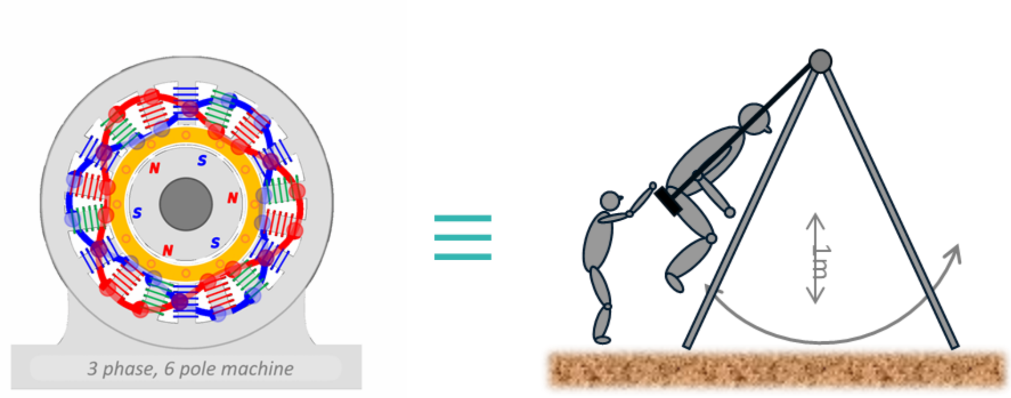
HBK Technology Days – Virtual Seminar Series

Tuesday, November 8, 2022



"Getting into the 'Swing' of things"

Instantaneous power calculations; active and reactive power, power factor and efficiency implications

Presented by Dr. Andrew Halfpenny,
Director of Technology – nCode Products, HBK

Instantaneous power calculations; active and reactive power, power factor and efficiency implications

Abstract

- Do you struggle explaining the difference between ‘active’, ‘reactive’ and ‘apparent’ power, in a way that colleagues can understand?
- Do they keep asking you why ‘phase-related reactive power’ should be separate from ‘frequency-related reactive power’?
- Does your line manager understand why dynamic power analysis and optimisation of variable speed electrical machines used in EVs, is so much more complicated than constant speed machines used in a factory?
- Would you like a nice story with pictures to replace pages of differential calculus?

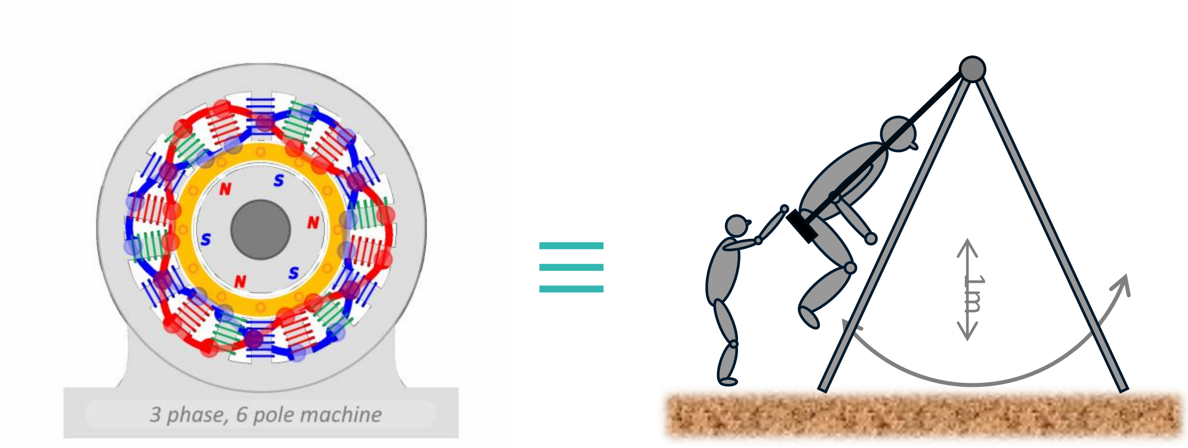
If you are an Automotive or Mechanical Engineer who wants a conceptual understanding of dynamic AC power analysis, or an electrical engineer who wants a non-mathematical refresher, then this presentation is for you!

About the presenter, Dr. Andrew Halfpenny, Director of Technology – nCode Products, HBK

Dr. Halfpenny has a PhD in Mechanical Engineering from University College London (UCL) and a Masters’ in Civil and Structural Engineering. With over 25 years of experience in structural dynamics, vibration, fatigue and fracture, he has introduced many new technologies to the industry including: FE-based vibration fatigue analysis, crack growth simulation and accelerated vibration testing. He holds a European patent for the ‘Damage monitoring tag’ and developed the new vibration standard used for qualifying UK military helicopters. He has worked in consultancy with customers across the UK, Europe, Americas and the Far East, and has written publications on Fatigue, Digital Signal Processing and Structural Health Monitoring. He is a founding member of NAFEMS PSE Certification scheme and sits on the NAFEMS committee for Dynamic Testing. He is a visiting lecturer on structural dynamics with The University of Sheffield.

Instantaneous Power Calculations

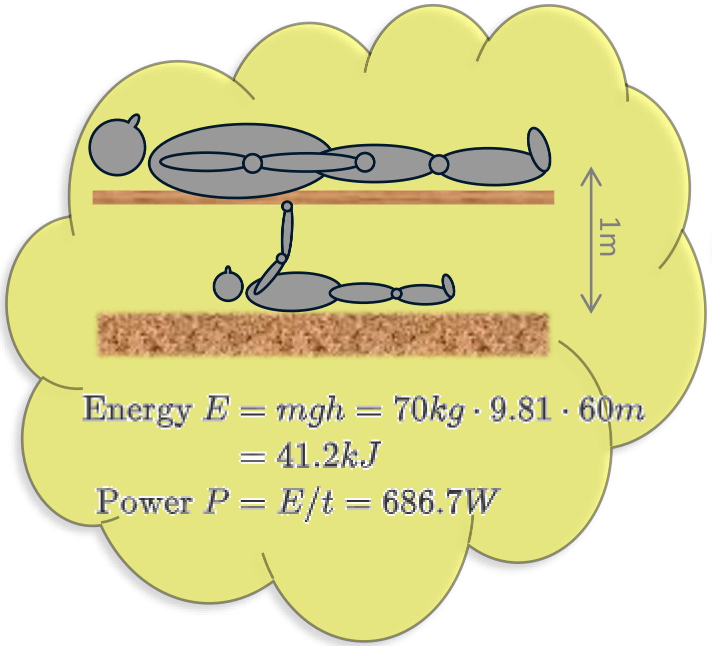
Active, Reactive and Apparent Power,
Power Factor and Efficiency Implications

