Wind Energy Conversion Systems

by *Liuchen Chang*
University of N. Brunswick, NB

Abstract

Wind power capacity has experienced tremendous growth in the past decade, thanks to wind power's environmental benefits, technological advance, and government incentives. This paper presents the recent developments in wind energy conversion systems, and their social and environmental benefits. The paper provides a review of the interconnection issues of distributed resources including wind power with electric power systems, and reports the developments of interconnection standards in Canada and IEEE. The paper also describes the recent R&D programs in wind energy conversion systems.

Sommaire

Le potentiel de l'énergie éolienne a connu une forte croissance lors de la dernière décennie, cela est du aux avantages écologique de cette énergie, aux percées technologiques dans le domaine et aux aides gouvernementales incitatives. Cet article présente les récents développements dans les systèmes de conversion d'énergie basés sur l'énergie éolienne et leurs avantages sociaux et environnementaux. Cet article présente aussi une revue des problèmes liés à l'interconnexion de ressources distribuées comprenant l'énergie éolienne et les systèmes électriques et rapporte les développements de standards d'interconnexion au Canada et au sein de l'IEEE. Cet article décrit enfin les récents programmes de recherche et développement dans les systèmes de conversion d'énergie.

1.0 Introduction

Differential heating of the earth's surface by the sun causes the movement of large air masses on the surface of the earth, i.e., the wind. Wind energy conversion systems convert the kinetic energy of the wind into electricity or other forms of energy. Wind power generation has experienced a tremendous growth in the past decade, and has been recognized as an environmentally friendly and economically competitive means of electric power generation.

More and more countries are ratifying the 1997 Kyoto Protocol, and wind power has become one of the most effective ways to reach its goals. The Kyoto Protocol sets targets for participating countries to reduce greenhouse gas emissions to at least 5% below the 1990 level in the commitment period of 2008 to 2012. According to the U.S. Energy Information Administration, world electricity consumption will increase from 12,833 TWh in 1999 to 22,230 TWh in 2020, mainly driven by developing countries, where two billion people are still without access to electricity [1]. The fuel mix for the world's electricity generation in 1999, as presented in Figure 1, indicates that fossil fuels accounted for 62% while renewables including hydropower, wind and solar etc. accounted for 20.2% [2].

Based on a life-cycle assessment of these power generation options conducted by Hydro Quebec, the greenhouse gas emissions from the 1999 fuel mix are 510 kilotons of equivalent CO2 per TWh [3], as compared to 9 kilotons of equivalent CO2 per TWh from wind power. A 660 kW wind turbine operating at a 0.35 annual capacity factor can generate about 2 GWh of electricity per year, enough for 250 typical Canadian homes. This single wind turbine can displace 1,000 tonnes of equivalent CO2 emissions based on the 1999 world fuel mix for electricity generation. If this wind turbine were to displace the electricity generated by a coal fired power plant, 1,930 tonnes of equivalent CO2 emissions could be avoided.

In addition to business opportunities as a result of deregulation in the electricity market, wind power generation has great potential to create employment in wind system development, manufacturing, maintenance and operation [4]. Table 1 shows the direct job creation by wind power as compared to other power generation technologies [5].

Figure 1: Fuel mix for world electricity generation in 1999.

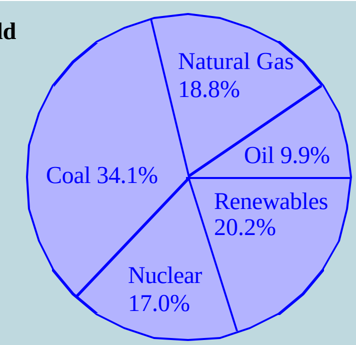

Table 1: Direct Job Creation

Technology	Jobs/TWh/yr
Nuclear	100
Geothermal	112
Coal 1	16
Solar Thermal	248
Wind	542

