1

AN OVERVIEW OF WIND FARM GENERATION TECHNOLOGIES

Dr Ian Chilvers

PBSI Limited

2

PRESENTATION OVERVIEW

- Electrical Generator Theory
- AC Synchronous Generators
- AC Asynchronous (Induction) Generators
- Wind Turbine Generator Theory
- Fixed Speed Wind Turbine
- Variable Speed Wind Turbine

PBSI Limited

3

PBSI LTD OVERVIEW

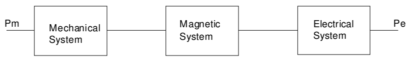
P&B TECHNICAL SERVICES	**Power system analysis consultants, generation connection studies, protection scheme design and settings, site audits and training**
P&B ENGINEERING	**Designers & Manufacturers of Motor & Feeder Integrated Protection, Control & Monitoring Systems.**
P&B POWER ENGINEERING	**Market Leaders in MV Circuit Breaker Retrofit with over 25 Fully Type Tested Designs. New MV Switchgear Design.**
P&B WEIR ELECTRICAL	**Designers & Manufacturers of Portable Earthing Equipment, Buchholz Relays & Electrical Instruments.**

PBSI Limited

4

THE ELECTRICAL GENERATOR

- Electromechanical energy conversion device

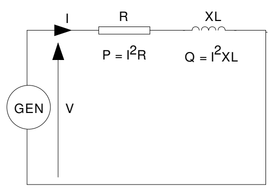


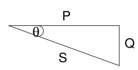
- Produces voltage at desired frequency within prescribed network limits
- Connection to an electrical network causes current to flow between generator and network
- Product of generated voltage and current gives power

PBSI Limited

5

ELECTRICAL POWER CONCEPTS 1



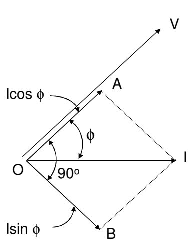


P = active (real) power
Q = reactive power
S = apparent power
θ = power factor angle

PBSI Limited

6

ELECTRICAL POWER CONCEPTS 2



Power = VI cos ϕ
= V x OI cos ϕ
= V x OA watts
(Active or Power component)

Power due to component OB
= V x OB cos 90^{o} = zero
OB = Reactive or Wattless component

Reactive Voltamperes (VARS)
= VI sin ϕ

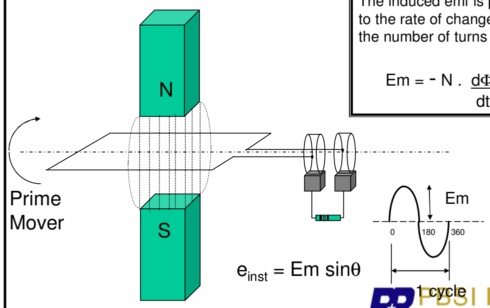
PBSI Limited

7

PRINCIPLE OF AC GENERATION

The induced emf is proportional to the rate of change of flux and the number of turns :

$$Em = - N \cdot \frac{d\Phi}{dt}$$



$e_{inst} = Em \sin\theta$

PBSI Limited

8

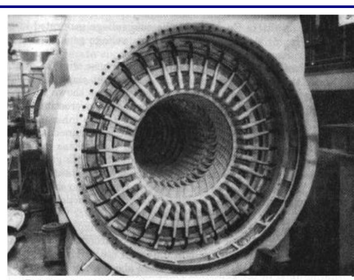
AC SYNCHRONOUS GENERATOR MAIN COMPONENTS

- STATOR: Fixed (stationary) consisting of a three phase armature winding with connection to electrical network
- ROTOR: Attached to prime mover shaft and free to rotate within hollow stator . Consists of a field winding which is energised from dc supply.
- EXCITER: Supply and control of dc power to field winding (GENERATOR EXCITATION). Maintains generator voltage within limits and source of reactive power.
- PRIME MOVER: Provides mechanical torque on shaft to turn rotor and source of electrical energy (active power)
- AIR GAP: Narrow air gap between rotor and stator provides path for magnetic coupling between field and armature windings

