Chapter 1

Introductory Chapter: Stability Control and Reliable Performance of Wind Turbines

Kenneth Eloghene Okedu

Additional information is available at the end of the chapter

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1. Renewable energy sources

Energy is essential for the growth and socio-economic development of any economy. Recently, the use of renewable energy sources for energy generation is on the raise. Wind energy is one of the renewable energy sources that is indigenous in nature and could help in mitigating fossil fuels dependency [1]. Presently, about 87% of total energy in the world is obtained from traditional fossil fuels (coal, oil and natural gas), while 6% is obtained from nuclear plants and the remaining 7% is generated from renewable sources (especially hydropower, wind and solar) [2]. Unfortunately, the amounts of fossil fuel and nuclear power resources are limited. Based on the current estimates given in the literature, natural uranium used for nuclear power technology will last only about 50 years; oil, no more than 100 years; natural gas, 150 years; and coal, 200 years.

Due to the fact that fossil and nuclear fuels are highly depended upon for energy generation, there are environmental pollution and safety challenges, which are now becoming dominant issues in the society and international world. Recently, there was a Paris climate agreement in France. "The agreement is within the United Nations Framework Convention on Climate Change (UNFCCC), dealing with greenhouse gas emissions mitigation, adaptation and finance, commencing in the year 2020" [3, 4]. The terms of the agreement was deliberated by 196 representatives during the 21st Conference of the UNFCCC in Paris and on December 12, 2015, it was adopted by consensus. The world is drastically focusing on clean and safe renewable energy sources due to the effects of environmental pollution on global warming. In the long run, the resulting change of climate has disastrous consequences on the planet.

There are enormous resources of wind energy, and it has been estimated in the literature that if 10% of the wind energy could be barely tapped, the electricity needs of the world could be supplied [2, 5]. With the recent advancement of variable speed wind turbines, power electronics, drives and control system technologies, wind energy is now competitive with traditional coal and natural gas power. However, one of the shortcomings of wind energy is that it is stochastic in nature, thus making its availability sporadic, consequently, needs back up by other conventional power sources.

The solar photovoltaic systems have the merit of being static and require less repair and maintenance. However, it is five times more expensive than wind power, although recently, there is huge research and development to produce low cost photovoltaic solar panels for widespread applications. Solar power conversion performance efficiency is basically 16%, and its availability is also sporadic like the wind power.

Hydrogen gas is the primary fuel for fuel cell energy or a fossil fuel type like gasoline or methanol, with a reformer. Fuel cells are static and have high conversion efficiency of about 60% compared to wind and solar power. However, fuel cells are heavy, expensive and possess poor transient response in their current state. Although, fuel cells show tremendous promise for the future, especially for electric cars, however, a tremendous amount of research and development is needed to achieve this aim.

2. Overview of wind energy technology

Wind energy is the indirect form of solar energy which is always being replenished by the sun. The differential heating of the earth's surface by the sun causes wind. It has been estimated that about 10 million MW of energy are continuously available in the earth's wind [6–8]. Wind energy could act as an environmental friendly alternative and national energy security especially during times of limited global reserves of fossil fuels, which threatens the long-term sustainability of global economy.

The technology of wind turbine has a technical identity and demand that is unique in terms of the design methods. Recently, remarkable advances and improved reliability in wind power design have been achieved owing to developments in modern technology. The structural dynamics advances and aerodynamics along with micrometeorology since 1980, have led to about 5% increase annually in wind turbines energy yield [9–13]. Present science and engineering research methods are producing better, stronger, lighter and more efficient blades for wind turbines. Wind turbines annual energy output has increased enormously and the weights, emitted noise of the wind turbine during operation have been halved over the last few years. A considerable amount of power can be obtained from wind energy technology by establishing more wind monitoring stations, effective selection of wind farm site with proper wind generator, enhanced maintenance procedures and practices of wind turbines, increase the wind generator availability, the use of large capacity wind generator, low wind regime turbine, higher heights of tower, wider rotor blade swept area, improved structural design and aerodynamics, proficient and enhanced technique for computer-based machining, improved power factor and better policies of the government.