2.0 Recent Development in Wind Industry

2.1 Installed Capacity

Worldwide development of wind energy expanded rapidly starting in the early 1990s. As shown in Figure 2, the average annual growth rate from 1994 to 2001 of the world installed capacity of wind power is 31% [6], making the wind industry one of the fastest growing. Unlike the last surge in wind power development during 1970s and early 1980s which was due mainly to the oil embargo of the OPEC countries, the current wave of wind energy development is driven by many forces that make it favorable. These include its tremendous environmental, social and economic benefits, its technological maturity, the deregulation of electricity markets throughout the world, public support and government incentives. In Denmark wind power accounted for 18% of electricity consumption in 2001, and this share will be increased to 50% by 2030. Canada has a total of 198 MW of installed wind power capacity as of 2001, with additional wind plants planned in Ontario, PEI and Alberta. Canada has tremendous wind resources from coast to coast. According to the Canadian Wind Energy Association (CanWEA), if the right government policies are implemented, wind energy can contribute 5% of Canada's electricity supply by 2010. CanWEA has released Wind Vision for Canada, recommendations for achieving 10,000 MW of installed wind power capacity by 2010.

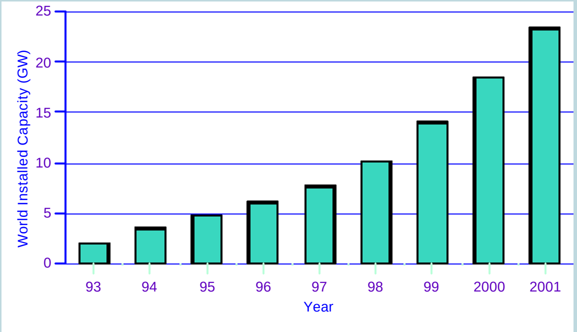

Figure 2: World installed capacity of wind power.

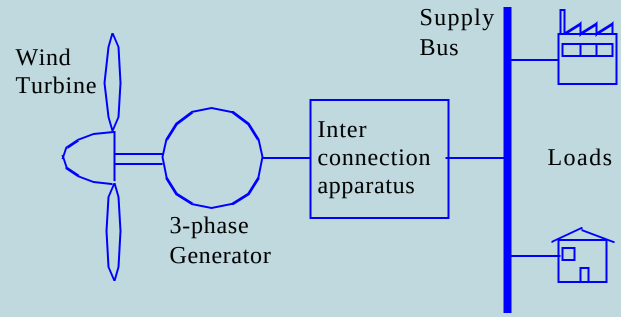

Figure 3: Structure of a typical wind energy system.

2.2 Technological Advance

Thanks to extensive R&D efforts during the past 30 years, wind energy conversion has become a reliable and competitive means for electric power generation. The life span of modern wind turbines is now 20-25 years, which is comparable to many other conventional power generation technologies. The average availability of commercial wind power plants is now around 98% [6]. The cost of wind power has continued to decline through technological development, increased production level, and the use of larger turbines. The cost of energy from wind power has fallen from around 35 ¢US/kWh in 1980 to 4-6 ¢US/kWh today [6][7]. The average capacity of new wind turbines deployed grew to 805 kW and the average installed capacity cost fell to $1000 US/kW in 2000. Table 2 presents a recent cost analysis for various wind power plants, if installed in Canada in 2001 [8]. In this table, "Large Wind Plant" is targeted at utility grade power generation; "One Small Turbine" is used for distributed generation for residential loads; and "Remote Community" refers to wind-diesel systems in remote communities.

2.3 Incentive Programs

The main market stimulation instruments for wind power development are a combination of capital subsidy and payment of premium prices for energy production. In a deregulated electricity market, many wind power generators can sell their electrical energy at a "green power premium." In Canada, the Federal Income Tax Act provides an accelerated rate of write-off for wind capital costs, allows the first exploratory wind turbine of a wind plant to be fully deducted in the year of its installation, and allows the use of flow-through share financing. In December 2001, the Federal Government implemented a wind power production incentive. The incentive includes a payment of 1.2 cents per kWh of production, gradually declining to 0.8 cents per kWh, and is available for the first 10 years of production.

