Alternator as a voltage Generating source and its response to the leading power factor loads

Presentation by:
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Study Material & References

- Kohler Learning Center
- Uninterruptible Power Supplies Ltd, UK (Kohler Company)
- Impact of Leading Power Factor on Data Center Generator Systems (APC- Schneider Electric White Paper)
- www.powerelectronics.com
- https://wiki.openelectrical.org/index.php?title=Power_Factor
- Electrical Machinery, by Dr. P. S. Bimbhra
- A Text-Book of Electrical Technology (VOL I & II), by B. L. Theraja & A. K. Theraja

Leading Power factor loads- examples

- Capacitors that are used in various facilities to improve the power factor (reduced electricity bill from the utility)
- High-intensity discharge (HID) or fluorescent lamps with capacitor starters (ignitors) e.g. garage lighting
- Harmonic limiting capacitor filters used with the non-linear type loads e.g. UPS
- In a GenSet paralleling application, when a large leading power factor load is applied to the first GenSet online.
- Any other examples?

Presentation Outline

- Power Triangle – KW, KVAR, KVA & Power factor
- Basic Principal behind the operation of the alternator, AVR & Exciter assembly
- What happens when an alternator is subjected to the leading power factor loads
- Theoretical derivation of the alternator capability curve
- Analyze the alternator capability curve published by the manufacturers
- Alternator's response to leading power factor loads: facts to remember
- Recommendations : open to discussion

Ten minutes refresher course!

- GenSet produces voltage
- Load establishes current
- Load characteristics establish the current characteristics.
- e.g. Purely resistive load establishes a current waveform that is in phase with the voltage waveform.
  - 100% of the current is utilized in transferring watts power to the load
- However, not all loads utilize 100% of the current towards the watts power consumption.
  - Out of phase current component, which is not aligned in time with the voltage waveform.

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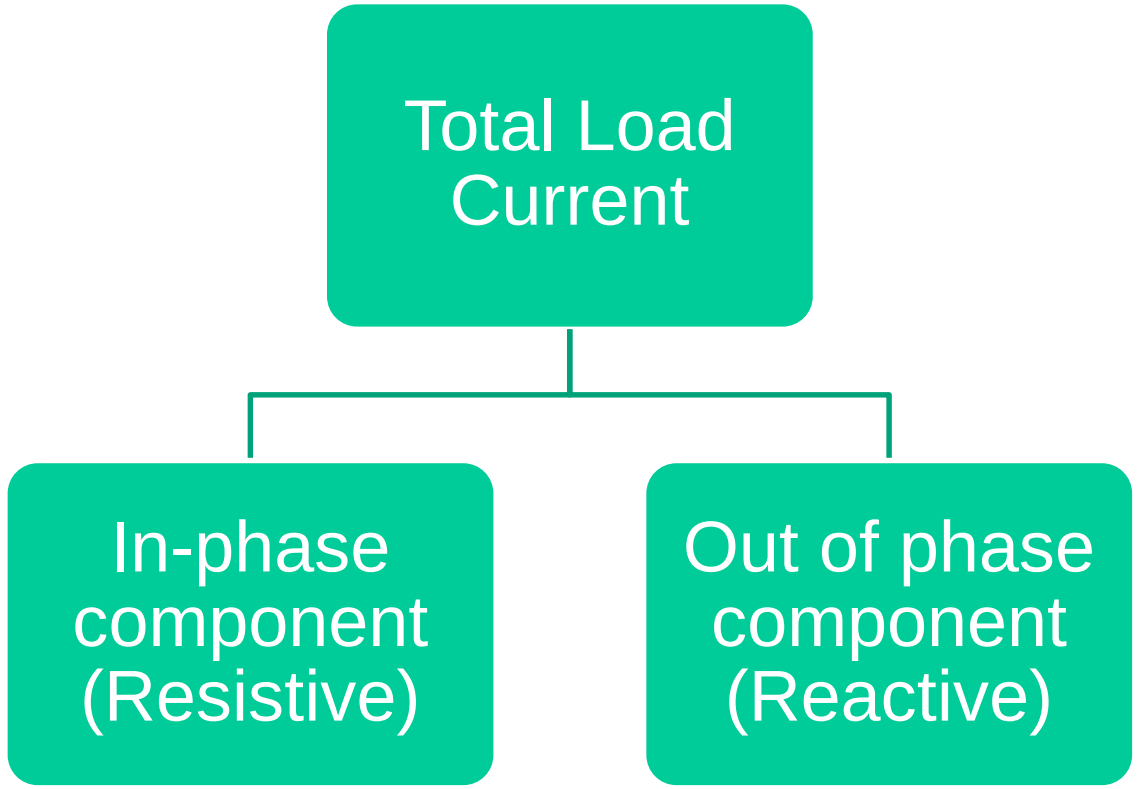

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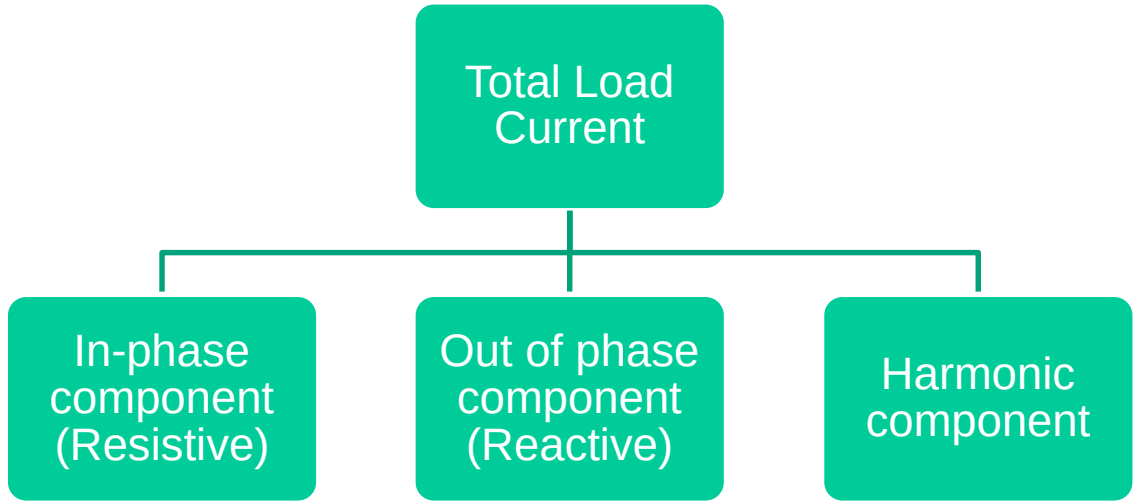