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Wind power generation has an edge over the other renewable energy technologies application, because of its technological maturity, good infrastructure and relative cost competitiveness. In the near future, wind energy is expected to play a vital role in both national and international levels regarding energy scenarios [1, 5, 14]. Basically the kinetic energy of the wind is converted to electrical energy via the wind turbine blades rotation. According to Greenpeace report in the literature, by the year 2020, about 10% electricity in the world can be obtained by the wind energy. However, wind power is already competitive with conventional fossil fuel power stations at good windy sites. With this enhanced and mature wind technology, together with superior economics, experts predict wind power would capture 5% of the world energy market by 2020. Advanced wind turbines must be more reliable, efficient, robust and less expensive than current wind turbines.

3. Wind turbine technology

There are three main types of wind turbines used nowadays [15]: the Fixed Speed Wind Turbines with Squirrel-Cage Induction Generator (FSWT SCIG), the Variable Speed Wind Turbines with Doubly Fed Induction Generator (VSWT DFIG) and the Variable Speed Wind Turbines with Permanent Magnet Synchronous Generator (VSWT PMSG). Wind energy technology has experienced important improvement in several last decades [16] due to the technological improvement of wind turbines from fixed speed to variable speed. A brief distinction of the three types of wind turbine driven generators is given below.

The SCIG are used in general as fixed speed wind turbine generators due to their superior characteristics such as brushless and rugged construction, low cost, maintenance free and operational simplicity. However, this type of wind turbine technology requires large reactive power to recover the air gap flux when a short circuit fault occurs or grid disturbances in the power system. SCIG wind turbine technology has limited ability to provide voltage and frequency control, except it is supported with some expensive external power electronic control strategy, hence not commonly used in modern wind turbines.

The variable speed turbines are becoming the norm for new wind farm installations, because of high energy capture efficiency couple with reduced drive train stresses [17]. The PMSG VSWT, also known as the direct-drive synchronous generator with permanent magnet excitation and the DFIG VSWT with doubly fed back-to-back power converter type technologies, have become the two generator alternatives. The former has the disadvantage of cost mainly due to a power converter rated for the full power. Although in the latter, a gear box is needed, the DFIG requires a converter of only 20–30% of the generator rating for an operating speed range of 0.7–1.3 per unit (p.u) resulting in a lower cost.

Although the DFIG is not as rugged and robust as the squirrel-cage wind turbine type, however, the brushes have little wear and sparking when compared to DC machines and is the only acceptable option for alternative energy conversion in the megawatts power range. With the help of modern power electronic devices, it is possible to recover the slip power dissipated in resistances [2]. The DFIG wind turbine use a back-to-back power inverter system connected between the rotor side and the grid side of the machine, while the stator is directly connected to the grid. The DFIG can effectively operate at a wide range of speed based on the available wind speed and other specific operation requirements. Consequently, better capture of wind energy [2, 18, 19], with dynamic slip and pitch control could lead to effective rebuilding of the wind turbine terminal voltage, at the same time maintaining the power system stability after clearance of an external short circuit fault [20]. Besides, DFIG wind turbine has shown better behavior regarding system stability during short circuit fault in comparison to SCIG, because of its ability to decouple the active and reactive power output control. The DFIG superior dynamic performance is achieved from the frequency or power converters which typically operates with sampling and switching frequencies of above 2 kHz [21]. The Insulated Gate Bipolar Transistors (IGBTs) of the DFIG converter system are normally off, during lower voltages down to 0% and the system remains in standby mode [22–26]. During grid disturbances, if the voltages are high above a set cutoff or threshold value, the DFIG wind turbine system is very quickly synchronized and is back in operation again.

The VSWT PMSG is connected through a back-to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride through capability during voltage dips, as compared to the VSWT DFIG technology. However, the use of this wind turbine technology is limited when compared to the DFIG technology due to high cost. The schematic diagrams of the three wind turbine technologies are shown in **Figures 1–3**, while a comparison between the fixed and variable speed wind turbine technology is given in **Table 1**.