Table 2: Costs of Various Wind Power Plants

Cost in Cdn $	Large Wind Plant	One Small Turbine	Remote Community
Plant Capacity (kW)	75,000	10	325
Turbine Size (kW)	750	10	65
Capital Cost ($/kW)	$1,400	$3,500	$3,000
Financing Rate (%)	7.5%	10%	8.5%
Capacity Factor (%)	35%	23%	25%
Energy Cost($/kWh)	$0.058	$0.237	$0.195

3.0 Structure of Wind Energy Conversion Systems

The major components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control systems, as shown in Figure 3. Wind turbines can be classified into the vertical axis type and the horizontal axis type. Most modern wind turbines use a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. The major components in the nacelle of a typical wind turbine are illustrated in Figure 4. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counterparts, however, they necessitate power electronic converters to provide a fixed frequency and fixed voltage power to their loads. Most turbine manufacturers have opted for reduction gears between the low speed turbine rotor and the high speed three-phase generators. Direct drive configuration, where a generator is coupled to the rotor of a wind turbine directly, offers high reliability, low maintenance, and possibly low cost for certain turbines. Several manufacturers have opted for the direct drive configuration in the recent turbine designs.

At the present time and in the near future, generators for wind turbines will be synchronous generators, permanent magnet synchronous generators, and induction generators, including the squirrel cage type and wound rotor type. For small to medium power wind turbines, permanent magnet generators and squirrel cage induction generators are often used because of their reliability and cost advantages. Induction generators, permanent magnet synchronous generators and wound field synchronous generators are currently used in various high power wind turbines.

Interconnection apparatuses are devices to achieve power control, soft start and interconnection functions. Very often, power electronic converters are used as such devices. Most modern turbine inverters are forced commutated PWM inverters to provide a fixed voltage and fixed frequency output with a high power quality. Both voltage source voltage controlled inverters and voltage source current controlled inverters have been applied in wind turbines. For certain high power wind turbines, effective power control can be achieved with double PWM (pulse width modulation) converters which provide a bi-directional power flow between the turbine generator and the utility grid.

4.0 Interconnection with Electric Power Systems

Thirty six states in US have adopted, and several Canadian provinces are considering adopting net metering programs, under which a utility customer can install a small on-site renewable power generator and sell electricity to the utility at the same rate at which he purchases it from the utility. Net metering programs have substantially improved the economy of small distributed resources (DR), including wind power. Although standards exist for large power plants connected to electric power systems, they fail to address special requirements for distributed resources. To provide guidelines for all stakeholders including utilities, independent power producers, users and equipment manufacturers, efforts are being made, both in Canada and internationally, to develop interconnection standards. Supported by Natural Resources Canada and Industry Canada, Electro-Federation Canada is developing Canadian guidelines for connecting small distributed resources to grids [9]. The

