Renewable Distributed Generation

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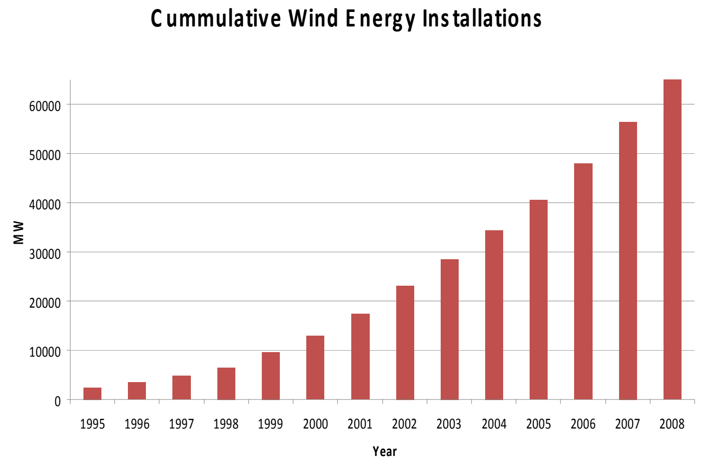
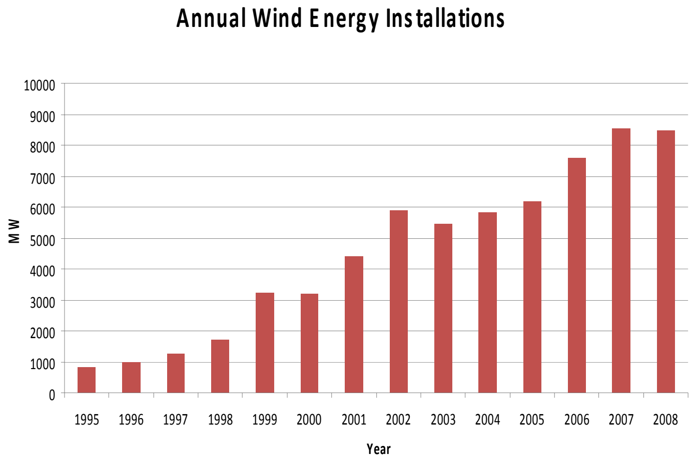
Background

- There is widespread consensus that burning fossil fuels at the current rate is having adverse consequences on the global climate on a scale that poses a threat to many regions of the world
- A large reduction in greenhouse gas emissions seems not only desirable but essential in order to reign-in global warming – Indeed, a recent UK Government document estimates that a 60-80% cut in emissions will be necessary by 2050
- This is one of the greatest challenges facing mankind because environmental wellbeing and economic growth are heavily inter-linked. However, some countries are already taken steps towards adopting a, so-called, low-carbon economy
- Some energy sectors are more amenable to becoming low-carbon than others, with the electricity sector leading the pack, followed by surface and air transport and domestic heating

Background

- Cost-effective, low-carbon electricity generation sources, together with effective demand-side and energy saving measures are seen as pre-conditions for a low-carbon electric energy sector
- Growth in wind generation continues to outstrip all other forms of renewable generation, driven, not only by concerns over climate change and energy diversity, but also by technological break-through in equipment and methods and a better understanding of the wind resource
- Wind farm projects in either the construction or the planning stages are at an all time high, particularly in Europe and the USA. These projects include both off-shore and on-shore wind farms where individual wind turbines are in the range of 5-7.5 MW


Cummulative Wind Energy Installations


Annual Wind Energy Installations

Renewable Generation Sources

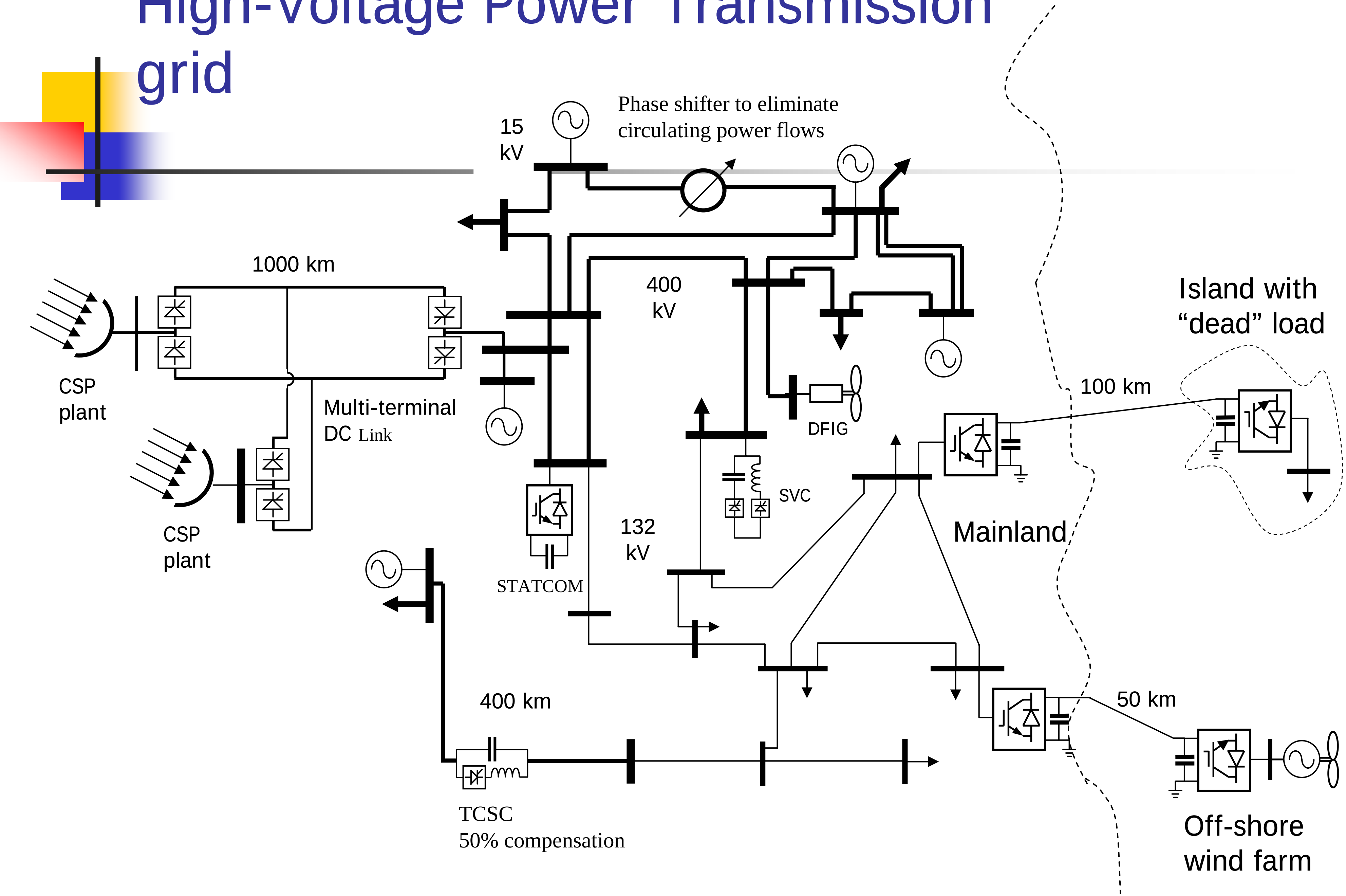
Renewable Generation Sources

- Hydro-electric power plants
- Wind power plants
- Wave power plants
- Thermo-solar power pants
- Photo-voltaic power plants
- Power plants with fuel cells
- Biomass-powered micro-plants
- Energy scavenging trees



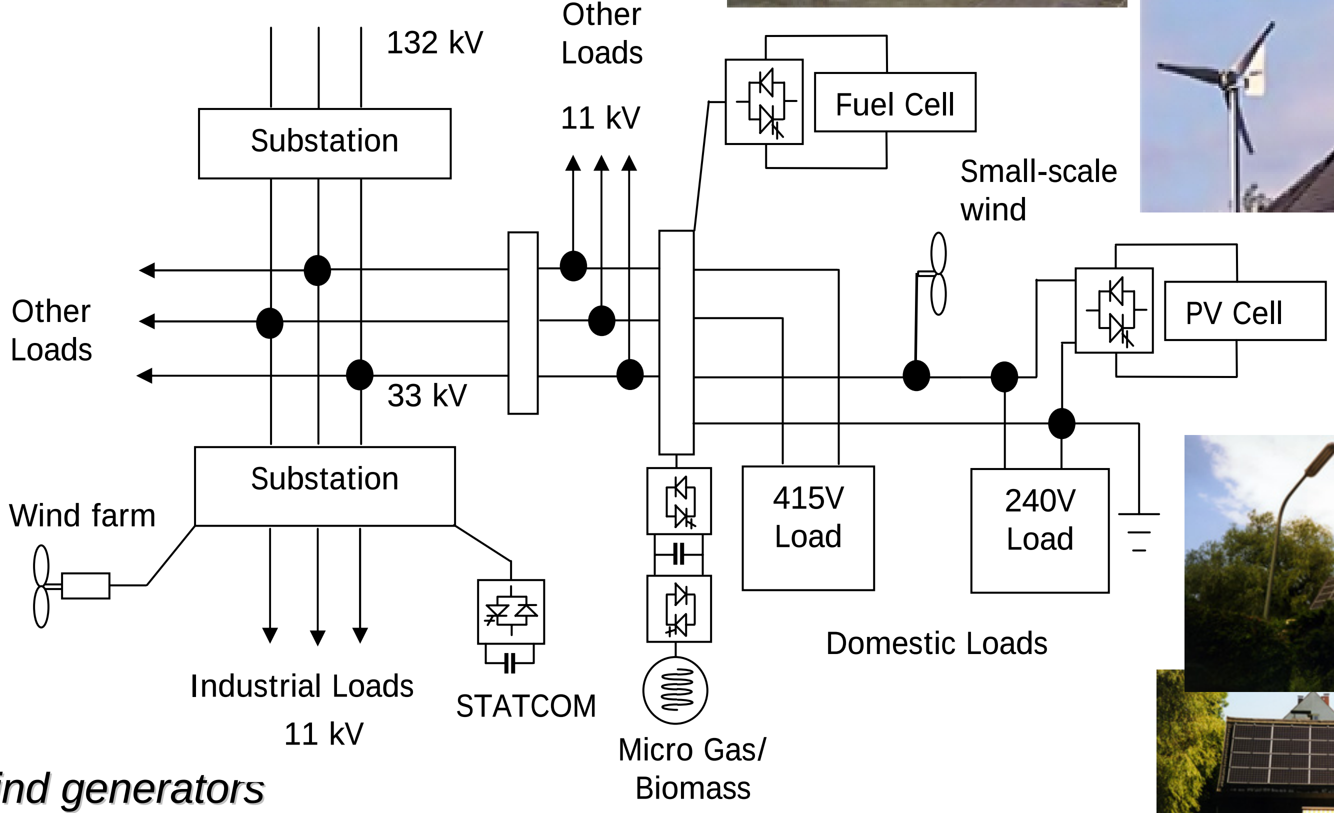



High-Voltage Power Transmission grid



Low Voltage Distribution Networks

Fuel cells use hydrogen as primary energy resource



On-shore wind farm using fixed-speed wind turbines

Wind generators use the wind as primary energy resource

Photo-voltaic cells use the sun energy as primary energy resource

Wind Generation Development

- In recent years, the trend has moved from wind farms containing a few dozens of wind turbines to the planning of wind farms with more than hundreds of megawatts of capacity, to rival large conventional power stations - this increased penetration of wind makes the power grid more dependent on, and vulnerable to, the varying wind resource

Wind Generation Development

- Most machines are built for electricity production linked to a grid but they also find application in autonomous systems

- Machines are manufactured in a wide range of capacities, up to the megawatt level. The figure opposite shows 6 MW rated machine:

  - rotor diameters of 126 m

  - tower heights of 135 m

- Contemporary wind turbine technology is variable-speed to comply with Grid Code connection requirements and a reduction in mechanical load

