11-2010

Linear Optimal Control of Wind Turbines in Region III

Aliakbar Dabbaghmanesh
Santa Clara University

Santa Clara University

Department of Mechanical Engineering

November 2010

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Aliakbar Dabbaghmanesh

ENTITLED

Linear Optimal Control of Wind Turbines in Region III

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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Thesis Advisor

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Chairman of Department

Linear Optimal Control of Wind Turbines in Region III

By

Aliakbar Dabbaghmanesh

Dissertation

Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Science

in Mechanical Engineering

in the School of Engineering at

Santa Clara University, 2010

Santa Clara, California

Dedicated to Hana

Acknowledgements

I would first like to thank my advisor, Professor Mohammad Ayoubi, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject.

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of this thesis.

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Department of Mechanical Engineering

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ABSTRACT

Designing wind turbines to maximize energy production and increase fatigue life is a major goal of the wind industry. To achieve this goal, we should design wind turbines to extract maximum energy and reduce component and system loads. This thesis applies a linear quadratic regulator (LQR) pitch-control algorithm based on disturbance correction to a two-bladed teetering-hub upwind machine. The design objective is to regulate turbine speed in region three (above-rated wind speed) and to enhance damping in several low-damped flexible modes of the turbine. A PI controller and a LQR- DAC (disturbance accommodation controller) are designed for a typical wind turbine model. We show that the LQR-DAC controller performs better than the PI controller by reducing the overshoot and pitch angle fluctuations during full-load operation.

This thesis is organized as follows. In Chapter one, we introduce different forms of renewable energy. Chapter two describes the wind energy conversion systems. Modeling of mechanical parts of a typical wind turbine is discussed in Chapter 3. In Chapter 4, we introduce control objectives and different control strategies for wind turbines. Finally, in the last chapter, we design an LQR-DAC controller for a typical wind turbine and compare the performance of the proposed controller with a classical PI controller.

Contents

1

Renewable Energy

1.1 Introduction

Renewable energy is a term used to describe energy that is derived from resources, like the sun and the wind; resources that are continually available to some degree or other all over the world. We never run out of them. And their use or capture does not inflict any material damage on the environment. Sunlight is the source of most renewable energy power, either directly or indirectly. Heat from the sun also produces wind, whose energy is captured by wind turbines and turned into electricity capable of powering entire towns. Hydroelectric power is produced from streams, rivers, and waterfalls that flow downhill, their tremendous power turning large turbines that convert the flow to electricity. Organic plant matter, known as biomass, can be burned, gasified, fermented, or otherwise processed to produce electricity, heat. Geothermal energy taps the Earth's internal heat in the form of steam for a variety of uses, including electric power production, and the heating and cooling of buildings. Some new systems are in development for harvesting even more power by injecting water back into underground heat sources to produce more steam. Ocean energy can also be used to produce electricity. In addition to tidal energy, energy can be produced by the action of ocean waves, which are driven by both the tides and the winds. Because of their link to winds and surface heating processes, ocean currents are considered as indirect sources of solar energy. In this chapter we want to present a general view of important renewable energy.

1.2 Biomass

Technology Definition

Biomass, also called bio power, is defined by any organic materials that can be burned and used as a source of fuel. There are a wide variety of biomass energy resources, including tree and grass crops and forestry, agricultural, and urban wastes. It is the oldest source of renewable energy known to humans, used since our ancestors learned the secret of fire. Wood being the main source of biomass such as saw-dust or any type of waste from wood is processed to make wood-pellets. In the future, Crops should be main source for energy production. Biopower reduces most emissions (including emissions of greenhouse gases-GHGs) compared with fossil fuel-based electricity. Through the use of residues, biopower systems can even represent a net sink for GHG emissions by avoiding methane emissions that would result from land filling of the unused biomass.

History, Current and Future Status

In the latter part of the 19th century, wood was the primary fuel for residential, commercial, and transportation uses. By the 1950s, other fuels had supplanted wood. In 1973, wood use had dropped to 50 million tons per year. At that point, the forest products and pulp-and-paper industries began to use wood with coal in new plants and switched to wood-fired steam power generation. The Public Utility Regulatory Policies Act (PURPA) of 1978 stimulated the development of nonutility cogeneration and small-scale plants to in the wood-processing and pulp-and-paper sectors and increased supply of power to the grid. The combination of low natural gas prices, improved economies of scale in combined cycle plans, and withdrawal of incentives in the late 1980s, led to annual installations declining from about 600 MW in 1989, to 300-350MW in 1990. There are now nearly 1,000 wood-fired plants in the United States, with about two-thirds of those providing power (and heat) for on-site uses only.

DOE is developing systems for village-power applications and for developed-world distributed generation that are efficient, reliable, and clean. These systems range in size from 3kW to 5MW and completed field verification by 2003.Approximately 15 million to 21 million gallons of biodiesel are produced annually in the United States. Utility and industrial biopower generation totaled more than 60 billion kWh in 2001, representing about 75% of non hydroelectric renewable generation. About two-thirds of this energy is derived from wood and wood wastes, while one-third of the biopower is from municipal solid waste and landfill gas. Industry consumes more than 2.1 quadrillion Btu of primary biomass energy.

The leveling cost of electricity (in constant 1997$/kWh) for biomass direct-fired and gasification configurations are projected to be:

Table 1-1 Cost of electricity for biomass [1]

	2000	2010	2020
Direct-fired	7.5	7.0	5.8
Gasification	6.7	6.1	5.4

Depicting Technologies for converting biomass to energy

Homogenization is a process by which feedstock is made physically uniform for further processing or for combustion (includes chopping, grinding, baling, cubing, and pelletizing). Gasification (via paralysis, partial oxidation, or steam reforming) converts biomass to a fuel gas that can be substituted for natural gas in combustion turbines or reformed into H2 for fuel cell applications. Anaerobic digestion produces biogas that can be used in standard or combined heat and power (CHP) applications. Agricultural digester systems use animal or agricultural waste. Landfill gas also is produced an aerobically. Biofuels production for power and heat provides liquid-based fuels such as methanol, ethanol, hydrogen, or biodiesel.

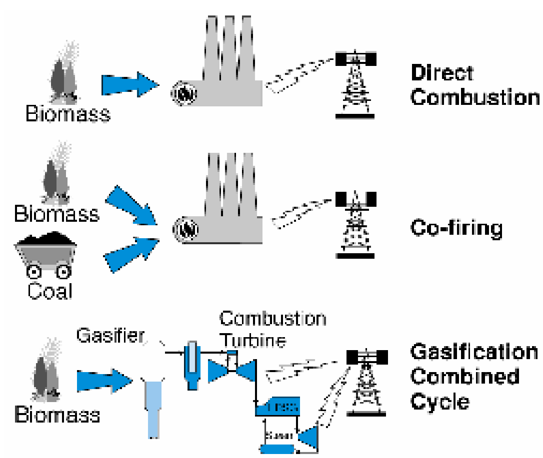


Fig.1-1. process of converting biomass to energy [1]

Direct combustion systems burn biomass fuel in a boiler to produce steam that is expanded in a Rankin Cycle prime mover to produce power. Cofiring substitutes biomass for coal or other fossil fuels in existing coal-fired boilers. Biomass or biomass-derived fuels (e.g. syngas, ethanol, biodiesel) also can be burned in combustion turbines (Brayton cycle) or engines (Otto or Diesel cycle) to produce power.

Combined heat and power (CHP) systems generate electricity and useful thermal energy in a single, integrated system. This contrasts with the common practice of separate heat and power (SHP) where electricity is generated at a central power plant, while on-site heating and cooling equipment is used to meet non-electric energy requirements. The thermal energy recovered in a CHP system can be used for heating or cooling in industry or buildings. CHP applications involve recovery of heat for steam and/or hot water for district energy, industrial processes, and other applications.

The existing biomass sector – nearly 1,000 plants – is mainly comprised of direct-combustion plants, with an additional small amount of cofiring (six operating plants). Plant size averages 20 MW, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MW in 1978 to more than 9,700 MW in 2001. More than 75% of this power is generated in the forest products industry's CHP applications for process heat. Wood-fired systems account for close to 95% of this capacity. Prices generally range from 8¢/kWh to 12¢/kWh. [1]

1.3 Geothermal Energy

Technology Definition

The word geothermal comes from the Greek words geo (earth) and therme (heat). Geothermal energy is heat from within the Earth. Geothermal energy is a renewable energy source because the heat is continuously produced inside the Earth. Geothermal energy is generated in the Earth's core. Temperatures hotter than the sun's surface are continuously produced inside the Earth by the slow decay of radioactive particles, a process that happens in all rocks. This energy can offset the emission of carbon dioxide from conventional fossil-powered electricity generation, industrial processes, building thermal systems, and other applications.

Geophysical, geochemical, and geological exploration locates resources to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids. Well fields and distribution systems allow the hot fluids to move to the point of use, and afterward, back to the earth. Utilization systems may apply the heat directly or convert it to another form of energy such as electricity.

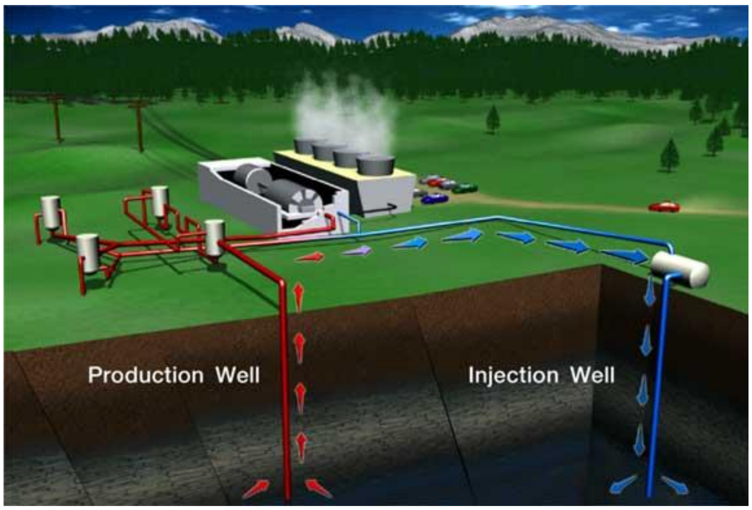


Fig.1-2 Geo Well [2]

History, Current and Future Status

In 1892, the world's first district heating system was built in Boise, Idaho, as water piped from hot springs to town buildings. Although no one imitated this system for nearly 70 years, there are now 17 district heating systems in the United States and dozens more around the world. In 1979, the first electrical development of a water-dominated geothermal resource occurred at the East Mesa field in the Imperial Valley in California. In 1981 with a supporting loan from DOE, Ormat International Inc. successfully demonstrated binary technology in the Imperial Valley of California. In 1997, a pipeline began delivering treated municipal wastewater and lake water to The Geysers steam field in California, increasing the operating capacity by 70 MW. The DOE Geothermal

Program sponsored research that won two R&D awards in 2003, advancing this renewable energy.

The leveling cost of electricity (in constant 1997$/kWh) for the two major future geothermal energy configurations are projected to be:

Table1-2 Cost of electricity for geothermal energy [1]

	2000	2010	2020
Hydrothermal Flash	3.0	2.4	2.1
Hydrothermal Binary	3.6	2.9	2.7

Representative Technologies

Exploration technologies identify geothermal reservoirs and their fracture systems. Drilling, reservoir testing, and modeling optimize production and predict useful lifetime. Steam turbines use natural steam or hot water flashed to steam to produce electricity. Binary conversion systems produce electricity from water not hot enough to flash. Direct applications use the heat from geothermal fluids without conversion to electricity. Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications.

With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity at less than 5¢/kWh. Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97%; advanced energy-conversion technologies are being implemented to improve plant thermal efficiency.

1.4 Concentrating Solar Power

Technology Definition

Concentrating solar power (CSP) technologies use mirrors to reflect and concentrate sunlight onto receivers that collect the solar energy and convert it to heat. This thermal energy can then be used to produce electricity via a steam turbine or heat engine driving a generator.

One way to classify concentrating solar power technologies is by how the various systems collect solar energy, in the following links:

Linear Concentrator Systems: Linear CSP collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to create superheated steam that spins a turbine that drives a generator to produce electricity.

Dish/Engine Systems: A parabolic dish of mirrors directs and concentrates sunlight onto a central engine that produces electricity. The two major parts of the system are the solar concentrator and the power conversion unit.

Power Tower Systems: numerous large, flat, sun-tracking mirrors, known as heliostats, focus sunlight onto a receiver at the top of a tower. A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat-transfer fluid (Fig.1.3).

Fig.1-3 Solar Towers Spain, 20 MW, 11MW [3]

One challenge facing the widespread use of solar energy is the reduced or curtailed energy production when the sun sets or is blocked by clouds. Thermal energy storage provides a workable solution to this challenge. In a CSP system, the sun's rays are reflected onto a receiver, creating heat that is then used to generate electricity. If the receiver contains oil or molten salt as the heat-transfer medium, then the thermal energy can be stored for later use.

History, Current and Future Status

Organized, large-scale development of solar collectors began in the United States in the mid-1970s under the Energy Research and Development Administration (ERDA) and continued with the establishment of the U.S. Department of Energy (DOE) in 1978.

New commercial plants are being considered for California, Nevada, New Mexico, Colorado, and Arizona. A 1MW power plant began operation in Arizona in 2005. The 10-MW Solar Two pilot power tower plants operated successfully near Barstow, California, leading to the first commercial plant being planned in Spain. Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%, saving plant operators $50 million.

The leveling cost of electricity (in constant 2003$/kWh) for three CSP configurations are projected at:

Table1-3 leveling cost of electricity for CSP [1]

	2003	2007	2012	2025
Power Tower	12.0	5.7	4.0	N/A
Dish/Engine	40.0	20.0	N/A	6

System Concepts

In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C to 800°C in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Sterling engines) to produce electricity at solar-to electric efficiencies for the system of up to 30%. CSP technologies provide firm, no intermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.

When the sun is not shining, steam can be generated with a fossil fuel to meet utility needs. Some of the new trough plants include thermal storage. Plant sizes can range from 1.0 to 100 MW. A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand, even when the sun is not shining. Plant size can range from 30 to 200 MW. A dish/engine system uses a dish-shaped reflector to power a small Sterling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in clusters (1-10 MW) for utility-scale applications, including end-of-line support

1.5 Photovoltaic

Technology Definition

Photovoltaic energy is the most promising and popular form of solar energy. In solar photovoltaic's, sunlight is actually converted into electricity. This is very different from a conventional understanding of solar power as only a way of heating water. Photovoltaic, now the biggest usage of solar energy around the world, is briefly explained below: Sunlight is made of photons, small particles of energy. These photons are absorbed by and pass through the material of a solar cell or solar photovoltaic panel. The photons 'agitate' the electrons found in the material of the photovoltaic cell. As they begin to move (or are dislodged), these are 'routed' into a current. This, technically, is electricity - the movement of electrons along a path. Wire conducts these electrons, either to batteries or to the regular electrical system of the house, to be used by appliances and other household electrical items. In many solar energy systems, the battery stores energy for later use. This is especially true when the sun is shining strongly.

Solar photovoltaic (PV) arrays use semiconductor devices called solar cells to convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV to produce hydrogen for fuel cells for electric vehicles, by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide. PV systems come in several flavors:

a) Grid Inter tied systems integrate solar electricity using the grid as a secondary power source.

b) Grid Inter tied with battery backup Add a battery to the system to collect excess solar energy for use when light is low.

c) Off Grid Photovoltaic Systems are not tied to the grid as a secondary power source.