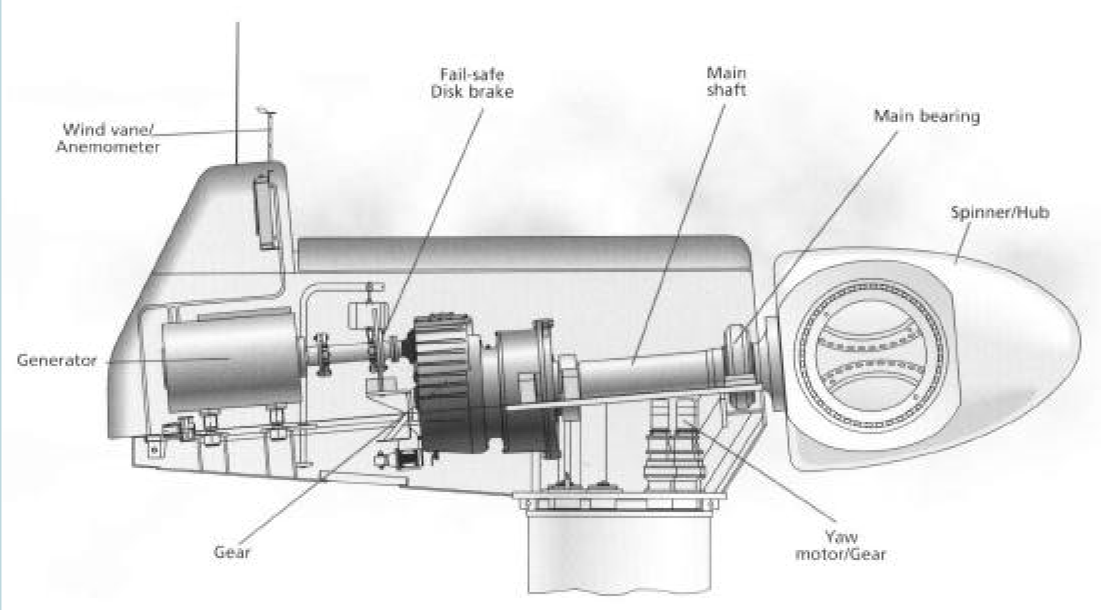

Figure 4: Major components inside the nacelle of a turbine.

guidelines will mainly address the interconnection issues of inverter-based small power generators such as photovoltaics, wind, fuel cells and microturbines. IEEE Standards Coordinating Committee 21 on Fuels, Photovoltaics, Dispersed Generation, and Energy Storage had formed working groups to develop IEEE P1547, the Draft Standard for Inerconnecting Distributed Resources with Electric Power Systems, and P1589, the Draft Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems (EPS).

Distributed resources connected with electric power systems are presented in Figure 5 as typical configurations. The major interconnection requirements for distributed resources can be summarized in the following three categories: general specifications, safety and protection, and power quality.

4.1 General Requirements

Voltage Regulation: A DR shall not cause the voltage at the Point of Common Coupling (PCC, see Figure 5) to go outside of Range A specified by Standard ANSI C84.1(or CSA CAN3-C235-83) [10]. For a 120/240V system, this specifies a maximum voltage of 126/252V and a minimum voltage of 114/226V.

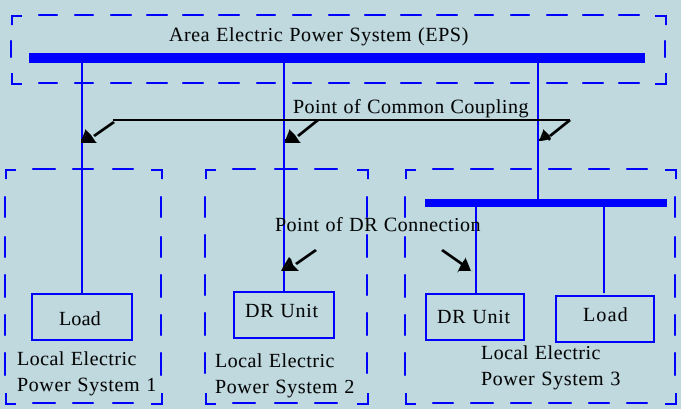

Figure 5: Distributed resources connected to a power system.

Synchronization: When synchronizing, a DR shall not cause more than +/-5% of voltage fluctuation at the PCC.

Monitoring: A DR of 250 kW or larger shall have provisions for monitoring connection status and real and reactive power output at the DR connection.

Isolation Device: A readily accessible, lockable, visible-break isolation device shall be located between the DR and the EPS.

4.2 Safety and Protection Requirements

Voltage Disturbances: At abnormal voltages, a DR shall cease to energize the EPS within the specified clearing time.

Frequency Disturbances: A DR shall cease to energize the EPS if the frequency is outside the range 59.3 - 60.5 Hz.

