**CHAPTER 2: REVIEW OF WIND ENERGY CONVERSION (WEC) SYSTEMS**

In this chapter, detailed survey of wind energy fundamentals and general overview of wind energy conversion systems will be summarized. To accomplish this, this chapter is divided into four main parts. In first part, wind turbine power equations and wind equations will be given and discussed. This data especially used in wind turbine investment calculations and wind potential estimation techniques. In next part, current wind turbine systems will be classified and evaluated according to their mechanical and electrical aspects. Then three main flux orientations in PM based systems will be shown and explained. Finally, importance of modularity in wind energy conversion systems and axial flux advantages and disadvantages will be evaluated.

1. **Power Equations**

The available shaft power (output power) P from a wind turbine can be expressed as a function of the wind speed as follows :

(1)

where,

is the mass density of air

is the power coefficient, a function of the tip speed ratio λ and the pitch angle β

is radius of the turbine blade

 is the wind velocity

**Power Coefficient ()**

Power coefficient, sometimes called performance coefficient, is basically can be defined as the ratio between captured wind power by the wind turbine and the available input power of the wind. Therefore it tells us how efficiently we utilize the wind turbine. Its value is sometimes taken from look up tables or can be assumed by nonlinear computations[3]. Since physical limitations are exist in nature such as friction and other mechanical losses, maximum value of the power coefficient *Cp* is lower than theoretical maximum of Betz, which is about 59%. Betz limit will be explained detailed in following parts.

In [[1](http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6226866&isnumber=6331663)] Power coefficient is defined as a nonlinear function of TSR(λ) and pitch angle(β)  as follows,

(2)

where,

(3)

These coefficients shown above depend on the turbine characteristics. In [6], authors searched for common used variable values. According to this work, most used values in literature for these *Ci* variables are given in Table 1. As can be seen from table, most values for same variable are very similar, therefore values in third column (ref. [9]-[17]) can be assumed valid for related calculations. Nominal power of the wind turbine generator is achieved by proper control algorithms. For this purpose, maximum value of the Cp is can be obtained by employing optimal set of pitch angle(β) and tip speed ratio[30].

*Table 1. Coefficients of Power Coefficient Cp ()*

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Ref.no  Coef. | [7] | [8] | [9]-[17] | [18]-[23] | [24] | [25]-[26] | [27]-[28] | [29] |
| *C0* | 0.5 | 0.5 | 0.5176 | 0.22 | 0.5 | 0.73 | 0.44 | 1 |
| *C1* | 116 | 116 | 116 | 116 | 72.5 | 151 | 124.99 | 110 |
| *C2* | -0.4 | -0.4 | -0.4 | -0.4 | -0.4 | -0.58 | -0.4 | -0.04 |
| *C3* | 0 | 0 | 0 | 0 | 0 | -0.002 | 0 | -0.002 |
| *C4* | - | 0 | 0 | 0 | 0 | 2.14 | - | 2.2 |
| *C5* | -5 | -5 | -5 | -5 | -5 | -13.2 | -6.94 | -9.6 |
| *C6* | -21 | -21 | -21 | -12.5 | -13.125 | -18.4 | -17.05 | -18.4 |
| *C7* | 0 | 0 | 0.0068 | 0 | 0 | 0 | 0 | 0 |

**Tip Speed Ratio-TSR (λ)**

Tip speed ratio  (TSR) is defined as a ratio of linear tip speed of turbine blade to speed of the wind. This ratio is very useful when designing a wind turbine. Optimal TSR is desired to obtain maximum power from wind as much as possible.

