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A CONCISE OVERVIEW OF GENERATORS FOR WIND ENERGY SYSTEM

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Abstract – Wind power generator have been operational since 1888. Over this period, various types of wind turbine generator have been developed from the existing types of electric machines. In this review, three main generators: DC generators, Induction generators and Synchronous generators along with their sub – types were examined on the basis of their construction, operation, inherent advantages and disadvantages. DC generator are uneconomical, the squirrel cage induction generators although rugged, simple and economical operates as a fixed speed generator. The wound rotor induction generator operate on a wider speed range than the squirrel cage induction generators but the speed range is smaller compared tothe double field induction generator (DFIG) configuration with speed range of $\pm$ 30%. The DFIG is an excellent generator for grid connected wind power system. The synchronous generator is an ideal variable speed generator for wind power generation and the permanent magnet type is very suitable for small stand –alone and large wind system.

Keywords: Wind generators, DC generators, induction generators, squirrel cage, wound rotor, synchronous generators and permanent magnet.

1. INTRODUCTION

For centuries, humans have learned to harness wind power for sailing boats and windmills for grinding and pumping water [1]. By the late 19th century, windmills could no longer compete with power from steam turbines, internal-combustion engine and electric motors [2].In 1888, electricity was generated from wind power for the first time [3].The production and utilization of commercial wind generators for electricity continued until the 1930swhen it started to decline due to increased rural electrification[4].

The fuel crisis of the 1970s coupled with the desire for renewable alternative energy sources that is not dependent on fossil fuels led to a resurgences in the research and production of wind power generators [4]. Research and production of wind power generators increased within 3 decades such that by the year2016, the total installed wind energy capacity was 486,790MW [5]. The cost of wind power generation has continue to fall and it is now within the range of fossil fuel power generation [6].

2. WIND ENERGY SYSTEM TECHNOLOGY

A wind energy system consist mainly of the blades and a generator. A wind turbine converts wind energy into rotational motion of the wind turbine blades. The available output power extracted from the wind turbine is expressed in (1) [7]:

$$P_{out} = \frac{1}{2}\rho A v^3 C_p (1)$$

where,P_{out} is the turbine output power, ρ is the density of air, A is the turbine blades swept area, v is the wind speed and $C_p$is the turbine power coefficient.

Modern wind turbines can be classified into two types. They are the horizontal-axis and vertical-axis turbines. In the horizontal-axis wind turbine, the rotating axis of the blades is parallel to the wind stream. Its advantages includes higher turbine efficiency, high power density, low cut-in wind speeds, and low cost per unit power output. It is the most common commercial wind turbine [8]. In the vertical-axis wind turbine, the blades rotates with respect to their vertical axes and are perpendicular to the ground. Its advantages includes: wind acceptance from any direction, no yaw control is needed and its cost is reduced because the gearbox and other main turbine components can be setup on the ground. However, because of its lower wind power efficiency, the vertical-axis wind turbines is not commonly used for large turbine applications, but used in small and residential wind turbines [8].

The generator converts mechanical rotation to electrical energy. It consist of the stator (stationary member) and the rotor (rotating member) separated by an air-gap.There are two sets of windings in a generator, the armature windings that produces the electromotive force (EMF) and the rated current and the field windingsthat produces the magnetic flux. The rotor and stator in a generator are configured such that if one member carries the field windings, the other member will carry the armature windings where the bulk energy is generated [9]. In some generators, permanent magnets are used in place of the field winding [4]. The rotor is coupled to the wind turbine blade shaft and spins on bearings. The EMF generated is based on the principles of electromagnetic induction. When there is a relative time variation between magnetic field and the conductor, the generated EMF is according to (2) [10]:

$$E = N\frac{d\varphi}{dt} \quad (2)$$

where, E is the induced EMF, N is the number of turns, $d\varphi$ is the change in flux and $dt$is the change in time. In wind turbines, variable low speed are desired. However, most AC generators are designed to run fast. Generators are coupled to the turbine blades through gearboxes to increase their speed. In some wind turbineapplications, the generators are designed such that they are coupled directly to the wind turbine without the use of gearboxes [11].

3. GENERATORS FOR WIND ENERGY SYSTEMS

The generators used for wind-power generation are: DC generators, Induction (Asynchronous) AC generators and Synchronous ACgenerators [12].