PBSI Limited

9

AC SYNCHRONOUS GENERATOR STATOR

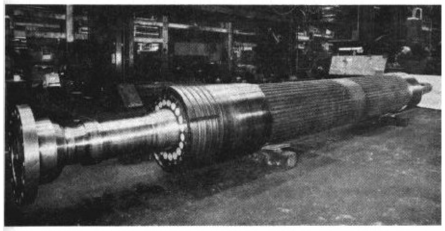


End view of the stator of a 26-kV 908-MVA 3600 r/min turbine generator with water-cooled windings. Hydraulic connections for coolant flow are provided for each winding end turn. (*General Electric Company.*)

PBSI Limited

10

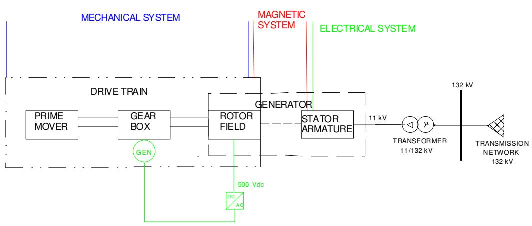
AC SYNCHRONOUS GENERATOR ROTOR



Rotor of a two-pole 3600 r/min turbine generator. (*Westinghouse Electric Corporation.*)

11

GENERATOR CONNECTED TO ELECTRICAL NETWORK



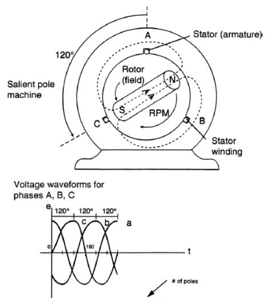
12

THEORY OF GENERATOR OPERATION: ARMATURE VOLTAGE INDUCTION

- Prime mover accelerates rotor to synchronous speed
- Rotating field winding is energised by external dc supply
- Magnetic flux set up in air gap rotating at speed of rotor. This moves relative to the fixed armature
- Voltage induced in each phase winding of armature [Faraday's basic law of electromagnetic induction]
- For parallel system, generator voltage is synchronised to network voltage and generator CB closed
- Frequency of generated voltage is proportional to speed of rotor magnetic flux (i.e. mechanical speed of rotor)

13

THEORY OF GENERATOR OPERATION: SYNCHRONOUS SPEED



Frequency (Hz) of generated voltage :-

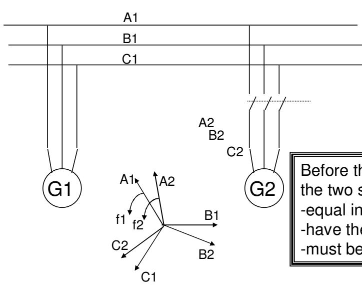
$$f = \frac{np}{60} \; *$$

* Where p=Number of pole pairs e.g. p=1 for a 2 pole machine. n=revs per minute

PBSI Limited

14

SYNCHRONISATION OF TWO GENERATING SOURCES



Before the switch can be closed the two sets of voltages must be:
-equal in magnitude
-have the same frequency
-must be in phase

PBSI Limited

15

THEORY OF GENERATOR OPERATION: ELECTRICAL POWER

- Mechanical power (torque) increased causing rotor to speed up
- Current flows into electrical network from generator armature. Current produces additional magnetic flux in air gap
- New flux in air gap caused an electrical torque to be produced which counteracts input mechanical torque [Ampere-Biort-Savart Law and Lenzes Law]
- Electrical torque slows rotor down restoring it to its synchronous speed
- SYNCHRONOUS GENERATOR IS A CONSTANT SPEED MACHINE

PBSI Limited

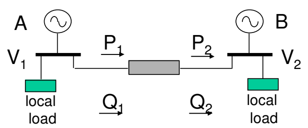
16

CONTROL OF POWER AND FREQUENCY

- If output exceeds demand :
  - machines speed & frequency rise.
- If demand exceeds output:
  - machines speed & frequency drop.
- Hence frequency is <u>not a constant</u> but varies continuously (usually too small to be noticed)
- If TOTAL generation cannot meet demand & drop in frequency > 1Hz then power station pumps , fans etc. may reduce station output & give a serious situation.Voltage must then be reduced , possibly followed by load shedding until frequency starts to rise.
- A complete loss of load can lead to OVERSPEEDING with risk of drastic mechanical breakdown.Special cut-off valves are usually provided to prevent this.