(4)

where,

*V* is the wind speed

*wm*  is the rotational rotor speed

*R* is the rotor radius

TSR is a kind of measurement of how speedy turbine blades and shaft rotate. Therefore high TSR is aimed when designing a wind turbine. This topic is very important because of the efficiency issues. If turbine blades turns too slow then incoming air to the turbine is not used efficiently (natural result of Betz limit). If turbine blades turns too fast, blades act like a solid wall to the turbine and then efficiency decreases again. Besides, high TSR has several other disadvantages. Edge parts of blades rotating at very high speeds are subjected to faster erosion due environmental factors like sand or dust particles. This effect can be seen in Figure 1. Also high rotational speed of blades result in audible noise and vibration. To avoid bad consequences (low efficiency, physical breakdown) of turbulence issue, choosing optimal TSR is really important. Each wind turbine has unique value of TSR regardless of the generator topology used in manufacture [32].

Approximate optimal TSR’s for a system[33]:

for TSR value ~6-7 Number of blades=2

for TSR value ~5-6 Number of blades=3

for TSR value ~2-3 Number of blades=5



Figure 1. Leading edge erosion effect on wind turbine blades[31]

**Betz Limit**

Theoretically, maximum 59% (approximately 16/27) of energy carried by the wind can be extracted by an ideal wind turbine. This result is concluded by German physicist Albert Betz in 1919. This limitation is valid for both vertical and horizontal axis wind turbines. Maximum value of performance coefficient (*Cp*) is limited by Betz criterion. Generally imperfections in blade manufacture reduces the actual energy yield of the turbine less than the useable energy. Therefore value of *Cp* is generally less than 0.59. As mention before previous parts, there is a relationship between TSR and *Cp* and this correlation is limited by Betz as can be seen in Figure 2 which is depicted for two bladed systems. Minimum wind speed that is needed to start to rotate the turbines' blade is cut-in wind speed while cut-out speed is the maximum speed of wind that turbine is allowed to continue operation.

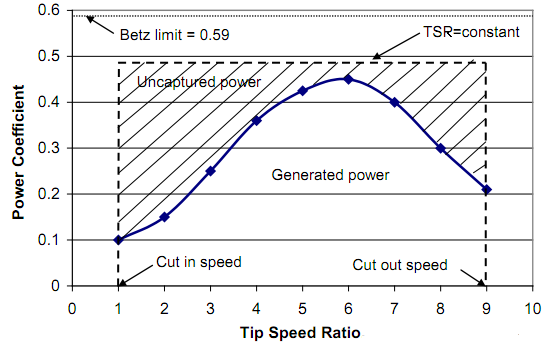


Figure 2. TSR and Power coefficient relation between cut-in and cut-out speeds, respectively for two bladed wind turbine [34]

**Wind profile and distributions**

Time dependent nature of the wind determines the production scheme of the WECs(Wind Energy Conversion Systems). There are some approaches for estimate the wind profile at given place. Wind profile at any given area is generally measured 10 meters above the ground level and estimated by 1/7 “Power Profile Law” as given follows[3] :

(5)

where,

*v* is desired wind speed,

*v0* is reference wind speed,

*h* is the desired height,

*h0* is the reference height

*α* value in the equation above can be calculated as follows[3],

this value is used approximately as "1/7" in calculations.

In [3], authors mentioned about wind profile estimation techniques based on different computational methods. Light Detection and Ranging, Adaptive Neuro-fuzzy interference system and particle filter based methods are main methods introduced among these estimation techniques.

Weibull distribution is used to determine the wind speed distribution and gives an indication of what percentage of time a certain wind speed occurs in a given site. This indication is need because of the probabilistic nature of wind. Weibull distribution function is given as follows:

(6)

where,

*v* is the wind speed

*k* is the shape parameter

*s* is the scale parameter

Another similar distribution function to obtain wind profile is Rayleigh distributions. In this distribution, main difference is using constant value of 2 for shape parameter *k*. According to [35] both distributions show similar performance when analyzing and predicting wind data. IEC 61400 standard which is specialized for design requirements of wind turbine, mentions Rayleigh and Weibull distributions as most common [36].