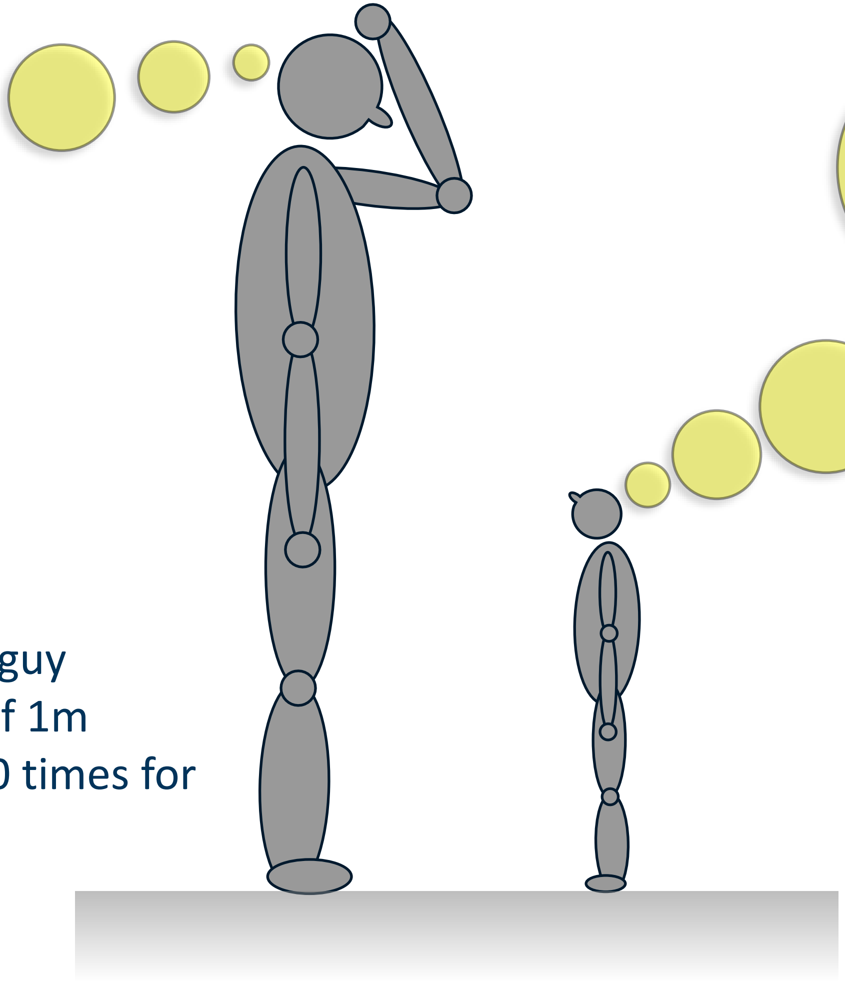


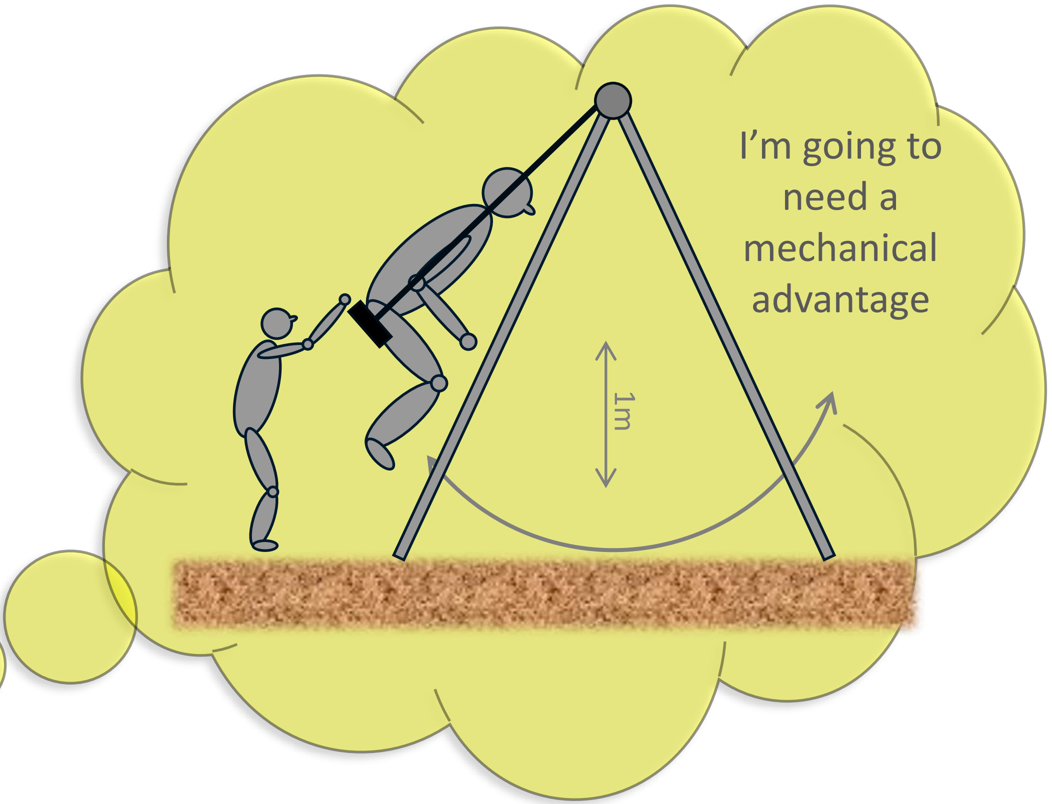
“Getting into the ‘Swing’ of things”

Dr. Andrew Halfpenny
Dr. Alexander Stock

Challenge







- The little guy must lift the big guy vertically through a distance of 1m
- He must repeat this at least 60 times for 1 minute!

"We can't change the laws of physics, but we can harness them rather than beating them into submission."

We need to work efficiently

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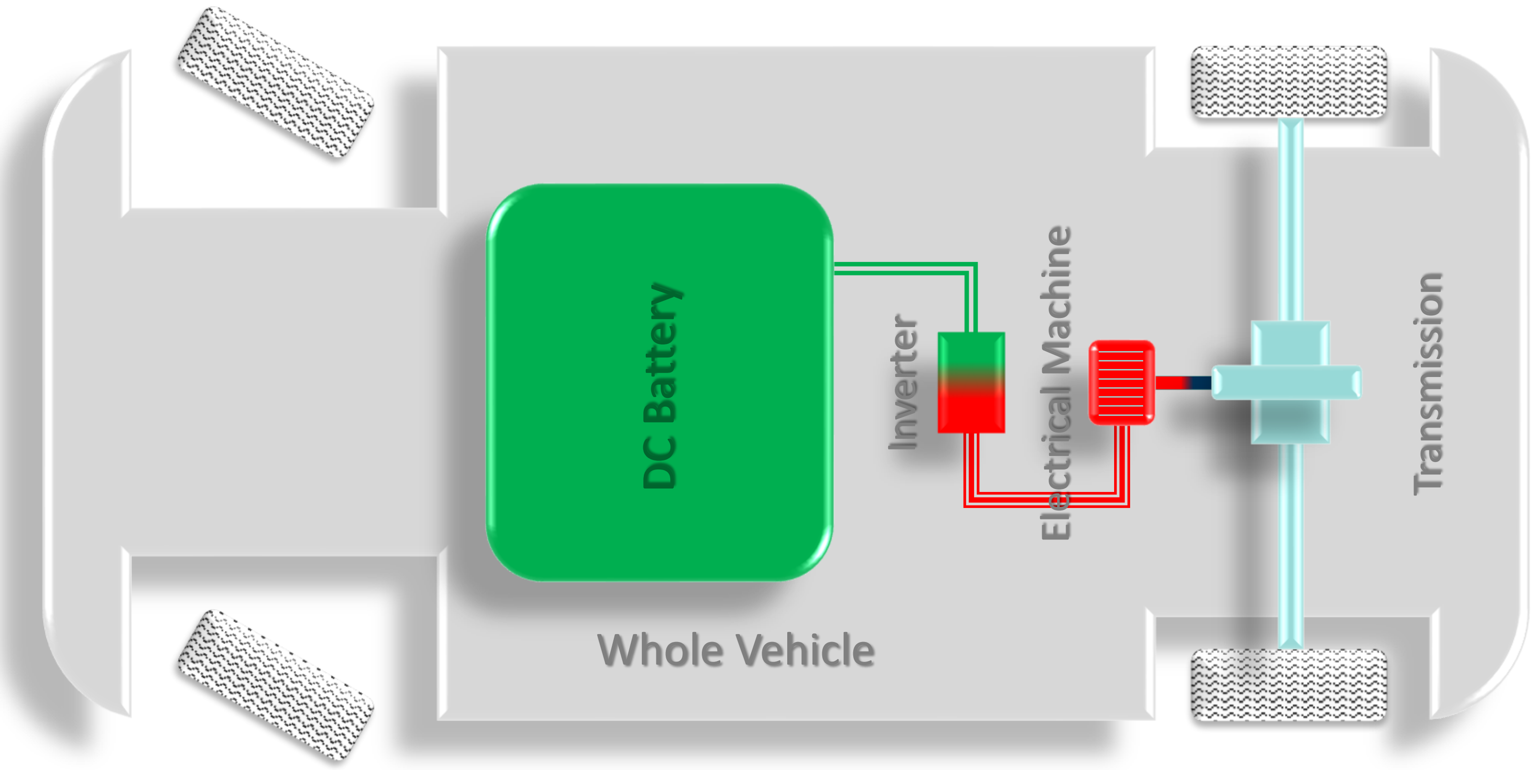
Efficiency of an Electrical Vehicle

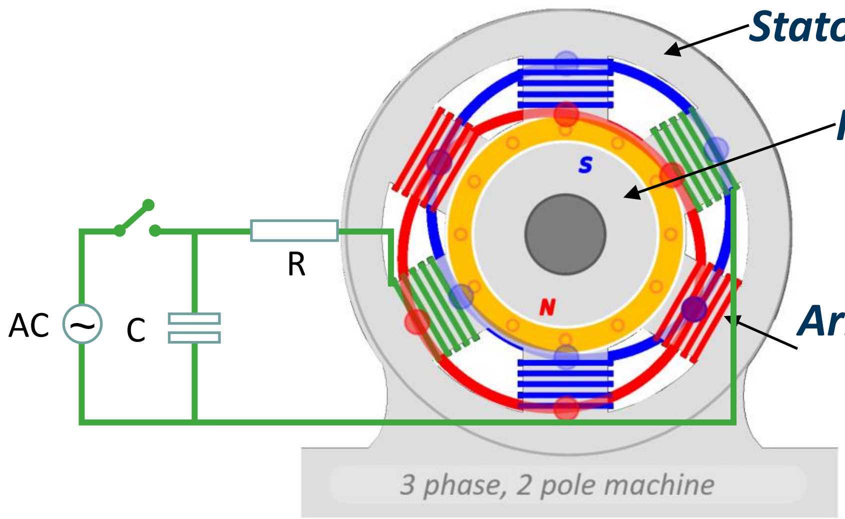
Energy conversion & efficiency losses



- Battery DC
- Inverter DC-AC
- Electrical Machine AC
- Transmission
- Whole vehicle

How to control the Electrical Machine to maximize efficiency?

What is an Electrical Machine?



