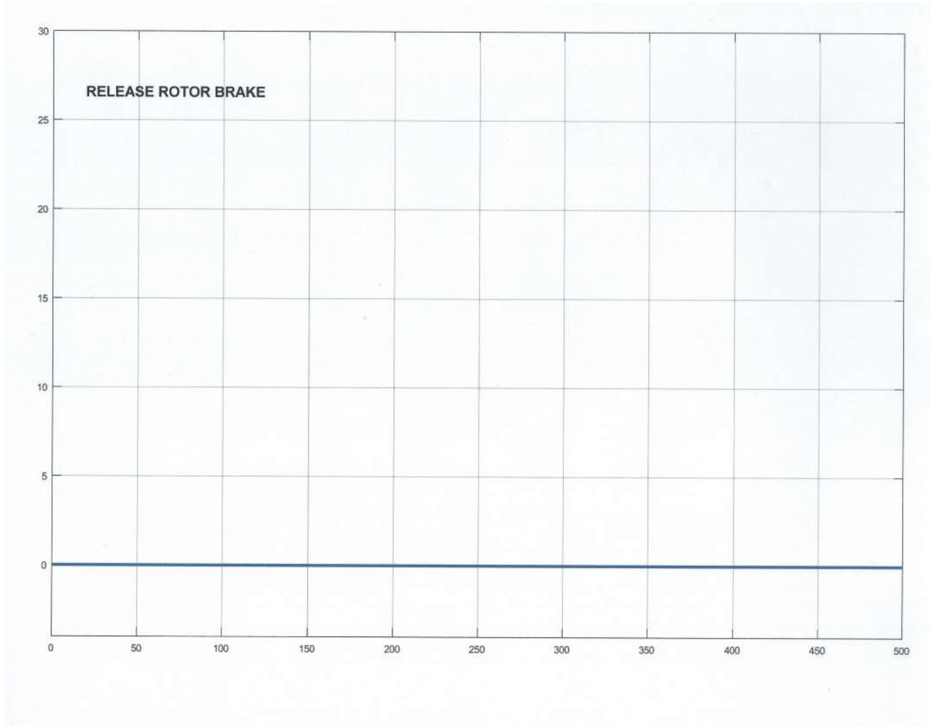


Fig. 7.17: The signal to the servo valve to release the rotor brake

7.7 The Wind Turbine Yaw Control

The yaw control will drive the WT to a new angular position depending on the wind vane angle relative to the actual angle of the WT horizontal axis. This angle must be periodically adjusted to keep the WT always pointed into the wind. The wind vane positions itself pointing down-wind. There is a sensor in the wind vane that provides a 4 – 20mA output signal which is input to the wind turbine control designating the wind direction. The wind vane is attached to the rear top of the nacelle and is permanently set so that its output = 12mA when pointing parallel to the horizontal axis of the WT. The yaw motor is controlled by a 24V signal to the CW or CCW motor control in the motor control center (MCC).

The yaw control also monitors the cable twist counter. Cables carry the current from the wind turbine generator down through the tower. The cables, however, will become more and more twisted if the turbine continually turns in the same direction. The WT is therefore equipped with cable twist counter limit switches –

there is a small enclosed gear mechanism (3:1 ratio) that trips the limit switches if the wind turbine makes three full revolutions CW or CCW.

The logic for the yaw control is:

if the wind vane angle becomes positive CW

then

drive the yaw motor CCW until the wind vane angle is zero

or

If the wind vane angle becomes positive CCW

then

drive the yaw motor CW until the wind vane angle is zero

also

if the CW cable twist limit switch closes

then

drive the yaw motor CCW until the zero twist limit switch closes

and

send a signal to the main control logic while driving the yaw motor

or

if the CCW cable twist limit switch closes

then

drive the yaw motor CW until the zero twist limit switch closes

and

send a signal to the main control logic blade while driving the yaw motor

Fig. 7.18 depicts the Simulink model of the yaw control.

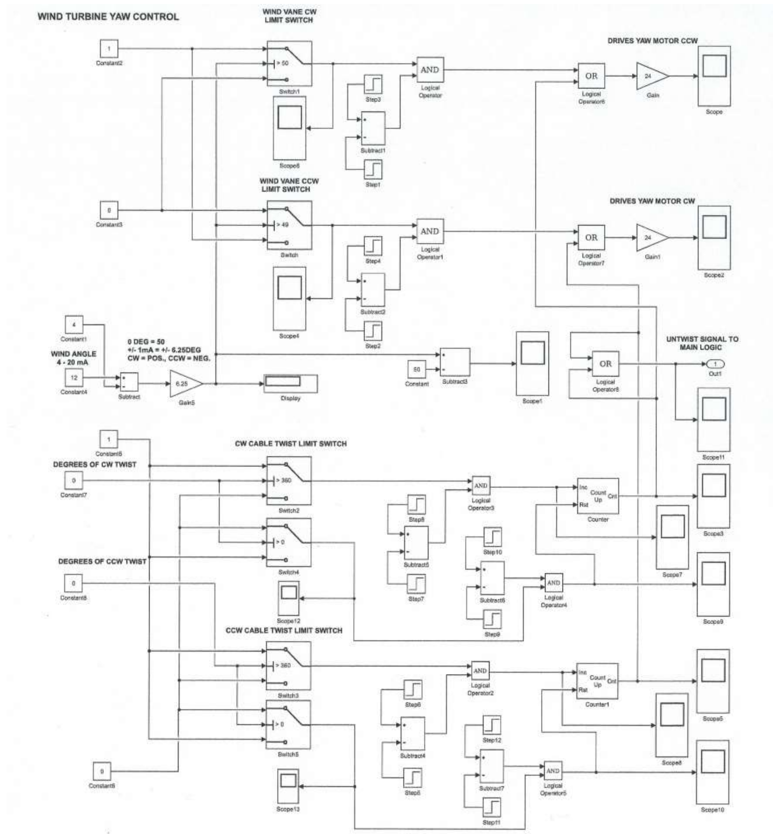


Fig. 7.18: Simulink Model of the Yaw Control

The Simulink Model includes:

1. wind vane CW and CCW limit switches
2. 6 AND gates to generate 10sec pulses
3. a subtractor to create a wind angle of zero
4. OR gates to drive the yaw motor from wind angle or untwist signal
5. CW and CCW twist limit switches
6. 2 counters to latch CW and CCW untwist drive signals
7. voltage gains to supply 24V to the CW and CCW yaw motor control
8. scopes to display the wind angle, limit switch positions, yaw motor control signals and the untwist signal

In summary, the model closes and opens the appropriate limit switches depending on the angle between the wind and the angle of the WT horizontal axis. The closing and opening of the limit switches determines when and if a signal is sent to the yaw drive motor control. When a drive motor control is energized, power is applied to the yaw motor to turn CW or CCW.

7.7.1 Yaw Control Simulation

Simulations were run on this model to demonstrate the response of the limit switches and the subsequent yaw motor control signals. Limit switches were opened and closed by applying different mA inputs to the wind angle converter and to the degrees of CW and CCW twist.

Table 7.1: Summary of Yaw Control Operation

WIND ANGLE mA	WIND ANGLE DEG	WIND ANGLE DIRECTION	WIND ANGLE SIGNAL	CW LIMIT SWITCH	CCW LIMIT SWITCH	YAW MOTOR RELAY
11	6.25	CCW	43.75	CLOSED	OPEN	CW
12	0.00		50.00	OPEN	OPEN	
13	6.25	CW	56.25	OPEN	CLOSED	CCW

Table 7.2: Twist Control Operation

WT TWIST CONTROL

CW LIMIT SWITCH	CCW LIMIT SWITCH	YAW MOTOR RELAY
0	0	OFF
0	1	CW
1	0	CCW

Fig. 7.19 and 7.20 depict the yaw motor drive signal with a wind angle = yaw angle. (i.e. no correction is needed) Fig. 7.21 and 7.22 depict the yaw motor drive signal with a wind angle = 6.25deg.

