CATAPULT
Offshore Renewable Energy

Electric Grid Influences on Floating Wind Turbines

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14.11.2023

ADOreD Symposium Twente University

Credit: Equinor Hywind Floating Offshore Wind Farm

The Day's Agenda

Event	Time
Round the Room	09:00 – 09:20
Setting the Scene	09:20 – 09:50
The Dreaded Black Box! Part 1	10:00 – 10:40
The Dreaded Black Box! Part 2	11:00 – 11:40
The Dreaded Black Box! Part 3	11:50 – 12:30
Lunch	12:30 – 13:20
Renewables and the Grid	13:20 – 14:00
Modelling Exercise	14:10 – 17:00

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Round the Room

Introductions

Welcome to the first Annual Meeting of ModConFlex!

As a bit of an icebreaker I'd like you to spend 3 mins getting to know the person next to you.

You will then introduce that person to the room, giving their **name** and an **interesting fact** about them.

Setting the Scene:

Why do I care about the electric grid I'm looking at floating platforms!

- Climate Change Agreements
- Proposed Solutions
- Consequences for the Electric Grid

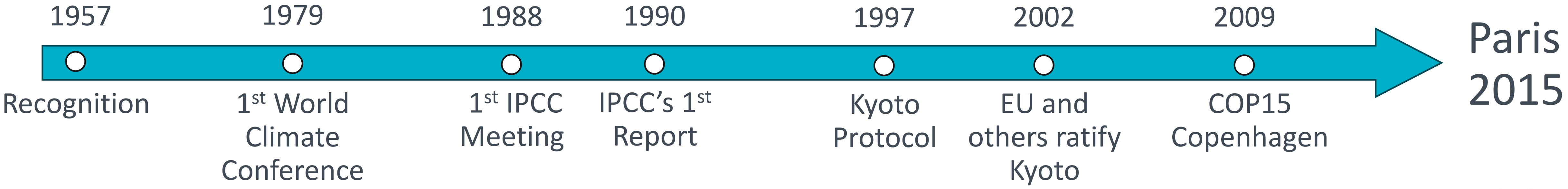
Carbon Ambitions

We can all agree, anthropogenic climate change bad

Paris agreement – 2015 at COP21 196 countries adopted legally binding treaty to prevent: “*the increase in the global average temperature to well below 2°C above pre-industrial levels*”

And “*to limit the temperature increase to 1.5°C above pre-industrial levels*”

Timeline of climate change science starts - Paris



The long road to Paris, UCL

Proposed Solution

This will be largely accomplished through significant deployment of renewables,

Solar, wind, wave and tide

In the UK for example there is an ambition to develop 50GW of offshore wind alone by 2030! Currently we only have circa 13 GW

Renewable vs. Traditional Generation

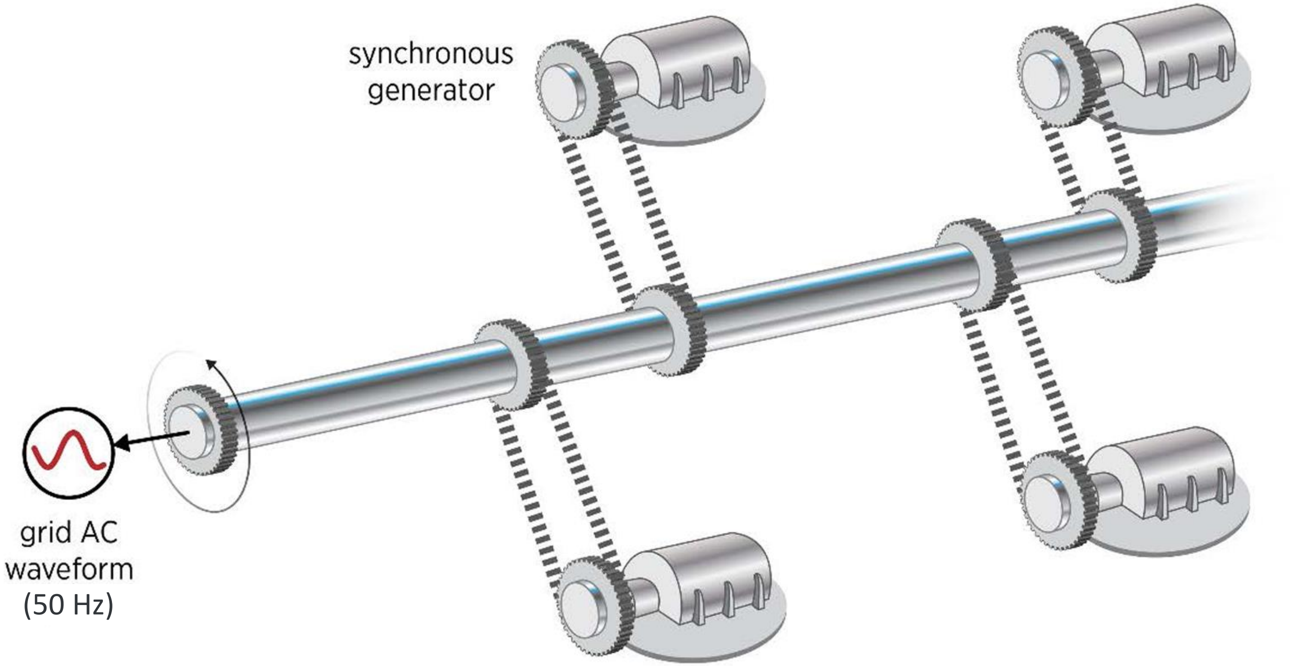
Traditional Power Plant

Traditional power generators are tied directly to the grid. Therefore, all traditional (thermal) power generators rotate in synchronism.

Any change to grid frequency requires all the spinning masses in the country to speed up or slow down. Therefore, there is in built inertia!

All the generation is “dispatchable” i.e. power can be increased or decreased at will.

Generators are composed of large amounts of copper winding. Therefore, they have large power overload capabilities.



https://www.nrel.gov/docs/fy20osti/73856.pdf

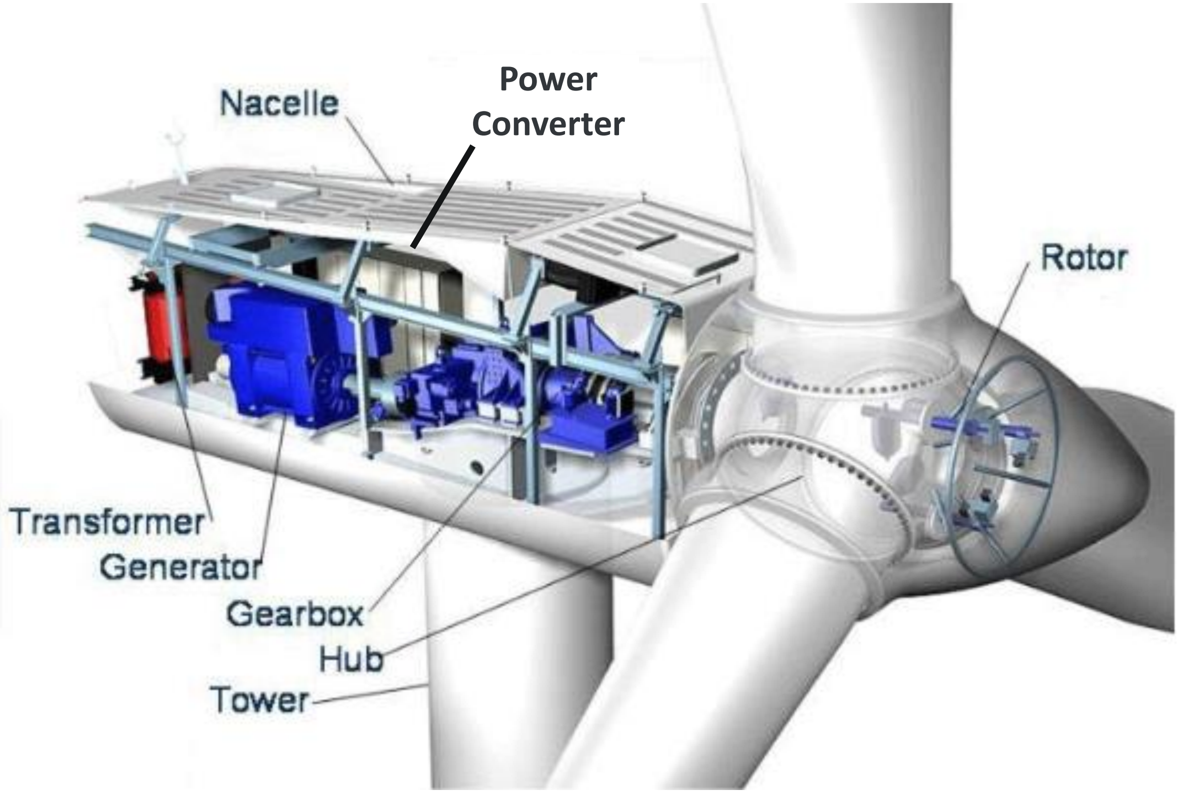
Renewable vs. Traditional Generation

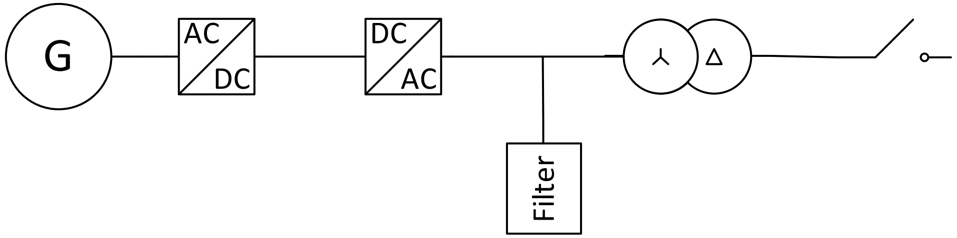
Renewable Power Plant

Modern offshore wind turbines use Permanent Magnet Synchronous Generators (PMSGs) with fully rated power converters between the generator and the grid.

This effectively separates the generator rotor from the electric grid.

Power electronics do not do well with over current.





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Electrical Challenges

Key Challenges from NG ESO

1. **Frequency**: system inertia reducing, increased changes in generation (because of renewables) system frequency more volatile and unpredictable.
2. **Stability**: Decline in inherent stability of system due to increased converter based renewables.
3. **Voltage**: Maintaining voltage levels more challenging because of reduced reactive power demand in the distribution network and reduced power flows in the transmission network. This means that there is an increased need to absorb reactive power in the transmission network.
4. **Thermal**: Thermal limits to various parts of the GB network. Need to build new infrastructure and/or manage these constraints.
5. **Restoration**: When the electricity system fails, historically large fossil fuel based generation takes care of restoration services. Now, that may need to be distributed and provided by a range of users in the future.