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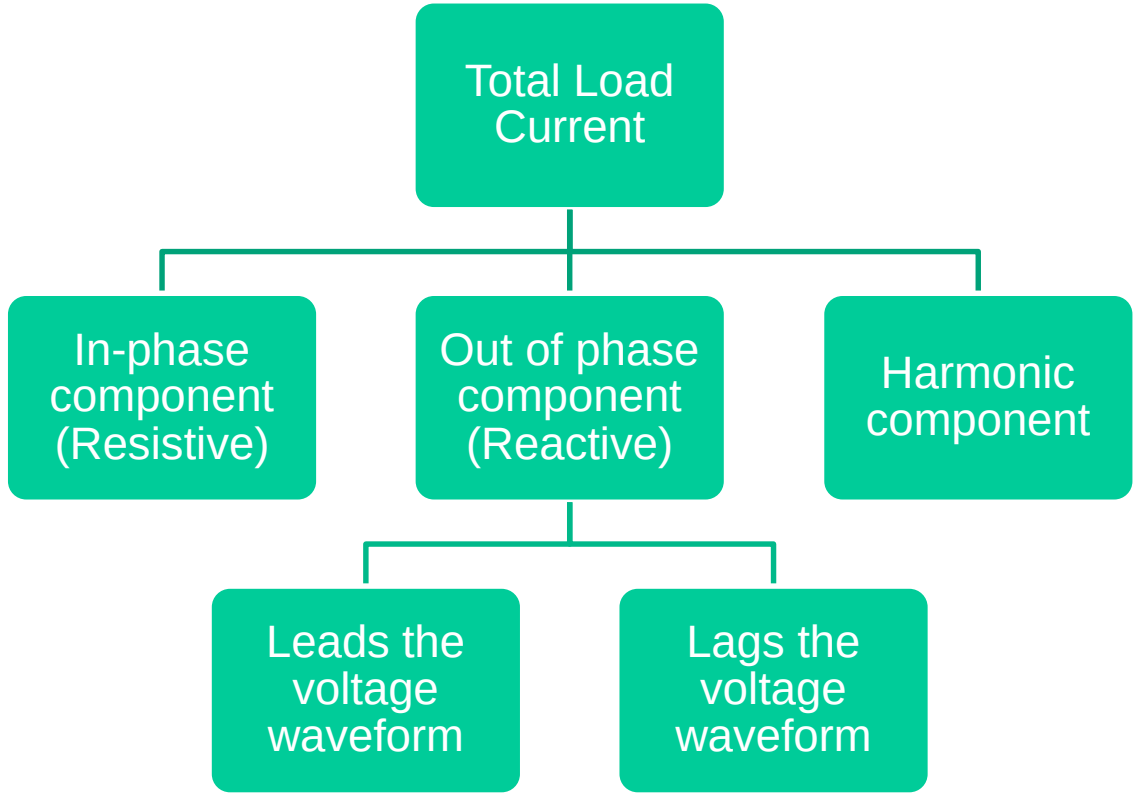
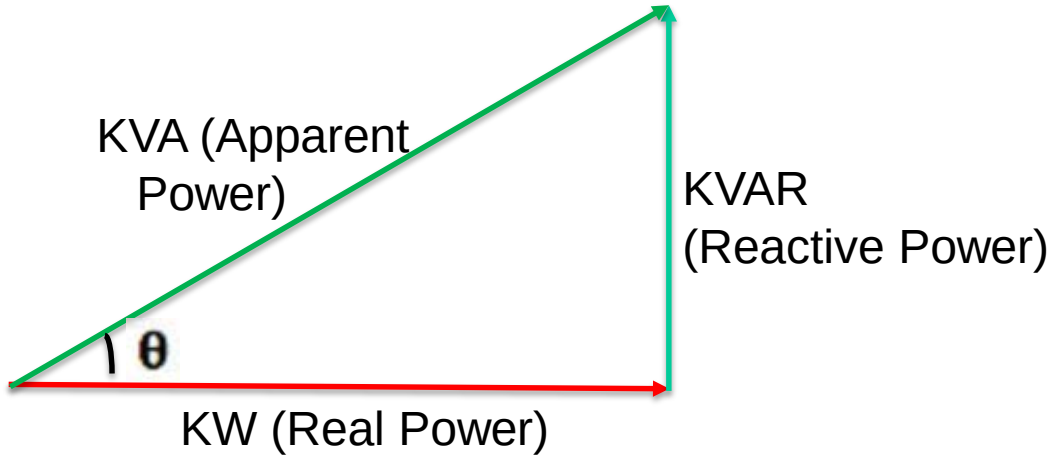


Power Triangle

Power Triangle

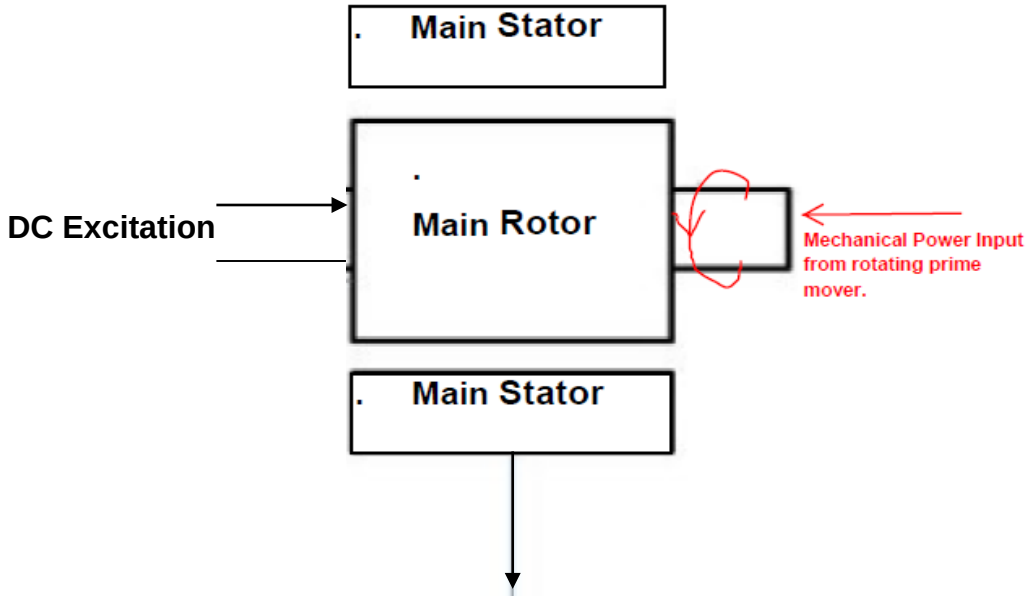


COS θ = KW / KVA

Power Factor

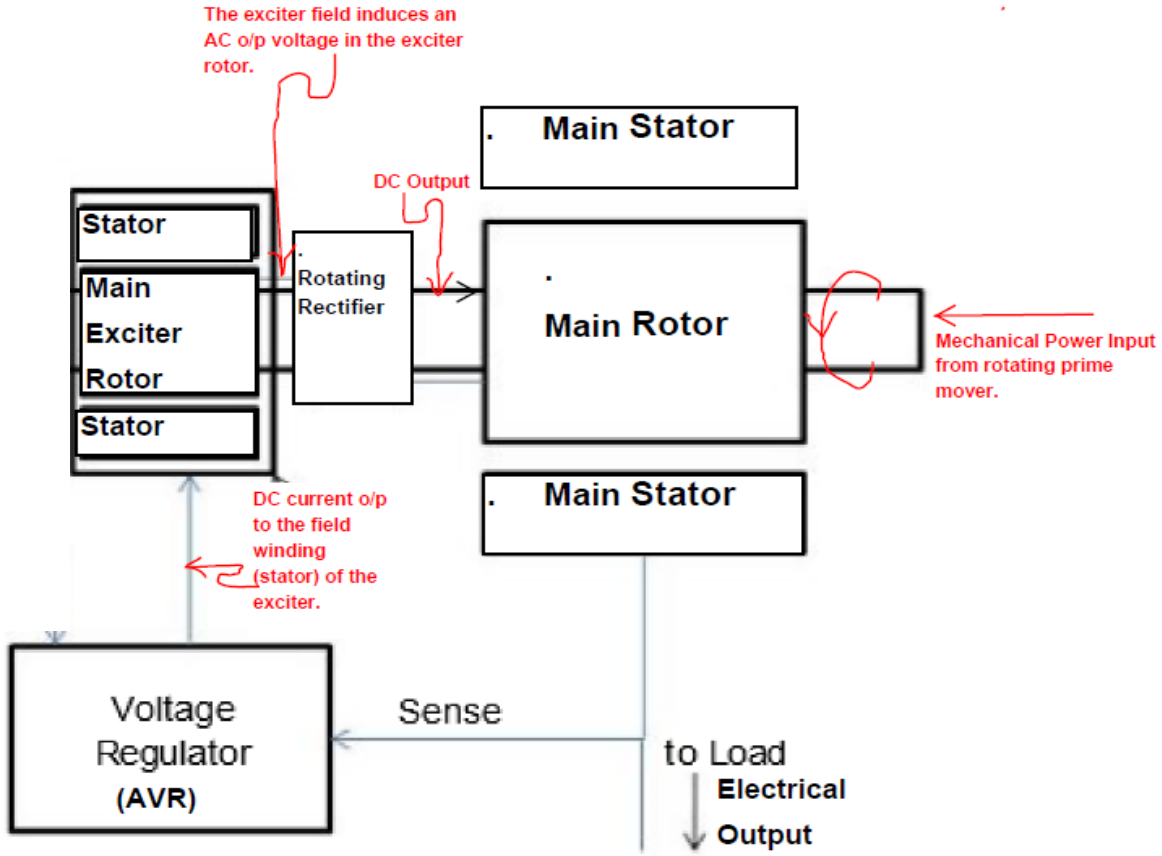
- It is a cosine of an angle between the voltage and current.
- When expressed as the power transferred to the load by the resistive and reactive components of the total load current → Power Triangle