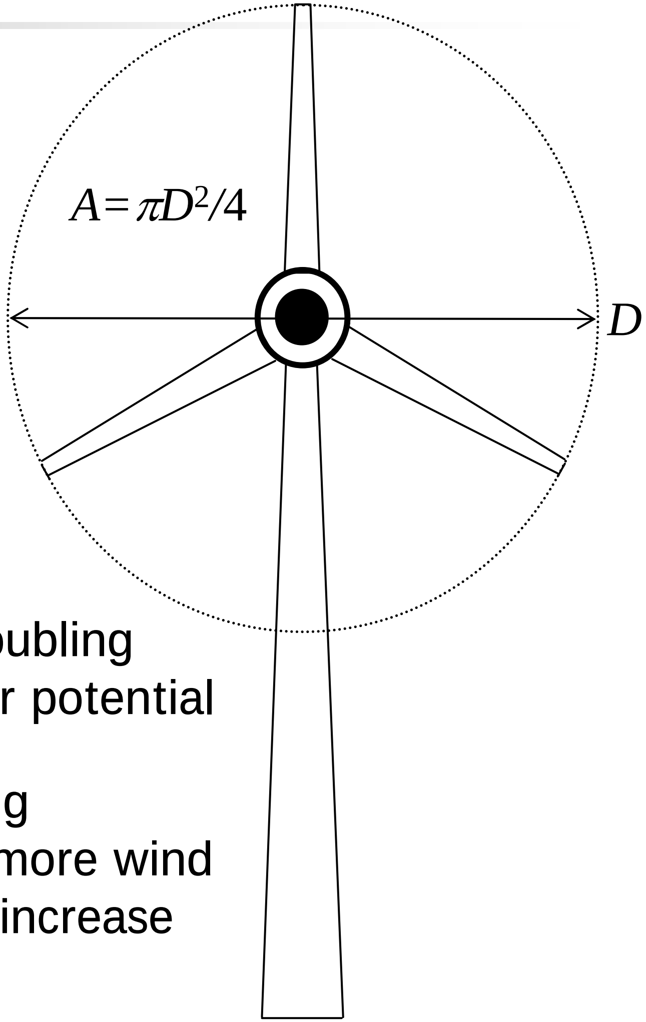
Power from the Wind

- A wind turbine of cross-section A, intercepting a wind front travelling at a speed u_0 and density ρ will produce power given by

$$P_T = \frac{1}{2} C_P A \rho u_0^3$$

where C_P is an efficiency factor termed power coefficient which varies with speed for individual machines

- Doubling A may yield twice the amount of power, doubling the wind speed would produce eight times the power potential
- This fact has an important bearing when investigating locations for a wind turbine. A location having 10% more wind resource than a second location, would yield a 33% increase in potential wind resource, i.e., $1.1 \times 1.1 \times 1.1 = 1.33$



Wind Generators

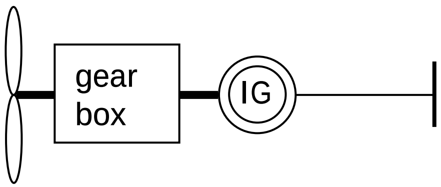
- In wind generation applications, other than micro-wind schemes, mechanical energy is converted in to electrical energy, using three-phase electrical generators. The most popular schemes are the following:

electrical coupling mechanical coupling

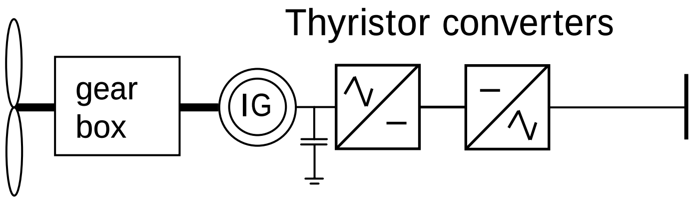
$$
\left\{
\begin{array}{l}
\text{induction generators}\left\{\begin{array}{l}\text{direct grid coupling}\\ \text{full inverter coupling}\\ \text{partial inverter coupling}\end{array}\right\}\text{gear box coupling}\\[3ex]
\text{synchronous generators}\left\{\begin{array}{l}\left.\begin{array}{l}\text{direct grid coupling}\\ \text{full inverter coupling}\end{array}\right\}\text{gear box coupling}\\ \left.\text{full inverter coupling}\right\}\text{direct coupling (no gear box)}\end{array}\right.
\end{array}
\right.
$$

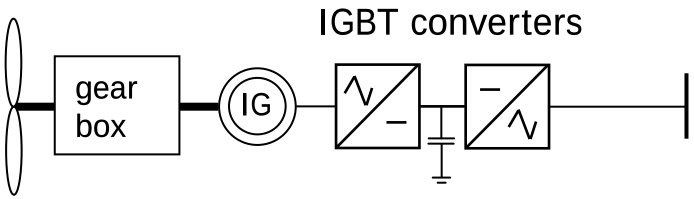
Wind Generators

Squirrel-cage induction machines

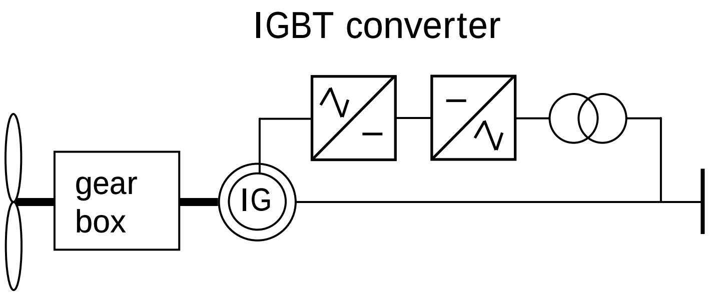


Fixed speed or dual speed by pole-number control





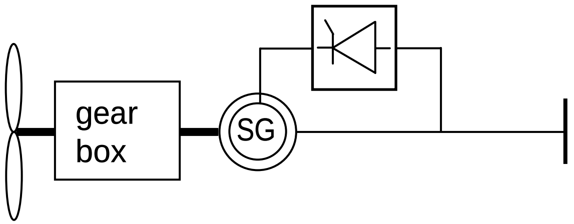
Double-fed induction machines

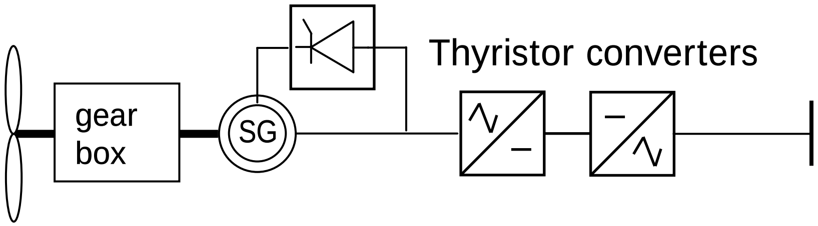


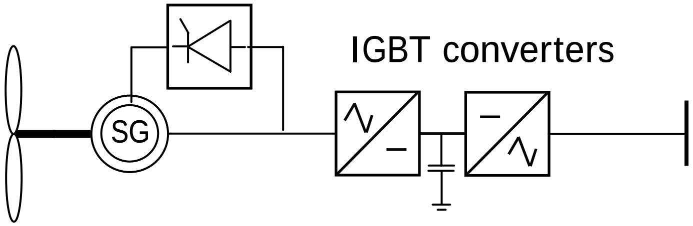
Variable speed by power electronic control, with double-fed machines requiring a smaller converter feeding the rotor, possibly half the size of one of the fully-rated converters used for stator connection to the grid

Wind Generators

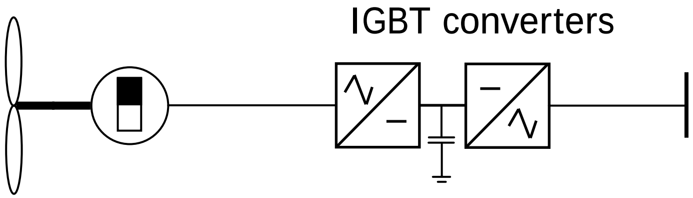
Synchronous machines with excitation system







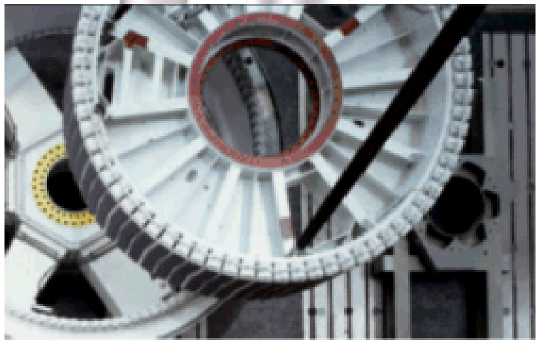
Permanent magnet machines



In direct drive generation, larger machines are necessary since they are rotating at the speed of the turbine. This will be in the region of 10-20 rpm for a large turbine. The pole number is high. They are axially short but radially quite large – several meters in diameter for a megawatt machine.

Wind Generators

- The two variable-speed configurations available are the DFIG wind turbine and the Fully Rated Converter wind turbine
- DFIG wind turbines use induction machines with high controllability, running at super-synchronous speed; a low-speed shaft and a high-speed shaft linked by a gear-box; and a half-rated power converter
- FRC wind turbines use multi-pole synchronous generators of short axial length and long radial length; one low-speed shaft for direct connection with the wind prime-mover - no gear box is used; a fully rated back-to-back HVDC link for connection with the grid



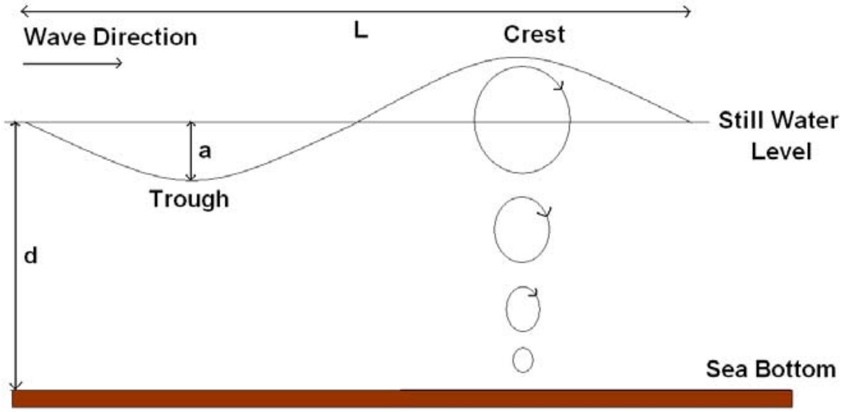
Power from the Waves

- In general, the energy contained in a sea wave is a function of the square of its height ($2a=H$), its length (L), its speed ($\omega=2\pi f= 2\pi/T$) and the water density (ρ):

$$L = \frac{g}{2\pi f^2} \quad (\mathrm{m})$$

$$P_w = \frac{1}{32\pi} \cdot g^2 \rho T H^2 \quad (\mathrm{W/m})$$

where $\rho=1025\ \mathrm{kg/m^3}$ and $g=9.81\ \mathrm{m/s^2}$



Waves with $d/L>0.5$ are referred to as deep water waves

- It is argued that in good wave locations, such as in parts of the Atlantic Ocean, where waves of wavelength of 100 m and amplitudes of 1.5 m can generate powers of 73 kW/m – source: J. Twidell and T. Weir, Renewable Energy Resources

Power from the Waves

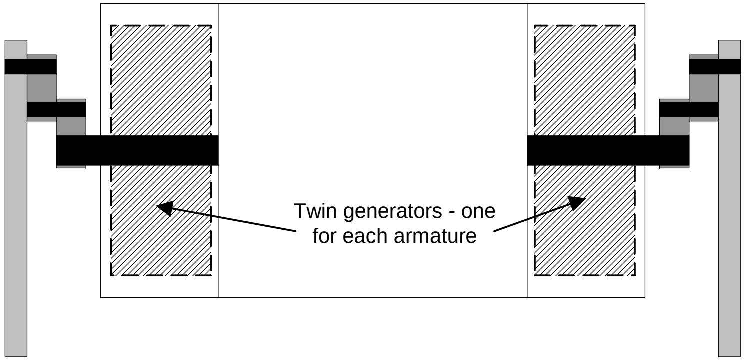
- The kinetic energy transmitted to the Bristol cylinder by the potential energy of the sea wave passing produces a rotational motion