The Dreaded Black Box:

Basic Electric Theory

- Introduction to Electricity?
- Equations and Laws
- Impedances
- AC Systems
- Semi-Conductors
- Power Converters

Electrical Introduction

Definitions

Electric current:	rate of **charge** flow past a point in an electric circuit
Electric Voltage:	also known as potential difference is the amount of energy needed to move a charge from one point to another
Direct Current (DC):	An electric current flowing in one direction only
Alternating Current (AC):	An electric current that reverses its direction at regular intervals

Electrical Introduction

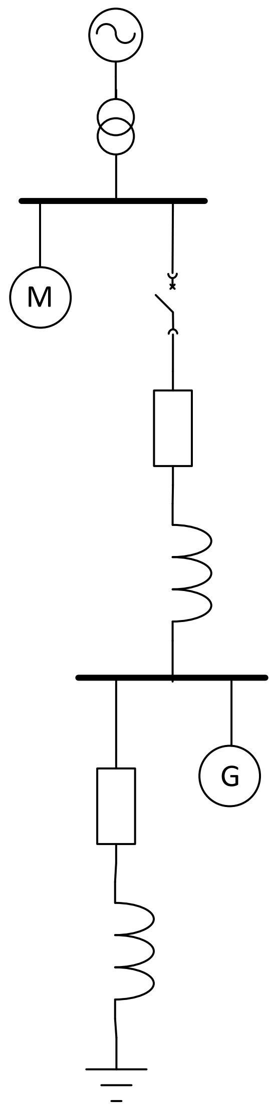
Single Line Diagrams

Single line diagrams (SLDs) are a simplified **electrical** depiction of a circuit and are an essential tool for all electrical engineers.

They are used as an input for everything from:

- a simple circuit analysis (back of the packet calcs)
- to full computer simulation analysis (equivalent to FEA)
- or depiction of the electrical layout of a building or country (similar to a blueprint)

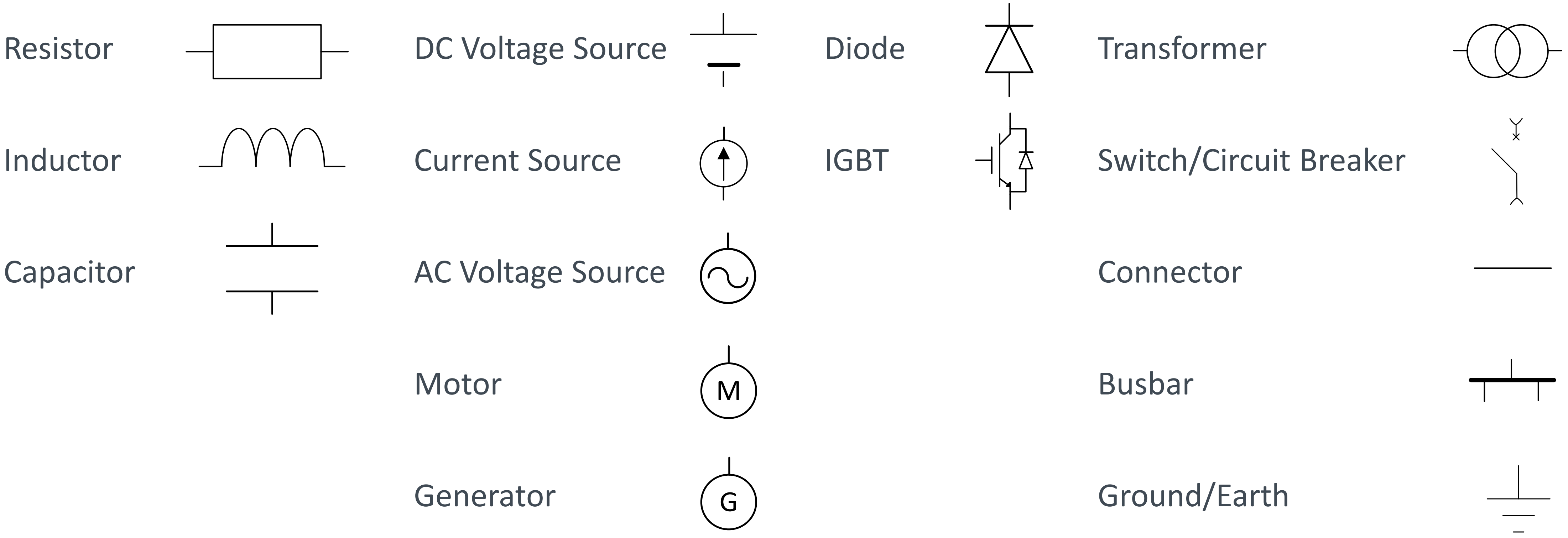
Note SLD’s are not drawn to scale they are an **electrical depiction** *not* a physical depiction!



Electrical Introduction

Single Line Diagrams

Fundamental Symbols:



Equations & Laws

Ohm's Law

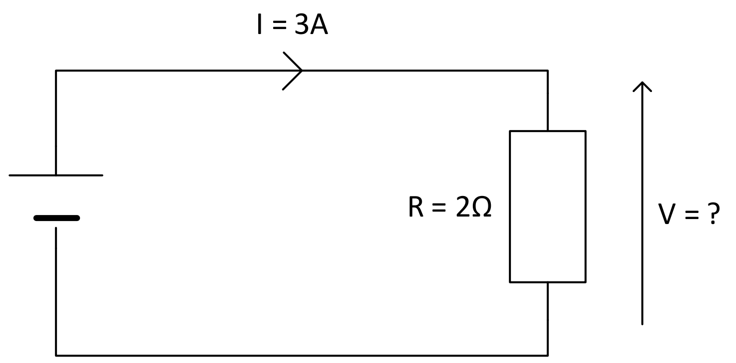
Electrical theory is easy! All you need to know is a few basic equations and laws and everything is built up from that. Starting with Ohms law:

$$V = IR$$

Where:

- V is Voltage
- I is current
- R is resistance

Example:

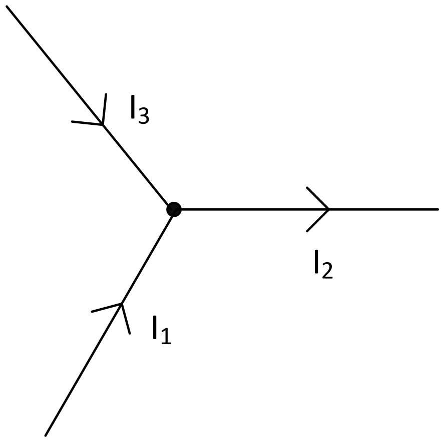


Equations & Laws

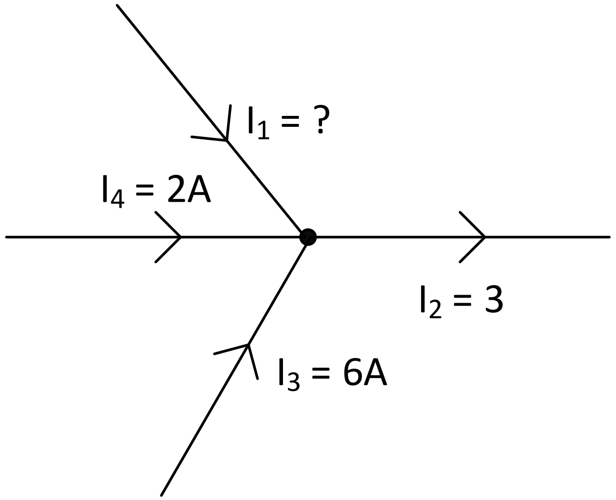
Kirchhoff's Current Law

Kirchhoff's first law (current law) states that the current flowing into and out of a node must sum to zero.

$$I_1 + I_2 + 1_3 = 0$$



Examples



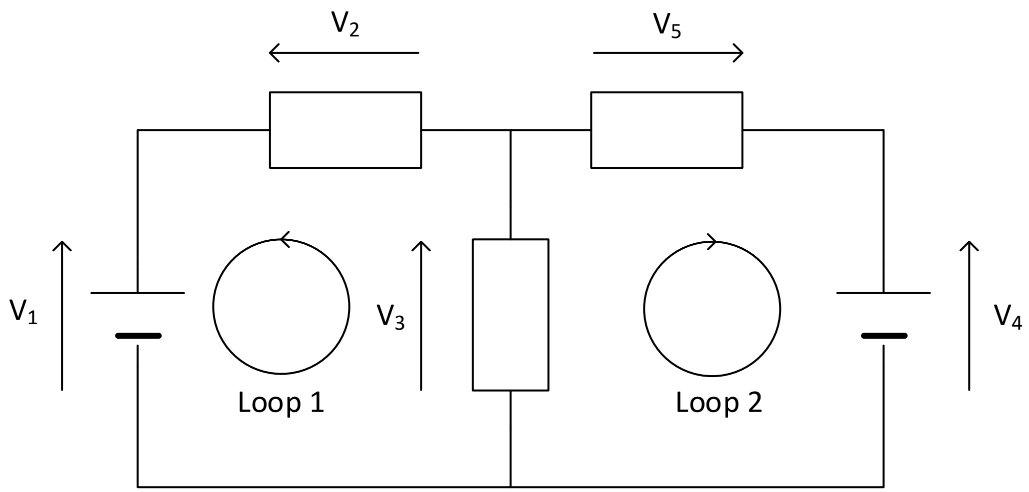
Equations & Laws

Kirchhoff’s Voltage Law

Kirchhoff’s second law (Voltage law) states that in any complete loop within a circuit, the sum of all voltages must equal zero.

