# **CHAPTER 2**

# **REVIEW OF WIND ENERGY CONVERSION (WEC) SYSTEMS**

In previous chapter, background of wind energy conversion systems is introduced and related wind energy statistics are summarized and tabulated. 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 five main parts. In first part, wind turbine power equations and key parameters during the selection of system will be given and discussed. This data especially used in wind turbine investment calculations and wind potential estimation techniques. Then challenges in wind energy conversion systems will be introduced and common problems will be addressed. 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. Also in this last part, reasons for choosing direct drive axial flux permanent magnet concept will be explained.

## Power Equations and Parameters

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 which is a function of the tip speed ratio λ and the pitch angle β, is radius of the turbine blade and  is the wind velocity. 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%. 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 physical characteristics. Investigation of these values is out of scope of this thesis. 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 and *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. Although TSR calculations will not be actively utilized in this thesis work, this topic is very important because of the efficiency issues. If turbine blades revolves too slow then incoming air to the turbine is not used efficiently as natural result of Betz limit. If turbine blades revolves 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. 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 for a conventional three blade wind turbine system is given as 5~6 in [33].

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.

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. Time dependent nature of the wind determines the production scheme of the WECs. 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] :

(4)

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.

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 needed because of the probabilistic nature of wind. Weibull distribution and Rayleigh distributions are used to estimate and analyze wind speed distribution. IEC 61400 standard which is specialized for design requirements of wind turbine, mentions Rayleigh and Weibull distributions as most common distributions for wind profile [36].

## Challenges in WEC Systems

High torque, losses and efficiency, gearbox, modularity, redundancy, **to be continued and explained**

**…**



## 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. Thus, main approach in this part when describing their properties is based on whether they are induction or synchronous generators. 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.

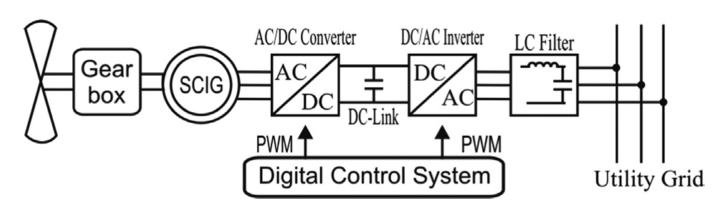
## Induction Generators

## Squirrel Cage Induction Generators (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.

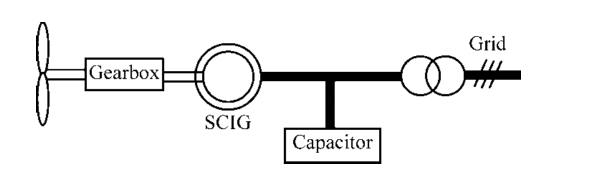
Capacitor banks and Static Synchronous Compensators(STATCOM) are commonly used for reactive power compensation with SCIGs. Additionally, STATCOMs used for active and reactive power flow control for variable speed applications of SCIGs.

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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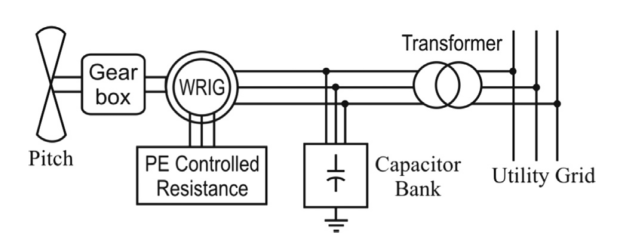
*SCIG with Danish concept*

## Wound Rotor Induction Generators (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

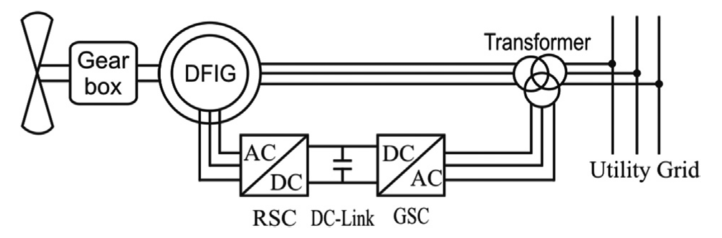
Also there exists shunt capacitors connected to line for compensation purposes.Typical WRIG schematic diagram with these capacitors is shown below.