Basic principle - alternator as a voltage generating source



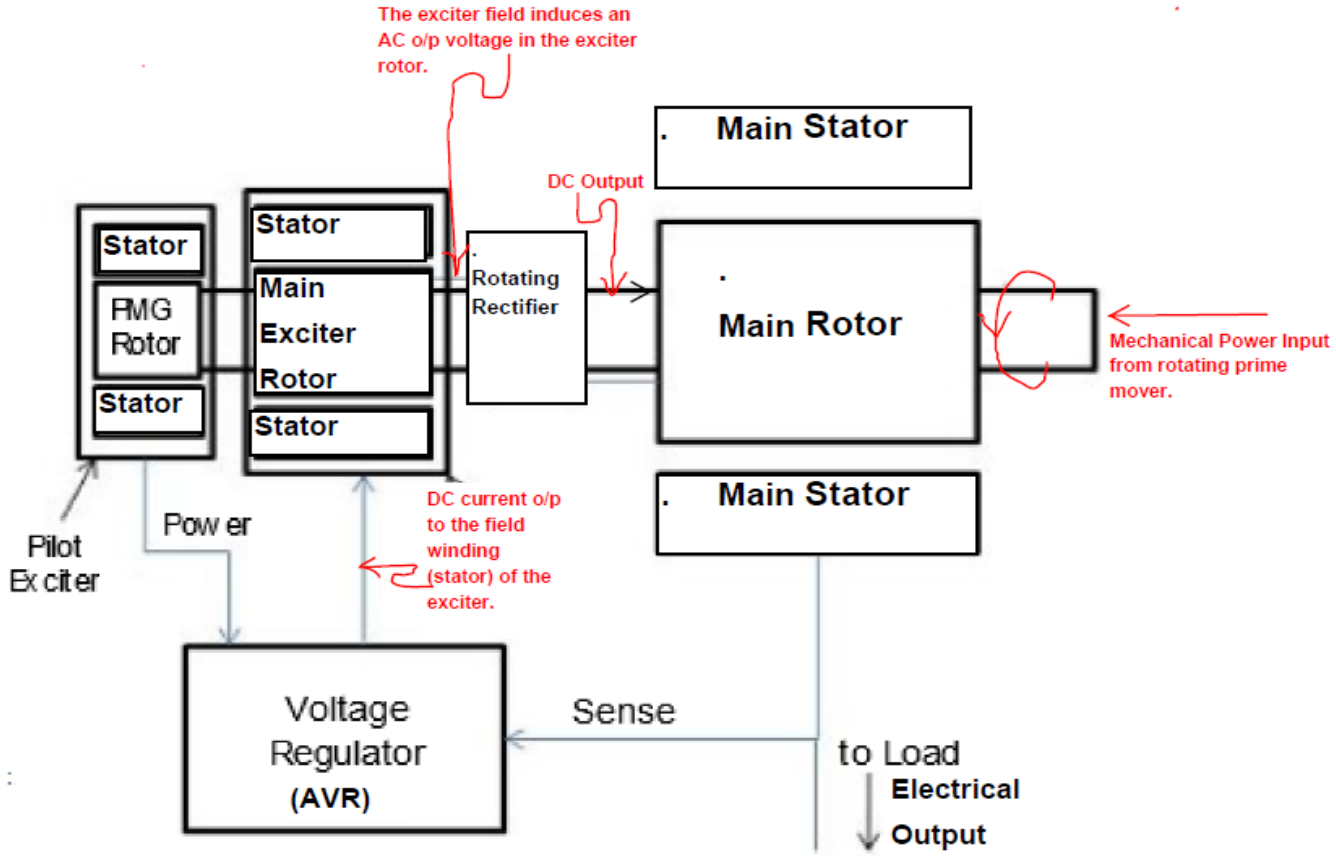
voltage induced at the stator output terminals (Load not yet applied)

Basic principle - Alternator as a voltage generating source



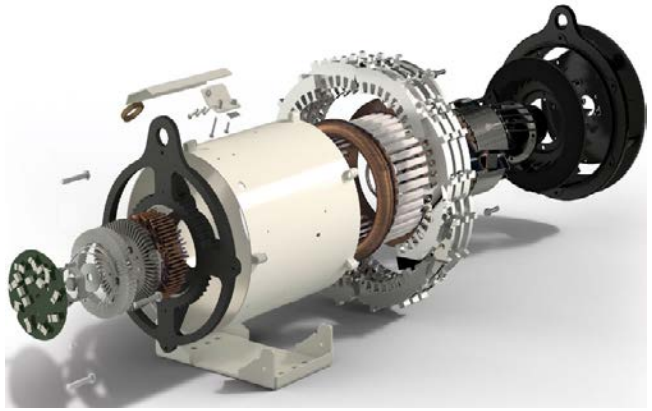
- **AVR function: To regulate the voltage at its rated value under the varying load conditions.**

Basic principle - alternator as a voltage generating source



- AVR function: To regulate the voltage at its rated value under the varying load conditions.
- By increasing/decreasing the excitation current, the alternator can supply increased/decreased power (KVA) at the desired nominal (rated) voltage.

Alternator



Automatic Voltage Regulator (AVR):
Regulates the alternator output voltage at its rated value under the varying load conditions.

AVR controls the main rotor magnetic *field* by changing the excitation current

AVR → excitation current change → main rotor magnetic field → regulators the alternator (stator) output voltage

Engine

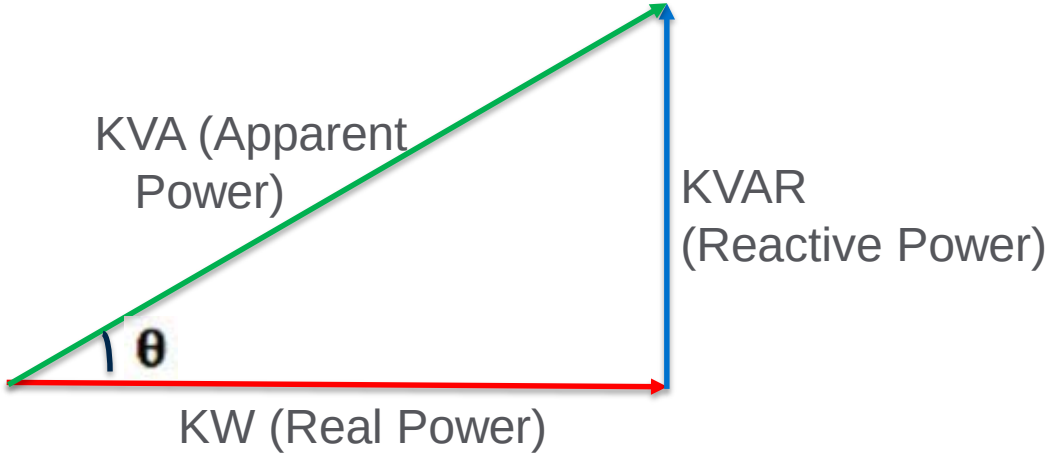
Frequency Governor (GOV):
Regulates the output frequency at its rated value under the varying load conditions

Governor controls the *engine speed* by changing the *fuel supply*

GOV →fuel change → engine speed →regulates the output frequency

Power Triangle

Power Triangle

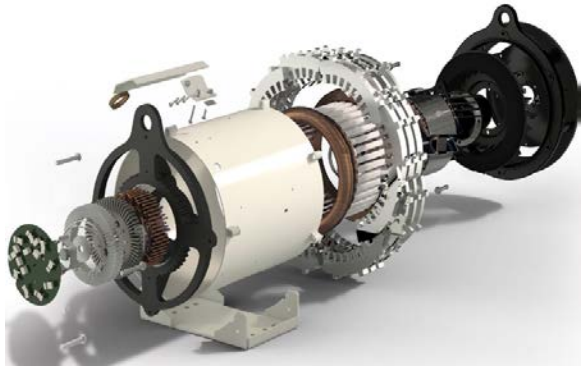


$\cos\theta = KW / KVA$

Power Factor

- It is the Cosine of an angle between the voltage and current.
- The ratio of real power consumed by the load (kW) to the apparent power (KVA) delivered to the load in an AC circuit.