Loop 1: $V1 + V2 + V3 = 0$

Loop 2: $V4 + V5 + V3 = 0$



Impedances

Resistors

Key Facts

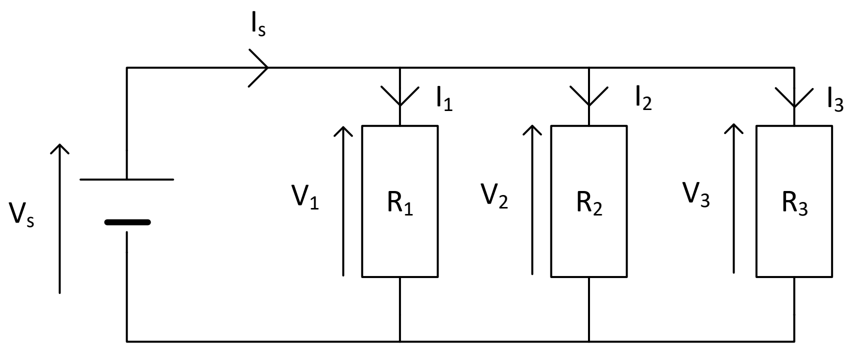
Symbol – Resistance, R

Units – Ohms, Ω

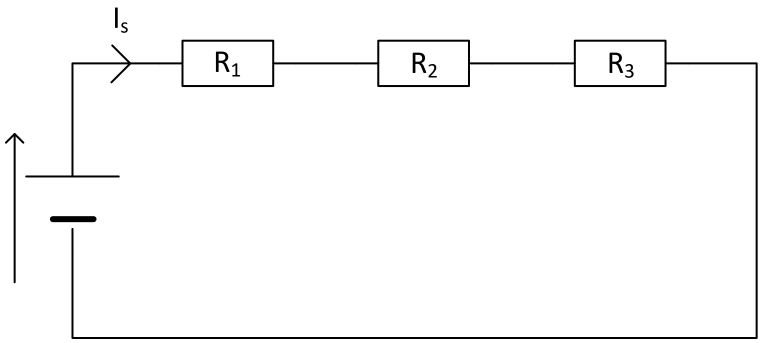
Dissipates energy as heat

Key Equations

- Resistance (R): $C = \frac{\epsilon_0 \epsilon_r A}{d}$
  - N, resistivity of material
  - l, length of material [m]
  - A, cross sectional area material [m^2]



Parallel Circuit



Series Circuit

Total series inductance: $R_t = R_1 + R_2 + R_3$

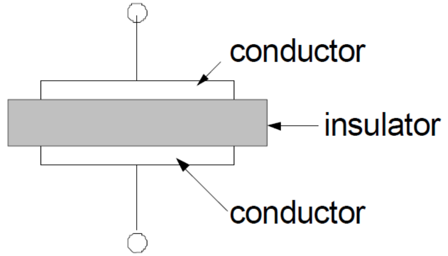
Total parallel inductance: $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

Power (P): $P = IV \quad P = I^2 R \quad P = \frac{V^2}{R}$

Voltage: $V = IR$

Impedances

Capacitors



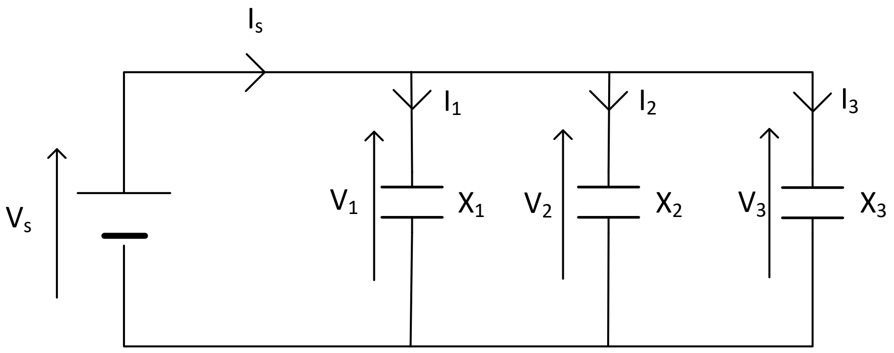
Key Facts

Symbol – Capacitance, C

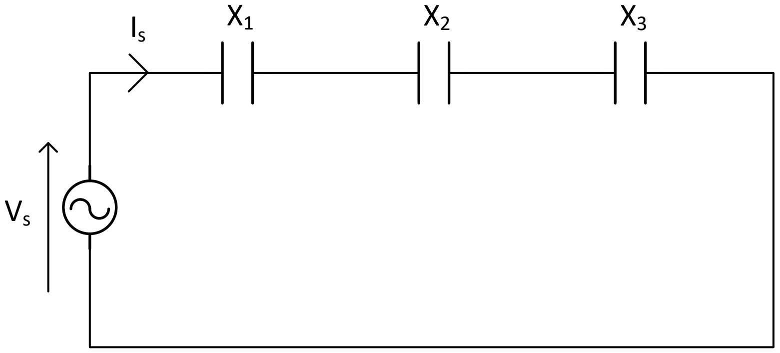
Units – Farads, F

Voltage doesn't change instantly

Stores electromagnetic energy



Parallel Circuit



Series Circuit

Key Equations

- Capacitance (C): $$C = \frac{\epsilon_0 \epsilon_r A}{d}$$
  - ε_0, relative permittivity of free space (8.85×10^{-12} [F/m])
  - ε_r, relative permittivity of the insulation material
  - A, cross sectional area of each plate [m^2]
  - d, distance between plates [m]

Energy (E): $$E = \frac{1}{2} C V^2$$

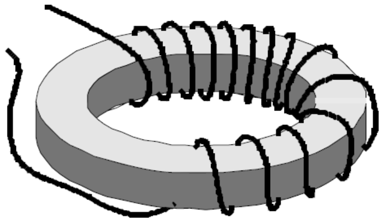
Total series capacitance: $$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Total parallel capacitance: $$C_t = C_1 + C_2 + C_3$$

Current: $$I = C \frac{dV}{dt}$$

Impedances

Inductors



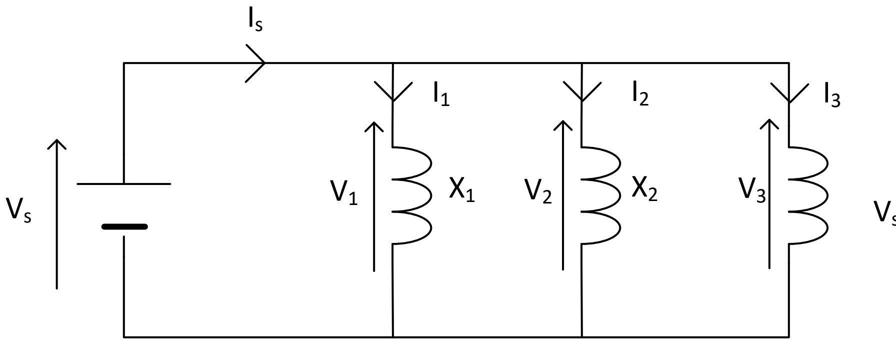
Key Facts

Symbol – Inductance, L

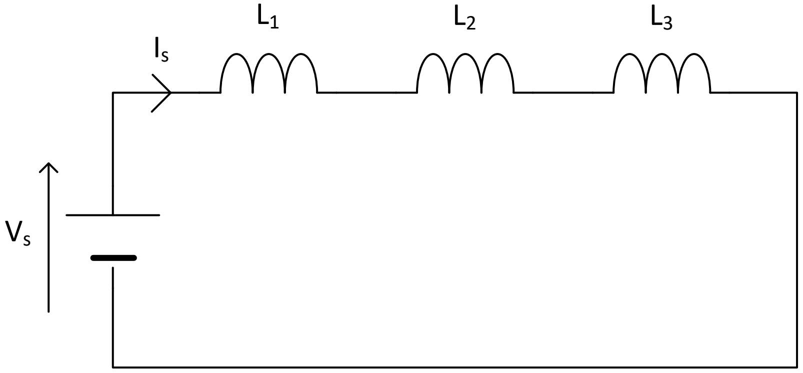
Units – Henrys, H

Current doesn't change instantly

Stores electromagnetic energy



Parallel Circuit



Series Circuit

Key Equations

- Inductance (L): $$L = \frac{N\mu_0\mu_r A}{l}$$
  - N, Nº of turns
  - μ_0, relative permeability of a vacuum ($4\pi \times 10^{-7}$ [H/m])
  - μ_r, relative permeability of the core material
  - A, cross sectional area of the core [m^2]
  - l, length of the flux path [m]

Energy (E): $$E = \frac{1}{2}LI^2$$

Total series inductance: $$L_t = L_1 + L_2 + L_3$$

Total parallel inductance: $$\frac{1}{L_t} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

Voltage: $$V = L\frac{dI}{dt}$$

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AC Systems

Introduction – single phase

This is great however, power is normally transferred via AC not DC.

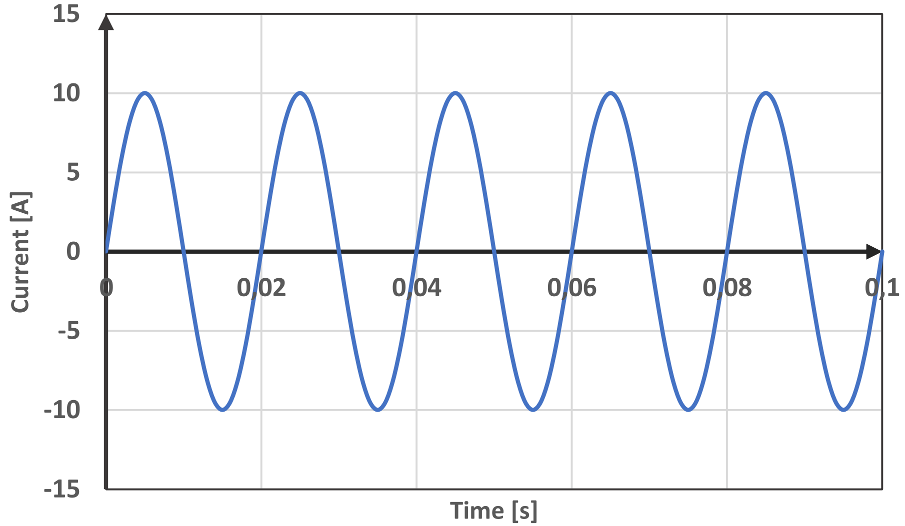
Why do we transfer power via AC?