Loss of Synchronism: A DR of 250 kW or larger shall have loss of synchronism protection function.

Reconnection: A DR may reconnect to the power system 5 min. after the EPS voltage and frequency return to normal.

Unintentional Islanding: A DR shall cease to energize the EPS within 2 sec. of the formation of an island.

4.3 Power Quality Requirements

Harmonics: The total demand distortion of a DR, which is defined as the total rms harmonic current divided by the maximum demand load current, shall be less than 5%. Each individual harmonic shall be less than the specified level.

DC Current Injection: A DR shall have a dc current injection of less than 0.5% of its rated output current.

Flicker: A DR shall not create objectionable flicker for other customers on the area EPS.

5.0 Test Facilities for Wind Energy Conversion Systems

To meet the increasing demands for wind power applications, tremendous R&D effort is needed to develop safe, reliable and cost effective technologies for wind energy conversion. Supported by the Canadian Foundation of Innovation, Atlantic Wind Test Site Inc., Natural Resources Canada and Université de Moncton, the University of New Brunswick has established a unique R&D and test facility for wind and

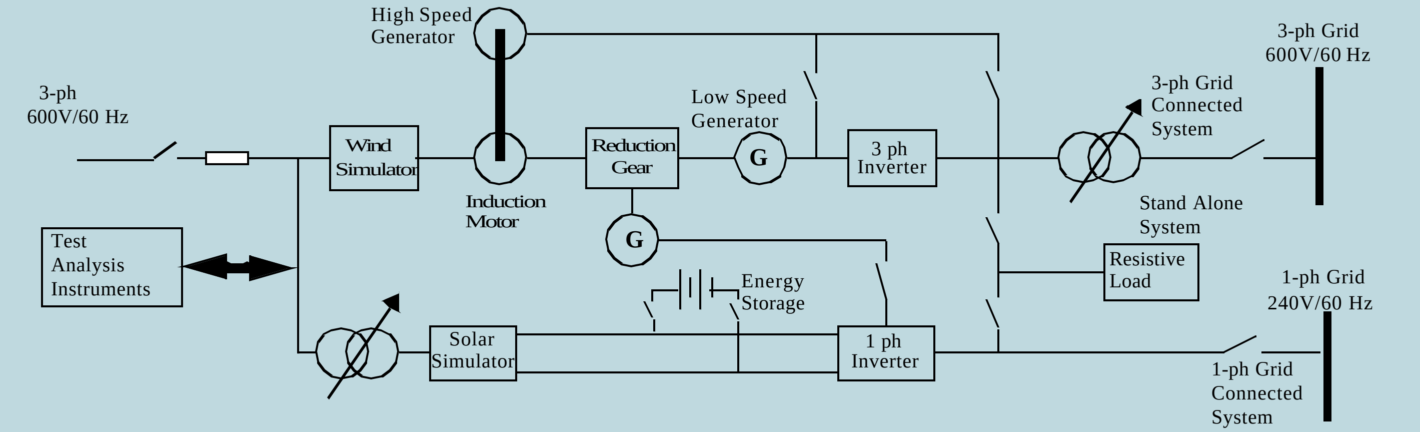

Figure 6: Single Line Diagram for UNB test facility for wind and solar energy conversion systems.

solar energy conversion systems. It is located close to the 5 MW wind plant at the Atlantic Wind Test Site in PEI. As illustrated in Figure 6, this facility includes wind and solar energy conversion components of various structures, such as high speed generators (fixed or variable speed, up to100 kW), direct drive variable speed generators (wound field and permanent magnet synchronous generators, up to 50 kW), a three-phase inverter (100 kW), single-phase inverters (grid-connected or autonomous, up to 25 kW), and storage batteries.