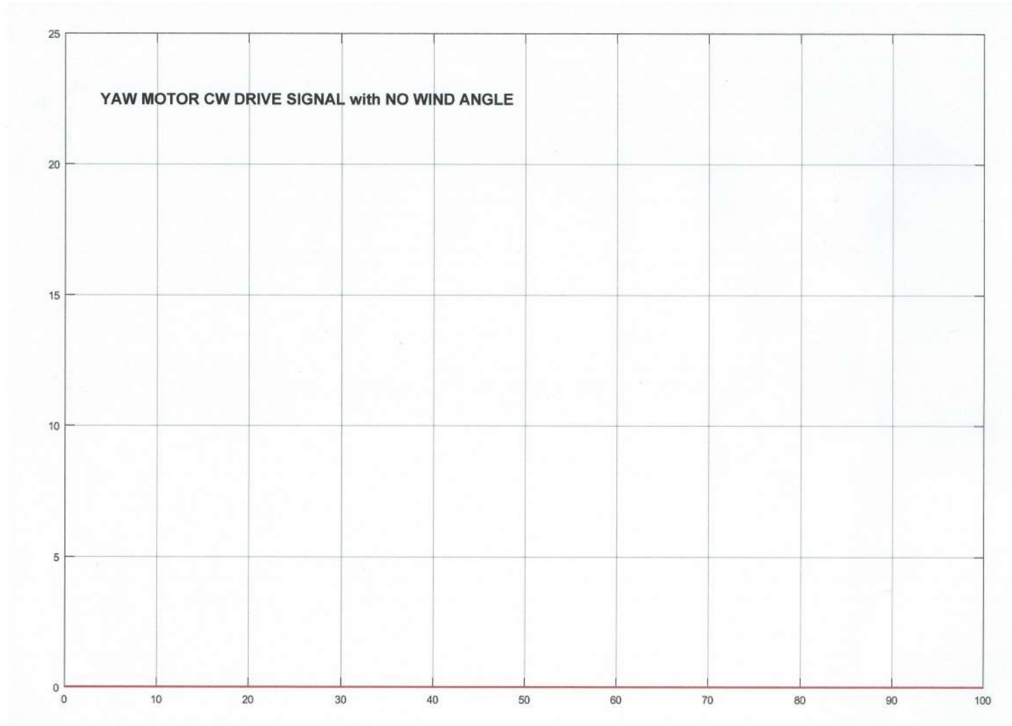


Fig. 7.19: Yaw motor CW drive signal with wind angle = 0deg

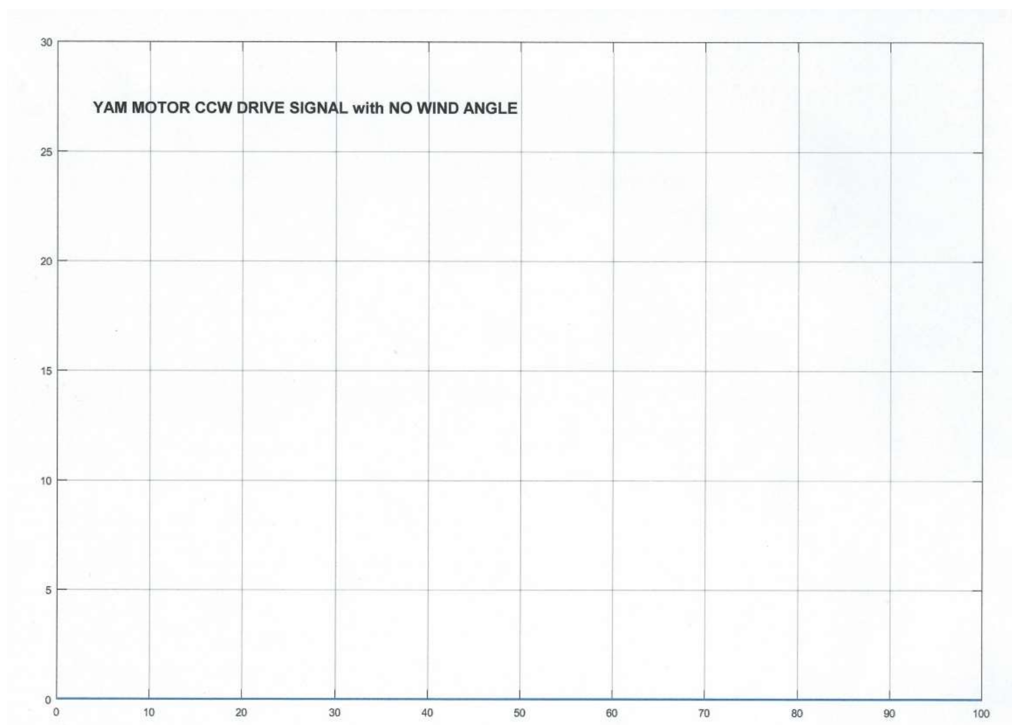


Fig. 7.20: Yaw motor CCW drive signal with wind angle = 0deg

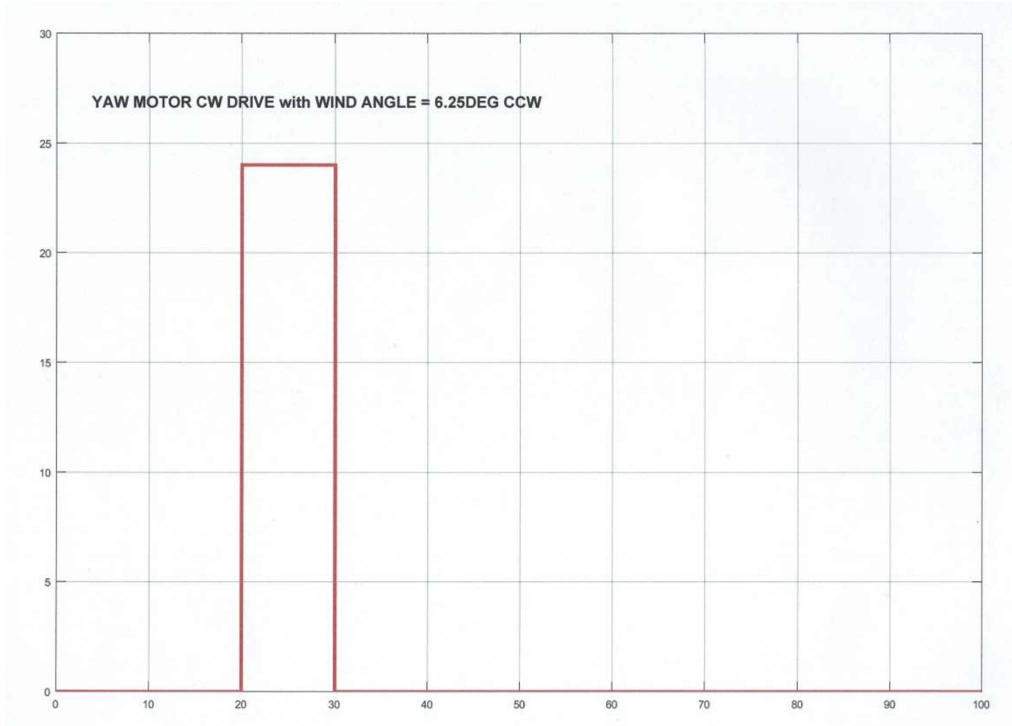


Fig. 7.21: Yaw motor CW drive signal with wind angle = 6.25deg CCW

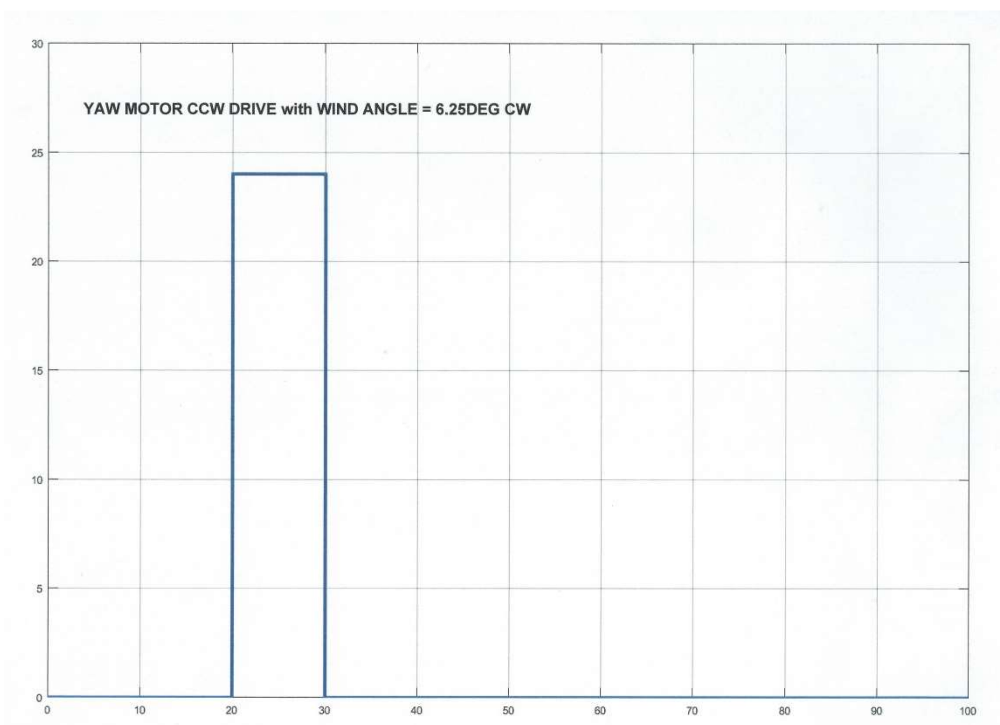


Fig. 7.22: Yaw motor CCW drive signal with wind angle = 6.25deg CW

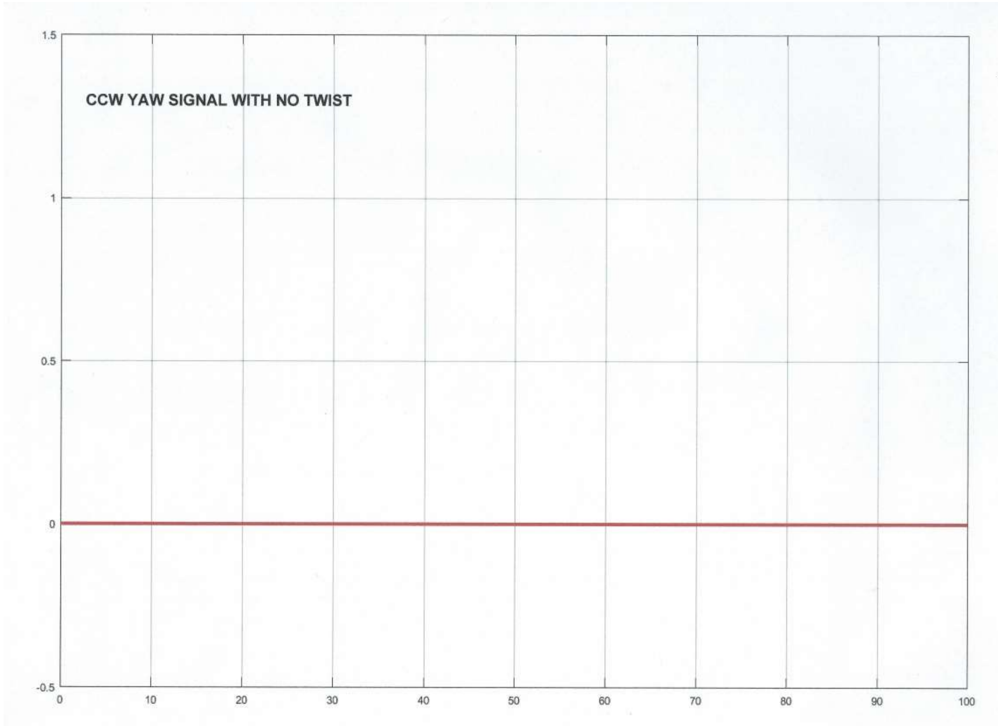


Fig. 7.23: Yaw motor CCW signal with no twist

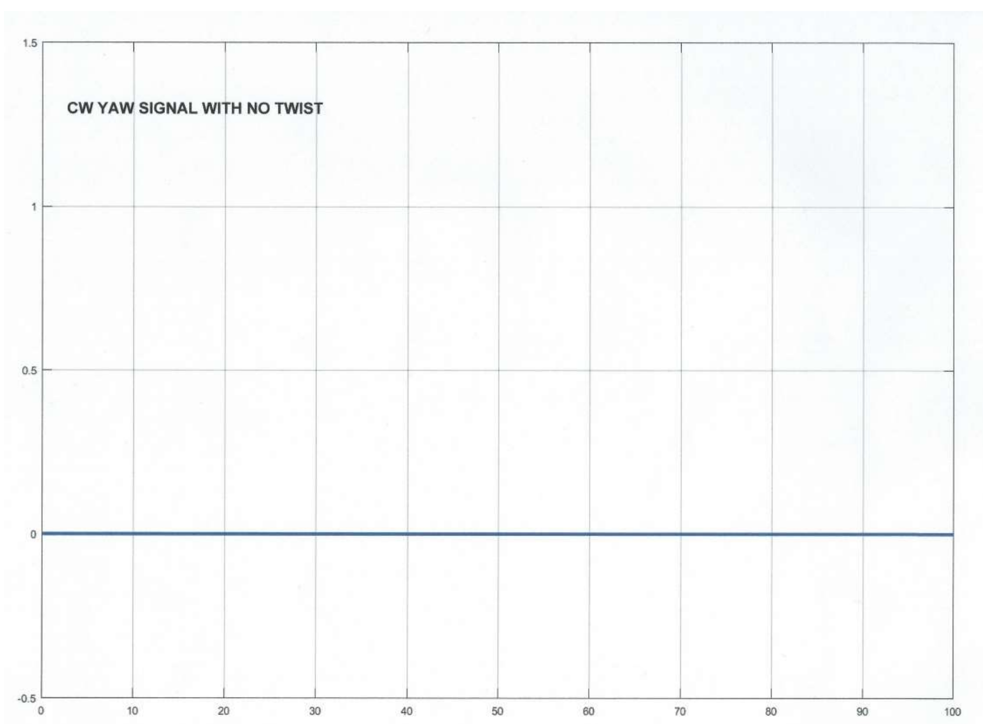


Fig. 7.24: Yaw motor CW signal with no twist

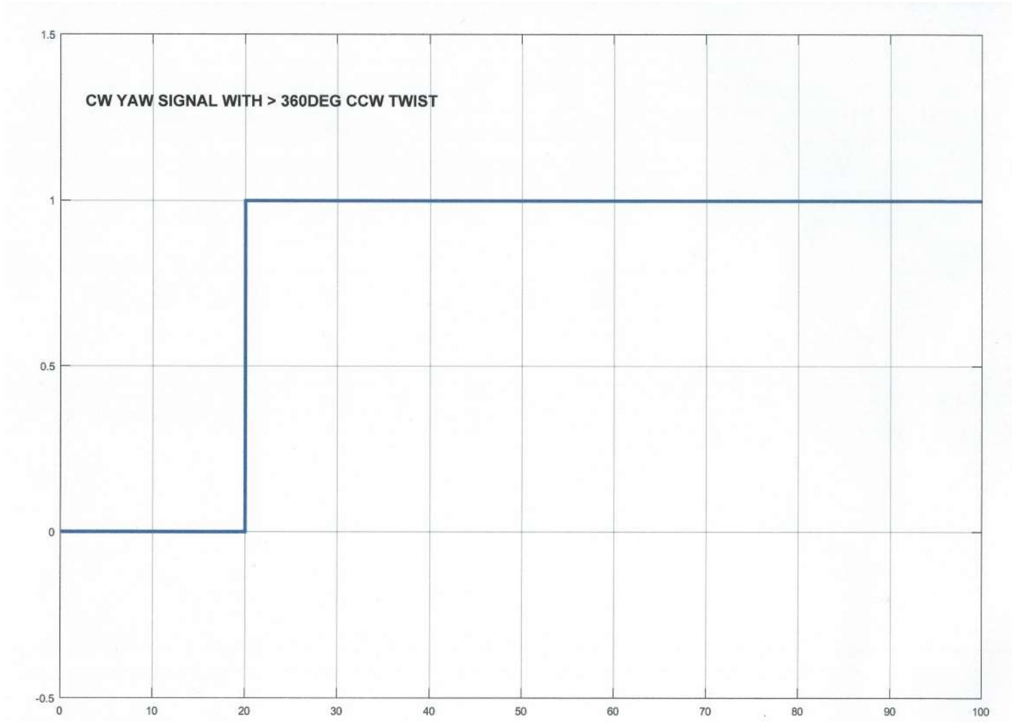


Fig. 7.25: Yaw motor CW signal with twist > 360deg

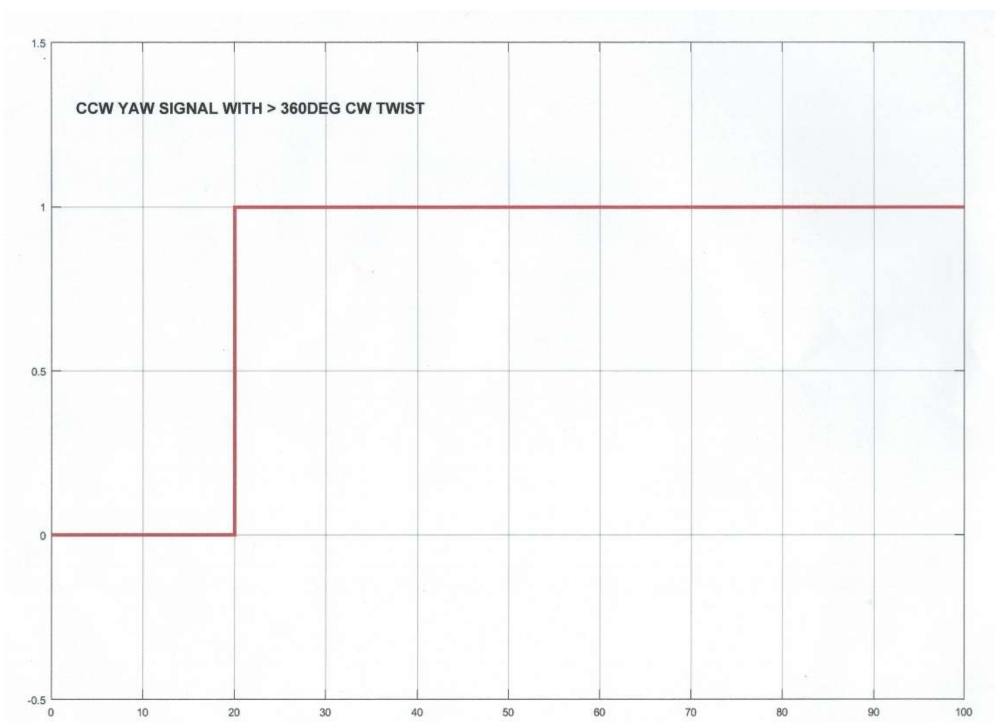


Fig. 7.26: Yaw motor CCW signal with twist > 360deg

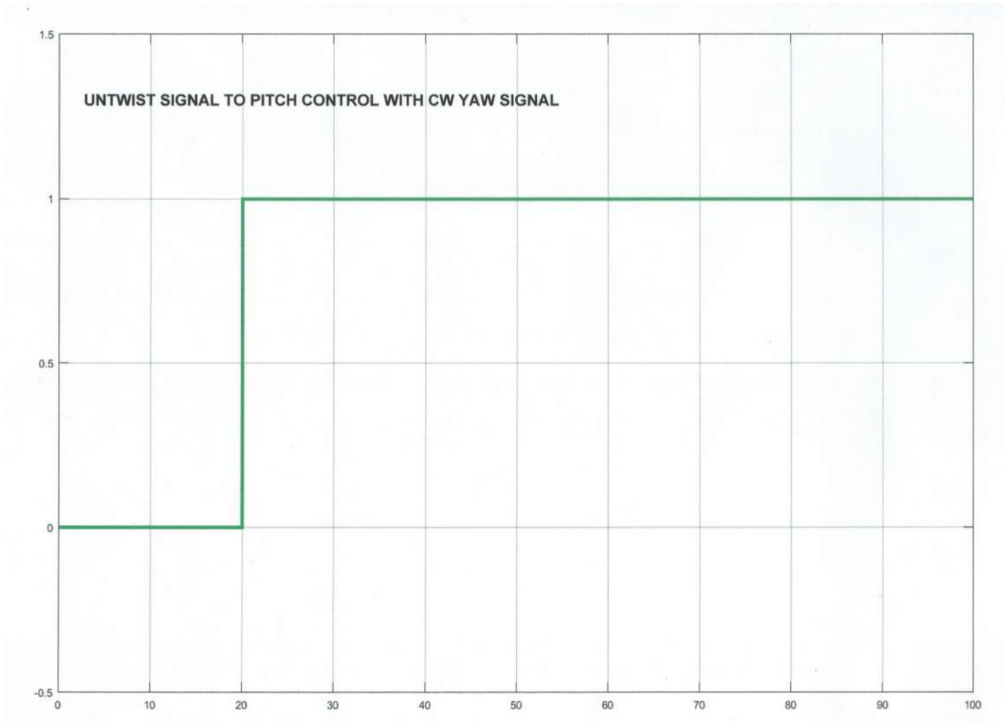


Fig. 7.27: Yaw motor CW signal to untwist

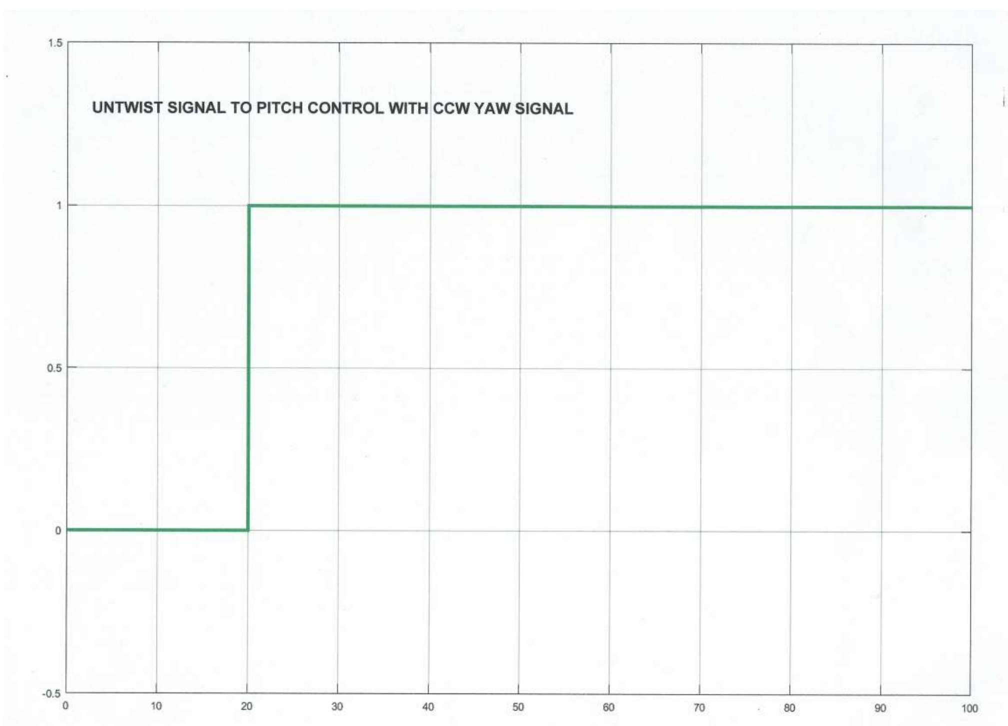


Fig. 7.28: Yaw motor CCW signal to untwist

7.8 Rotor Blade Pitch Servomotor Control

The rotor blades capture the wind and transfer its power to the rotor hub. On the Target WT, each rotor blade measures 40 meters in length (from the tip to the wind turbine horizontal axis) and is designed much like a wing of an airplane. At the base of each wind turbine blade is an interior round flange which is bolted to a matching flange in the rotor hub that can rotate to adjust the blade pitch. Attached to this hub flange is a ring gear, which is meshed with a smaller gear on a servomotor assembly. The servomotor and coaxial gearbox turns the rotor blade between 0° and 90° around its longitudinal axis. There are three independent blade pitch mechanisms located in the hub, 120 degrees radially apart.

The rotor blades can turn and change the pitch a few degrees every time the wind speed changes in order to keep them at the optimum angle which maximizes output for all wind speeds. The amount of surface area available for the incoming wind is most important to increasing aerodynamic forces on the rotor blades. The angle at which the blade is adjusted is referred to as the angle of attack. This angle is measured with respect to the incoming wind direction and the chord line of the blade [45]. When wind speeds are below rated speed, the rotor blades are turned fully towards the wind which means that the pitch is positioned for full power, an angle of 90deg. At increasing wind speeds, the pitch of the blades is controlled in order to limit the power output of the turbine to 3.00MW. When wind speeds increase to cut-out speed, the rotor blades are turned fully away from the wind (feathered) which means that the pitch is positioned for no power, an angle of 0deg.

Each servomotor is a closed-loop servomechanism that uses position feedback to control its motion and final position. The input to its control is a signal representing the desired position for the blade pitch. The motor is paired with an encoder to provide blade position feedback. The measured angle of the blade is compared to the desired position, the input to the controller. If the output position differs from that required, an error signal is generated which then causes the motor to rotate in either direction, as needed to bring the blade pitch to the correct position. As the angle approaches the correct blade angle, the error signal reduces to zero and the servomotor stops. In case of power loss to the WT, backup batteries are located in the hub to drive the blade pitch to minimum power [33].

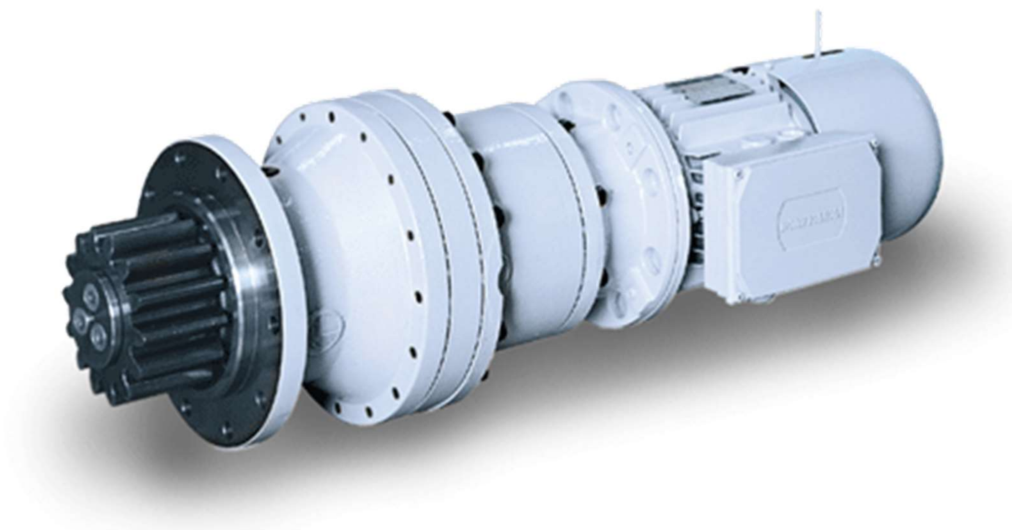


Fig. 7.29: A coaxial servomotor, gearbox and drive gear [34]

Fig. 7.30 depicts the Simulink model of the blade pitch servomotor control

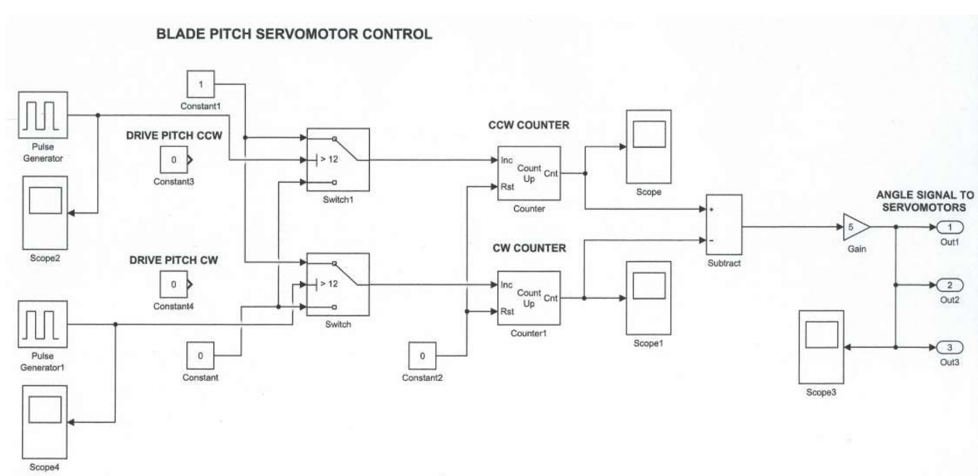


Fig. 7.30: The Simulink model of the blade pitch servomotor control

The Simulink Model includes:

1. pulse generators to simulate drive signal inputs
2. 2 limit switches to detect CCW and CW commands
3. 2 counters to count CCW and CW commands
4. A subtractor to calculate the current required angle to the servomotors
5. scopes to display the counter outputs and the required angle

In summary, the model closes and opens the appropriate limit switches depending on the signals from the main control logic to increase or decrease the required blade pitch angle

7.8.1 Blade Pitch Servomotor Control Simulation

Several simulations were run on this model to demonstrate how different power demands position the blade angles.

Fig. 7.31 and 7.32 depict the CCW and CW pitch counters. Fig. 7.33 depicts the blade pitch position demand signal to the servomotors. It can be seen that the trend is to turn the blades CCW, to a position of 25 degrees, increasing power. This can be interpreted to mean that the wind speed is above rated speed and the main control logic is controlling the blade pitch to maintain constant output power during a period of decreasing wind speed.

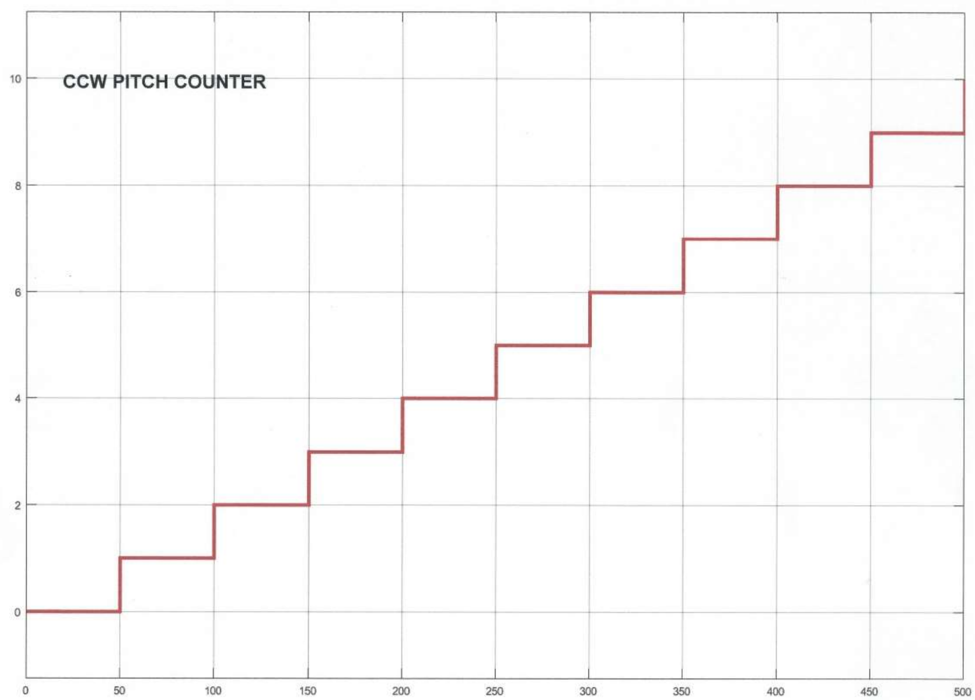


Fig. 7.31: CCW pitch angle counter

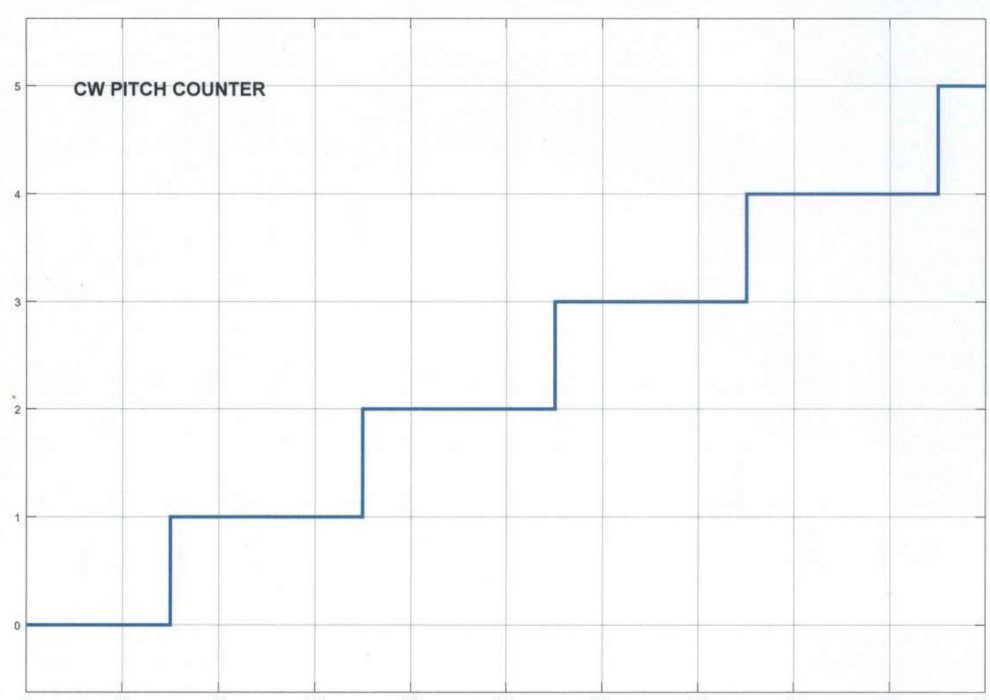


Fig. 7.32: CW pitch angle counter

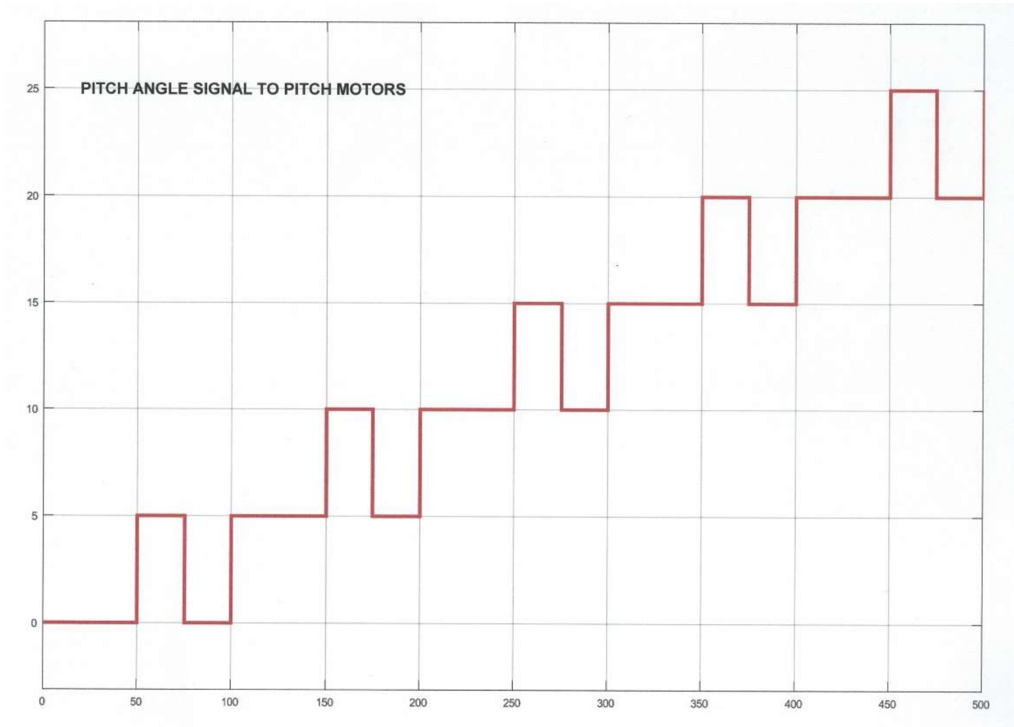


Fig. 7.33: Blade pitch position demand signal to the servomotors

7.9 The Main Control Logic

The main control logic will:

1. signal the blade pitch servomotor control to drive the pitch motors CW or CCW
2. signal the rotor brake control to actuate or release the rotor brake
3. signal the generator breaker control to trip the breaker or that it is "ok to close breaker"

The inputs to the main control logic are:

1. rotor brake release signal from the rotor brake control ($24V_{DC}$)
2. generator breaker closed signal from the generator breaker control ($24V_{DC}$)
3. power reference signal from the Remote Control and Monitoring (4 – 20 mA = 0 – 3000kW)

4. the AC to AC converter V_{LN} and $I\Phi$ signals (all three) from the PTs and CTs (4 – 20 mA)
5. anemometer signal from the anemometer signal conditioner (4 – 20 mA)
6. untwist signal from the yaw control (0 or $5V_{DC}$)

The main control logic is the heart of the control system. The blade pitch control will signal the blade pitch servomotor control, rotor brake control and the generator breaker.

- adjusting the blade pitch to a new position by demanding the pitch servomotor to either rotate CCW or CW.
- a blade pitch CW position of 0 degrees is the angle of minimum power. The blade pitch must be minimum if the PMG frequency < 0.08Hz (cut-in speed) or > 10.4Hz (cut-out speed) and the rotor brake must be actuated to help stop the rotor
- from 0.08Hz (cut-in speed) up to 7.2Hz (rated speed), the blade pitch is set for maximum power, a blade angle of 90 degrees and the rotor brake must be released
- between 7.2Hz and 10.4Hz, the blade pitch must be continually adjusted to maintain rated power of 3.00MW.
- if the un-twist signal is enabled, the blade pitch is set for minimum power and the rotor brake is actuated. When the signal is subsequently disabled, the control resumes normal operation.
- anytime the rotor brake is actuated, the generator breaker is tripped.

Table 7.3 provides a summary of the main control logic functions.

Fig. 7.34 depicts the Simulink model of the main control logic.