Alternator



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KVAR demand by the load is seen by the alternator

Engine

Frequency Governor (GOV):
Regulates the output frequency at its rated value under the varying load conditions

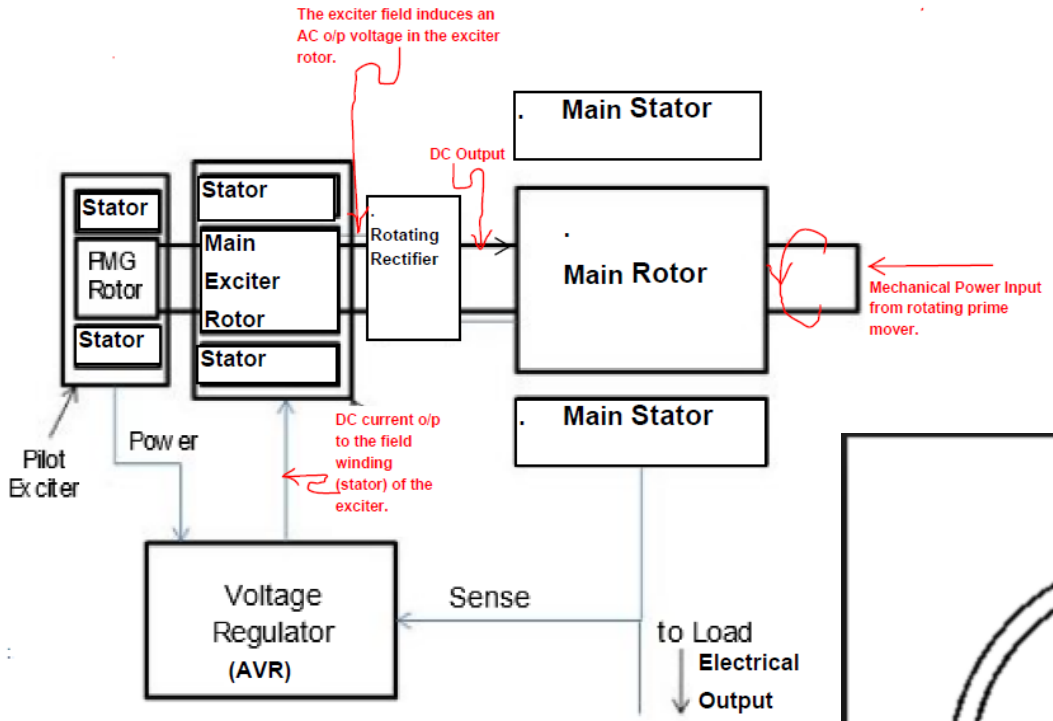
Governor controls the *engine speed* by changing the *fuel supply*

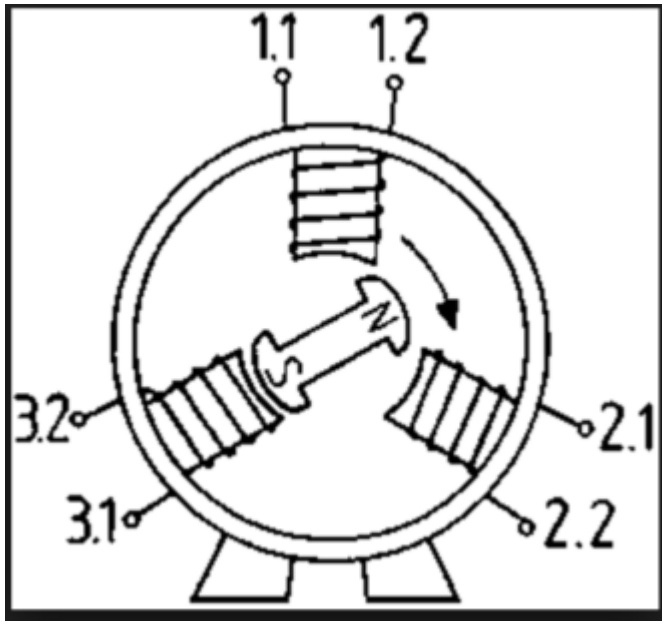
GOV →fuel change → engine speed →regulates the output frequency

KW demand by the load is seen by the engine

When an alternator is subjected to the Leading PF loads!

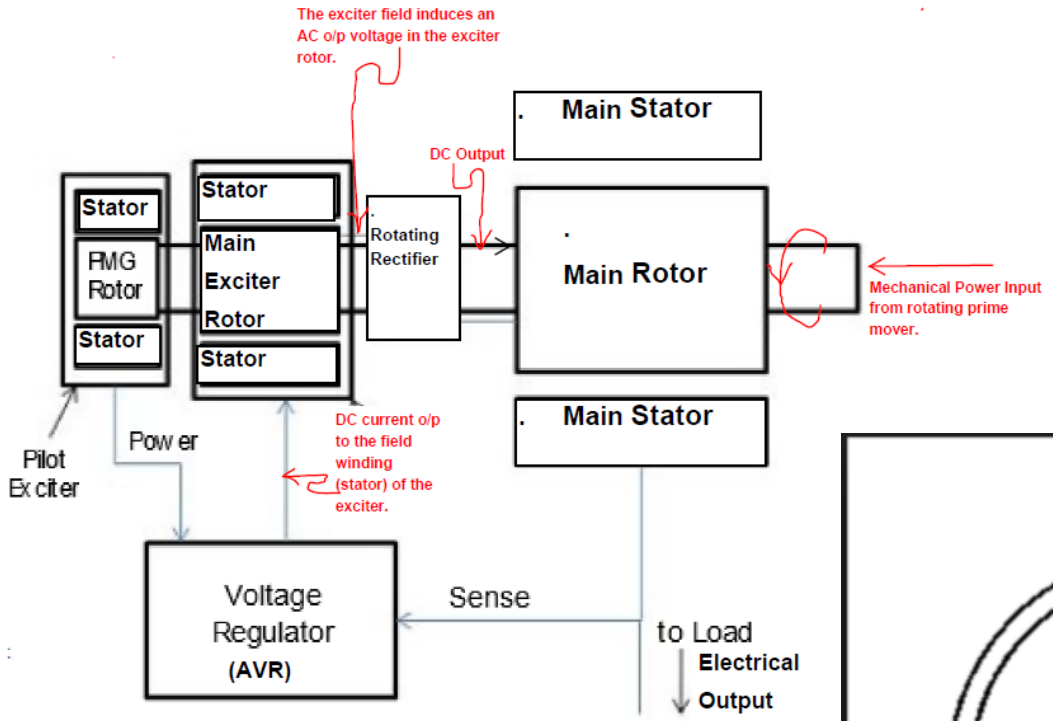
- Unity PF Load → Main Rotor winding field strength is determined solely by the excitation current that is controlled by the AVR.
- Reactive PF Load→ Out of phase component in the load current → induces out of phase magnetic field in the main rotor → may strengthen or weaken the main rotor magnetic field.
- For example: Lagging out of phase component of the load current → partially cancels the main rotor magnetic field → AVR must increase its excitation to compensate.

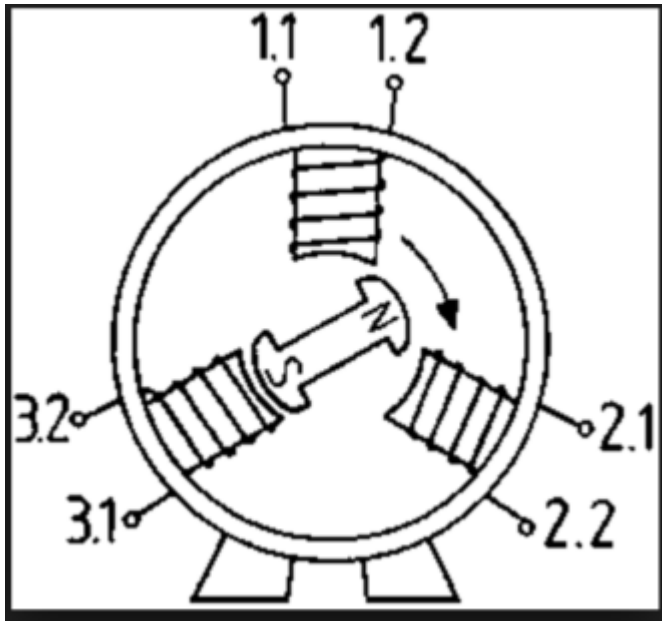




When an alternator is subjected to the Leading PF loads!