- Rotating machines naturally produce AC
- Easy to set up and down voltage, Q: why do this though? ($P = I^2R$)
- Easier protection

Standard Voltage/Current form:

$$u = U \cdot \sin(\omega t + \theta)$$
$$i = I \cdot \sin(\omega t + \theta)$$

- ω, frequency [rad/s]
- t, time [s]
- u, instantaneous voltage [V]
- i, instantaneous current [A]
- θ, phase angle [rad]
- *U, Peak voltage [V]*
- *I, Peak current [A]*



An ideal single phase, 50 Hz current waveform

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AC Systems

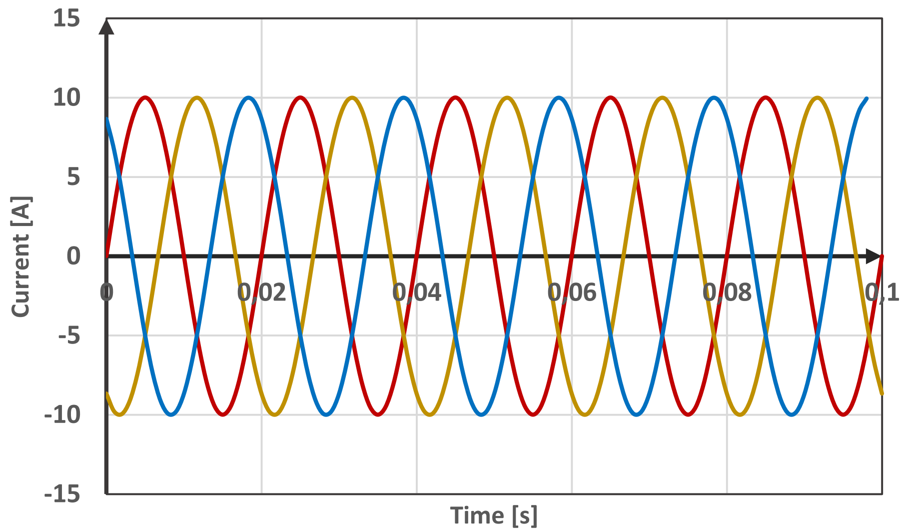
Introduction – 3 phase

That said, distribution and transmission networks are actually 3-phase systems, but why? A hint, each phase is 120^{o} apart.

$$I\sin(\omega t + 0) + I\sin\left(\omega t - \frac{2}{3}\pi\right) + I\sin\left(\omega t + \frac{2}{3}\pi\right) = 0A$$

Therefore fewer cables are required to transfer the same power as we don't need a return!

In reality transmission and distribution systems use 4 wires (phases, A, B, C and neutral) as this only works for "balanced systems" where each phase carries equal current.



An ideal three phase, 50 Hz current waveform

AC Systems

Star and Delta Loads

AC systems do complicate calculations though as voltage and current are no longer static values…

RMS (Root Mean Square)

$$U = \sqrt{\frac{1}{T}\int_0^T \left(\hat{U} \cdot \sin(\omega t + \theta)\right)^2}$$ for ideal sine waves: $$U = \frac{1}{\sqrt{2}}\hat{U}$$

Phase Voltage to Line Voltage Star Connected

$$u_{AB} = u_a - u_b \quad u_{BC} = u_b - u_c \quad u_{CA} = u_c - u_a$$
$$i_A = i_a \quad i_B = i_b \quad i_C = i_c$$

For ideal sine waves: $U_{AB} = \sqrt{3}U_a \angle 30^o$

Phase Voltage to Line Voltage Star Connected

$$i_A = i_a - i_c \quad i_B = u_b - u_a \quad i_C = u_c - u_b$$
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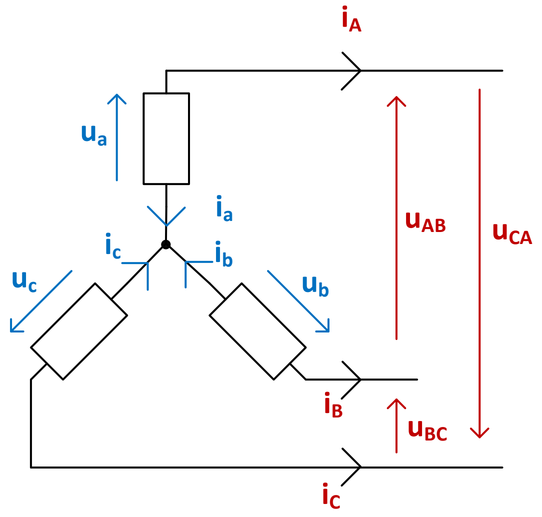
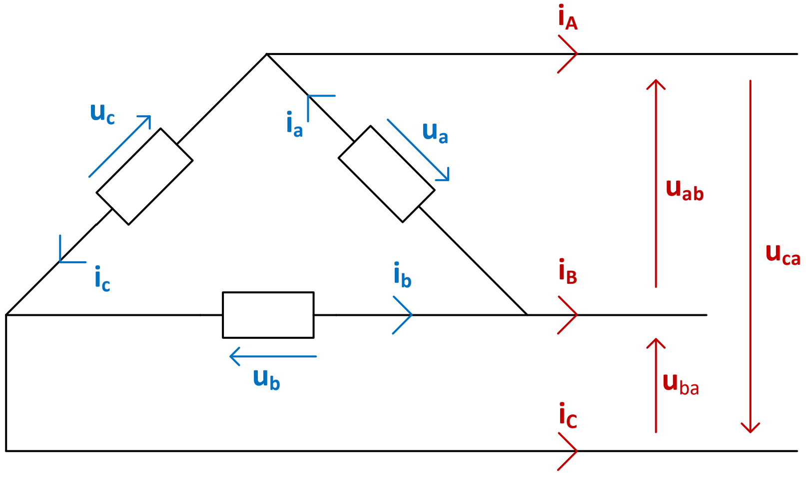


Phase
Line

Star Connected Load



Delta Connected Load

AC Systems

Loads

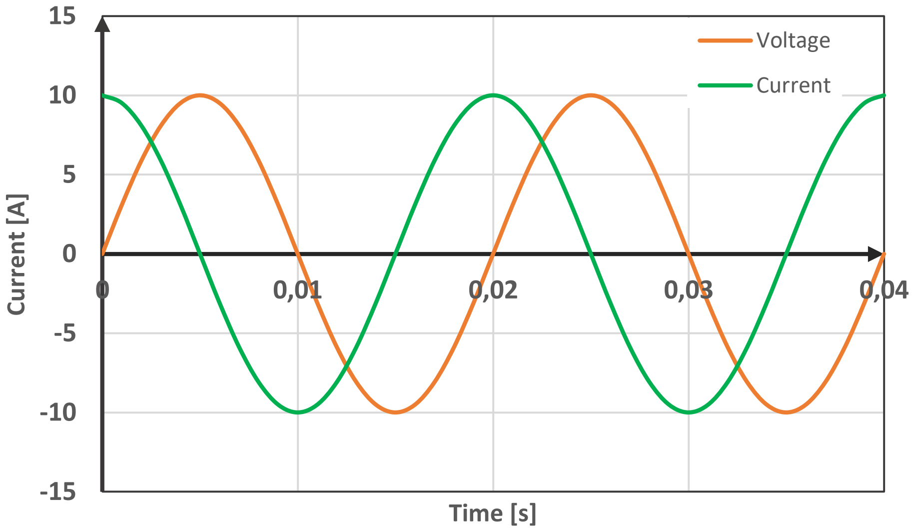
Remember that in a capacitor: $i(t) = C\frac{du(t)}{dt}$

and in an inductor: $u(t) = L\frac{di(t)}{dt}$

Therefore, the voltage across a capacitor in an AC system:

$$u(t) = \frac{1}{C}\int \hat{I}\cos(\omega t + \theta)\,dt$$

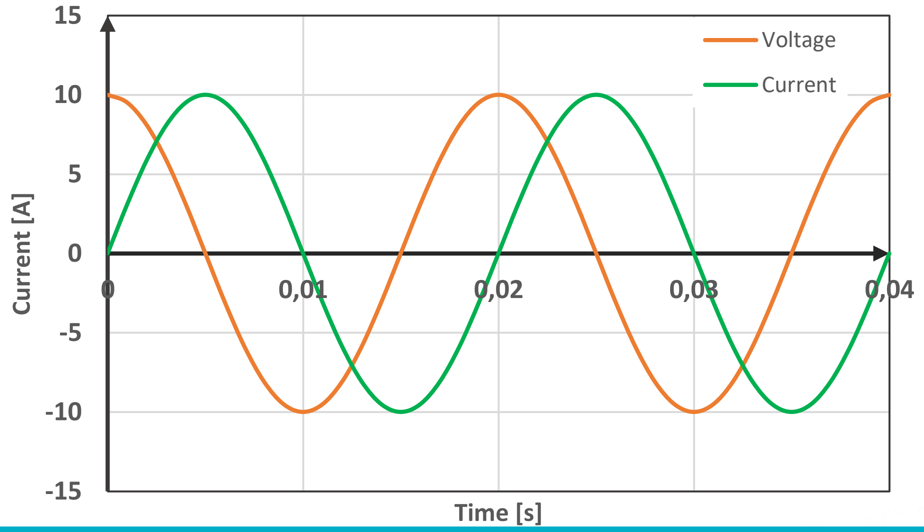
$$u(t) = \frac{1}{\omega C}\hat{I}\sin(\omega t + \theta)$$



Therefore, the current across an inductor in an AC system:

$$i(t) = L\int \hat{U}\cos(\omega t + \theta)\,dt$$

$$i(t) = \frac{1}{\omega L}\hat{U}\sin(\omega t + \theta)$$



AC Systems

Phasor diagrams

Now we see that voltages and currents are no longer necessarily in phase. Therefore, it is important to consider their angle and magnitude. This complicates things when trying to calculate parameters in our circuit diagrams… Fortunately phasor diagrams present a method to simplify things:

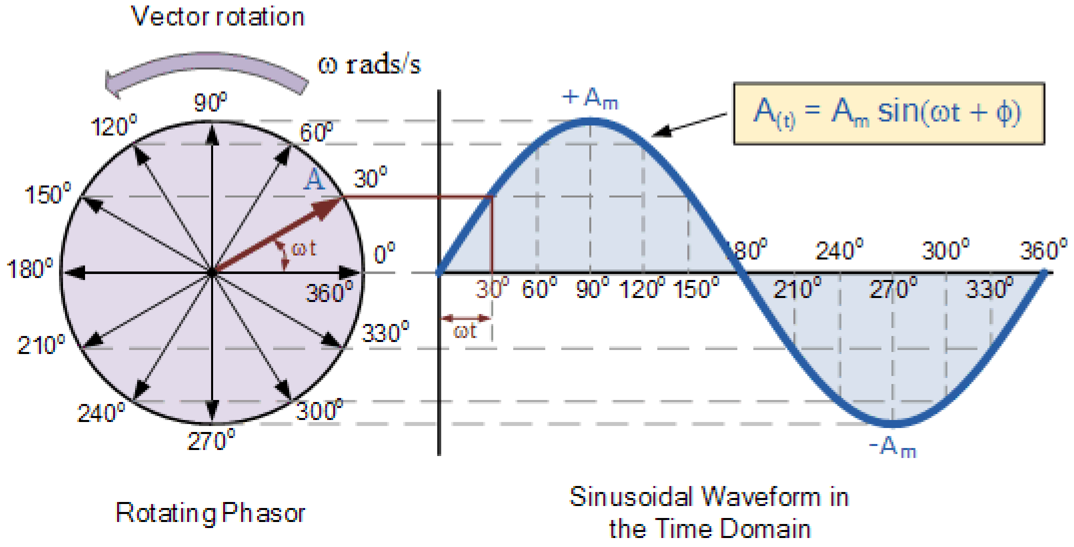


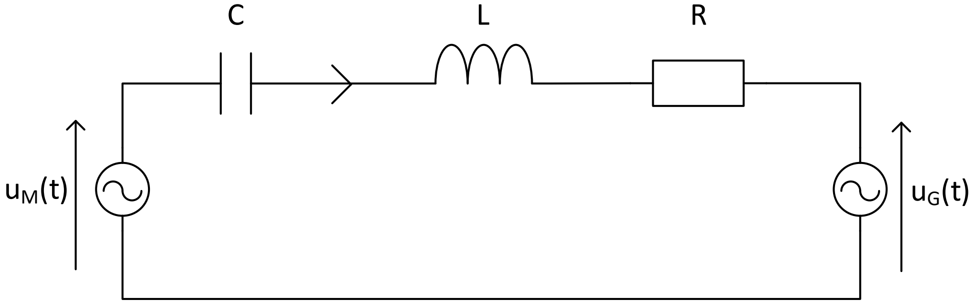
Fig 1. Phasor diagram

Fig1. https://www.electronics-tutorials.ws/accircuits/phasors.html

AC Systems

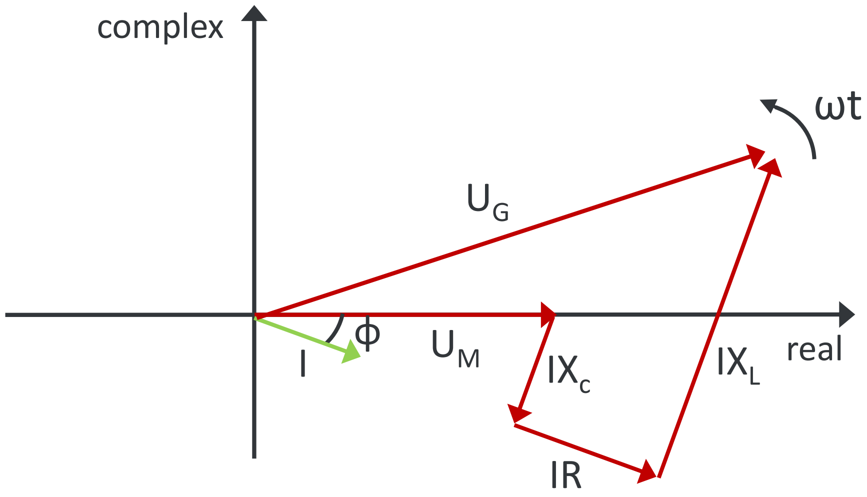
Phasor diagrams

We can therefore create a simple phasor diagram to represent any circuit for example:



Where:

$$X_L = \omega L \text{ and } X_C = \frac{1}{\omega C}$$



Note all magnitudes are RMS values in phasor diagrams!

Fig1. https://www.electronics-tutorials.ws/accircuits/phasors.html

AC Systems

Phasor Notation

Rectangular Form

Z = x + jy

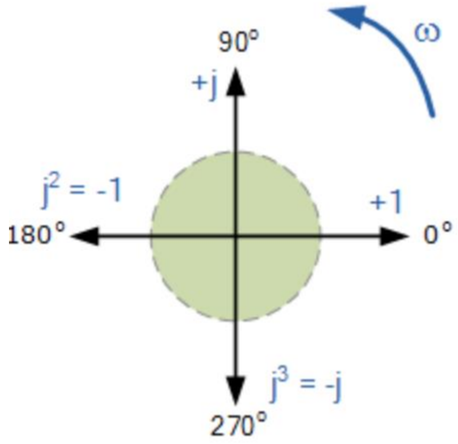
Where $j = \sqrt{-1}$

Polar Form

$Z = A\angle\theta$

Exponential Form

Using Eulers law:



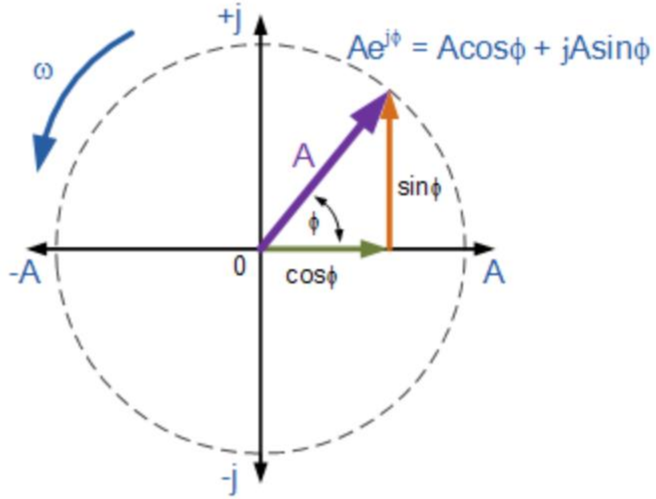


Fig1. https://www.electronics-tutorials.ws/accircuits/phasors.html

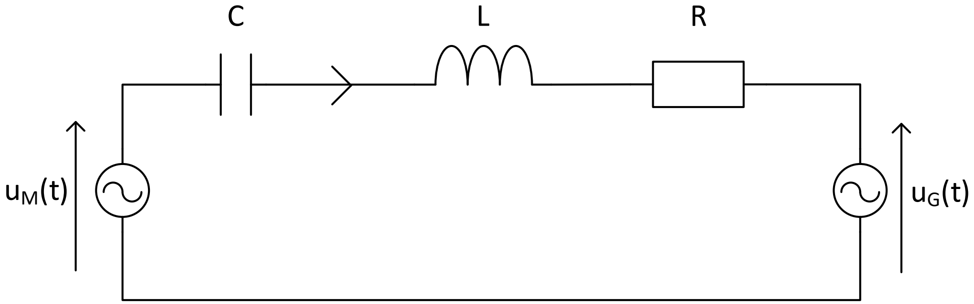
AC Systems

Example

Calculate U_G given that:

- $C = 3mF$
- $L = 10mH$
- $R = 2\Omega$
- $u_M = 400\sin(\omega t)$
- $f = 50$
- $I = 3\sin(\omega t - \phi)$
- $\Phi = 20^o$

$$X_L = \omega L \text{ and } X_C = \frac{1}{\omega C}$$



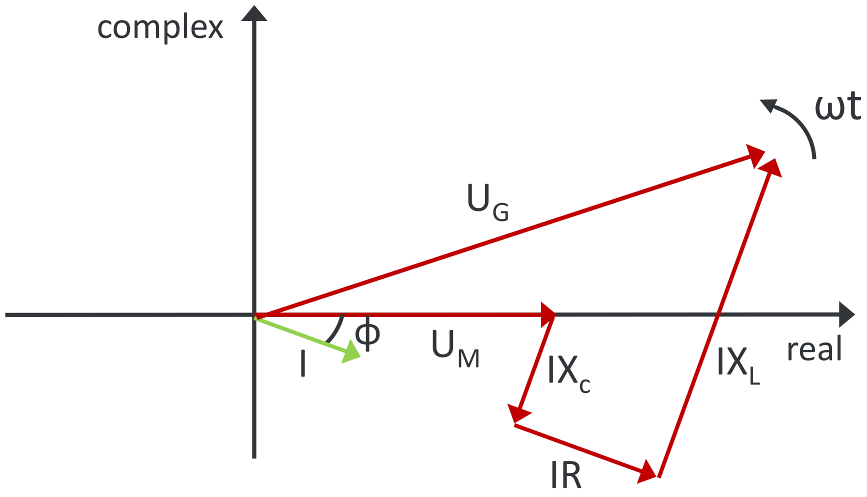


Fig1. https://www.electronics-tutorials.ws/accircuits/phasors.html

AC Systems

Power

This also means that the calculation of Power in AC systems is also not quite as straight forward as current and voltage are rarely in phase and therefore can't be simply multiplied together. Therefore, we need to introduce a couple of new concepts:

Active Power (P) [W]

This is the "real" or "useful" power and is the multiplication of the real components of current and voltage. This is the component that drives a motor round or heats a resistor.

$$P = IV \cos\phi$$

Reactive Power (Q) [Var]

The "imaginary" power is the multiplication of the imaginary components of the current and voltage. This doesn't do any real work but merely oscillates between the circuit capacitances and reactances at 2ω. **$Q = IV \sin\phi$**

Apparent Power (S) [VA]

Is the power you "appear" to have if you don't take into account phase differences between current and voltage. **$S = IV$**

Power Factor (pf): $pf = cos\theta = \frac{P}{S}$, ideally pf = 1

https://www.independent.co.uk/life-style/food-and-drink/international-beer-day-2019-cheapest-places-uk-pint-pub-liverpool-london-a9036511.html

AC Systems

Power

OK so if reactive power is “imaginary” and doesn’t do anything why do we care? Surely only active or real power contributes to losses right?

Right and wrong, if the current in the circuit has a larger reactive current component then it’s magnitude will still be larger… and since $P = I^2R$ then there are still issues

OK so then why do we include reactors and capacitors the circuit? If we didn’t add those components then we wouldn’t have an issue…

Not quite, unfortunately all components have an element of inductance, capacitance and resistance. Similar to representing mechanical systems through springs (L and C) and dampers (R).

So we’re stuck then?