Stator: the stationary part

Rotor: the rotating part

Air gap: between stator and rotor

Armature: wire windings (induction coils) on ferromagnetic core

(maybe part of Stator or Rotor)

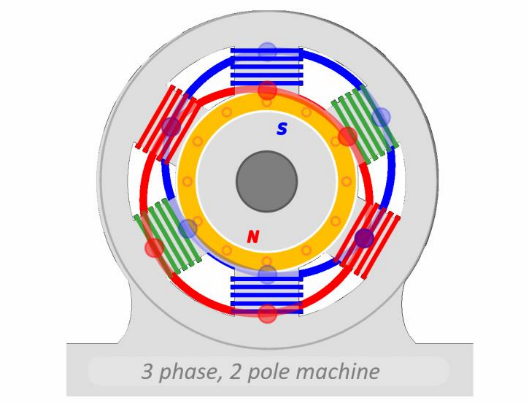
- ***Electrical Machine***:
  *"A device that converts between **electrical** and **kinetic** energy."*
  - ***Motor***: electrical → kinetic
  - ***Generator***: kinetic → electrical

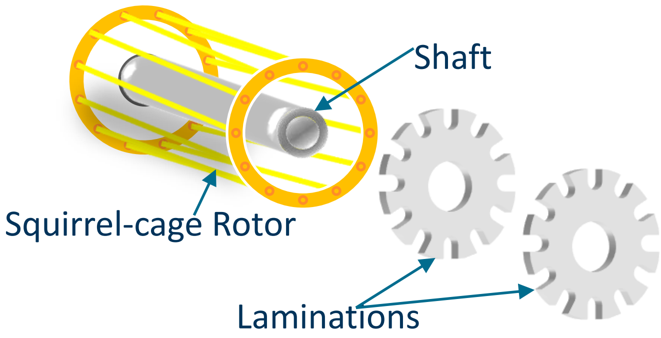
- Rotor **speed** and **torque** depends on shaft rotation relative to a rotating magnetic field.
- Rotating magnetic field created by electromagnetic induction coils in the **Armature**.
- Induction coils are driven by an Alternating Current (with Resistance and Capacitance)

How to Control an Electrical Machine

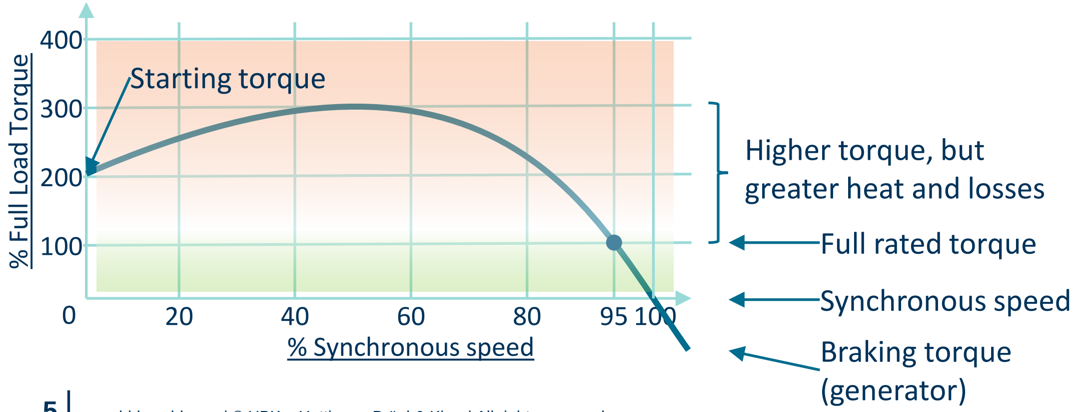
Asynchronous

- Induction machine





- Rotating magnetic field induces a current in the rotor coil. The rotor spins to keep up.
- Torque controlled by **'Slip Speed'**

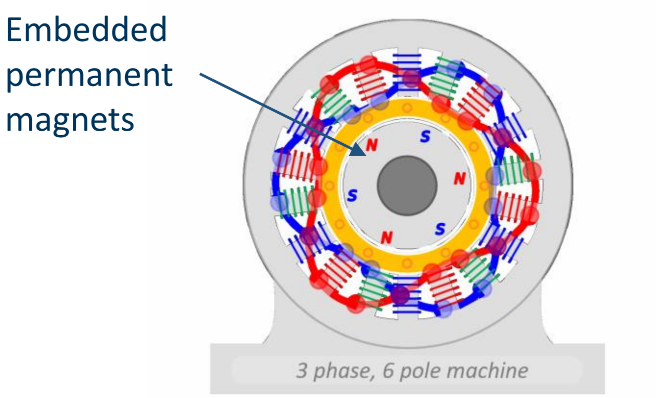


Relatively **easy** to control
Forgiving

Difficult to control
Unforgiving

Synchronous

- Permanent Magnet
- Switch reluctance
- Hybrid



- **Rotor is synchronous** with the rotating electromagnetic field
- Torque controlled by instantaneous **'Phase Angle'** between rotor and electromagnetic field

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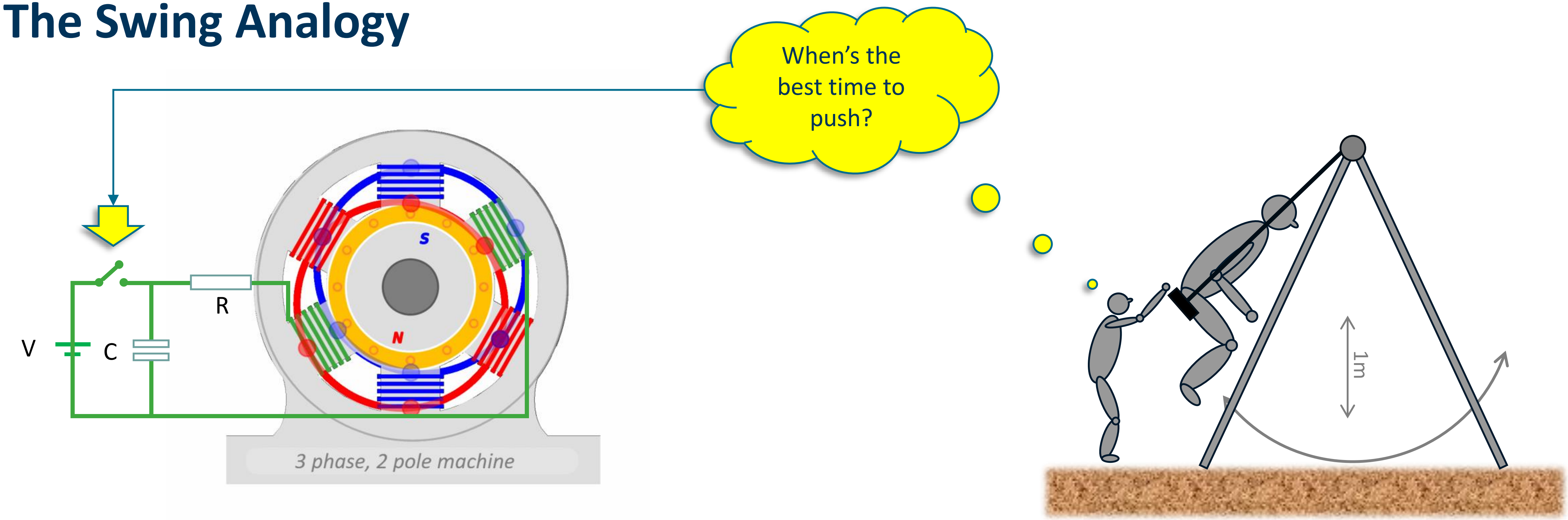
The Swing Analogy



