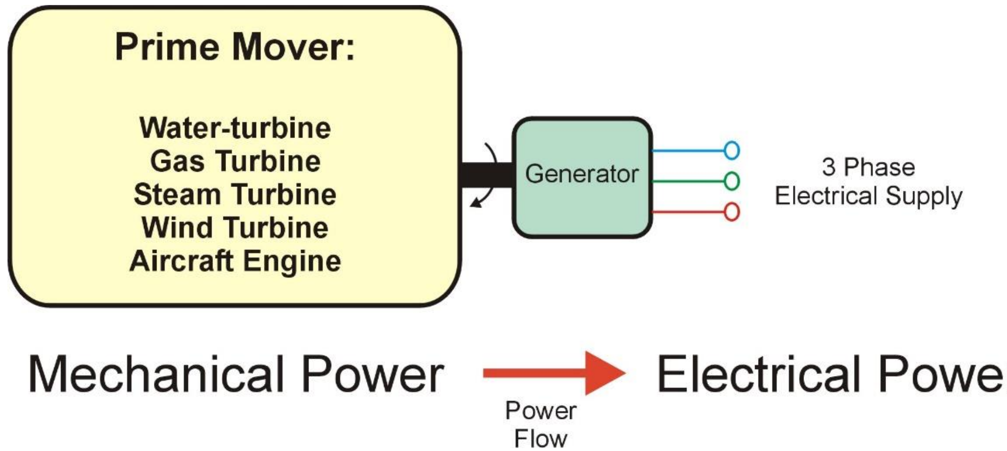
POWER ENGINEERING
#15 ELECTRICAL GENERATOR

2018

University of Glasgow

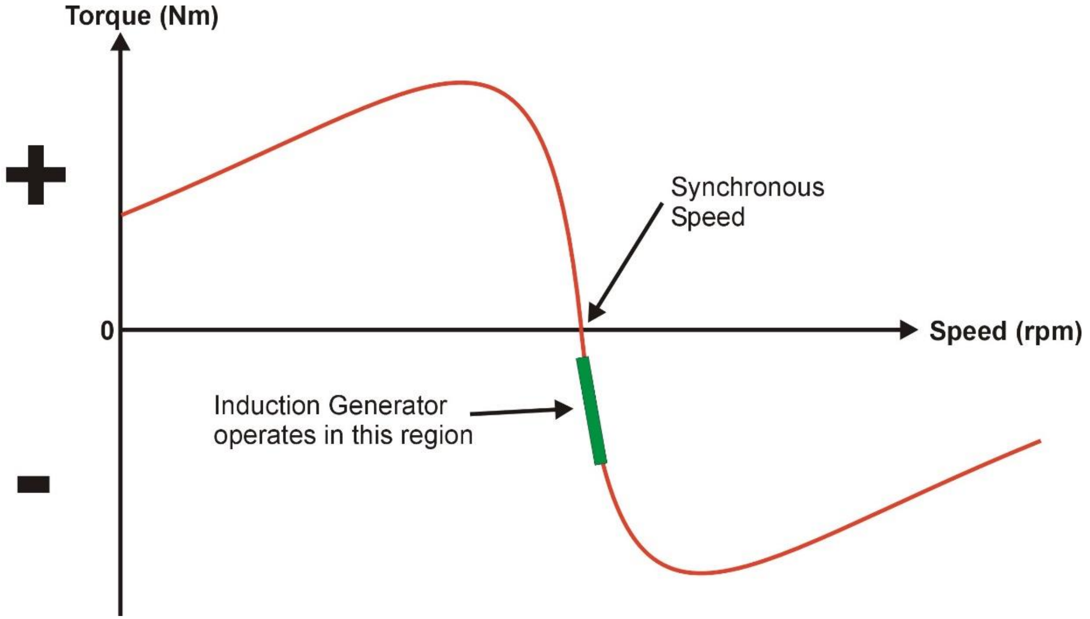
Electrical Generators



Introduction to Electrical Generators:

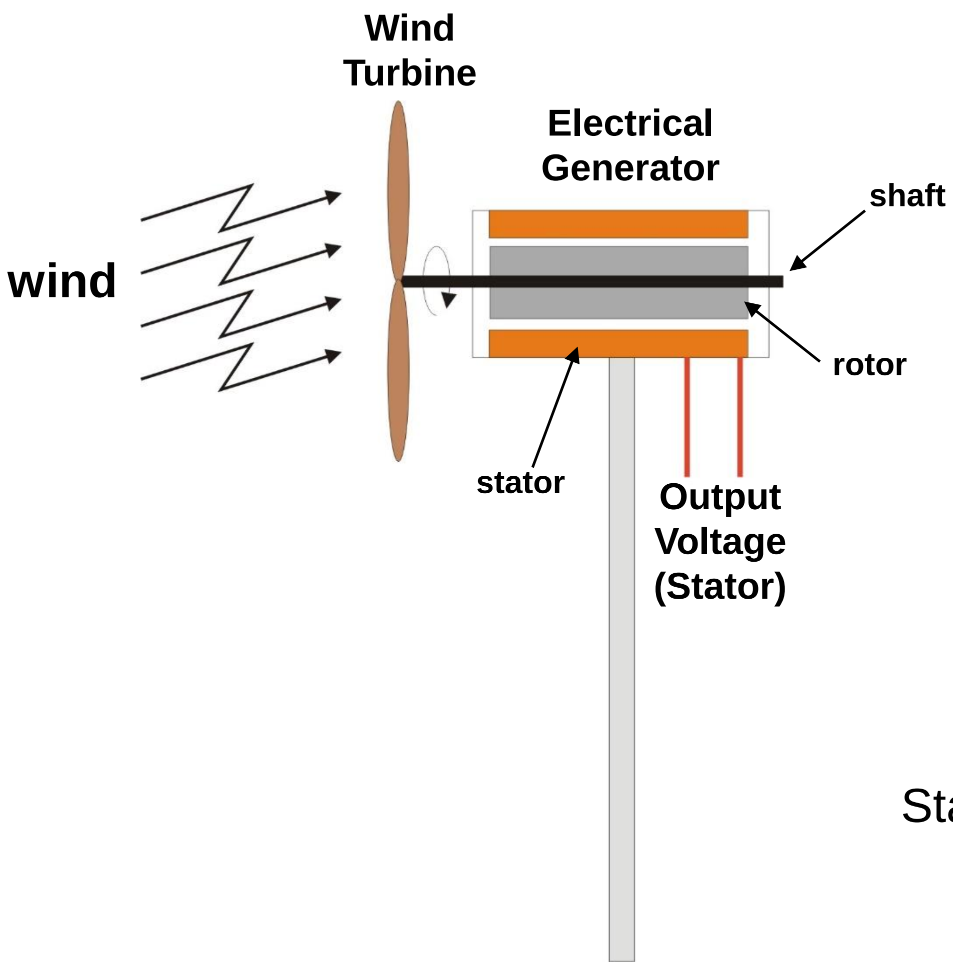
- Induction Generators
- A basic Permanent Magnet (PM) Generator
  - Basic principles of operation
  - Generator connection to Electrical Systems
  - Application Examples
  - Large PM Generators
- Wound Field Synchronous Generators
  - Wound Rotor replaces rotor magnets
  - Basic operation and control of Stator Voltages
- Synchronous Generator Equivalent Circuit

the most common type of large wind generator uses an **Induction Machine:**

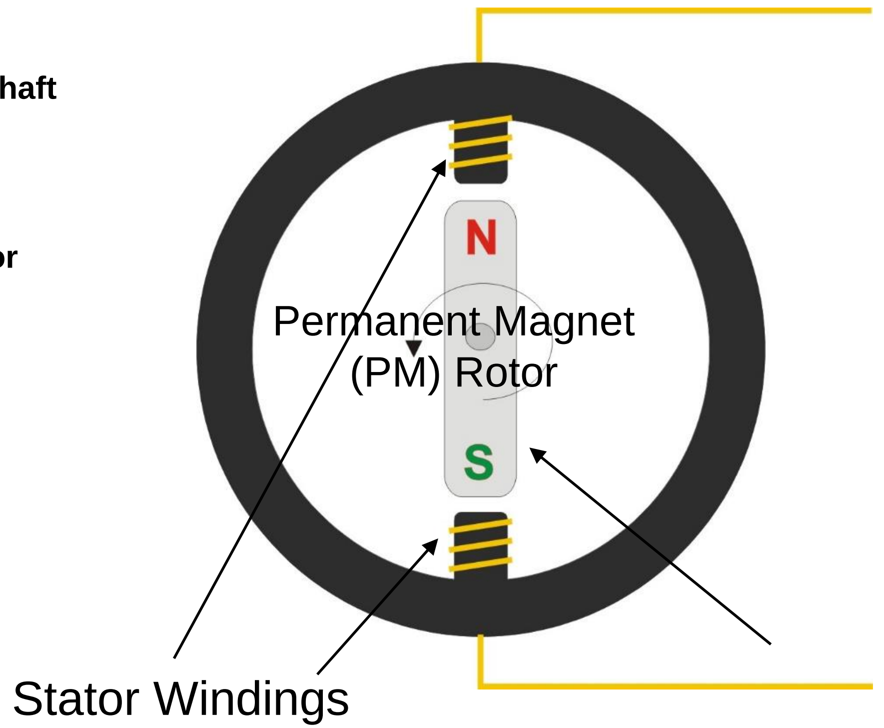


The wind turbine drives the Induction Machine **ABOVE** synchronous speed which results in the sign of the torque (power) changing and therefore electrical **GENERATION**