- For example: Leading out of phase component of the load current → tends to strengthen the main rotor magnetic field → Stator output voltage rises → AVR must reduce its excitation to compensate. i.e. regulate the voltage.
- This leading out of phase current component produces reverse KVAR.
- If the leading PF load keeps on increasing → increases reverse KVAR → continues to boost the main rotor magnetic field → AVR continues to reduce excitation



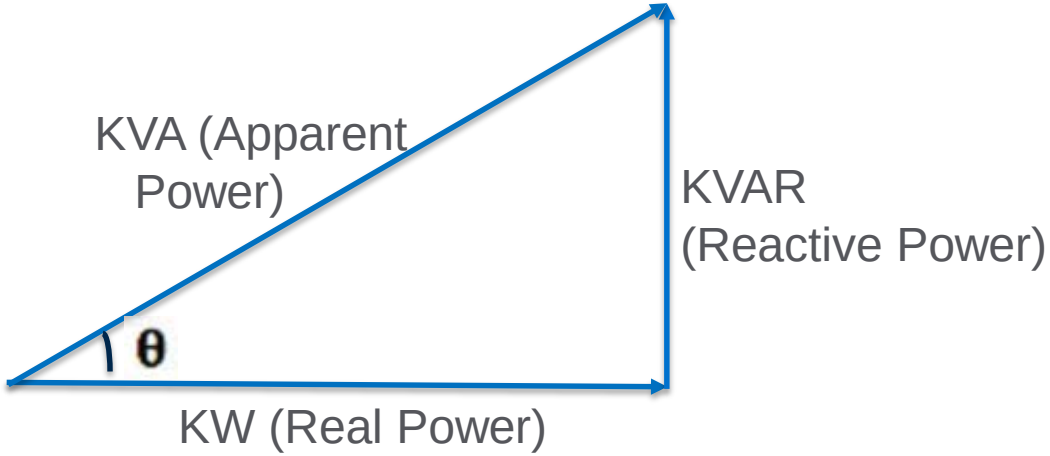


How do you know how much Reverse KVAR or the leading out of phase current can be withstood by an alternator?

We never ask this question to the utility company (!)

Power Triangle

Power Triangle



Power Factor

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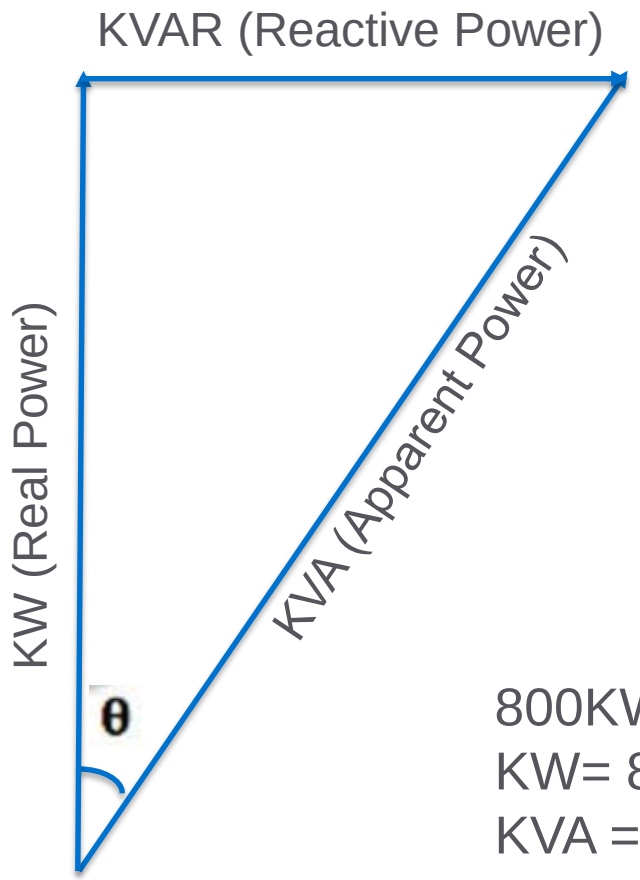
Alternator Capability Curve



Example:

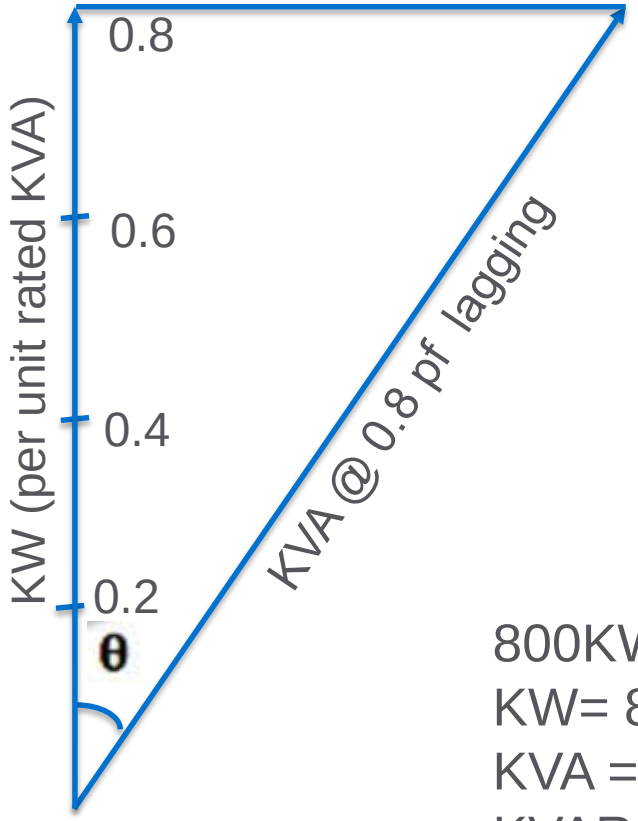
800KW GenSet at 0.8pf lagging

KW= 800

KVA = 1000

KVAR = 600

Alternator Capability Curve



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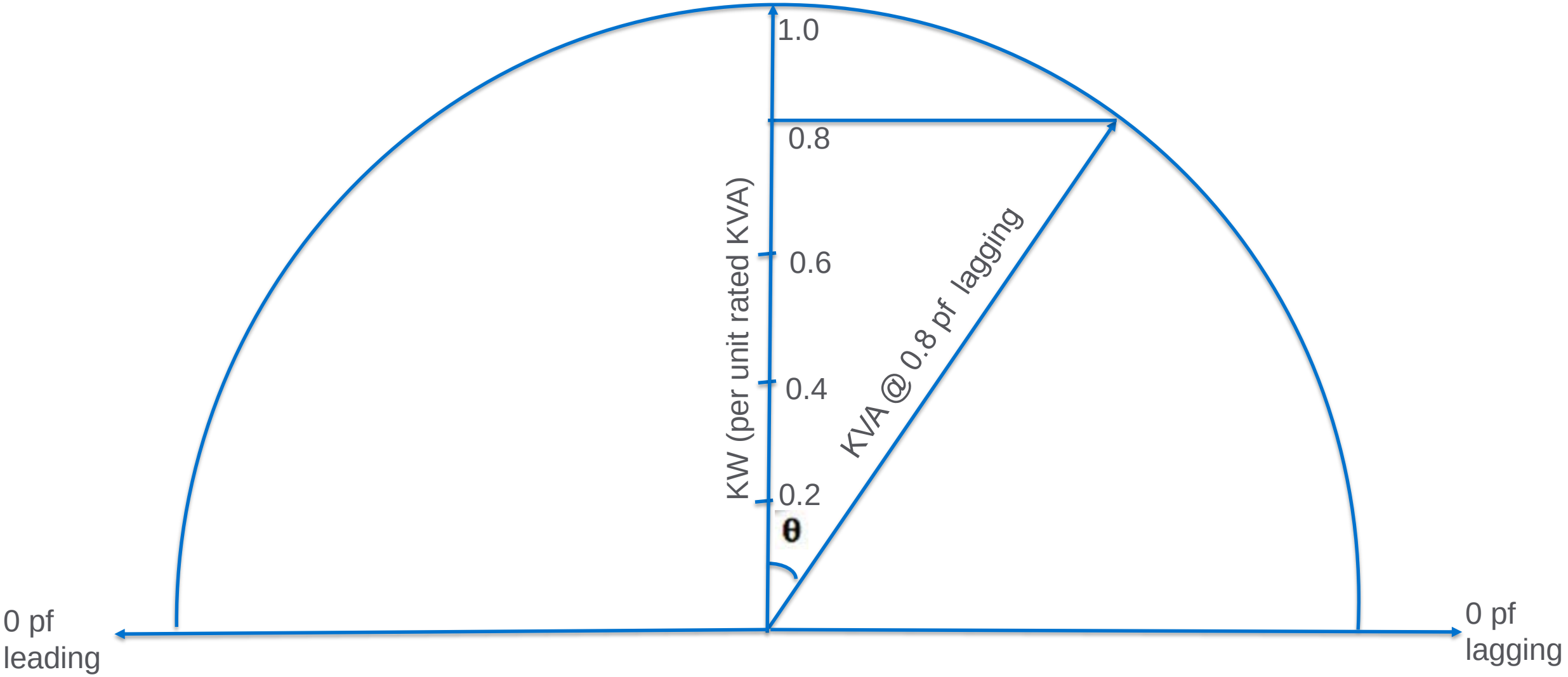