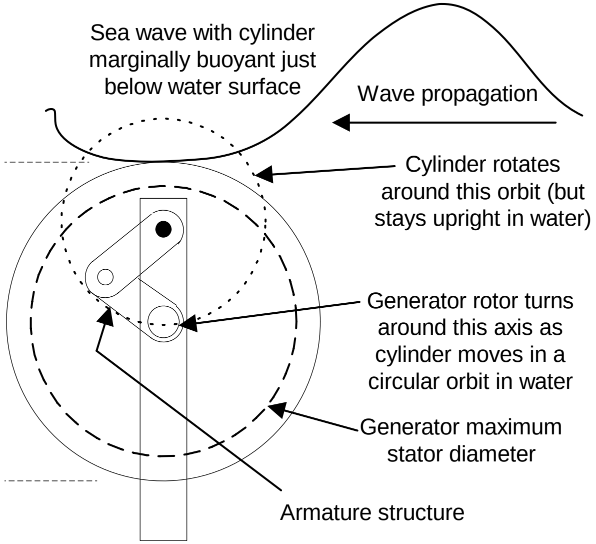
- The ensuing driving torque of the Bristol cylinder depends mainly on its revolution speed and the potential energy contained in the sea waves

- The moment of inertia J of a Bristol cylinder of mass m and diameter D, rotating on the sea surface can be treated as a solid cylinder rotating about an external axis:

$$J = m\left(D^2/8 + r^2\right)$$

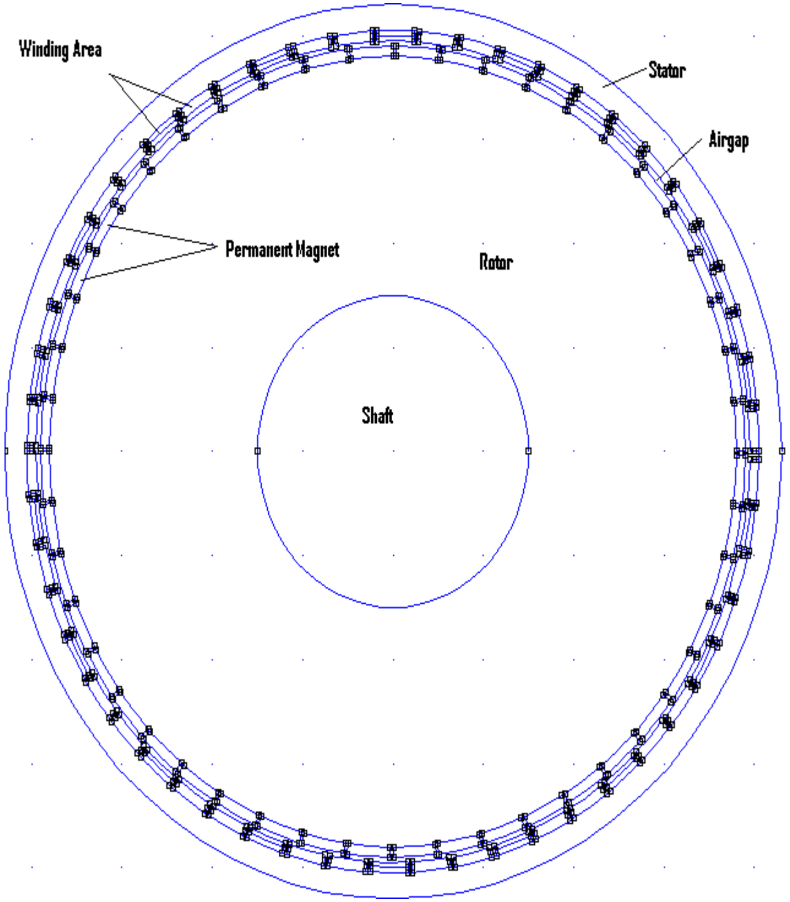
where r is the rotational radius





Power from the Waves

- The prime movers (e.g. Bristol cylinder) in wave power applications rotate at low speed (e.g. 6 m/s) and are variable in both speed and power
- These characteristics call for a permanent magnet, slot-less, synchronous generator with a large number of poles (e.g. 48)
- This has the advantage of an increased torque to inertia ratio, increased power density, no rotational cogging torque and decreased core losses
- These generators are of short axial length and long radial length

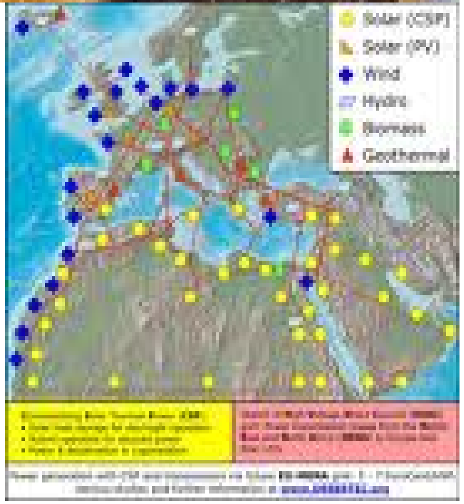


Power from the Sun

- Collectors with concentrators can achieve temperatures of just under 700°C to operate a heat engine at reasonable efficiency, which can then be used to generate electricity
- However, building a tracking bowl of even 30 m carries considerable engineering difficulties, with current materials. The maximum power that such a bowl would yield would be:

  $\pi\times(15\mathrm{m})^2\times(1\mathrm{kW/m}^2)=700\mathrm{kW}$ which would translate in around $200\ \mathrm{kW}$ of electricity

- A solar power station large enough to make an appreciable contribution to the grid (say $10\ \mathrm{MW}$) may be build by a central power tower, such as the scheme illustrated above
- Such a concept is gaining favour in Europe and South East Asia



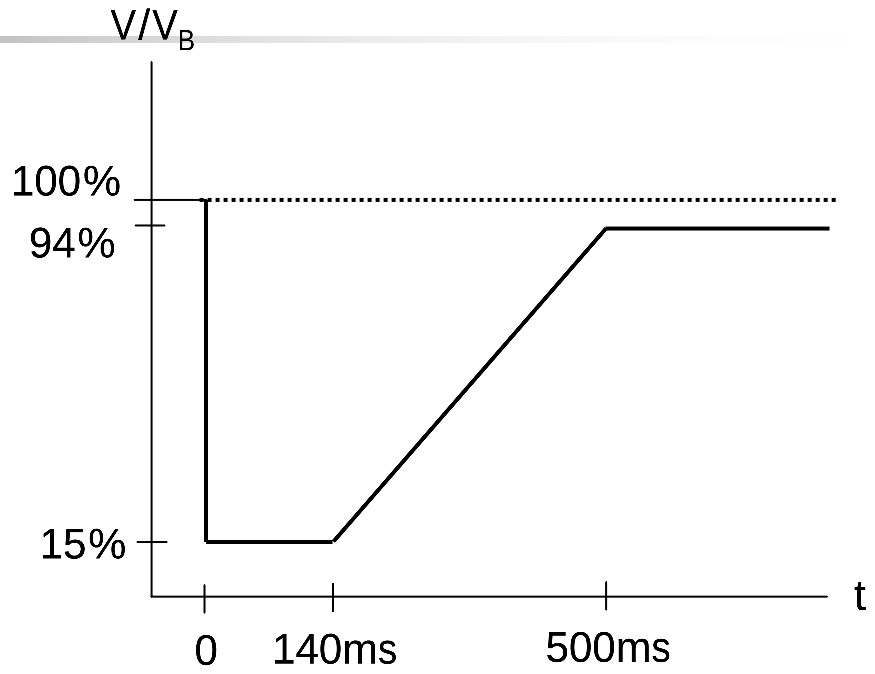
Impact on the Power Grid

Impact on the Power Grid

- The renewable energy resource, in its many forms, provides an abundant, free source of electricity with little damage to the environment
- On the main, the renewable energy resource is not a firm resource; it exhibits a marked variability that prevents the grid-connected renewable generating plant from being dispatched like a conventional fossil fuel, synchronous generator
- Such variability in the primary energy resource brought about new challenges to power system planners and operators charged with running a power grid where generation and demand must balance each other at each point in time
- For instance, early wind farms employed induction generators running at near-fix speed and no voltage regulation
- Power electronic equipment and methods has enabled the incorporation of many forms of renewable generation in a more efficient and reliable manner

Grid Code

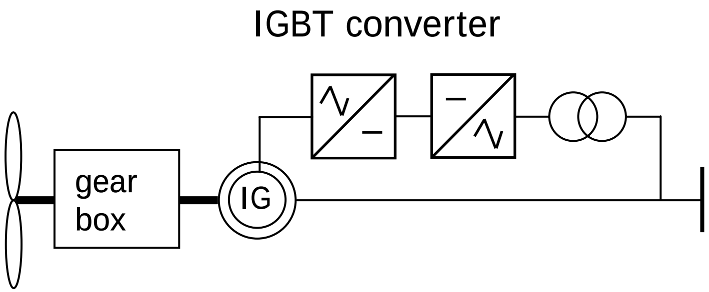
- Grid connection codes specify the mandatory minimum technical requirements that a power plant should fulfil for grid connection
- The grid codes vary from country to country to reflect the characteristics of individual grids, but they have many elements in common

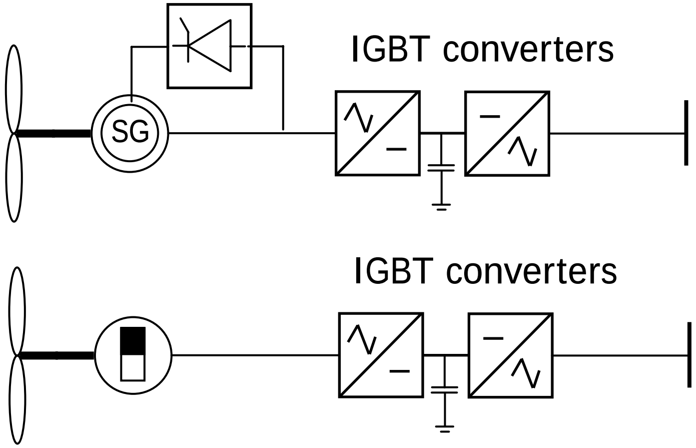


- For instance, grid codes demand fault ride-through capability for grid-connected wind turbines. The figure above illustrates the pattern of voltage tolerance that UK operators demand nowadays
- The UK Grid Code also require that wind farms should be able to provide primary frequency response

Impact on the Power Grid

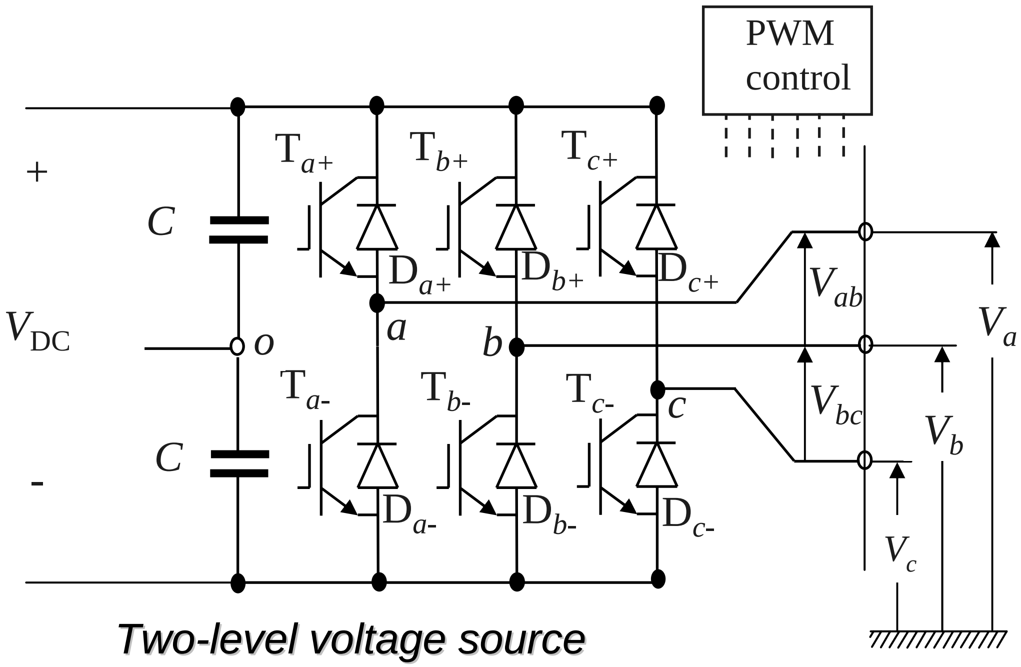
- Grid connection of wind generators using power electronic converters enable them to meet the very stringent requirements of contemporary grid codes
- The two main schemes in wind applications are the DFIG and the FRC