Inductance, Resistance and Capacitance

$$L\ddot{Q} + R\dot{Q} + \frac{1}{C}Q = emf(t)$$

$$M\ddot{x} + C\dot{x} + Kx = f(t)$$

Inductance *L*: *store energy in a magnetic field*

Resistance *R*: *resist the flow of charge*

Capacitance *C*: *store energy in an electrical field*

Mass *M*: *store kinetic energy by inertia*

Damping *C*: *resist the swing by the flow of air*

Stiffness *K*: *store potential energy using gravity*

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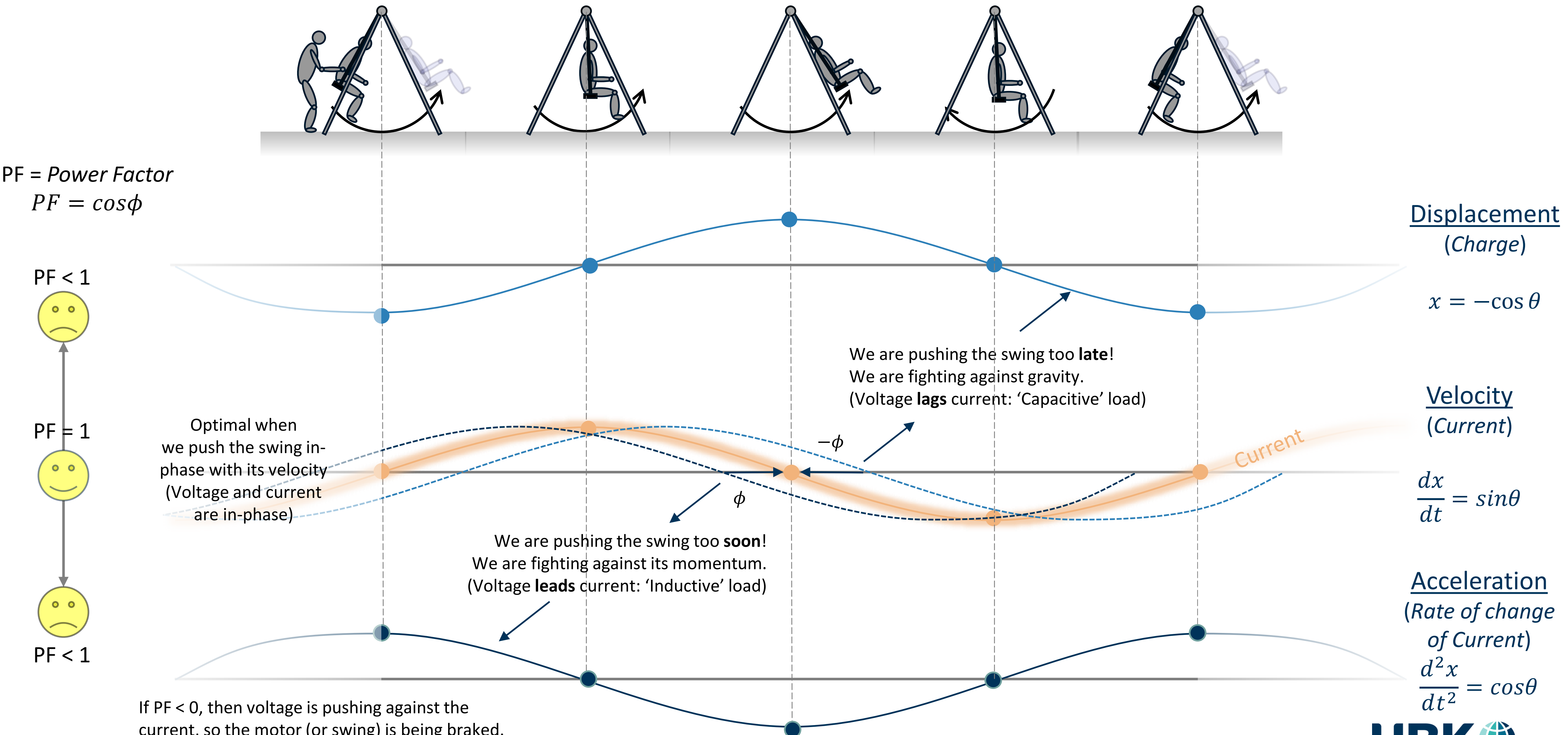
When's the best time to push? – *Voltage and Current should be in-phase*

PF = *Power Factor*

$PF = cos\phi$



If PF < 0, then voltage is pushing against the current, so the motor (or swing) is being braked.

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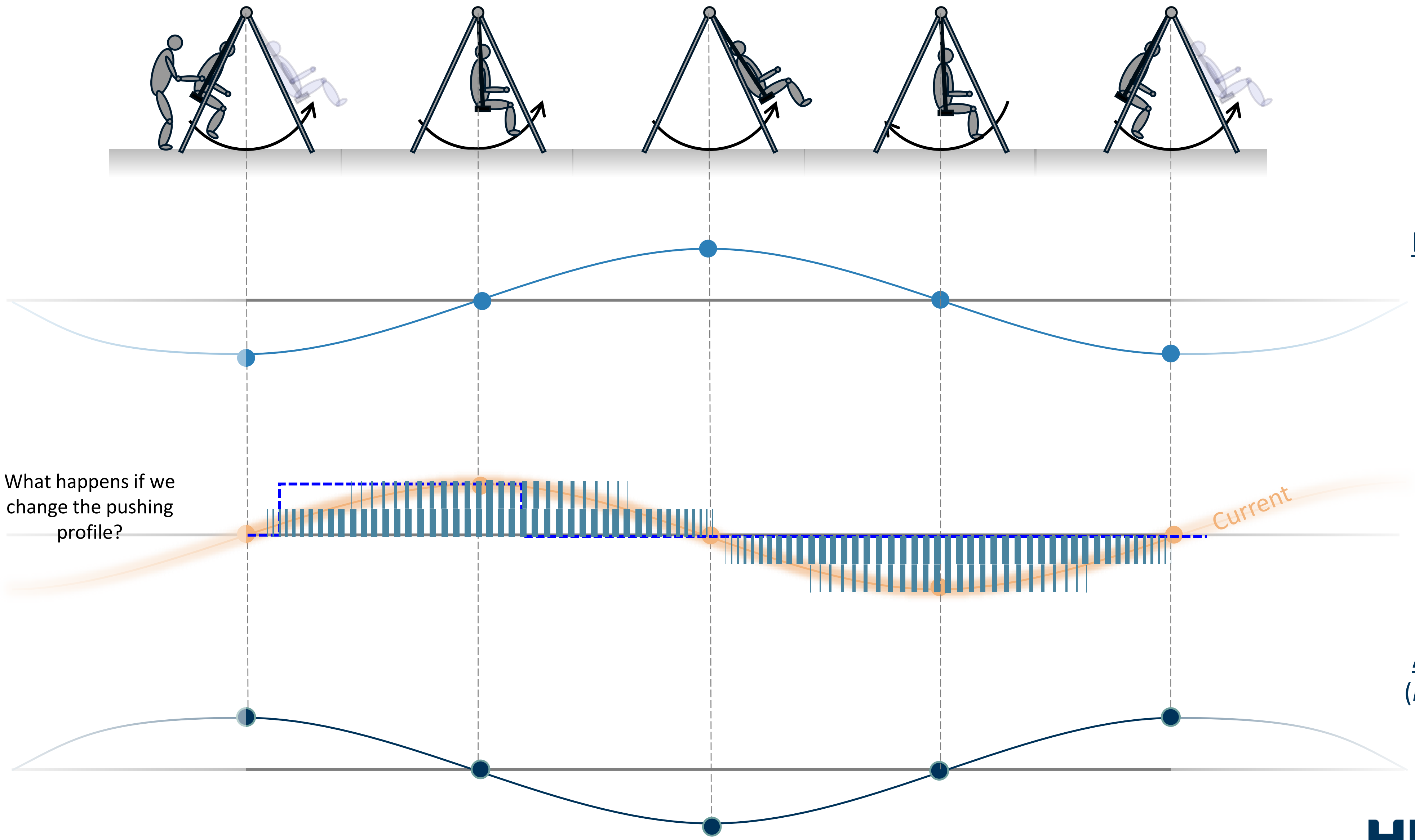
How to push? *– Voltage waveform should be same as Current*



What happens if we change the pushing profile?

Displacement
(*Charge*)

$x = -\cos\theta$

Velocity
(*Current*)

$\frac{dx}{dt} = sin\theta$

Acceleration
(*Rate of change of Current*)

$\frac{d^2x}{dt^2} = cos\theta$

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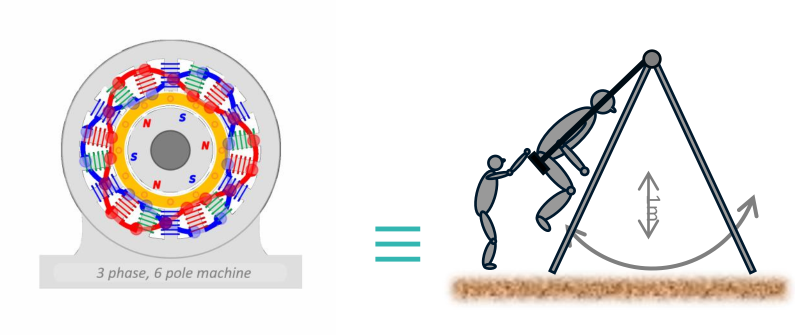
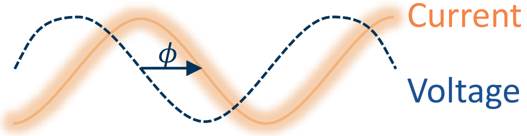
Agenda

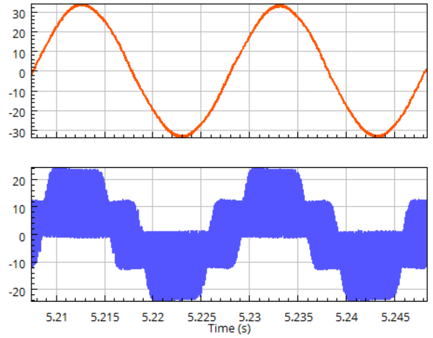
1. Introduction to Efficiency and the 'Swing Analogy'