Not quite – remember that the impedances introduced by capacitors and inductors are 180^{o} apart and hence cancel each other! – more on this later

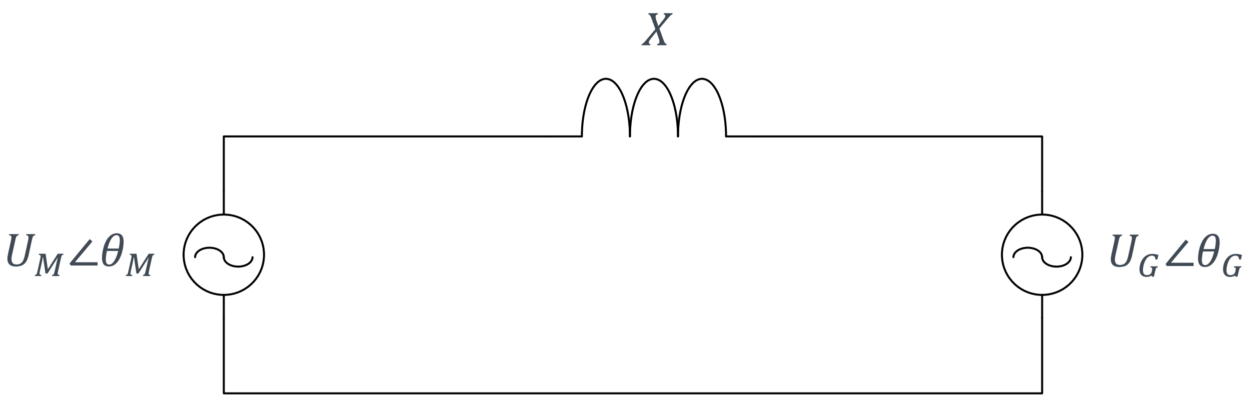
https://www.independent.co.uk/life-style/food-and-drink/international-beer-day-2019-cheapest-places-uk-pint-pub-liverpool-london-a9036511.html

AC Systems

Power Flow

$$S_G = P_G + jQ_G = U_G I$$

$$S_G = U_G \frac{U_M \angle \theta_M - U_G \angle \theta_G}{jX}$$



Then some algebra…

$$S_G = \frac{U_M U_G}{X} sin\delta + j\frac{U_M U_G cos\delta - U_G^2}{X} \qquad \delta = \theta_M - \theta_G$$

$$P = \frac{U_M U_G}{X} sin\delta \qquad Q = \frac{U_G^2 - U_M U_G cos\delta}{X}$$

Then, for the engineering bit…

Since $U_G \approx U_M$ then we can say that $U_G = U_M = U$ and we can use small angle theory and simplify these equations:

$$P \approx \frac{U^2}{X}\delta \qquad Q \approx \frac{U}{X}\Delta U$$

Therefore we can see that active power flow is dictated by the voltage angle and reactive power by the voltage difference

Semi-Conductors

Diode

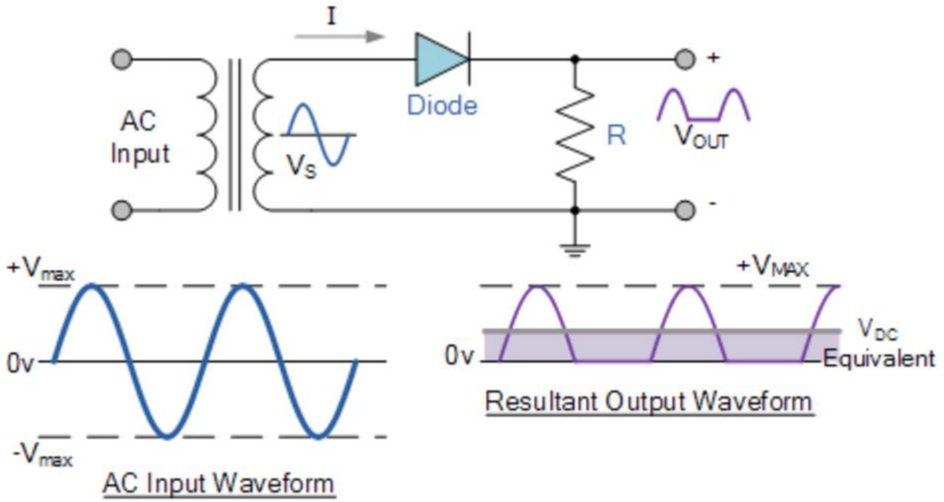
Semi conductors are materials that only conduct under certain conditions – hence they are semi-conductors.

For the standard diode, it only conducts current in one direction (forward biased) and blocks current in the opposite direction (reverse biased).

It is therefore called a passive power electronic device as you cannot control when it turns on or turns off.

That said if you connect it to a strong AC grid, you can rectify the voltage.

Diodes are very simple, cheap and reliable. However, they provide poor power quality and no controllability



Semi-Conductors

IGBT

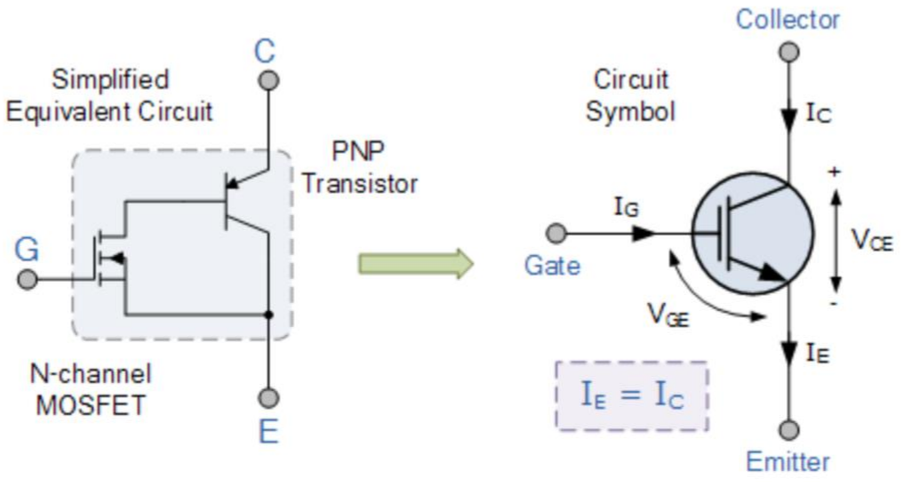
The Insulated Gate Bi-polar Transistor (IGBT) is a power electronic device that allows complete control.

It can be turned on by providing a small voltage between the Gate and Emitter and turned off by removing the voltage between the Gate and Emitter.

When it is turned on, current can flow between the Collector and Emitter with a relatively low on-state resistance and hence low power loss.

When it is turned on, no current flows and therefore there is also no power loss.

Unfortunately, it cannot turn on or off instantly so there is a period of high current and high voltage across the device creating switching losses.



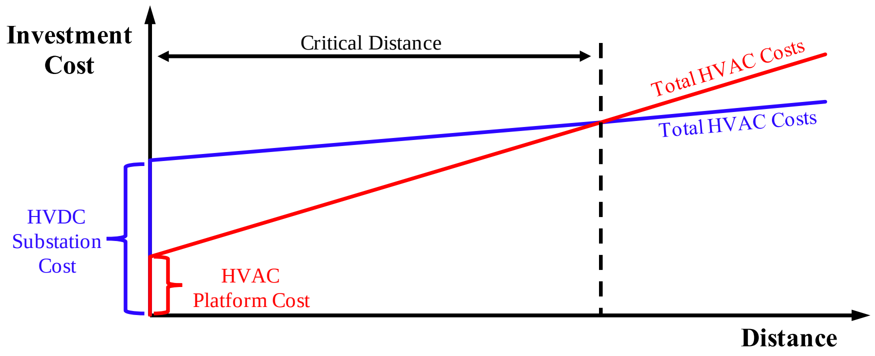
Power Converters

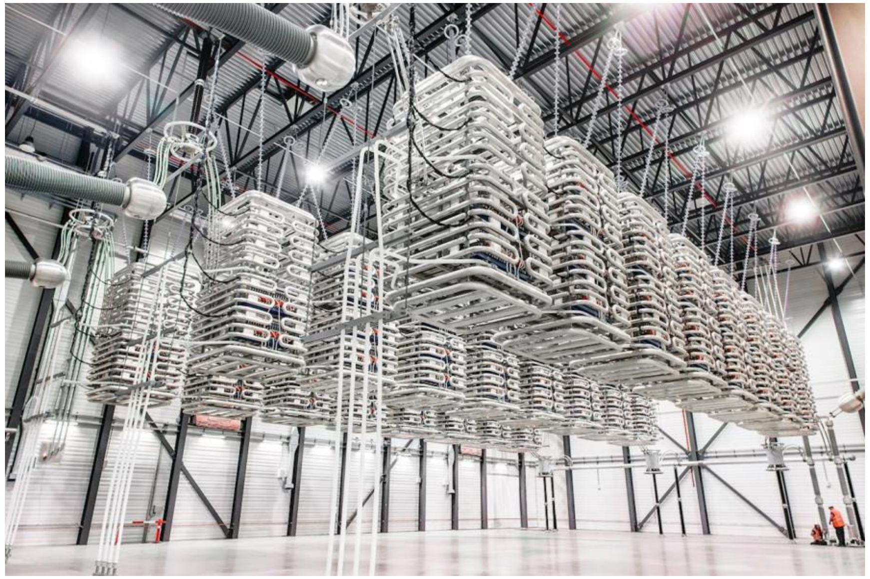
Purpos e

Power converters are used to convert between an AC and DC system, between different frequency AC systems, to isolate 2 AC systems or convert between different voltages in a DC network.

Within the wind industry they are used in two primary applications:

1. To facilitate variable speed wind turbines by allowing the generator to operate at a different frequency from the grid.
2. To allow power transfer over longer distances using HVDC cables





https://new.abb.com/news/detail/19701/abb-wins-600-mw-hvdc-order-to-reinforce-japanese-power-supply-through-hvdc-jv-with-hitachi