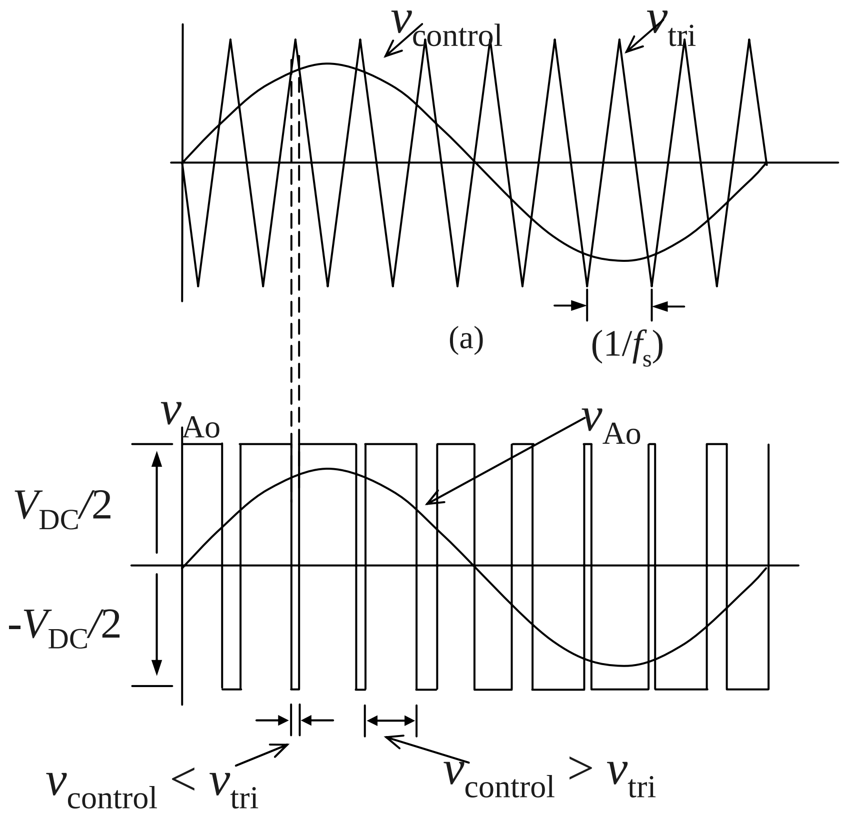


- It is envisaged that in wave applications, the FRC option will gain favour
- Power electronic converters using IGBT valves and PWM control may bring the problem of waveform distortion back, with unwanted high order frequencies

Power Converters with IGBTs and PWM Control

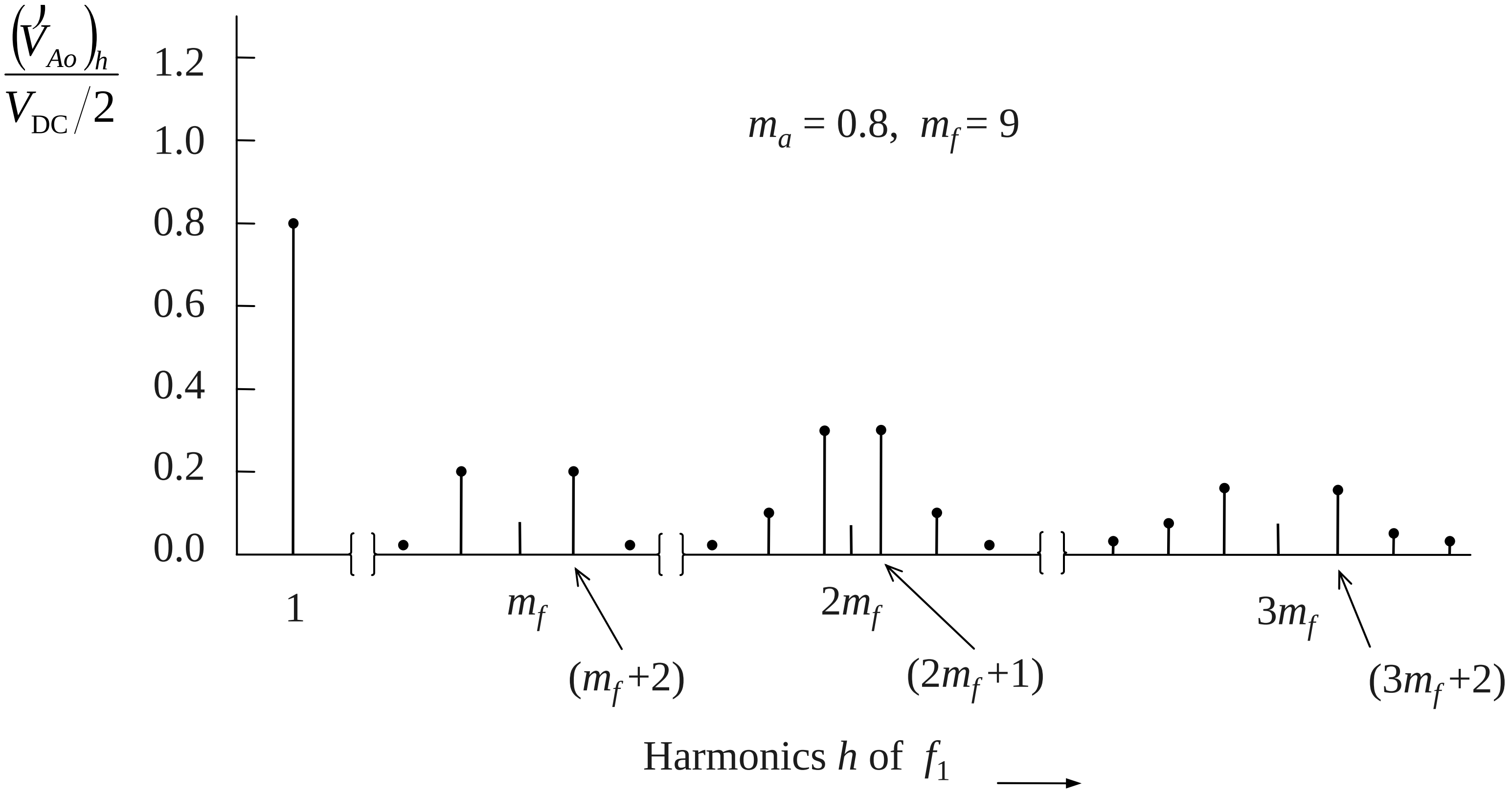


Two-level voltage source converter

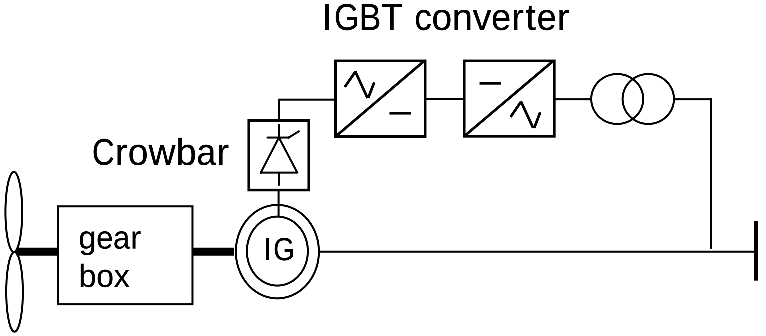


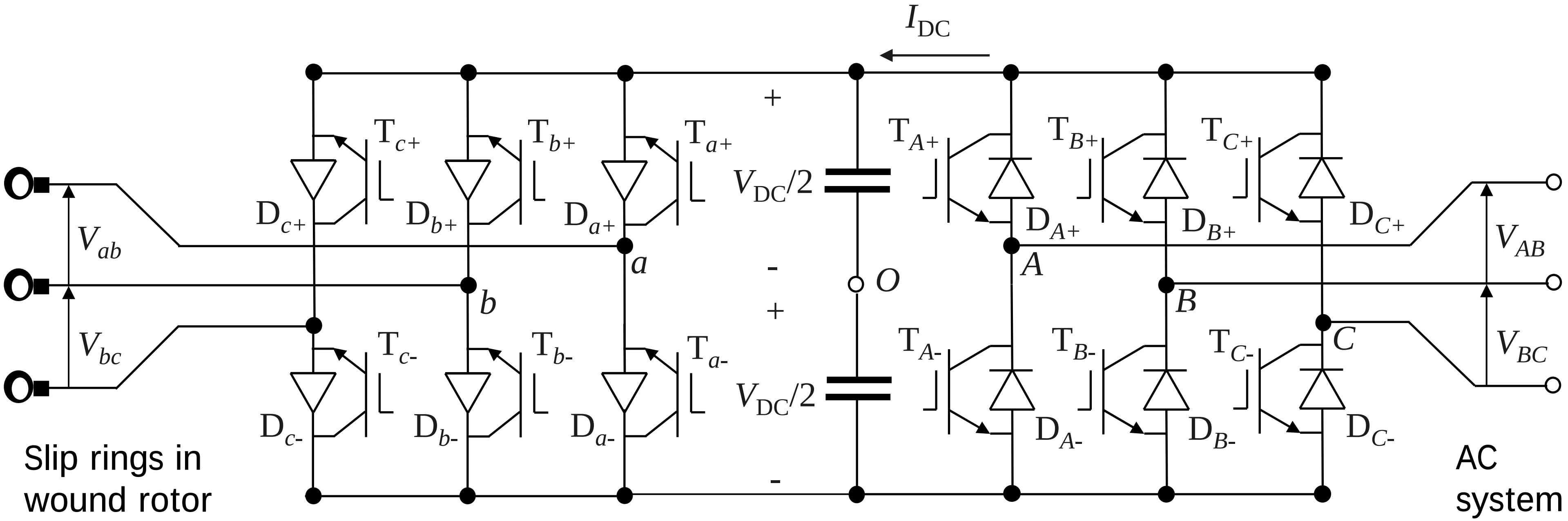
Power Converters – PWM Control

- The PWM waveforms of the three-phase inverter and its harmonic content are shown in the figures below:

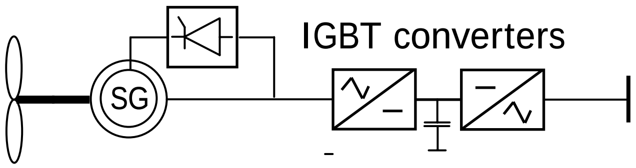


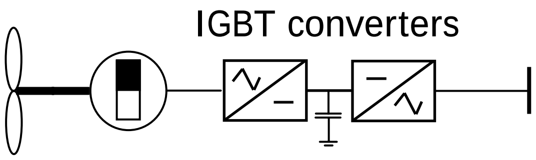
Converters Arrangement for FRC Wind Generation