In particular, the wind turbine simulator provides researchers with a controlled test environment for wind turbine generators, inverters and system operations, resulting in improved research productivity. The facility also provides an infrastructure for the development of advanced control methodologies to improve aspects of system performance such as maximum power extraction from wind or solar sources. The wind turbine simulator emulates the output characteristics of a wind turbine at various wind speeds using an adjustable speed induction drive system [11], as shown in Figure 7. For the turbine generator and power electronic converters, the induction motor drive behaves the same as a variable speed wind turbine. The wind simulator, as a part of the test facility for wind and solar energy conversion systems is shown in Figure 8 along with various generators.

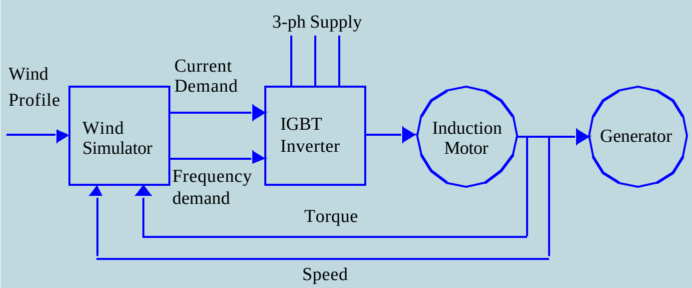

Figure 7: Wind turbine simulator.

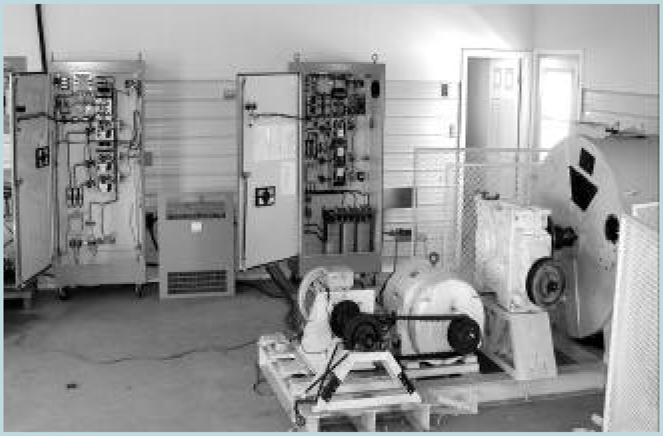

Figure 8: Wind turbine simulator.

Currently, the researchers at the University of New Brunswick are focusing on the development of innovative power electronic converters and advanced control strategies for variable speed wind turbine systems. Two of the several development platforms include the single-phase 10kW/240V grid-connected IGBT inverter used on a Bergey Excel 10 kW wind turbine in Charlottetown, PEI, and the three-phase 100kW/380V grid-connected IGBT inverter used on a Lagawey LW18 80kW wind turbine in North Cape, PEI. The 10 kW system was developed for residential power generation (Figure 9), and the 100 kW system was developed for wind-diesel applications in remote communities (Figure 10). Figure 11 shows another view of the site. The R&D work has expanded to include distributed generation packages powered by micro-hydro units and microturbines, in addition to wind turbines.

Figure 9: Bergey Excel 10 kW wind turbine for inverter research and development.

Figure 10: Lagawey LW18 80 kW wind turbine for inverter research and development.

6.0 References

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About the author

Liuchen Chang holds a B.Sc. (E.E.) from Northern Jiaotong University in Beijing, M.Sc. from the China Academy of Railway Sciences in Beijing, and Ph. D. from Queen's University in Kingston.

He is a professor of Electrical and Computer Engineering and NSERC Chair in Environmental Design Engineering at the Department of Elect. & Comp. Eng., University of New Brunswick.

His principal research interests and experience include distributed power generation, renewable energy conversion, analysis and design of electrical machines, variable-speed drives, power electronics, and electric vehicle traction systems. LChang@unb.ca.

Figure 11: A view of the Windmill park in PEI. The photograph shows the 5.28 MW North Cape Wind Plant and wind test facilities of Atlantic Wind Test Site Inc. (AWTS), located at North Cape, the northernmost tip of Prince Edward Island.