Power Converters

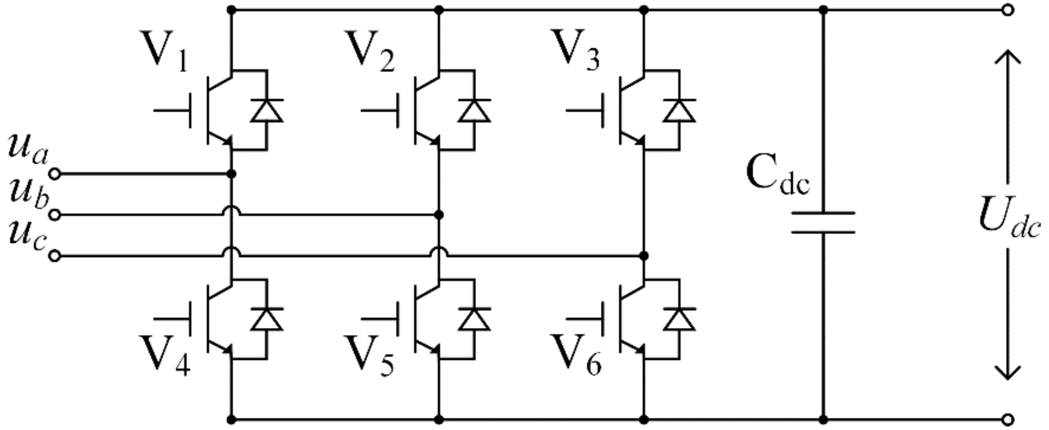
2 Level Converter

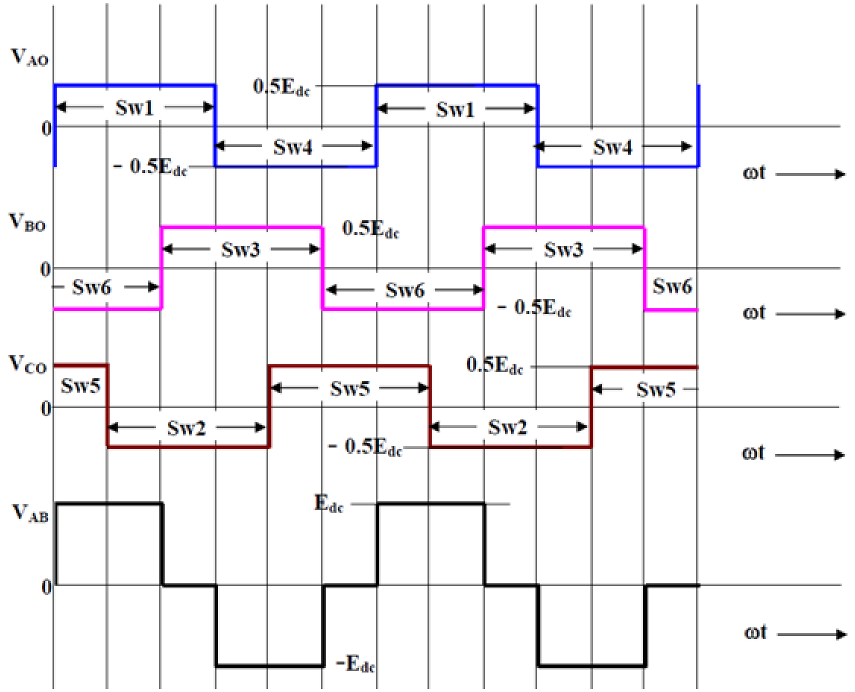
The most basic bi-directional power converter.

Constructed of an IGBT semi-conductor switch with “freewheeling” diode

At no point can both switches in each arm be on.

Gives a square wave on the output





https://protorit.blogspot.com/2012/10/3-phase-voltage-source-inverter.html

Power Converters

Pulse Width Modulation

As a 2 level power converters only produce 2 Voltage levels we can use Pulse Width Modulation (PWM) to better approximate a sine wave.

A reference wave (what we want) is produced by the controller and compared to a high frequency carrier wave.

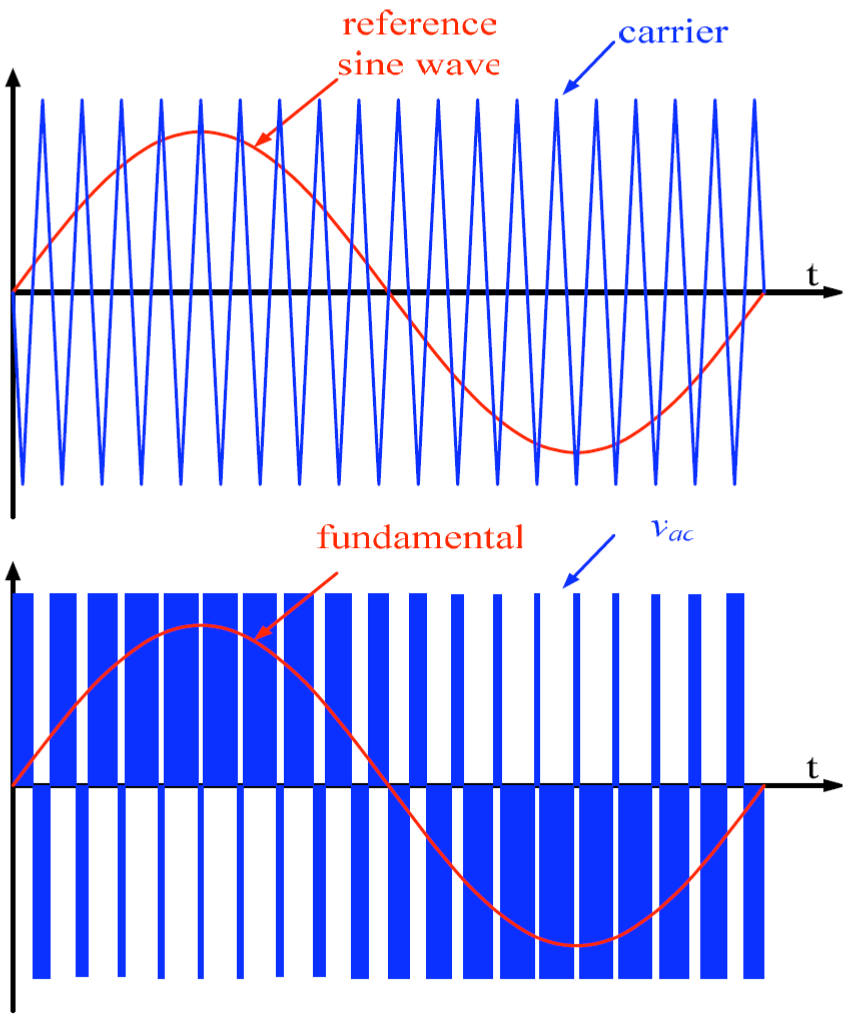
If $u_{ref} > v_c$ then switch on switch.

If $u_{ref} < v_c$ then switch off switch.

Carrier frequency should be odd to avoid even harmonics.

Modulation index, $m = \frac{\hat{u}_{ref}}{V_c}$

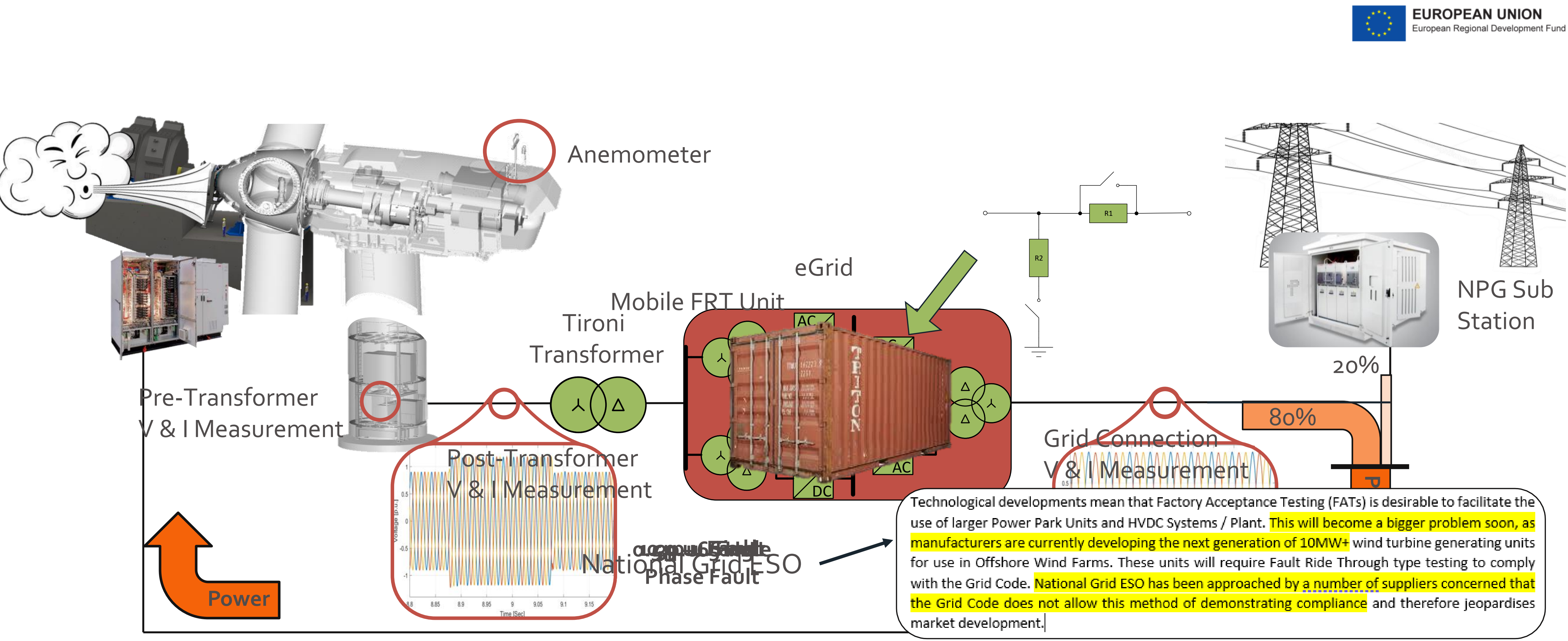
$$\hat{u} \approx mU_{dc}$$



Renewables and the Grid

- Why do testing?
- What is the grid code and standards
- How to do testing
- Future of testing

Offshore Renewable Energy



eGrid Testing: Bringing testing *in house*.