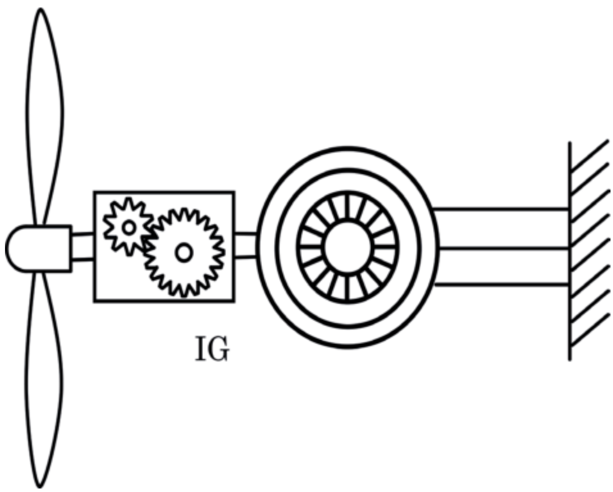

Figure 1. Fixed speed induction generator wind turbine.

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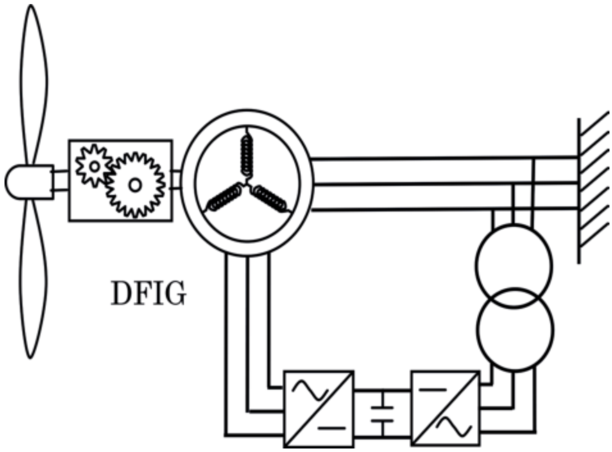

Figure 2. Doubly fed induction generator variable speed wind turbine.

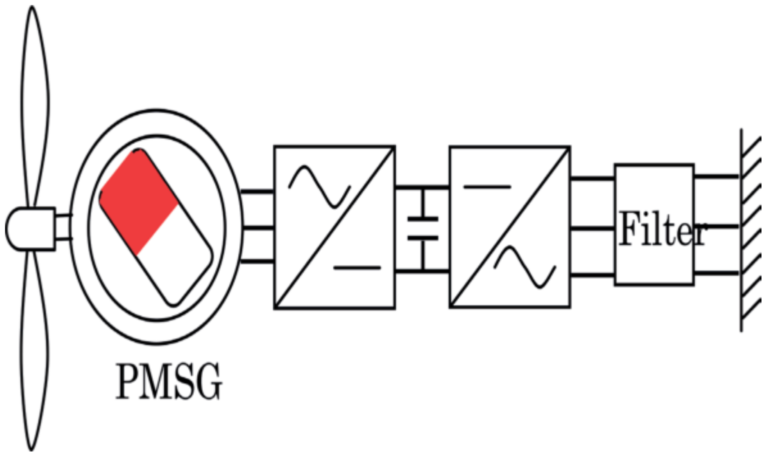

Figure 3. Permanent magnet synchronous generator variable speed wind turbine.

Fixed speed wind generator	Variable speed wind generator
1. This type of wind turbine has fixed speed operation, thus the power captured is in limited range.	1. This type of wind turbine has variable speed operation, making it possible to achieve a high efficiency of energy conversion compared to constant speed operation especially in low wind speed areas.
2. The technology of this turbine has limited ability to provide voltage and frequency control.	2. The technology of this turbine has ability to decouple control of active and reactive powers rapidly and independently by secondary excitation control. Thus, the grid connected turbine system tends to be more stable during network disturbances.