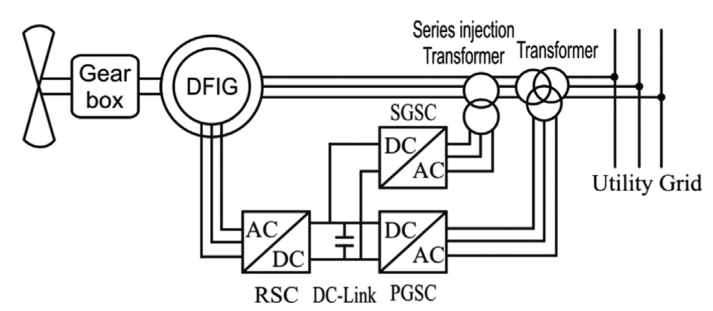
*WRIG schematic diagram*

## Doubly-fed Induction Generator(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. Both kind of configuration of DFIG is shown in figure below.

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*Conventional grid connected DFIG*

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*DFIG configuration with double GSC*

A commercial wind turbine Nordex N131/3600 is given figure below.

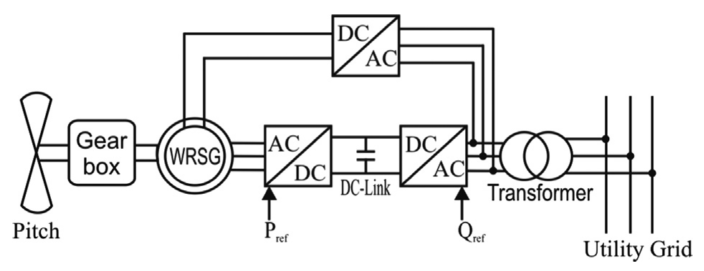


*NORDEX N131 [courtesy of NORDEX]*

## Synchronous Generators

## Wound Rotor Synchronous Generators

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.

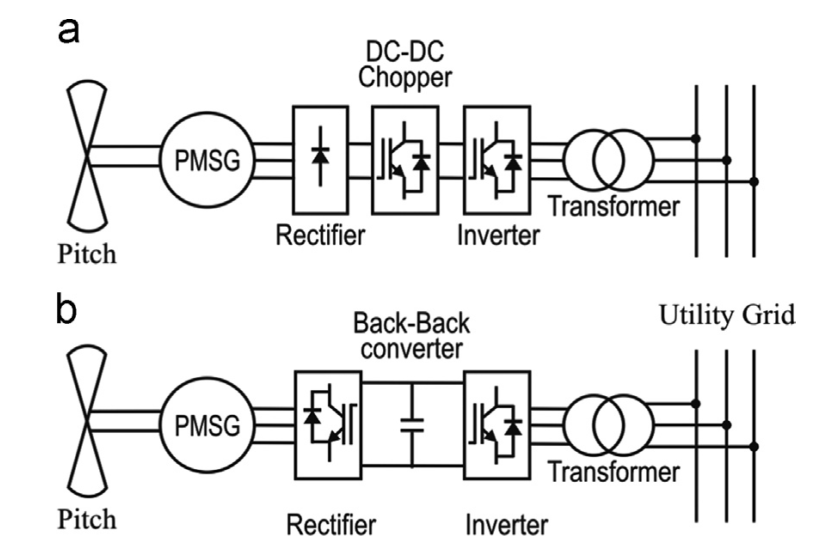
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*WRSG-Wound rotor Synchronous Generator grid connection*

## Permanent Magnet Synchronous Generators

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 also.



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

Vestas commercial 3.45 MW wind turbine with PMSG technology is given below.



## Flux Orientations in PM based Systems

## Importance of Modularity in WEC Systems and AFPM

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