Determining wind speed profile of a given site by using Weibull distribution is useful together with the power curve of turbine, when calculating energy yield over a time. Therefore energy yield over a period of time T can be defined with the help of Weibull distribution as follows,

(7)

where,

*Ey* is the energy yield

*P* is the generated power

*f(v)* is the Weibull function

*T* is 8760 hours (1 year)

1. **Current Wind Turbine Systems**

In this part, generators are categorized according to their mechanical and electrical properties. In mechanical categorization, drivetrain approach is considered. In electrical categorization, most used generator types in WECs namely induction and synchronous generators are considered in terms of wind turbine point of view. Reaching megawatts of power capability per turbine, generator technology gaining more attention than its past. Therefore its design is the main focus point of both this study and current research activities on this area.

1. **Mechanical Aspects**

Wind turbines can be categorized based on mechanical construction (or drivetrain) as “geared drive” and “direct drive”. Both concepts are explained in detailed below.

**Geared Drive**

In this type of generator, turbine blades with hub structure connected to shaft of the generator via a gear-box, which increases the rotational speed of the low-speed shaft. Gearbox allows generator to operate at high speeds, therefore smaller diameters can be used with same amount of torque needs. Torque-diameter relationship is explained more detailed in direct drive section. Gear ratio is a measure of relationship between output and input speeds of dynamic system. Drivetrain of a VSCF (variable speed constant frequency) turbine generally consists of blades, low and high speed shafts, gear-box and generator. Gearbox in a wind turbine system is responsible of transmission of aerodynamic power from turbine to the generator shaft. Turbine shaft can be referred as low speed shaft while generator shaft is referred as high speed shaft. In Figure 3 , a representation of geared drivetrain of wind turbine generator can be seen.

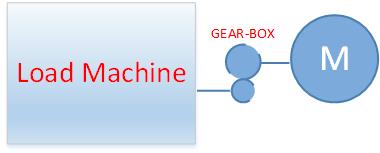


Figure 3. Schematic of geared drivetrain

Gearbox system is the main source of mechanical faults and losses in wind turbine systems. Also, it’s necessary to make periodic lubrication and maintenance for gearbox components in order to avoid an unexpected failure. Because of these reasons, manufacturers and designers start to develop gearless drive systems for wind turbines from early 1990s. However, geared systems still offer cheaper solutions than large diameter direct drive systems [37].

**Direct Drive**

As the name refers, in direct drive generators gearbox and all bearing structures are eliminated. Therefore, turbine blades and generator are connected on same shaft rotating at low speed. With this eliminated gearbox and other mechanical structures, direct drive systems offer lower maintenance cost and increased efficiency and reliability. In Figure 4, a representation of direct drive schematic of wind turbine generator can be seen. Main purposes of the direct-drive concept for wind turbines are; increasing energy yield, reducing gearbox failures and lower maintenance problems. There are two types of direct-drive namely, rotational and linear direct drives. But, linear direct drives are out of the scope of this thesis. In electrical generator design, one of the main criterion is torque. Due to tip speed limitation and natural result of gearless topology, direct drive wind turbine generators operate at low speed. Relationship between power and torque according formula which defines the output power of generator:

(8)

where,

*P* is the output power,

*T* is the torque,

*wm* is the mechanical speed of the shaft

Torque must be increase inverse proportional to decrease of angular speed in direct drive generators. According to [38], electromagnetic torque of an axial flux permanent magnet machine is proportional to outer diameter as shown in (9). In some designs [2] ratio of axial length to air gap diameter, *k* is optimized.

(9)

To do that when scaling up the turbine sizes, amount of material is increased in order to maintain the air-gap against deflection forces between stator and rotor parts. This means direct drive machines are heavier and larger in diameter size rather than other types of machines in order to produce same amount of power. More material also means extra cost which is a big disadvantage for this type of generators. Torque per volume and torque per mass parameters are important during the design of the generator system. Direct drive axial flux type permanent magnet machines are advantageous in torque to volume ratio among other machine topologies while torque per mass values are not much attractive. Torque per volume advantage is due to shorter axial length and compact structure rather than radial flux counterpart. Torque per mass disadvantage is related to large diameter penalty of this type of generators mentioned above.