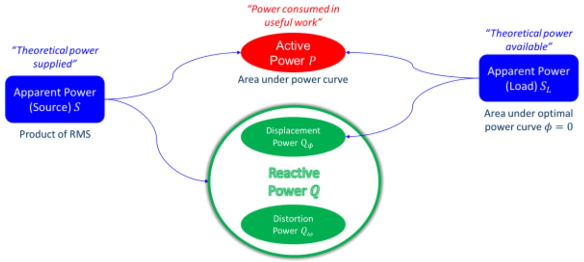
"Getting into the 'Swing' of things"

2. **'When to Push'**
   - The Effect of Phase





3. **'How to Push'**
   - The Effect of Frequency and Waveform
4. Conclusion
   - Active, Reactive and Apparent Power
   - Two (or more) definitions



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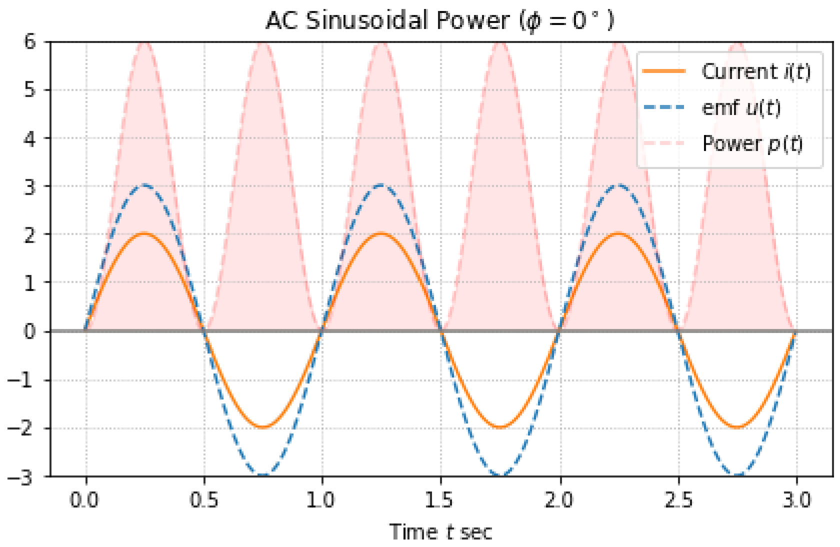
The effect of Phase – *Active P*, *Reactive Q_ϕ* and *Apparent S Power*



$u(t) = 3\sin(\omega t + 0^\circ)$ $i(t) = 2\sin(\omega t)$ $\omega = 2\pi$
Active power $P = 3.0000$ W
Reactive power $Q = 0.0000$ VAr
Apparent power $S = 3.0000$ VA

<u>"Resistive" load</u>

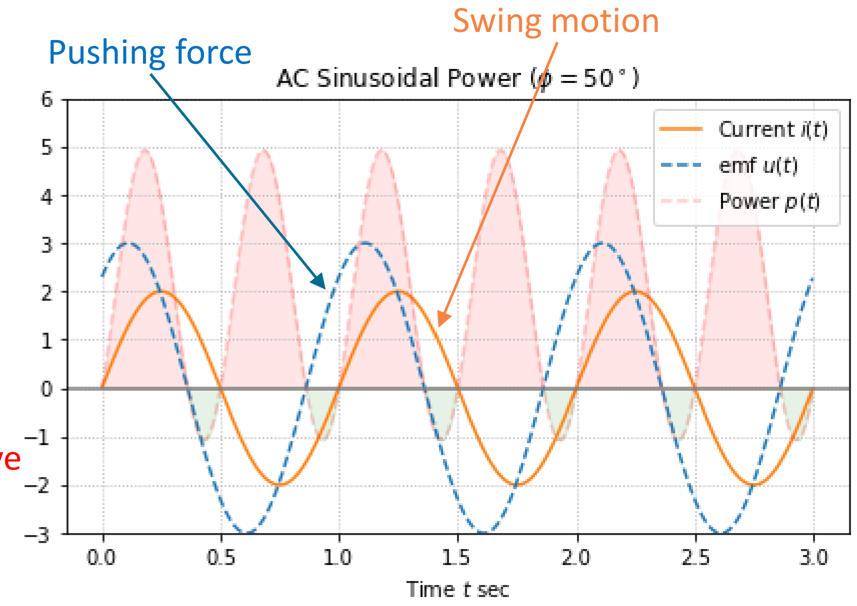
Push swing just right

Instantaneous Power
$p(t) = u(t)\,i(t)$

Active Power P = area under power curve
(Consumed in useful work)

Apparent power S = rms(u) x rms(i)
(Optimal power available)

Reactive Power Q
(Not contributing to useful work)



$u(t) = 3\sin(\omega t + 50^\circ)$ $i(t) = 2\sin(\omega t)$ $\omega = 2\pi$
Active power $P = 1.9284$ W
Reactive power $Q = 2.2981$ VAr
Apparent power $S = 3.0000$ VA

<u>"Inductive" load</u>

Push swing too early

- Power is sinusoidal, amplitude $\frac{\hat{u}\hat{i}}{2}$, frequency 2ω, wholly +ve
- **<u>All</u> energy consumed in useful work**

  $P = S, \quad Q = 0$
- Voltage and current in-phase: "Resistive" load

- Power is still sinusoidal ✓, amplitude $\frac{\hat{u}\hat{i}}{2}$ ✓, frequency 2ω ✓, BUT mix of +ve and –ve power
- **<u>Some</u> energy consumed in useful work**

  $P < S, \quad Q \neq 0, \quad S = \sqrt{P^2 + Q^2}$
- Voltage leads current: "Inductive" load

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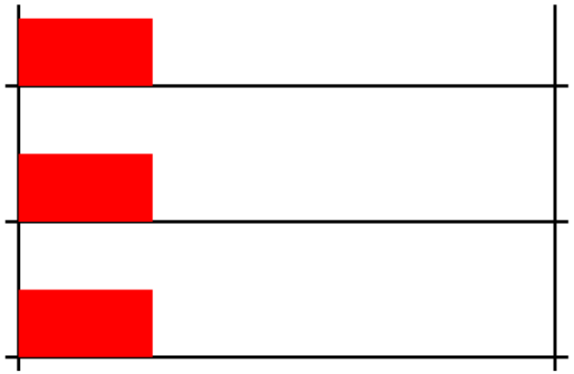
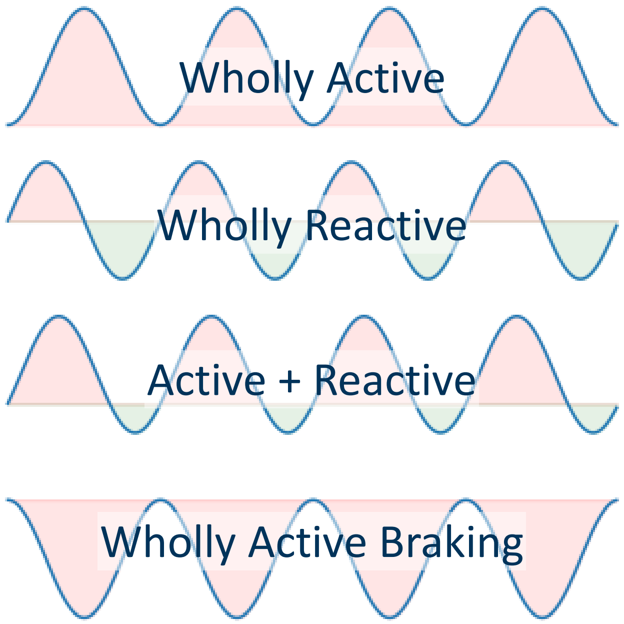
The effect of Phase – *Active P , Reactive Q ϕ and Apparent S Power*





$\phi = 0$ All power consumed in useful work 😉

$\phi = \pm 90°$ No useful work 😥

Some useful work 😐

$\phi = \pm 180°$ All power consumed in braking 😉

	ϕ (deg)	P (W)	Q (VAr)	PF
Wholly Active	$0°$	$P = S$	$Q = 0$	1.0
Wholly Reactive	$\pm 90°$	$P = 0$	$Q = S$	0.0
Inductive load /	$\phi > 0°$	$P < S$	$Q > 0$	$PF < 1$
Capacitive load	$\phi < 0°$		$Q < 0$	
Braking load	$\phi > 90°$ or $< -90°$	$P < 0$	–	$PF < 0$