Table 7.3: Summary of Main Logic Control

GENERATOR BREAKER	WIND SPEED m/s	ROTOR BRAKE	CUT-IN LIMIT SWITCH WS > 3.5	RATED SPEED LIMIT SWITCH WS > 14	CUT-OUT LIMIT SWITCH WS > 25	POWER Kw	CW DRIVE	CCW DRIVE	BLADE PITCH ANGLE
TRIPPED	0	ON	OFF	OFF	OFF			ON	ROTATING TO FULL CCW
TRIPPED	7.5	OFF	ON	OFF	OFF		ON		ROTATING TO FULL CW
TRIPPED	15	OFF	ON	ON	OFF				FULL CW
TRIPPED	30	ON	ON	ON	ON				ROTATING TO FULL CCW
CLOSED	7.5	OFF	ON	OFF	OFF	2994	PULSES		ROTATING CW
CLOSED	15	OFF	ON	ON	OFF	3005		PULSES	ROTATING CCW
CLOSED	24	OFF	ON	ON	OFF	2994	PULSES		ROTATING CW
CLOSED	30	ON	ON	ON	ON				ROTATING TO FULL CCW

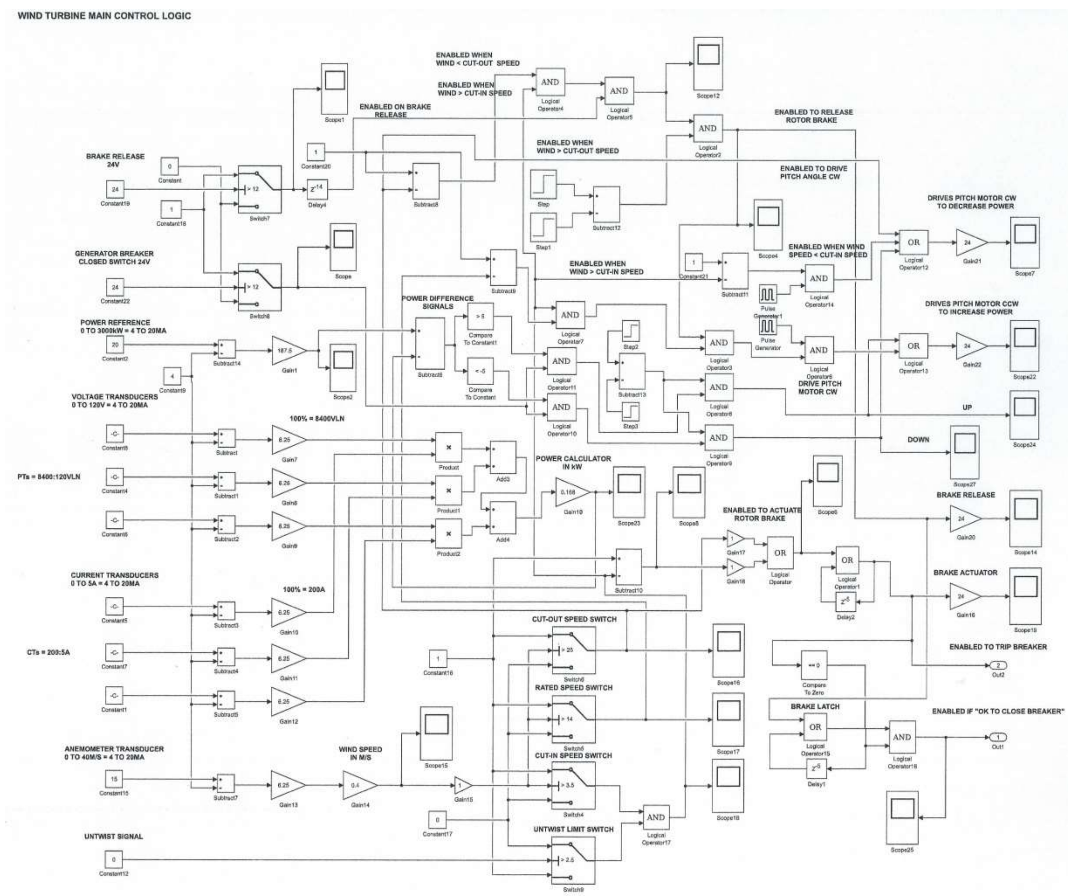


Fig. 7.34: Simulink Model of the Main Control Logic

The Simulink Model includes:

1. wind speed calculator
2. 3 limit switches to detect wind speed
3. untwist limit switch
4. converter voltages and currents calculator
5. power calculator
6. brake release limit switch and generator breaker limit switch
7. power difference calculator
8. pitch control logic
9. rotor brake control logic
10. generator breaker control logic
11. scopes to display limit switch actions and calculator results

In summary, the model closes and opens the appropriate limit switches depending on input signals and calculates outputs to control pitch, rotor brake and generator breaker.

Table 7.4: Voltage and Current Signals (mA) vs Power

AT THE GENERATOR BREAKER

	EIGHTH POWER	**QUARTER POWER**	**HALF POWER**	**RATED POWER**	**CUT-OUT POWER**	
P	0.375	0.75	1.50	3.00	3.00	MW
V_{LL}	13.8	13.8	13.8	13.8	13.8	kV RMS
V_{LN}	7.9674	7.9674	7.9674	7.9674	7.9674	kV
Ia	15.7	31.4	62.8	125.5	125.5	A RMS
V	19.176	19.176	19.176	19.176	19.176	mA
I	5.255	6.510	9.020	14.041	14.041	mA

7.9.1 Main Control Unit Simulation

A number of simulations were run on this model to demonstrate logic and calculator performance.

7.9.2 Wind Speed Calculation and Limit Switches

Fig. 7.35 through Fig. 7.38 depicts the wind speed and limit switch action at a wind speed of 0m/s.

Fig. 7.39 and Fig. 7.40 depict the wind speed and cut-in speed limit switch action at a wind speed of 5m/s. Note the 100sec delay to assure the wind speed is steady.

Fig. 7.41 and Fig. 7.42 depict the wind speed and rated speed limit switch action at a wind speed of 15m/s.

Fig. 7.43 and Fig. 7.44 depict the wind speed and cut-out speed limit switch action at a wind speed of 27.5m/s.