History, Current and Future Status

French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next three quarters of a century. Major steps toward commercializing PV were taken in the 1940s and early 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon. In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had an efficiency of 4%. In 1958, the U.S. Vanguard space satellite carried a small array of PV cells to power its radio. The cells worked so well that PV technology has been part of the space program ever since. Even today, PV plays an important role in space, supplying nearly all power for satellites. The commercial integrated circuit technology also contributed to the development of PV cells.

A new generation of potentially lower-cost technologies (thin films) is entering the marketplace. A 30-megawatt amorphous silicon thin-film plant by United Solar reached full production in 2005. Two plants (First Solar and Shell Solar) using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the MW-scale. Cell and module efficiencies for these technologies have increased more than 50% in the past decade. A unique multifunction (III-V materials alloy) cell was spun off to the space power industry, leading to record cell efficiency

(35%) and an R&D 100 Award in 2001. This device configuration is expected to dominate future space power for commercial and military satellites. Recent champion cell efficiency has reached 39% under concentrated sunlight. DOE is interested in this technology (III-V multi junctions), as an insertion candidate for high efficiency terrestrial PV concentrator systems. The leveling cost of electricity (in constant 2003$/kWh) for PV are projected to be:

Table1-4 leveling cost of electricity for PV [1]

	2003	2007	2020	2025
Utility-owned	0.25-0.40	0.22	0.8-0.10	N/A
Concentrator	0.40	0.20	N/A	0.04-0.06

Worldwide, approximately 1,200 MW of PV were sold in 2004, with systems valued at more than $7 billion; total installed PV is more than 2 GW. The U.S. world market share fell to about 12% in 2004. Worldwide, market growth for PV has averaged more than 20%/year for the past decade as a result of reduced prices and successful global marketing. Worldwide sales grew 36% in 2001, 44% in 2002, 33% in 2003, and 60% in 2004. Hundreds of applications are cost-effective for off-grid needs. However, the fastest-growing segment of the market is battery-free, grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems to reduce their dependence on natural gas, especially for peak daytime loads that match PV output, such as air-conditioning.

System Concepts

Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., semitransparent solar canopy). The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen (electrolysis of water). PV systems are expected to be used in the United States for residential and commercial buildings, peak-power shaving, and intermediate daytime load. With energy storage, PV can provide dispatch able electricity and/or produce hydrogen. Almost all locations in the United States and worldwide have enough sunlight for cost-effective PV. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar insulation location in the United States (such as the desert Southwest) could generate all of the electricity needed in the country.

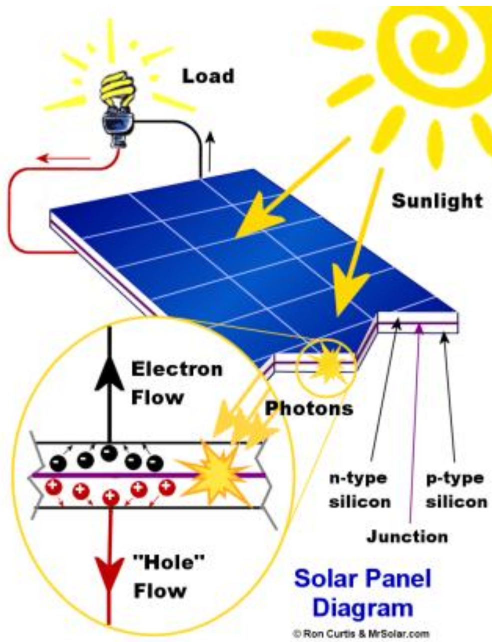


Fig.1-4.Solar Panel Diagram [4]

1.6 Wind Energy

Technology Definition

Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries. Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind "pushing" the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed or directly link to the grid or at variable speed for better performance using a power electronics system for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and standalone power applications. The most common machine configuration is a three-bladed wind turbine, which operates "upwind" of the tower, with the blades facing into the wind.

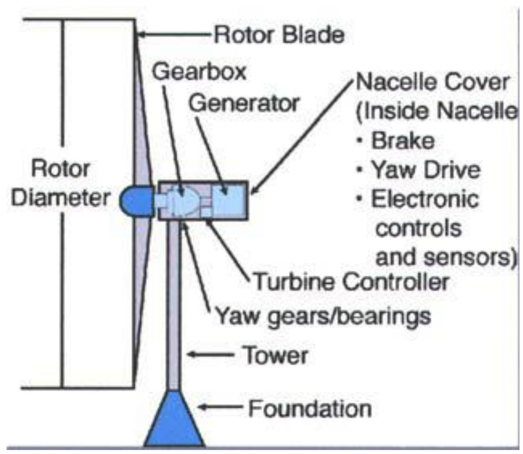


Fig.1-5 Wind Turbine [1]

History, Current and Future Status

In 1989, the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000 for sites with average wind speeds of 16 mph. The program and the wind industry met the goals as part of dramatic cost reductions from 25¢-50¢/kWh in the early 1980s to 4¢-6¢/kWh in 2005. Wind power is the world's fastest-growing energy source. In the past decade, the global wind energy capacity has increased tenfold from 3,500 MW in 1994 to almost 50,000 MW by the end of 2004. During 2004, nearly 8,000 MW of new capacity was added worldwide. Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power throughout the country. The National Wind

Technology Center (operated by the National Renewable Energy Laboratory in Golden, Colorado) is recognized as a world-class center for wind energy R&D and has many facilities – such as blade structural test stands and a large gearbox test stand – not otherwise available to the domestic industry. Prior to 1980, DOE sponsored (and NASA managed) large-scale turbine development – starting with hundred-kilowatt machines and culminating in the late 1980s with the 3.2-MW, DOE-supported Mod-5 machine built by Boeing. Small-scale (2-20 kW) turbine development efforts also were supported by DOE at the Rocky Flats test site. Numerous designs were available commercially for residential and farm uses.

In 1981, the first wind farms were installed in California by a small group of entrepreneurial companies. PURPA provided substantial regulatory support for this initial surge. During the next five years, the market boomed, installing U.S., Danish, and Dutch turbines. By 1985, annual market growth had peaked at 400 MW. Following that, federal tax credits were abruptly ended, and California incentives weakened the following year. In 1988, European market exceeded the United States for the first time, spurred by ambitious national programs. A number of new companies emerged in the U.K. and Germany. In 1989, DOE's focus changed to supporting industry-driven research on components and systems. At the same time, many U.S. companies became proficient in operating the 1,600 MW of installed capacity in California. They launched into value engineering and incremental increases in turbine size. DOE program supported value-engineering efforts and other advanced turbine-development efforts. In 1992, Congress passed the Renewable Energy Production Tax Credit (REPI), which provided a 1.5 cent/kWh tax credit for wind-produced electricity. Coupled with several state programs and mandates, installations in the United States began to increase. In 1997, Enron purchased Zond Energy Systems, one of the value-engineered turbine manufacturers. In 2002, General Electric Co. purchased Enron Wind Corporation. In FY2001, DOE initiated a low wind-speed turbine development program to broaden the U.S. cost-competitive resource base. In 2004, Clipper Wind power began testing on its highly innovative, multiple-drive 2.5 MW Liberty prototype wind turbine. In 2005, the U.S. wind energy industry had a record-breaking year for new installations, adding more than

2,400 MW of new capacity to the nation's electric grid. In 2006, the U.S. Department of Energy signed a $27 million contract with General Electric to develop a multi megawatt offshore wind power system; and Clipper Wind power begins manufacturing its multiple-drive, 2.5 MW turbines.

The levelized cost of electricity (2002 $/MWh) for wind energy technology is projected to be:

Table1-5 leveling cost of electricity for wind energy [1]

	2010	2020	2030	2040
Class 4	4.0	3.1	2.9	2.9
Class 6	3.0	2.6	2.5	2.4

Installed wind capacity in the United States expanded from 2,554 MW to 4,150 MW during the period of 2000 to 2005, but still make up less than 1% of total U.S. generation. California has the greatest installed wind capacity, followed by Texas, Iowa, Minnesota, Oregon, Washington, Wyoming, New Mexico, Colorado, and Oklahoma. Wind technology is competitive today in bulk power markets at Class 5 and 6 wind sites, with support from the production tax credit – and in high-value niche applications or markets that recognize non-cost attributes. Its competitiveness is negatively affected by policies regarding ancillary services and transmission and distribution regulations. Continued cost reductions from low wind-speed technologies will increase the resource areas available for wind development by 20-fold and move wind generation five times closer to major load centers. Wind energy is often the least variable cost source of generation in grid supplied electricity and due to its less predictable (variable resource) supply; wind usually displaces natural gas and coal generated electricity as these sources adjust to hourly changes in demand and supply. Emerging markets for wind energy include providing energy for water purification, irrigation, and hydrogen production. Utility restructuring is a critical challenge to increased deployment in the near term because it emphasizes short-term, low-capital-cost alternatives – and lacks public policy to support deployment of sustainable technologies such as wind energy, leaving wind power at a disadvantage. In the United States, the wind industry is thinly capitalized, except for

General Electric Wind Energy, which recently acquired wind technology and manufacturing assets in April 2002. About six manufacturers and six to 10 developers characterize the U.S. industry. In Europe, there are about 10 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market. Initial lower levels of wind deployment (up to 15%-20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Because the wind resource is variable, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of onshore wind turbines. However, offshore resources are located close to major load centers.

Wind Turbine Privileges

Wind is given to any natural movement of air in the atmosphere. A renewable source of energy used to turn turbines to generate electricity. Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries. There are a range of advantages of wind energy:

- Wind energy is fueled by the wind, so it's a clean fuel source. Wind energy doesn't pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas. Wind turbines don't produce atmospheric emissions that cause acid rain or greenhouse gasses.
- Wind energy is a domestic source of energy, produced in the United States. The nation's wind supply is abundant.
- Wind energy relies on the renewable power of the wind, which can't be used up. Wind is actually a form of solar energy; winds are caused by the heating of the atmosphere by the sun, the rotation of the earth, and the earth's surface irregularities.

- Wind energy is one of the lowest-priced renewable energy technologies available today, costing between 4 and 6 cents per kilowatt-hour, depending upon the wind resource and project financing of the particular project.
- Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land.

In this day and age, the world needs to look at the different natural energy sources available to us. Global warming could be due our energy craving lifestyle, so we should look into more environmentally friendly energy sources. Wind energy offers many advantages, which explains why it's the fastest-growing energy source in the world [5]. In the next chapters we present more precisely the wind energy and wind energy conversion systems.

2

Wind Turbine Basics

2.1 Wind

The wind is generated due to the pressure gradient resulting from the uneven heating of earth's surface by the sun. The wind is driven by the temperature difference, is called the geotropic wind, or more commonly the global wind.

A precise knowledge of wind characteristics is a pre-requisite for the efficient planning and implementation of any wind energy project. Wind is stochastic in nature. Average wind velocity gives us a preliminary indication on a site's wind energy potential. In the region up to 100 m above the ground, the wind pattern is further influenced by several local factors such as Land and sea breezes. The wind is retarded by frictional resistance offered by the earth surface. The speed and direction of wind change rapidly while it passes through rough surfaces and obstructions like buildings, trees and rocks. This is due to the turbulence generated in the flow.

A smooth ridge accelerates the wind stream passing over it. The acceleration is caused by the squeezing of wind layers over the mount as shown in the figure. Velocity and direction of wind change rapidly with time. In tune with these changes, the power and energy available from the wind also vary. The variations may be short time fluctuation, day-night variation or the seasonal variation. For estimating the wind energy potential of a site, the wind data collected from the location should be properly analyzed and interpreted

One of the most important information on the wind spectra available at a location is its average velocity. In simple terms, the average velocity (V_m) is given by

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{2.1}$$

where V is the wind velocity and n is the number of wind data. Apart from the average strength of wind over a period, its distribution is also a critical factor in wind resource assessment. Wind turbines installed at two sites with the same average wind speed may yield entirely different energy output due to differences in the velocity distribution. One measure for the variability of velocities in a given set of wind data is the standard deviation (σ_v)Standard deviation tells us the deviation of individual velocities from the mean value. Thus

$$\sigma_v = \sqrt{\frac{\sum_{i=1}^{n}(V_i - V_m)^2}{n}} \tag{2.2}$$

Lower values of σ_v indicate the uniformity of the data set.

2.2 Wind Energy Conversion Systems

From wind 'mills' to the modern wind electric generators, the wind energy conversion systems (WECS) have transformed to various sizes, shapes and designs, to suit the applications for which they are intended for.

The modern wind turbine is a sophisticated piece of machinery with aerodynamically designed rotor and efficient power generation, transmission and regulation components. Size of these turbines ranges from a few Watts to several Mega Watts. Modern trend in the wind industry is to go for bigger units of several MW capacities, as the system scaling up can reduce the unit cost of wind generated electricity. Most of today's commercial machines are horizontal axis wind turbines (HAWT) with three bladed rotors. Though research and development activities on vertical axis wind turbines (VAWT) were intense during the end of the last century, VAWT could not evolve as a reliable alternative to the horizontal axis machines.

The turbines may be grouped into arrays, feeding power to a utility, with its own transformers, transmission lines and substations. Stand-alone systems catering the needs of smaller communities are also common. As wind is an intermittent source of energy, hybrid systems with back up from diesel generators or photovoltaic panels are also popular in remote areas.

For the efficient and reliable performance of a WECS, all its components are to be carefully designed, crafted and integrated. In this chapter, we will discuss the constructional features of WECS giving emphasis to various components, systems and sub-systems. As off shore installations are getting prominence in the recent years, details of such turbines are also included. Wind powered water pumps, which are still relevant in remote rural areas, are also featured in this chapter.

2.2.1 Wind Electric Generators

Electricity generation is the most important application of wind energy today. The major components of a commercial wind turbine are (Fig.2-1):

1. Tower
2. Rotor
3. High speed and low speed shafts
4. Gear box
5. Generator
6. Sensors and yaw drive
7. Power regulation and controlling units
8. Safety systems

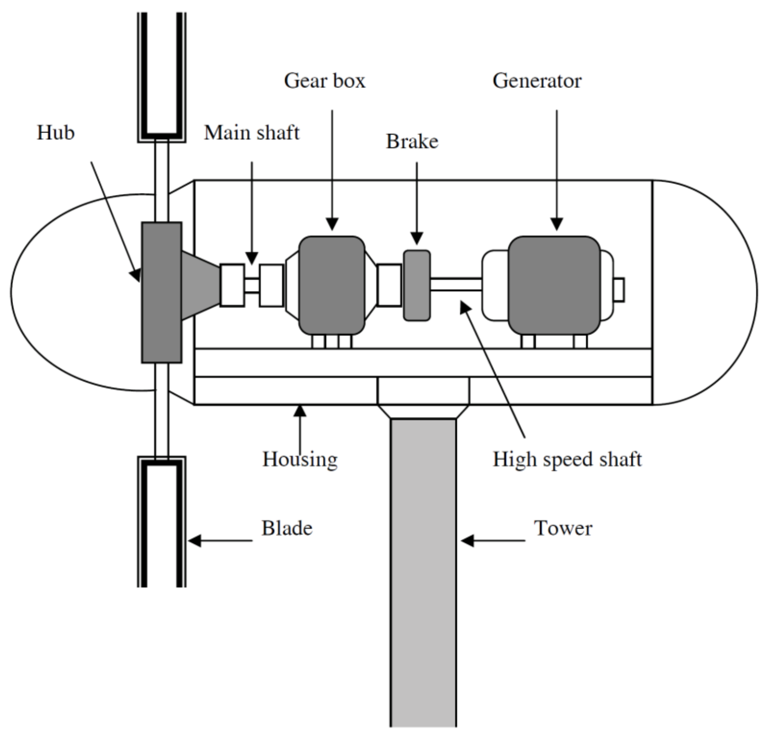


Fig.2-1. Components of a wind electric generator [6]

Tower

Tower supports the rotor and nacelle of a wind turbine at the desired height. The major types of towers used in modern turbines are lattice tower and tubular steel tower. Schematic views of these towers are shown in Fig.2.2.