Fixed speed wind generator	Variable speed wind generator
3. This wind turbine has superior characteristics such as brushless and rugged construction, low cost, maintenance free and operational simplicity.	3. This wind turbine technology has reduction of mechanical stresses and acoustic noise.
4. The technology of this wind turbine requires large reactive power to recover the air gap flux when a short circuit fault or grid disturbance occurs in the power system.	4. The technology of this wind turbine improves the power quality of the grid connected system without expensive external reactive power compensation devices.
5. This wind turbine requires the installation of expensive external reactive power compensation devices to provide and support reactive power, thus, increasing the overall cost of the system.	5. This wind turbine has the required capacity of the power converters for secondary excitation, and this can be less than half for the case of a DFIG system, thus the total cost decreases.

Table 1. Comparative study of fixed and variable speed wind generators.

4. Wind turbines and operational grid requirements

The fast growth and penetration of wind generation through the installation of large number of wind turbines has led to primary concern about the effect of wind power on the transient and frequency stability of the electric utility grid. In several countries, institutional support on renewable energy sources has led to implementation of a large number of wind farms [27]. As the amount of wind power is drastically increasing in years to come, maintaining power system, voltage and frequency stability during a short circuit fault or grid disturbance will be more paramount in order to ensure power supply safety and other important tasks. It would

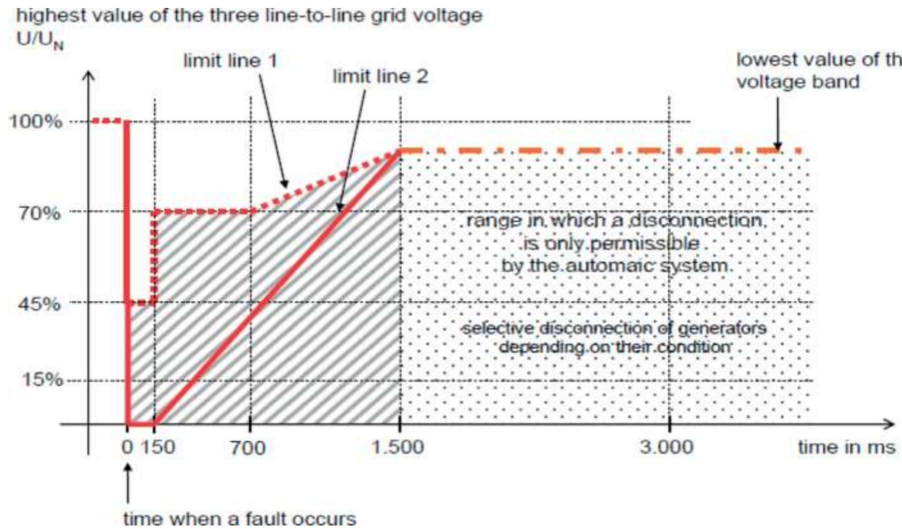

Figure 4. Fault ride through (low voltage ride through) requirement for wind farms as set by E.ON NETZ GmbH.

be imperative to perform new studies to evaluate the behavior of the wind farms during and after severe faults, in order to improve the design of the wind farms in an efficient and economy way. Hence, the most demanding requisite for wind farm is the Fault Ride Through