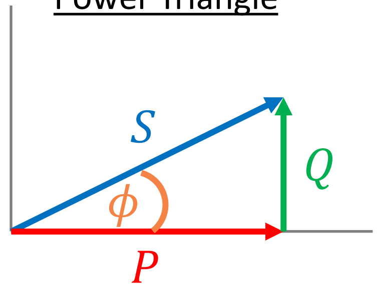
Apparent Power

$$S = \sqrt{P^2 + Q^2}$$

Power Factor

$$PF = \cos\phi = \frac{P}{S}$$

Power Triangle



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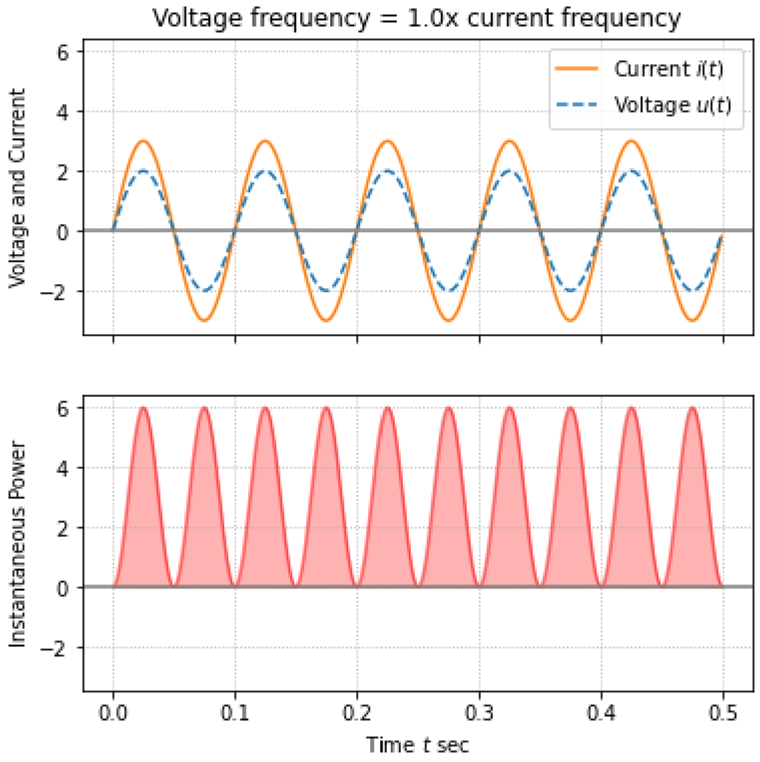
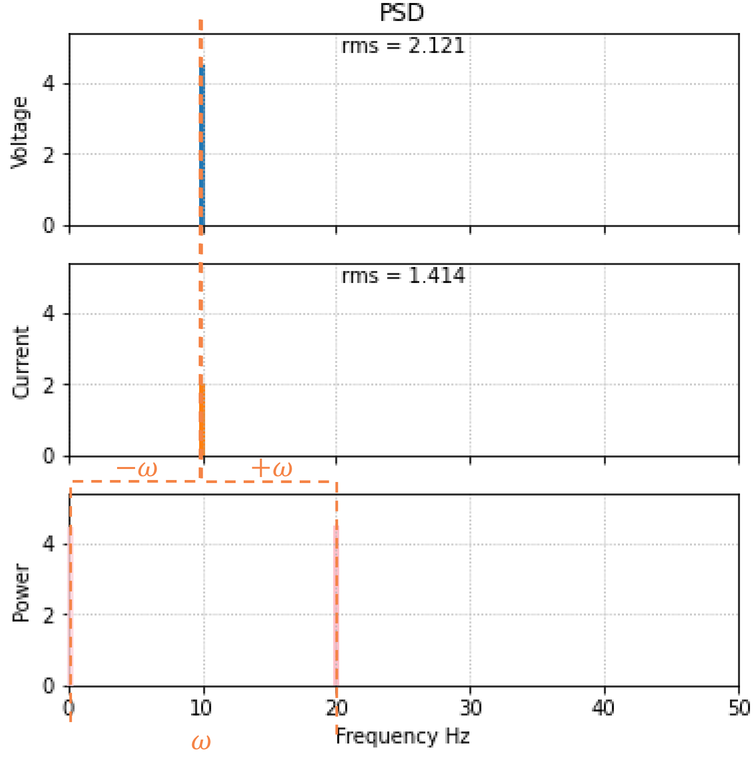
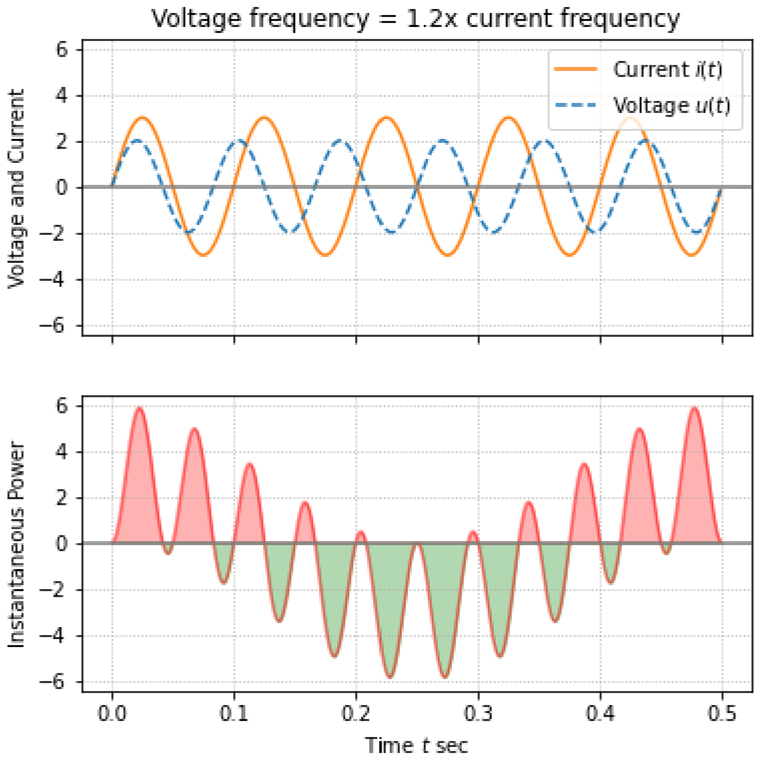
The effect of Frequency – *Active P* , *Reactive Q_ϕ* *and Apparent S Power*

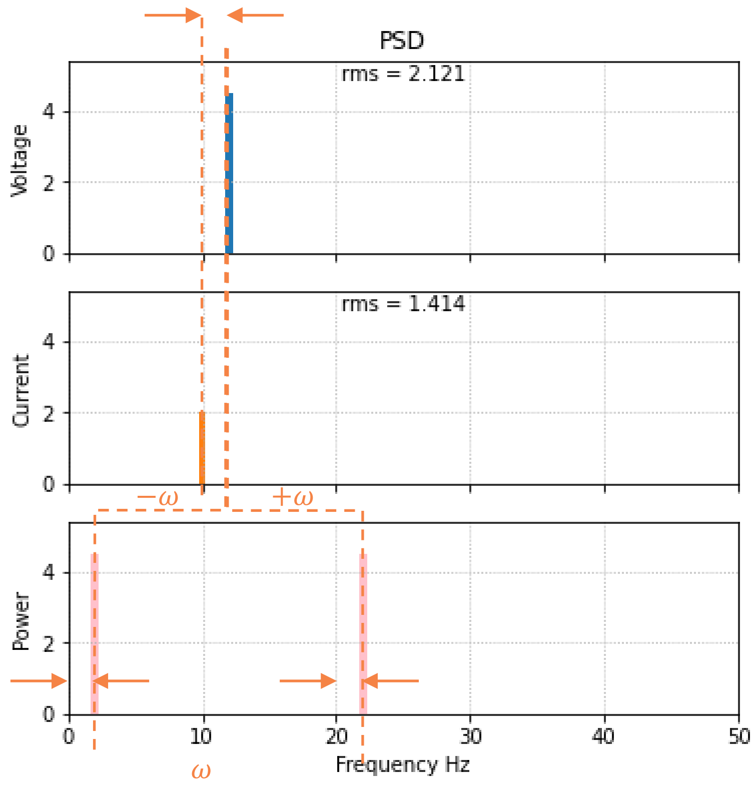




- Sinusoidal Voltage and Current
- Voltage frequency = Current frequency
- Instantaneous Power is sinusoidal with frequency twice that of voltage and current
- Zero Hz component accounts for DC offset

The effect of Frequency – *Active P , Reactive Q_{ϕ} and Apparent S Power*





- Power modulates in and out of phase
- Over time, net useful power → 0

$$\begin{aligned} p(t) &= u(t)\, i(t) \\ &= \hat{u}\sin(\omega_1 t)\, \hat{i}\sin(\omega_2 t) \\ &= \frac{\hat{u}\hat{i}}{2}\left\{ \sin\left[(\omega_1+\omega_2)t\right] + \sin\left[(\omega_1-\omega_2)t\right] \right\} \end{aligned}$$