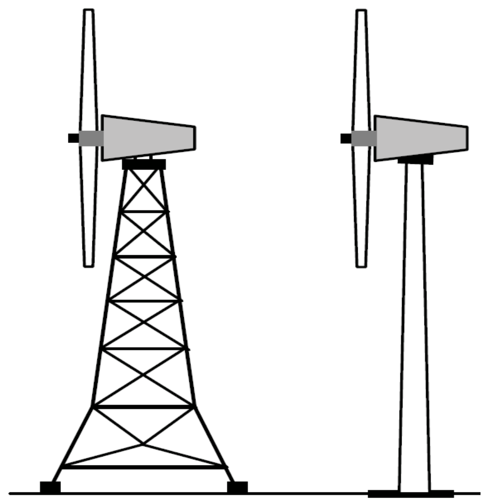


Fig.2-2. Different types of towers [6]

The lattice towers are fabricated with steel bars joined together to form the structure as shown in the figure. They are similar to the transmission towers of electric utilities. Lattice towers consume only half of the material that is required for a similar tubular tower. This makes them light and thus cheaper. Legs of these towers are spread widely as shown in the figure. As the load is distributed over a wider area, these towers require comparatively lighter foundation, which will again contribute to the cost reduction.

Lattice towers have several demerits. The major problem is the poor aesthetics as they may be visually unacceptable to some viewers. Similarly, avian activities are more intense around the lattice towers as the birds can conveniently perch on its horizontal bars. This may increase the rate of avian mortality. Lattice towers are not maintenance friendly. At installations where the temperature drops to an extremely low level, maintenance of systems with lattice towers is difficult as workers would be exposed to the chilling weather. Moreover, as these towers do not have any lockable doors, they are less secure for maintenance.

Due to these limitations, most of the recent installations are provided with tubular steel towers. These towers are fabricated by joining tubular sections of 10 to 20 m length. The complete tower can be assembled at the site within 2 or 3 days. The tubular tower, with its circular cross-section, can offer optimum bending resistance in all directions. These towers are aesthetically acceptable and pose less danger to the avian population.

Load acting on the tower increases with size of the turbine. Hence, the recent trend for MW sized systems would in turn demand for higher tower dimensions in terms of diameter and wall thickness. This impose limitations while transportation of these towers. Usually, inland transportation of structures with size higher than 3.3 m and weight more than 50 to 60 tons is difficult. Further, fabricating these huge structures is not an easy task, as rolling and welding plates with wall thickness more than 50 mm is difficult. Due to these problems, hybrid towers are proposed for high capacity systems.

Rotor

Rotor is the most important and prominennt part of a wind turbine. The rotor receives the kinetic energy from the wind stream and transforms it into mechanical shaft power. Components of a wind turbine rotor are blades, hub, shaft, bearings and other internals.

Blades of the wind turbine have airfoil sections. Though it is possible to design the rotor with a single blade, balancing of such rotors would be a real engineering challenge. Rotors with single blade run faster and thus create undue vibration and noise. Further, such rotors are not visually acceptable. Two bladed rotors also suffer from these problems of balancing and visual acceptability. Hence, almost all commercial designs have three bladed rotors. Some of the small wind turbines, used for battery charging, have more number of blades- four, five or even six-as they are designed to be self starting even at low wind speeds. Size of the rotor depends on the power rating of the turbine. The turbine cost, in terms of $ per rated kW, decreases with the increase in turbine size. Hence, MW sized designs are getting popular in the industry.

Blades are fabricated with a variety of materials ranging from wood to carbon composites. Use of wood and metal are limited to small scale units. Most of the large scale commercial systems are made with multi layered fiberglass blades. Attempts are being made to improve the blade behavior by varying the matrix of materials, reinforcement structures, ply terminations and manufacturing methods. The traditional blade manufacturing method is open mold, wet lay-up. Some of the manufacturers are making their blades by vacuum assisted resin transfer molding (VARTM).

With the increase in size, carbon-glass hybrid blades are being tried by some manufactures. These blades are expected to show better fatigue characteristics under severe and repetitive loading. The high stiffness characteristic of carbon reduces the possibility of blade bending in high winds and hence, they can be positioned close to the tower. Carbon also improves the edgewise fatigue resistance of the blades which is an advantage for bigger rotors. Weight of the blades can be reduced by 20 per cent by introducing carbon in the design. Usually, weight increases with the cube of the blade length. This can be restricted to an exponent of 2.35 in case of blades with carbon. A lighter blade demands lighter tower, hub and other supporting structures and thus may contribute to the economy of the system. Most of the modern wind turbines have up-wind rotors. During wind loading, the blades of these rotors may be pushed towards the tower. This reduces the effective blade length and thus the rotor area. This back bending may also cause fatigue to the blades in due course. To avoid this problem, modern rotors have pretend geometries. The pre-bend blades stretch to its total lengths under wind loading, and thus exploit the full potential of the rotor as shown in Fig.2-3.

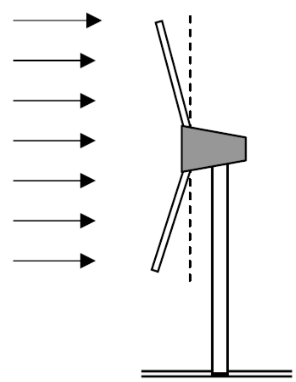


Fig.2-3. Pre-bending of blades [6]

The theories considered are the axial momentum theory, blade element theory and the strip theory. Based on these theories, a procedure was also evolved for the design of wind turbine blades. It should be noted that, we have discussed only the basic concepts of the design in these sections. Conditions under which a wind turbine is put to work are severe and unpredictable and thus cannot be fully defined by mathematical formulations. Further, the flow around the rotor is a very complex process, involving dynamic interactions between the fluid particles and blades elements. Expertise in atmospheric fluid dynamics, aerodynamics and structural dynamics is essential for understanding the behavior of the system under fluctuating conditions of wind regime. Hence, accurate and reliable prediction of wind ro98 tor performance still remains a challenge to the scientists and engineers working in this area.

Various numerical methods are being followed by the researchers as well as industrial experts to design the rotor and estimate its performance. Some of the popular approaches are the Blade Element Momentum method [7, 8], Vortex Lattice method [9] and Reynolds-averaged Navier stokes method [10, 11]. Computer codes based on these models are also available for the design. All these methods have their inherent merits and demerits. For example, Blade Element Momentum and Vortex Lattice methods are strong in predicting the pre-stalled behavior of the rotor. However, they are inadequate in defining the stall and stall delay performances. Hence, these models may not be accurate in higher wind speeds. Reynolds-averaged Navier stokes method is preferred under these conditions. However, this model is inefficient in predicating the rotor vortex wake convection and boundary layer turbulence. Performances of these models under different flow conditions are compared in [12]. Further, based on the typical flow conditions, different variations of these models are also being used.

The blades of the rotor are attached to hub assembly. The hub assembly consists of hub, bolts, blade bearings, pitch system and internals. Hub is one of the critical components of the rotor requiring high strength qualities. They are subjected to repetitive loading due to the bending moments of the blade root. Due to the typical shape of the hub and high loads expected, it is usually cast in special iron alloys like the spherical graphite (SG) cast iron. Forces acting on the hub make its design a complex process. Three dimensional Finite Element Analysis (FEA) and topological optimization techniques are being effectively used for the optimum design of the hub assembly [13].

The main shaft of the turbine passes through the main bearings. Roller bearings are commonly used for wind turbines. These bearings can tolerate slight errors in the alignment of the main shaft, thus eliminating the possibility of excessive edge loads. The bearings are lubricated with special quality grease which can withstand adverse climatic conditions. To prevent the risk of water and dirt getting into the bearing, they are sealed, sometimes with labyrinth packing. The main shaft is forged from hardened and tempered steel. Replacing the bearings of an installed turbine is a very costly work. Hence, to ensure longer life and reliable performance, hybrid ceramic bearings are used with some recent designs. The advantages of ceramic hybrids are that they are stiffer, harder and corrosion free and can sustain adverse operating conditions. These bearings are light in weight and offer smoother performance. Electrically resistant nature of ceramic hybrids eliminates the possibilities of electrical arcing. These bearings are costlier than the standard bearings. However, they can be economical in the long run due to its better performance.

Gear box

Gear box is an important component in the power trains of a wind turbine. Speed of a typical wind turbine rotor may be 30 to 50 r/min whereas; the optimum speeds of generator may be around 1000 to1500 r/min. Hence, gear trains are to be introduced in the transmission line to manipulate the speed according to the requirement of the generator. An ideal gear system should be designed to work smoothly and quietly-even under adverse climatic and loading conditions-throughout the life span of the turbine. Due to special constraints in the nacelle, the size is also a critical factor.

In smaller turbines, the desired speed ratio is achieved by introducing two or three staged gearing system. Thus a gear ratio of 25 is required, which is accomplished in two stages as shown in the figure. Low speed shaft from the rotor carries a bigger gear which drives a smaller gear on the intermediate shaft. Teeth ratio between the bigger and smaller gear is 1:5 and thus the intermediate shaft rotates 5 times faster than the low speed shaft. The speed is further enhanced by introducing the next set of gear combination with bigger gear on the intermediate shaft driving a smaller gear on the generator shaft. Finally the desired 1:25 gear ratio is achieved.

If higher gear ratios are required, a further set of gears on another intermediate shaft can be introduced in the system. However, the ratio between a set of gears are normally restricted to 1:6. Hence, in bigger turbines, integrated gear boxes with a combination of planetary gears and normal gears are used. A typical gear box may have primary stage planetary gears combined with a secondary two staged spur gears to raise the speed to the desired level. By introducing the planet gears, the gear box size can be considerably reduced. Moreover, planet gears can reliably transfer heavy loads.

Due to its compact design, it is difficult to dissipate the heat generated during the power transmission in planetary gears. Another problem is the complexity in manufacturing these gears. Beveled gears are less noisy due to the smooth transfer of loads between the adjacent teeth. However, bevel gears cannot be used in planetary gear system.

Bearings for different points of the gear box are selected based on the nature of loads to be transmitted. Hence cylindrical roller bearings are recommended. The output shaft has to transmit high speed and low radial loads and hence cage guided cylindrical bearings may be used. Other possible options at this point are self aligning bearings or four point contact ball bearings.

Gears are designed on the basis of duration and distribution of loads on individual gear teeth. The load duration and distribution pattern (LDD), under a given set of wind conditions, are analyzed. This is further extrapolated for the life time of the gears to arrive at the final design. Advanced numerical simulation tools are also being used for characterizing the dynamic response of wind turbine gears and other power trains [6].

Power Regulation

Power curve of a typical wind turbine is shown in Fig.2-4. The turbine starts generating power as the wind speeds crosses its cut-in velocity of 3.5 m/s. The power increases with the wind speed up to the rated wind velocity of 15 m/s, at which it generates its rated power of 250 kW. Between the rated velocity and cut-out velocity (25 m/s), the system generates the same rated power of 250 kW, irrespective of the increase in wind velocity. At wind velocities higher than the cut-off limit, the turbine is not allowed to produce any power due to safety reasons.

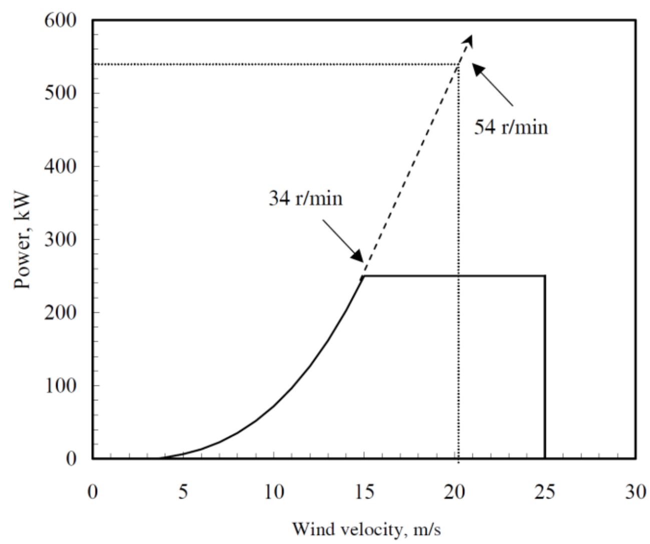


Fig.2-4. Power curve of a typical wind turbine [6]

Power generated by the turbine is regulated to its rated level between the rated and cut-out wind speeds. If not regulated, the power would have been increased with wind speed as indicated by the dotted lines as in the figure. In the above example, we can see that the power corresponding to 20 m/s is more than twice the rated power of the system. However, if we want to harness the power at its full capacity even at this high velocity, the turbine has to be designed to accommodate higher levels of power. This means that, the system would require stronger transmission and bigger generator. On the other hand, probability for such high wind velocities is very low in most of the wind regimes. Hence, it is not logical to over design the system to accommodate the extra power available for a very short span of time.

Speed of the rotor also increases with the wind velocity. In the above example, the rotor speed increases from 34 r/min to 54 r/min, while the velocity changes from 15 m/s to 20 m/s. With further increase in velocity, the rotor may further speed up, finally reaching the run-away situation. It should also be noted that this increase in speed occurs in a short span of time, resulting in rapid acceleration. Hence it is vital that the power of the turbine should be regulated at constant level, at velocities higher than the rated wind speed. The common methods to regulate the power are pitch control, stall control, active stall control and yaw control.

Wind turbine blades offer its maximum aerodynamic performance at a given angle of attack. The angle of attack of a given blade profile changes with the wind velocity and rotor speed. Principle of pitch control is illustrated in Fig.2-5. Here V_R is the rated wind velocity; V_T is the velocity of the blades due to its rotation and α is the angle of attack. In a pitch controlled wind turbine, the electronic sensors constantly monitors the variations in power produced by the system. The output power is checked several times in a second. According to the variations in power output, the pitch control mechanism is activated to adjust the blade pitch at the desired angle as described below.

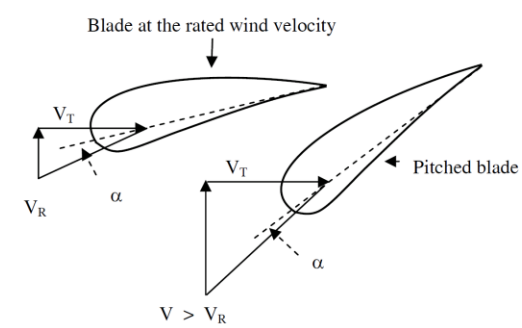


Fig.2-5. Principle of pitch control [6]

Between the cut-in and rated wind speeds, the turbine is made to operate at its maximum efficiency by adjusting the blade pitch to the optimum angle of attack. As the wind velocity exceeds V_R, the control mechanism change the blade pitch resulting in changes in the angle of attack as shown in the figure. From Fig.2-6, we can see that, any changes in the angle of attack from its optimum level would in turn reduce the efficiency of the rotor. Thus, at wind speeds higher than V_R, we are shedding the excessive rotor power by spoiling the aerodynamic efficiency of the blades. Once the velocity comes down to the rated value or below, the blades are pitched back to its optimum position.