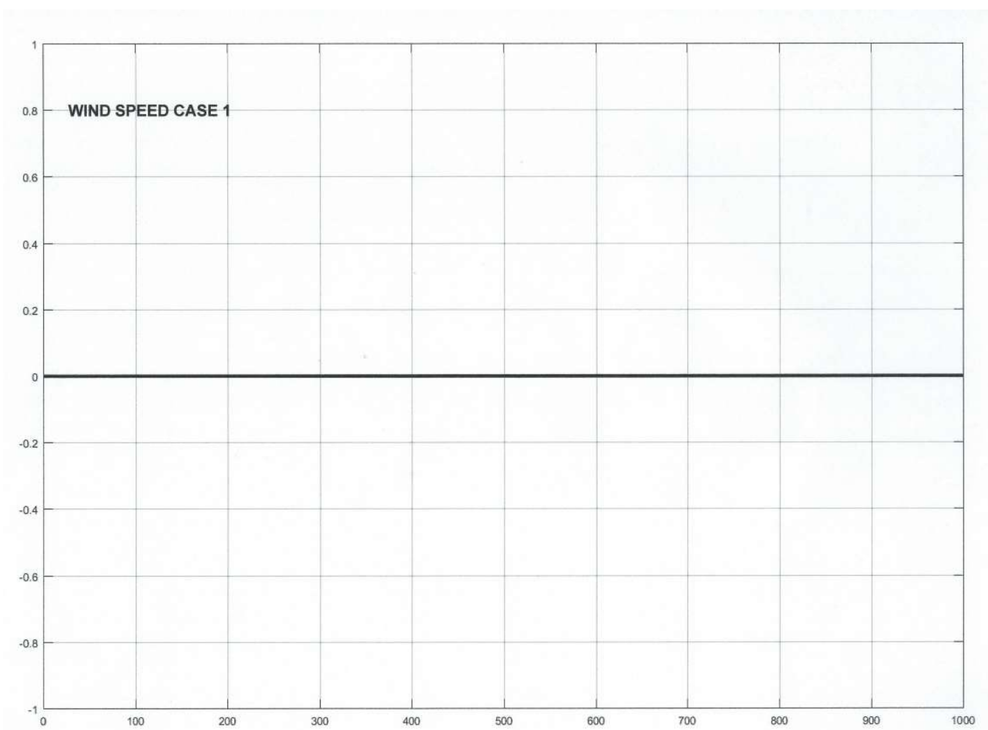


Fig. 7.35: Wind Speed = 0m/s

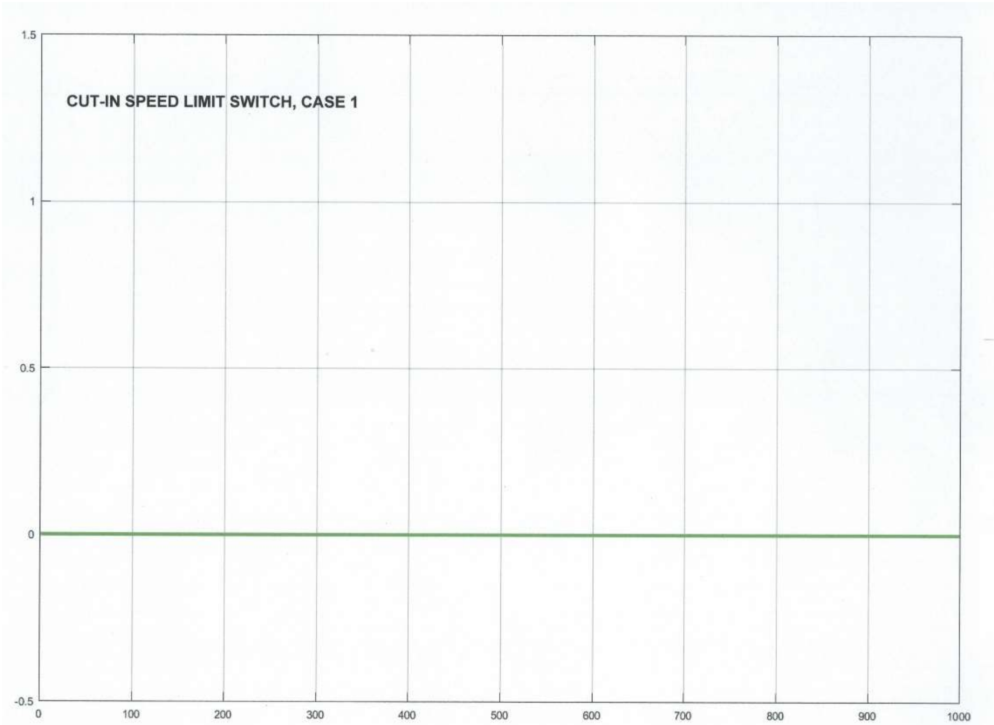


Fig. 7.36: Cut-in Speed Limit Switch, Wind Speed = 0m/s

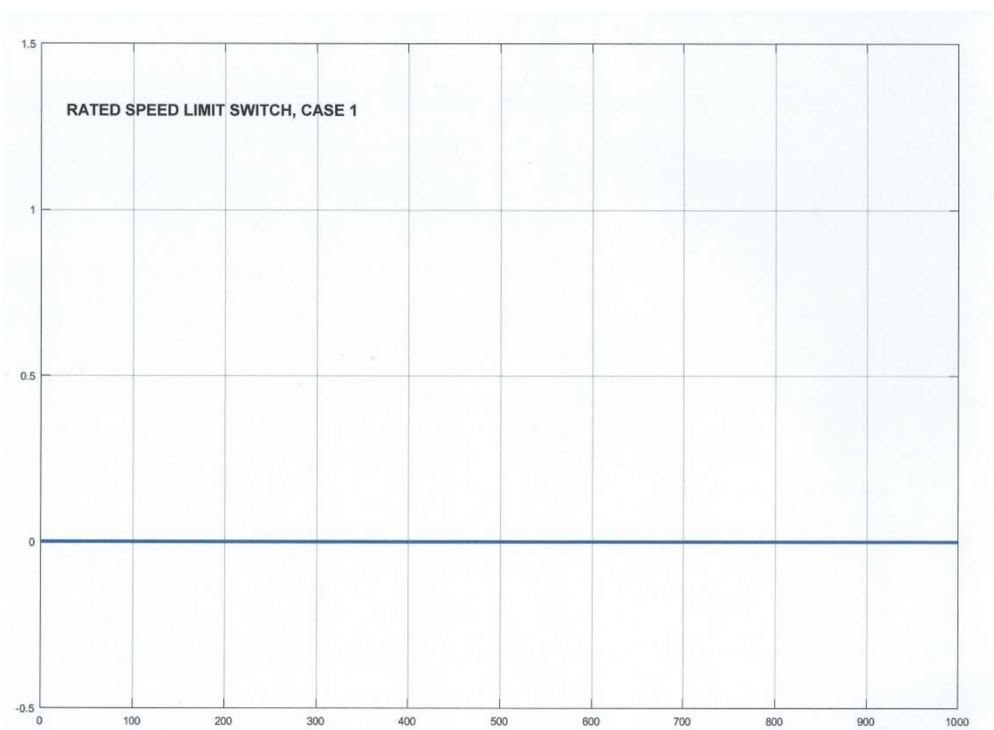


Fig. 7.37: Rated Speed Limit Switch, Wind Speed = 0m/s

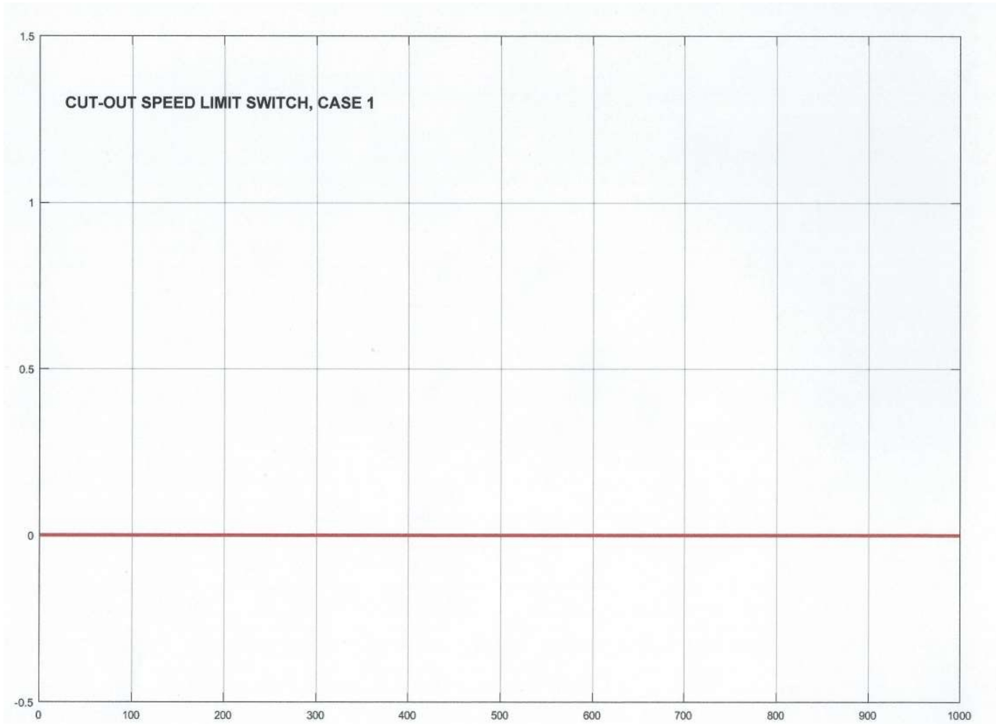


Fig. 7.38: Cut-out Speed Limit Switch, Wind Speed = 0m/s

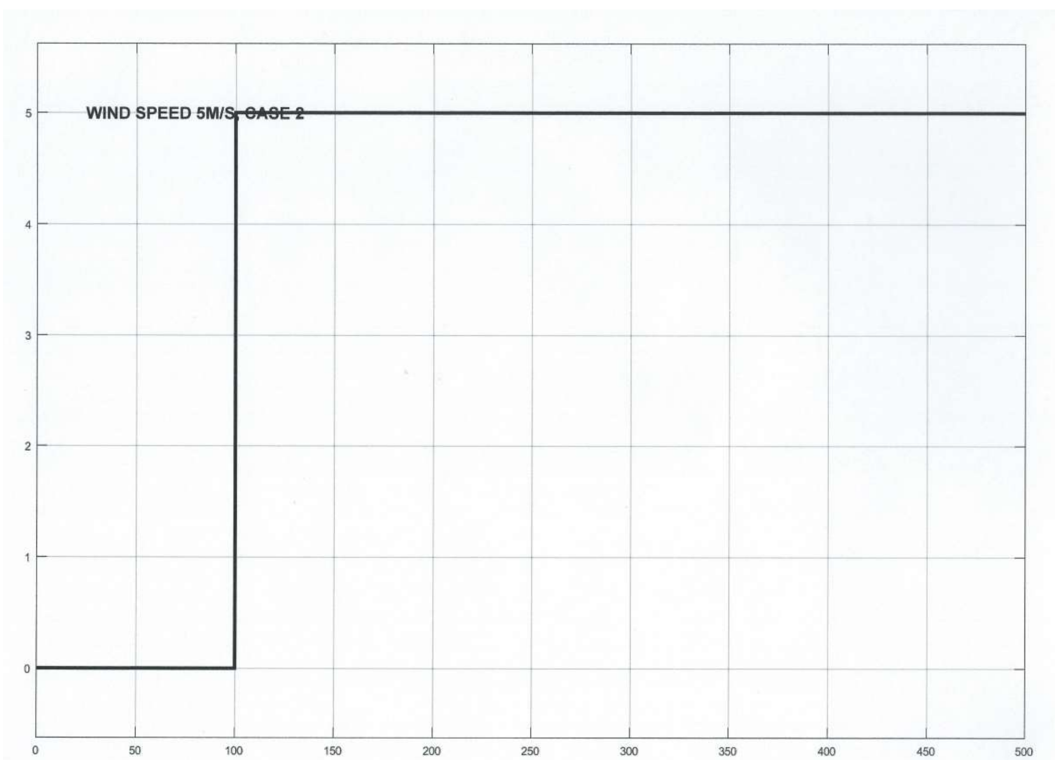


Fig. 7.39: Wind Speed = 5m/s

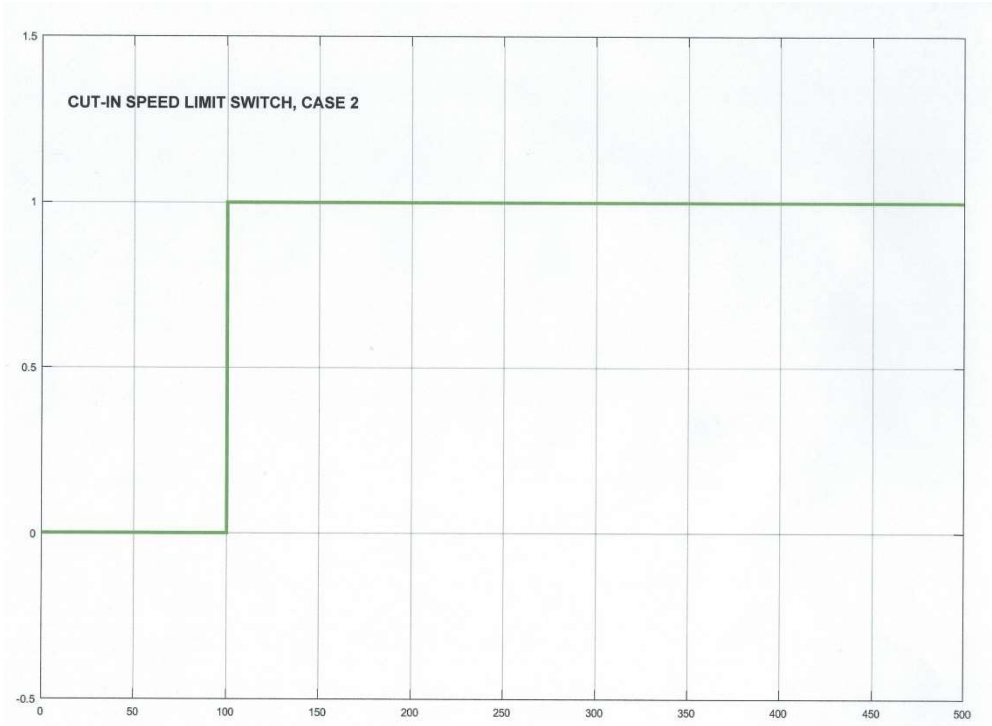


Fig. 7.40: Cut-in Speed Limit Switch, Wind Speed = 5m/s

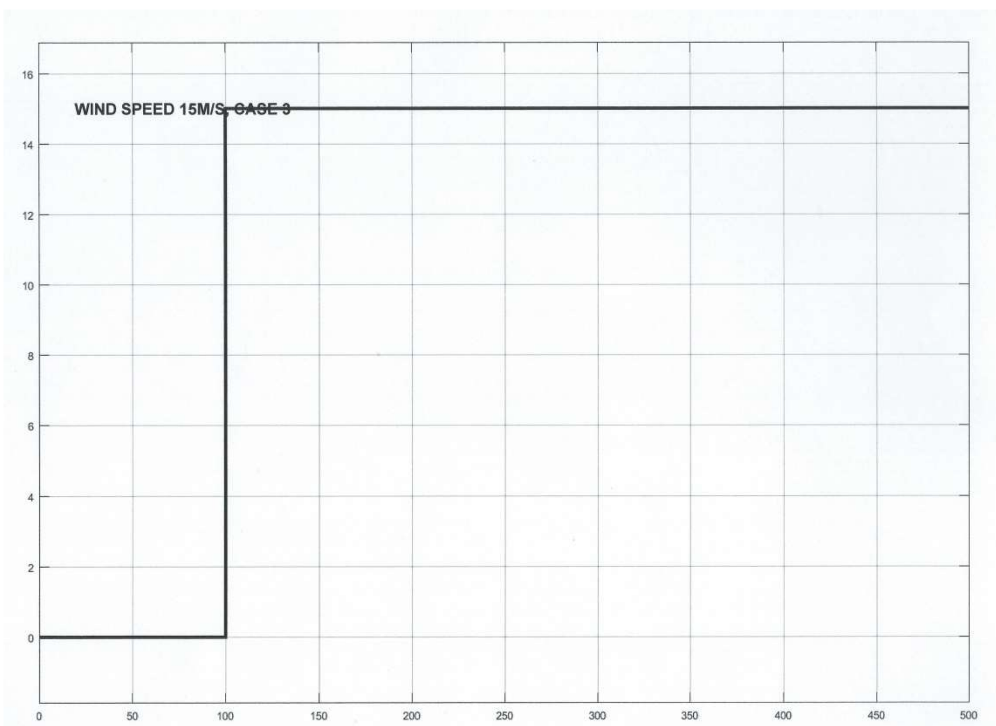


Fig. 7.41: Wind Speed = 15m/s

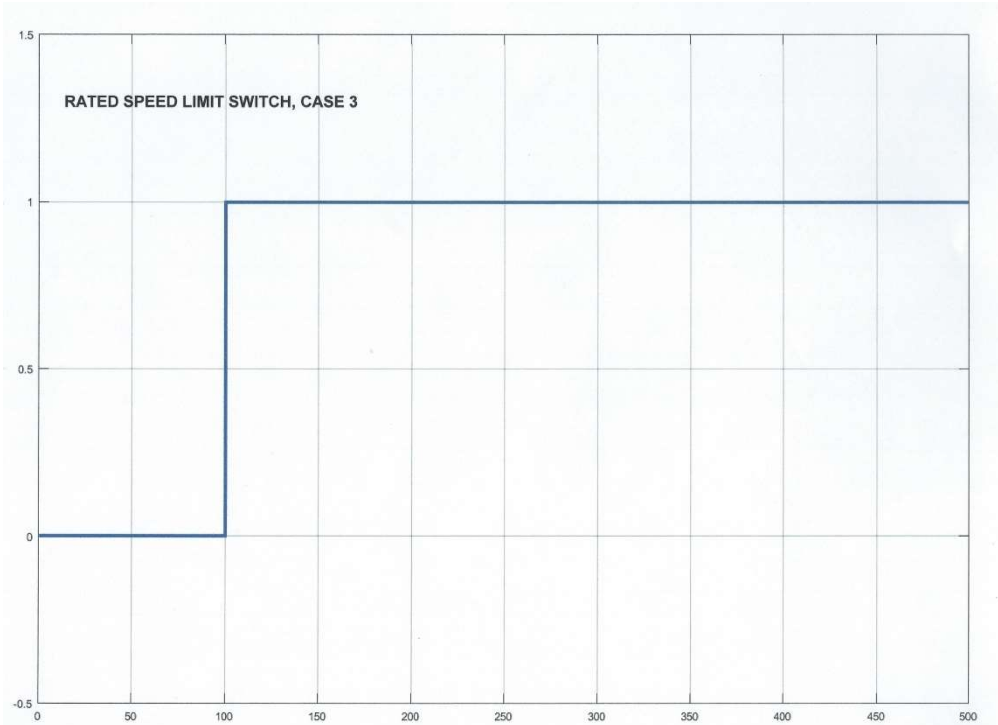


Fig. 7.42: Rated Speed Limit Switch, Wind Speed = 15m/s

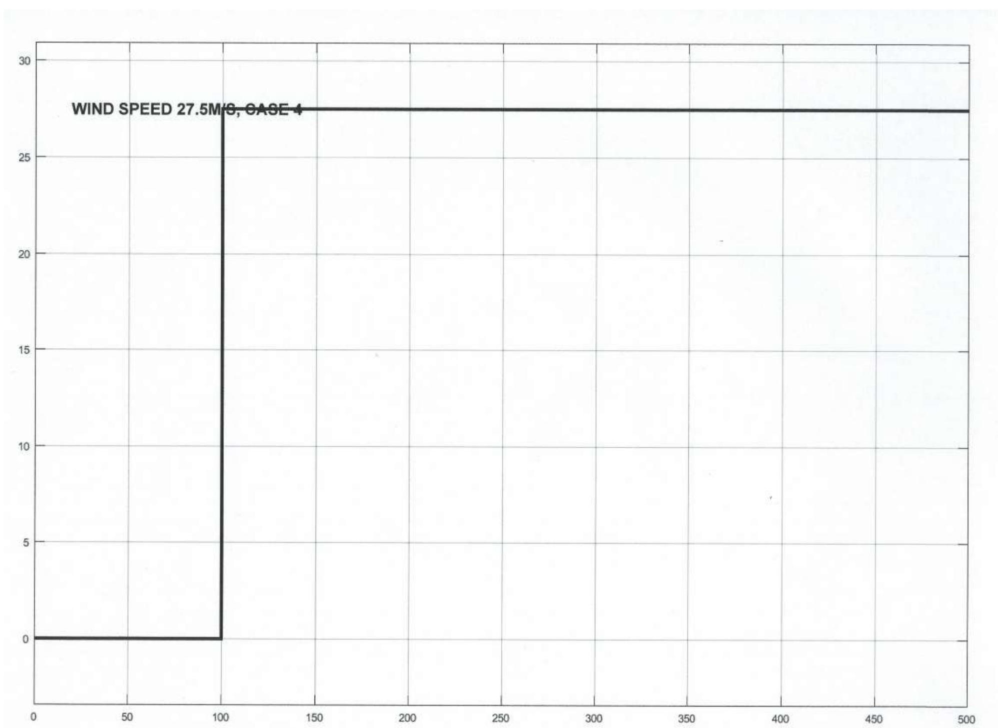


Fig. 7.43: Wind Speed = 27.5m/s

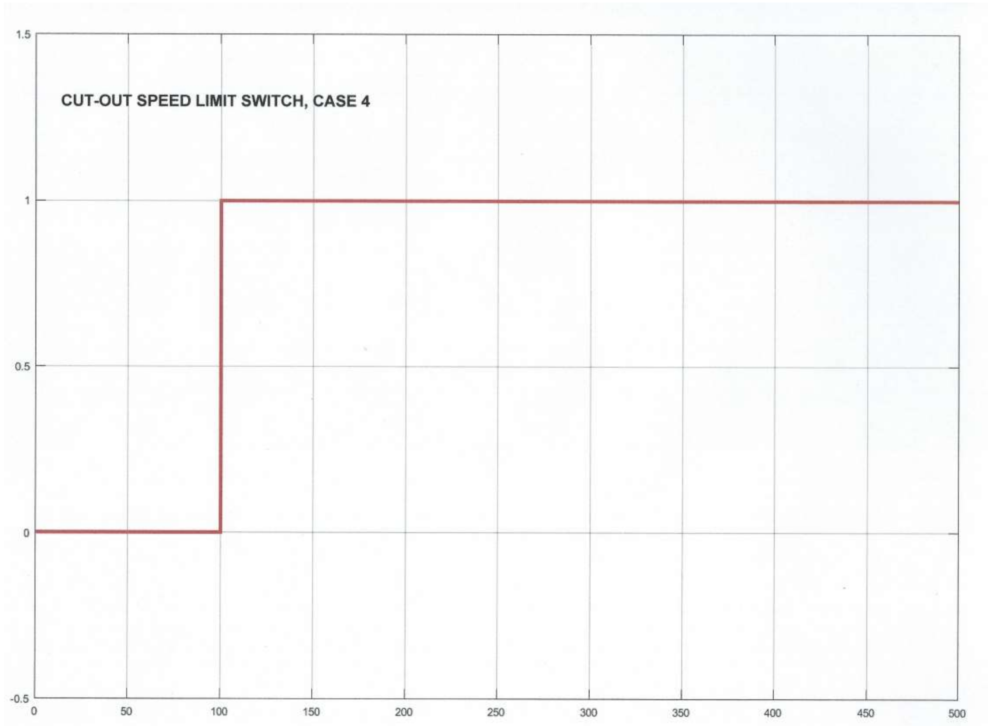


Fig. 7.44: Cut-out Speed Limit Switch, Wind Speed = 37.5m/s

7.9.3 Power and Blade Pitch Signals

Fig. 7.46 through Fig. 7.48 depicts the power signals at rated power of 3000kW.

Fig. 7.49 through Fig. 7.51 depicts the power and blade pitch signals when the power reference is decreased.

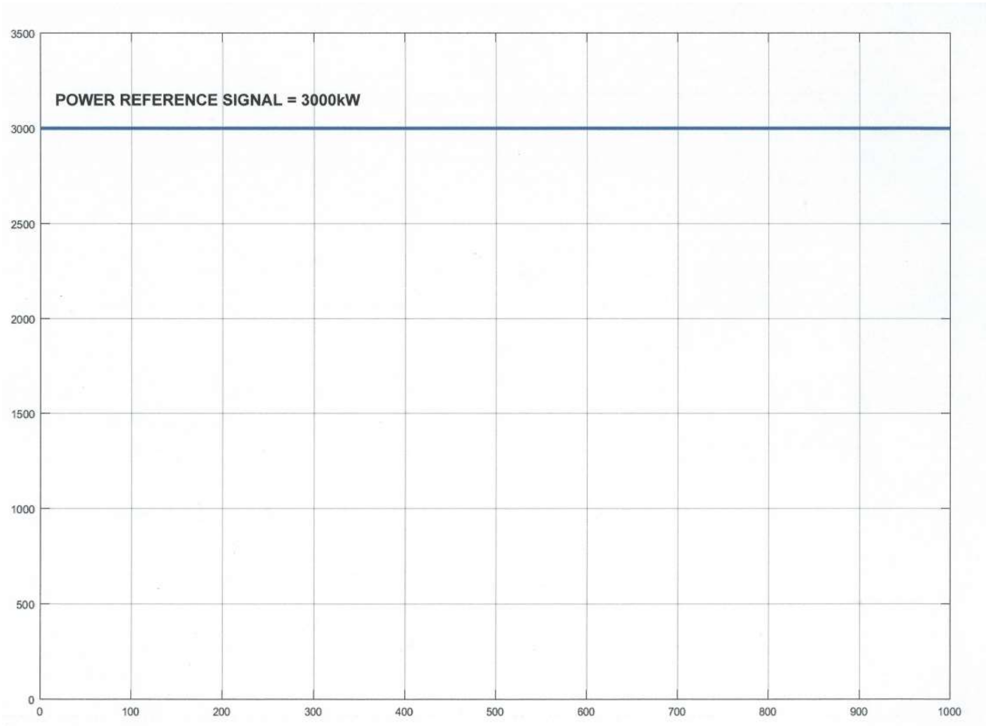


Fig. 7.46: Power Reference Signal of 3000kW

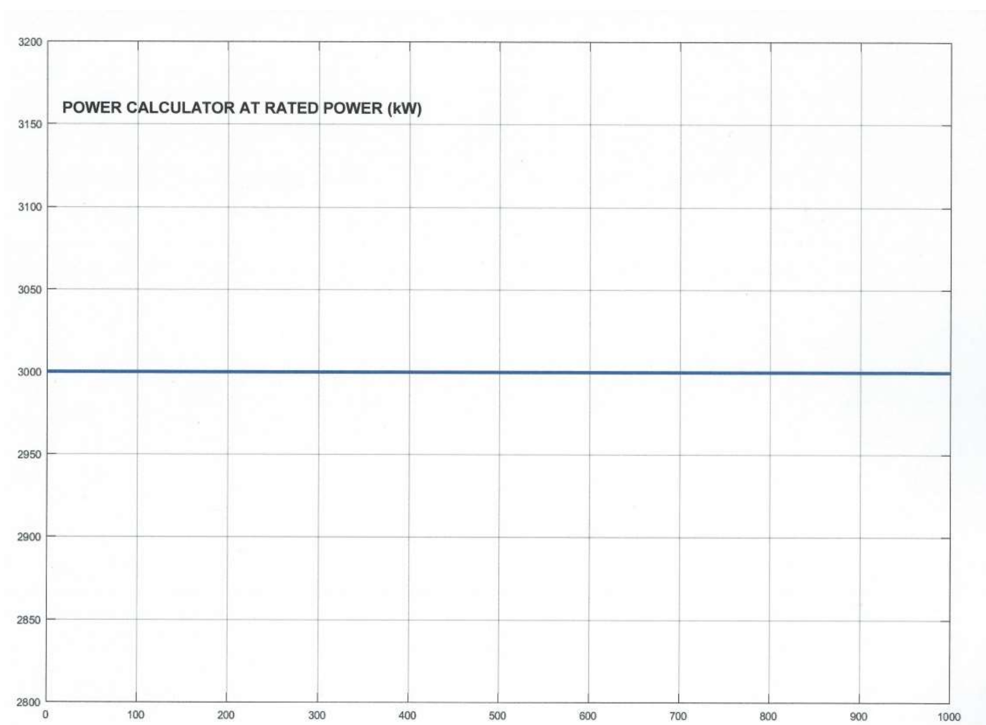


Fig. 7.47: Power Calculator at Rated Power (3000kW)

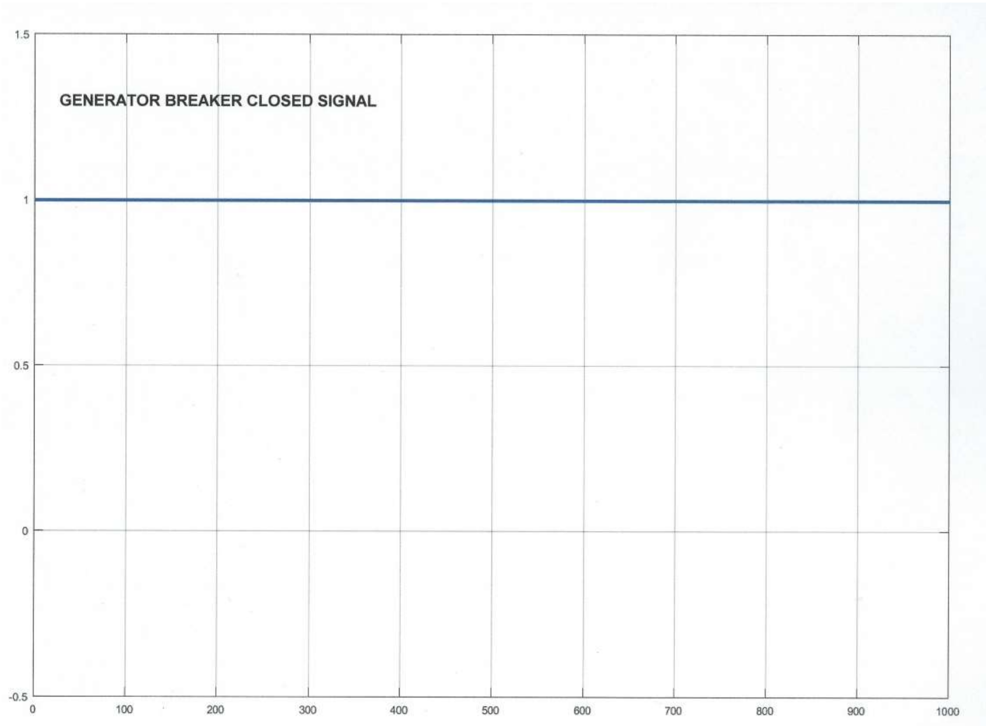


Fig. 7.48: Generator Breaker Closed Signal

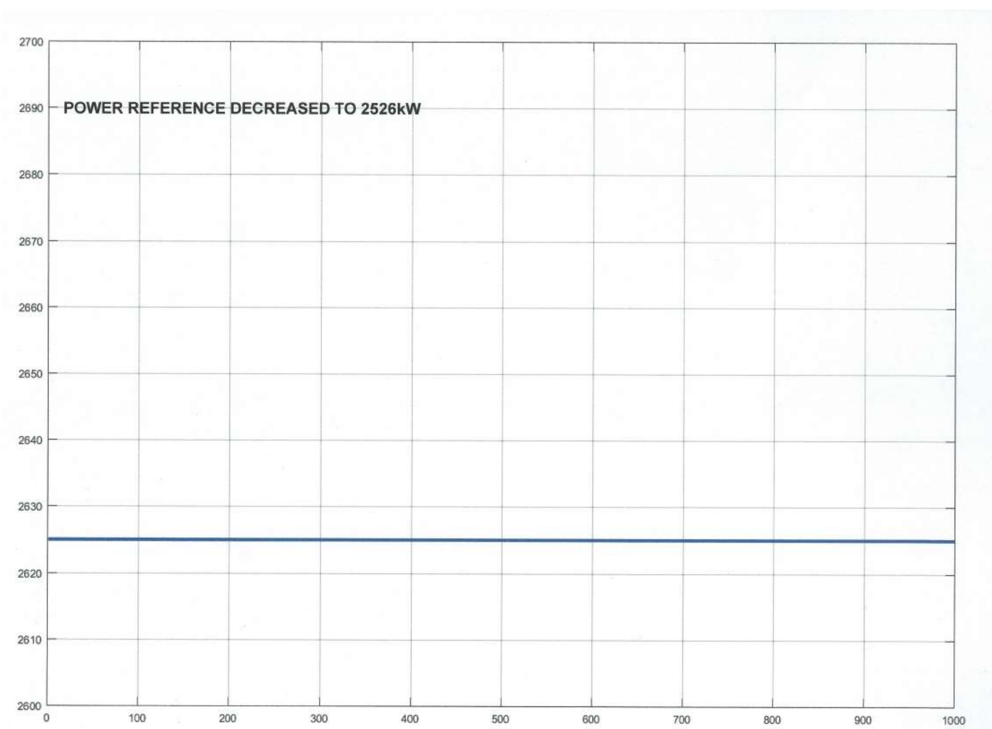


Fig. 7.49: Power Reference Decreased to 2526kW

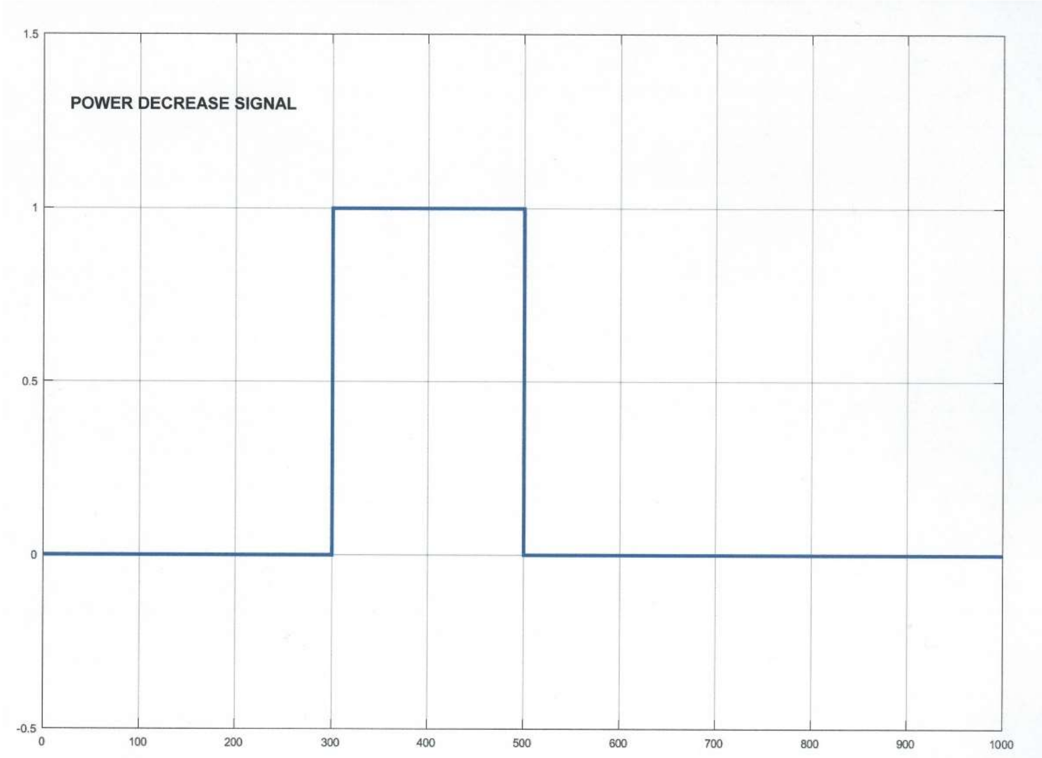


Fig. 7.50: Power Decrease Signal

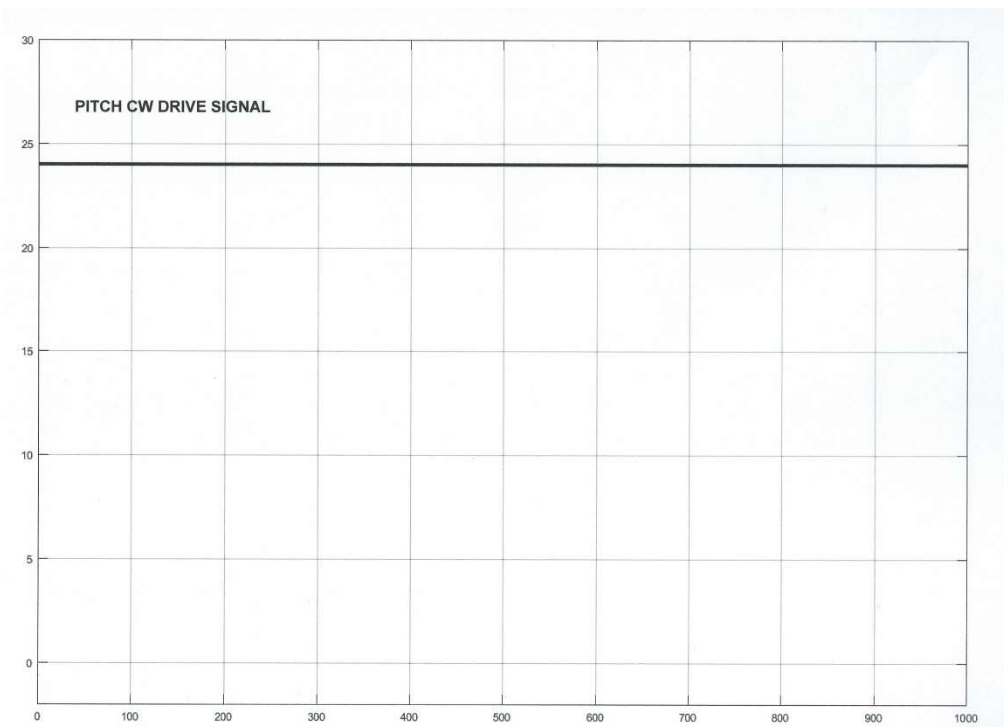


Fig. 7.51: Pitch CW Drive Signal

7.10 The Generator Breaker Control

The generator breaker control computes close and trip controls – signals to close or trip the breaker. The generator breaker is closed if the phase frequency detector (PFD) computes no phase shift between the voltage output of the full power converter and the grid voltage [46].

The logical function for this control is:

close the generator breaker if the PFD = 0
after 500 seconds of testing
or
trip the generator breaker if the trip breaker signal is enabled

Fig. 7.52 depicts the Simulink model of the generator breaker control logic.

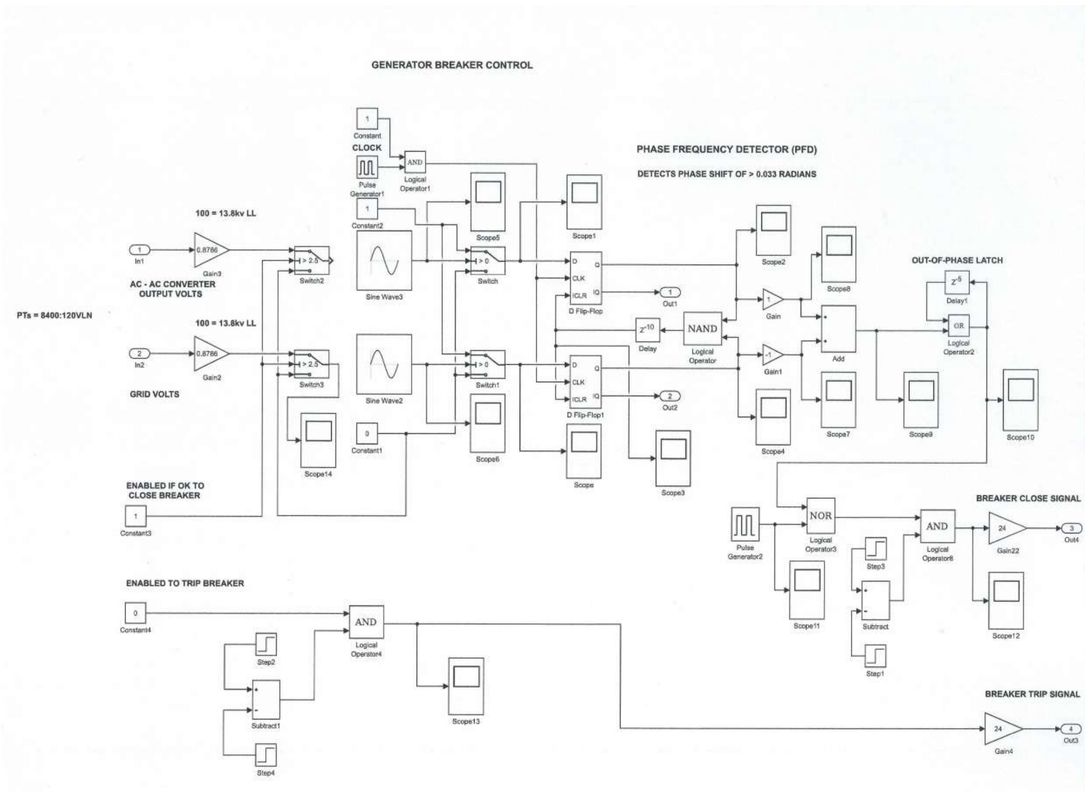


Fig. 7.52: Simulink Model of Generator Breaker Control

The Simulink Model includes:

1. converter and grid voltage calculators and limit switches
2. voltage stimulators to facilitate testing the model
3. phase frequency detector (PFD)
4. out-of-phase latch
5. pulse generator signal to initiate the breaker close signal
6. pulse generator signal to initiate the breaker trip signal
7. scopes to display limit switch actions and calculator results

In summary, the model closes and opens the appropriate limit switches, depending on input signals, to provide the phase sensitive inputs to the PFD and after a time period, closes the generator breaker. It also can trip the breaker, based on an input signal

7.10.1 Breaker Control Simulation

A number of simulations were run on this model to demonstrate PFD and logic performance.