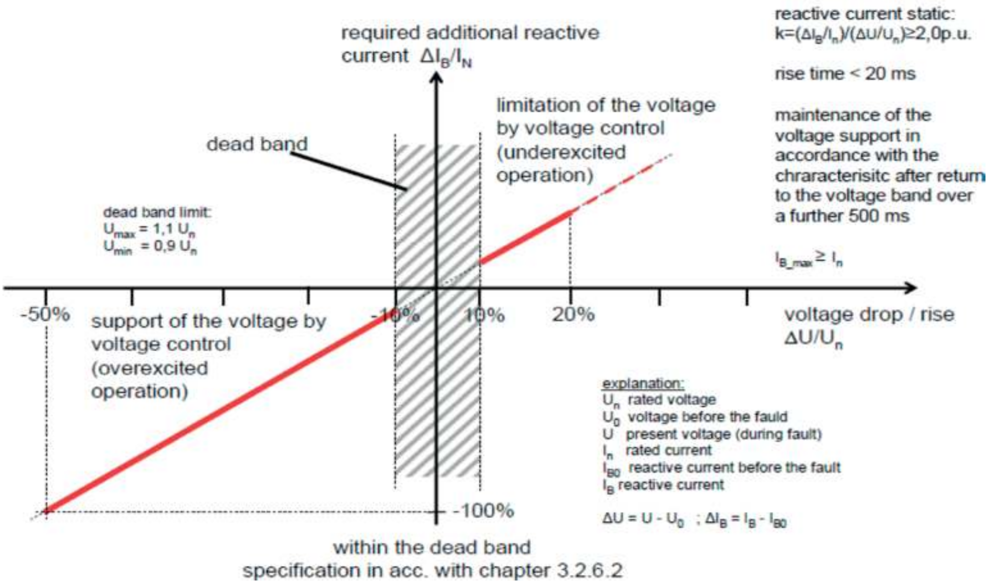

Figure 5. The rule of voltage support during grid fault as set by E.ON NETZ GmbH.

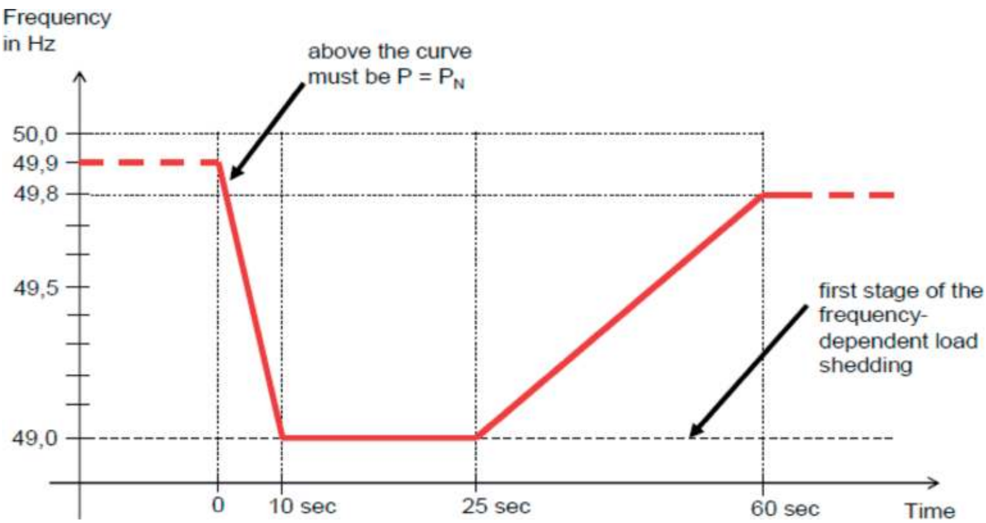

Figure 6. Grid frequency requirement of wind farms as set by E.ON NETZ GmbH.

(FRT) or Low Voltage Ride Through (LVRT) capability. Wind farms connected to high voltage transmission system must stay connected when a voltage dip or frequency disturbance occurs in the grid, otherwise, the sudden disconnection of great amount of wind power may contribute to the voltage dip and drop of frequency, with terrible consequences in the utility grid. Therefore, the transient and dynamic analysis of wind generators in wind farms are necessary. Several solutions could be used in the stability analysis and improvement of wind turbines during grid disturbances, so that they can contribute to voltage and frequency control. Some of these solutions are the use of power electronic devices and reactive power compensation units like static synchronous compensator (STATCOM), superconducting magnetic energy storage (SMES), energy capacitor system (ECS), crowbar, static series compensator (SSC), a dynamic voltage restorer (DVR), series dynamic braking resistor (SDBR), superconducting fault current limiter (SFCL), passive resistance network, series antiparellel thyristors and among others discussed in the literature.