A Basic Permanent Magnet Generator



Single Phase Electrical Generator

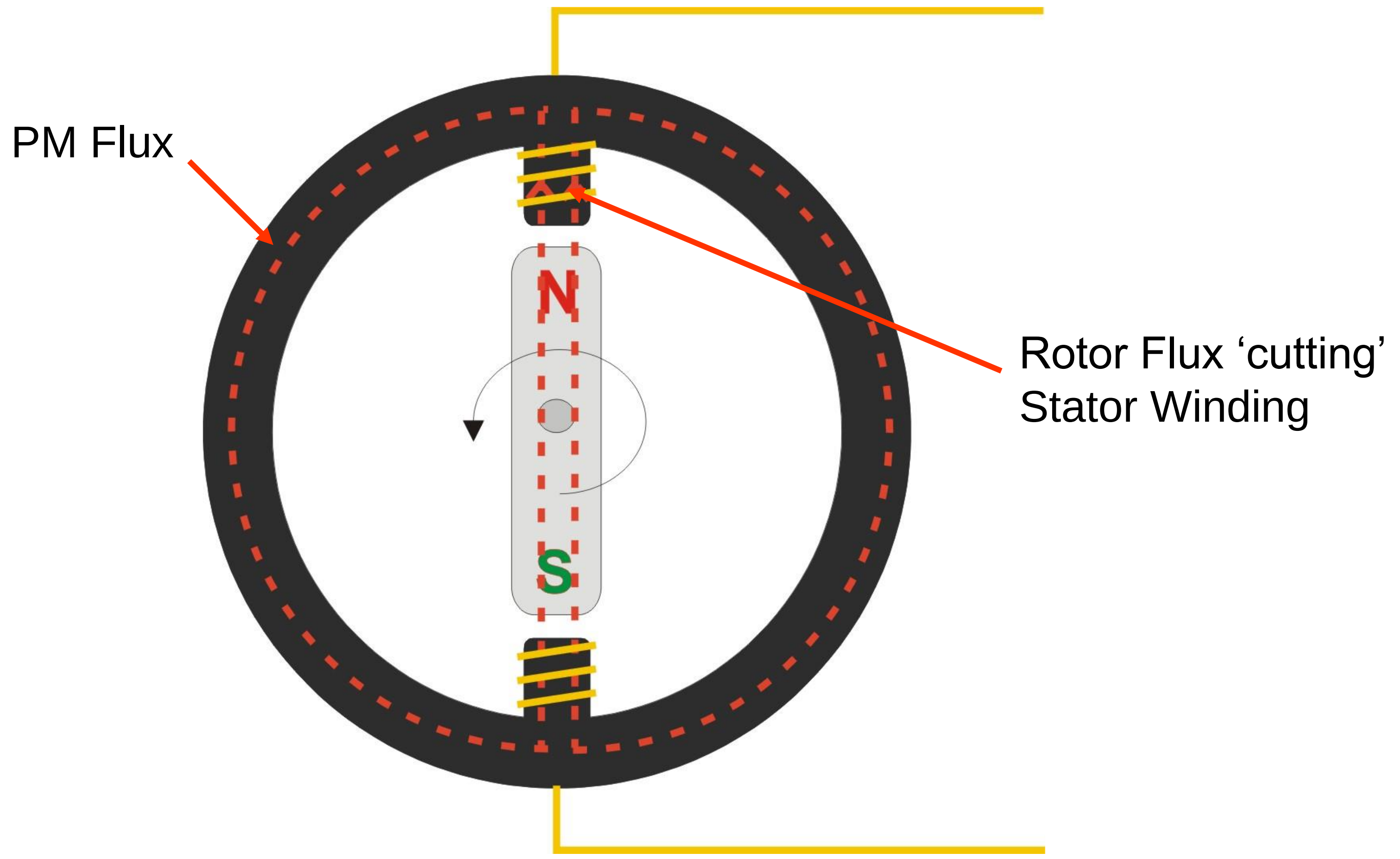


The rotor spins at speed set by wind turbine

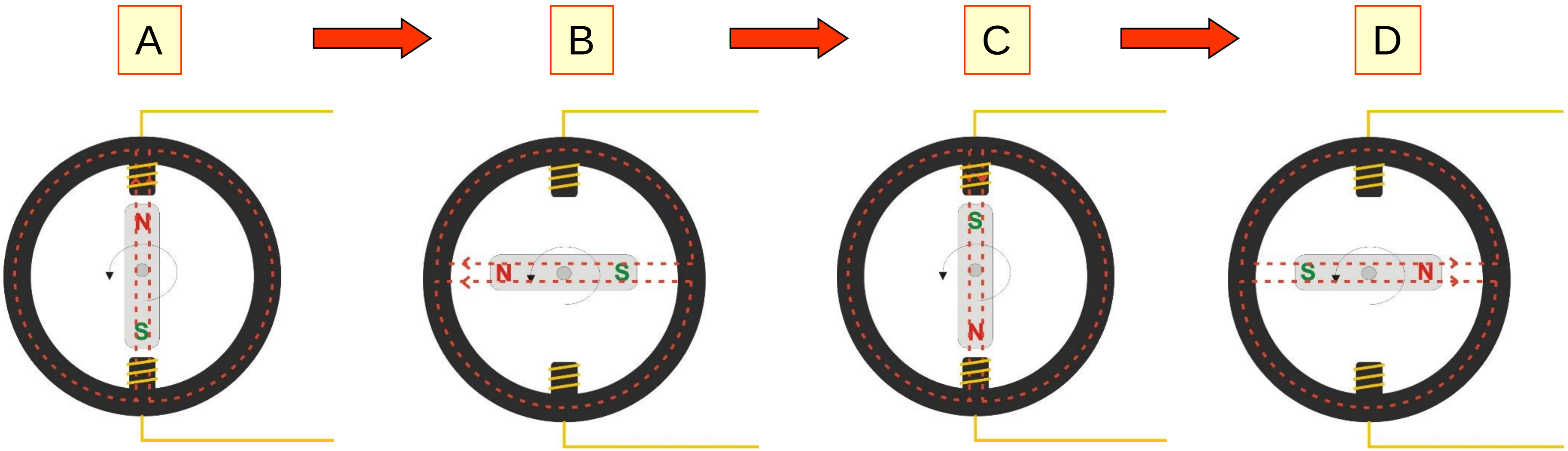
Side View

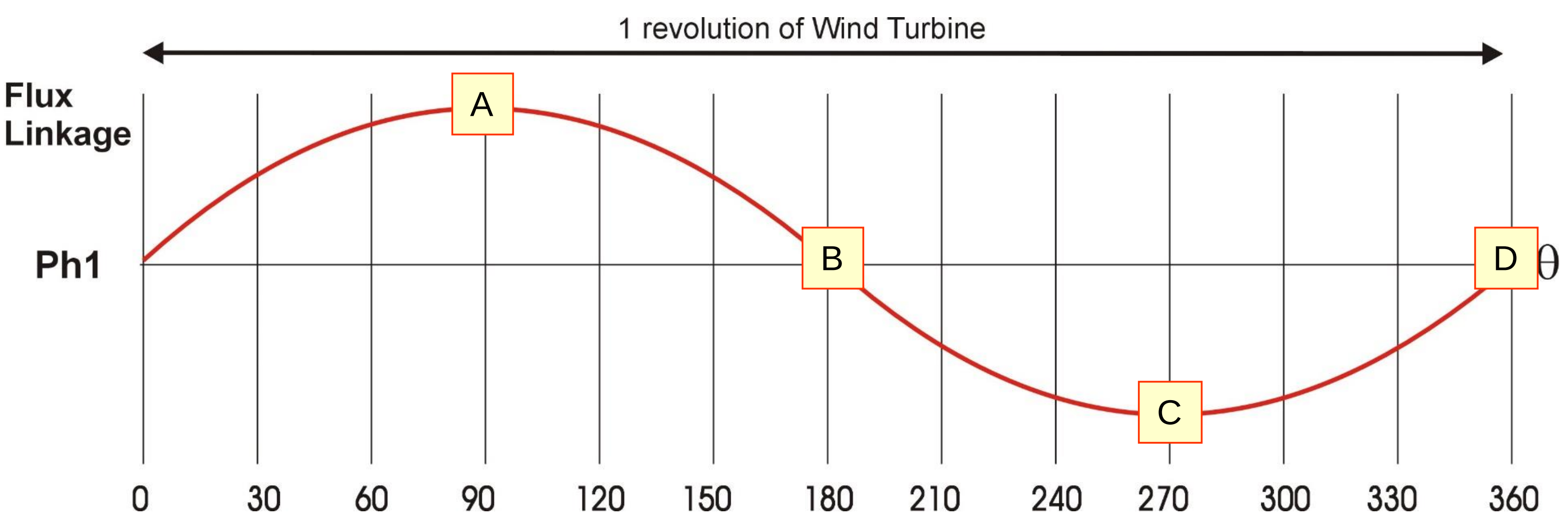
End View

Rotor Permanent Magnet (PM) Flux



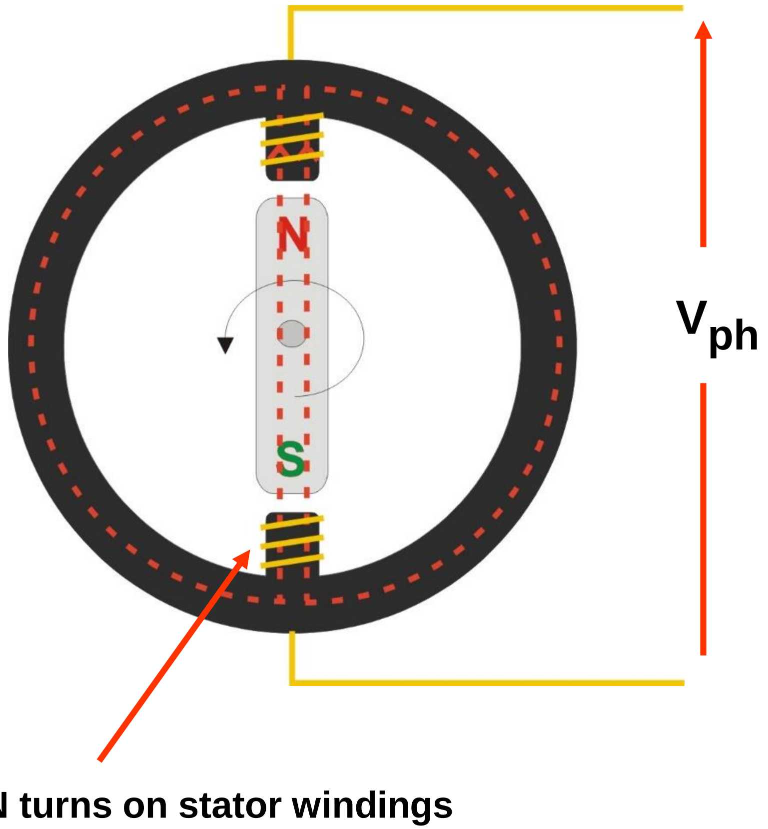
PM 'cutting' Flux (Flux Linkage) v Rotor Position