17

CONTROL OF VOLTAGE AND REACTIVE POWER



P=active Power (WATTS)
Q=reactive Power (VARS)

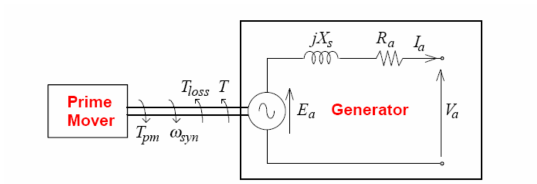
X>>R

Flow of Active Power P depends on transmission angle
Flow of Reactive Power depends on voltage difference V_1 - V_2

- Can reverse the direction of reactive power by varying excitation such that $V_2 > V_1$.
- Can send Power from A to B or from B to A by adjusting amount of fuel to turbine.
- Active Power & Reactive Power are largely independent of each other.
- An over-excited machine generates VAR's
- An under-excited machine absorbs VAR's i.e. generates negative or leading VAR's.
- Can inject Q at a busbar to raise the voltage.e.g. shunt capacitor.

18

SYNCHRONOUS GENERATOR EQUIVALENT CIRCUIT



19

SYNCHRONOUS GENERATOR SUMMARY

- Constant speed machine (synchronous!!)
- Excitation produced by external dc supply
- Produces active and reactive power
  - Active power – useful energy
  - Reactive power – magnetisation energy
- Operates in parallel mode, but must be synchronised with electrical network voltage
- Operates in isolated mode, synchronisation is not an issue

PBSI Limited

20

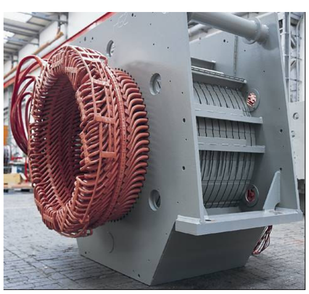
AC ASYNCHRONOUS (INDUCTION) GENERATOR MAIN COMPONENTS

- STATOR: Fixed (stationary) consisting of a three phase armature winding with connection to electrical network
- ROTOR: Attached to prime mover shaft and free to rotate within hollow stator . Typically consists of a cage rotor which forms a pseudo field winding
- EXCITATION: The machine is excited by the armature supply. There is no separate dc power supply required. Reactive power is drawn from the electrical network to provide this. Induction generator cannot produce reactive power
- PRIME MOVER: Provides mechanical torque on shaft to turn rotor and source of electrical energy (active power)
- AIR GAP: Narrow air gap between rotor and stator provides path for magnetic coupling between field and armature windings

PBSI Limited

21

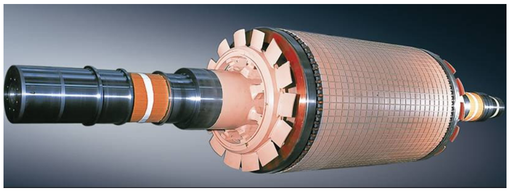
AC ASYNCHRONOUS (INDUCTION) GENERATOR STATOR



PBSI Limited

22

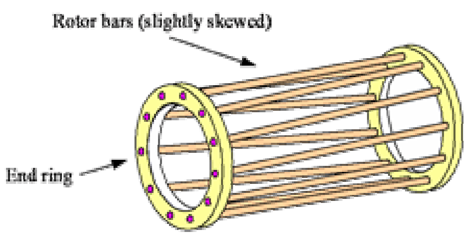
AC ASYNCHRONOUS (INDUCTION) GENERATOR ROTOR 1



PBSI Limited

23

AC ASYNCHRONOUS (INDUCTION) GENERATOR ROTOR 2



PBSI Limited

24

AC ASYNCHRONOUS (INDUCTION) THEORY OF OPERATION

- Stator winding connected to external electrical network
- Voltage across stator winding causes magnetisation current to flow setting up rotating magnetic flux (synchronous speed) in air gap
- Magnetic flux induces a voltage across the bars of the cage rotor [Faraday's basic law of electromagnetic induction]
- Current flows in cage rotor as bars are short circuited by end ring. This produces additional rotating flux in air gap.
- Cage rotor flux rotates at the slip speed
  - Slip = (Ns – Nr) / Ns
- Nr > Ns then machine operates as generator and exports active power to system. Reactive power is imported from system