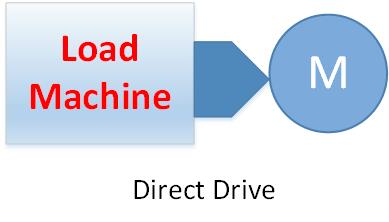
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Figure 4. Schematic of direct drive generator

**Drivetrain modelling**

In previous parts, different drive types are described as geared and direct drive. In this section, mathematical model of drivetrain is explained by two mass model and related equations. Drivetrain can be modelled single-mass or two mass model according to application [3]. If the system response to transients and other stability issues are the main focus of the analysis, two mass model is employed [3]. Two mass model of the drivetrain system is given in Figure 5.

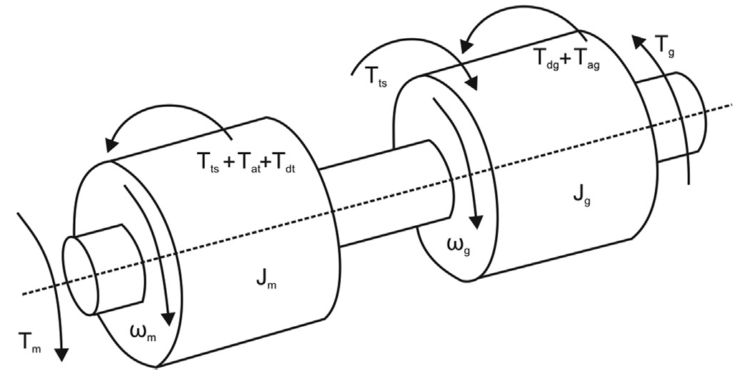


Figure 5. Two mass model of the drivetrain[3]

**Note:** mass with the “m” indice denotes turbine moment of inertia and other mass with "g" indice denotes generator moment of inertia.

Equations for angular speeds at the both end of the two-mass model are as follows[4],

(10)

(11)

where ,  
  
*Jm* is moment of inertia of blades and hub  
  
*Tm* is mechanical torque,  
  
*Tdt* is resistant torque in the wind turbine bearing  
  
*Tat* is resistant torque in the hub and blades   
  
*Jg* is moment of inertia of rotor of the generator  
  
*Tg* is electrical torque,  
  
*Tdg* is resistant torque in generator bearing  
  
*Tag* is resistant torque for airflow in generator   
  
*Tts* is torsional stiffness torque

1. **Electrical Aspects**

There are two main type of generators in this section: Induction Generators and Synchronous Generators.

i) Induction Generators

-Squirrel Cage Induction Generator(SCIG)

- Wound Rotor Induction Generator(WRIG)

- Doubly fed Induction Generators(DFIG)

ii) Synchronous Generators

- Wound rotor Synchronous Generators(WRSG)

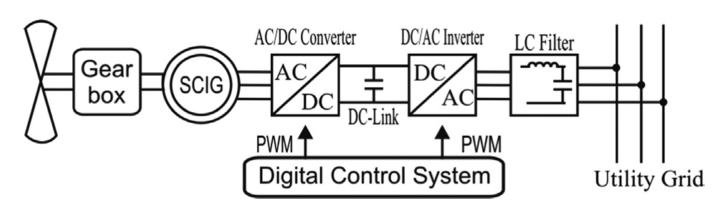
- Permanent Magnet Synchronous Generators(PMSG)

**Squirrel Cage Induction Generator(SCIG)**

This type of machine can be used with both fixed(Danish concept) and variable speed. Robustness, stable operation, lower maintanence makes SCIG preferable in WECs. But in order to get more efficient operation SCIG should be constructed with low number of poles because high number of poles contruction becomes a drawback for SCIG. Thefore gear-boxes are generally used with SCIGs.