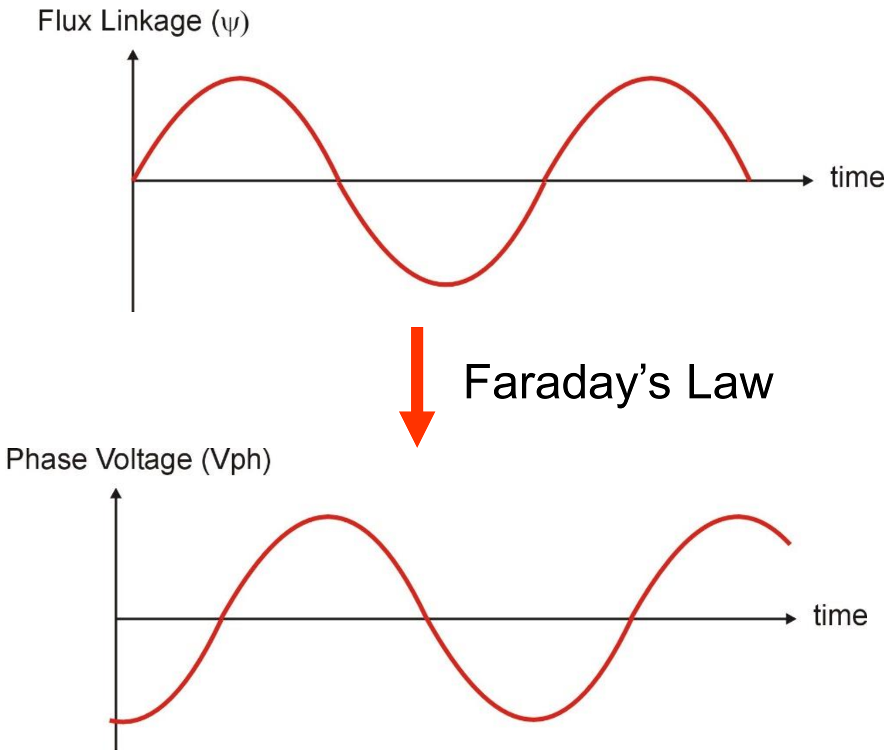




Stator Winding Open Circuit Voltage (V_{ph})

$$\boxed{\psi = N\phi}$$



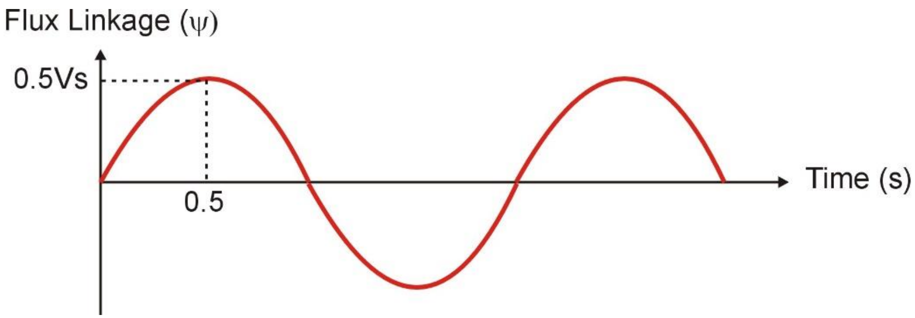


$$\boxed{V_{ph} = \frac{Nd\phi}{dt} = \frac{d\psi}{dt}}$$

Note: Flux magnitude FIXED by Permanent Magnet

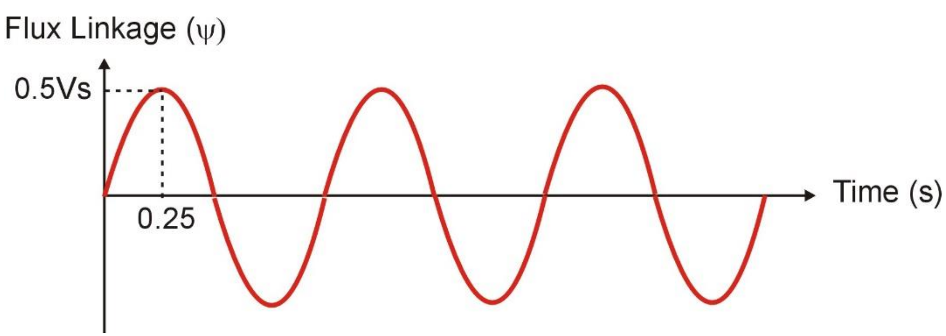
Stator Winding Voltage (V_{ph}) v Rotor (turbine) speed