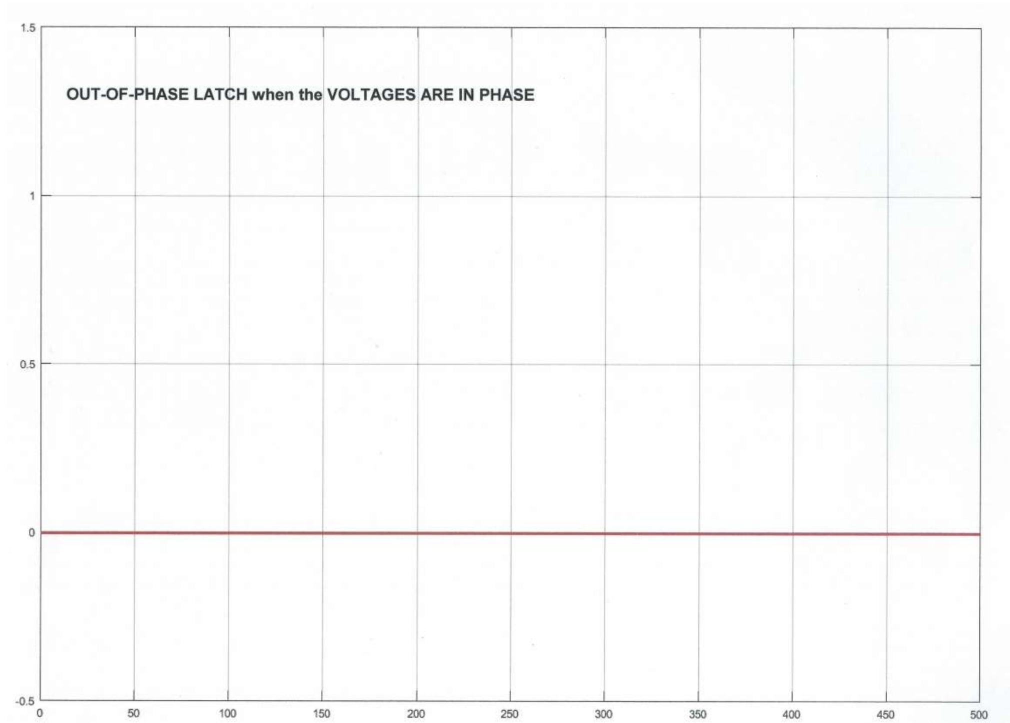


Fig. 7.53: Out-of-Phase Latch with Voltages In Phase

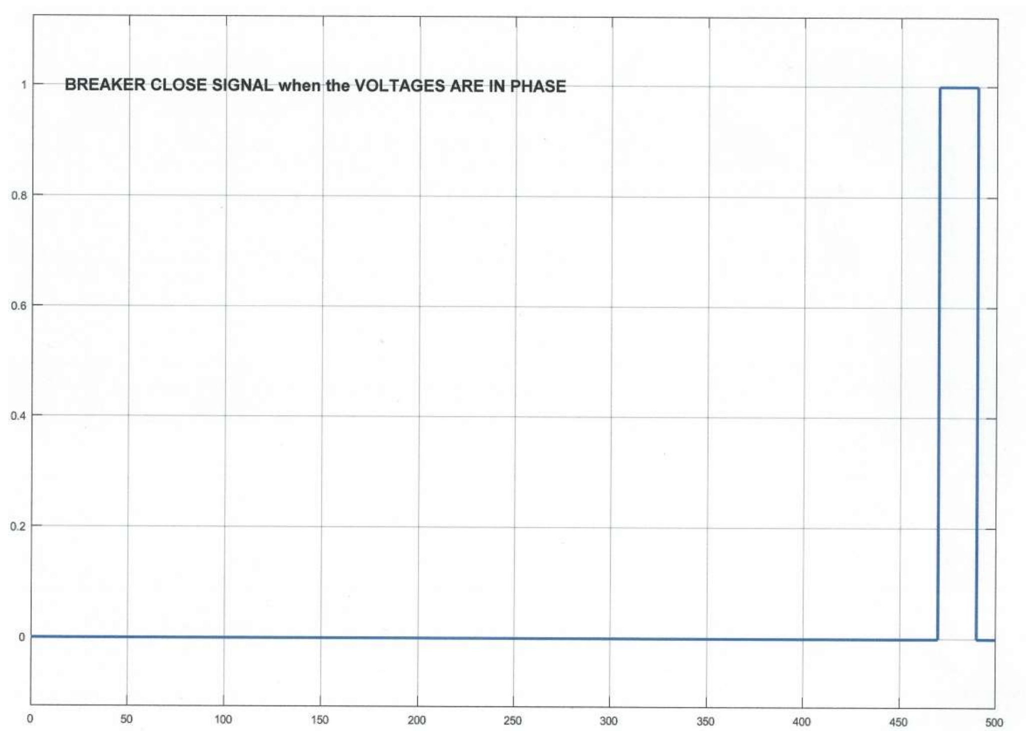


Fig. 7.54: Breaker Control Signal with Voltages In Phase

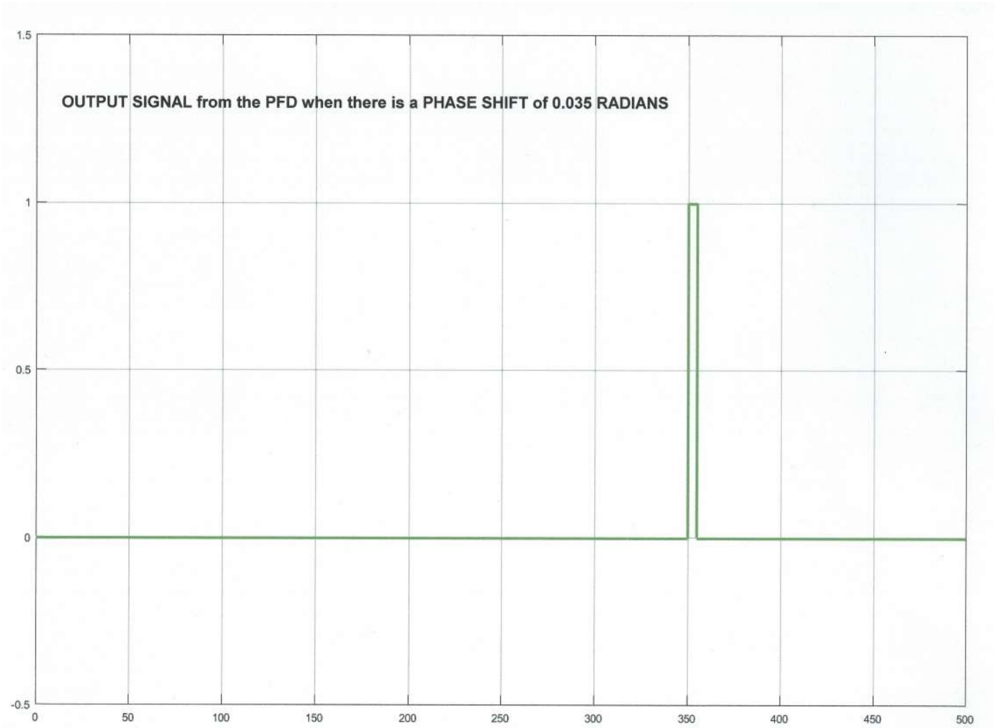


Fig. 7.55: PFD Signal with Phase Shift of 0.035 Radians

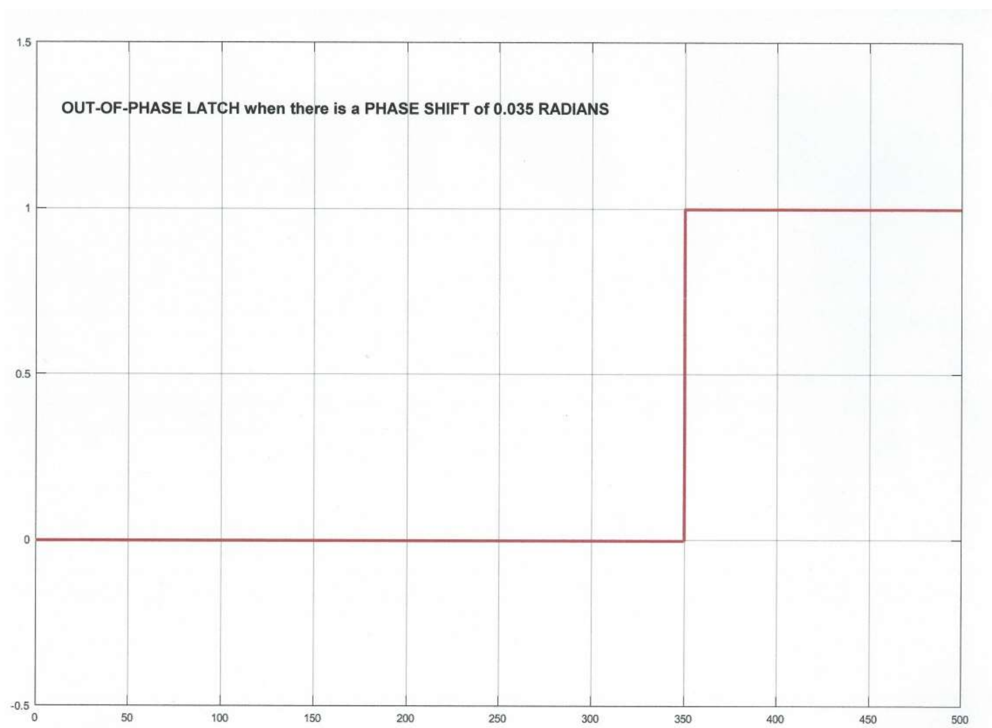


Fig. 7.56: Out-of-Phase Latch with Voltages out-of-Phase

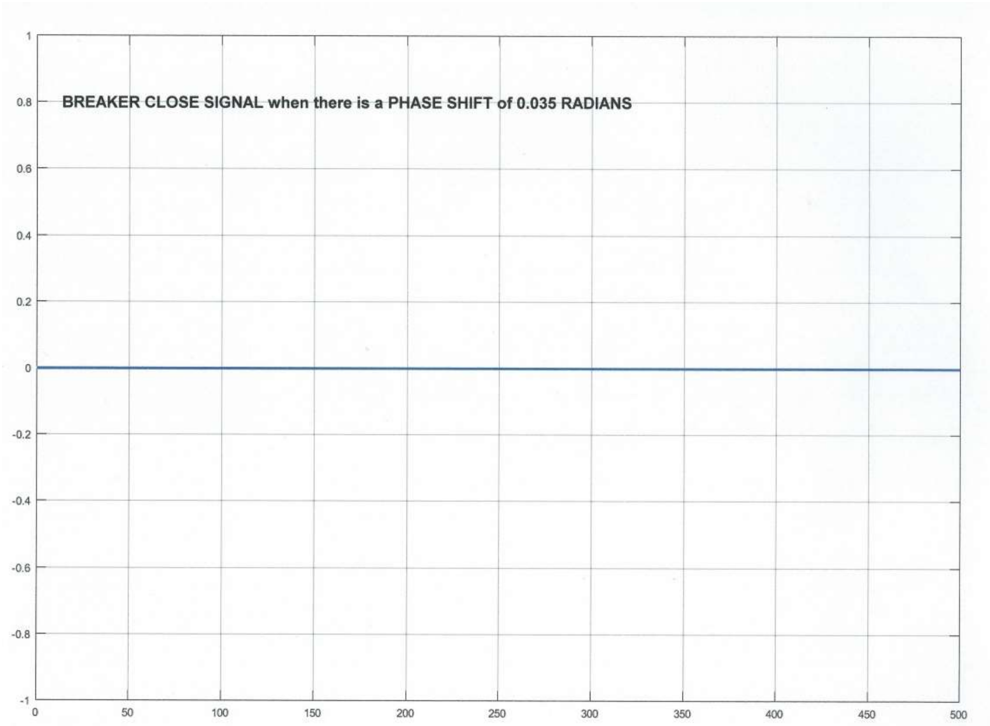


Fig. 7.57: Breaker Control Signal with Voltages out-of-Phase

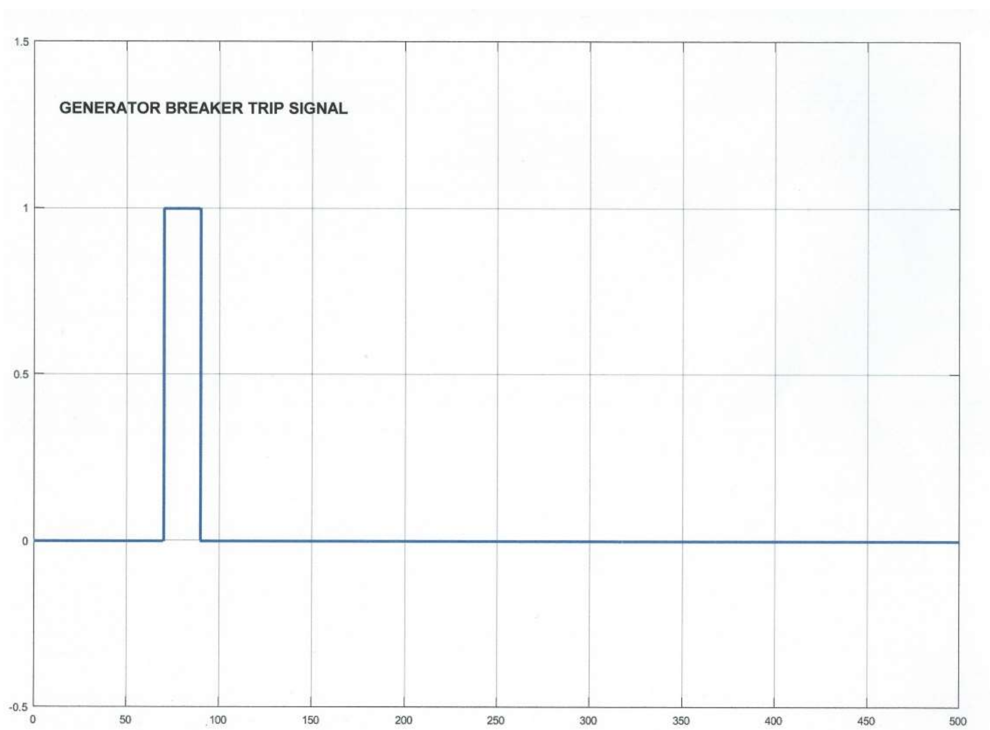


Fig. 7.58: Generator Breaker Trip Signal

8. The First Off-Shore Wind Farm in the U.S.

Block Island is a teardrop-shaped piece of land some 13 miles off the coast of Rhode Island. It's best known for its beaches, wind-swept bluffs and summer vacation homes. But a new attraction rises three miles off its southeastern shore [7].

There, in the choppy Atlantic surf, Deepwater Wind has developed America's first offshore wind farm. The farm has five wind turbines, each rising to nearly twice the height of the Statue of Liberty [7]. Starting commercial operation in December, 2016, they generate a combined 30 megawatts of electricity — enough to supply 17,000 homes — now Block Island is the most powerful coastal enclave in the northeast [12].

Offshore wind is still much more expensive, but that could change. Europe has shown that, when produced on a big enough scale, such power can compete. There, the price has fallen 46% in the last five years to an average of 13 cents per kWh [7].

The Block Island wind turbines, whose blade tips tower 600 feet above the water, are GE Haliade* off-shore direct drive WTs, with permanent magnet generators that produce 6 megawatts of power. GE advertises that this new product has the potential to transform the *GE Renewables* business both in the U.S. and abroad [12].

8.1 GE Renewables

Jérôme Pepecresse, President & CEO, GE Renewable Energy, reports to GE CEO Jeff Immelt. GE Renewable Energy claims to be a 9 billion dollar start-up, with 13,000 employees in more than 40 countries. Headquartered in Paris, GE Renewable Energy claims to have the broadest renewable energy portfolio in the industry [12].

8.2 Product Summary

The GE Haliade* 150-6MW is a three-bladed wind turbine with a 150 m diameter rotor and a rated power of 6 MW. The turbine has been designed to be suitable for sites with a reference wind speed of 50 m/s (10 minutes average) and a 50-year extreme gust speed of 70 m/s (3 seconds average). GE states that strength and durability are maximized in an exceptionally light blade, 73.5 m long, uniquely developed for this WT. The large diameter rotor maximizes the capture of wind energy. According to GE, the combination of this 150m rotor diameter and the 6 MW rated power of the generator produce an annual energy production (AEP) of more than 3 times the conventional and recent onshore wind turbines. The offshore turbine is equipped with what GE calls, an "Advanced High Density" direct drive permanent magnet generator (PMG). GE claims outstanding reliability in the turbine drive train; with no gearbox coupled to the generator, the turbine has fewer rotating parts. GE advertises that this design maximizes turbine availability and reduces maintenance costs.

The GE Haliade* also features what GE calls "*GE Pure Torque**" technology, a rotor support concept GE claims is unique in that it will protect the drive train from unwanted wind buffeting by deflecting it towards the tower, improving turbine efficiency and durability. This technology also includes an elastic drive coupling, featuring rubber elements that prevent any undesired load on the generator.

GE describes the wind turbine nacelle as air-cooled and pressurized. Construction materials and protection treatments are specifically designed for offshore environments. Heat exchangers and pressuring units prevent salty air entering while dehumidifiers prevent corrosion of components inside the wind turbine. GE advertises this proven technology and innovation are combined in Haliade* to deliver best in class cost efficiency.

To complement these wind turbine installations, GE offers an offshore AC/DC converter sub-station which converts the power generated by the wind turbines in alternating current (AC) to direct current (DC) for transmission to shore using submarine power cables. According to GE, they offer the HVDC technology for sustainable grid connections and efficient transmission over long distances [12].

Fig. 8.1: GE 150-6 Off-Shore Wind Turbine [12]

* Trademark of General Electric Company

9. Summary

Energy is the world's top problem and it is critical to modern society. Energy affects economies and economic development, international relations and politics. This is the major motivation for developing renewable energy. Wind Energy most likely will be a part of the energy solution.

Wind Power is growing fast in the U.S. and is now the greatest renewable energy source other than hydro-power. While off-shore wind power is just now starting to grow off the coast of New England, it already has made a significant penetration into northern Europe. While off-shore wind farms require a large up-front investment, the benefits of higher annual energy production and higher power output from each wind turbine may result in greater US penetration in the near future.

The target wind turbine model discussed in this paper provides a rated output of 3.00MW at 13.8kV and 126A. It has a distinct advantage of no gearbox and computer controlled yaw and blade pitch. All the pertinent equations for calculating:

- power from the wind
- wind density
- power vs wind temperature
- power of the wind turbine
- rotor speed and stator frequency
- generator torque, voltages and currents
- generator equivalent circuit values

are presented along with tables and graphs which illustrate these data.

The focus of this paper was to provide an analytical study of a grid connected off-shore direct drive PMG wind turbine. This analytical study used Matlab scripts and Simulink models to calculate, model and simulate every facet of the Target Wind Turbine. The PMG, full power converter and control system were all modeled in accurate detail and many simulations were used to demonstrate the actual performance of each. The converter and control system were found to be stable and transients were well damped.

In Appendix A, there is a description and procurement source for many of the control components. This should be helpful in further understanding mechanical-electrical transducers and their signal conditioners. Also, the electro-mechanical devices used to control the motors and actuators are described with their procurement sources.

In Appendix B, there is the code for each Matlab script used for calculations in this paper.

In Appendix C, there is a compilation of Simulink Models deployed in this paper.

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Appendix A

Component Description and Procurement

1. Signal Conditioners

Omega http://www.omega.com/pptst/CCT.html

Description

The CCT series DIN rail signal conditioners are designed to accept a broad range of input signals, such as ac and dc voltage and current, frequency, temperature (thermocouple and RTD), and process transducers, and provide standard process outputs of either 0/4 to 20 mA, or 0 to 10 Vdc. The CCT series features a modern housing design, that is easily mounted on standard DIN rails. Connections are safely and securely made, with input and output connections on the opposite sides of the module.

Internal Design

The CCT series is designed using an internal plug-in three module system that provides flexibility in selecting and changing the power supply, input signal and output signal. The units are supplied with 110 Vac power standard, Consult sales for 220 Vac, and 24 Vdc power.

Isolation

The three internal modules in each signal conditioner (signal input, signal output and power supply) are isolated up to 2 kVeff.

Outputs

Each CCT series signal conditioner is available with current and voltage output (only one may be used at a time). Available output types include 4 to 20 mA or 0 to 20 mA (jumper-selectable) and 0 to 10 Vdc.

Standard outputs are linear and proportional to the signal input. Thermocouple input modules feature special circuitry to linearize the output to the actual temperature, and not to the non-linear signal produced by thermocouple sensors.

2. Potential Transformers and Current Transformers

Flex-Core - Outdoor Potential Transformer

Catalog Number: 765C130103

Rated Primary Voltage: 8400V

Ratio: 70:1

Rated Secondary Voltage: 120V

Flex-Core - Current Transformer

Catalog Number: 180RL-201

Current Ratio: 200:5

3. Anemometer

CAMPBELL SCIENTIFIC

Reliable, Accurate Wind Speed

Detailed Description

The 014A is constructed of corrosion-resistant, stainless-steel and anodized aluminum. Its three-cup anemometer assembly contains a sealed magnetic reed switch. Rotation of the cup-wheel produces a pulse that is directly proportional to wind speed.

The 014A monitors wind speed for the range of 0 to 45 m/s with a threshold of 0.45 m/s.

Benefits and Features

- Sealed magnetic reed switch
- Designed for continuous, long term, unattended operation in adverse conditions

Range	0 to 45 m/s (0 to 100 mph)
Starting Threshold	0.45 m/s (1.0 mph)
Accuracy	0.11 m/s (0.25 mph) or 1.5%
Contact Rating	10 mA (maximum)
Temperature Range	-50° to +70°C
Cable Description	Quick-connect connector with vinyl jacketed, shielded cable
Radius	10.4 cm (4.1 in.)
Height	34.8 cm (13.7 in.)
Sensor Weight	318 g (11 oz)
Cable Weight	140 g (5 oz) per 3 m (10 ft) length

4. Wind Vane

NRG SYSTEMS

Wind Vane

A wind vane always positions itself according to the wind direction.

There is a small sensor at the foot of the wind vane that notifies the wind turbine controller of the wind direction. 4 – 20ma output.

HYBRID MC VANE

Reliably measure wind direction for turbine control

HYBRID MC VANE #9378 4 - 20MA OUTPUT

When your turbine control sensors are not working, your turbines are not producing, so we designed our sensors to maximize your turbine availability. Our Hybrid MC technology is based on 25 years of icing climate sensor experience and data from over 70,000 fielded sensors.

Hybrid MC sensors are engineered with a two-stage contamination protection system to prevent dust, dirt, and water from damaging the bearings. The first level of defense is a fully sealed body that minimizes contamination ingress. Inside, a sealed bearing cartridge system prevents contamination from affecting the bearings. The result: extended bearing life and a recommended maintenance interval of 10 years, meaning fewer trips to your turbines.

5. Electrohydraulic Servo Valve

PARKER

TWO-STAGE TORQUE MOTOR SERVO VALVE – BD SERIES

VALVE STYLE

Servo Valve

RESISTANCE (OHMS)

60, 1016, 591, 243, 138, 90, 22, 5.7, 36, 118/118

FLOW RATE (LPM)

3.8, 37.9, 56.8, 9.5, 75.7, 18.9, 94.6, 113.6, 151.4

TEMPERATURE RANGE (F)

+30 to 180°

An electrohydraulic servo valve (EHSV) is an electrically operated valve that controls how hydraulic fluid is ported to an actuator. Servo valves and servo-proportional valves are operated by transforming a changing analogue or digital input signal into a smooth set of movements in a hydraulic cylinder. Servo valves can provide precise control of position, velocity, pressure and force with good post movement damping characteristics.