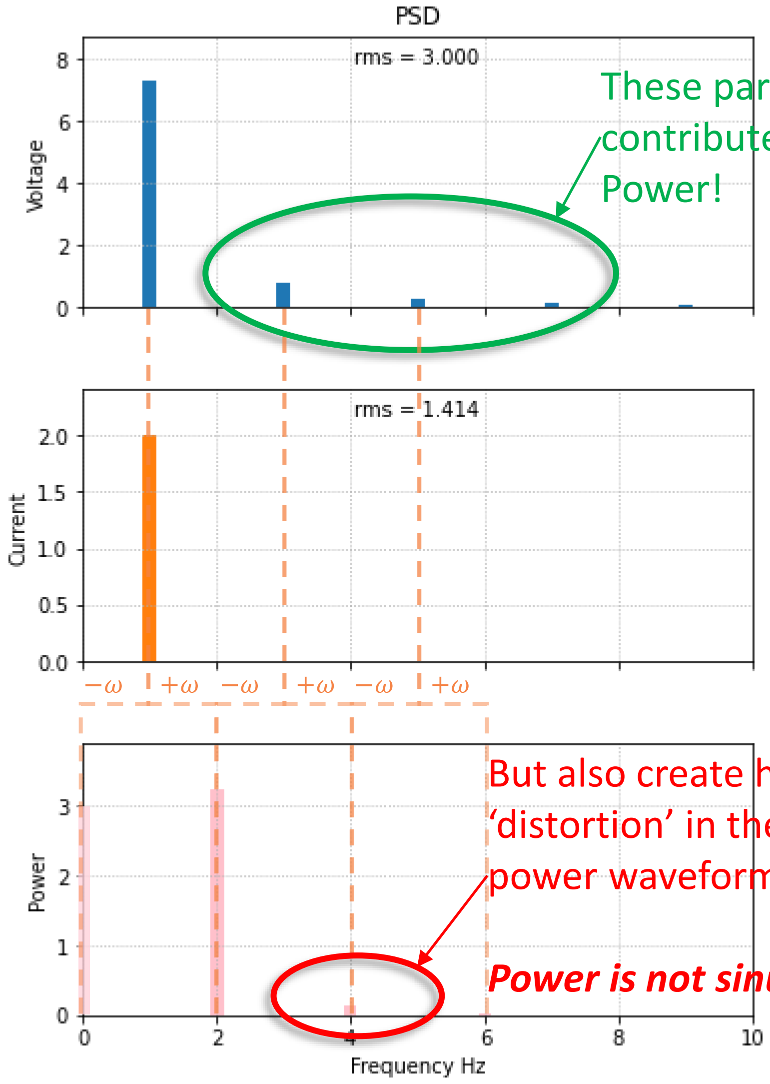
Power frequency

Modulation frequency

Voltage frequency ≠ Current frequency
No Useful Work

The effect of Waveform – *Active P* , *Reactive* Q_{ϕ} *and Apparent S Power*

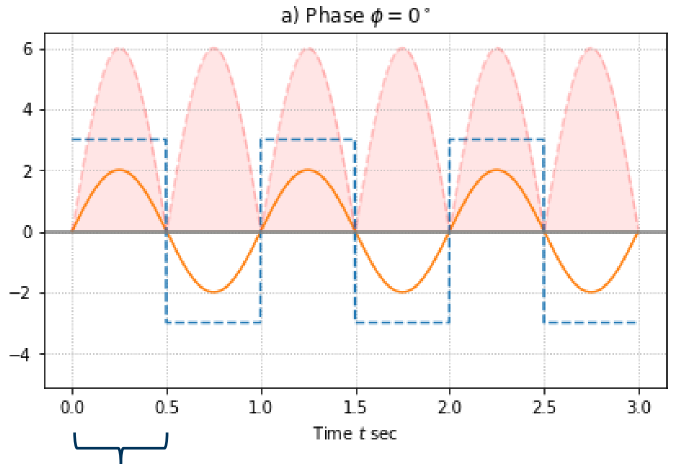
PSD of electrical power



These partially contribute to Active Power!

But also create harmonic 'distortion' in the ideal power waveform

Power is not sinusoidal

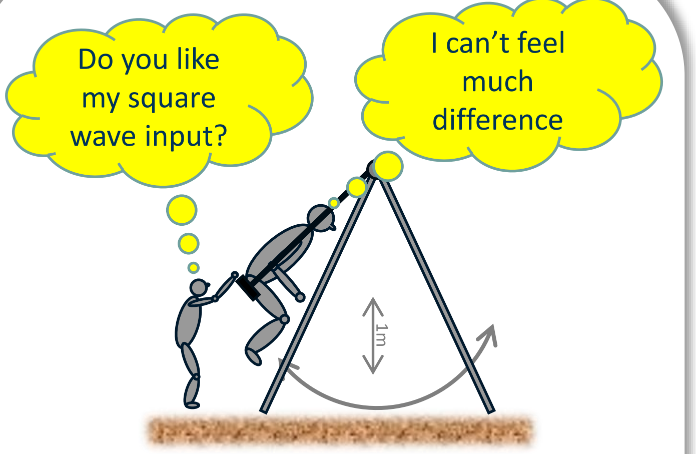


Theoretical optimal power $\phi = 0$

$$P = \frac{\hat{u}\hat{i}}{\pi}\int_0^{\pi} \sin(\theta)\, d\theta = \frac{2\hat{u}\hat{i}}{\pi} = 0.6366\, \hat{u}\hat{i}$$

Product of the RMS:

$$\mathrm{rms}(u)\,\mathrm{rms}(i) = \frac{\hat{u}\hat{\imath}}{\sqrt{2}} = 0.7071\, \hat{u}\hat{\imath}$$



Two definitions of Apparent Power

1. Perspective of the **Source** (*product of RMS*)
2. Perspective of the **Load** (*area under power curve*)

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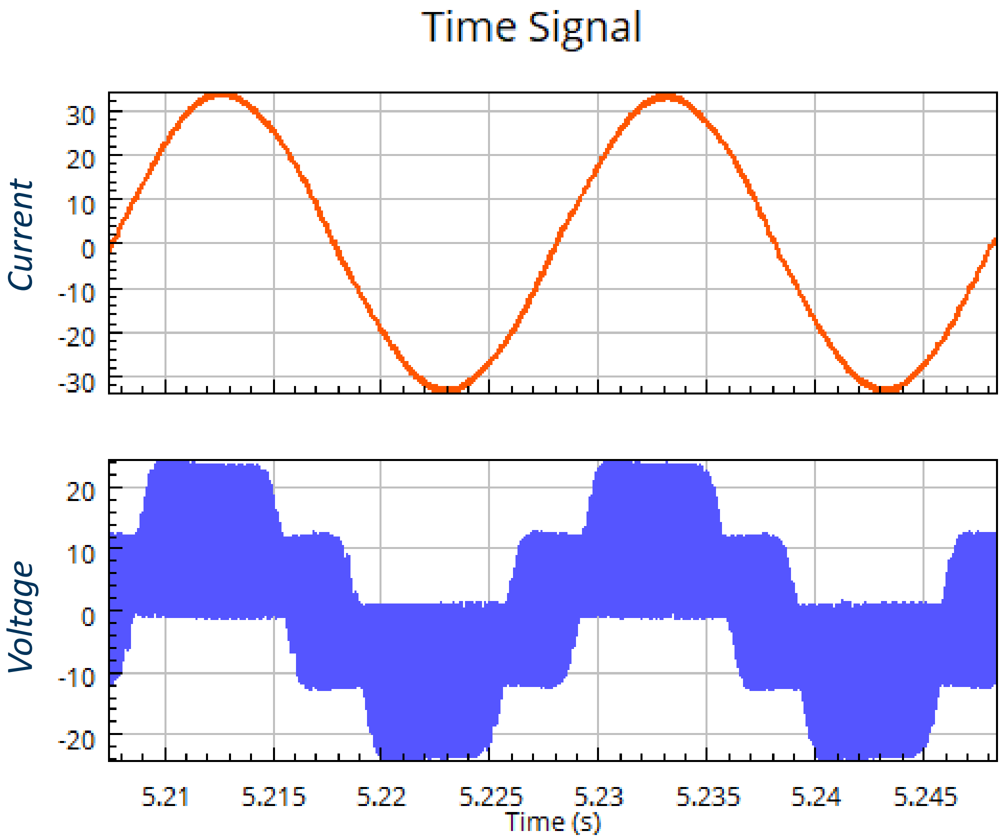
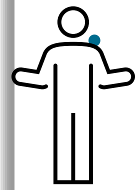
Why is Waveform Important for Electrical Vehicles?