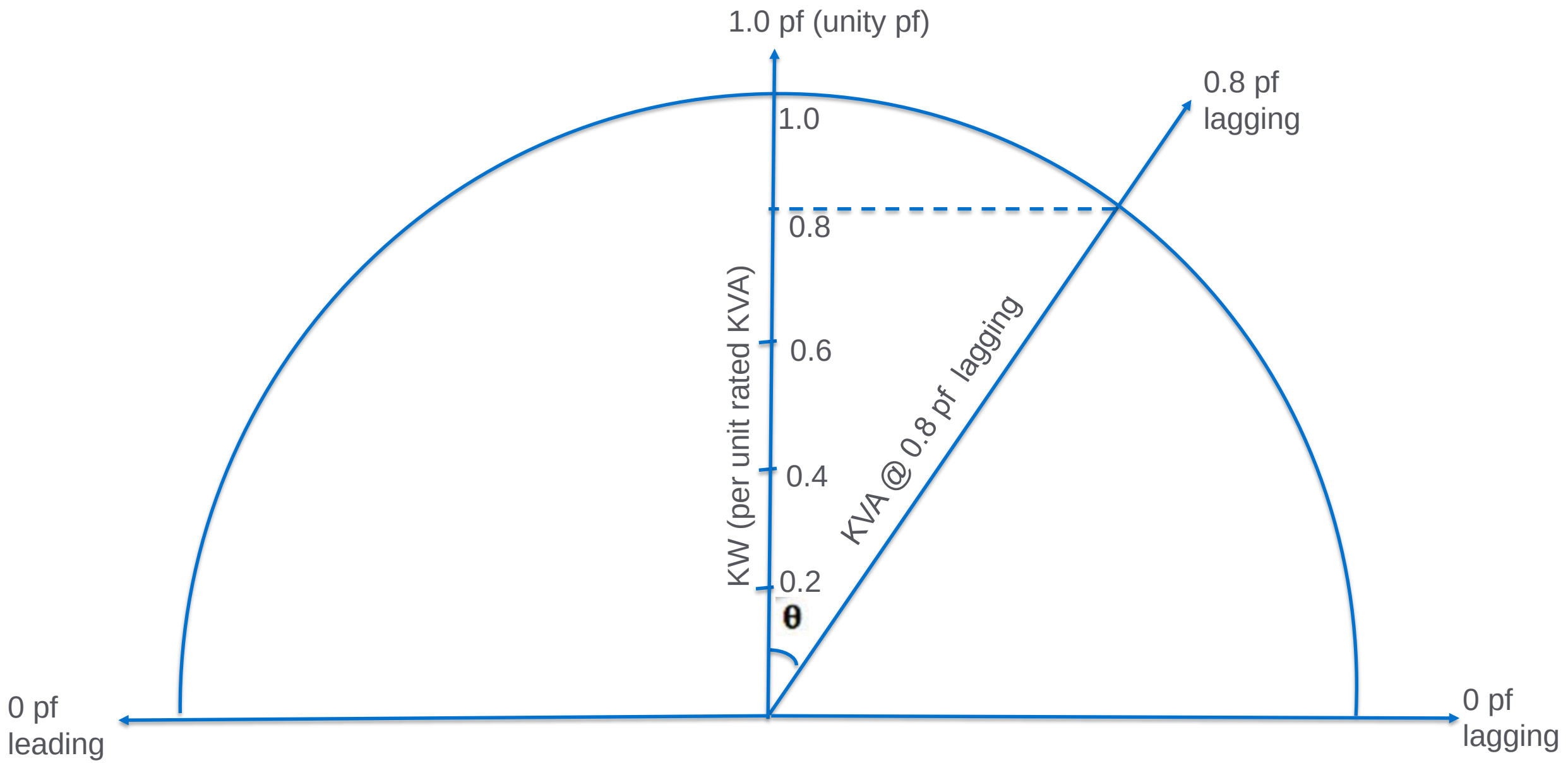
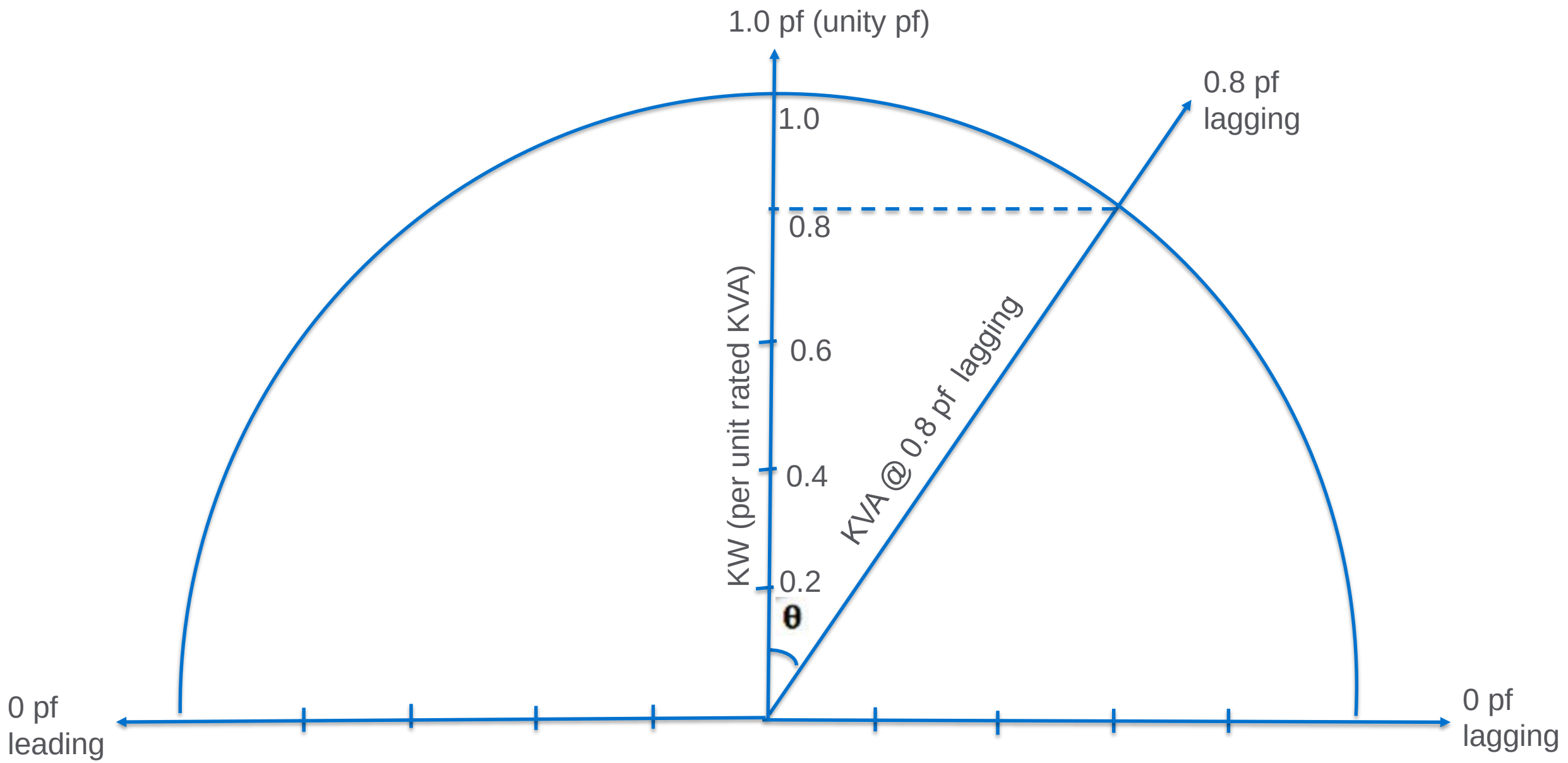
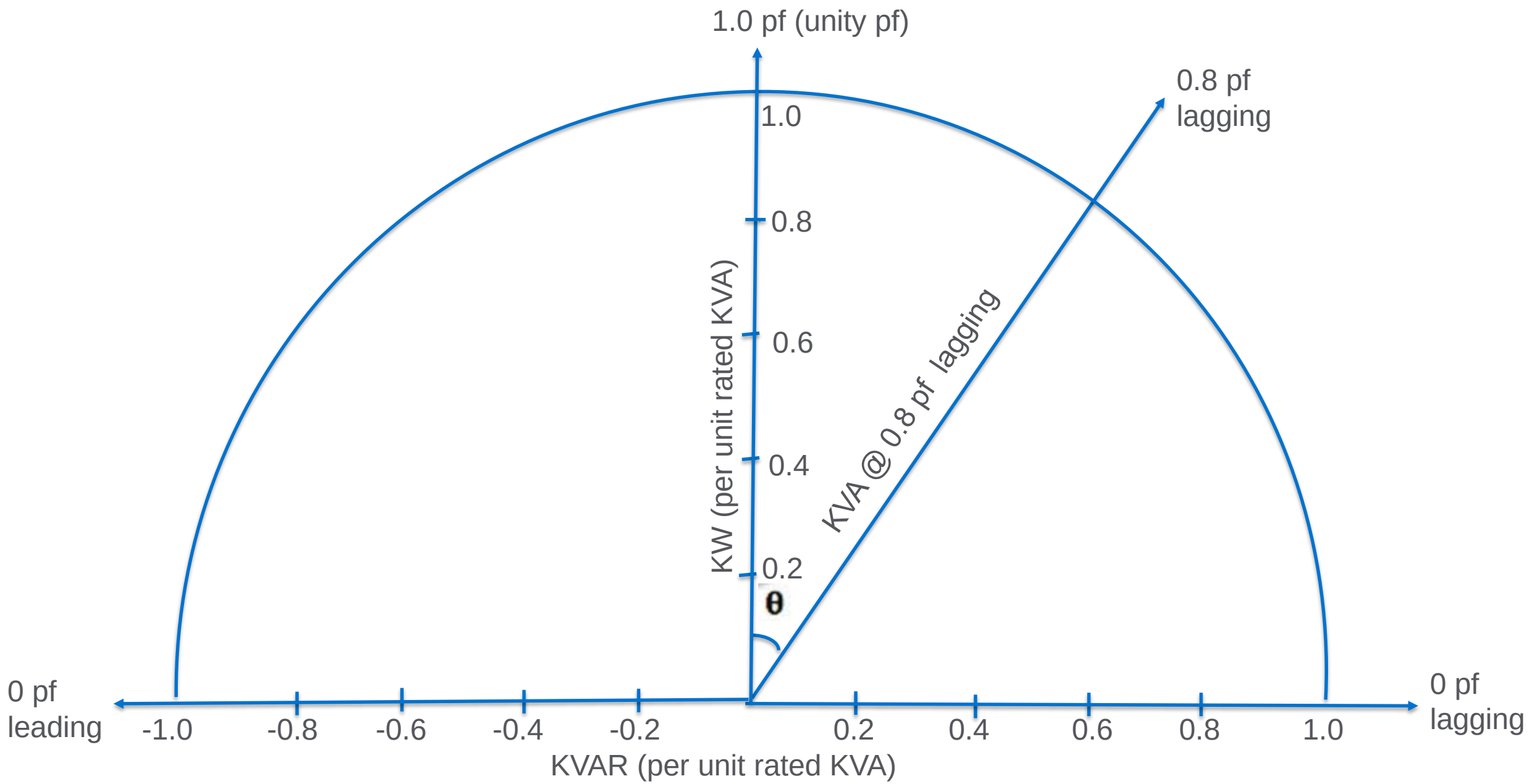
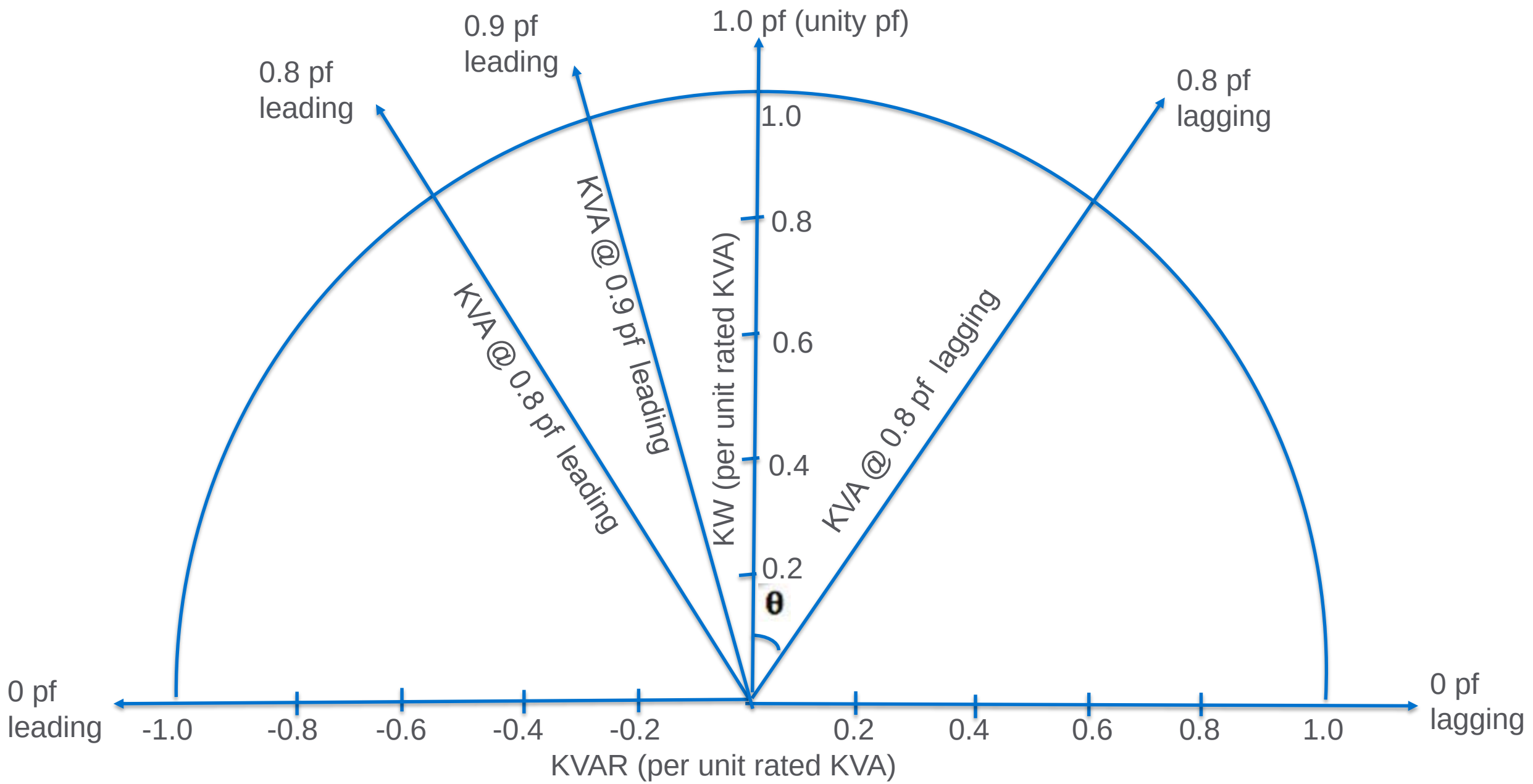
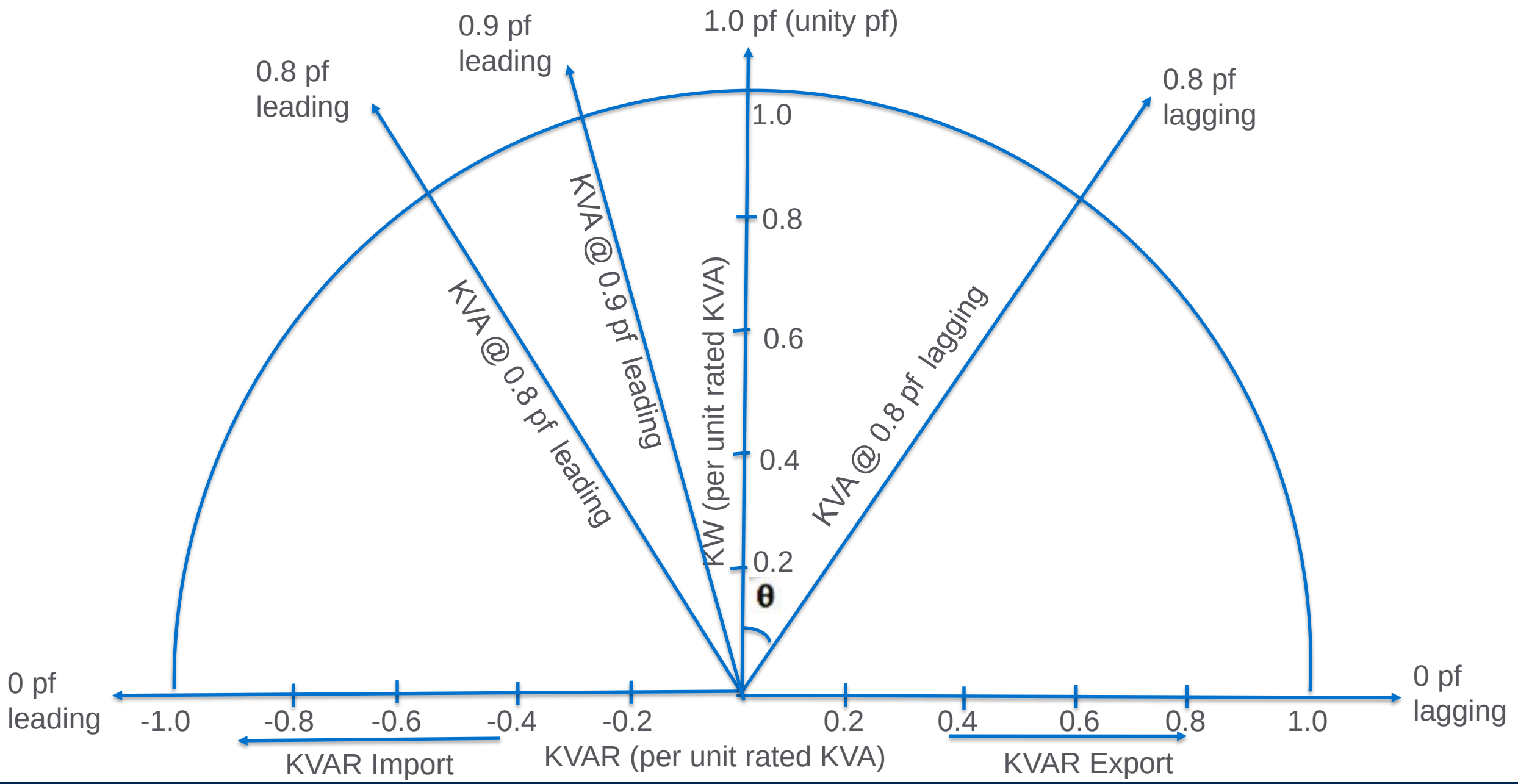