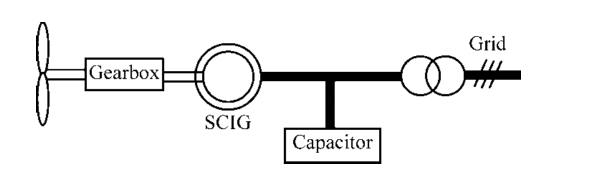
Capacitor banks and Static Synchronous Compensators(STATCOM) are commonly used for reactive power compensation with SCIGs. Additionally, STATCOMs used for active and reactive power flow control for variable speed applications of SCIGs.

In variable speed applications of SCIG back-to-back voltage source converters(VSCs) are employed in order to meet grid codes[25]. Schematic diagram of a this type WEC is given below.



*SCIG with back-to-back VSC converter*

Danish concept is known for fixed speed operation and can be applied to SCIG . Generator speed is determined according to grid electrical frequency.Circuit schematic and Danish-concept turbine is given below.

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*SCIG with Danish concept*

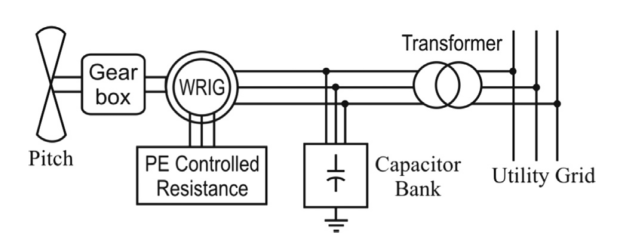
**Wound Rotor Induction Generator(WRIG)**

These type of generators are used for variable speed applications, thus there will be dynamic slip control[3].This control is applied by connecting electronically controlled resistor blocks to rotor of the generator. Slip denotes the relation between the rotor speed and synchronous speed and is given by the formula as follows,

where,

s is the slip  
  
Ns is synchronous speed  
  
Nr is rotor speed

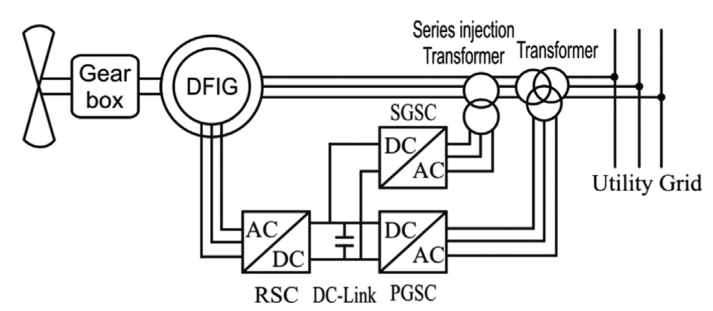
Also there exists shunt capacitors connected to line for compensation purposes.Typical WRIG schematic diagram with these capacitors is shown below.



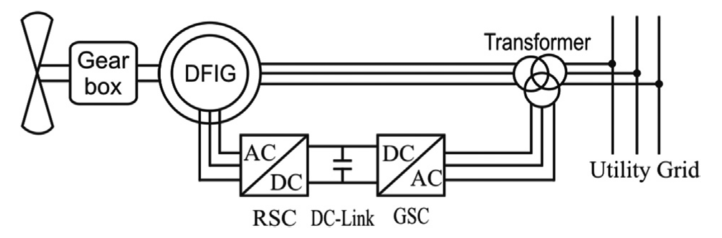
*WRIG schematic diagram*

**Doubly-fed Induction Generators(DFIG)**

Among these generator types, doubly-fed induction generator system with 3 stage gearbox (DFIG-3G) is the most common configuration at present [5]. Although it consists more complicated power electronic control, it can control active and reactive power flow from to control within supply side or rotor side. Stator is connected to grid via transformer while rotor connected to grid via power electronic converter blocks. Sometimes second PGSC(parallel grid side converter) is used parallel with dc-link in order to control unbalanced conditions better. This kind of configuration of DFIG is shown in figure below.