Current waveform
almost sinusoidal



Voltage waveform
contains significant high-frequency switching harmonics

- From inverter controller's perspective
  Optimize Phase – (push at the right time)



- From source perspective
  Optimise waveform – (minimise transmission losses)

- We want to separate Active Power P,
  from Phase-related (Displacement Power Q_{ϕ})
  and Waveform-related (Distortion Power Q_{ω})

- One persons' signal is another persons' noise

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Apparent, Active, and Reactive Power

"Power consumed in useful work"

Active Power P

Area under power curve

Inverter Controller

"Theoretical power available"

Apparent Power (Load) S_L

Area under optimal power curve $\phi = 0$

Displacement Power Q_ϕ

"Phase displacement ϕ between voltage & current" (*when to push!*)

Returned as:

- Displacement Power (i.e. power units)
- Power Factor (i.e. efficiency ratio):
  $PF = \cos\phi$
- Phase angle ϕ

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Apparent, *Active*, *and Reactive Power*

Power Source

"Theoretical power supplied"

Apparent Power (Source) S

Product of RMS

"Power consumed in useful work"

Active Power P

Area under power curve

"Power not contributing to useful work" (billing $ purposes)

Reactive Power Q

Noise

Useful for optimization

Apparent, *Active*, *and Reactive Power*

"Power consumed in useful work"

Power Source
"Theoretical power supplied"

Apparent Power (Source) S

Product of RMS

Active Power P

Area under power curve

Displacement Power Q_ϕ

Reactive Power Q

Distortion Power Q_ω

"Power not contributing to useful work" (billing $ purposes)

"Harmonic distortion btn voltage & current" (minimise transmission losses)

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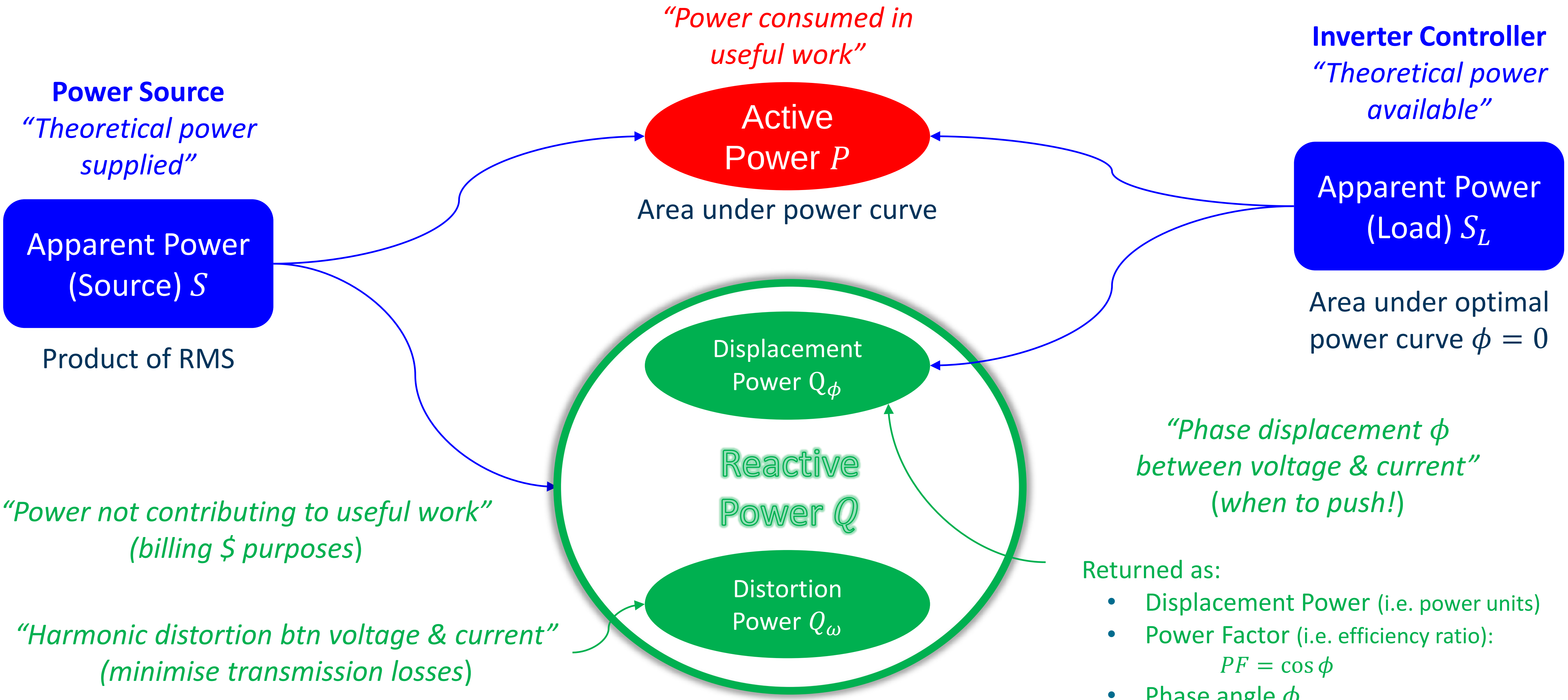
Apparent, Active, and Reactive Power

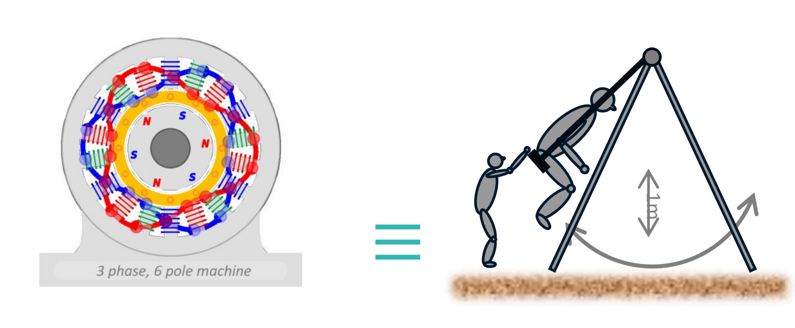


Returned as:

- Displacement Power (i.e. power units)
- Power Factor (i.e. efficiency ratio): $PF = \cos\phi$
- Phase angle ϕ

Conclusion

1. Introduction to Efficiency and the 'Swing Analogy'



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2. **'When to Push'**
   - The Effect of Phase

3. **'How to Push'**
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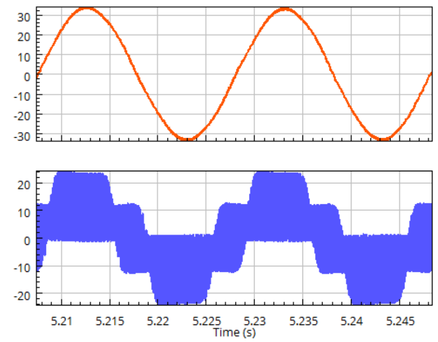

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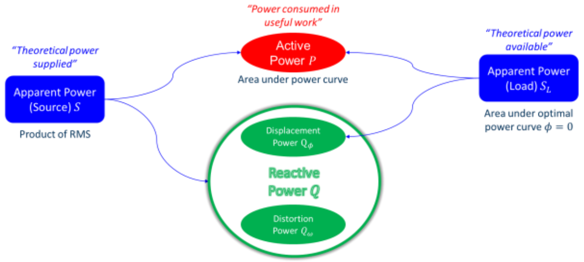

Questions *and links to other relevant presentations*

Coming soon:

- **"eMobility for Non-Electrical Engineers"** By Dr. Andrew Halfpenny and Dr. Alexander Stock

Previous presentations:

- **"Reliability Techniques for Determining Battery Life in Electric Vehicles"** (originally presented April 28, 2022)
  https://www.reliasoft.com/videos/reliability-techniques-for-determining-battery-life-in-electric-vehicles-new

- **"Improving the Durability and Efficiency of Electric Vehicles with Powerful Analysis"**
  (originally presented November 10, 2021)
  https://www.ncode.com/videos/improving-the-durability-and-efficiency-of-electric-vehicles-with-powerful-analysis

- 2020 Technology Days Archive – "Day 1 - Electric Vehicles" – for session 2 presentations:
  - **"Novel permanent magnet machines for electric vehicles"**
  - **"Test and measurement of electric powertrain – a complex electromechanical problem"**
  - **"Analysis of electric powertrain measurements – torque, power, efficiency, vibration"**

  https://www.hbkworld.com/en/academy/events/2020-hbk-technology-days#day1
  (use the "ACCESS 2020 ARCHIVE" button at the top of this page)

Coming soon:

“eMobility for Non-Electrical Engineers”

By Dr. Andrew Halfpenny and Dr. Alexander Stock

Thank You

Dr. Andrew Halfpenny

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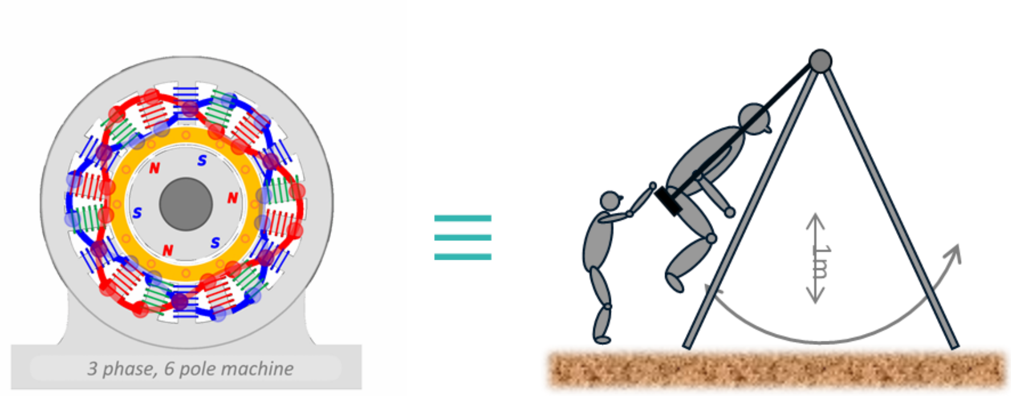

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