3.1. DC Generators

The DC generators consist of armaturewinding on the rotor, the armature coils are terminated at the split ring commutator, a ring of splitted copper segment separated by insulation and stationary field winding or permanent magnets on the stator that generates the magnetic field [13].The commutator reverses the armature winding connections in the external circuit and produces a pulsating voltage instead. The output power is delivered to an external source by means of an arrangement of carbon brushes that makes contact with the commutator [14]. In DC generators, EMF is generated when the coils in the rotor rotates within a uniform magnetic field created by the field windings or permanent magnet. The voltage produced by a dc generator is proportional to the speed of the rotor as shown in (3) [15]:

$$E = \frac{Z\varphi N}{60} \times \frac{P}{A} (3)$$

where,φ is the flux/pole,Z is the total number of armature conductors, P is the number of generator poles, A is the number of parallel paths in armature, N is the armature rotation in revolutions per minute (RPM) and E is the EMF induced in any parallel path in the armature.

The DC generators with wound field winding are classified according to the connection of the field windings. If the field windings are connected to an external source of excitation, it is call a separately excited DC generator. If on the other hand the field winding is excited by the current from the armature windings, it is called the self-excited DC generator. The self-excited DC generator is further classified according to how the field winding is connected to the armature windings. If the field windings are connected in series with the armature windings, it is called a DC series generator. If the field windings are connected in parallel with the armature windings, it is called a DC shunt generator [14].

Thewind driven DC shunt generator are applied in low power loads or as abattery-charger [4, 12]. As shown in figure 1, a DC – DC converterbased controller regulates the output voltageto charge a battery or the DC output can be converted to AC through an inverter to a desired voltage level.

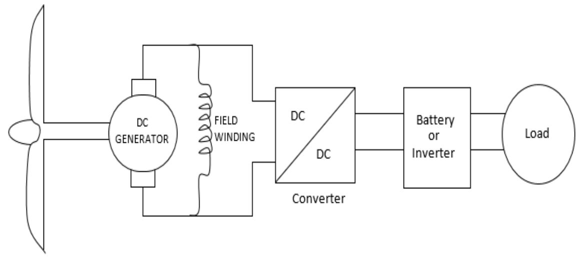

Fig.1. A wind driven DC shunt generator

The DC generators are rarely used because their brushes and commutator require regular maintenance, they are uneconomical [12]. They have been replaced by the more economical AC generators because the AC can easily be converted into DC by means of solid-state rectifiers [12, 16].

3.2. Asynchronous (Induction) Generators

An induction machinestructure consist of astationary stator with slots that accommodates a balanced polyphase windings and a rotor that is configured either as a squirrel-cage rotor where conductors in the form of bars are inserted within the cylindrical rotor, with the conductor bars short circuited by end rings or a wound rotor with a balance polyphasewindings of the same number of poles as the stator with brushes and slip ring for an external connection [14].Figure 2 illustrates the structure of a wound rotor induction machinesand a squirrel cageinduction machines.

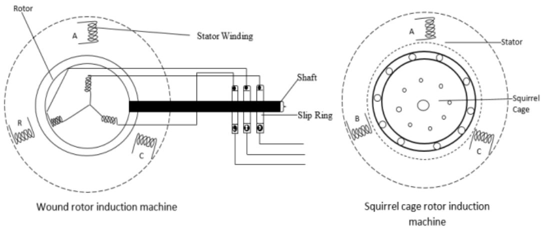

Fig.2. Wound rotor and Squirrel Cage rotor Induction machinesstructure

The rotor of an induction motorrotates below its synchronous speed(the speed of the rotating magnetic field produced). In induction generators,the rotor rotates above its synchronous speed [15]. The rotating synchronous speed is express as (4) [14]:

$$n_s = \frac{120\,f}{p} (4)$$

where,n_s is the synchronous speed or the speed of the rotating magnetic field, f is the operating electrical frequency and p is the number of poles.The difference in speed between the rotating magnetic field and the rotor speed is called slip. It is expressed as (5) [14]:

$$s = \frac{n_s - n_r}{n_s} (5)$$

where, s is the slip, n_s as defined in (4) andn_r is the speed of the rotor.

The speed torque characteristics of aninduction machine shown in figure 3 indicates that, the slip is positive when the machine operates in the motoring modewhile in thegenerating mode, the slip is negative [17].An induction generator can only generate electricity when it is driven above its synchronous speed [18]. The rotational torque created by wind energy varies with the wind speed, thus the rotational speed of the wind driven induction generator can be increased by applying the gearbox [19].