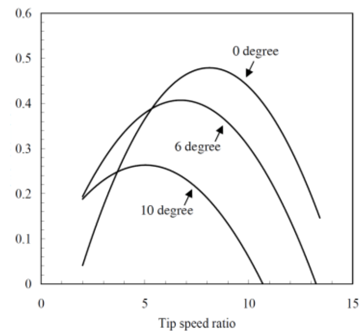


Fig.2-6. Effect of blade pitch on the rotor performance [6]

In a pitch controlled turbine, the blades are to be turned about their longitudinal axis by the pitch control mechanism in tune with the variations in wind speed. The pitch control mechanisms are driven by a combination of hydraulic and mechanical devices. In order to avoid sudden acceleration or deceleration of the rotor, the pitch control system should respond fast to the variations in wind velocity. Similarly, for maximum performance, the pitching should exactly be at the desired level. Thus, the pitch control system should be very sensitive.

Another method to regulate the power at high wind velocities is stall regulation. The basic principle of stall regulated turbines is illustrated in Fig.2-7. In these turbines, profile of the blades is designed in such a way that when the wind velocity exceeds beyond the rated limit, the angle of attack increases as shown in the figure. With this increase in angle of attack, air flow on the upper side of the blade ceases to stick on the blade.

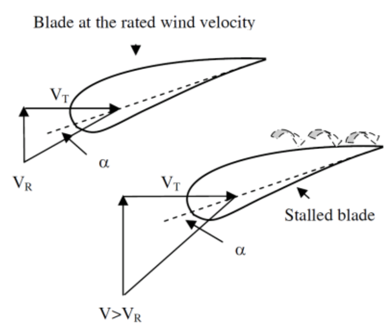


Fig.2-7. Principle of stall control [6]

Pitch controlled turbines can capture the power more effectively in moderate winds as the blades can be set to its optimum angle of attack by pitching. However, moving components are to be introduced in the blade itself for adjusting its angle, which is a drawback of these systems. Similarly, the control unit should have high sensitivity towards wind fluctuations which makes them costlier.

On the other hand, stall controlled blades do not require any control system or pitching mechanism. However, the blades are to be aerodynamically twisted along its longitudinal axis. Design and manufacturing of such blades demand sophistication. Structural dynamics of the system should be carefully analyzed before the design to avoid any possible problems like the stall induced vibrations. Performance of these turbines at higher wind speeds is not impressive as the power falls below the rated level. In spite of these limitations, many wind power plants are still installed with stall controlled turbines.

Some modern turbines exploit the advantages of both the pitch and stall controlled options for regulating its power. This is called the active stall controlled power regulation. In this method, the blades are pitched to attain its best performance in lower winds. However, once the wind exceeds the rated velocity, the blades are turned in the opposite direction to increase the angle of attack and thus forcing the blades into a stall region. The active stall allows more effective power control and the turbine can be run nearly at its rated capacity at high winds.

Safety Brakes

During the periods of extremely high winds, wind turbines should be completely stopped for its safety. Similarly, if the power line fails or the generator is disconnected due to some reason or the other, the wind turbine would rapidly accelerate. This leads the turbine to run-away condition within a few seconds. As the rotor accelerates rapidly, the safety brakes should have rapid reactive response to prevent the run-away condition. Two types of brakes are commonly used with wind turbines. They are aerodynamic brakes and mechanical brakes. In order to ensure the safety, wind turbines usually have two braking systems, one functioning as the primary brake and the other as a backup option which comes in to action if the primary system fails.

Aerodynamic brakes are the primary system in most of the wind turbines. Aerodynamic braking in pitch and stall controlled turbines are different. In pitch and active stall controlled systems, the entire blade is turned 90° along its longitudinal axis, there by hindering the driving lift force. Thus the rotor would stop after making a few more rotations.

Mechanical brakes are friction devices, consisting of brake disc, brake caliper, brake blocks, spring loaded activator and hydraulic control. The brake disc is fixed to the high speed shaft coming from the gear box. Under normal operation, the brake disc and blocks are held apart by hydraulic pressure. When the system is to be braked due to safety reasons, this pressure is released and the brake spring presses the block against the disc. This will bring the system to halt. Being frictional devices operating under extreme loading, the brake blocks are made with special alloys which can tolerate high stress and temperature.

Generator

Generator is one of the most important components of a wind energy conversion system. In contrast with the generators used in other conventional energy options, generator of a wind turbine has to work under fluctuating power levels, in tune with the variations in wind velocity. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few Watts to kilo Watts in capacity. Bigger systems use single or three phase AC generators. As large-scale wind generation plants are generally integrated with the grid, three phase AC generators are the right option for turbines installed at such plants. These generators can either be induction (asynchronous) generators or synchronous generators.

Induction Generator

Most of the wind turbines are equipped with induction generators. They are simple and rugged in construction and offer impressive efficiency under varying operating conditions. Induction machines are relatively inexpensive and require minimum maintenance and care. Characteristics of these generators like the over speed capability make them suitable for wind turbine application. As the rotor speed of these generators is not synchronized, they are also called asynchronous generators.

Induction machines can operate both in motor and generator modes. Let us first consider it as a motor and then look into the generator option. The cross sectional view of an induction motor is shown in Fig.2-8. Stator consists of a number of wound coils placed inside its slots. The stator windings are connected to the power supply. They are wound for a specified number of poles depending on the speed requirement.

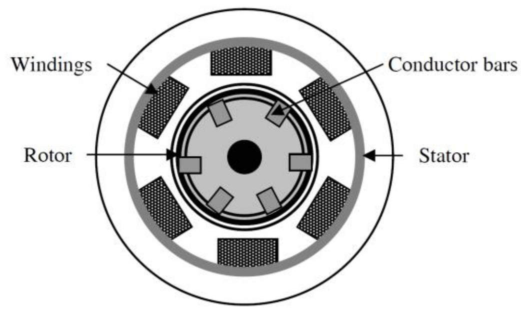


Fig.2-8. Cross-sectional view of an induction motor [6]

External excitation is essential for an induction generator before it is put to work. For grid integrated systems, this is not a limitation as it can draw the required current from the grid. However, in standalone mode, external devices like capacitors or batteries are required to provide the necessary excitation current to the generator.

During calm periods, the wind turbine is idle and there is no external driving force for the generator. Hence, the system will draw current from the grid and start behaving as a motor, driving the rotor like a huge fan. To avoid this situation, the generator is disconnected from the grid during calm periods. At wind speeds lower than the cut-in speed, the rotor is allowed to rotate freely without generating any power. At wind speeds preset on the basis of the cut-in velocity, the system is gradually connected to the grid to receive excitation and then to function as a generator as explained above. This is accomplished by special electronic contacts called thyristors. Thus, thyristors allow gradual loading of the turbine and thus eliminate the possibilities of transmission failure and grid damage due to sudden surging of current. Once the system is cut-in, the thyristors are bypassed using bypass switches. Then the flow will be directly from the generator to the grid, avoiding power loss due to the thyristors.

Synchronous Generator

As we have seen, speed of the rotor lags behind the synchronous speed in an induction generator. In contrast, rotor and magnetic field rotates at the same speed in a synchronous generator. Cross-sectional view of a synchronous generator, in its simplest form, is shown in Fig.2-9. It consists of a rotor and a three-phase stator similar to an induction generator. The stator and rotor have the same number of poles. The generator shown in the figure has two poles. The stator has coils wound around them, which are accommodated in slots as shown in the figure. The stator windings are displaced circumferentially at 120° interval.

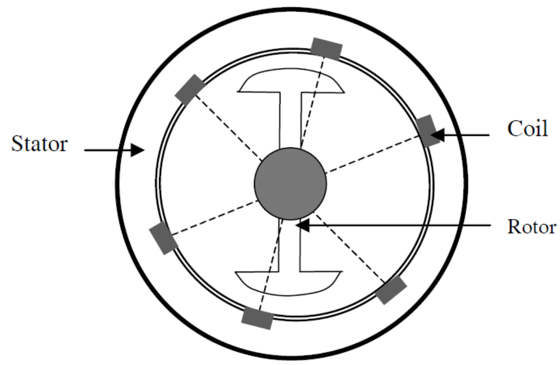


Fig.2-9. Principle of synchronous generator [6]

Fixed and Variable Speed Operations

A wind turbine can be designed to run at fixed or variable speeds. In fixed speed turbines, the rotor is coupled with an induction generator via speed increasing gears as shown in Fig.2-10 Stator winding of the generator is directly wired to the grid. As we have seen, induction generators require excitation power from the grid. This may result in undesirable voltage variations, especially in weaker networks. To avoid this problem, capacitors are provided in the circuit as shown in the figure. With this configuration, the wind turbine will run at constant (or nearly constant) speed and feed the grid with power in a predetermined frequency (50 Hz or 60 Hz).

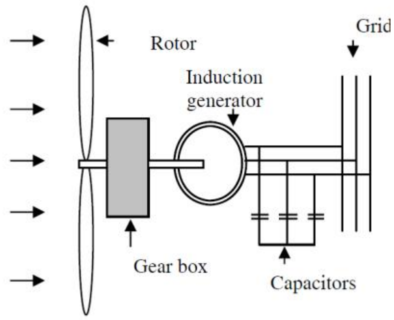


Fig.2-10 Fixed speed wind turbine [6]

Wind turbines which operate in variable speeds are equipped with either synchronous generators or a doubly fed induction generators. In systems with synchronous generator, the operating speed changes randomly with fluctuations in the wind velocity and hence the output voltage and frequency would also vary. This output cannot be directly fed to the grid due to its poor power quality. Thus the wind turbine is totally decoupled from the grid in the variable speed option. The power is fed to the grid after conditioning through a suitable interface (Fig. 2-11). Thus, the AC generated by the synchronous generator is first rectified into direct current and then inverted back to AC at standard grid frequencies (50 Hz or 60 Hz), before feeding it to the grid.

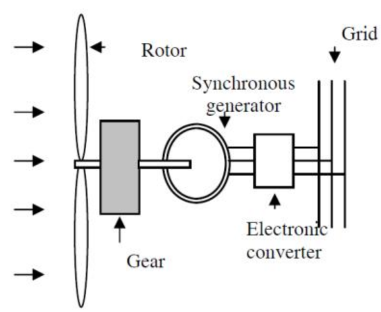


Fig.2-11. Variable speed wind turbine with synchronous generator [6]

In variable speed turbines with doubly fed induction generators, the stator winding is directly connected to the grid. However, the rotor winding is fed through a converter which can vary the electrical frequency as desired by the grid. Thus the electrical frequency is differentiated from the mechanical frequency, which allows the variable speed operation possible. Typical configuration of such a system is shown in Fig. 2-12.

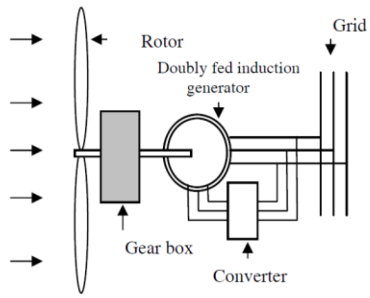


Fig.2-12 Variable speed wind turbine with doubly fed induction generator [6]

The fixed speed turbines are simple in construction and thus tend to be cheaper than the variable speed option. However, as it cannot track the ever fluctuating wind speed, the energy capture is not as efficient as in fixed speed systems. As we have discussed, a wind rotor offers maximum power coefficient at its design tip speed ratio. For constant speed operation, this maximum power coefficient can only be attained at the design wind velocity of the turbine. This is illustrated in Fig.2-13. Here, V_1 is the design wind velocity at which the turbine operates at a speed of N1 and generates a power of power P_1. At this wind speed, the turbine works at its maximum power coefficient. However, when the wind speed varies from V_1 to say V_2, as the fixed speed system could operate only at the same speed N_1, the power developed is P_2 as in the figure. Thus, the peak power of P_3 developed by the rotor at V_2 is not fully utilized by the system as the turbine has to run at its fixed speed N_1. On the other hand, if variable speed operation is possible, the system can be designed to run at a speed of N_2 at velocity V_2, and thus generating the highest possible power P_3 at this velocity. Thus the variable speed option allows the turbine to operate at its optimum level at a wide range of wind speeds. In other words, by allowing the turbine to operate at variable speed, the energy capture can be maximized. This is highly beneficial at locations with highly fluctuating wind regimes. The energy capture can be 8 to 15 per cent more in some specific sites.

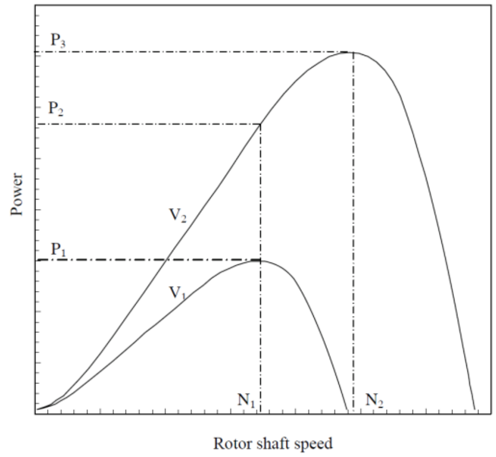


Fig.2-13. Rotor speed versus power at two different wind velocities [6]

Variable speed operation also reduces the load on the drive trains. Operating the turbine at constant speed under varying power levels results fluctuations in the torque transmitted. On the other hand, if speed is allowed to vary, the torque can be held almost constant over a wide range of power. This alleviates the stresses imposed on the structural components and thus, the turbine can be made lighter and cheaper. The rotor operating at variable speed can absorb the excess energy due to wind gust by speeding up and give it back to the system while the wind slows down. They offer better power quality as the flicker problem is minimized. As the rotational speed is low at lower wind speeds, variable speed turbines are less noisy making them acoustically acceptable.

However, variable speed turbines require complex and costly power electronics. Another problem is the excitation of structural resonance. In spite of these, variable speed design is getting popular these days. Several commercial manufactures are shifting to the variable speed option, especially for their offshore designs.

Grid Integration

Till the recent years, contribution of wind power to the grid was not significant to affect the power quality. Hence, integrating wind energy to the power grid was not a matter of concern. Share of wind generated electricity in the grid is increasing day by day. For example, wind energy penetration in some areas of Europe has reached to a level of 10 to 15 per cent. In some specific pockets in Denmark, it is as high as 80 per cent

[14]. Grid penetration at this level definitely warrants careful integration of wind energy to the electrical network.

The quality of the electrical network to which wind energy is fed is one of the important factors to be considered in the grid integration. The output frequency has to be maintained very closely to 50 or 60 Hz, depending on the local needs. The grid should be strong enough to withstand the characteristics of wind generated electricity. Instability in the grid can cause the wind farm to shut down. This becomes more critical if the penetration rate is high.

Matching the supply with the demand is quite important. Usually the supply system may consist of a number of power plants connected to the network. This may include nuclear, combined cycle gas turbine, hydro-electric plants, coal etc, along with wind turbines. Some of these plants provide the base load where as others may be utilized as the load tracking plants. Due to obvious economic reasons, the plants with high initial cost and low running cost are chosen to meet the base load where as systems requiring lower capital and higher running cost meets the additional demand.

Wind, like other renewable, is an ideal base load supplier. Apart from economic criteria, environmental issues and regulatory requirements are also in favor of using wind generated electricity to meet the base load. As the running cost of wind turbines is negligible in comparison with technologies like coal, it is advantageous to utilize the turbines at their full potential throughout the day. In many parts of the world, it is obligatory for the utility company to purchase all the electricity generated from wind. In countries like UK, wind energy has the ‘must take’ privilege under the Non Fossil Fuel Obligation, which demands the utilities to meet certain percentage of their electricity supplies from renewable.