4.1. Operational grid requirements

The big challenges that wind farms must face is voltage and frequency dip in the grid during grid disturbances [28]. The magnitude of the voltage is controlled by the reactive power exchange, while the frequency is controlled by the active power. **Figure 4** displays the typical requirement for fault ride through grid code regarding terminal voltage of the wind farm. The wind farm must remain connected to the grid if the voltage drop is within the defined r.m.s. value and its duration is also within the defined period as shown in the curve. **Figure 5** shows the required reactive current support from the generating plants during voltage dip, while **Figure 6** shows the permissible grid frequency requirement [29].

5. Structure of wind turbines

Some of the structures and installation configurations of wind turbines are presented in **Figure 7**. In **Figure 7a**, the complete layout of a typical wind turbine connection is shown. The major components of the wind turbine are the rotor blade, gearbox, nacelle, generator, power cables and tower. The output power of the wind turbine is distributed to the network grid via transformer and switchyard. The wind turbine generator is housed in the nacelle and **Figure 7b** and **c** shows the detailed structure of the nacelle containing the low speed shaft, gearbox, controller, anemometer, wind vane, high speed shaft, yaw motor tower and others. In **Figure 7d**, the details of the wind turbine blades and other ancillary components are described. The wind turbine rotor blade is basically made of glass reinforced plastic, while the Yaw shaft with the slip ring ensures 360° rotation. The tail pole and wind connects the body of the wind turbine through a sensitive bearing, while the tower of the wind turbine is of high quality spray painting and galvanized to be salt and acid proof. The wind turbine generator in the nacelle is extremely light and small, low in sound, swift in startup, quick in heat dissipation and of high efficiency. The nose cone of the wind turbine is made up of reinforced aluminum alloy and antisepsis casting.

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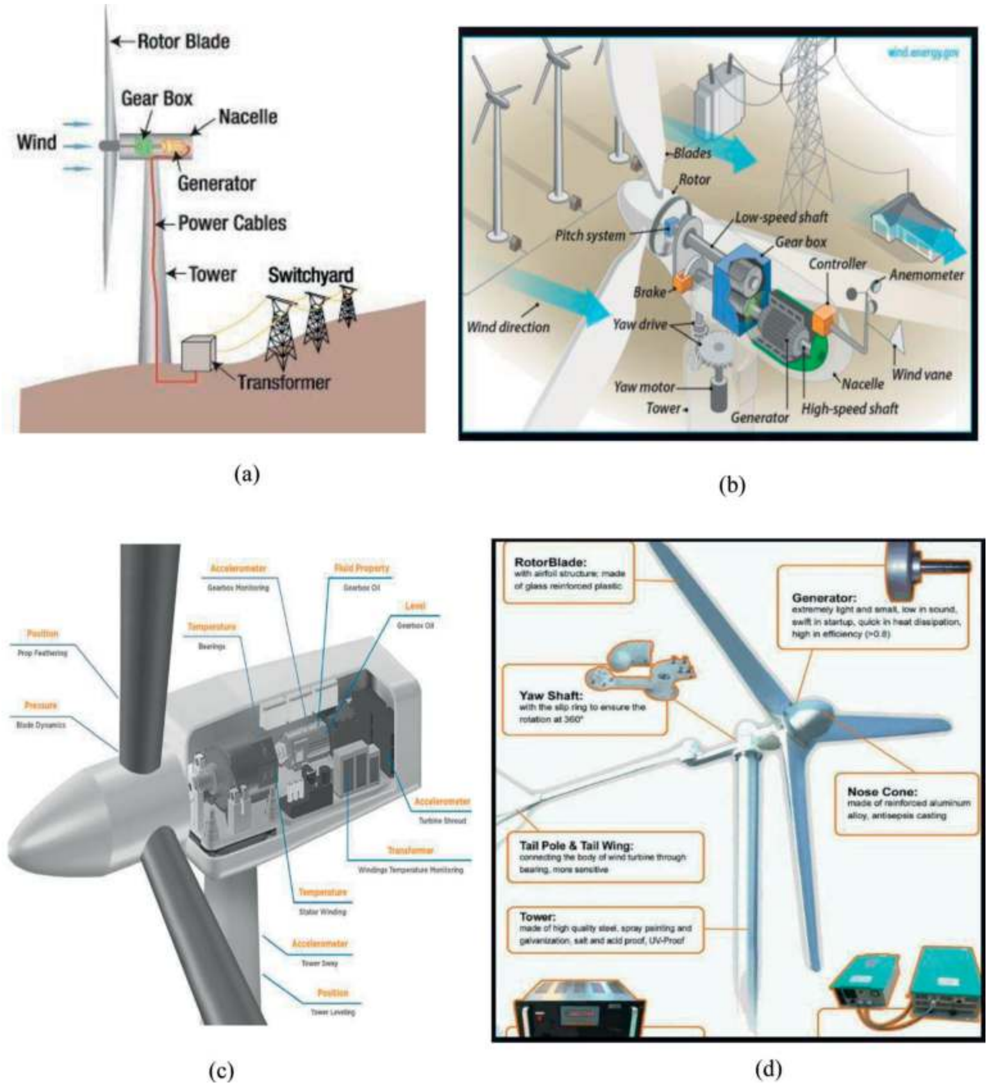