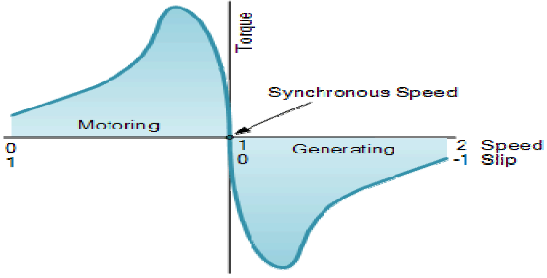

Fig.3.Torque/Speed Characteristics of an Induction Machine

Source: http://www.alternativeenergytutorials.com/wind-energy/induction-generator.html

The mathematical relationship between the torque and slip of an induction machine is given by (6) and (7) [15]. Figure 4 illustrates the induction machine slip.

$$T = \frac{K\,sE_2^2R_2}{R_2^2+(sX_2)^2}(6)$$

where, the constant $K = \frac{3}{2\pi n_s'}$ and $n_s' = \frac{n_s}{60}$ is the synchronous speed in rev/sec, X_2 is the rotor reactance at stand still, E_2 is the induced EMF in the rotor at stand still, R_2 is the rotor resistance and s is the slip.

The torque/slip equation in (6) can be further expressed as (7)[15]:

$$T = \frac{ks}{R_2}(7)$$

By varying the value of R_2 in (7), the slip can be controlled and variable speed operation can be achieved. The slip can be controlled by adding external resistance to the rotor circuit as expressed in (8) [15].

$$T = \frac{Ks}{R_2+r}(8)$$

where, r is the external resistance that should be added to control the slip.The addition of external resistance is impossible in squirrel cage induction generators because it lacks the slip rings and brushes, but it is possible in the wound rotor induction generators.

3.2.1. Squirrel Cage Induction Generators (SCIG)

In squirrel cage induction generators, magnetic field is created by the reactive power absorbed from a shunt capacitor bank connected across the generator terminals or from the grid. A residual voltage produced from the residual magnetism in the rotor circuit drives the capacitor current, resulting in the voltage build up [20, 21]. When the reactive power of an induction generator is supplied by a capacitor bank, it is also known as the self-excited induction generator (SEIG) [20].A stand-alone self-excited wind driven squirrel cage induction generator is illustrated in figure 4.

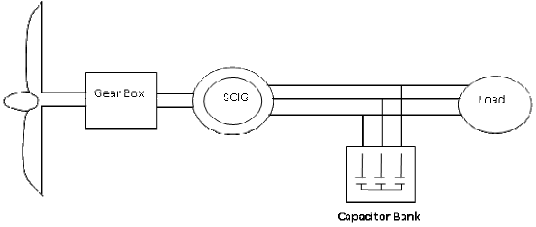

Fig.4. Astand-aloneself – excited wind driven squirrel cage induction generator (SCIG)

The squirrel cage induction generator is directly connected to the grid through a soft starter and a transformer as shown in figure 5. The soft-starter limit the induction generator inrush current by means of a bypass switch that delay the connection to the grid by some few seconds or transient period [22]. A capacitor bank is connected to the generator terminal to compensate for the reactive power supplied by the grid.

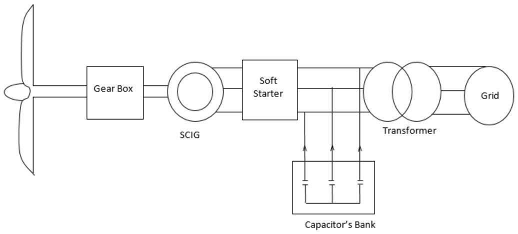

Fig.5. A grid connected wind driven squirrel cage induction generator (SCIG)

The advantages of the squirrel cage induction generator includes low cost, high reliability, maintenance and operational simplicity, rugged construction, brushless operation, protection against overloads and short circuits [16,19]. The disadvantage of the squirrel cage induction generator is that its operating range is limited, it cannot operate as a variable speed generator. Also, fixed capacitor alone cannot provide the required reactive power needed at all possible speed and loading conditions [23].

3.2.2. Wound Rotor Induction Generator (WRIG):

The wound rotor induction generator can be configured in two ways, they are: the resistive control wound rotor induction generatorand the double fed induction generator. In the resistive control method, the stator winding is connected to the grid through a soft starter[24]. The rotor winding is connected to anexternal resistor. The external resistance can be adjusted to achieve a variable-speed operation of up to 10% above the synchronous speed because the slip of the induction generator can be controlled by the use of the external resistance. The speed control depends on the rating of the external resistance. As the speed increases,thereactive power increases and an additional reactive power compensation will be required [25]. The resistive control WRIG is illustrated in figure 6.