Speed 1: 30rpm

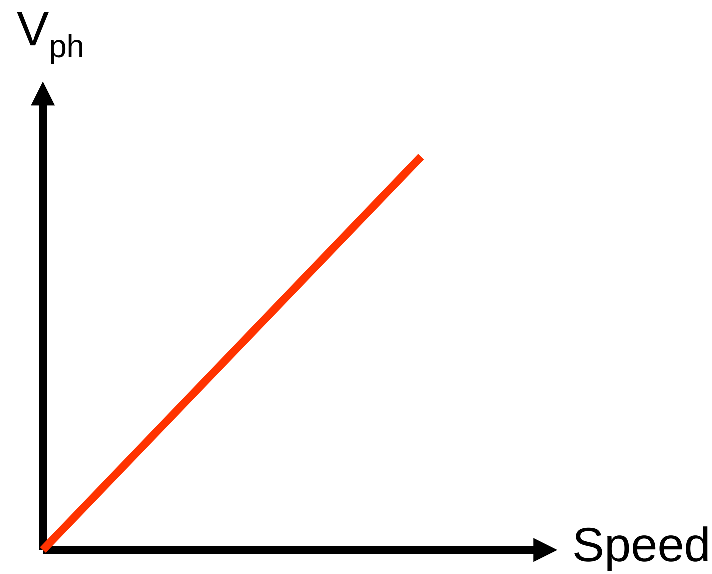


$$V_{ph} = \frac{d\psi}{dt} = \frac{0.5}{0.5} = 1V$$

Speed 2: 60rpm



$$V_{ph} = \frac{d\psi}{dt} = \frac{0.5}{0.25} = 2V$$



Linear Relationship between Stator Voltage and turbine speed

Increasing the PM Generator Output Voltage

Typically we want a generator to operate at as high a voltage as possible as this will limit I^2R losses for a given power output. The question is how can we achieve this in a basic PM generator?

Faraday's Law gives us an insight:

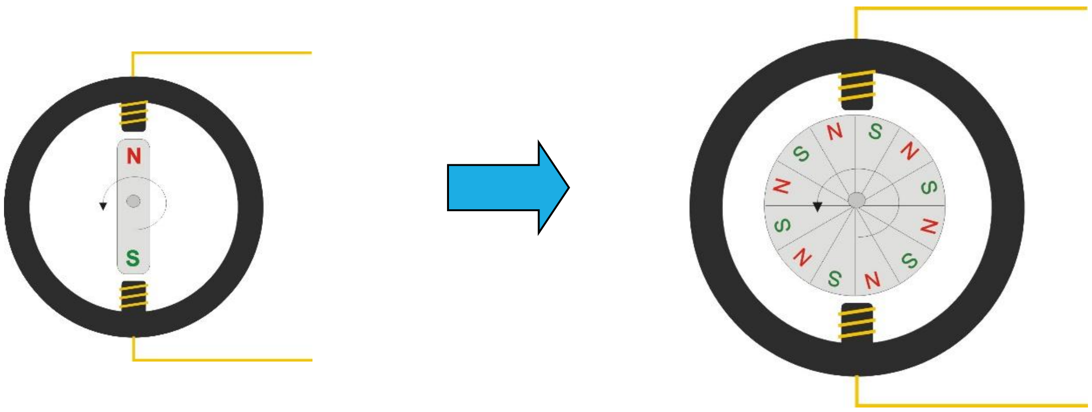
$$\boxed{V_{ph} = \frac{N d\phi}{dt}}$$

Options:

1. Increase the number of turns (N) on the stator winding (limited by I^2R losses)

2. Increase $d\Phi/dt$

Note we cannot increase Φ as this is set by the magnet



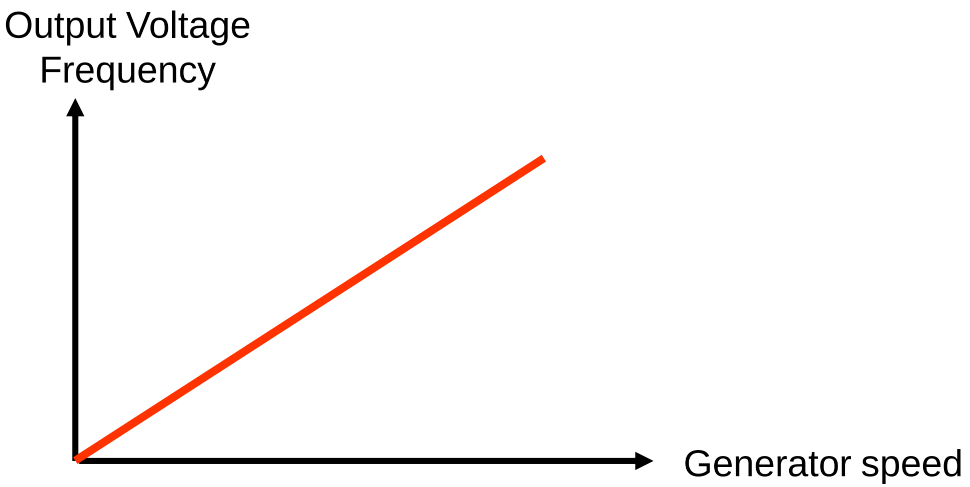
The result is that PM generators typically have a high number of magnet poles on the rotor

Frequency of Generator Output Voltage (f_s) as a function of generator speed (N_r) and number of rotor poles (P)

$$f_s = \frac{N_r.P}{120}$$

where:
f_s (Hz)
N_r (rpm)

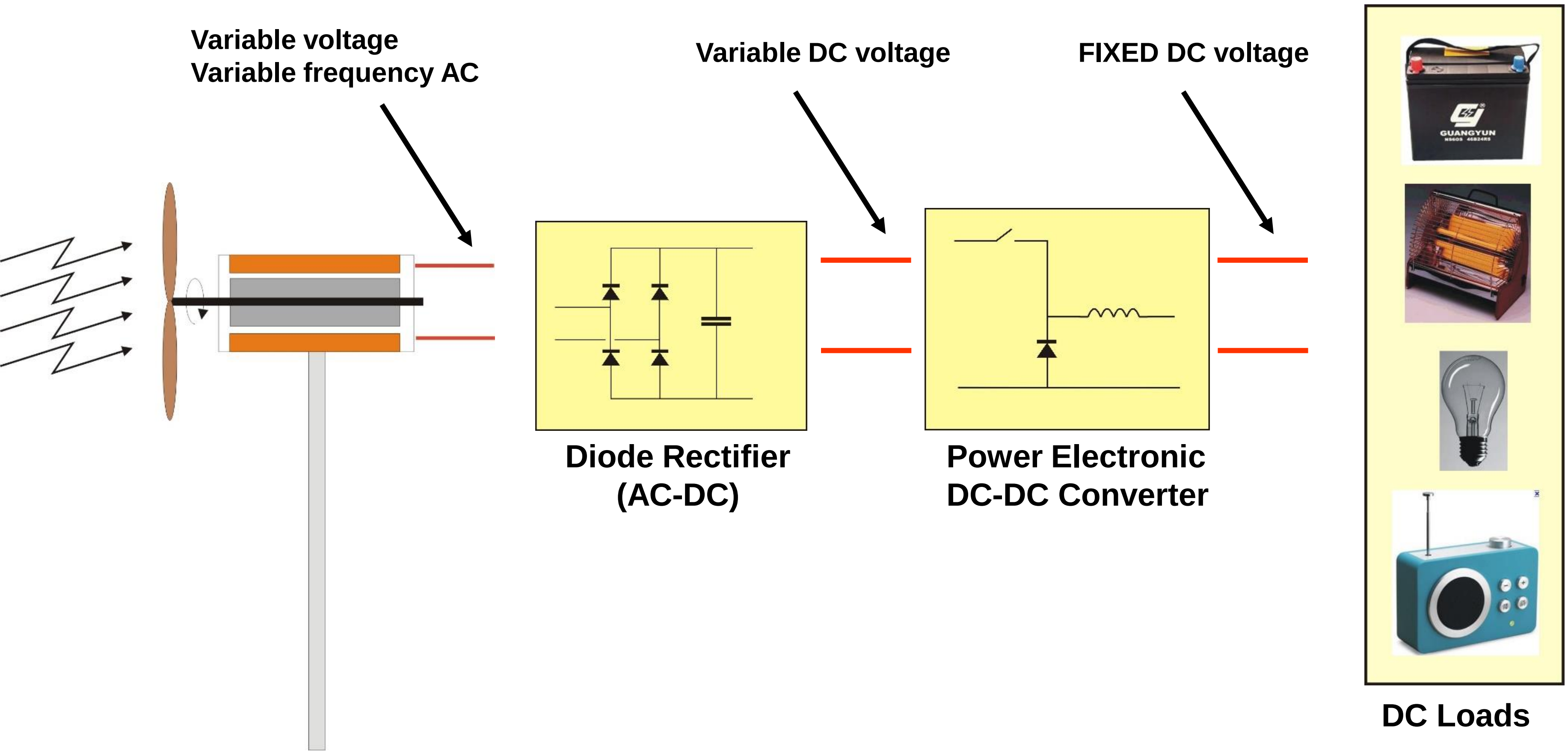
Note: given the electrical frequency is at the same frequency as the rotor, we call this a **SYNCHRONOUS** machine



