**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 fist 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 :

where,

ρair is the mass density of air

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

r is the blade length

v 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.[25]

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  as follows,

Where

These coefficients shown above depends on the turbine characteristics.

**Tip Speed Ratio**

Tip speed ratio  (TSR) is defined as a ratio of tip speed of turbine blade to speed of the wind. This ratio is very useful when designing a wind turbine.

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 turn. 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 (Remember Betz limit!). If turbine blades turns too fast, blades act like a solid wall to the turbine and then efficiency decreases again.To avoid bad consequences(low efficiency, physical breakdown) of turbulence issue,choosing optimal TSR is really important.

Approximate optimal TSR’s for a system:

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

**Betz Limit**

Theoretically maximum 59% (theoretical maximal of Cp ) of energy carried by the wind can be extracted by a wind turbine. This result is concluded by German physicist Albert Betz. Generally imperfections and in blade manufacture reduces the actual energy yield of the turbine less than the useable energy.

**Weibull Distribution and other issues**

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[25] :

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[25],

this value is approximated as "1/7" in calculations.

One remote sensing tecnique of the wind profile is LIDAR(Light Detection and Ranging) which is based on Doppler Effect to determine wind characteristics. In another method, ANFIS(Adaptive Neuro-fuzzy interference system) based clustering algorithm is used to predict wind speed.

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

where,

v is the wind speed

k is the shape parameter

α is the scale parameter

Therefore energy yield over a period of time T can be defined as follows,

where, P is the generated power

f(v) is the Weibull function

T=8760 hours (1 year)

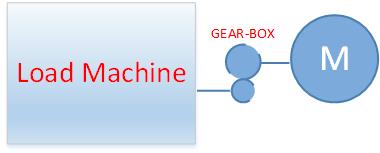
Minimum wind speed that is needed to start to rotate the turbines' blade is cut-in wind speed.

1. **Current Wind Turbine Systems**
2. **Mechanical Aspects**

Wind turbines can be categorized based on mechanical construction(or drivetrain) as “geared drive” and “direct drive”.

Geared Drive:

In this type of generator, turbine blades with hub structure connected to shaft of the generator via a gear-box,which incereases the speed speed of the generator. Gear ratio is a measure of relationship between output and input speeds of dynamic system. Drivetrain of a VSCF 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.

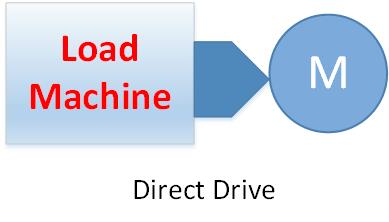


Direct Drive:

Main purposes of the Direct-drive(Ddrive) concept for wind turbines are;increasing energy yield,reducing gearbox failures and lower maintenence problems. There are two types of DD namely, rotational and linear direct drives. Due to tip speed limitation they are operating at low speeds which is a important advantage. But according to the formula:

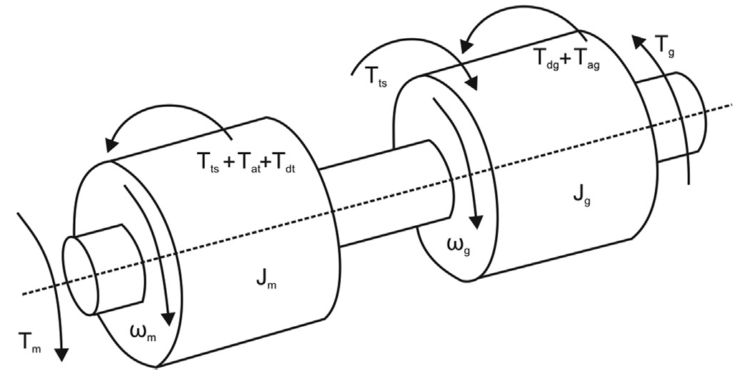
Torque must be increase inverse proportional to decrease of angular speed. To do that when scaling up the turbine sizes, amount of material is increased in order to maintain the air-gap against deflection forces between stator and rotor parts. This means DDrive machines are heavier than other types of machines. Torque/volume and torque/mass parameters are important during the design of the generator system. In some designs[2] ratio of axial lenght to airgap diameter, K is optimized.

More material also means extra cost which is big disadvantage for this type of generators.

**

**Drivetrain modelling**

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 analyze, two mass model is employed[3]. Two mass model of the drivetrain system is given as follows,



*2 mass model of the drivetrain*

**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],

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 stifness 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)

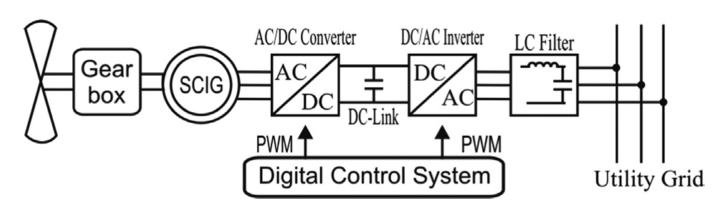
- Permanent Magnet Synchronous Generators(PMSG)

**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.

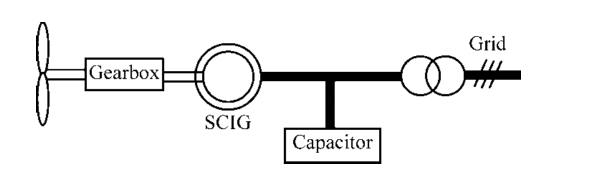
Capacitor banks and Static Synchronous Compensators(STATCOM) are commonly used for reactive power compensation with SCIGs. Additionally, STATCOMs used for active and reactive power flow control for variable speed applications of SCIGs.

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.