6. Thermocouple and Transmitter

Bayonet Style Thermocouples with Stainless Steel Cable BT

- Service Temperature to 480°C (900°F) Except for Type T Thermocouple
- A Wide Variety of Immersion Lengths, Styles and Mounting Arrangements Are Available
- Standard Configurations for Fast Delivery
- 304 Stainless Steel Construction
- Flexible 7 mm (0.275") Stainless Steel Cable [1.5 m (60") Standard] Hollow Tube Design
- Glass Braid Insulated 20 Gage Solid Thermocouple Wire
- Stranded Wire Available as Option

-200 to 1000	**E**	-328 to 1832	50 (90)	±0.1°C

DIN Rail Universal Smart Transmitter
TXDIN101

High Accuracy

- Integral LED display
- Universal Input: T/C, RTD and mV
- Galvanic Isolation
- Configuration and Calibrations are PC-based Software (It requires the USB cable p/n TX69-CABLE sold separately)

Temperature Transmitters - Description

The TXDIN101 is a computerized, PC programmable, galvanically isolated two-wire smart transmitter. The unit converts 13 types of thermocouple sensors; 12

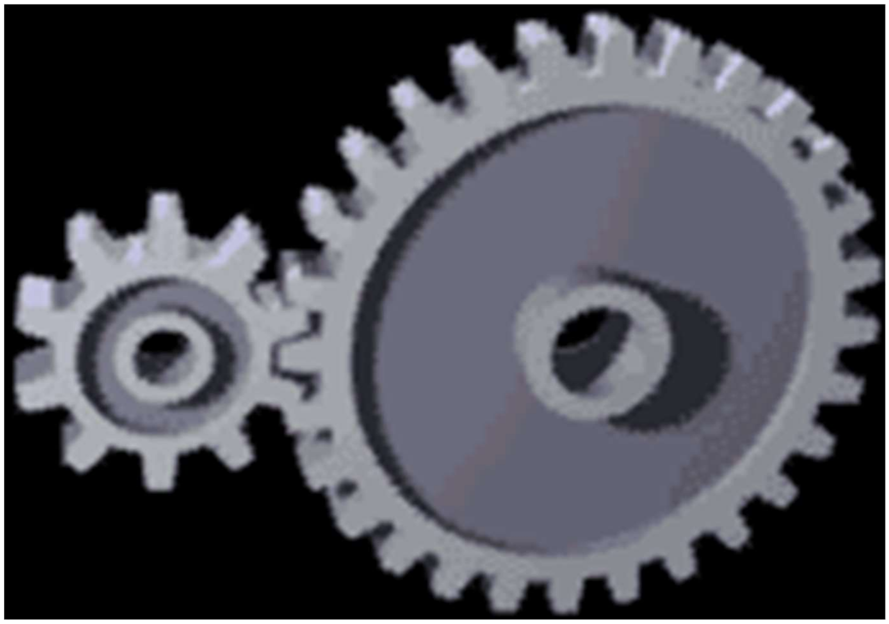
types of RTD sensors, configured as 2-, 3- and 4-wires; potentiometer, resistor and millivolt inputs, single or differential—into process current loop. Integral 3% digits LED display forms a transmitter—monitor unit which is visiable in dark installations. The light intensity varies as a function of the current loop, which serves as the light energy source 24-bit A/D converter and two microprocessors are the heart of the outstanding performance. The transmitter can be set and wired to perform differential measurement conversions of temperature sensors as well as mV sources. The output current is temperature linearized and can be set to be 4 to 20/20 to 4mA—or any range within these limits. The current is limited to 3.9 and 22 mA.The TXDIN101 samples and updates the output current in a rate of 2 to 4 samples per second depends on the sensor type. The transmitter is fully configurable in dry-configuration mode by which the connection to PC is performed with no external power source. The configuration parameters are stored in a nonvolatile memory. Exceptional digital accuracy of typically ±0.1°C is provided for most sensors regardless of the calibrated span. Internal Pt-100 temperature sensor provides precise cold junction compensation throughout the entire ambient range. Detection of sensor breakage or disconnection of input leads, forces the output to a predefined up/down scale value. The unit continuously monitors the sensor and automatically returns to normal operation mode when the sensor is recovered. The TXDIN101 is housed in a plastic enclosure mounted on a standard DIN rail. Special red filter is provided for optimal view.

Housing Specifications
Material: Plastic polycarbonate
Screw Connection: 6 terminals
Mounting: Standard DIN rail
Operating Position: Any
Protection Level: IP20; UL-94-V0 flame retardant
Weight: 85 g (0.18 lb)
Programming
Software Package: CONCAL for COM and USB ports
Modem Cord CONUSB:
Length: 1.5m with USB connector for USB connection
Configured Parameters: Tag information, sensor type, Input range, selection of connection type, output offset, output curve correction, damping factor, burnout type, output current mode, sensor calibration

GE Model 7700 Motor Control Center

- Lighting contactor bucket inserts
- Motor Starter combination bucket inserts
- AC Drives
- Lighting panels
- Reduced voltage starters
- Transformer Inserts
- Insulated and isolated vertical bus with polyester barriers
- Vertical ground and load ground bus
- Horizontal and vertical bus shutters
- Shallow Back-to-Back Design
- Windows Base Pricing/Sizing Program
- Flexibility, Reliability, Simplicity & Safety
- Easy maintenance
- Cycle time to support your needs
- System Type: 208, 240, 380, 480, 575 volt; 50/60 Hz; 3-phase/3-wire; 3-phase/4-wire
- 22, 25, 42, 65, 100K Short Circuit Bracing
- 42, 65, 100K Bus Bracing
- 600, 800, 1200A aluminum plated Horizontal and Main Bus
- 600, 800, 1000, 1200, 2000, 2500A copper Neutral Bus (tin or silver plated)
- 300, 450, 600A copper Vertical Bus (tin or silver plated)
- 300, 600A Aluminum Ground Bus With Multiple Plating Options
- Indoor and Outdoor Enclosures
- Complies with NEMA ICS 2-322, UL-845, CSA C22.2, and EEMAC Standards

A motor controller is a device that provides a manual or automatic means for starting and



stopping a motor, selecting forward or reverse rotation, selecting and regulating the speed.

7. Gear Set

Appendix B

Matlab Scripts

```
edit PMG_at_rated_speed
char = 'CALCULATE WIND POWER PASSING THRU A CIRCLE'
T = 15; %temperature = 15degC
rho = 1.225;  %kg/m^3
L = 40;   %m
V = 14;      % wind speed in m/s
A = pi*L^2      %m^2
Pwind = (rho*A*(V^3))/2  %Wind Power
char = 'WIND POWER IN MW'
PwindM = Pwind/(10^6)
char = 'EFFICIENCY'
nu = .355
char = 'TURBINE POWER'
Pt = nu*Pwind
char = 'TURBINE POWER IN MW'
PtM = Pt/(10^6)
P1 = 3;      %MW
char = 'rotor speed in rpm'
n = 12
char = 'CALCULATE ROTOR SPEED in r/s'
wr = n*120*pi
char = 'TURBINE TORQUE in kNm'
Tt = (P1/wr)*1000
char = 'GENERATOR TORQUE IN kNm'
Tg = Tt
char = 'GENERATOR POWER in MW'
P2 = Tg*n/10^3
char = 'CALCULATE FREQUENCY of STATOR VOLTAGES in Hz'
P = 72      %P = # of poles
f = (n/60)*(P/2)    %f in Hz
Vrated = 9.200*10^3  %kV
Irated = 188
char = 'CALULATE COMPLEX POWER and POWER FACTOR'
S3p = 3*Vrated*Irated
pf = Pt/S3p
char = ' CALCULATE COMPLEX TERMINAL CURRENT'
theta = acosd(Pt/S3p)
It = Irated*(cosd(theta)+(1*j*sind(theta)))
printPol(It)
```

```
edit PMG_at_cut_out_speed
char = 'CALCULATE WIND POWER PASSING THRU A CIRCLE'
T = 15; %temperature = 15degC
rho = 1.225;  %kg/m^3
L = 40;   %m
V = 25;      % wind speed in m/s
A = pi*L^2      %m^2
Pwind = (rho*A*(V^3))/2  %Wind Power
char = 'WIND POWER IN MW'
PwindM = Pwind/(10^6)
char = 'EFFICIENCY'
nu = .06236
char = 'TURBINE POWER'
Pt = nu*Pwind
char = 'TURBINE POWER IN MW'
PtM = Pt/(10^6)
P1 = 3;      %MW
char = 'rotor speed in rpm'
n = 18
char = 'CALCULATE ROTOR SPEED in r/s'
wr = n*120*pi
char = 'TURBINE TORQUE in kNm'
Tt = (P1/wr)*1000
char = 'GENERATOR TORQUE IN kNm'
Tg = Tt
char = 'GENERATOR POWER in MW'
P2 = Tg*n/10^3
char = 'CALCULATE FREQUENCY of STATOR VOLTAGES in Hz'
P = 72      %P = # of poles
f = (n/60)*(P/2)    %f in Hz
Vcut = 13.8*10^3  %kV
Icut = 126
char = 'CALULATE COMPLEX POWER and POWER FACTOR'
S3p = 3*Vcut*Icut
pf = Pt/S3p
char = ' CALCULATE COMPLEX TERMINAL CURRENT'
theta = acosd(Pt/S3p)
It = Icut*(cosd(theta)+(1*j*sind(theta)))
printPol(It)
```

```
edit WIND_TURBINE_PMG_MODEL_VOLTAGE_CURRENT_FREQUENCY
char = 'DIRECT DRIVE SYNCHRONOUS GENERATOR'
char = '72 POLE, 3000kW, RFPM'
char = 'TURBINE POWER'
Pt = 0.375
char = 'ROTOR SPEED in RPM'
n = 1.5
char = 'CALCULATE FREQUENCY of STATOR VOLTAGES'
P = 72      %no. of poles
f = (n/60)*(P/2)
char = 'CALCULATE VOLTAGES'
Kvf = 9.2/7.2
VLL = Kvf*f   %VLL, RMS
VLN = VLL/sqrt(3)
Vpk = VLL*sqrt(2)
char = 'CALCULATE CURRENTS'
Ia = 1000*Pt*sqrt(3)/(3*VLL) %Ia, RMS
Ipk = Ia*sqrt(2)
```

```
edit POWER_IN_THE_WIND
char = 'CALCULATE WIND POWER PASSING THRU A CIRCLE'
T = 15; %temperature = 15degC
rho = 1.225;  %kg/m^3
L = 40;   %m
V = 14;     % wind speed in m/s
A = pi*rad^2      %m^2
V = 3.5
while V < 25.01
    Pwind = (rho*A*(V^3))/2  %Wind Power
    V = V + 0.5
end
```

```
edit WIND_POWER_VS_TEMP
char = 'CALCULATE WIND POWER PASSING THRU A CIRCLE'
L = 40;   %m
V = 14;     % wind speed in m/s
A = pi*rad^2      %m^2
T = -25
while T < 35.01
    rho = -1*(0.00425*T) + 1.2922 %kg/m^3
    Pwind = (rho*A*(V^3))/2  %Wind Power
    T = T + 5
end
```

```
edit WIND_TURBINE_POWER_VS_WIND_TEMPERATURE
char = 'CALCULATE WIND POWER PASSING THRU A CIRCLE'
L = 40;   %m
V = 14;      % wind speed in m/s
A = pi*rad^2      %m^2
Eff = .0355
T = -25
while T < 35.01
    rho = -1*(0.00425*T) + 1.2922 %kg/m^3
    Pwind = (rho*A*(V^3))/2 %Wind Power
    Pt = Eff*Pwind
    T = T + 5
end
```

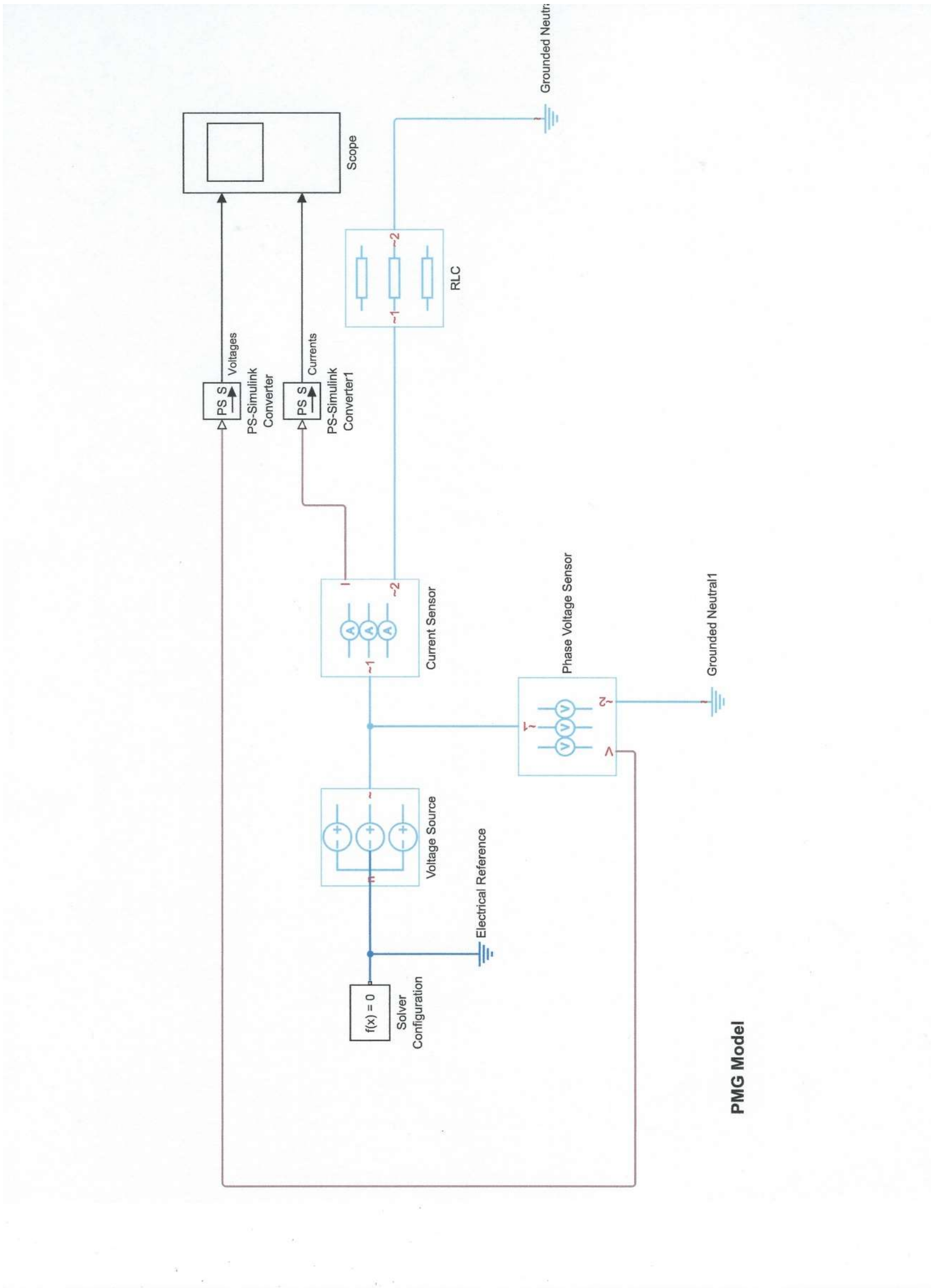
```
edit MEAN_P_AND_CP
CHAR = 'MEAN WIND SPEED'
v = 9.3
char = 'CALCULATE PERCENT WT POWER'
PP = 46.25-(24.19*v)+(3.711*v^2)-(0.1218*v^3)
char = 'TURBINE POWER'
Pt = 3*PP/100
char = 'CALCULATE CP'
Prated = 3.0
Erated = 365.25*24*Prated
Eactual = 365.25*24*Pt
CP = Eactual/Erated
char = 'CALCULATE AEP'
Eactual
```

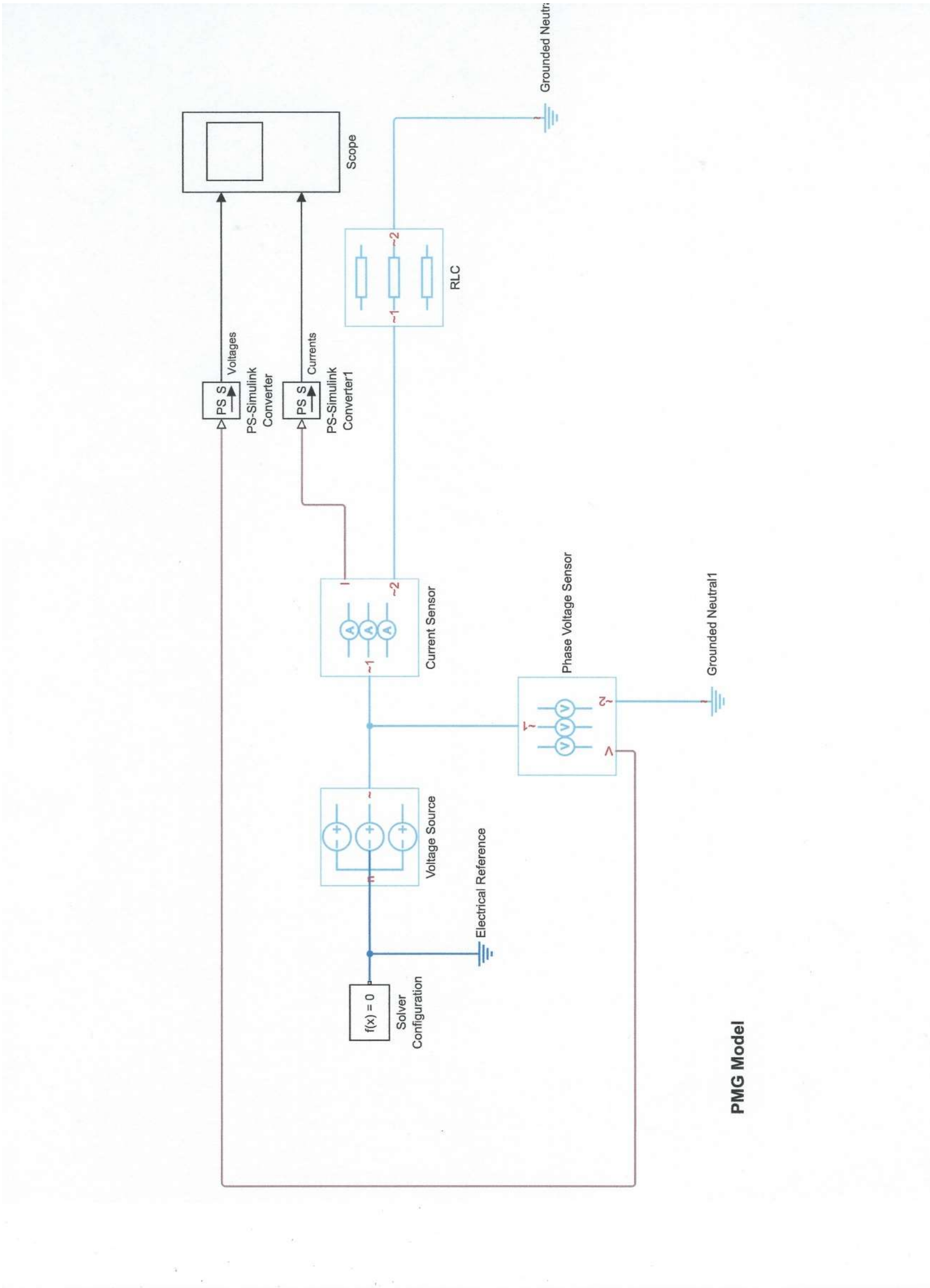
```
edit WT_OC_AND_SC

char = 'CALCULATE OPEN CIRCUIT VOLTAGE'
f = 7.2
Ea = -2.2558*f^3+58.789*f^2+177.6*f+2427.6;
printPol(Ea)

char = 'CALCULATE SHORT CIRCUIT CURRENT'
f = 7.2
Vt =0
L = 0.3;
Ra = 0.1;
Xs = 2*pi*f*L
Ea = 5912*(cosd(25.6)+(1*j*sind(25.6)))
printPol(Ea)
Ia = Ea/(Ra+(1*j*Xs))
printPol(Ia)

char = 'CALCULATE STATOR WINDING LOSSES'
char = 'AT RATED SPEED'
f = 7.2
Vt = f*737.725   %Van 7967.434, 5311.622; Vt constant = 737.725
Ia = 188
Ra = 0.1;
SWL = 3*(Ia^2)*Ra
```

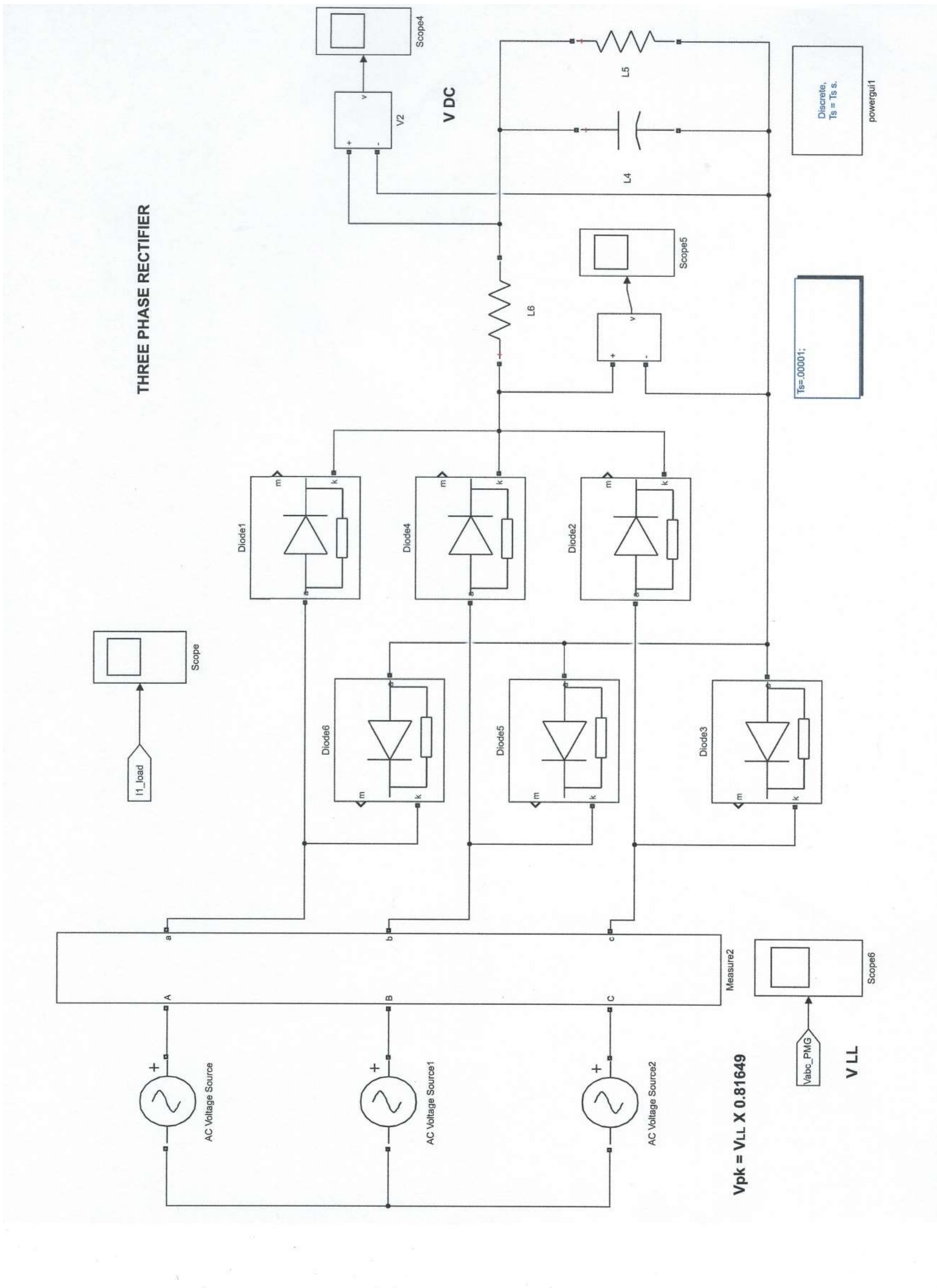
```
edit THREE_PHASE_RECTIFIER
char = 'THREE PHASE DIODE BRIDGE RECTIFIER'
char = 'CALCULATE THE RATED PHASE VOLTAGE'
Vrms = 9.2/sqrt(3)
Vp = Vrms*sqrt(2)
f = 7.2
w0 = 2*pi*f
t = 0
while t < 0.151
    Van = Vp*cos(w0*t)
    Vbn = Vp*cos((w0*t)-(2*pi/3))
    Vcn = Vp*cos((w0*t)-(4*pi/3))
    Vdc = abs(Van)+abs(Vbn)+abs(Vcn)
    t = t+0.001
end
```