PBSI Limited

25

AC ASYNCHRONOUS (INDUCTION) GENERATOR STARTING

- Stator winding connected to external electrical network
- Voltage across stator winding causes magnetisation current to flow setting up rotating magnetic flux (synchronous speed) in air gap
- Magnetic flux induces a voltage across the bars of the cage rotor [Faraday's basic law of electromagnetic induction]
- Current flows in cage rotor as bars are short circuited by end ring. This produces additional rotating flux in air gap.
- Cage rotor flux rotates at the slip speed
  - Slip = (Ns – Nr) / Ns
- Nr > Ns then machine operates as generator and exports active power to system. Reactive power is imported from system

PBSI Limited

26

AC ASYNCHRONOUS (INDUCTION) GENERATOR SUMMARY

- Generator operates at speed greater than synchronous speed (slip speed)
- Excitation produced by stator network connection
- External dc supply and exciter not required
- Produces active power only
- Reactive power for excitation is taken from stator network connection. GENERATOR CANNOT PRODUCE REACTIVE POWER OR PROVIDE VOLTAGE CONTROL
- Operates in parallel mode, but does not have to be synchronised with electrical network voltage
- Cannot operate in isolated mode, as no excitation power supply

PBSI Limited

27

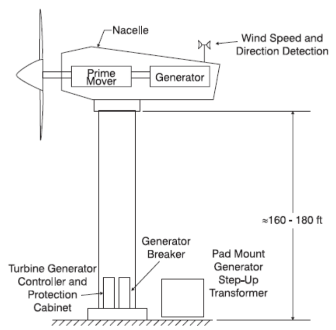
WIND TURBINE GENERATORS

- Fixed Speed Machines
  - Asynchronous (cage rotor induction generator) connected directly to grid
- Variable Speed Machines
  - Asynchronous (wound rotor induction generator). Stator is connected directly to grid. Rotor is connected to grid via converter.
  - Synchronous generator connected to grid via converter.

PBSI Limited

28

WIND TURBINE GENERATORS TYPICAL ARRANGEMENT

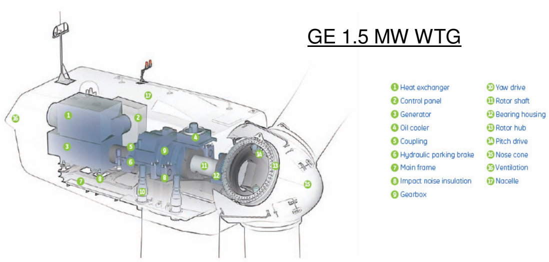


PBSI Limited

29

WIND TURBINE GENERATOR NACELLE

GE 1.5 MW WTG



PBSI Limited

30

WIND TURBINE THEORY 1

- Kinetic energy extracted from the wind as it passes through the rotor blades
- Developed power :-

$$P = C_p \rho V^3 A / 2$$

C_p = power coefficient

P = power (W)

V = wind velocity (m/s)

A = swept area of rotor disc (m^2)

ρ = density of air (1.225 kgm^{-3})

PBSI Limited

31

WIND TURBINE THEORY 2

- Available developed power in air is not all extracted by the wind turbine
- Power co-effiecient Cp is a measure of how much of the wind energy is extracted by the turbine
- Cp is proportional to relative speed of rotor and wind (tip – speed ratio) and blade pitch angle . Maximum value approx. 0.4 (Betz limit!)