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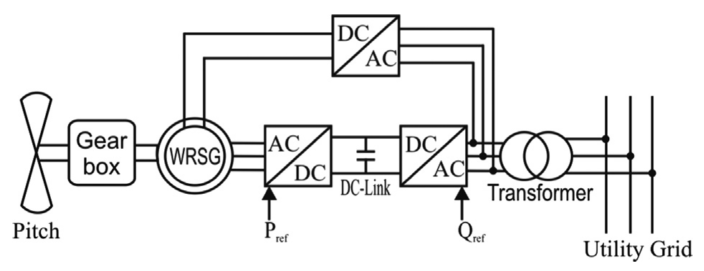
*DFIG configuration with double GSC*

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*Conventional grid connected DFIG*

**Wound rotor Synchronous Generators(WRSG)**

This type of SG can be operated with variable speed applications with suitable grid connected power electronic block and proper vector control algorithm. Schematic diagram of WRSG is given below. Additionally, this machine type has cost advantage since no PM exists for field.

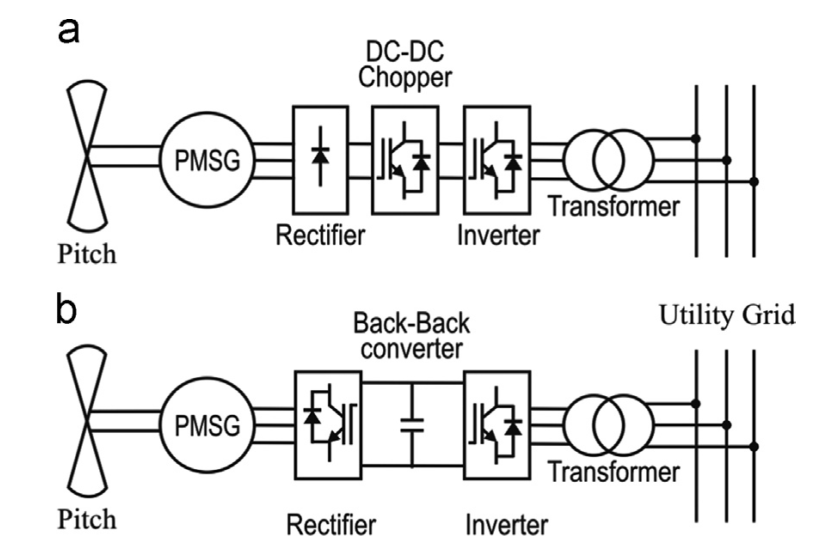
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*WRIG-Wound rotor Synchronous Generator grid connection*

**Permanent Magnet Synchronous Generators(PMSG)**

In this thesis work, Direct drive PMSG is chosen for the design. It becomes very popular especially for last decade because of its high energy yield, improved reliability, efficiency and low maintanence. Reliability can be increased by developing modular and fault tolerant PMSG. These days capacity of PMSG wind turbines increased up to 8 MW.

Conventional PMSG are connected to the grid via back-to-back converters as shown below in figures. This type of generator can be connected with diode front end system too.



*PMSG based WECs a)diode front end system b)back to back converter system*

1. **Flux Orientations in PM based systems**

One of the important options in design of the machine is magnetic flux path directions. Current technology in this topic can be classied as three main subgroups as follows:

* Radial flux (path of the magnetic flux is perpendicular to the direction of the rotor shaft)
* Axial flux (path of the magnetic flux is perpendicular to the radial direction of the rotor shaft)
* Transverse flux (path of the magnetic flux is perpendicular to the direction of the rotor rotation)

1. **Importance of modularity in WEC systems**

Modular construction of electrical machines aims to get easy assemble and disassemble operations during maintain and repair conditions. This concept also allows each module can work individually thus better fault-tolerance.By this modular structure technique, identical machines can be stacked in order to increase power output. These stacked generator sets can be grouped in parallel fashion, thus overall reliability of overall system increases. When large diameters and single bulky structure is considered, modular solutions for permanent magnet direct drive generator topologies become preferable.

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