For regulating the generation, demand at different time’s scales has to be accurately forecasted. There are short time variations in demand ranging from several seconds to 10 minutes as well as long time variations involving 10 minutes to several hours. Short term variations are often regulated by adjusting the generators.

A certain time period is required for starting the generators and synchronizes it with the grid. Hence the fluctuations in the load are to be predicted beforehand. This will help us to decide which system should be committed to the grid, at what time. Demand prediction models are used for this purpose. These models use the historical demand data along with meteorological predictions (to forecast chills etc.) and daily event schedules (holidays/working days or any special programs in the TV etc.) to arrive at load estimations.

2.2.2 Wind Farms

Wind turbines of various sizes are available commercially. Small machines are often used for standalone applications like domestic or small scale industrial needs. When we have to generate large quantities of power, several wind turbines are clubbed together and installed in clusters, forming a wind farm or wind park. There are several advantages in clustering wind machines. The installation, operation and maintenance of such plants are easier than managing several scattered units, delivering the same power. Moreover, the power transmission can be more efficient as the electricity may be transformed to a higher voltage.

Several steps are involved in the successful planning and development of a wind farm. They are:

1. Preliminary site identification
2. Detailed technical and economical analysis
3. Environment, social and legal appraisal and
4. Micro-sitting and construction

The first step in the development of a wind farm is to identify a suitable location, having reasonably high wind velocity. Once the broad geographical region for the development of the proposed wind farm is identified, it may be possible to locate several sites which could be used for constructing the wind farm. Wind data available from local weather stations, airports etc. or published documents like wind maps may be used for this purpose. A candidate site must usually have a minimum annual average wind speed of 5 m/s. Once such sites available in the region are identified, computer models are used for estimating the energy potential of these sites in different time frames. The WERA model, provided with this book, can be used for this purpose. Thus the candidate sites are compared and short listed on the basis of their wind potential.

In the first stage we relied on existing information to rate the potentiality of the sites. In the next stage, more rigorous analysis is required. The nature of the wind spectra available at the sites is to be thoroughly understood for the detailed technical analysis. For this, wind speed has to be measured at the hub height of the proposed turbines. Anemometers installed on guyed masts are used for wind measurement. Several anemometers, installed at different locations, are preferred for accurate analysis. Wind speed at the site has to be monitored at least for six months. If time and resources permit, the duration may further be increased to one year or even more.

Fig.2-14.A land based wind farm [15]

Once long term wind data collected over short periods are available, detailed wind resource analysis is possible using computer programmers like WERA. As discussed in the next chapter, the total kWh output from a turbine, at a given site, depends on the matching between the site's wind profile and the machine characteristics. Hence, it is advisable to include the behavior of the turbines, proposed to be installed at the site, in the performance model. This gives us the capacity factor and kWh output from the turbines over different time intervals.

Apart from the sites wind potential, other factors like access to the grid, roads and highways, existing infrastructure for power transmission and ground condition at the site are also to be critically analyzed while choosing the site. The local electricity distribution system at these sites should be examined to ensure that minimum infrastructures are additionally required for feeding the power to the grid. Similarly, accessibility to major highways and roads is also an important factor, as we have to transport the turbine and its components to the site. Availability and cost of land for the wind farm development is another major consideration. If our intention is to sell the generated power, an understanding on the prevailing energy market is also essential. The physical condition of the site should be thoroughly examined at this stage. This will give us an idea about the cost of foundation and other related constructions. The size (power rating) and number of turbines required for the project can be decided. Cost of the turbines and its accessories as well as the mode of maintenance may be negotiated with the manufacturer or local suppliers. Once all these issues are examined and costs involved are estimated.

For bringing the project to a reality, apart from being economically viable, it should be environmentally acceptable. The major concerns are visual effects, avian interaction, noise emission and ecological factors. Local survey and consultation with the local planning authority would be helpful in determining the environmental acceptability of the project. It should also be ensured that the proposed project is acceptable to the local residents. The developer should discuss the proposed project with the local community for avoiding any possible hassles in a later stage. It should be ensured that the project comply with the statutory requirements prevailing in the region. The sites, which do not meet the requirements in the above aspects, may be dropped from the 'short list'.

When several turbines are installed in clusters, the turbulence due to the rotation of blades of one turbine may affect the nearby turbines. In order to minimize the effect of this rotor induced turbulence, a spacing of 3 D_T to 4 D_T is provided within the rows, where D_T is the rotor diameter. Similarly, the spacing between the rows may be around 10 D_T, so that the wind stream passing through one turbine is restored before it interacts with the next turbine. These spacing may be further increased for better performance, but may be expensive as we require more land and other resources for farther spacing.

2.2.3 Offshore Wind Farms

In the recent years, there is a strong trend to shift the wind farm activities to offshore. Offshore wind farms are not a new concept as the possibilities for such projects were explored even during the 1970s and 1980s. Today, a number of ambitious offshore projects are in the pipeline. At the current growth rate, worldwide contribution from offshore projects is estimated to be 4,500 MW by 2010 [6].

Offshore wind energy projects have several attractions. Offshore winds are stronger and steadier than the onshore wind. For example, at 10-15 m from the shore, the velocity of wind is higher by 20-25 per cent. As the wind velocity at the site critically influences the energy generated and thus the cost of unit generation, this stronger wind spectra is a significant advantage.

Fig.2-15. Middelgrunden offshore wind farm, Denmark [16]

Further, in comparison with the onshore wind, offshore wind is less turbulent. This reduces the fatigue loads on turbines and thus increases their service life. Similarly, the sea offers lesser resistance to the wind flow, resulting in lower wind shear. This means that taller towers may not be required for the offshore projects (However, there may still be an increase in wind speed with height at offshore, so an economically optimum tower height is recommended).

Offshore wind projects are more environmentally acceptable as the land use, noise effect and visual impact may not be major concerns for planning approvals. Land based turbines are often made to run at tip speed ratios lowers than the optimum to reduce the noise pollution. Offshore systems can be designed to operate at higher speeds-sometimes 10 per cent higher-resulting in better aerodynamic efficiency. Similarly, offshore units are bigger in size and hence have better economics. Currently, bigger turbines of 2 MW or more capacity are being used for offshore installations. As aesthetic is not a major concern at offshore, it is possible to go for two bladed rotors instead of the conventional three bladed designs. This not only reduces the weight, but also improves the aerodynamic efficiency.

For offshore installation, turbines are to be adapted to the marine environment. A clear understanding of the offshore conditions is essential for the design. Apart from the wind characteristics, the important factors are depth of water, wave conditions, see bed characteristics, proximity to electrical network, possibility of ice formation and effect on marine habitat. With the present day's technology, it is not feasible to build the farms at water depths over 40 m. Hence most of the farms are built near to the shore-probably within 10 km-where we have shallow water.

Height of waves increases with the wind velocity and depth of seabed. Wave heights vary between 4 to 8 m at shallow bed where as at water depths between 16 to 29 m, the wave height could be as high as 16 to 20 m [31]. If site-specific measurements are not available, wave characteristics are to be modeled prior to the farm design. Similarly, possibilities of ice formation should also be taken into account.

Offshore turbines are to be guarded against corrosion with special surface finishing. Tower and nacelle are made airtight to avoid the exposure of sensitive components to salty air. Some designs are also provided with a dehumidification system. Due to the harsh marine environment, it may be difficult to reach the turbine frequently for maintenance. Hence, these high reliability- minimum maintenance turbines are designed to be remote controlled, as far as possible. Some of the modern turbines, tailor made for offshore use, are provided with special cranes for easy repair and maintenance of the blades and generator. Special platforms with cranes are also provided at the base for handling the components.

The distinct feature of offshore installations is its foundation, which are embedded in the seabed. The major types of foundations are gravity based foundation and piled foundation, the latter being the most common among offshore installations. The piled foundations can be mono-pile or tripod type as shown in Fig.2-16. In tripod structures, load is distributed over a wider area. In gravity based structures, the tower and the turbine are fixed on a large and heavy mass of material. Due to the higher volume of material required, cost of the gravity based structures are higher than the piled foundations. Lattice and tubular towers can be used with both the piled and gravity based foundations, as shown in the figure.

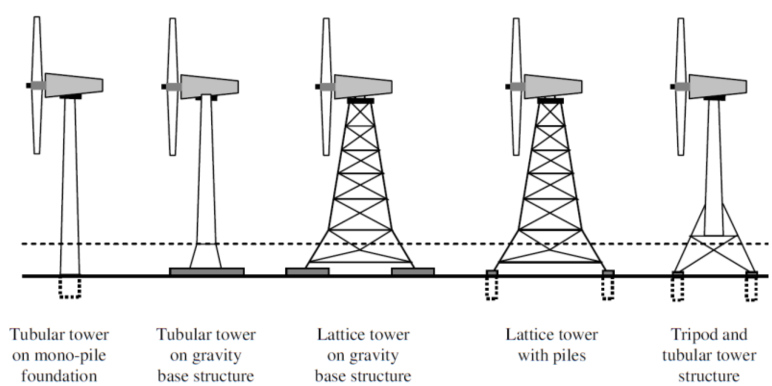


Fig.2-16. Different foundations for offshore turbines [6]

Another type of foundation, proposed for offshore turbines, is floating structure. Here, several turbines are placed together on a single platform. However, they are in the conceptualization phase and yet to be commercially adopted.

Owing to its special needs, offshore wind farms are costlier than onshore projects. The wind farm economics depends on several parameters like wind resource, characteristics of the location, access to grid, and prevailing energy market. At the current rate, an offshore wind farm approximately costs between $ 14,000 and $ 17,000 per kW installed capacity, which is around 30 per cent higher than the onshore installations. The major items adding to the installation costs are the foundation and grid connections. The foundation cost increases steeply with the water depth and wave height, while the distance from the shore determines the grid connection cost. In some cases, cost of support structure and grid connection went up to 40 per cent of the total project outlay. However, this high capital investment is often justified by the better energy yield from offshore farms.

Although some of the major environmental concerns of the land based wind farms are not relevant to offshore projects, they also have some environmental problems. Construction activities for installing offshore turbines may affect the marine habitats. This include the transportation of turbine and its components, construction of piles and other structures for the foundation, laying and burying of the cables and usage of chemicals and oils for the construction. It should be noted that, all these installation activities are usually completed within six months. The operational phase does not considerably affect the marine life. Though the operating noise from wind turbines may travel underwater, these low frequency waves are not audible to many marine species. The major environmental concern during the operation of offshore project is the bird collision. This is a site specific issue and, as in case of land based projects, areas of intensified avian activities should be avoided. European Commission has suggested a detailed procedure for the design of offshore wind farms [17].

3

Wind Turbine Aerodynamics Modeling

3.1 Introduction

In the field of wind turbine design, accurate structural modeling is one of the most important research areas. Structural modeling is required to accurately predict the stress field, which is important in determining the turbine's lifetime. Our objective is to derive a model of the entire system. An accurate but highly complex model might not be useful to a practical design of the control system. So, a feasible structural model could involve some points of compromise between accuracy and efficiency. The purpose of the model is to predict the behavior the wind turbine sufficiently well for design and analysis of controllers for power limitation. A linearized model that is truly useful in the design of controls must be obtained from linearization about the periodic steady state [18].

Bindner in [19] presents a model for design and analysis of controllers for pitch controlled wind turbines in order to evaluate and improve pitch controllers for conventional three bladed pitch controlled wind turbines. This model is simple and first orders linear differential equation. The equations of motion in [20] are derived with Lagrangian mechanics, applied on a model with flexibly interconnected rigid bodies. These equations are not only nonlinear but also very complex. Therefore they are not explicitly presented here. However, the model is given by the degrees of freedom, and the model of the external loads. The nonlinear equations are linearized, for analysis and design. In order to facilitate linearization, the rotor speed is assumed constant, which makes the resulting system periodically time-varying.

Paper [21] said "Unsteady Aerodynamics Experiment field testing showed that the typical outdoor conditions under which a wind turbine operates are incredibly complex. This led to the recognition that a major factor contributing to modeling tool limitations was due to inadequacies in the aerodynamics algorithms within the tools themselves."

Paper [22] discuss about modeling tools and methods. It said that "in recent years, progress has been made in developing and validating simulation codes for predicting wind turbine loads and response. Bladed is one such code that has been developed by

Garrad Hassan. It uses Blade Element Momentum (BEM) theory to calculate blade aerodynamic forces and uses a modal representation to formulate the wind-turbine equations of motion. The equations of motion allow DOF for modeling blade flexibility (flap and lag) as well as rotor teeter, drive train torsion, flexible mountings of the drive train to the turbine bedplate, generator dynamics, as well as turbine yaw and tower flexibility. In the United States, a general-purpose commercial multi-body dynamics code ADAMS'(Automatic Dynamic Analysis of Mechanical Systems) has been adapted for wind turbine use. Due to its comprehensive nature, one can model a wind turbine having almost any configuration without developing new codes from scratch. Flexible components such as blades and towers are modeled as a series of rigid bodies connected by elastic elements. It is common for a typical ADAMS wind turbine model to contain 200-300 DOF. A big issue is run-time for such large models and the steep learning curve. Another issue is the difficulty in generating a linear model for control design. ADAMS is not well suited for use as a control design tool, although the code does allow one to incorporate almost any type of control system into the code and simulate the system response. A more streamlined code FAST-AD has been developed and refined in the United States. This code is specifically intended for simulating both two- and three-bladed wind turbines. The code uses a modal approach in combination with Kane Dynamics to develop the equations of motion (EOM). The code also runs significantly faster than a large comprehensive code such as ADAMS because of the use of the modal approach with fewer DOFs to describe the most important turbine dynamics."

3.2 Wind turbine model

Wind turbine modeling is an ever-developing field of research that has made great strides in recent years; however, there is much yet to be learned about complex turbine aerodynamics. Modeling tools such as SymDyn (Stol and Bir 2003) and FAST (Buhl et al. 2003) can be used to model numerous degrees of freedom (DOF) for a large variety of HAWTs and have undergone validation studies (Stol and Bir 2000, Buhl et al. 2001). The advantage of creating a simple model rather than using one of the previously validated codes lies in the fact that the simple model is able to run more quickly [29].

From a system viewpoint, the conversion chain can be divided into four interacting main components which will be separately modeled; into four main functional blocks, namely the aerodynamic, mechanical, electrical, and pitch servo subsystems. The aerodynamic subsystem is devoted to the conversion of the harnessed wind energy into useful mechanical energy. The mechanical subsystem fulfils two main functions. The first one, carried out by the drive-train, is to transfer the torque from the rotor to the electric generator. The second one is to support the rotor and other devices in height while withstanding the thrust force. The electrical subsystem performs the conversion of mechanical power at the generator shaft into electricity. Finally, the pitch servo subsystem consists of a hydraulic or electromechanical device that rotates (part of) the blades around their longitudinal axes, thus modifying the pitch angle. The WECS subsystems are usually treated individually; a global WECS model suitable for control structure design is obtained by adding models of their interactions.

A model for the entire WECS can be structured as several interconnected subsystem models as it is shown in Fig.3-1.