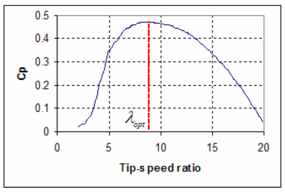
$\lambda = \omega_r r / \upsilon$

λ = tip speed ratio
ω_r = aerodynamic rotor speed
r = radius of rotor
υ = wind velocity

PBSI Limited

32

WIND TURBINE THEORY 3



$\lambda = \omega_r r / \upsilon$

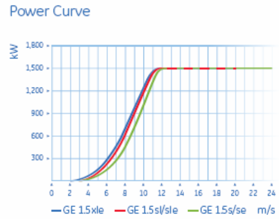
λ = tip speed ratio
ω_r = aerodynamic rotor speed
r = radius of rotor
υ = wind velocity

- For a given rotor and wind speed (rotor radius is fixed): Cp will be maximum (Aerofoil Theory)

PBSI Limited

33

WIND TURBINE GENERATOR POWER CURVE



GE 1.5 MW WTG

Operating data

- Rated capacity: 1,500 kW
- Cut-in wind speed: 4 m/s
- Cut-out wind speed (10 min. avg.): 25 m/s
- Rated wind speed: 13 m/s
- Wind Class - IEC: IIa
- Wind Class - DIBt WZ: II/III

Rotor

- Number of rotor blades: 3
- Rotor diameter: 70,5 m
- Swept area: 3904 m²
- Rotor speed (variable): 12,0 – 22,2 rpm

Tower

- Hub heights - IEC: 64,7 m

PBSI Limited

34

WIND TURBINE GENERATORS

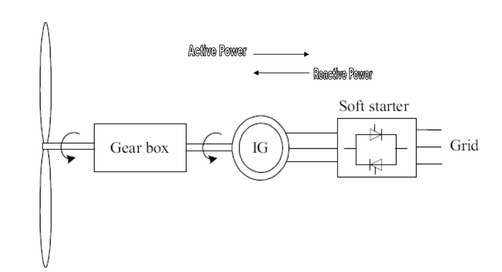
- Fixed Speed Machines
  - Asynchronous (cage rotor induction generator) connected directly to grid
- Variable Speed Machines
  - Asynchronous (wound rotor induction generator). Stator is connected directly to grid. Rotor is connected to grid via converter.
  - Synchronous generator connected to grid via converter.

PBSI Limited

35

FIXED SPEED WIND TURBINE GENERATORS 1

- Asynchronous (cage rotor induction generator) connected directly to grid



ted

36

FIXED SPEED WIND TURBINE GENERATORS 2

- Speed of Generator locked to frequency of grid
  - Nr = (60*f) / p   where f = 50 Hz
  - Gear box required
- Deviation in wind speed has little impact on turbine speed. Mechanical torque deviates varying electrical output power (NOT IDEAL!)
- Machine only export active power (difficult to control as proportional to wind speed). Power / frequency control not possible
- Machine imports reactive power only from grid (NOT IDEAL). V or Q control not possible
- Machine must be started by soft starter to minimise starting inrush current

PBSI Limited

37

FIXED SPEED WIND TURBINE GENERATORS 3

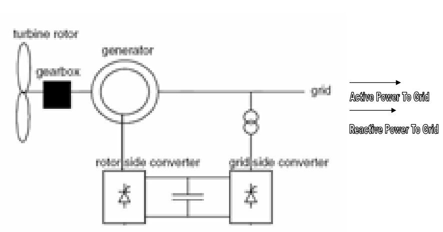
- WTG cut out works by STALL REGULATION
- “Angle of Attack” angle at which wind hits blade
  - Wind speed increases, then at certain angle the airflow will no longer follow the blade.
  - Turbulence produced causing Cp to reduce
  - At certain wind speed angle of attack reaches value where stall occurs
  - This is cut out wind speed, WTG does not generate and is closed down to prevent damage to turbine
- For STALL REGULATION no active blade pitch control system is required

PBSI Limited

38

VARIABLE SPEED WIND TURBINE GENERATORS 1

- Asynchronous (wound rotor induction generator). Stator is connected directly to grid. Rotor is connected to grid via converter.