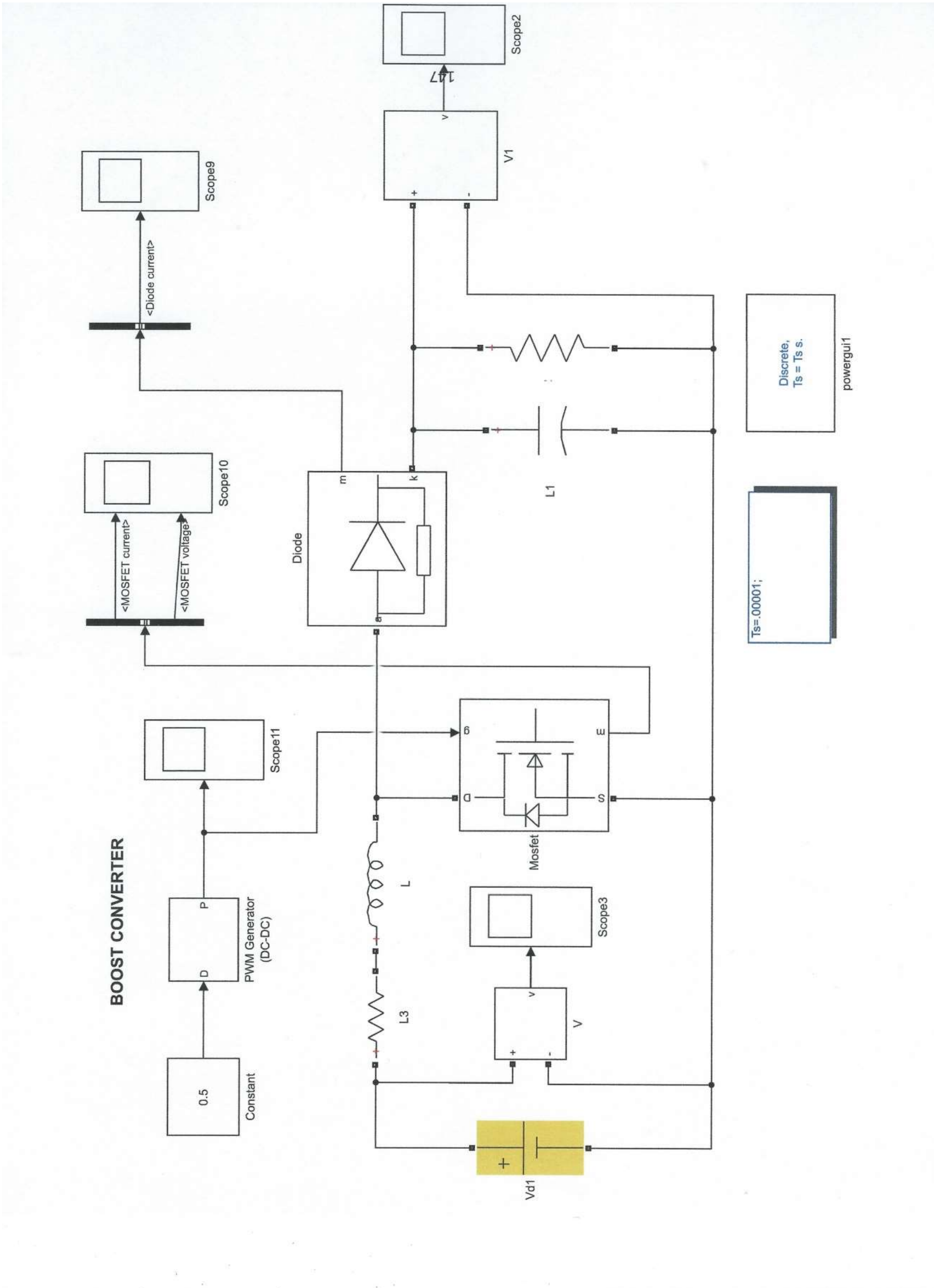
Appendix C

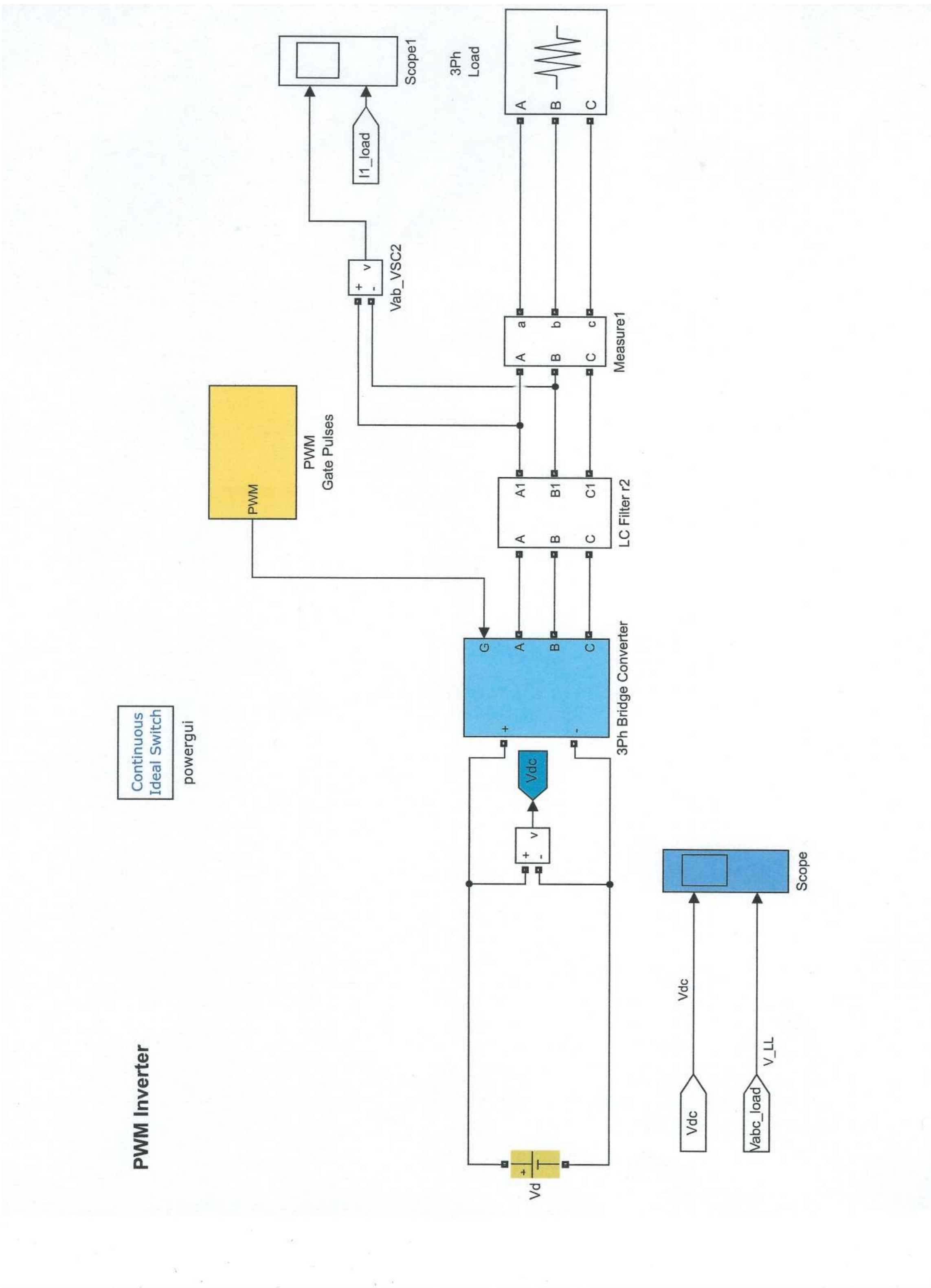
Simulink Models

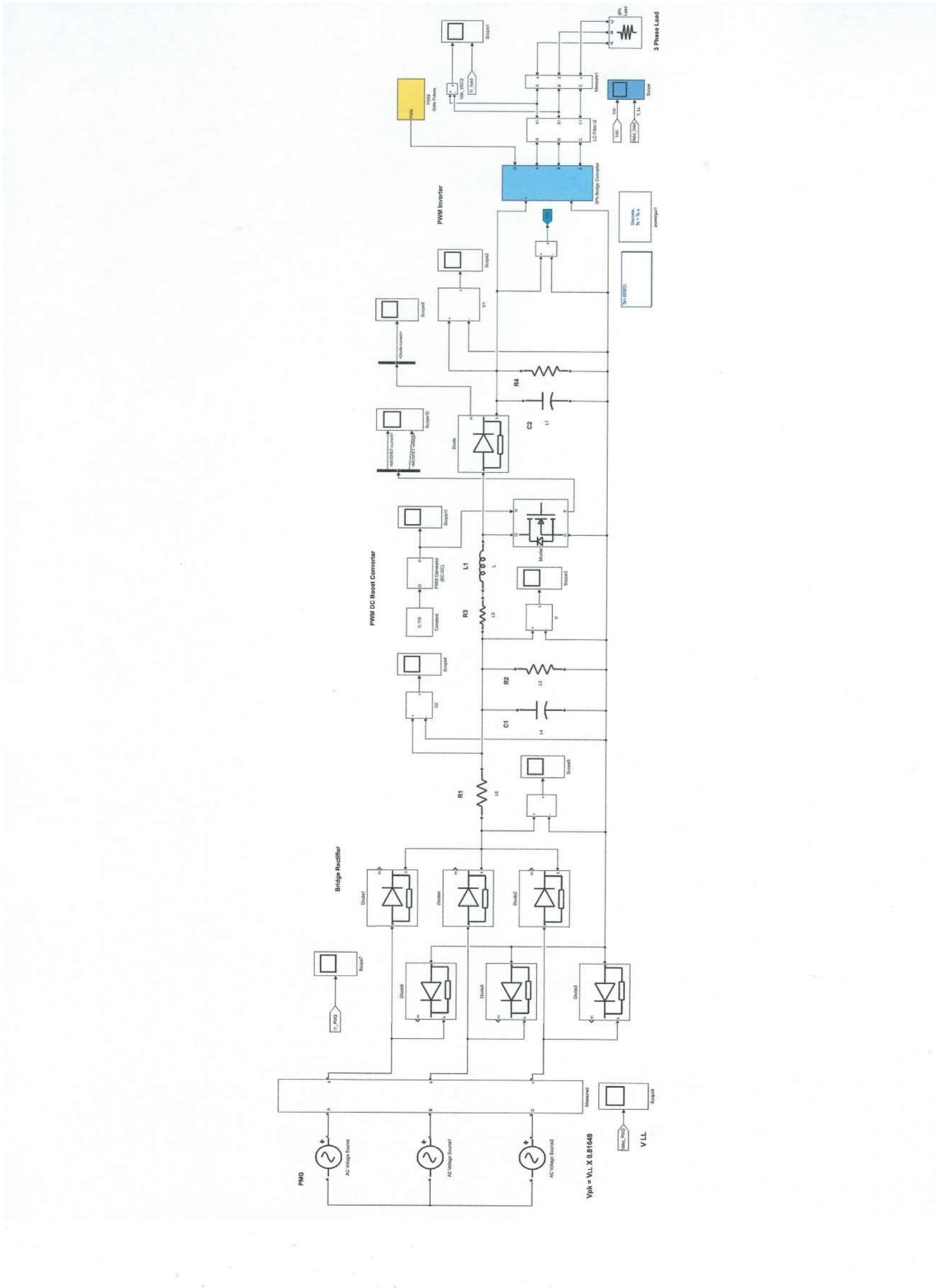

PMG Model
Solver Configuration
f(x) = 0
Electrical Reference
Voltage Source
Phase Voltage Sensor
Grounded Neutral1
Current Sensor
PS-Simulink Converter
PS-Simulink Converter1
Voltages
Currents
RLC
Scope

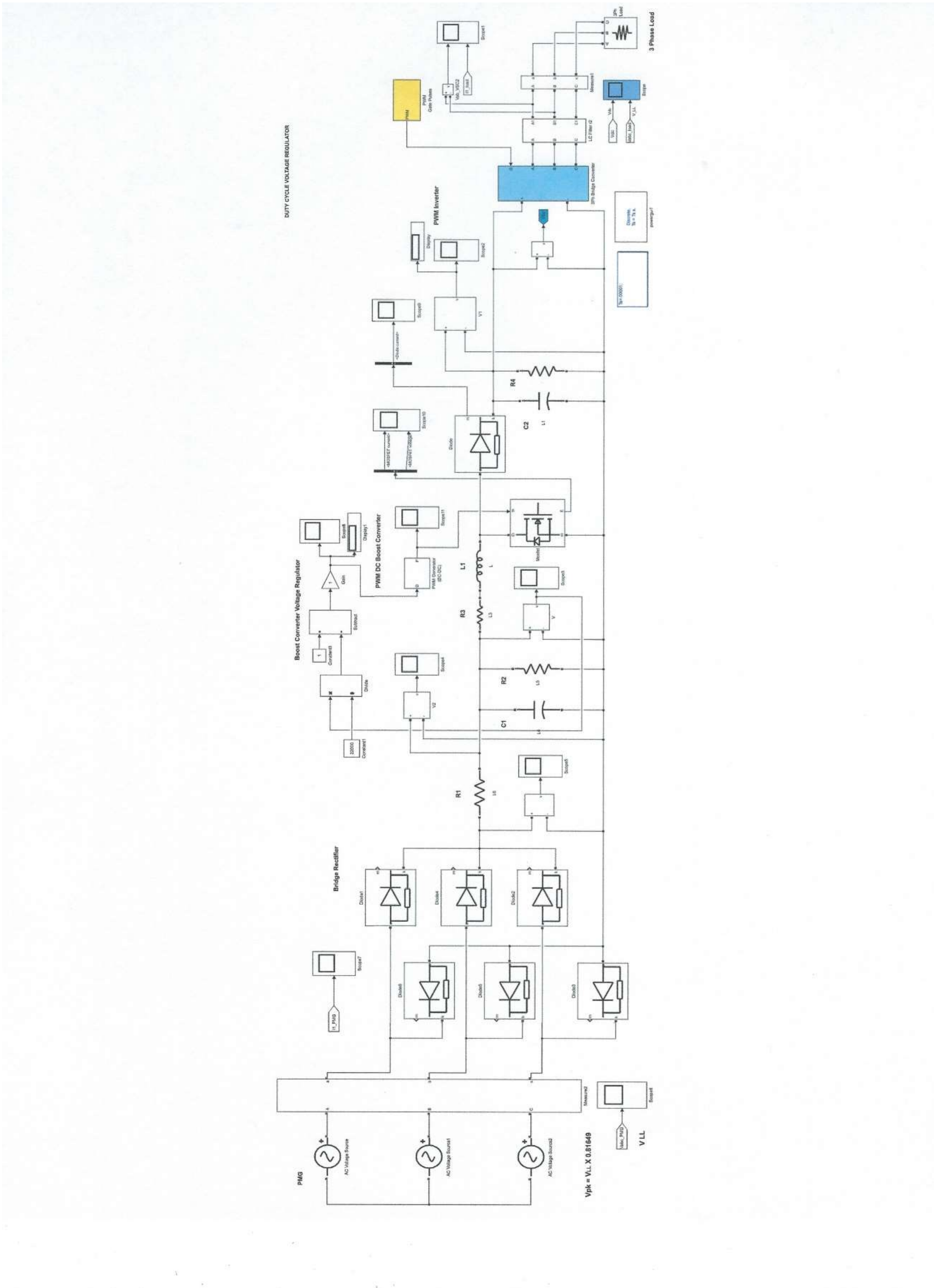

Scope
PS S
PS-Simulink
Converter
Voltages
PS S
PS-Simulink
Converter1
Currents
RLC
~1
~2
Grounded Neutral
Current Sensor
I
~1
~2
Phase Voltage Sensor
V
~1
~2
Grounded Neutral1
Voltage Source
~
n
Electrical Reference
f(x) = 0
Solver
Configuration
PMG Model


THREE PHASE RECTIFIER
V DC
Scope4
V2
L5
L4
L6
Scope5
Discrete,
Ts = Ts s.
powergui1
Ts=.00001;
Diode1
Diode4
Diode2
Diode6
Diode5
Diode3
Scope
I1_load
Measure2
Scope6
Vabc_PMG
V LL
Vpk = VLL X 0.81649
AC Voltage Source
AC Voltage Source1
AC Voltage Source2

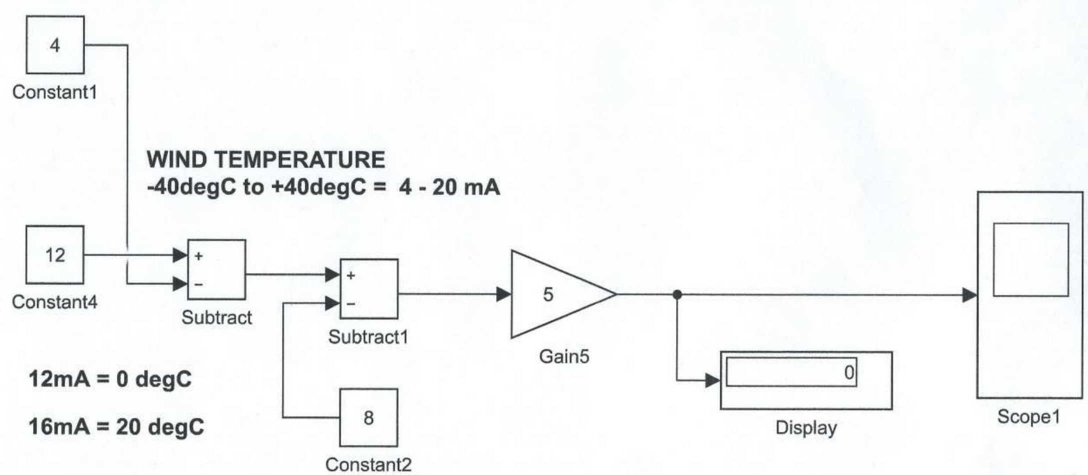

BOOST CONVERTER
0.5
Constant
PWM Generator
(DC-DC)
Scope11
Scope10
<MOSFET current>
<MOSFET voltage>
Scope9
<Diode current>
Scope2
V1
Diode
Mosfet
L
L3
L1
V
Scope3
Vd1
Discrete,
Ts = Ts s.
powergui1
Ts=.00001;

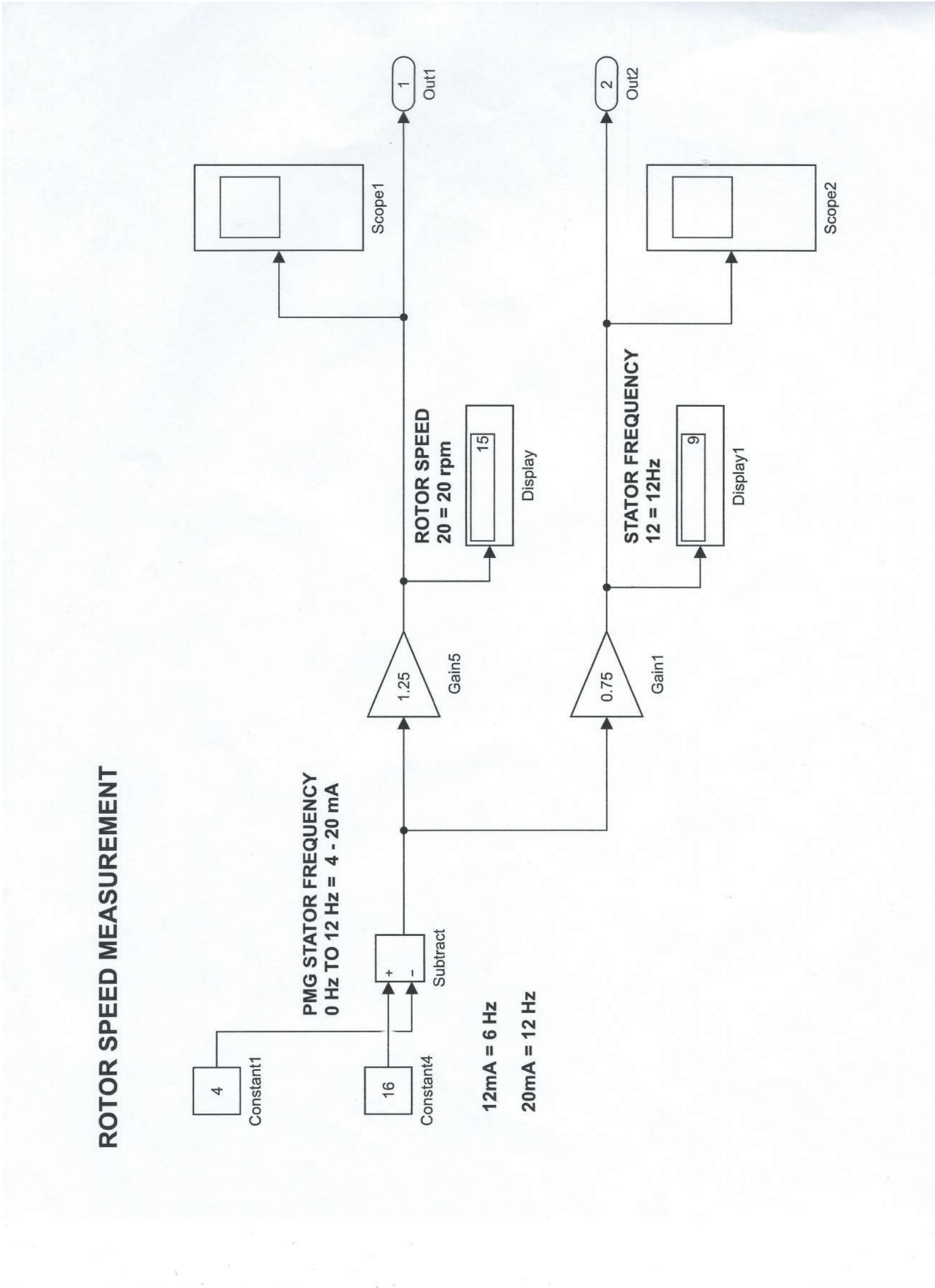

PWM Inverter
Continuous
Ideal Switch
powergui
Vd
Vdc
3Ph Bridge Converter
PWM
PWM
Gate Pulses
LC Filter r2
Measure1
Vab_VSC2
I1_load
Scope1
3Ph
Load
Vdc
Vabc_load
V_LL
Scope