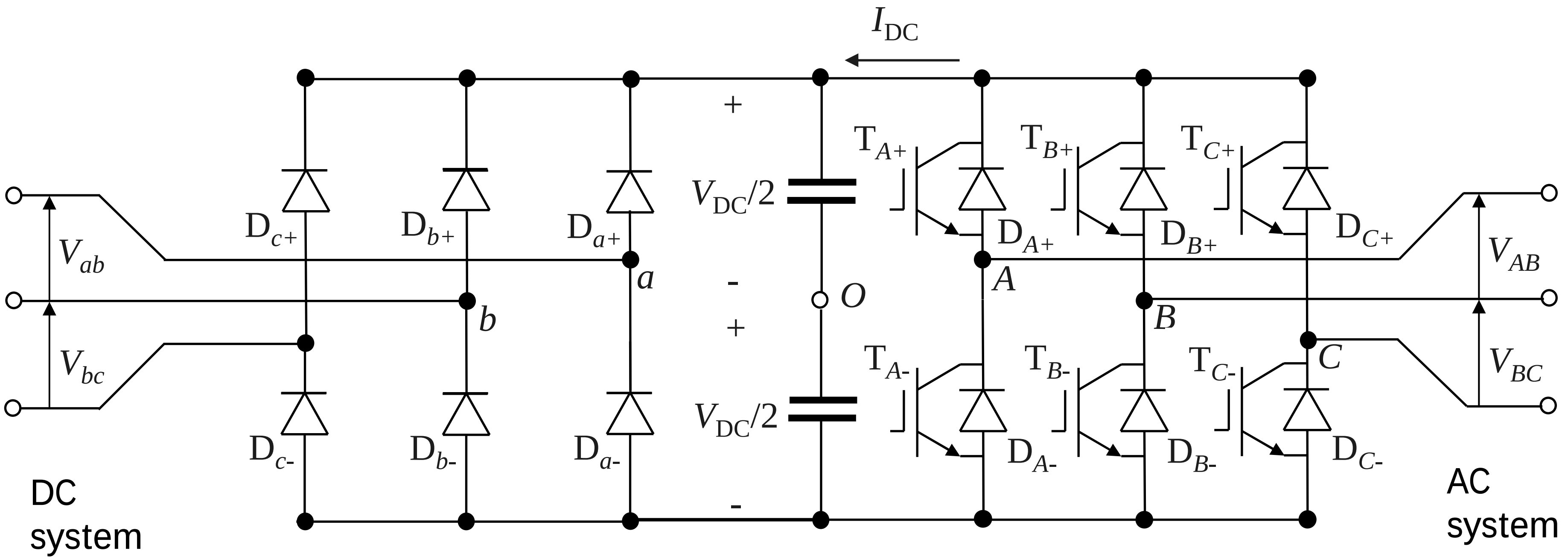




Converters Arrangement for FRC Wind Generation







Steady-State Power Flow Solutions with Induction Generators and PV Generators

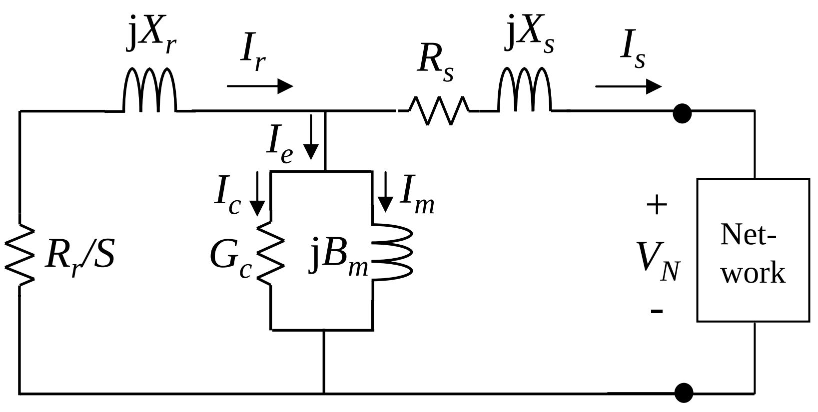
Squirrel Cage Induction Machines – Power flow model

- The equivalent circuit of the induction generator is used to develop a power flow model to enable electrical energy studies of power networks with a mix of synchronous generation and induction generation

$$Z_{eq} = Z_s + \frac{1}{Y_m + Y_r} = R_s + jX_s + \frac{1}{G_c + jB_m + \frac{1}{\frac{R_r}{S} + jX_r}} = R_{eq} + jX_{eq}$$

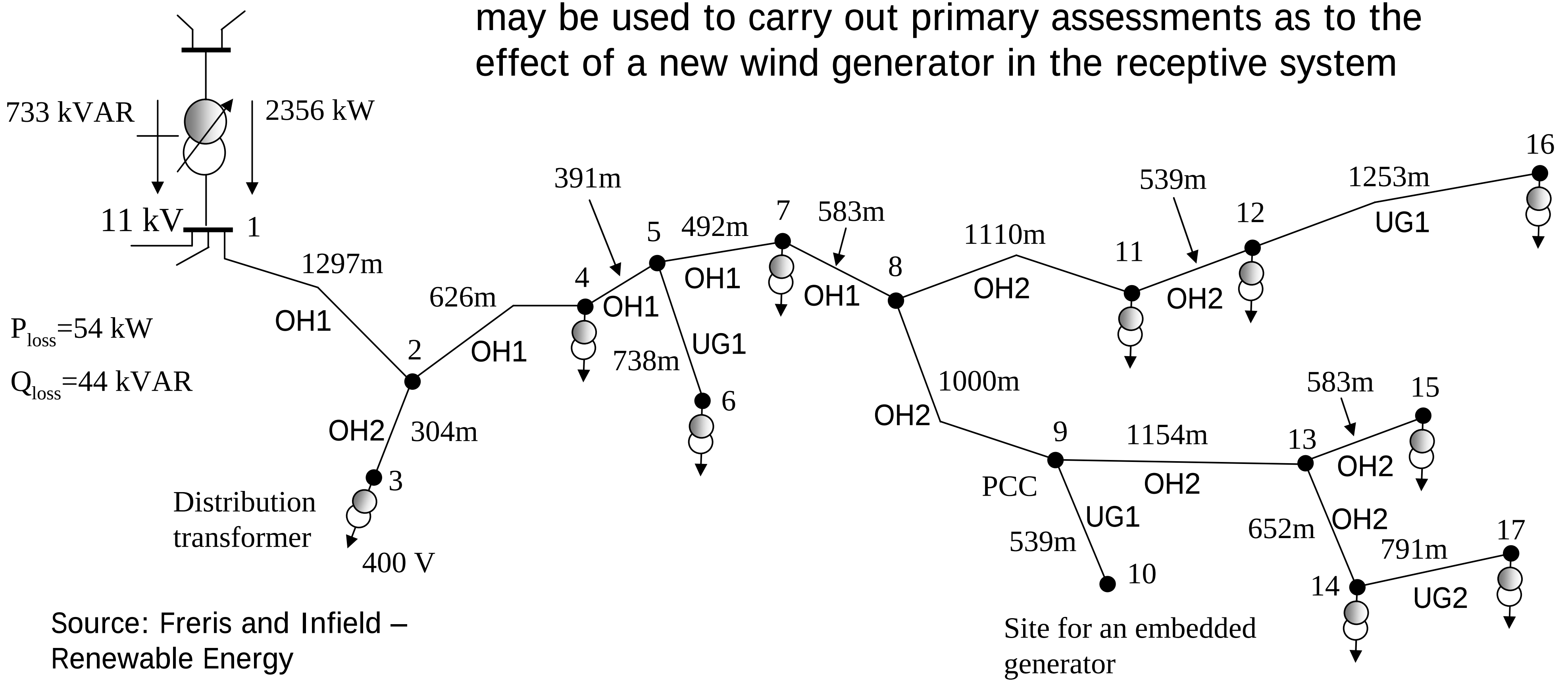
$$R_{eq} = R_s + \frac{\left(G_c + \frac{SR_r}{R_r^2 + S^2X_r^2}\right)}{\left(G_c + \frac{SR_r}{R_r^2 + S^2X_r^2}\right)^2 + \left(B_m - \frac{S^2X_r}{R_r^2 + S^2X_r^2}\right)^2}$$

$$X_{eq} = X_s - \frac{\left(B_m - \frac{S^2X_r}{R_r^2 + S^2X_r^2}\right)}{\left(G_c + \frac{SR_r}{R_r^2 + S^2X_r^2}\right)^2 + \left(B_m - \frac{S^2X_r}{R_r^2 + S^2X_r^2}\right)^2}$$



Power Flow – Case study

Wind generation impacts on both nodal voltages and line loading throughout the distribution system – Power flows may be used to carry out primary assessments as to the effect of a new wind generator in the receptive system



Source: Freris and Infield – Renewable Energy

Power Flow – Case study

The type of transmission line, either over-head or under-ground, together with the lines' lengths are on the circuit diagram. The impedance parameters and lines' ratings are given in the table below

Code	Type	R (Ω/km)	R (Ω/km)	Rating (A)
OH1	50 AAC	0.550	0.372	219
OH2	100AAC	0.277	0.351	345
UG1	185AL	0.164	0.085	255
UG2	95AL	0.320	0.087	170

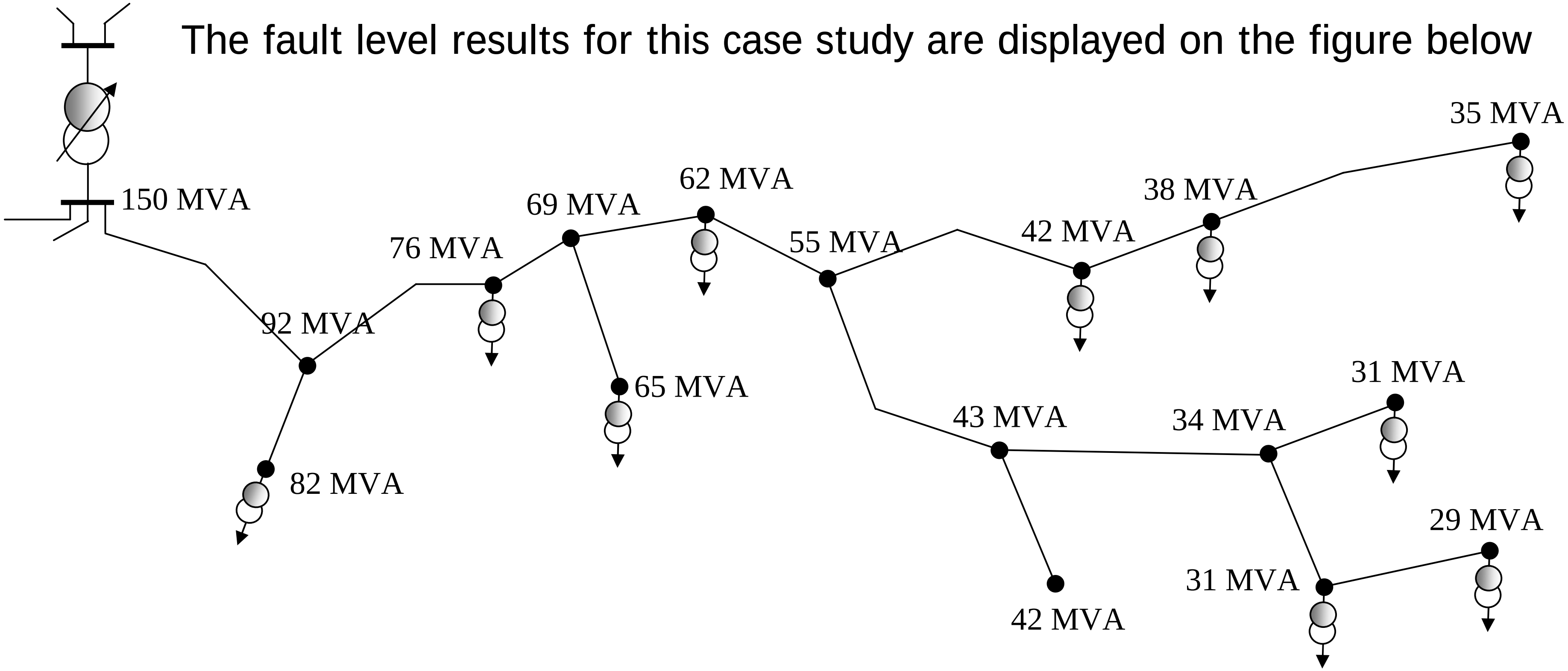
System loading data

Bus	P (kW)	Q (kVAR)
3	238	71
4	159	48
6	340	102
7	178	53
10	0	0
11	458	137
13	221	66
14	97	29
15	386	116
16	161	48
17	64	19
Total	**2302**	**689**