PBSI Limited

39

VARIABLE SPEED WIND TURBINE GENERATORS 2

- Asynchronous (wound rotor induction generator). Stator is connected directly to grid. Rotor is connected to grid via converter.
- Converter decouples rotor speed and grid frequency. This allows rotor to operate at variable speeds without impacting on grid frequency
- Variable wind speed operation can lead to a fixed tip-speed ratio
- Optimum tip-speed ratio gives maximum developed power by WTG (Cp is maximum)
- WTG control schemes designed to vary rotor speed relative to wind speed.

$$\lambda = \omega_r r/v$$

PBSI Limited

40

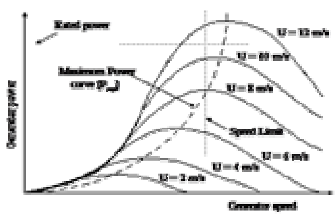
VARIABLE SPEED WIND TURBINE GENERATORS 3

- Rotor variable speed operation is achieved by injecting a voltage into the machine rotor winding
- DFIG machine acts like a synchronous generator which gives
  - Frequency or active power control
  - Voltage or reactive power control
- Fixed speed machine gives constant active power export and reactive power import only
- UK grid code calls for large wind farms to provide frequency and voltage control
- WTG technology is now largely DFIG machines in order to meet requirements of grid code

PBSI Limited

41

VARIABLE SPEED WIND TURBINE GENERATORS 4

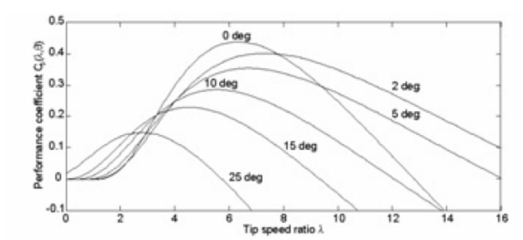


Curve of generator maximum power versus rotor and wind speed (tip speed ratio)

PBSI Limited

42

VARIABLE SPEED WIND TURBINE GENERATORS 5



Variation in power coefficient Cp with tip speed ratio and blade pitch angle

PBSI Limited

43

VARIABLE SPEED WIND TURBINE GENERATORS 6

- DFIG Control Philosophy
  - At low to medium wind speeds on power curve variable speed control is obtained by injecting voltage into machine rotor winding (synchronous generator operation). Constant Cp
  - At higher speeds pitch regulation is utilised. The blades are rotated about their axis to limit the power developed. The angle of attack is increased until the airflow does not flow along the blade.
  - Pitch control is achieved used either hydraulic or electric actuators
  - For very high wind speeds pitch control will operate until the cut out speed is reached

PBSI Limited

44

CONFIGURATION AND OPERATION OF OFFSHORE WIND TURBINE ELECTRICAL SYSTEMS

Dr Ian Chilvers

PBSI Limited

45

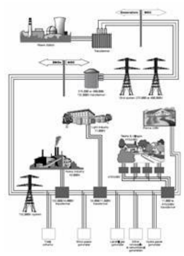
PRESENTATION OVERVIEW

- Overview of UK Power System
- Offshore wind farm configurations
- Wind farm electrical system design
- Electrical power system studies for wind farm design

PBSI Limited

46

UK POWER SYSTEM SHOWING WIND FARM CONNECTION



PBSI Limited

47

OFFSHORE WIND FARM SUPPLY CONFIGURATION OPTIONS

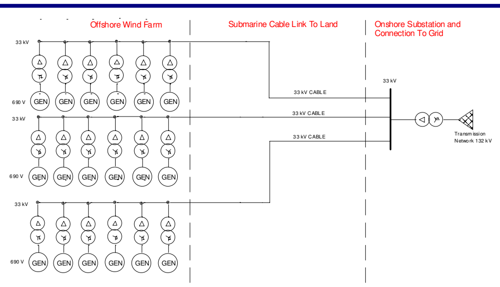
The supply connection type dictates the wind farm configuration and design :-

- Supply Type 1: Multiple High Voltage (HV) AC Cables
- Supply Type 2: Single Extra High Voltage (EHV) AC Cable
- Supply Type 3: High Voltage Direct Current (HVDC) System