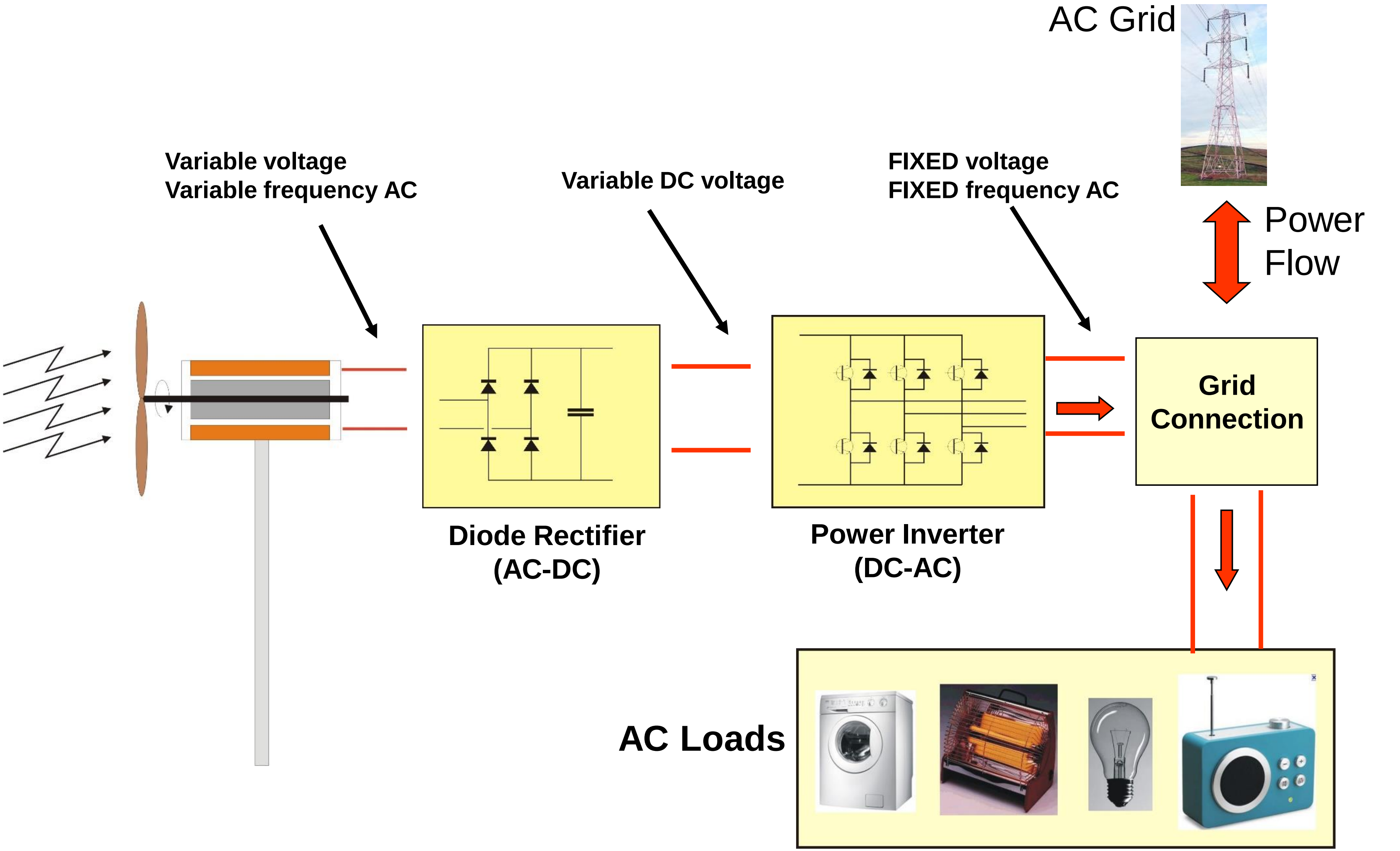
The result is that both the Output Voltage magnitude and frequency are linearly proportional to generator speed – Question is how do we interface this to an electrical system?

Option 1: Connection to a Stand Alone DC System

Typical applications are isolated locations requiring an electrical supply (remote farmhouses, Telecoms stations, mountain huts), and small boats

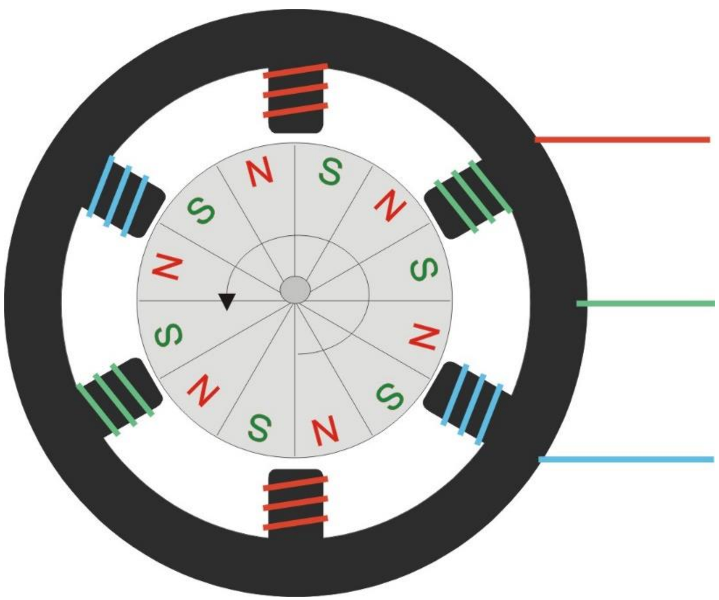


Option 2: Connection to existing AC GRID System (240V/50Hz)

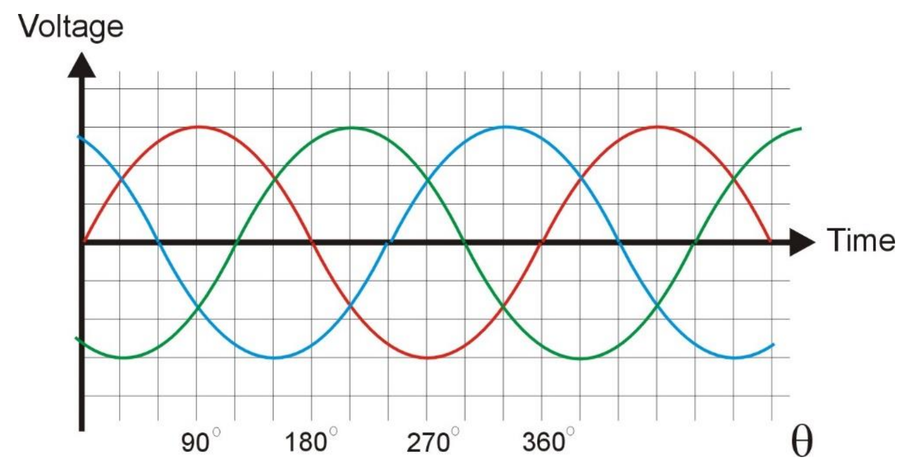


3 Phase Permanent Magnet Generator

As discussed in a previous lecture the power density of a 3 phase machine is superior to its single phase equivalent, hence 3 phase PM generators are common