Figure 7. Structures and configuration of a typical wind turbine [30].

6. Onshore and offshore wind farms

A wind farm is a collection of wind turbines of the same type of technology or different type of technology. Although, in most wind farms, the technology of the wind turbines are same, however, it has been proposed in the literature to developed modern wind farms to compose of both fixed speed and variable speed wind turbine technology. This is because the variable speed wind turbine technology can be used to stabilize the fixed speed type, while at the same time generating power to the grid system. **Figure 8** shows typical onshore and offshore wind farms. More winds are achieved in offshore or coastal wind farms than onshore wind farms, however, the cost of installation and maintenance is high for this type of wind farm.

(a) (b)

Figure 8. Onshore and offshore wind farms.

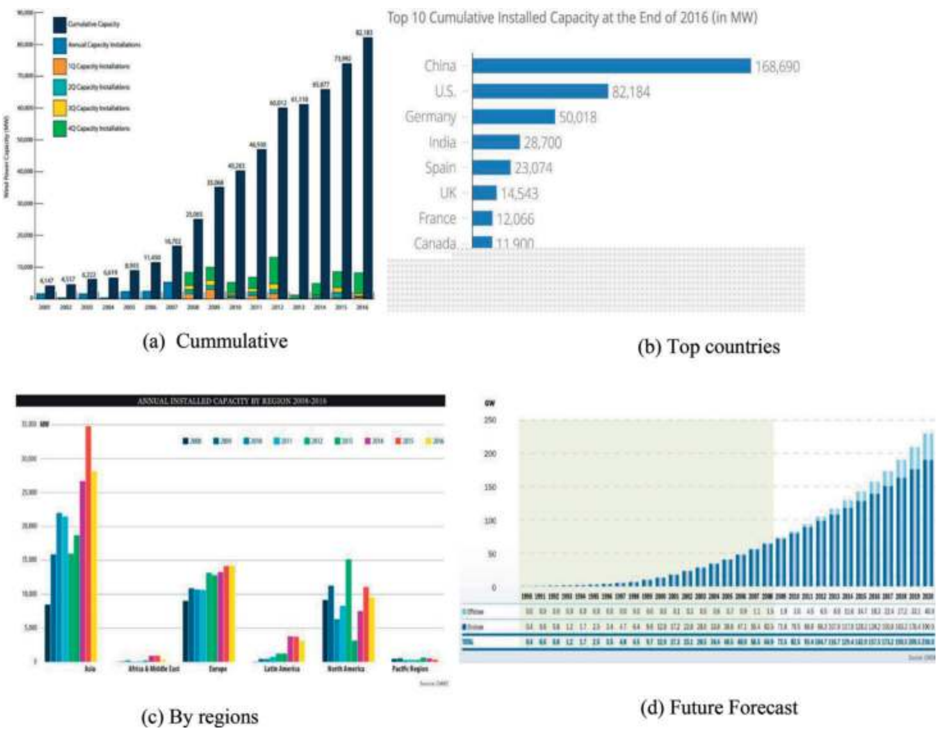


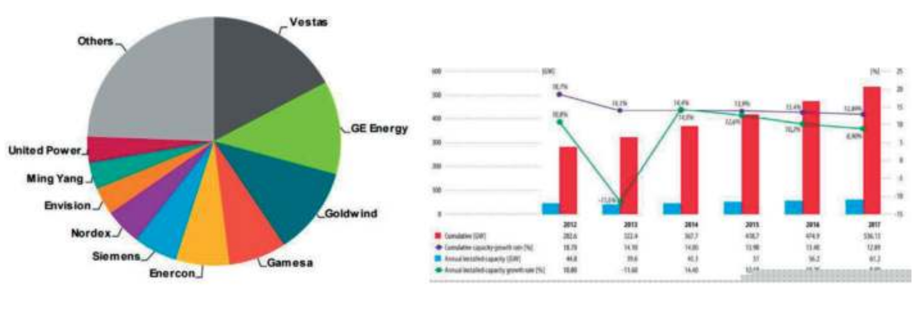
Figure 9. Global wind turbine installations [30]. (a) Cummulative; (b) Top countries; (c) By regions; (d) Future Forecast.

6.1. Global wind turbine installation capacity

Figure 9a shows the cumulative capacity, annual capacity installations, first, second, third and fourth quarter capacity installations of wind turbines globally from the year 2001 to 2016. This is tremendous increase in the number of wind turbine installations over the years from the figure. As at 2016, the wind power capacity is already 82,183 MW as against 4147 MW in the year 2001. The cumulative installed capacity over these years by countries is shown in **Figure 9b**, with China taking the lead, then the United States and Germany behind China. The wind turbine installation by regions of the world is shown in **Figure 9c**, from 2008 to 2016. Asia is leading with about 35,000 MW annual installed capacity in 2015. This value, however, dropped in 2016 to about 28,000 MW. There was considerably decrease in the annual installed capacity of wind turbines in Asia during 2012 from the