Power Flow – Case study

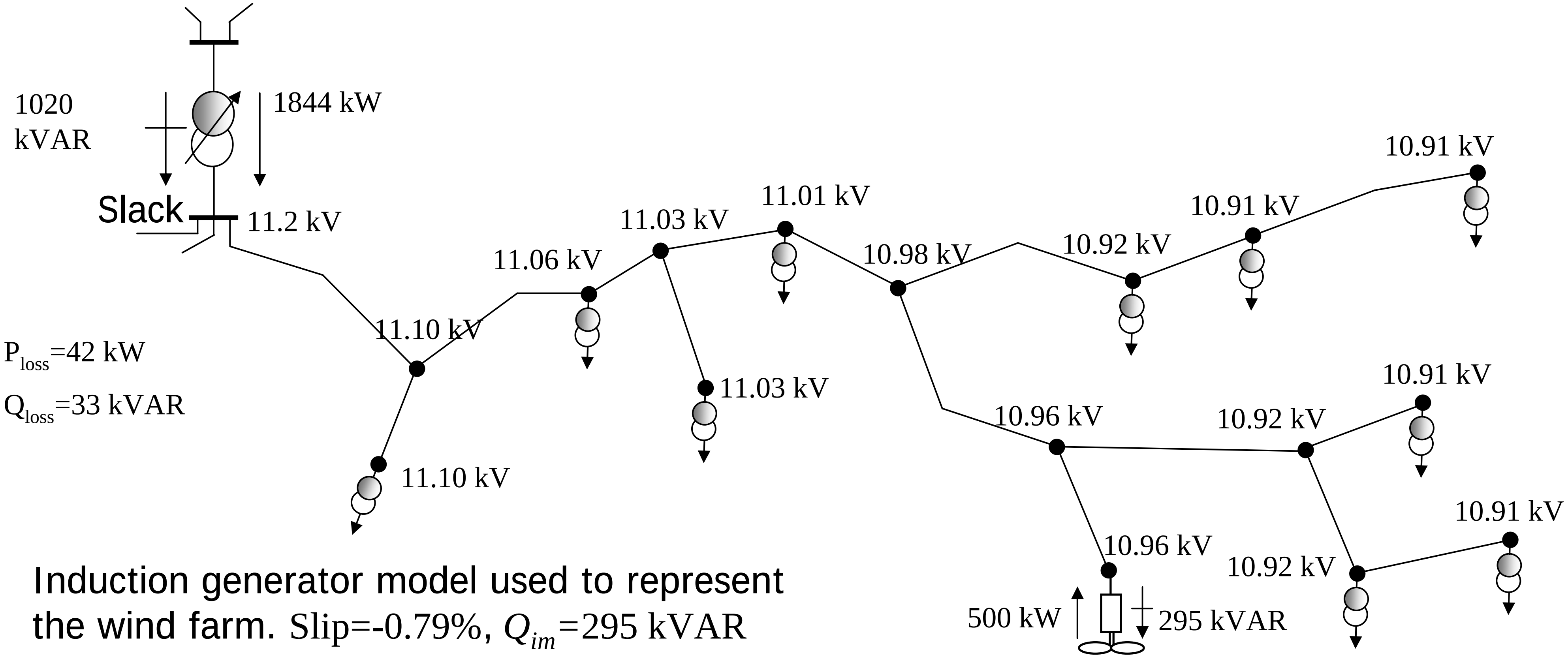
A fault level assessment of the network is carried out to determine whether or not a given bus of the network would be a suitable candidate for the wind farm connection

The fault level results for this case study are displayed on the figure below



Power Flow – Case study

A power flow induction generator model is used to represent the wind farm. The voltage results do not differ much with respect to the previous case



P_{loss}=42 kW

Q_{loss}=33 kVAR

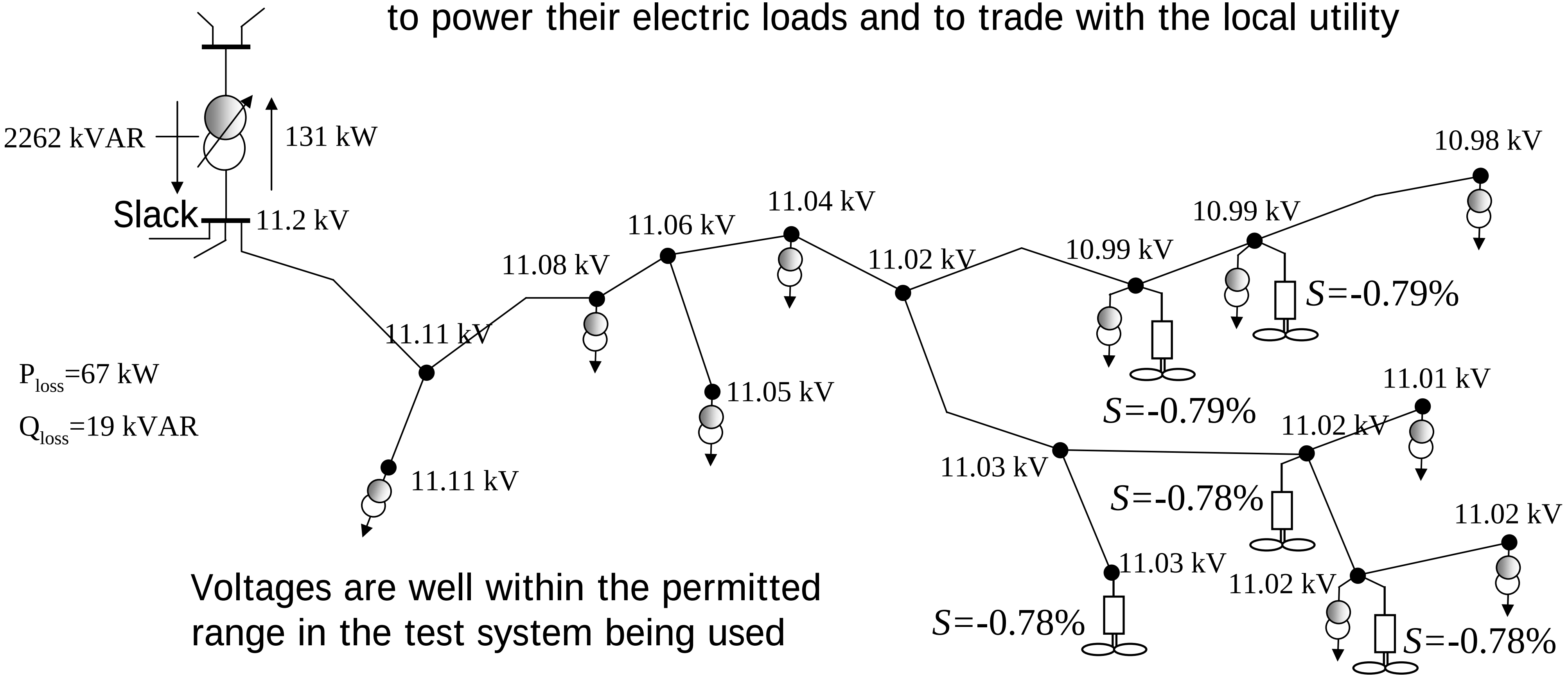
Induction generator model used to represent the wind farm. Slip=-0.79%, Q_{im}=295 kVAR

Power Flow – Case study

- The voltage profile at consumer loads is within 1% which is well within the accepted limits
- At the point of common coupling (PCC), the voltage raises due to the injection of active power into the network, which is somehow moderated by the consumption of reactive power by the induction generator
- The slip is below 1%, which is negative to emphasize the fact that the machine is operating in generating mode
- In the event of capacitors being installed at the wind turbine location, to improve power factor, the voltage is expected to rise as a function of capacitor size – a trade-off would be required
- Thermal limits should also be kept in check, since power flows increase in some transmission lines and cables as a result of the new generator

Power Flow – Case study

- A current trend in Scotland is developing where interested parties in villages are joining in to install wind mills of sufficient capacity to power their electric loads and to trade with the local utility



P_{loss}=67 kW

Q_{loss}=19 kVAR

Voltages are well within the permitted range in the test system being used

Power Flow – Case study

- A different scenario is shown below, where the five 500 kW turbines are all connected at bus 10. A bank of capacitors is added to supply locally some of the reactive power requirement of the wind farm

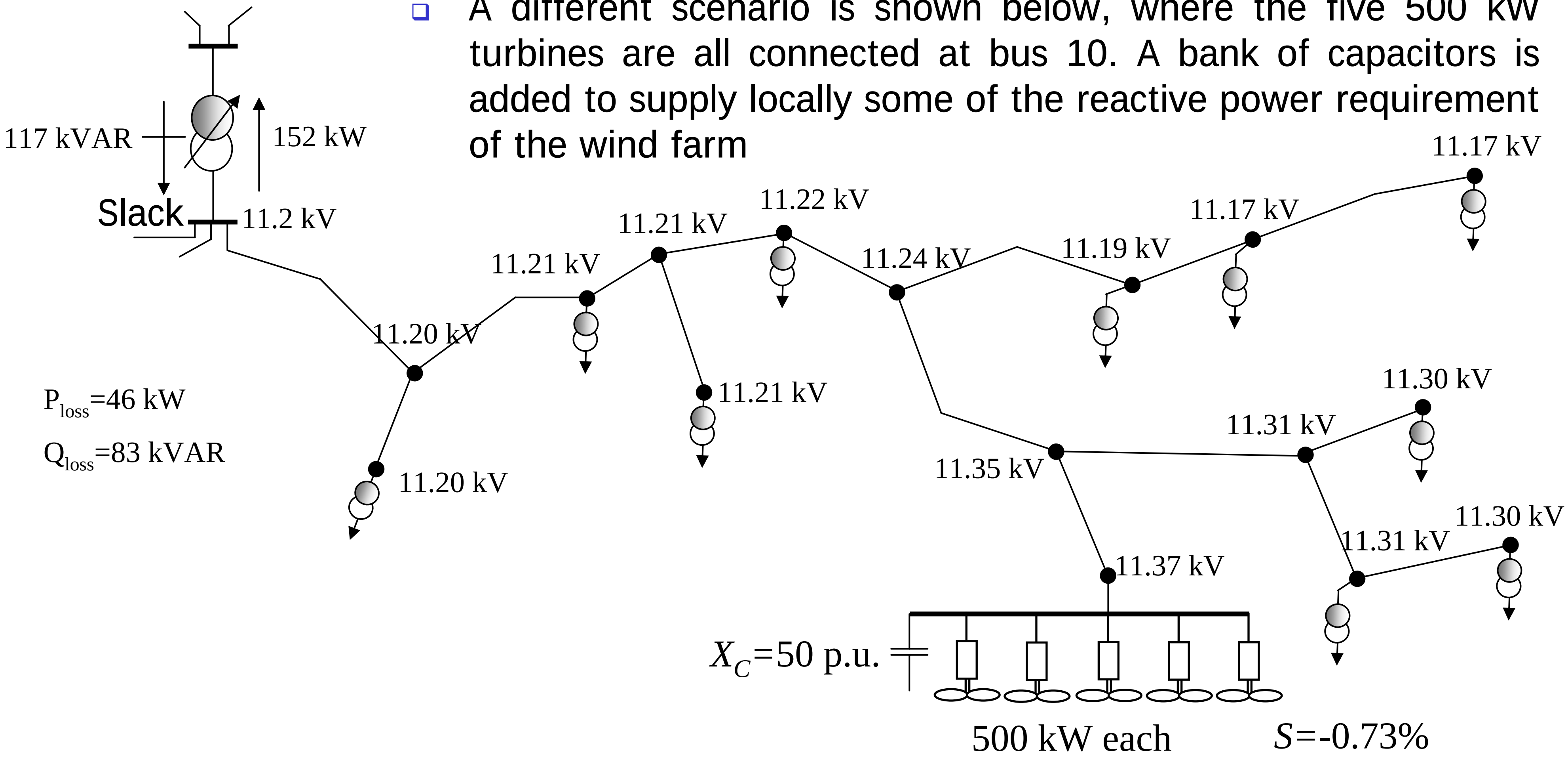
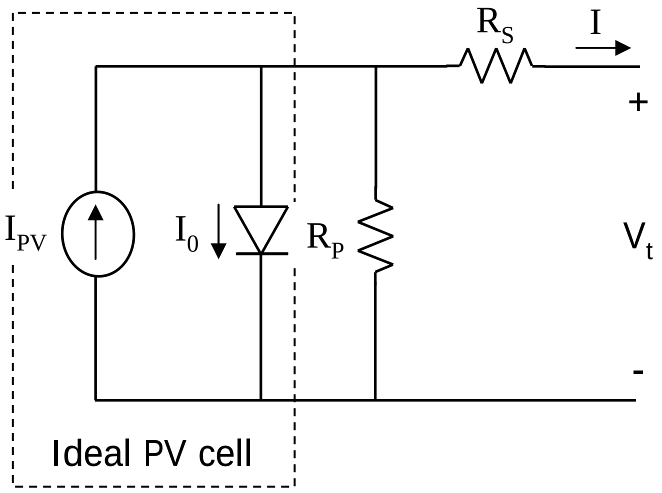
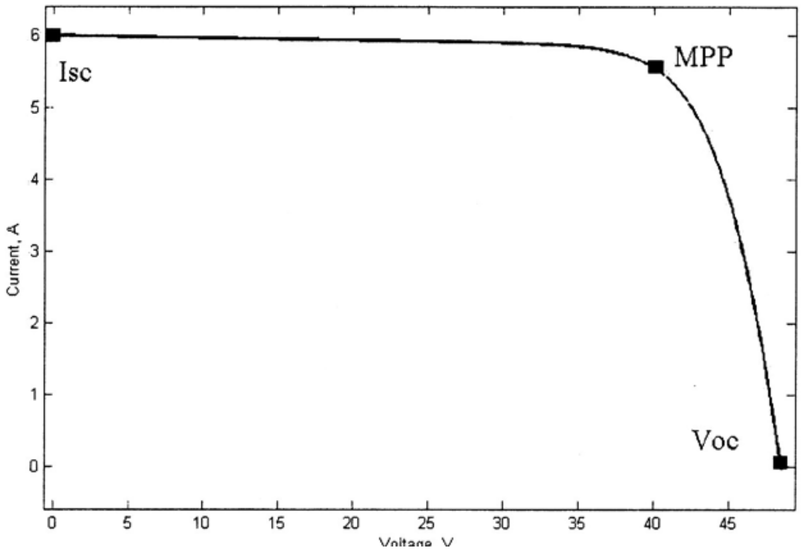