3 Phase Output Voltage



Small PM Generator Examples

6kW Proven Generators on island of Eigg

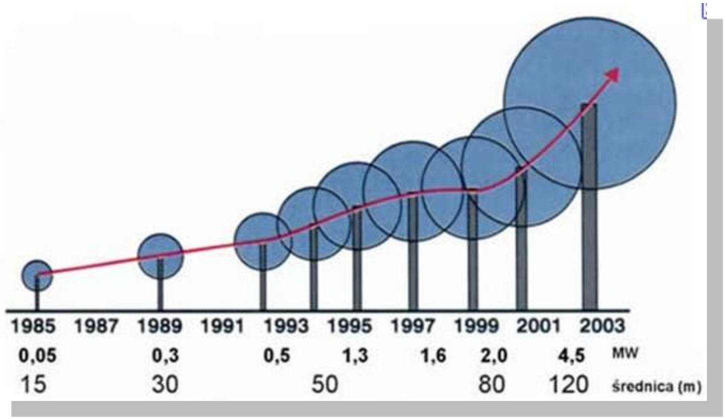
Rutland 50W boat charger

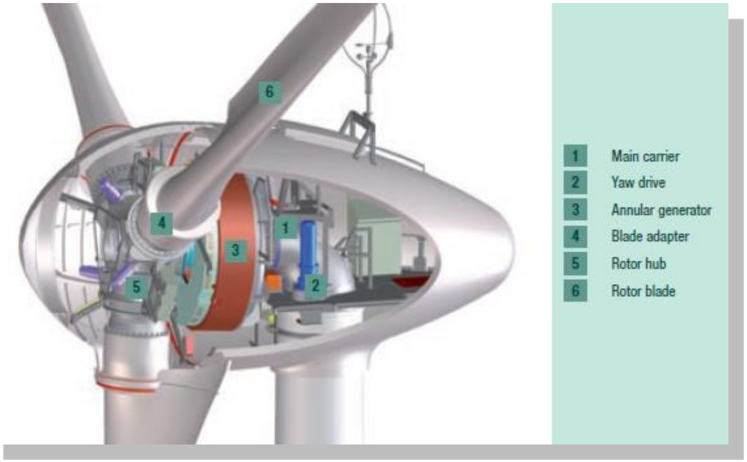
3.3kW Quiet Revolution Vertical Axis Turbine

2.5kW Proven Generator
On Shell Gas Rig

So how big do PM Generators get?

The company Enercon have been developing permanent magnet wind turbines for a number of years now. Their biggest generator is rated at 7.5MW.





So what about installations which require bigger generators, what types of machines are used here?

Examples:

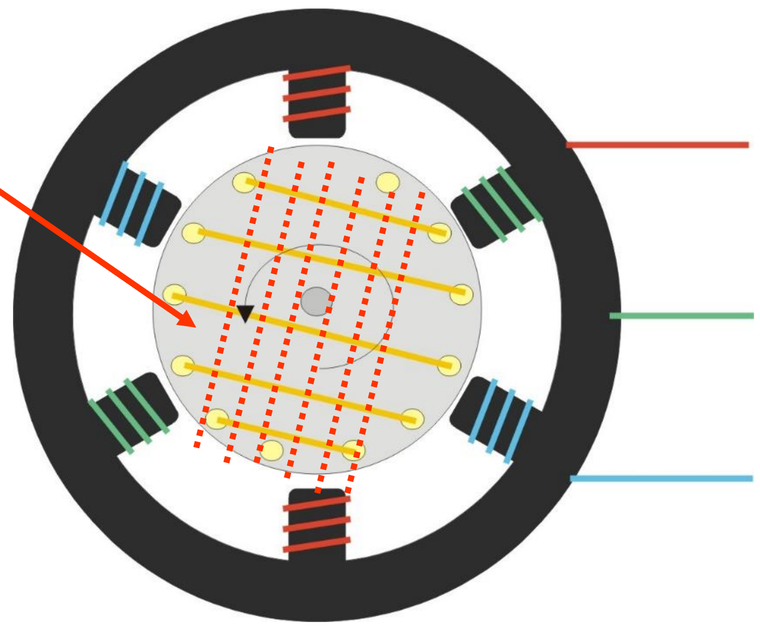
Longannett coal powered electrical power station on the Forth has two 300MW electrical generators

Cruachan Hydro Electric scheme uses four 100MW electrical generators

Answer: **Wound Field Synchronous Generators**

The wound field synchronous generator is similar to the permanent magnet generator but with the permanent magnets replaced by electro-magnets on the rotor.

DC Current is supplied to the rotor winding to produce rotor Magnetic Flux

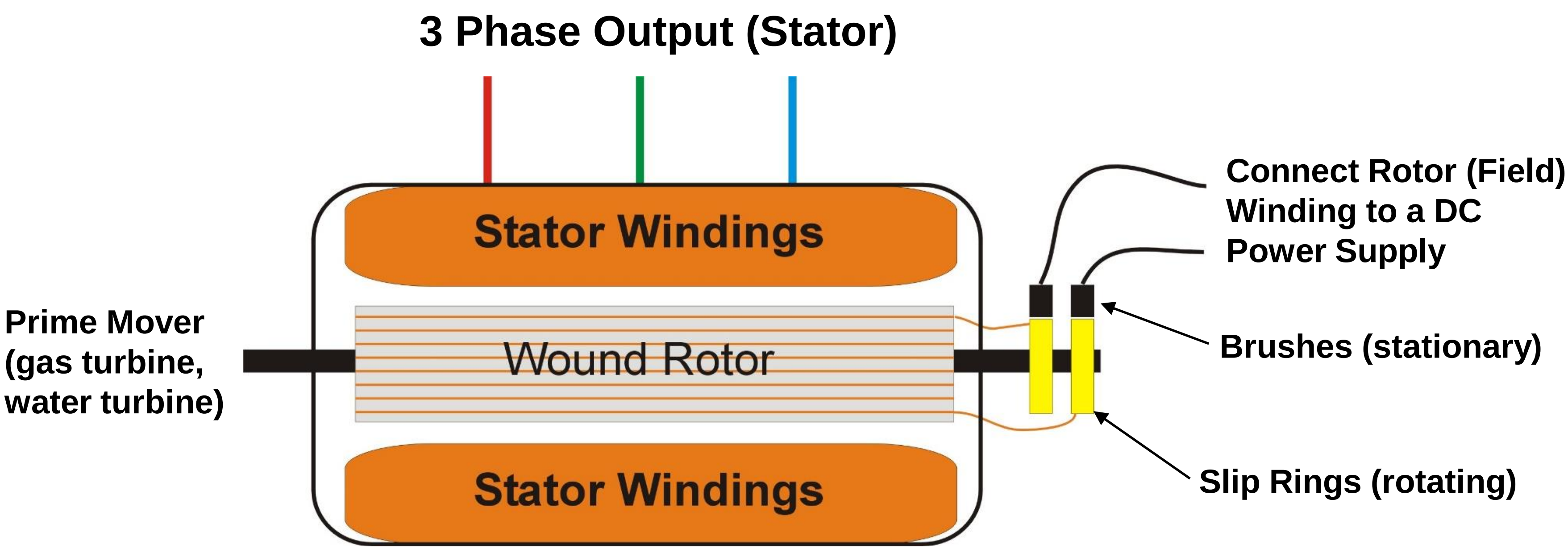


3 phase Electrical Output

Note: this shows a simplistic 2 pole rotor winding – in reality high pole numbers are common as well

IMPORTANT: large synchronous generators are FIXED speed machines to give a fixed frequency (50Hz) Output Voltage

Anatomy of a Wound Field Synchronous Generator



Operation: The prime mover rotates the shaft at a given speed. DC current (I_f) in the Field Winding produces a rotating magnetic flux. This flux links with the 3 phase stator windings to produce 3 phase sinusoidal voltages from the 3 Stator (power) windings. These windings are connected to an electrical load

Relationship between Rotor Field Winding Current (I_f) and the three phase Stator Winding voltages:

Rotor Field Current (I_f)

↓

Rotor Field Intensity ($H = nI_f/L$)

↓

Rotor Flux ($\Phi = \mu HA$)