- An artificial grid that can be manipulated to create any electrical event (frequency change, low voltage, high voltage) no matter how extreme or rare at the touch of a button.
- Essential to deployment of Haliade 150 and Haliade X – Thousands of tests performed
- No impact on other grid users

Field Testing: Some limitations remain

- Requires wait for correct weather conditions to run tests and re-run tests
- Test equipment stresses local grid and no longer available for next gen turbines
- Limited test scenarios possible

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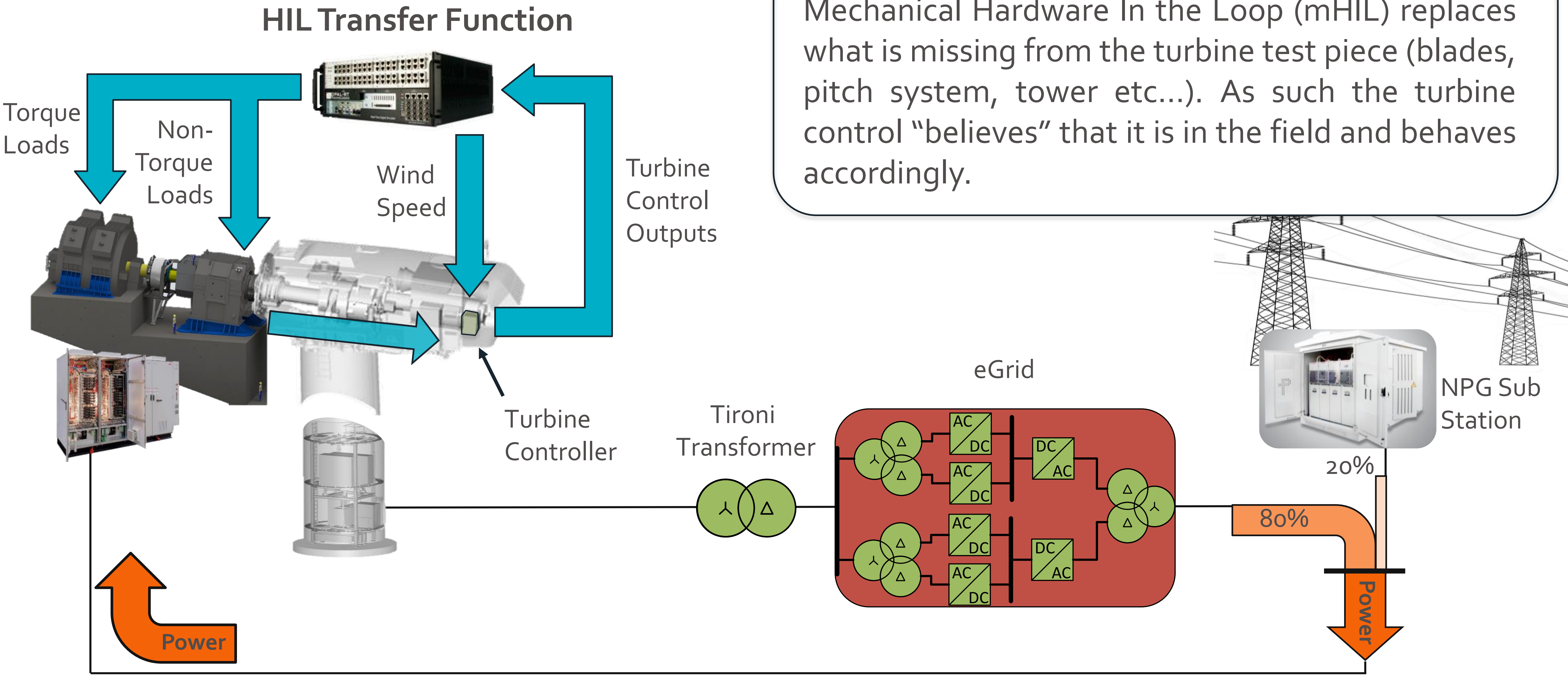
Mechanical Hardware In the Loop (mHIL) replaces what is missing from the turbine test piece (blades, pitch system, tower etc…). As such the turbine control "believes" that it is in the field and behaves accordingly.



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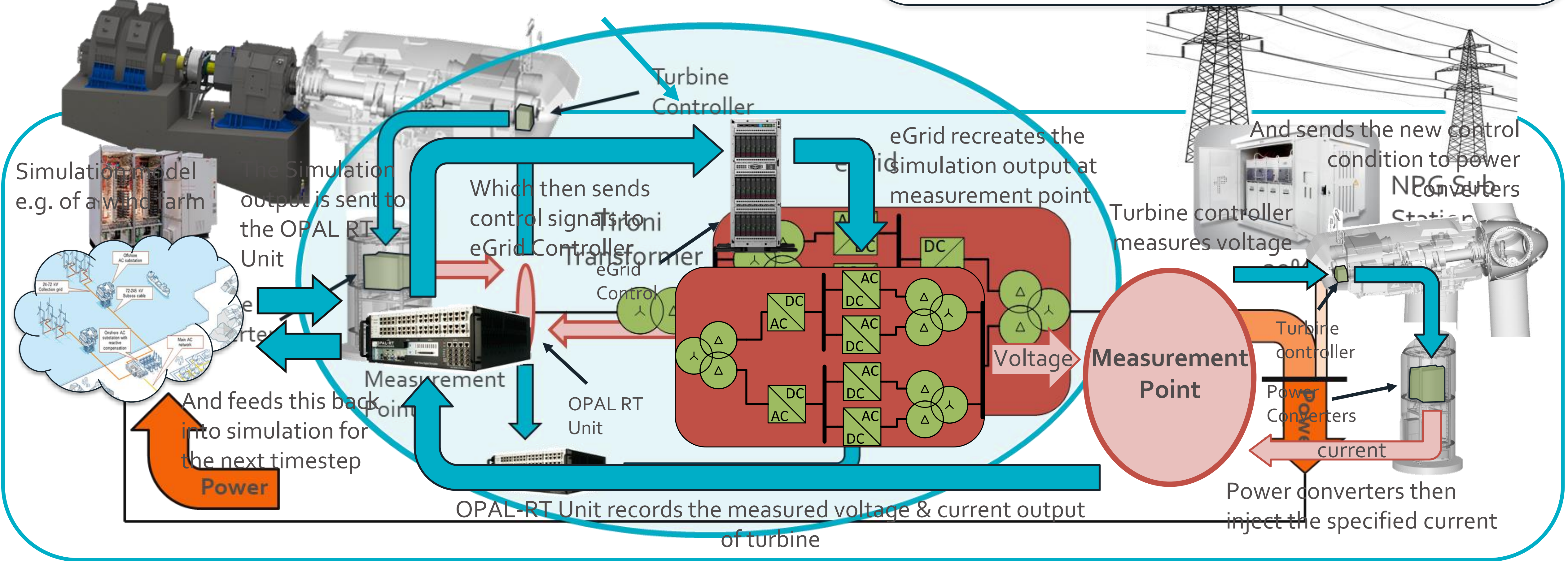
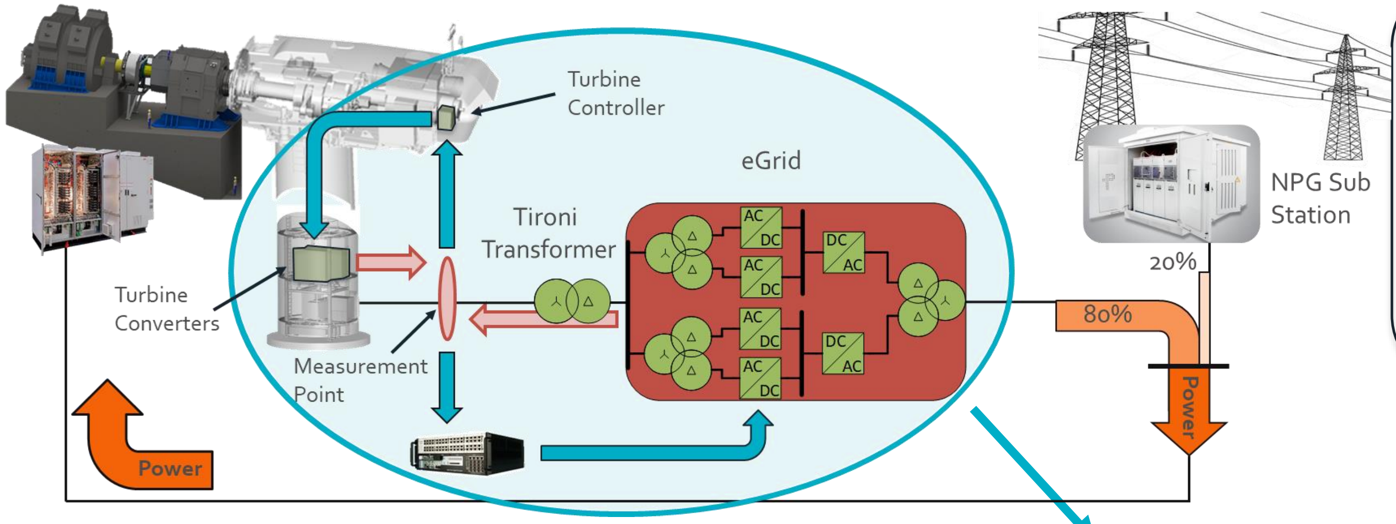
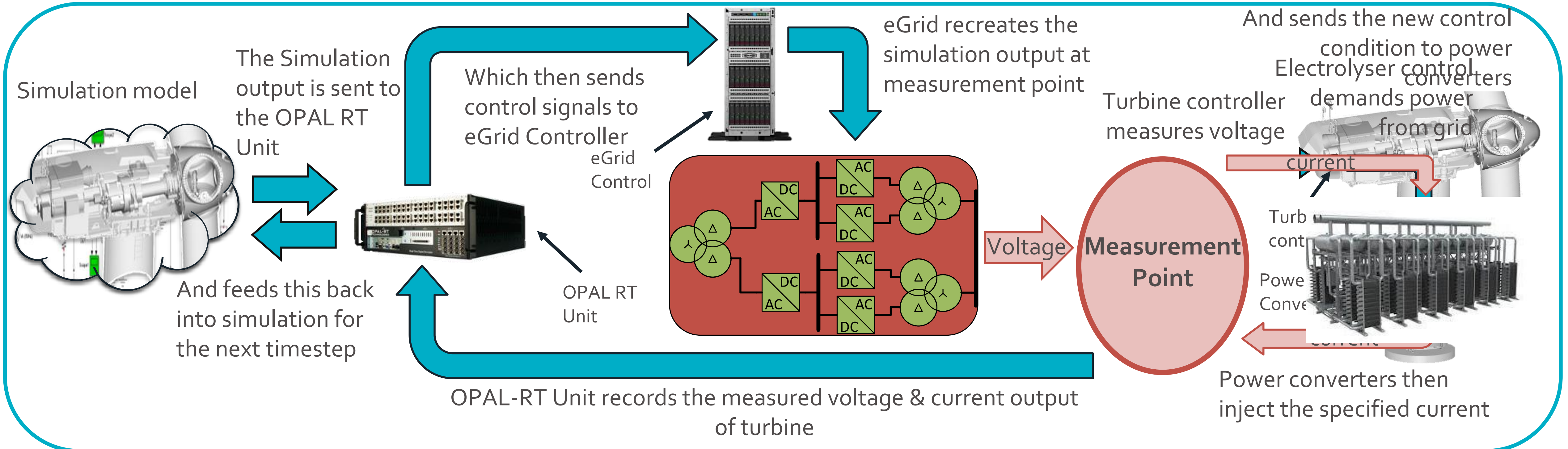
Electrical Hardware In the Loop (eHIL) adds additional elements to the test regime. For example the rest of the wind farm and grid connection. This can help expedite wind farm commissioning for example.





Using gives us lots of other options too:

- Greater control over eGrid inputs (impedance modelling)
- HVDC substation interactions
- Device emulation including wind turbine for electrolyser testing



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