Photo-Voltaic Cell – Power flow model

- The equivalent circuit of the photo-voltaic (PV) cell is used to develop a power flow model to enable electrical energy studies of power networks with a mix of synchronous generation and PV generators

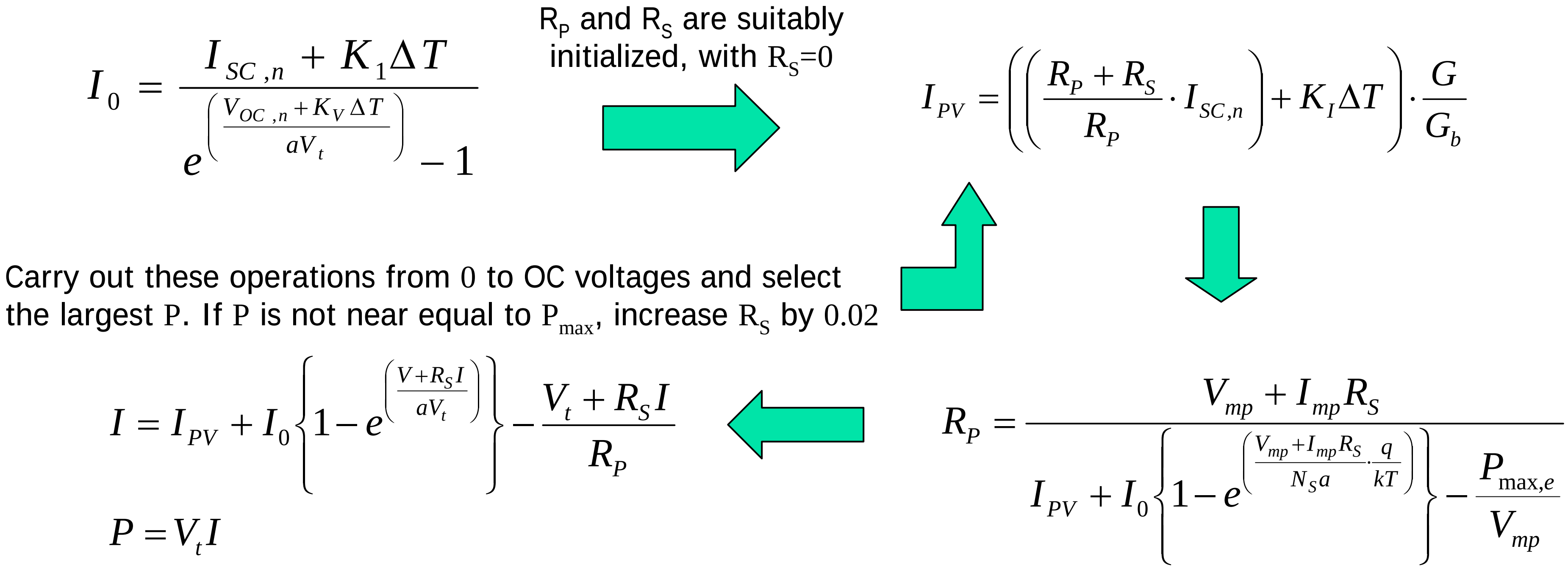




- The V-I characteristic, as supplied by a PV cell manufacturer, is used to adjust the circuit parameters that best fit the three key points of the characteristic, namely open circuit (OC), short-circuit (SC) and maximum power point (MPP)

Photo-Voltaic Cell – Power flow model

- The ambient temperature (T) at which the PV panel is working at and the irradiance (G) are entered as given parameters
- The following equations are used to determine the PV output power, voltage and current



$$I_0 = \frac{I_{SC,n} + K_1 \Delta T}{e^{\left(\frac{V_{OC,n} + K_V \Delta T}{aV_t}\right)} - 1}$$

R_P and R_S are suitably initialized, with $R_S=0$

$$I_{PV} = \left(\left(\frac{R_P + R_S}{R_P} \cdot I_{SC,n}\right) + K_I \Delta T\right) \cdot \frac{G}{G_b}$$

$$R_P = \frac{V_{mp} + I_{mp} R_S}{I_{PV} + I_0 \left\{1 - e^{\left(\frac{V_{mp} + I_{mp} R_S}{N_S a} \cdot \frac{q}{kT}\right)}\right\} - \frac{P_{\max,e}}{V_{mp}}}$$

$$I = I_{PV} + I_0 \left\{1 - e^{\left(\frac{V + R_S I}{aV_t}\right)}\right\} - \frac{V_t + R_S I}{R_P}$$

$$P = V_t I$$

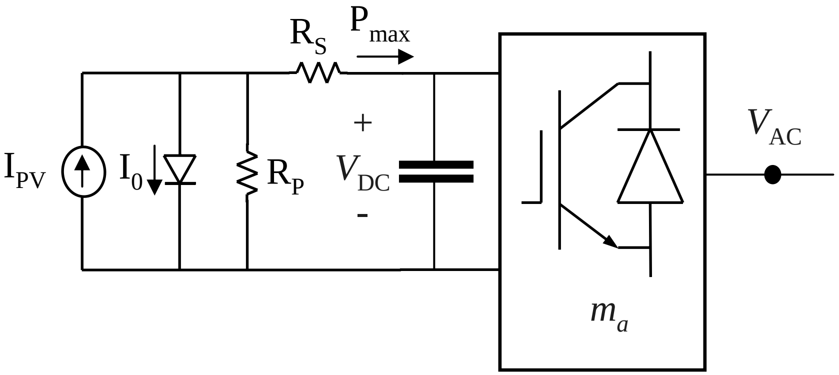
Carry out these operations from 0 to OC voltages and select the largest P. If P is not near equal to $P_{\max}$, increase R_S by 0.02

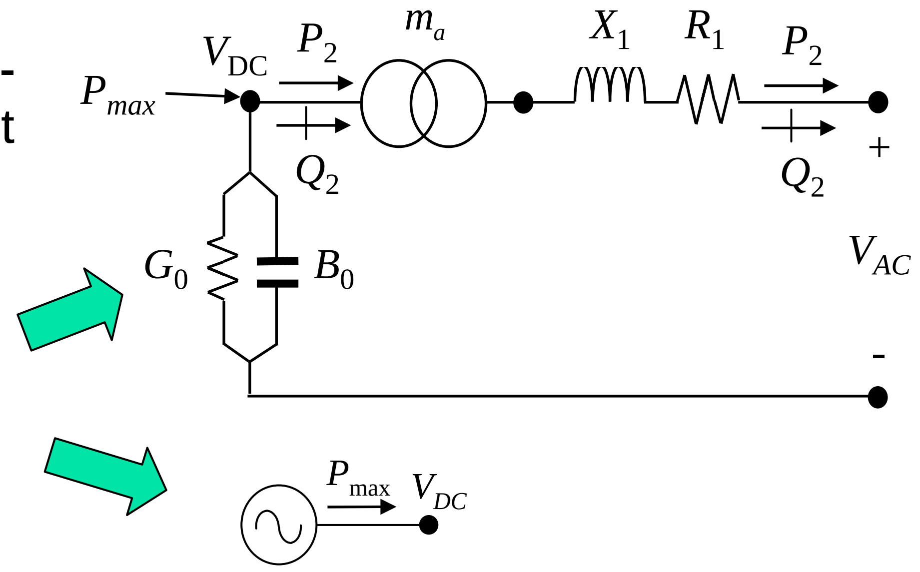
Photo-Voltaic Cell – Power flow model

- In grid-connected PV applications, a power electronic inverter is used to interface the otherwise DC generator with the AC power grid

- Provided there is an economical justification, there are technical advantages in selecting a VSI as the power electronic interface. For instance, the PV terminal voltage that yields maximum power output can be kept by suitable selection of amplitude modulation index, m_a

- From the power flow solution point-of-view, there are various models that can be used for representing the VSI





PV Module Data

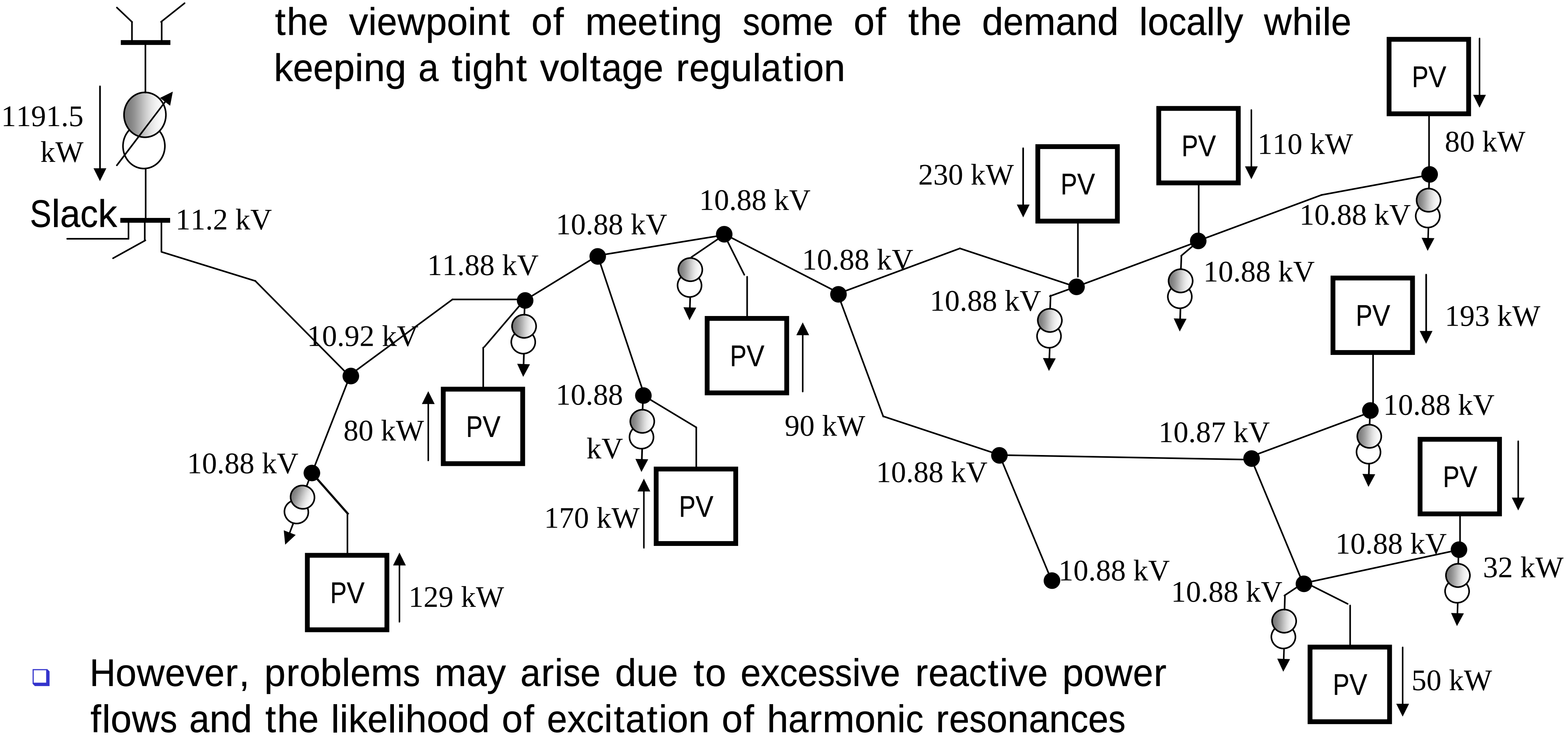
Parameters of the SUNPOWER SPR-220 (CS) array in 25°C and 1000 W/m^2