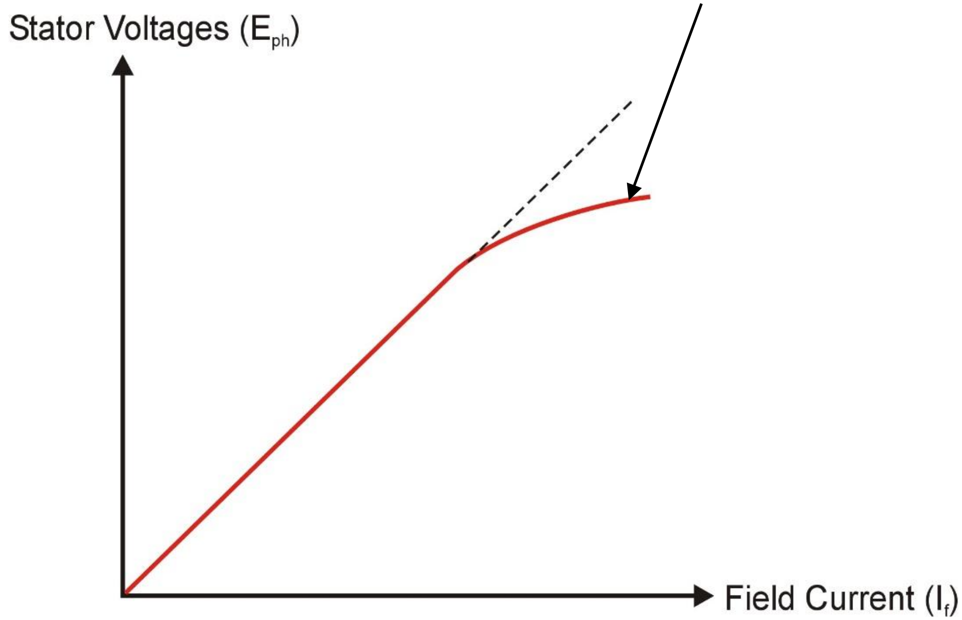
↓

$d\Phi/dt$

↓

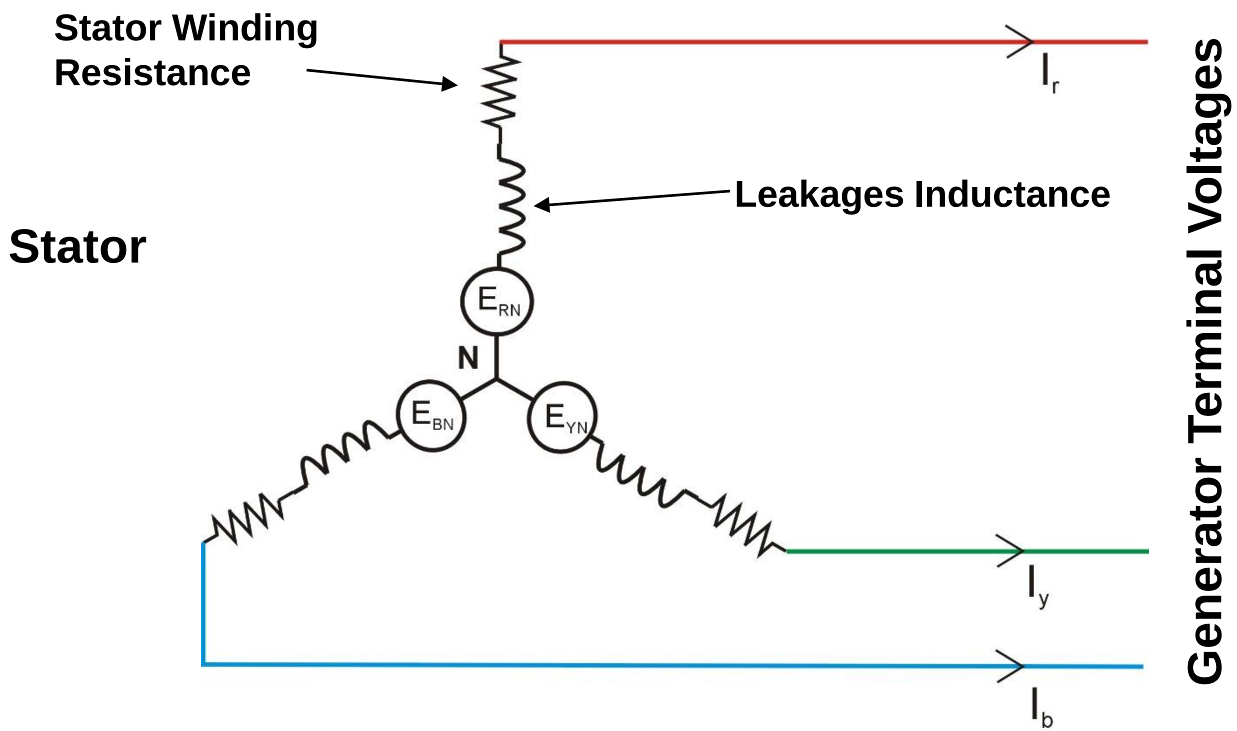
3 Phase Stator Voltages (E_{ph})

Due to saturation of the iron laminations at high flux levels (BH curve for iron!)



Result: we can control (REGULATE) the Stator **Excitation** Voltages by controlling the DC Field Current (I_f)

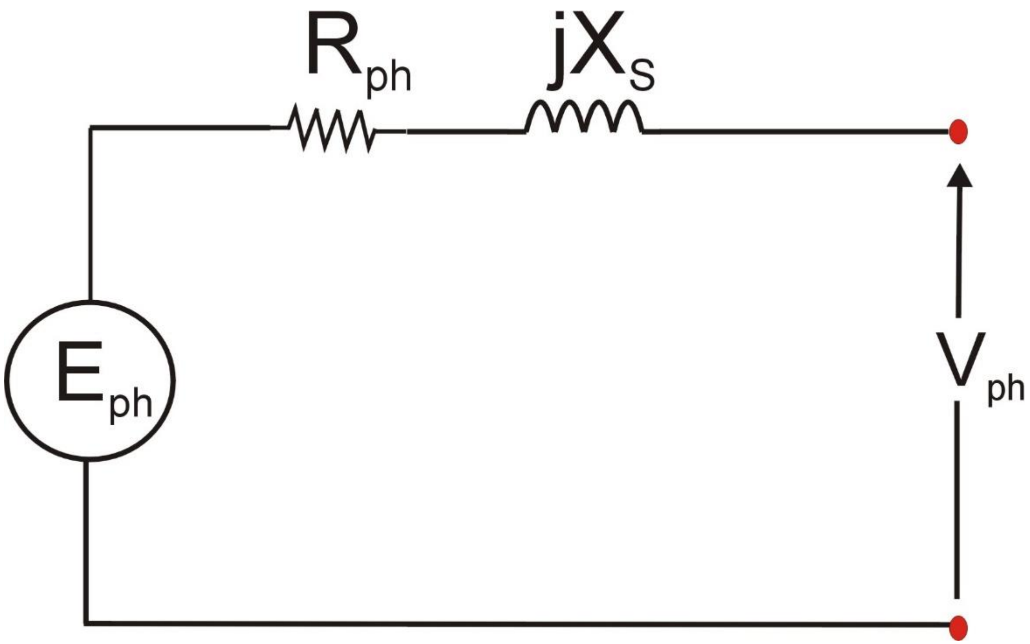
Wound Field Synchronous Generators



Line currents I_R, I_Y and I_B will flow if 3 phase load connected to Generator terminals

DC Field Winding Current I_f creates rotor magnetic field which induces 3 (proportional) AC Excitation voltages E_{RN}, E_{YN} and E_{BN}

Per Phase Equivalent Circuit:



Terminology:

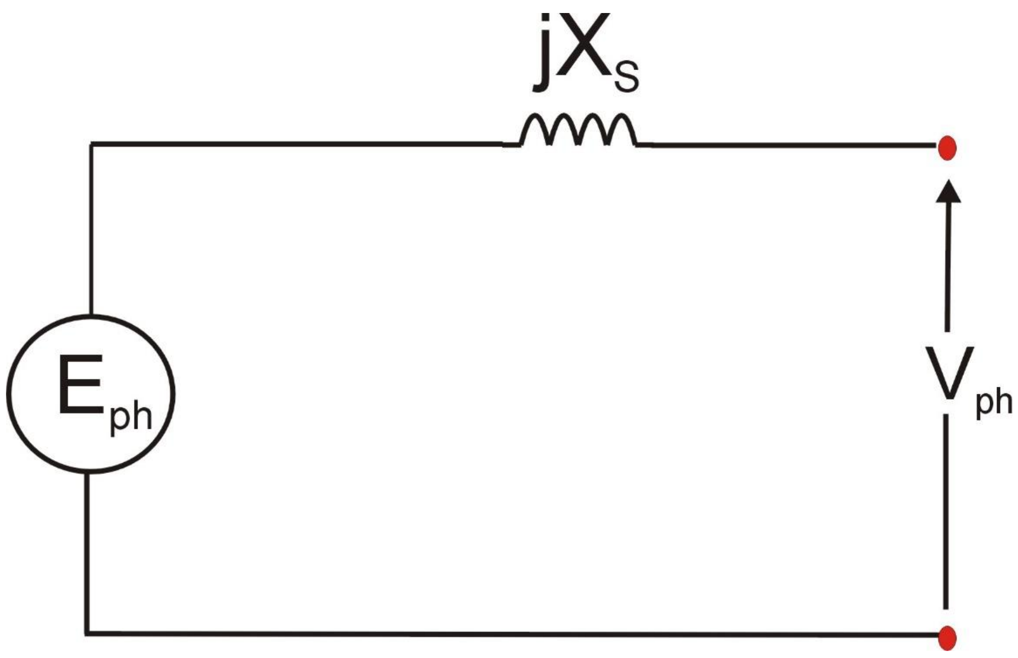
E_{ph}: Excitation Voltage (set by I_F)

R_{ph}: Stator winding Resistance (negligible voltage drop so ignore)

jX_S: SYNCHRONOUS Reactance

V_{ph}: Terminal Phase Voltage

Per Phase Equivalent Circuit:



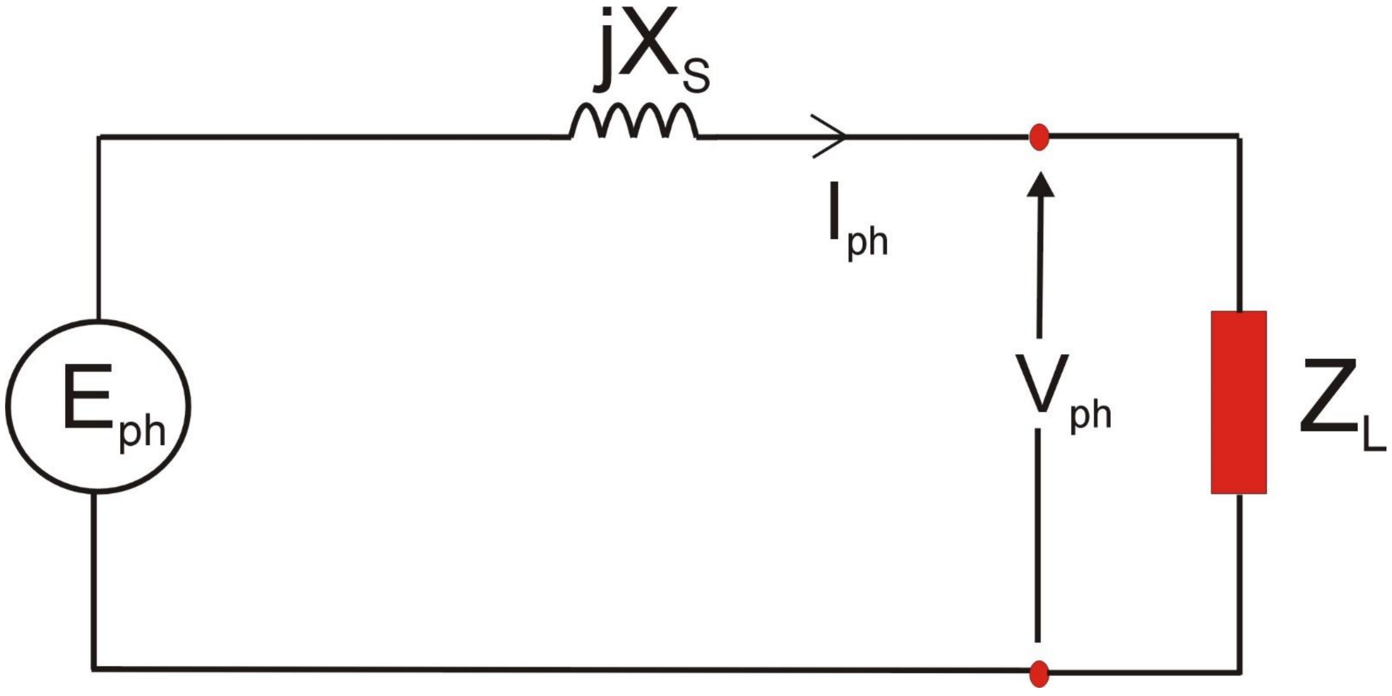
Terminology:

E_{ph}: Excitation Voltage (set by I_F)

jX_S: SYNCHRONOUS Reactance

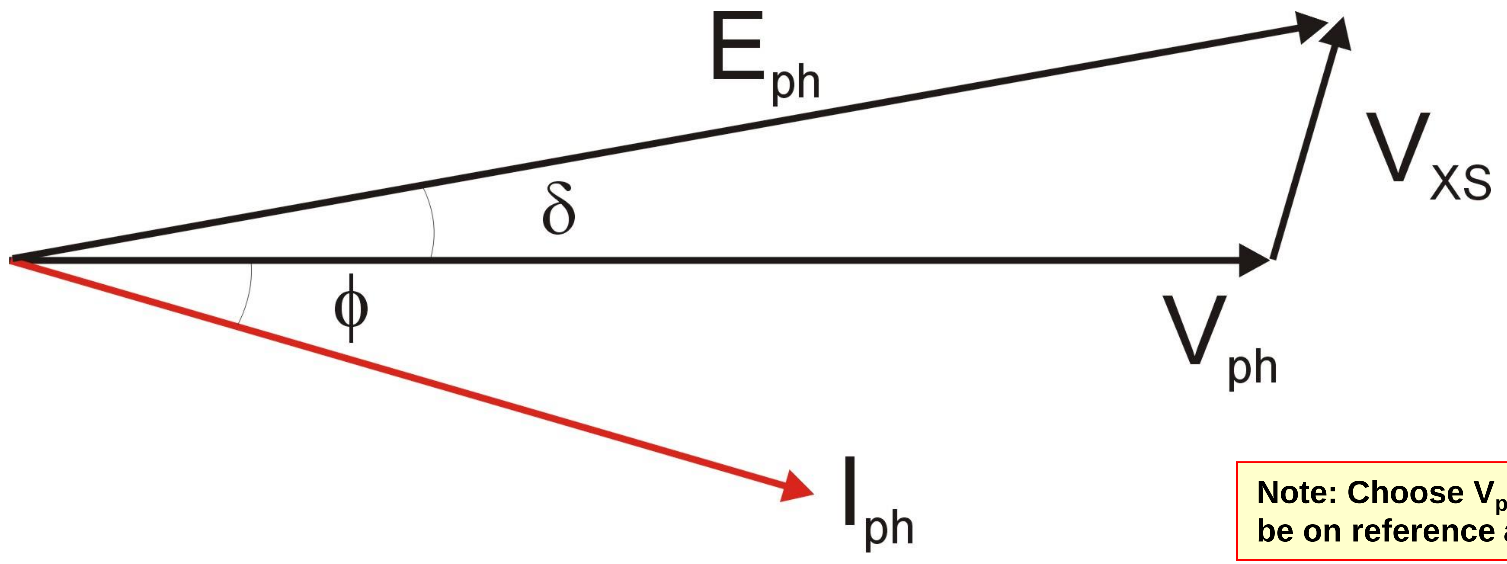
V_{ph}: Terminal Phase Voltage

Per Phase Equivalent Circuit with Load Impedance Z_L:



A Phase current I_{ph} will flow through load Z_L, the magnitude and phase of which is determined by E_{ph}, X_S and Z_L. The Terminal Voltage V_{ph} can the be determined once I_{ph} is known.

Typical (per phase) Phasor Diagram



Note: Choose V_{ph} to be on reference axis

Notes:

1. The angle Φ is the load **Power Factor Angle** (angle between V_{ph} and I_{ph})

2. The Voltage across the Synchronous Reactance (V_{XS}) leads the phase current I_{ph} by 90º ($V_{XS} = I_{ph}.jX_S$)

3. $E_{ph} = V_{ph} + V_{XS}$ (phasor arithmetic)

4. The Angle δ between V_{ph} and E_{ph} is termed the **LOAD ANGLE**