PBSI Limited

48

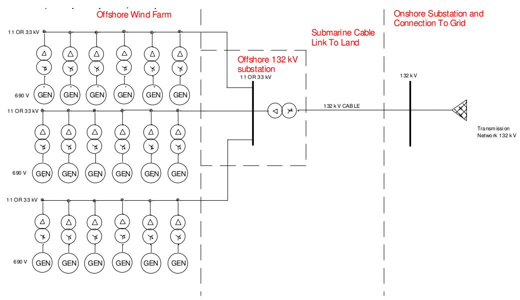
WIND FARM CONFIGURATION 1



PBSI Limited

49

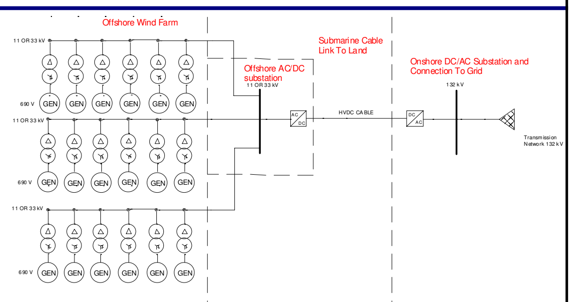
WIND FARM CONFIGURATION 2



PBSI Limited

50

WIND FARM CONFIGURATION 3



PBSI Limited

51

OFFSHORE WIND FARM ELECTRICAL SYSTEM DESIGN

Final wind farm configuration dependent on the following factors :-

- Wind farm rating
- Wind turbine generator type and rating
- Design of array electrical system
- Connection to onshore

Other factors to consider :-

- Overview of computer based power system studies
- Control systems
- Communication systems

PBSI Limited

52

WIND FARM RATING

- Wind farm rating IMPACTS on overall design
- Existing offshore wind farms
  - Blythe, Northumberland (4 MW – 2 * 2 MW)
  - North Hoyle, North Wales (60 MW – 30 * 2 MW)
  - Scroby Sands, Norfolk (60 MW – 30 * 2 MW)
  - Horns Rev, Denmark (160 MW, 80 * 2 MW)

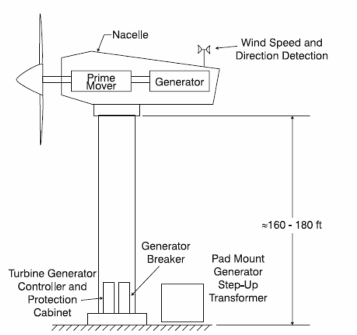
- Future off shore GW range
  - Great Gabbard, Suffolk (500 MW – 140 turbines)
  - Horns Rev area up to 1.8 GW

- Wind farm growth: kW to MW to GW

PBSI Limited

53

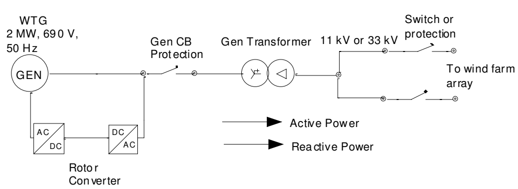
WIND TURBINE GENERATOR TYPE AND RATING 1



PBSI Limited

54

WIND TURBINE GENERATOR TYPE AND RATING 2



PBSI Limited

55

ELECTRICAL SYSTEM FOR ARRAY

- OBJECTIVE
  Number of collector circuits
  Number of turbines per collector circuit
- Rated voltage of collector circuit
  - 33 kV circuit (25 – 30 MW array)
  - 11 kV circuit (Up to 10 MW array)
  - Turbine tower design
- Wind farm configuration
  - Type1: No offshore substation (33 kV to shore)
  - Type 2: Offshore substation (33 kV or 11 kV)
- Collector circuit cable sizing
- Redundancy
- Overall cost benefit analysis

PBSI Limited

56

ELECTRICAL CONNECTION TO SHORE

- OBJECTIVE
  Requirement for offshore substation
  Voltage and number of circuits back to shore
- Total wind farm rating dictates power export to shore
  - 33 kV circuit: 25 – 30 MW per circuit
  - 132 kV circuit: 350 – 450 MW
- Offshore substation design
- Cable sizing
- Redundancy
- Grid interface
- Communication and control links to shore
- Overall cost benefit analysis

PBSI Limited

57

OFFSHORE SUBSTATION DESIGN 1

EXAMPLE: HORNS REV OFFSHORE SUBSTATION

- 33 kV / 150 kV substation
- Platform rests on three legs, 20*28m, 1200 tonnes, 14m above sea level
- Idea based on oil platform, however :-
  - Oil platform max voltage 11 or 13.8 kV
  - EHV cables do not enter/ leave platforms
- Main electrical power equipment :-
  - 150 kV switchgear
  - 33 kV switchgear
  - 33 / 150 kV transformer
  - 33 kV and 150 kV cables