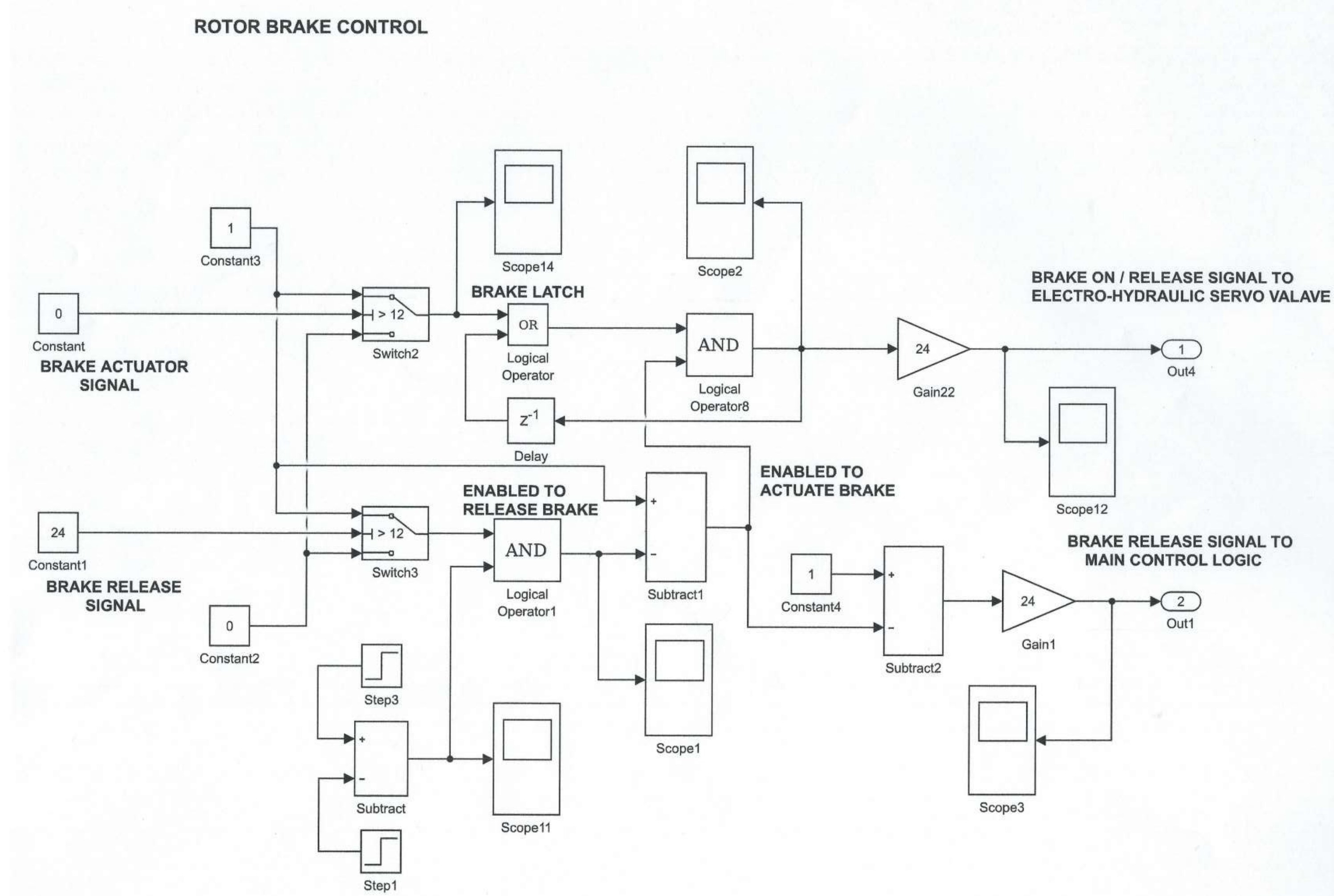

PMG
Bridge Rectifier
PWM DC Boost Converter
PWM Inverter
3 Phase Load
R1
C1
R2
R3
L1
C2
R4
Vpk = VLL X 0.81649
V LL

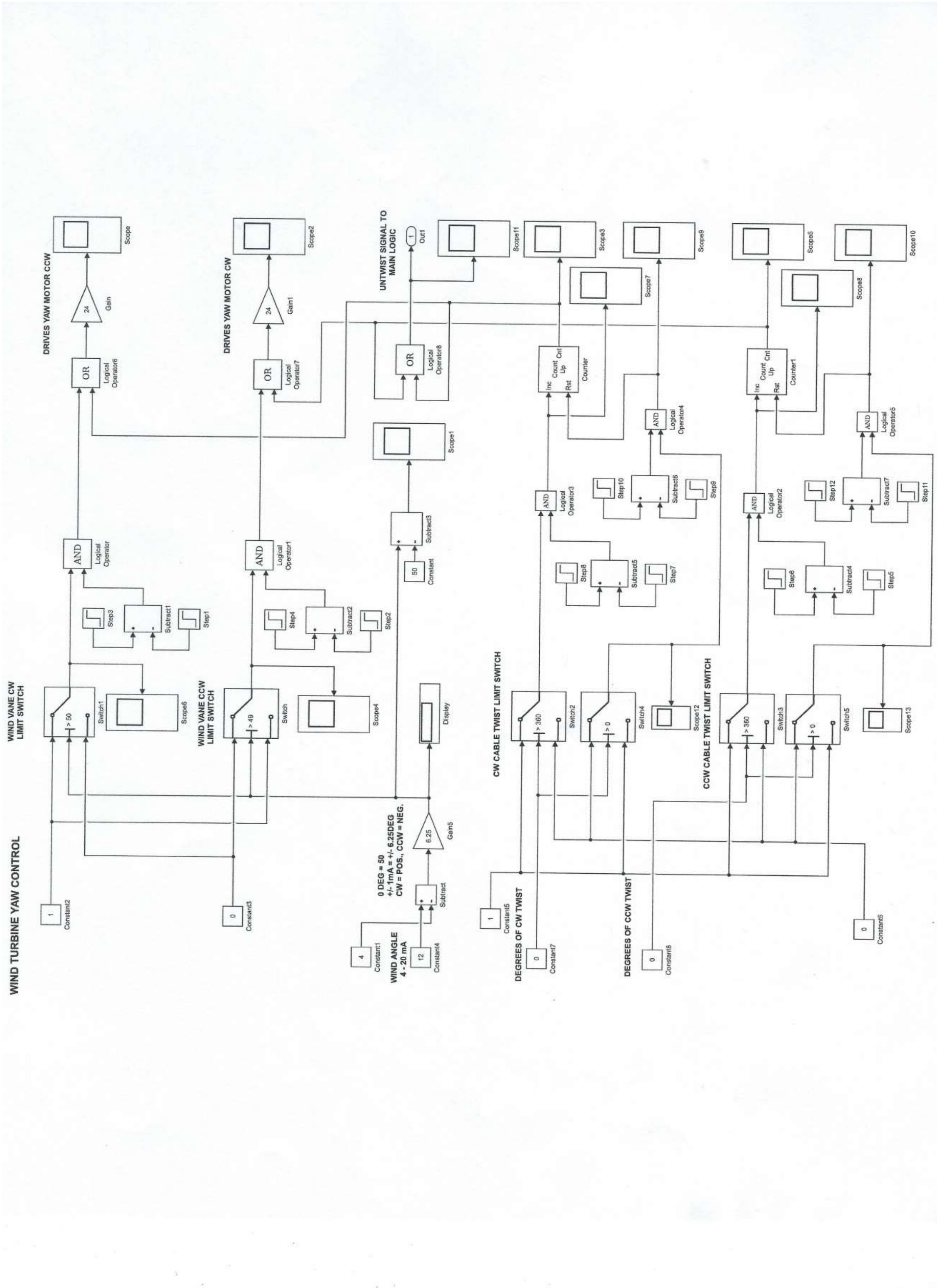

DUTY CYCLE VOLTAGE REGULATOR
PMG
Bridge Rectifier
Boost Converter Voltage Regulator
PWM DC Boost Converter
PWM Inverter
3 Phase Load
R1
R2
R3
R4
C1
C2
L1
Vpk = VLL X 0.81649
V LL

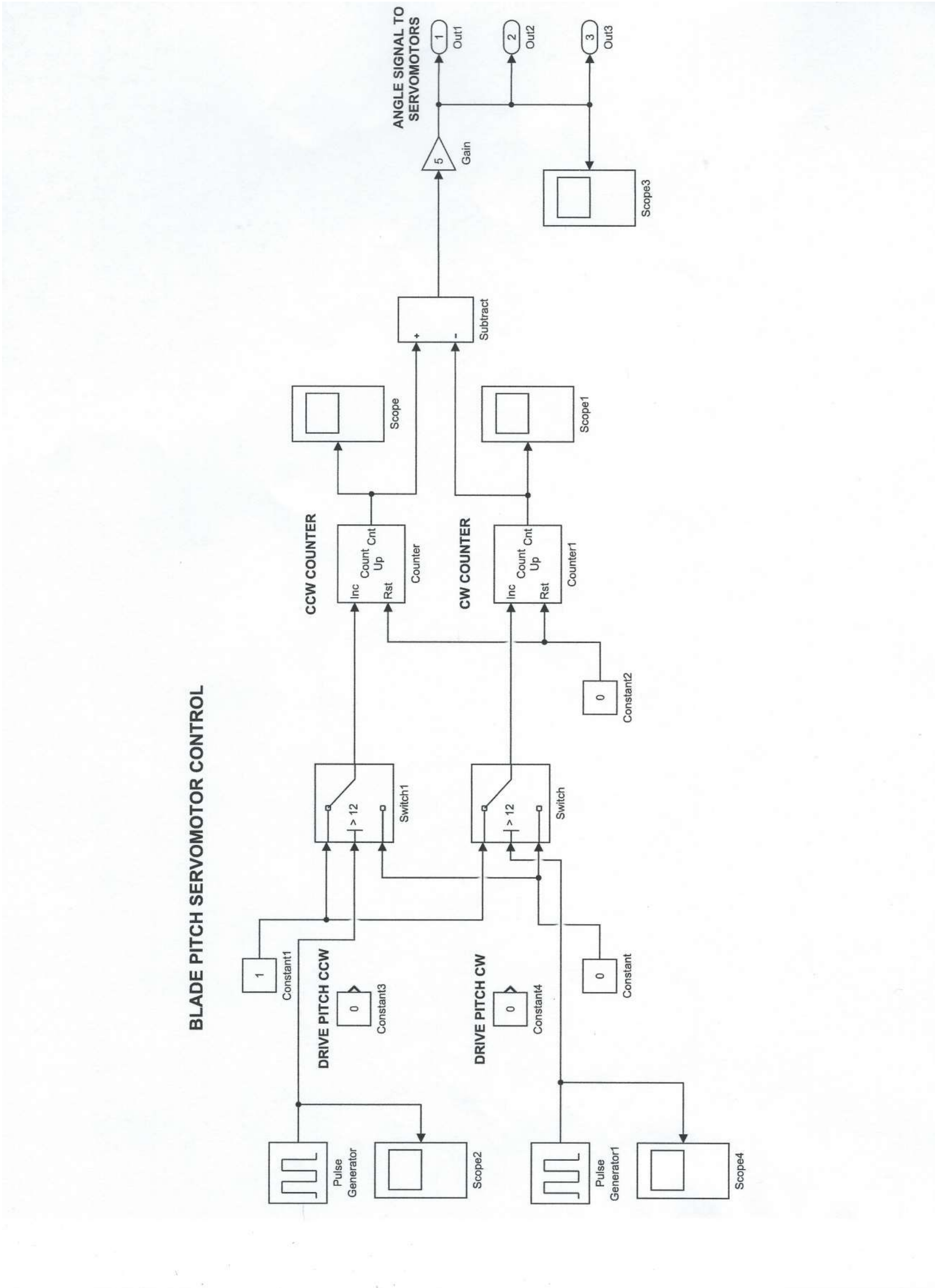
WIND TEMPERATURE MEASUREMENT

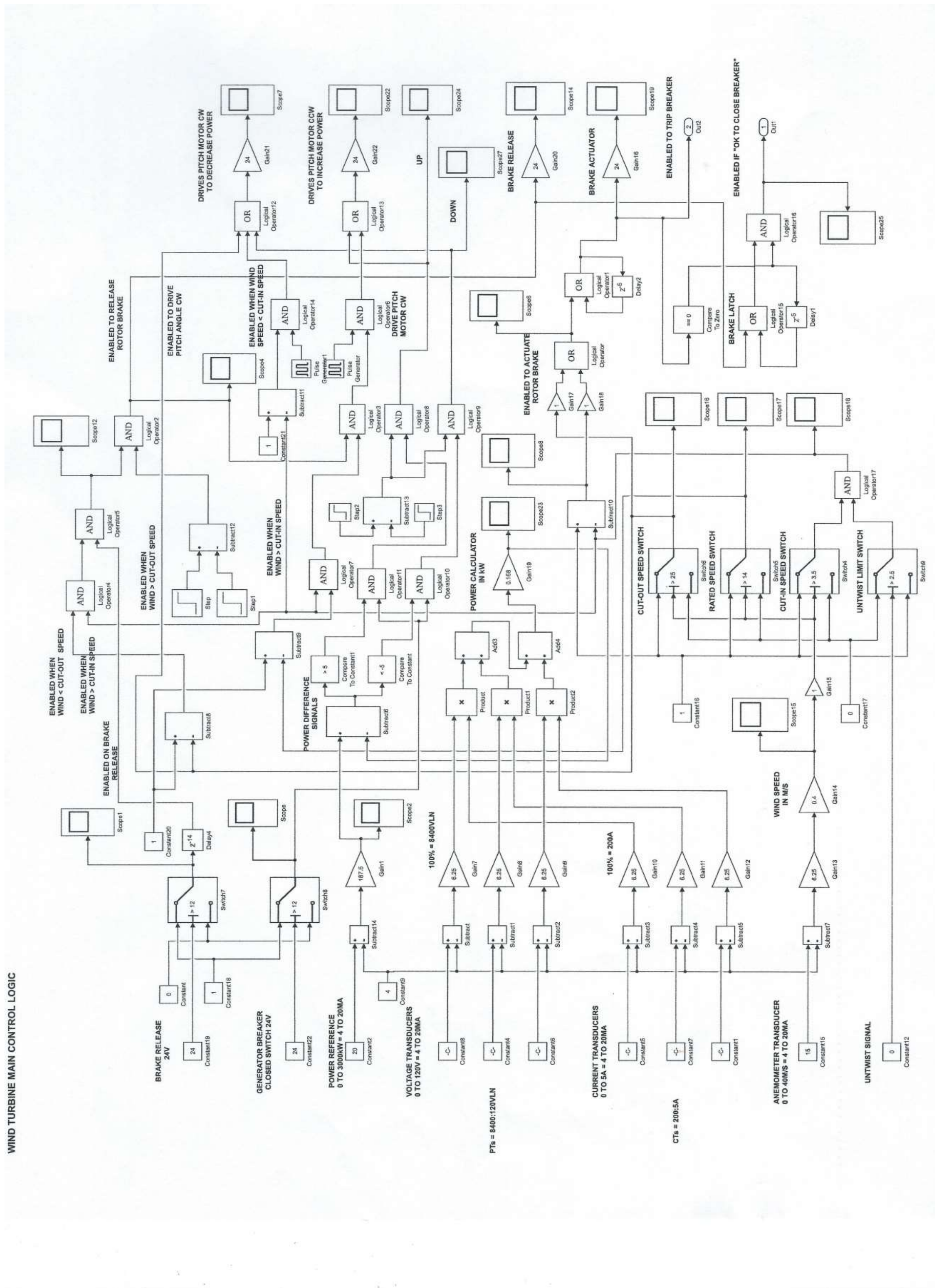


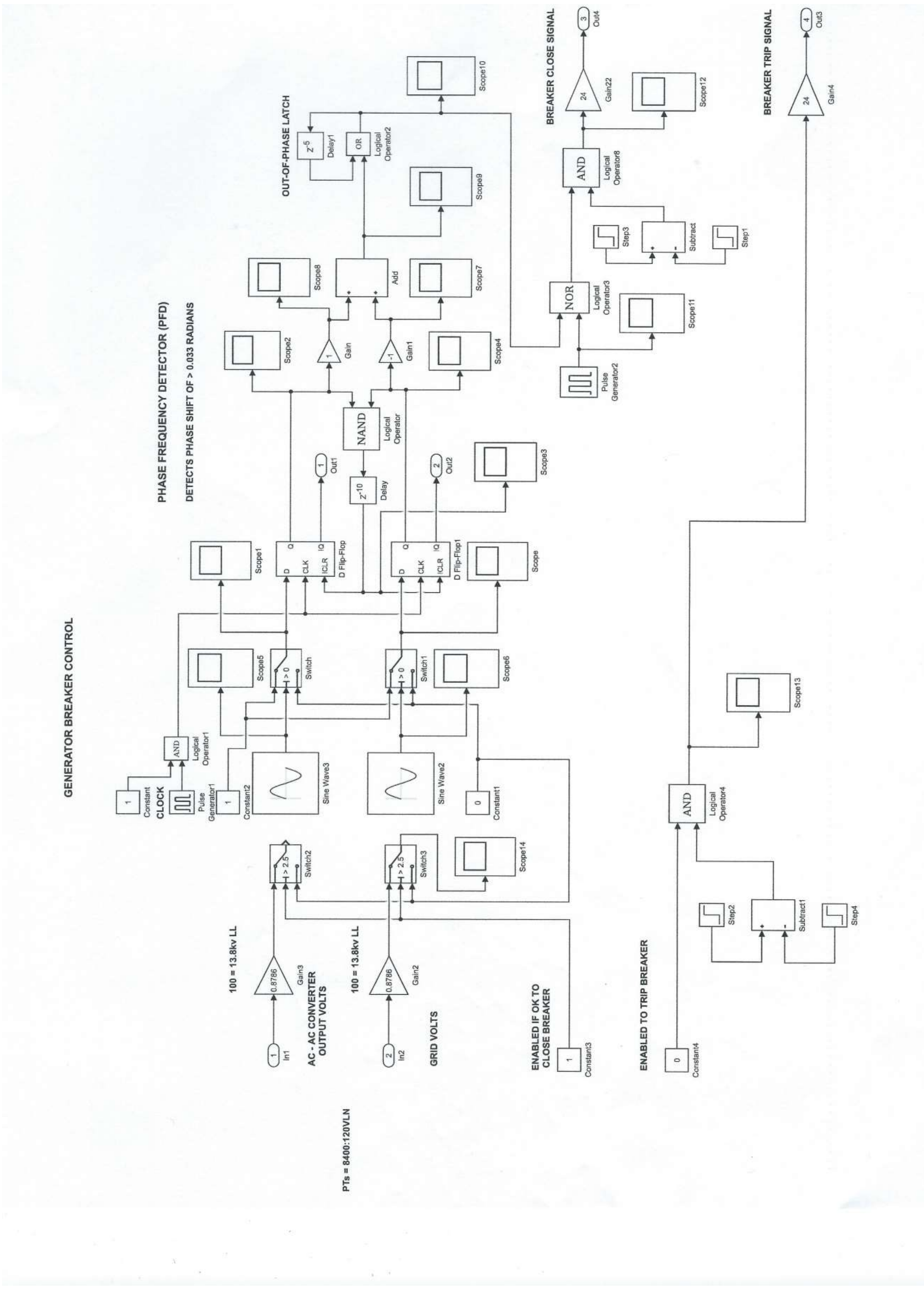

ROTOR SPEED MEASUREMENT
4
Constant1
16
Constant4
+
-
Subtract
PMG STATOR FREQUENCY
0 Hz TO 12 Hz = 4 - 20 mA
12mA = 6 Hz
20mA = 12 Hz
1.25
Gain5
0.75
Gain1
ROTOR SPEED
20 = 20 rpm
15
Display
STATOR FREQUENCY
12 = 12Hz
9
Display1
Scope1
Scope2
1
Out1
2
Out2


ROTOR BRAKE CONTROL
0
Constant
BRAKE ACTUATOR SIGNAL
1
Constant3
> 12
Switch2
Scope14
BRAKE LATCH
OR
Logical Operator
z-1
Delay
Scope2
AND
Logical Operator8
24
Gain22
Scope12
1
Out4
BRAKE ON / RELEASE SIGNAL TO ELECTRO-HYDRAULIC SERVO VALAVE
24
Constant1
BRAKE RELEASE SIGNAL
0
Constant2
> 12
Switch3
ENABLED TO RELEASE BRAKE
AND
Logical Operator1
Subtract1
Scope1
ENABLED TO ACTUATE BRAKE
1
Constant4
Subtract2
24
Gain1
2
Out1
BRAKE RELEASE SIGNAL TO MAIN CONTROL LOGIC
Scope3
Step3
Subtract
Step1
Scope11


WIND TURBINE YAW CONTROL
WIND VANE CW LIMIT SWITCH
WIND VANE CCW LIMIT SWITCH
DRIVES YAW MOTOR CCW
DRIVES YAW MOTOR CW
UNTWIST SIGNAL TO MAIN LOGIC
CW CABLE TWIST LIMIT SWITCH
CCW CABLE TWIST LIMIT SWITCH
DEGREES OF CW TWIST
DEGREES OF CCW TWIST
WIND ANGLE 4 - 20 mA
0 DEG = 50
+/- 1mA = +/- 6.25DEG
CW = POS., CCW = NEG.


BLADE PITCH SERVOMOTOR CONTROL
DRIVE PITCH CCW
DRIVE PITCH CW
CCW COUNTER
CW COUNTER
ANGLE SIGNAL TO SERVOMOTORS
Pulse Generator
Scope2
Pulse Generator1
Scope4
1
Constant1
0
Constant3
0
Constant4
0
Constant
> 12
Switch1
> 12
Switch
0
Constant2
Inc
Count Up
Cnt
Rst
Counter
Inc
Count Up
Cnt
Rst
Counter1
Scope
Scope1
+
-
Subtract
5
Gain
Scope3
1
Out1
2
Out2
3
Out3


WIND TURBINE MAIN CONTROL LOGIC
BRAKE RELEASE 24V
GENERATOR BREAKER CLOSED SWITCH 24V
POWER REFERENCE 0 TO 3000kW = 4 TO 20MA
VOLTAGE TRANSDUCERS 0 TO 120V = 4 TO 20MA
PTs = 8400:120VLN
100% = 8400VLN
CURRENT TRANSDUCERS 0 TO 5A = 4 TO 20MA
CTs = 200:5A
100% = 200A
ANEMOMETER TRANSDUCER 0 TO 40M/S = 4 TO 20MA
UNTWIST SIGNAL
WIND SPEED IN M/S
ENABLED ON BRAKE RELEASE
ENABLED WHEN WIND < CUT-OUT SPEED
ENABLED WHEN WIND > CUT-IN SPEED
ENABLED WHEN WIND > CUT-OUT SPEED
POWER DIFFERENCE SIGNALS
ENABLED WHEN WIND > CUT-IN SPEED
POWER CALCULATOR IN kW
ENABLED TO RELEASE ROTOR BRAKE
ENABLED TO DRIVE PITCH ANGLE CW
ENABLED WHEN WIND SPEED < CUT-IN SPEED
DRIVE PITCH MOTOR CW
DRIVES PITCH MOTOR CW TO DECREASE POWER
DRIVES PITCH MOTOR CCW TO INCREASE POWER
UP
DOWN
BRAKE RELEASE
ENABLED TO ACTUATE ROTOR BRAKE
BRAKE ACTUATOR
ENABLED TO TRIP BREAKER
BRAKE LATCH
ENABLED IF "OK TO CLOSE BREAKER"
CUT-OUT SPEED SWITCH
RATED SPEED SWITCH
CUT-IN SPEED SWITCH
UNTWIST LIMIT SWITCH


GENERATOR BREAKER CONTROL
PHASE FREQUENCY DETECTOR (PFD)
DETECTS PHASE SHIFT OF > 0.033 RADIANS
OUT-OF-PHASE LATCH
BREAKER CLOSE SIGNAL
BREAKER TRIP SIGNAL
CLOCK
100 = 13.8kv LL
AC - AC CONVERTER OUTPUT VOLTS
GRID VOLTS
ENABLED IF OK TO CLOSE BREAKER
ENABLED TO TRIP BREAKER
PTs = 8400:120VLN
D Flip-Flop
D Flip-Flop1
NAND
NOR
AND
OR
Sine Wave3
Sine Wave2
Pulse Generator1
Pulse Generator2
Out1
Out2
Out3
Out4
In1
In2