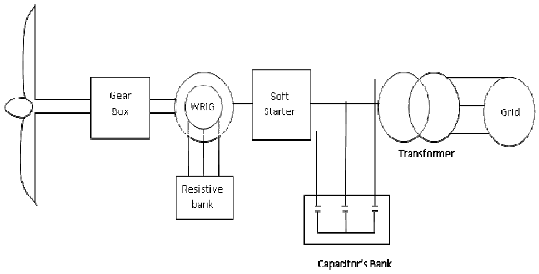

Fig.6. Resistive control wound rotor induction generator

Although limited for wider applications, the WRIG has a wider range of speeds above synchronous speed when compared to the squirrel cage induction generator. However, its efficiency is reduced because much of the rotor energy is dissipated in the external resistance [25, 26].

Another method of configuring the wound rotor induction generators (WRIG) is the doubly-fed method. In this method, both the rotor and stator supply the output power hence it is also called a double fed induction generator (DFIG). The stator winding is connected to the grid directly while its rotor winding is connected to the grid through a power electronic back-to-back or AC – DC – AC converter [24, 27]. It operates at variable speedof about ±30% of the synchronous speed [25], and supply voltage at constant frequency. Figure 7 shows the DFIG.

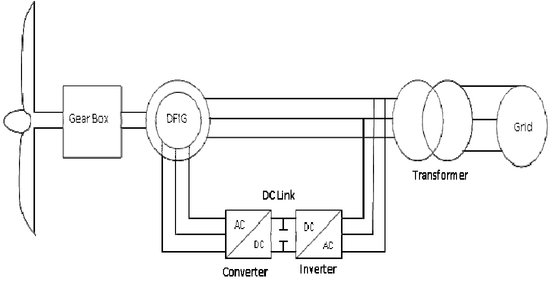

Fig.7. The double fed induction generator (DFIG)

The converter on the rotor side controls the generator active and reactive power, while the grid side converter controls the DC-Link voltage to control the variable speed [28].The double fed induction generator can tolerate high fault current because the fault current can be diverted to a crowbar protection circuit [24]. The DFIG is very efficient, it has the ability to deliver its maximum power in super synchronous speeds and sub synchronous speeds [29]. It is widely used in wind farms.

3.3. Synchronous Generators

In Synchronous generators, the speed of the rotating stator flux and rotor is the same i.e. the rotor speed is equal to the synchronous speed given by (4) [14]. The stator winding is a balanced polyphase winding that are 120^{o} apart, similar to the stator winding of an induction machine. The stator windings supplies the electric power to the load or grid. The rotor supplies the magnetic field that induce EMF in the stator winding. Therefore the synchronous generator can be described either as a wound rotor synchronous generator (WRSG) or a permanent magnet synchronous generator (PMSG). The rotor magnetic field is produced by the field windings in the rotor or a permanent magnet [30].

The WRSG is also called the electrically excited synchronous generator because its winding are supplied with direct current to produce magnetic field[12]. The WRSG structure is illustrated in figure 8.

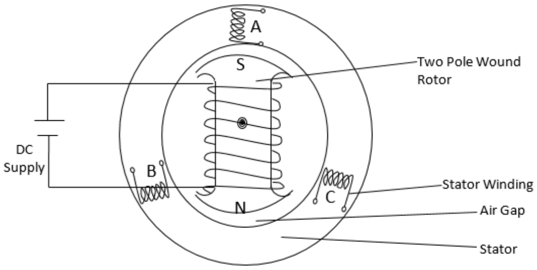

Fig. 8. Wound rotor synchronous generator structure

The rotor design may be salient pole for low speed or cylindrical rotor for high speed [14]. The field windings is usually excited by a dc current. Since the rotor rotates, the DC power is supplied from an external dc source through the slip rings and brushes in the rotor or from a brushless exciteri.e. a small AC generator whose output is rectified to direct current by means of a rectifier circuit mounted on the shaft and a small field circuit mounted on the stator [30].

The wind driven wound rotor synchronous generator or electrically excited synchronous generator is presented in figure 9.

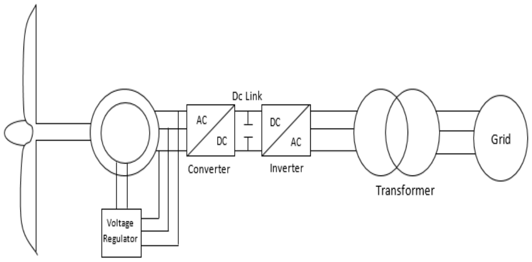

Fig.9. Wind driven wound rotor synchronous generator

The wound rotor synchronous generator can be operated over a wide range of speed with a back to back converter to improve the load characteristics and performance. Therefore, for lower speed operation, the number of poles will be large leading to a larger diameter and large physical size [31]. Gearbox may be required to limit the physical size.