**

*SCIG with Danish concept*

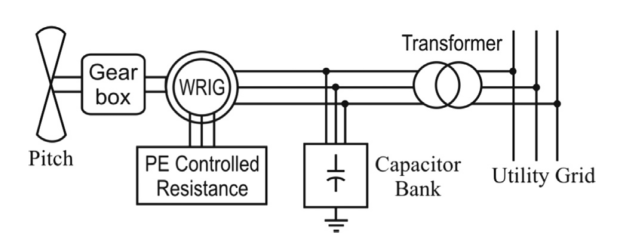
**Wound Rotor Induction Generator(WRIG)**

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

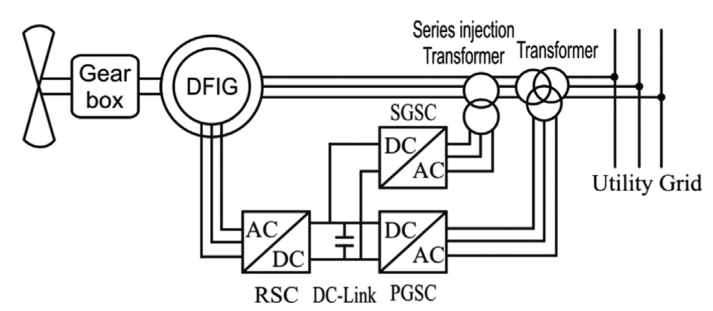
Also there exists shunt capacitors connected to line for compensation purposes.Typical WRIG schematic diagram with these capacitors is shown below.



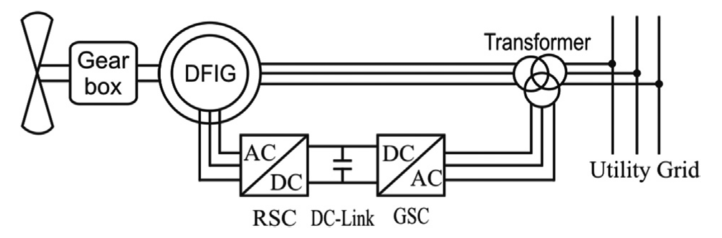
*WRIG schematic diagram*

**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.

****

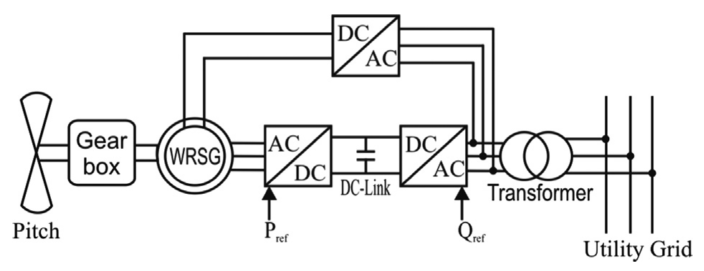
*DFIG configuration with double GSC*

****

*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.

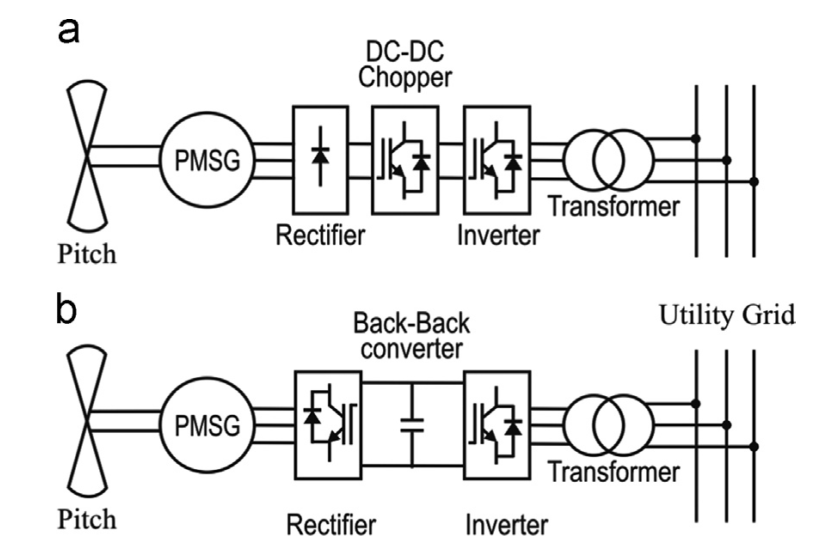
******

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

**References**

[1] Y. Xia, K. H. Ahmed and B. W. Williams, "Wind Turbine Power Coefficient Analysis of a New Maximum Power Point Tracking Technique," in IEEE Transactions on Industrial Electronics, vol. 60, no. 3, pp. 1122-1132, March 2013.

[2] S. Engström and S. Lindgren, “Design of NewGen direct-drive generator for demonstration in a 3.5 MW wind turbine”, EWEC (European Wind Energy Conference & Exhibition, Milan, Italy, May 7-10 2007.

[3] O. P. Mahela, A. G. Shaik, Renewable and Sustainable Energy Reviews 57, 260-281 (2016).

[4] R. Melício, V.M.F. Mendes, J.P.S. Catalão, Fractional-order control and simulation of wind energy systems with PMSG/full-power converter topology, Energy Conversion and Management, Volume 51, Issue 6, June 2010, Pages 1250-1258, ISSN 0196-8904, <http://dx.doi.org/10.1016/j.enconman.2009.12.036>.

[5] Xu Yang; Patterson, D.; Hudgins, J., "Permanent magnet generator design and control for large wind turbines," in Power Electronics and Machines in Wind Applications (PEMWA), 2012 IEEE , vol., no., pp.1-5, 16-18 July 2012.