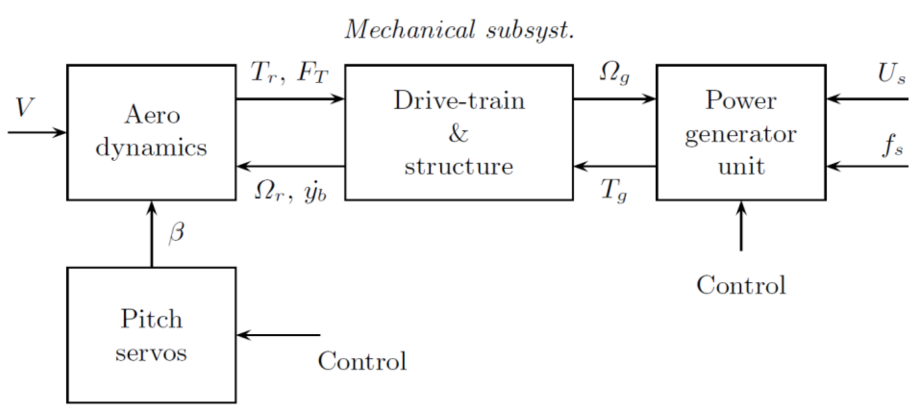


Fig.3-1. Subsystem-level block diagram of a variable-speed variable-pitch WECS [23]

3.3. Fixed-point Wind Speed Model

From a system point of view, the wind speed represents the main exogenous signal applied to the WECS and determines its behavior. Its erratic variation, highly dependent on the given site and on the atmospheric conditions, makes the wind speed quite difficult to model. Usually the thermal equilibrium of the atmosphere nearby Earth is assumed [24] Therefore, turbulence results mainly from the friction between air and ground, due to the ground roughness. When designing WECS, the history of the wind speed extreme values (gusts) is considered for the mechanical structure design and also for control purposes.

Wind near the Earth's surface is generally modeled by a spatial (3D) speed distribution. Assuming that the turbine is equipped with a vane (or yawing equipment) and that changes in wind direction are sufficiently slow, then the turbine rotor is maintained normal to the wind and WECS analysis requires only the longitudinal wind speed being synthesized/modeled. Thus, in the present book only scalar (1D) wind speed models will be used. As the interest here is focused on WECS behavior in normal operating regimes, the developed models will not include extreme operating conditions like wind gusts.

Wind dynamics result from combining meteorological conditions with particular features of a given site. Thus, wind speed is modeled in the literature as a non-stationary random process, yielded by superposing two components [24, 25, 26, 23]

$$v(t) = v_s(t) + v_t(t) \tag{3.1}$$

where $v_s(t)$ is the low-frequency component (describing long term, low-frequency variations) and $v_t(t)$ is the turbulence component (corresponding to fast, high frequency variations).

3.4. Variable-pitch Case

The wind turbine torque computation procedure can be synthesized as in these steps [27, 28].

1. Input (constant) data: number of blades, blade length, air density, number of finite elements and chord variation along the blade, pitch variation along the blade, aerodynamic characteristics C_z and C_x depending on the incidence angle.
2. Input variables: wind velocity, rotational speed, and pitch angle (at the hub).

3. For each element j, compute:

a) elementary tip speed ratio $\lambda_r(j)$;

$$\lambda_r(j) = \frac{r(j).\Omega}{v} \tag{3.2}$$

b) elementary distance to the hub $r(j)$, total pitch corresponding to the element, $\beta(j)$;

c) elementary incidence angle, $i(j)$

$$i(j) = \tan^{-1}\left(\frac{1}{\lambda_r^2(j)}.\frac{1-a(j)}{1+b(j)}\right) - \beta(j) \tag{3.3}$$

d) elementary axial and tangential interference factors, $a(j)$ and $b(j)$;

$$a(j) = \frac{k}{(1-k)^2}.\frac{\lambda_r^2(j)}{1+\lambda_r^2(j)/(1-k)^2} \tag{3.4}$$

$$b(j) = \frac{k}{(1-k)}.\frac{1}{1+\lambda_r^2(j)/(1-k)^2} \tag{3.5}$$

e) relative wind speed, $w(j)$

$$w(j) = v.\sqrt{(1-a(j))^2 + \lambda_r^2(j).(1-b(j))^2} \tag{3.6}$$

f) lift and drag coefficients, $C_z(i)$ and $C_x(i)$, and also their report $1/\varepsilon(i)$;

$$\varepsilon(i) = {C_x(i)}/{C_z(i)} \tag{3.7}$$

Dependence of coefficients $C_z(i)$ and $C_x(i)$ vs. the incidence angle are known for a given blade profile ([31] - Fig.3-2).

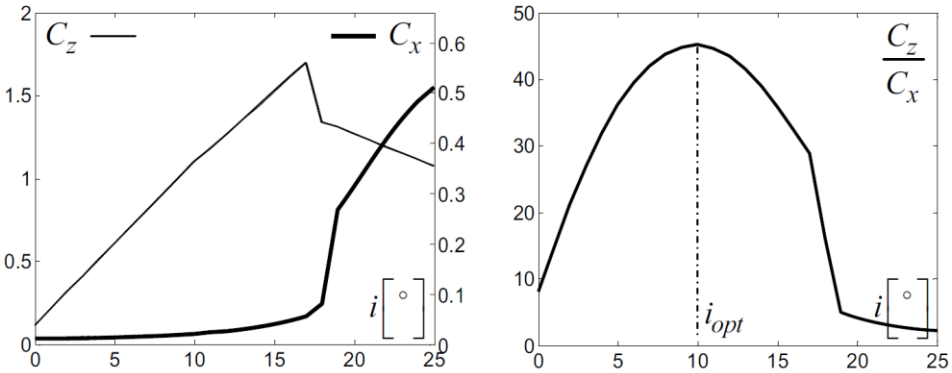


Fig.3-2. *Cx*, *Cz* and 1/*ε* profiles vs. the incidence angle, *i* [30]

Elementary torque

$$dF_t(j) = 0.5\rho\, c(j)\, w(j)^2\, C_z(i).\sin[\beta(j)+i(j)].\{1-\varepsilon.\cot[\beta(j)+i(j)]\}.dr \qquad (3.8)$$

4. Numerically integrate the elementary torque equation (using a suitably chosen method).Each blade element develops an elementary torque:

$$d\Gamma(j) = r(j).dF_t(j) \qquad (3.9)$$

By integrating Equation 3.9 along the blade length and by using Equation 3.8, one obtains the total torque developed by the wind turbine rotor:

$$d\Gamma(j) = \int r(j).dF_t(j) \qquad (3.10)$$

3.5. Drive Train Modeling

The main element of a rigid drive train is the single-stage rigidly-coupled speed multiplier, of (fixed) ratio i and efficiency η (Fig.3-3).

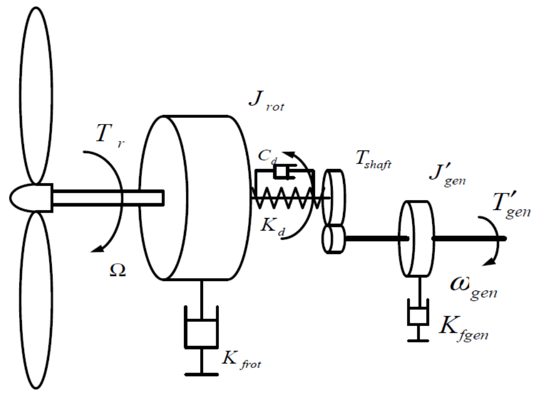


Fig.3-3. rigid drive train [32]

In this case, the model consists of a first-order motion equation, rendered either at the low-speed or at the high-speed shaft. The aerodynamic torque expression for our purpose, is given by [33].

$$T_r = \frac{1}{2}\frac{\pi\rho R^2 C_P(\beta,\lambda)}{\lambda} v(t)^2 \tag{3.11}$$

The torque coefficient $Cp(\beta,\lambda)$ depends on the blade pitch angle β and the tip-speed ratio λ which is defined as follows [33, 34],

$$C_P(\beta,\lambda) = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5).e^{-\frac{22.5}{\lambda_i}} \tag{3.12}$$

in which, ρ is the density of air, R is the radius of rotor, $v(t)$ is the wind speed, β is the pitch angle, λ is tip speed ratio (equation 3.2),
Ω is the rotor speed, which indicates wind turbines efficiency of converting wind energy to usable mechanism power. Cp is function of tip speed ratio λ and blade pitch angle β .

4

Control of Wind Turbines

4.1 Literature review

Stol and Balas [35] use Disturbance Accommodating Control (DAC) techniques to estimate fluctuating wind disturbances. Their control objective is to regulate rotor speed at above-rated wind speeds while mitigating cyclic blade root loads. Their modeled turbine is a two-bladed, downwind machine with simple blade and tower flexibility having four degrees of freedom. Comparisons are made to a time-invariant DAC controller and to a proportional integral- derivative (PID) design. Their results indicate that the state-space control designs are effective in reducing blade loads without a sacrifice in speed regulation.

Hand and Balas [36] implement disturbance accommodating control (DAC) methods in a structural dynamics code to mitigate blade loads and maintain constant power production in above-rated wind speeds. Their results show that this reduced equivalent fatigue load as much as 30% compared to a standard proportional-integral (PI) controller. A realizable DAC controller that incorporates only the vertical shear component of the vortex reduced loads by 9% compared to a PI controller, and as much as 29% when the vortex is superimposed over normal turbulence.

Koa, Jatskevicha, Dumonta and Gi-Gap Yoon [37] use the linear quadratic regulator (LQR) for multi-input multi-output systems to control voltage for a grid-connected wind farm on Vancouver Island, Canada. That is accomplished by representing the underlying control optimization problem in terms of a system of linear-matrix-inequality (LMI) constraints and matrix equations that are simultaneously solved. The solution of LMI equations involves a form of quadratic Lyapunov function that not only gives the stability property of the control system but also be used for achieving certain performance specifications. They consider a state observer to make the control design applicable to realistic systems, with noise and disturbances in the measured signals. The proposed methodology is also flexible and readily applicable to larger wind farms of different configurations.

Bottasso, Croce and Savini [38] formulate and compare a wind-scheduled PID, a LQR controller and a novel adaptive non-linear model predictive controller, equipped with observer of the tower states and wind. The simulations include gusts and turbulent winds of varying intensity in nominal as well as off-design operating conditions. The experiments highlight the possible advantages of model-based non-linear control strategies. They use two different models of a representative 1.5MW wind turbine. The first one is a high-fidelity fine-scale aeroelastic model based on a multi-body approach, which is used for simulating the plant. The second one is a reduced coarse-scale model used by the model-based controllers; scope of this model is to capture of the to-be-controlled response of the plant with only relatively few degrees of freedom.

A PID and a LQR control is implement and investigate for a 2D airfoil section in order to formulate a control strategy by Peter B. Andersen [39]. An aerodynamic model coupled with a rigid spring/damper model is used. The standard deviation of the normal load is reduced by 74% for the PID regulation and 82% for the LQR, when the flap wise deflection is used as state variable for the control. The PID control is chosen over the LQR because of simplicity and computational speed.

A disturbance accommodating Linear Quadratic Regulator (LQR) method is applied in pitch control system to achieve good performance by Jianlin Li, Hongyan Xu, Lei Zhang, Zhuying, Shuju, Hu [32]. The disturbance can be estimate by designing state estimator, and a feedback is added into the input to eliminate disturbance effect. The feedback matrix is calculated in accordance to LQR theory. A wind turbine dynamic model is set up, and simulation of the control system is preformed based on Matlab7.1/simulink. The simulation results show that the controller ensure pitch control actuator little fatigue, and has smaller overshoot. The proposed method is has better performance and easy to realize.

4.2 Control objective

A WECS should be designed to minimize the cost of supplied energy ensuring safe operation as well as power quality standards. The minimization of the energy cost involves maximization of energy capture, preventing the WECS from excessive dynamic mechanical loads, so this idea leads us to find the best method to control the wind turbines. The term ‘modes of operation’ denote the various ways wind turbines can be programmed to work. Since wind turbines work under different conditions, these modes of operation are usually combined to attain the control objectives over the full range of operational wind speeds. Accordingly, from control objective wind turbines can be classified into four categories, namely (I) Fixed-speed fixed-pitch, (II) Fixed-speed variable-pitch, (III) Variable-speed fixed-pitch and (IV) Variable-speed variable-pitch.

Fixed-speed Fixed-pitch (FS-FP)

In this scheme, the asynchronous electric machine is directly coupled to the power network. Thus, its torque characteristic cannot be modified. Consequently, the generator speed is locked to the power line frequency. By this reason, it is said that the WECS operates at fixed speed. In reality, the speed varies a few percent along the torque characteristic of the generator because of the slip. Since no extra hardware is purposely added to implement the control strategy, FS-FP WECS are very simple and low-cost. As an adverse consequence, their performance is rather poor.

Fixed-speed Variable-pitch (FS-VP)

Fixed-speed operation means that maximum power conversion is attainable only at a single wind speed. Therefore, conversion efficiency below rated wind speed cannot be optimized. This kind of turbine is usually programmed to operate at fixed pitch below rated wind speed. However, variable-pitch operation in low wind speeds could be potentially helpful to enhance somewhat the energy capture. In above rated wind speeds, power is limited by continuously adjusting the pitch angle. There are basically two methods of power regulation by pitch control, namely pitch-to-feather and pitch-to-stall.

The former method is conventionally referred to as pitch angle control, whereas the second method is also known as ‘active stall’ or ‘combi stall’.

Variable-speed Fixed-pitch (VS-FP)

The benefits commonly ascribed to variable-speed operation are larger energy capture, dynamic loads alleviation and power quality enhancement. With wind energy currently reaching large penetration factors, the demands for power quality improvement gave a decisive impetus to the use of variable-speed schemes. Maximum efficiency conversion is achieved at $\beta = \beta_0$ and $\lambda = \lambda_0$, where β is blade angle and λ is tip speed ratio. Therefore, to maximize energy capture below rated power, both the pitch angle and the tip-speed-ratio must be kept constant at these values. In particular, the condition $\lambda = \lambda_0$ means that the rotor speed must change proportionally to wind speed, i.e.

$$\Omega_{r0} = \frac{\lambda_0 . v}{R} \tag{4.1}$$

As it is known, variable-speed operation requires decoupling the rotational speed from the line frequency.

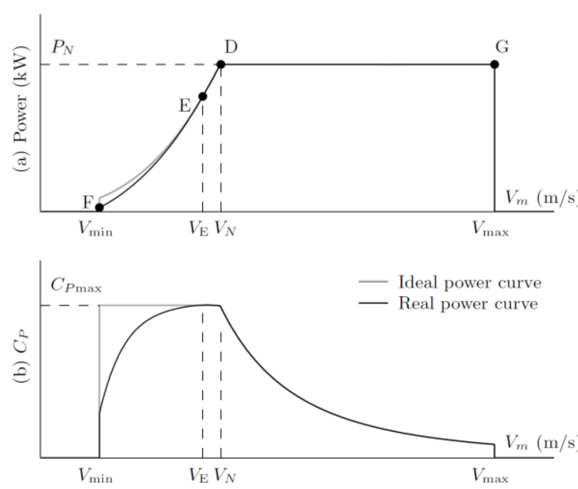


Fig.4.1.Basic fixed-speed pitch-to-feather and pitch-to-stall control strategies (a) Output power and (b) power efficiency vs. wind speed [23]

A suitable control of the underlying electronic converters produces parallel displacements of the generator torque characteristic towards higher or lower speeds. Thus, the turbine can be controlled to operate at different points. The maximum power locus on the torque vs. speed plane can be obtained by replacing λ, β and V in:

$$T_{r0} = \frac{1}{2}\frac{\pi\rho\, R^{5}\, C_{P\max}}{\lambda_{o}^{3}}\,\Omega_{ro}{}^{2} \tag{4.2}$$

This is the equation of a parabola in the torque - rotational speed plane. In low wind speeds, variable-speed wind turbines are controlled to track more or less tightly this $C_{P\max}$ locus. Thus, variable-speed control strategies essentially differ in the way power is limited above rated wind speed. For VSFP wind turbines, there are basically two approaches based on passive and speed-assisted stall, respectively. In this subsection we restrict our analysis to these basic VS-FP control strategies.