PBSI Limited

58

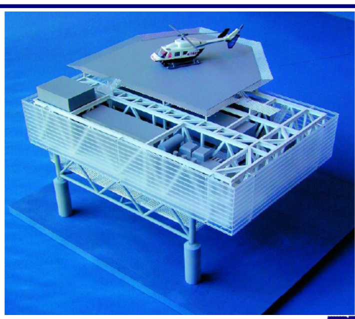
OFFSHORE SUBSTATION DESIGN 2

EXAMPLE: HORNS REV OFFSHORE SUBSTATION

- Back up emergency diesel generator and fuel supplies
  - Electrical substation control systems
  - Wind farm essential equipment such as climate control, safety, control and shutdown systems
- Communication and control systems
  - SCADA
  - UPSs
  - Radio / fibre optic links

59

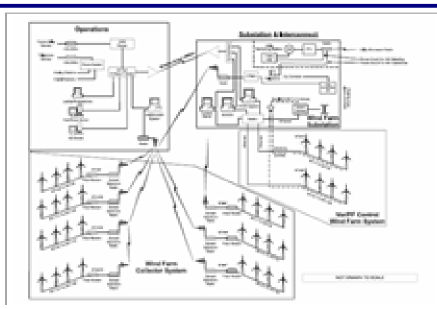
OFFSHORE SUBSTATION DESIGN 3



Model of Horns Rev Platform

60

COMMUNICATION AND CONTROL



61

POWER SYSTEM STUDIES TO SUPPORT WIND FARM DESIGN 1

- Power Flows
  - Continuous rating of electrical equipment
  - Voltage control strategies
  - Capacitor bank connection
  - Power factor studies
- Fault Analysis
  - Classical / G74 / IEC 60909 / IEC 61363
  - Rotating machine contribution
  - Electrical equipment short circuit rating
  - Fault current for protection relay setting

PBSI Limited

62

POWER SYSTEM STUDIES TO SUPPORT WIND FARM DESIGN 2

- Protection Scheme Design
  - Electrical system protection philosophy
  - Protection relay specification
  - Relay graphical co-ordination
    - Time current curves
    - Impedance diagram
    - Differential relay current diagram
  - Relay settings
  - Site commissioning and technical assistance

PBSI Limited

63

POWER SYSTEM STUDIES TO SUPPORT WIND FARM DESIGN 3

- Transient Based Studies
  - Electrical machine stability
    - Synchronous machine rotor angle
    - Induction machine voltage magnitude
  - Generator starting
  - System impact of transformer inrush
  - Overvoltage studies (surge arrestor application)
    - Generator switching
    - Faults on unearthed / peterson coil systems
    - Line / long cable energisation

PBSI Limited

64

POWER SYSTEM STUDIES TO SUPPORT WIND FARM DESIGN 4

- Power Quality
  - Impact on electrical equipment which is sensitive to variation in voltage magnitude, phase and frequency
  - Generator power converters, computer based control systems
  - Wind farms impact on power quality
- Problems for wind farm generators
  - Voltage sag (decrease in voltage 0.1 to 0.9 pu for < 1 min).
    - Caused by faults on electrical network
    - Generators overspeed leading to instability and tripping
  - Voltage swells – overvoltages produced during faults and circuit breaker switching
  - Harmonic distortion (non linear loads inject current at multiples of fundamental frequency)
    - Causes voltage distortion which can damage electrical insulation
    - Can overload electrical generators causing tripping by protection

PBSI Limited

65

POWER SYSTEM STUDIES TO SUPPORT WIND FARM DESIGN 5

- Problems introduced by wind farm generators
  - Voltage flicker
    - Dynamic change in voltage causing low frequency voltage variations
    - Based on variation in incandescent lamp brightness which can annoy the human eye
    - Generator power variations caused by wind turbulence and tower shadow
    - Periodic power pulsations produced at frequency which the blades pass the tower (~ 1 Hz)
    - Oscillations also caused by turbine mechanical dynamics (few Hz)
  - Harmonic current injection
  - Unbalance currents
  - Increase in system fault levels

PBSI Limited