figure, however, between 2013 and 2016, the annual installed capacity increased. In Europe, the annual installed capacities in 2015 and 2016 are same with a rough estimate of 14,000 MW. In North America, the highest annual installed capacity of 15,000 MW wind turbine was achieved in the year 2012, and in 2013, the value dropped drastically to 2500 MW. In 2015, the annual installed capacity rose to about 12,000 MW, thereafter, in 2016, the value dropped below 10,000 MW. The distribution of wind turbine installation in North America is irregular over the years due to less interest in renewable energy. The Pacific region, Africa and the Middle East are the least in annual installed capacity of wind turbine, respectively. The future forecast of the installed onshore and offshore wind turbines from 1990 to 2020 is shown in **Figure 9d**, with a value of 230 GW wind capacity excepted by 2020.

7. Wind turbine manufacturers and market trend

Some of the manufacturers of wind turbines are shown **Figure 10a**. The top major wind turbine manufacturers are Vestas, GE energy, Goldwind, Gamesa, Enercon, Siemens, Nordex, Envision, Ming Yang and United Power, respectively. The designs and control strategy employed in the wind turbine system is slightly different for each manufacturer. The wind turbine market trend is shown in **Figure 10b** from 2012 to 2017. There is cumulative increase



(a) (b)

Figure 10. Wind turbine manufacturers and market trend [30] (a) Wind turbine manufacturers; (b) Wind turbine market trend.

in power (GW) from 2012 to 2017, the cumulative capacity growth rate and annual installed capacity growth rate decreased over the considered years. There is little or no difference in the annual installed capacity (GW) over the considered years.

Author details

Kenneth Eloghene Okedu

Address all correspondence to: kenokedu@yahoo.com

Department of Electrical and Computer Engineering, National University of Science and Technology, Muscat, Sultanate of Oman

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