Variable-speed Variable-pitch (VS-VP)

In this scheme, the turbine is programmed to operate at variable speed and fixed pitch below rated wind speed and at variable pitch above rated wind speed. Both pitch-to-feather and pitch-to-stall strategies can be followed. Variable-speed operation increases the energy capture at low wind speeds whereas variable-pitch operation enables an efficient power regulation at higher than rated wind speeds. Note that this control strategy also achieves the ideal power curve. In addition, variable-pitch operation alleviates transient loads. This is an important advantage of this control strategy in comparison with VS-FP ones, particularly for large-scale wind turbines.

4.3 Disturbance accommodating disturbances theory

Many actively controlled systems are subject to unknown and unwanted disturbances. As the level of desired performance rises, it becomes necessary for the controller to become aware of the disturbances and to adequately control the system in the presence of all disturbances it might encounter. First developed in 1967 by C.D.

Johnson, disturbance accommodating control (DAC) provides a generalized tool with which to model and estimate disturbances within a control loop to achieve the desired plant performance [40]. DAC models the waveform disturbances with functions, rather than the statistical description used with noise disturbances. This particularly suits the disturbances associated with a mass imbalance, as they ale sinusoidal in nature.

The purpose of the disturbance modeling and estimation is to be able to distinguish between the output state of the plant and the disturbance without any additional information about the disturbance other than its function structure and the disturbed plant output. The output of the undisturbed plant is then used to drive the control effort. Since the DAC affects only the state observer, the same controller is used for the plant as would normally be employed. Figure 4.2 shows a typical use of DAC in a control block diagram with the disturbance entering at the output as a measurement error; this is the same type of disturbance that will be modeled for the momentum wheel mass imbalance. Other types of disturbances can enter the system as input errors to the plant.

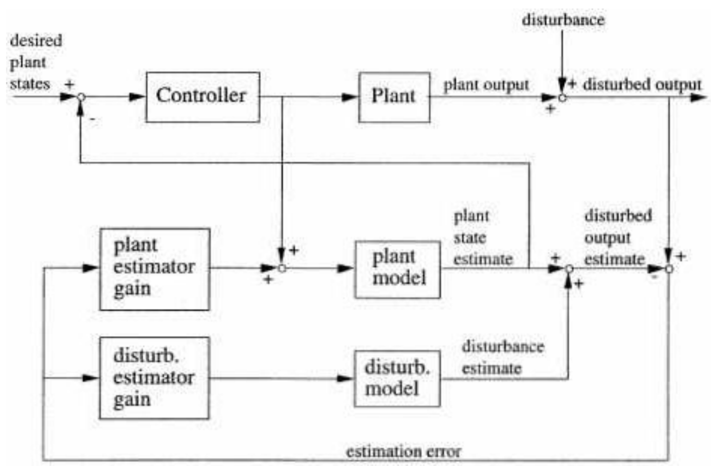


Fig.4.2Typical Control Loop with DAC [41]

4.3.1 State Models for Waveform Disturbances

DAC can model disturbances which exhibit waveform structure. This set of waveforms includes piecewise constant functions, ramps, exponentials, sinusoids, and linear combinations of these. In general, the waveform structure refers to disturbances which can be described by

$$w(t) = c_1 f_1(t) + c_2 f_2(t) + ... + c_m f_m(t) \tag{4.3}$$

where $f_i(t)$ are known basis functions and c are unknown weighting coefficients. The weighting constants (c_i) in these waveform descriptions are allowed to vary in a random, piecewise constant manner to account for the unknown characteristics of the disturbance.

In order for the information about the waveform Structure of the disturbance to be used in the Laplace transform analysis and control of the system, the state model or governing set of first order differential equations associated with the disturbance waveform structure must be determined. This amounts to finding the differential equation for which $w(t)$ in equation (4.3) is a solution. This is accomplished by first taking the Laplace transform of each basis function $f\ (t)$, which gives

$$F_i(s) = \frac{P_{mi}(s)}{Q_{ni}(s)} \tag{4.4}$$

where $F_1(s)$ is a ratio of polynomial expressions of the Laplace transform of $f_i(t)$, and $P_{mi}(s)$ and $Q_{ni}(s)$ are polynomials in s of degree m and n respectively. The numerator and denominator polynomials must be of finite degree with the further restriction that $0 \le m_i \le n_i$. Assuming the c_i behave temporarily as constants, the Laplace transform of the disturbance in equation 4.3 can be expressed as

$$\begin{aligned} W(s) &= L\{w(t)\} \\ &= c_1 F_1(s) + c_2 F_2(s) + \cdots + c_m F_m(s) \\ &= \sum_{i=1}^{m} c_i \frac{P_{mi}(s)}{Q_{mi}} \\ &= \frac{P(s)}{Q(s)}, \end{aligned} \tag{4.5}$$

where the c_i coefficients are found in *P(s),* and *Q(s)* is the least common denominator of the set of $Q_{ni}(s)$ and is described by

$$Q(s) = s^{\rho} + q_{\rho} s^{\rho \;\; 1} + \cdots + q_2 s + q_1 \tag{4.6}$$

where ρ is the degree, and q_i are the known coefficients of the polynomial *Q(s).* The last expression of equation 4.5 indicates that the disturbance *w(t)* can be thought of as the output of a fictitious transfer function

$$G(s) = \frac{1}{Q(s)} \tag{4.7}$$

subject to the initial conditions on the disturbance *w(0)* and its time derivatives. This in conjunction with the Laplace transform leads to the numerator polynomial *P(s).* Taking the inverse Laplace transform of the description of *W(s)* by equation 4.7 gives the differential equation

$$\frac{d^{\rho} w}{dt^{\rho}} + q_{\rho} \frac{d^{\rho \;\; 1} w}{dt^{\rho \;\; 1}} + q_{\rho} \frac{d^{\rho \;\; 2} w}{dt^{\rho \;\; 2}} + \cdots + q_{\rho} \frac{dw}{dt} + q_1 w = 0 \tag{4.8}$$

where the q are determined by the known set of basic functions *fi*(*t*).

The above derivations were done under the assumption that the coefficients c_i were constant, when in reality, they are only piecewise constant, and may undergo abrupt changes from one constant value to another. The incorporation of the unknown values of the c_i is accounted for mathematically by the addition of an input forcing function $\sigma(t)$. This forcing function is a series of impulses arriving at random, unknown times and having unknown amplitudes. This modifies the homogeneous equation 4.8 to a mathematically correct

$$\frac{d^{\rho}w}{dt^{\rho}}+q_{\rho}\frac{d^{\rho-1}w}{dt^{\rho-1}}+q_{\rho}\frac{d^{\rho-2}w}{dt^{\rho-2}}+\cdots+q_{\rho}\frac{dw}{dt}+q_{1}w=\sigma(t). \qquad (4.9)$$

The impulsive forcing function $\sigma(t)$ is included in the description only for theoretical correctness. They are of no practical value in the design of disturbance estimators as their characteristics are completely unknown. With the remaining assumption that the coefficients c change slowly compared to the plant dynamics, then equation 4.8 will accurately describe the disturbance.

The single, higher order differential equation of equation 4.8 can be equivalently expressed in linearized state-space control canonical form by

$$\begin{aligned}\dot{\underline{v}}&=\underline{\underline{D}}\,\underline{v}+\underline{\sigma}\\ \underline{w}&=\underline{\underline{H}}\,\underline{v}\end{aligned} \qquad (4.10)$$

where $\underline{v}$ is the state of the disturbance, and $\underline{w}$ is the disturbance output. The components of the state equation 4.10 are

$$\begin{aligned}\underline{v}&=\begin{bmatrix}v_1\\ v_2\\ \vdots\\ v_{\rho}\end{bmatrix},\ \underline{\sigma}=\begin{bmatrix}\sigma_1\\ \sigma_2\\ \vdots\\ \sigma_{\rho}\end{bmatrix}\\ \underline{\underline{D}}&=\begin{bmatrix}0&1&0&\cdots&0&0\\ 0&0&1&\cdots&0&0\\ \vdots&\vdots&\vdots&\ddots&\vdots&\vdots\\ 0&0&0&\vdots&\vdots&\vdots\\ -q_1&-q_2&-q_3&\cdots&-q_{\rho-1}&-q_{\rho}\end{bmatrix}\\ \underline{\underline{H}}&=\underbrace{\begin{bmatrix}1&0&\cdots&0\end{bmatrix}}_{1\times\rho}.\end{aligned} \qquad (4.11)$$

Even with constant coefficients, this state model can describe disturbances with basic functions of Constants, ramps, polynomial expressions, decaying or growing sinusoids, and exponentials. The list of possible basis functions increases further if the coefficients in the above matrices are allowed to be time-varying. This linear state model will later be used in the disturbance estimator to control the undisturbed system.

4.3.2 DAC Estimator Design

The disturbance model can be used in tandem with the plant estimator to predict the states of the plant and disturbance given only the system outputs and control efforts. The usefulness of this would be to use the plant states to drive the controller and thus control the desired state of the plant instead of allowing the disturbances to influence the plant control. A system and disturbances, both input and output, described by the linear state equations

$$\begin{aligned} \dot{\underline{x}} &= \underline{\underline{A}}\,\underline{x} + \underline{\underline{B}}\,\underline{u} + \underline{\underline{F}}\,\underline{w}_{in} \\ \underline{y} &= \underline{\underline{C}}\,\underline{x} + \underline{\underline{D}}\,\underline{u} + \underline{\underline{D}}\,\underline{w}_{out} \end{aligned} \tag{4.12}$$

can use a DAC observer to determine the plant and disturbance states. In equation (4.12), $\underline{x}$ is the plant state vector, $\underline{u}$ is the input vector, $\underline{y}$ is the plant output, $\underline{w}_{in}$ and $\underline{w}_{out}$ and are the input and output disturbances respectively. In addition, the disturbances are assumed to be represented by

$$\begin{aligned} \dot{\underline{v}} &= \underline{\underline{D}}\,\underline{v} + \underline{\sigma} \\ \underline{w} &= \underline{\underline{H}}\,\underline{v} \end{aligned} \tag{4.13}$$

where $\underline{v}$ is the disturbance state vector, $\underline{\sigma}$ is the random impulse input, and $\underline{w}$ is the disturbance output vector.

These state equations can be combined to describe the resultant coupled system which can be used with conventional techniques to design estimators for the plant and disturbance states. This composite state estimator is determined by C.D. Johnson to be

$$\begin{bmatrix} \dot{\hat{\underline{x}}} \\ \dot{\hat{\underline{v}}} \end{bmatrix} = \begin{bmatrix} \underline{\underline{A}} + \underline{\underline{K}}_1\underline{\underline{C}} & \left(\underline{\underline{F}} + \underline{\underline{K}}_1\underline{\underline{C}}\right)\underline{\underline{H}} \\ \underline{\underline{K}}_2\underline{\underline{C}} & \underline{\underline{D}} + \underline{\underline{K}}_2\underline{\underline{G}}\,\underline{\underline{H}} \end{bmatrix} \begin{bmatrix} \hat{\underline{x}} \\ \hat{\underline{v}} \end{bmatrix} \begin{bmatrix} \underline{\underline{K}}_1 \\ \underline{\underline{K}}_2 \end{bmatrix} \underline{y} + \begin{bmatrix} \underline{\underline{B}} \\ \underline{\underline{K}}_2 \end{bmatrix} \underline{u} \tag{4.14}$$

where $\hat{\dot{x}}$ is the estimate of the plant state, $\hat{\dot{v}}$ is the estimate of the disturbance state, $\underline{\underline{K}}_1$ and $\underline{\underline{K}}_2$ are the gains for the plant and disturbance estimators respectively. The estimator gains are chosen to drive the error between the estimates and the actual states to zero quickly.

4.4 LQR Pitch control

We consider a wind-scheduled multi-input-multi-output (MIMO) LQR, based on a collective pitch non-linear wind turbine reduced model which includes drive-train shaft dynamics, elastic tower fore-aft motion, blade pitch actuator dynamics and electrical generator dynamics [42] as:

$$(I_{LSS}+I_{HSS})\dot{\Omega}+T_l(\Omega)+T_{ele}-T_a(\Omega,\beta_e,V-\dot{d},V)=0 \tag{4.15a}$$

$$M_T\ddot{d}+C_T\dot{d}+K_Td-F_a(\Omega,\beta_e,V_w-\dot{d},V)=0 \tag{4.15b}$$

$$\ddot{\beta}_e+2\zeta\omega\dot{\beta}_e+\omega^2(\beta_e-\beta_c)=0 \tag{4.15c}$$

$$T_{ele}+1/\tau\,(T_{ele}-T_{elc})=0 \tag{4.15d}$$

The equation (4.15a), describes the drive-train dynamics, where d is the tower top fore-aft displacement and β_e is the effective blade pitch angle. The tower motion d can be reconstructed on-line by using observers from measurements provided by an accelerometer and a strain gage. Moreover, I_{LSS} is the sum of the moments of inertia about the rotation axis of the rotor hub and of the three rotor blades (low speed shaft inertia), while I_{HSS} is the moment of inertia of the rotating part of the electric generator and of the high speed shaft referred to the low speed shaft. The torques acting upon the drive-train includes the mechanical losses on the shaft bearings T_l, the effective electrical reaction torque T_{ele} referred to the low speed shaft and the aerodynamic torque T_a. The mechanical loss T_l is modeled by means of a speed-torque look-up table. The second equation, Eq. (4.15b), models the fore-aft tower dynamics. Here, M_T, C_T and K_T are,

respectively, the tower equivalent modal mass, structural damping and bending stiffness, which may be computed by modal reduction of a detailed finite element model of the tower. Finally, F_a indicates the aerodynamic force generated by the rotor. The third equation, Eq. (4.15c), is a second order model of the blade pitch actuator, where ω is the undamped natural frequency, ξ the damping factor and β_c the blade pitch control input. The model also includes upper and lower limits on the pitch and the pitch rate. The fourth and last equation, Eq. (4.15d), is a first order model of the electrical generator that includes a time delay τ , while T_{elc} is the commanded electrical torque input.
The rotor aerodynamic force and torque are computed [42] as:

$$T_a = \frac{1}{2}\rho AR\frac{C_P(\lambda,\beta_e,V)}{\lambda}(V_\omega-\dot{d})^2 \tag{4.16a}$$

$$F_a = \frac{1}{2}\rho AC_F(\lambda,\beta_e,V)(V_\omega-\dot{d})^2 \tag{4.16b}$$

where C_P and C_F are the power and force coefficients, respectively, and λ is the corrected TSR, defined as $\lambda = \Omega R/(V_\omega - \dot{d})$, i.e. the TSR which accounts for the apparent wind due to the tower fore-aft motion. Finally, $V_\omega = V + V_t$ is the turbulent upstream wind speed obtained as the sum of the mean wind *V* and the turbulent wind V_t. For this reduced model, the mean wind *V* is computed by spatially averaging over the rotor disk the wind speed profile. Similarly, the longitudinal turbulent wind V_t is defined, at each time step, as the spatial average over the rotor disk of the Kaimal turbulence model centered at the hub. The dependence of the power and force coefficients in Equations (4.16a) and (4.16b) on the wind speed *V*, typically neglected, accounts for the possible effects due to the deformability of tower and blades under high winds.