Parameter	Type
I_{mp}	5.56 A
V_{mp}	40.03 V
P_{max}	222 W
I_{SC}	5.988 A
V_{OC}	48.53 V
K_V	-0.152 V/K
K_I	0.000232 A/K
NS	72

Node	Modules in series	Modules in parallel	P_{max} (kW)
3	8	90	160
4	8	60	107
6	8	96	171
7	8	60	107
11	8	132	235
13	8	63	121
14	8	30	53
15	8	120	214
16	8	60	107
17	8	30	53

Power Flow – PV case

- Distributed PV generators seems to be a good solution from the viewpoint of meeting some of the demand locally while keeping a tight voltage regulation



- However, problems may arise due to excessive reactive power flows and the likelihood of excitation of harmonic resonances

Harmonic Resonances in Low-Voltage Distribution Systems

HVDC-VSC Installations

- The HVDC-Light at Eagle Pass - Piedras Negras uses IGBT-based converters, which during commissioning was set to switch at 1260 Hz ($m_f = 1260/60 = 21$)
- It connects the 138 kV grids of CFE and AEP-TCC. It consists of two 36 MVAR VSCs
- PWM harmonics are generated at: $f_h = \left(\beta m_f \pm \kappa\right) f_1$

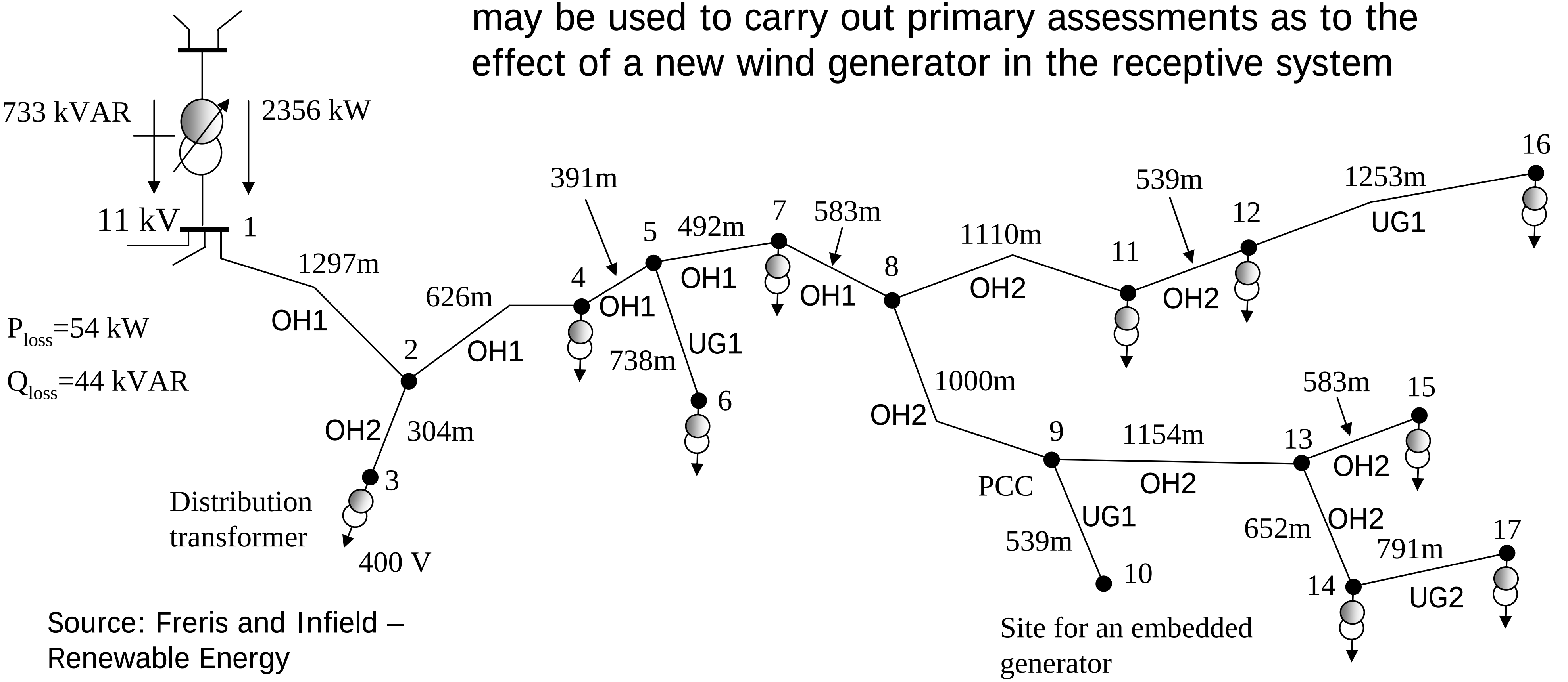
β	Harmonic order
1	19, 21, 23
2	39, 41, 43, 45
3	59, 61, 63, 65, 67
4	81, 83, 85, 87
…	…
10	207, 209, 211, 213
…	…

The 3rd harmonic was significant

The 207th harmonic varied between 13% and 40% of the power frequency voltage, depending on the operation of the BtB and phase angle between the two inverters

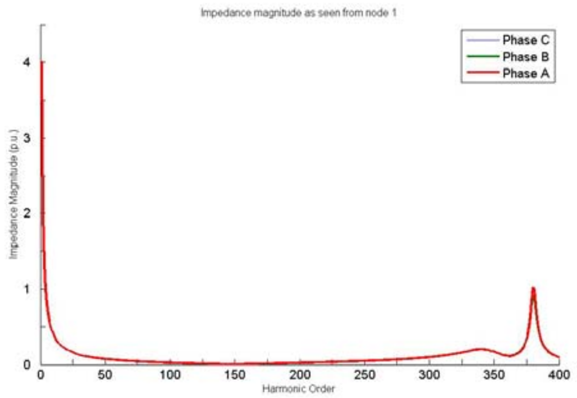
Test Distribution System

Wind generation impacts on both nodal voltages and line loading throughout the distribution system – Power flows may be used to carry out primary assessments as to the effect of a new wind generator in the receptive system

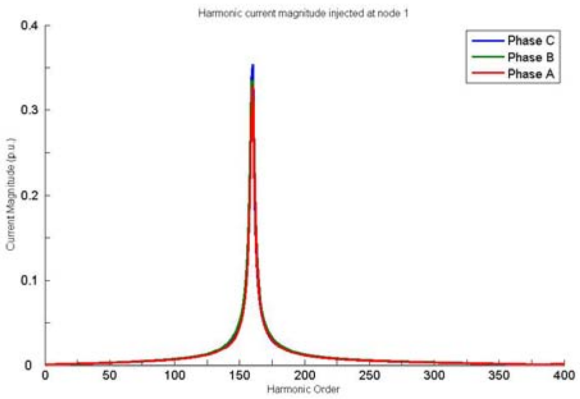


Source: Freris and Infield – Renewable Energy

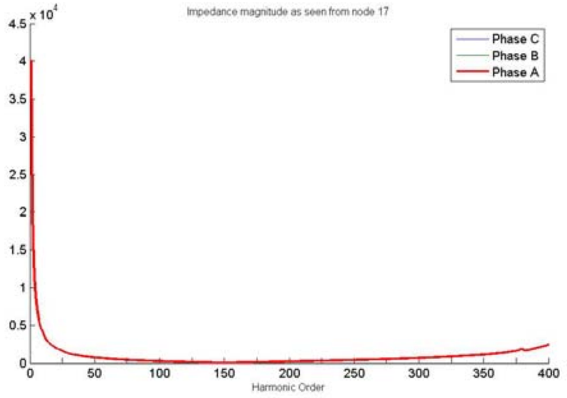
Resonances in Distribution Systems - Test network made up of only OH lines



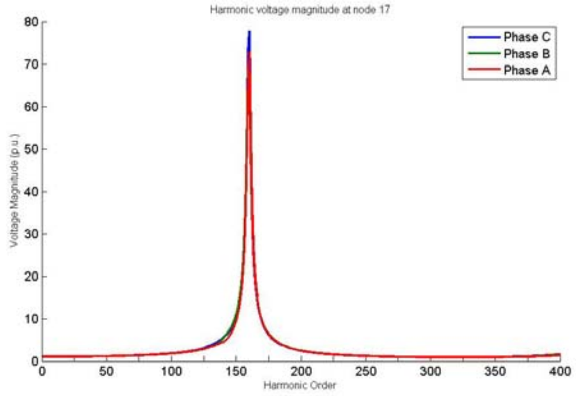
Harmonic impedance as seen from node 1



Harmonic current injected at node 1 by a harmonic voltage source of 1 p.u. at node 1

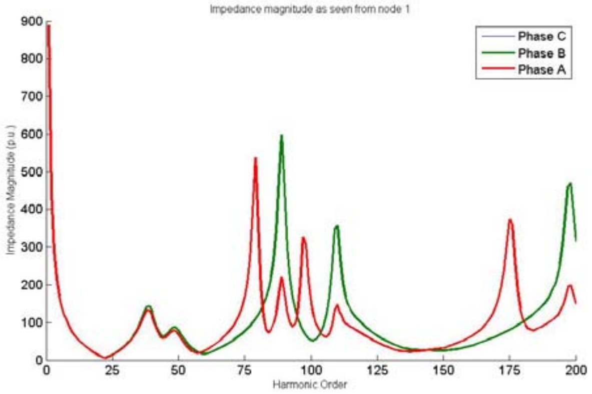


Harmonic impedance as seen from node 17

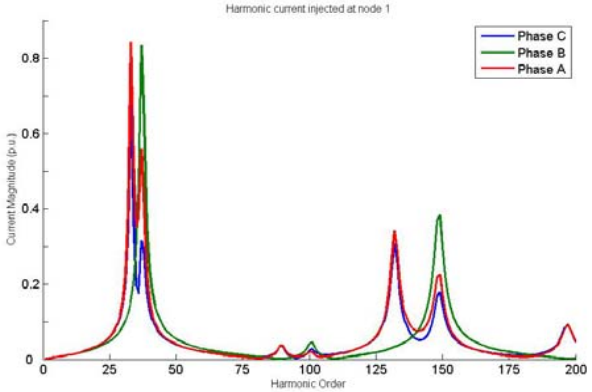


Harmonic voltage at node 17 due to a harmonic voltage injection of 1 p.u. at node 1

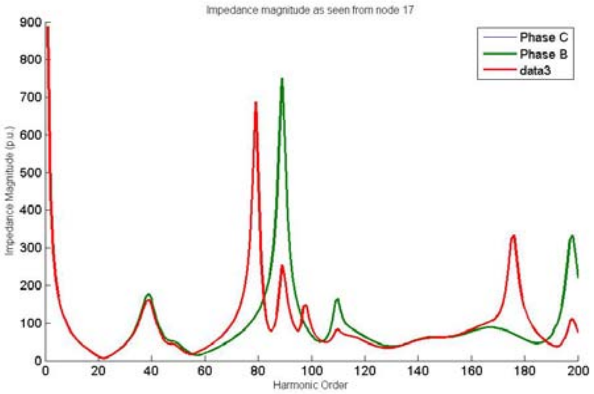
Resonances in Distribution Systems - Test network made up of only UG cables



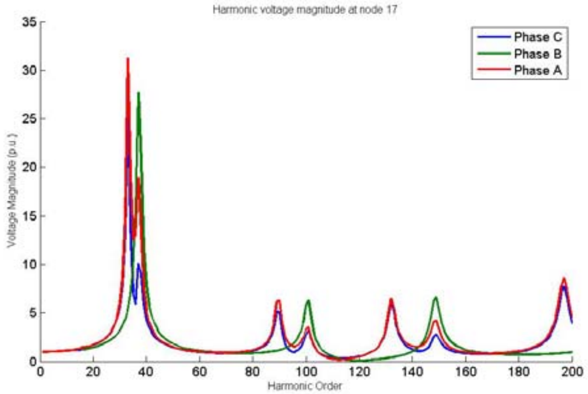
Harmonic impedance as seen from node 1



Harmonic current injected at node 1 by a harmonic voltage source of 1 p.u. at node 1



Harmonic impedance as seen from node 17



Harmonic voltage at node 17 due to a harmonic voltage injection of 1 p.u. at node 1