The permanent magnet synchronous generator (PMSG) is similar to the wound rotor synchronous generator except that the field winding is absent and is replaced by permanent magnets [31]. The permanent magnets can be surfaced mounted, surfaced inserted or buried (embedded) [32]. Figure 10 shows thelayout of the types of permanent magnet rotor, a four pole permanent magnet structure is illustrated.

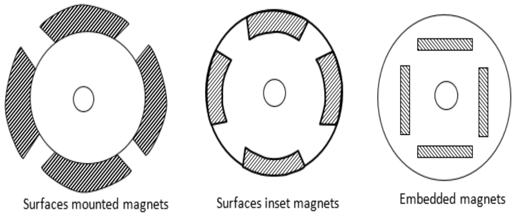

Fig. 10. Types of permanent magnet rotor layout.

The magnetic field of the PMSG is created by the permanent magnets. The PMSG can be design with higher number of poles. Hence, it is suitable for variable and low speed application without the use of gearbox [31]. For turbine of larger ratings, the number of poles is limited anda gearbox may be required as a compromiseto reduce the physical size.A wind driven PMSG generator is illustrated in figure 11.

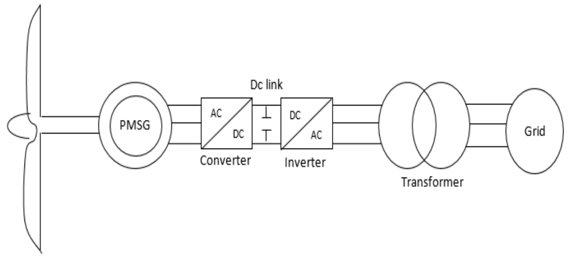

Fig.11. A wind driven permanent magnet synchronous generator **(PMSG)**

The PMSG are rugged, reliable, light in weight, highly efficient, higher power densityand can easily be maintained[33, 34].The disadvantages of the PMSG are their high cost, due to the high cost of rare earth magnets. They are susceptible to corrosion and the magnets can be demagnetized because they are sensitive to heat [31].

4. RECENT TREND IN WIND TURBINE GENERATOR

The squirrel cage induction generators (SCIG)were the most popular wind turbines generators in the 1980s and 1990s and were often referred to as the Danish concept [31]. SCIG have been replaces by the more efficient variable speed generators such asdouble field induction generators (DFIG) and the Permanent magnet synchronous generator (PMSG) [35]. Wind power turbines can be grouped as either small wind turbines or large wind turbines. The small wind turbines are ≤ 100 kW [36]. The permanent magnet synchronous generators is the choice for small-scale wind turbines because of its high power density, compactness, efficiency, low maintenance cost and the elimination of gearbox [37]. Large wind systems are dominated by the double field induction generators (DFIG) and the Permanent magnet synchronous generator (PMSG) as the most suitable generators with the PMSG having an edge over the DFIG, but the switched reluctance generator is gaining interest as a potential generator for wind energy system [35].

5. CONCLUSION

Three main generators: DC generators, Induction generators and Synchronous generators along with their sub – types have been examined based on their construction, operation, advantages and disadvantages. From the overview, DC generators when applied in wind turbine are direct driven but are rarely used because they are uneconomical. The squirrel cage induction generator (SCIG) are rugged, economical, reliable, easy to maintain and simple. However, their application in wind turbines are limited because they are fixed speed generators. The operating speed of the SCIG is slightly above the synchronous speed and a gearbox will be required for its operation. The wound rotor induction generator (WRIG) operates at a wider range of speed compared to the squirrel cage induction generator. However, it is limited for wider applications and its efficiency is reduced because much of rotor energy is dissipated in an external resistance. The double fed induction generator(DFIG) is commonly used as a wind power generator because it operates at variable speed and is highly efficient. Synchronous generator are wide ranged variable speed generator, hence they can be direct driven. However, for lower speed operation, the use of gear box is necessary to limit their physical size. The wound rotor synchronous generator(WRSG) efficiency is lesser compared to the permanent magnet synchronous generator (PMSG). The PMSG are rugged, reliable, easily maintained, light weight and highly efficient. The permanent magnet synchronous generator along with the DFIG are now the most widely applied wind turbine generators. Though they are both applied in large wind systems but the PMSG are the obvious choice for small wind power systems.

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