Equations (4.15) can be written in compact form as

$$\begin{aligned} &f(\dot{x},x,u,w,t)=0 \\ &y=h(x) \end{aligned} \tag{4.17}$$

by defining state and input vectors

$$\begin{aligned} x &= (d, \dot{d}, \Omega, \beta_e, \dot{\beta}_e, T_{ele})^T \\ u &= (\beta_c, T_{ele})^T \end{aligned} \tag{4.18}$$

where $w = (V, V_w)$ is a vector of wind parameters and y are outputs. Although the model is rather simple, its accuracy can be substantially enhanced by a proper modeling of the crucial aerodynamic coefficients C_P and C_F. The entries of the table being λ and the blade pitch β_e (and possibly the mean wind speed V if one wants to account for flexibility effects on the rotor power and force coefficients). This way, the reduced model inherits the aerodynamic modeling of the fine scale solver, while keeping a very simple implementation and extremely low computational cost. A quadratic cost function for the regulation problem at the trim point is defined as

$$J = \frac{1}{2}\int_0^\infty (\Delta y^T Q\, \Delta y + \Delta u^T\, R\, \Delta u)\, dt \tag{4.19}$$

where $Q \geq 0$ and $R > 0$ are symmetric matrices of weights which may be scheduled in terms of the mean wind V, i.e. $Q = Q(V)$, $R = R(V)$; tuning of the weights for specific goal-oriented performance is explained in [42]. The scheduling of the weight matrices with respect to the wind speed accounts for the changes in the operating conditions of the machine for increasing wind, and can help in improving performance. We remark again however, that in the present implementation the same control structure and logic is used throughout the whole operating range of wind speeds, with no specific account for the fact that the machine crosses different operating regimes denoted by different regulation policies.

4.5 Simulation and numerical results

The modeled turbine is a downwind, two-bladed machine resembling the 650Kw horizontal-axis wind turbine. The major properties are listed in Table 4.1.

Table 4.1 Geometric properties of the turbine

Description	Value
Rated Power	650Kw
Rotor Diameter	43m
Gear Box Transmission ratio	43.16

The equivalent model of wind turbine is shown in Fig.3.3. The aerodynamic torque gained is given by Eq. (3.11), in which *Cp* is given by Eq. (3.12) and λ_i satisfies：

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \tag{4.20}$$

Although wind turbine is a nonlinear model, at some point near by it can be treated as linear model. The Linearizing of nonlinear aeroelastic plant T_r is represented by the following vector equation: torque at point (V_0,Ω_0,β_0) nearby:

$$Tr=Tr(V_0,\Omega_0,\beta_0)+\alpha\Delta V+\gamma\Delta\Omega+\xi\Delta\beta \tag{4.21}$$

In which, $\Delta\Omega=\Omega-\Omega_0$, $\Delta V=V-V_0$, $\Delta\beta=\beta-\beta_0$, $\alpha=\left.\frac{\partial T_r}{\partial V}\right|_{(V_0,\Omega_0,\beta_0)}$, $\gamma=\left.\frac{\partial T_r}{\partial \Omega}\right|_{(V_0,\Omega_0,\beta_0)}$,

$\xi=\left.\frac{\partial T_r}{\partial \beta}\right|_{(V_0,\Omega_0,\beta_0)}$. State variable q_1 and q_2 are blade angle and rotor angle respectively

$$T_{shaft}=K_d(q_1-q_2)-C_d(\dot{q}_1-\dot{q}_2) \tag{4.22}$$

$$\Delta T_{shaft} = K_d(\Delta q_1 - \Delta q_2) - C_d(\Delta \dot{q}_1 - \Delta \dot{q}_2) \tag{4.23}$$

$$J_{rot}\ddot{q}_1 = T_r - T_{shaft} - K_{frot}\Omega \tag{4.24}$$

$$J_{gen}\Delta \dot{q}_2 = \Delta T_{shaft} - \Delta T_{gen} - K_{fgen}\Delta \omega_{gen} \tag{4.25}$$

Above, K_d is elastic coefficient of propeller shaft, C_d is damping coefficient on propeller shaft, J_{rot} and J_{gen} are rotation inertia of low speed side and generator (calculated in low speed side), K_{fgen} and K_{frot} are friction coefficient of high speed side and low speed side respectively. T_{shaft_0} is counter torque at working point (V_0, Ω_0, β_0). The speed acceleration is 0, so：

$$T_r(V_0, \Omega_0, \beta_0) = T_{shaft_0} + K_{frot}\Omega_0 \tag{4.26}$$

Then:

$$J_{rot}\ \ddot{q}_1 = \Delta T_r - \Delta T_{shaft} - K_{frot}\ \Delta\Omega \tag{4.27}$$

Assume $x_1 = \Delta \dot{q}_1, x_2 = K_d(\Delta q_1 - \Delta q_2), x_3 = \Delta \dot{q}_2$, so

$$J_{rot}\ \dot{x}_1 = (\gamma - C_d - K_{frot})x_1 - x2 + C_d x_3 + \xi\Delta\beta + \alpha\Delta V \tag{4.28}$$

$$\dot{x}_2 = K_d(x_1 - x_2) \tag{4.29}$$

According to the torque equation of generation：

$$J_{gen}\ \dot{x}_3 = C_d x_1 + x_2 - (C_d + K_{fgen})x_3 - \Delta T_{gen} \tag{4.30}$$

In state space form：

$$\begin{cases} \dot{x} = Ax + Bu + \Gamma u_D \\ y = Cx + Du \end{cases} \tag{4.31}$$

Where

$$A = \begin{bmatrix} \frac{(\gamma - C_d - K_{frot})}{J_{rot}} & \frac{-1}{J_{rot}} & \frac{C_d}{J_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{J_{gen}} & \frac{1}{J_{gen}} & \frac{-C_d - K_{fgen}}{J_{gen}} \end{bmatrix}, B = \begin{bmatrix} \frac{\xi}{J_{rot}} & 0 \\ 0 & 0 \\ 0 & \frac{-1}{J_{gen}} \end{bmatrix}, \Gamma = \begin{bmatrix} \frac{\alpha}{J_{rot}} \\ 0 \\ 0 \end{bmatrix},$$

$$C = [0 \quad 0 \quad 1], D = [0]$$

input $u = \lfloor \Delta\beta, \Delta T_{gen} \rfloor$, disturbance quantity $u_D = \Delta V$.

At present pitch actuator has hydraulic and electric two forms. For simplicity, pitch actuator can be simplified to a first-order inertia model; no matter it is hydraulic or electric actuator. The pitch actuator transmission function is:

$$Act(s) = \frac{1}{\tau_\beta s + 1} \tag{4.32}$$

To verify the control performance of LQR algorithm based on disturbance correlation, a numeric simulation was performance that is showed in Fig. 4.3.

The wind turbine model parameter is shown in table 4.1. Choosing work point at $V_0 = 17m/s, \Omega_0 = 42rpm, \beta_0 = 13.35$ in LQR algorithm and linearizing at this point. Then wind turbines state function is Eq. (4.31), where:

$$A = \begin{bmatrix} -0.198 & -3.108 \times 10^{-6} & -3.108 \times 10^{-5} \\ 2.69 \times 10^{7} & 0 & -2.69 \times 10^{7} \\ 1.56 \times 10^{-4} & -1.56 \times 10^{-5} & -0.0624 \end{bmatrix}, B = \begin{bmatrix} -7.5 \times 10^{-3} \\ 0 \\ 0 \end{bmatrix}$$

choosing $\boldsymbol{R} = 1$, $Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1\times10^{-12} & 0 \\ 0 & 0 & 50 \end{bmatrix}$.

From matrix A, B, Q and R, state feedback matrix: $K = \begin{bmatrix} 2.2219 & 1.6905\times10^{-8} & -1.3289 \end{bmatrix}$

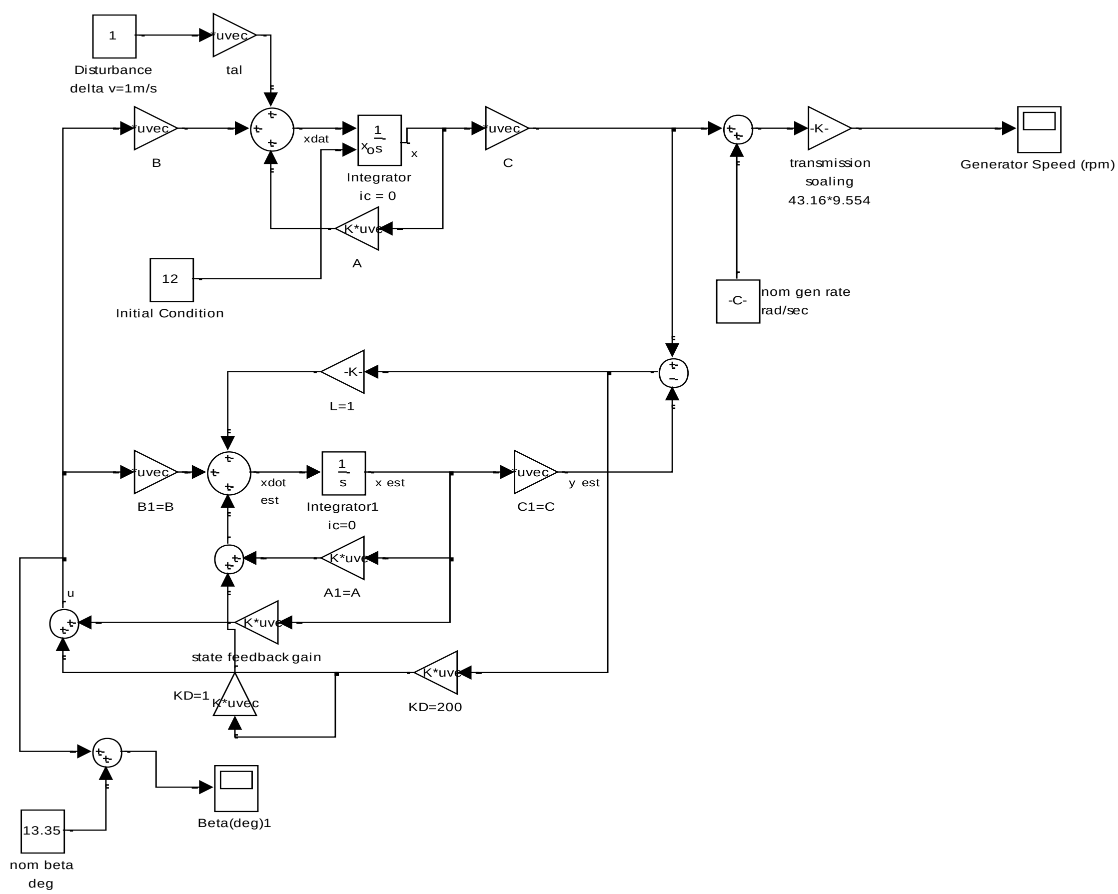
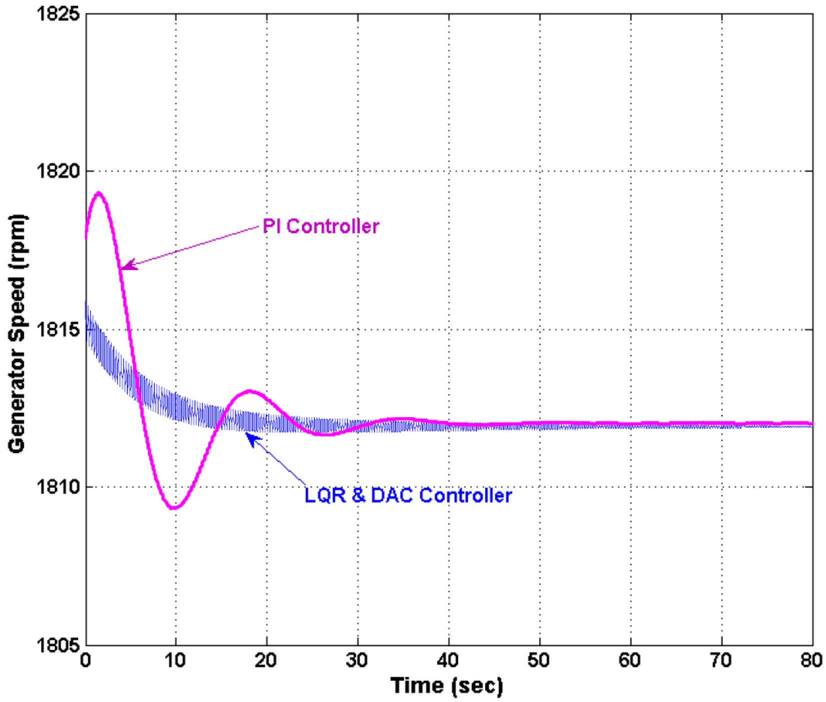


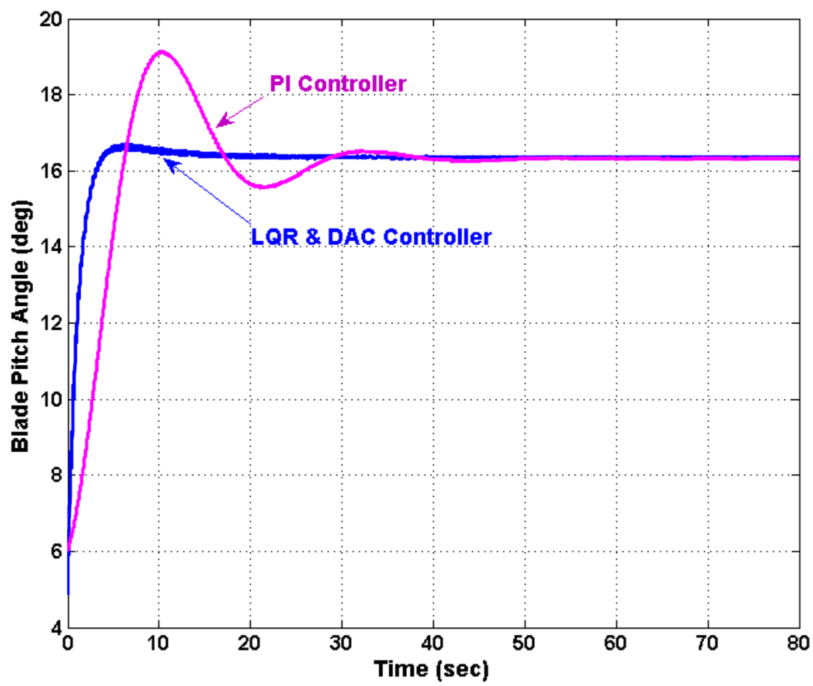
Fig.4.3 Simulink Model

In the simulation, wind speed stepped from 17m/s to 18m/s at $t = 0$ moment. In PI regulation, $K_P = 8$, $K_I = 1.5$, simulation result is shown in Fig.4.4.

It can be seen from Fig.4.4 PI regulation method has a lager overshoot, while LQR algorithm has a much smaller one. In Fig.4.4 (b), after adopting LQR algorithm, the overshoot can be very small, which can reduce the action of pitch actuator.



(a)Generator rotating speed



(b)Pitch angle

Fig.4.4 simulation waveform of LQR algorithm base on disturbance and PI control

While PI regulation has a larger overshoot, pitch angle fluctuated for a moment, which is harmful for pitch actuator. So as to enhance pitch control performance of large wind turbine, this paper constructed wind turbines dynamics model, giving a LQR pitch-control algorithm based on disturbance correction according to LQR control theory. This method could reduce pitch actuator's movement and had good control performance on generator rotate speed. The simulation results showed that this method has good performance and it is simple and effective. So it has the great potential to be applied into engineering.

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