1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.8 pf lagging
θ
0 pf
leading
0 pf
lagging


1.0 pf (unity pf)
0.8 pf
lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.8 pf lagging
θ
0 pf
leading
0 pf
lagging

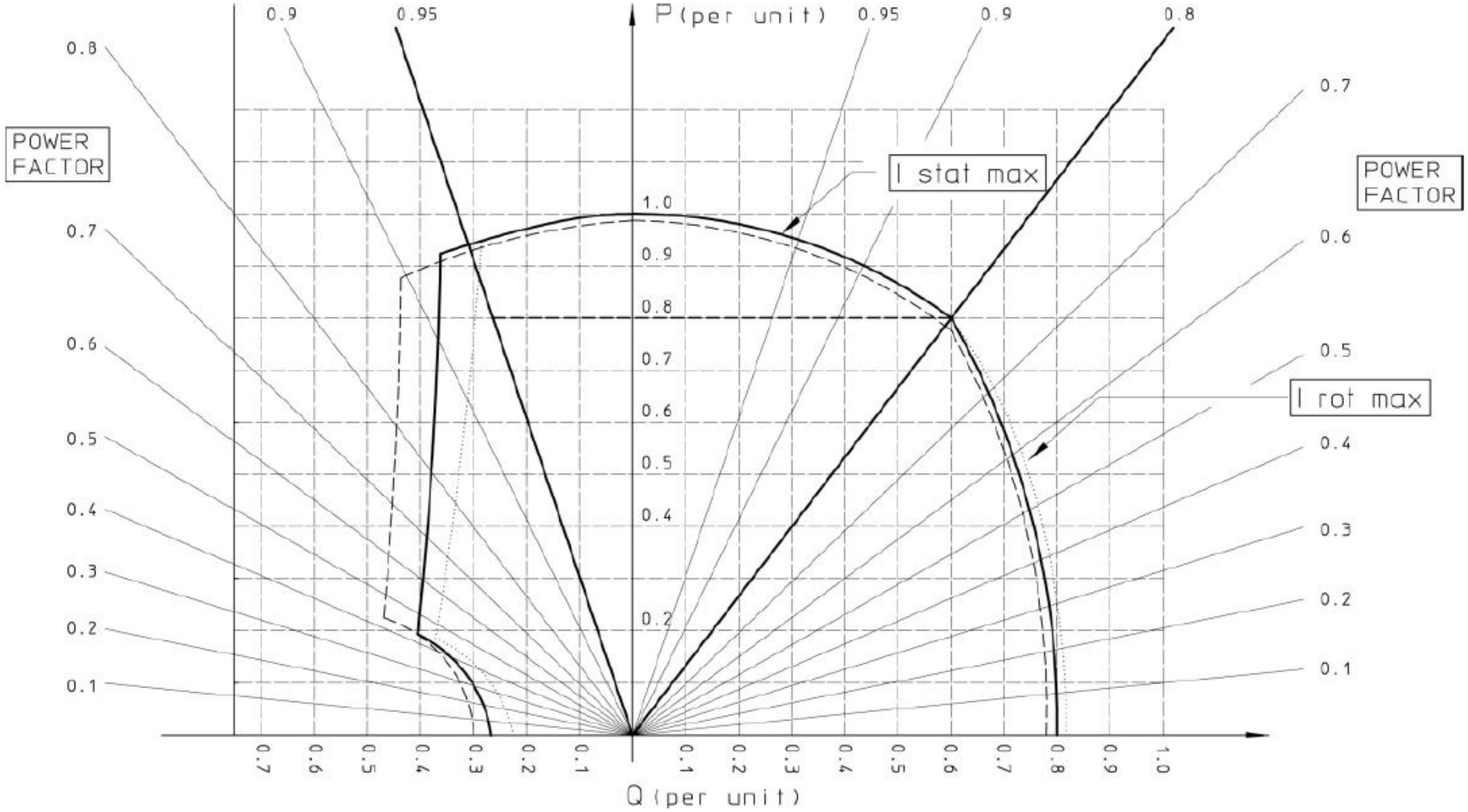

1.0 pf (unity pf)
0.8 pf
lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.8 pf lagging
θ
0 pf
leading
0 pf
lagging

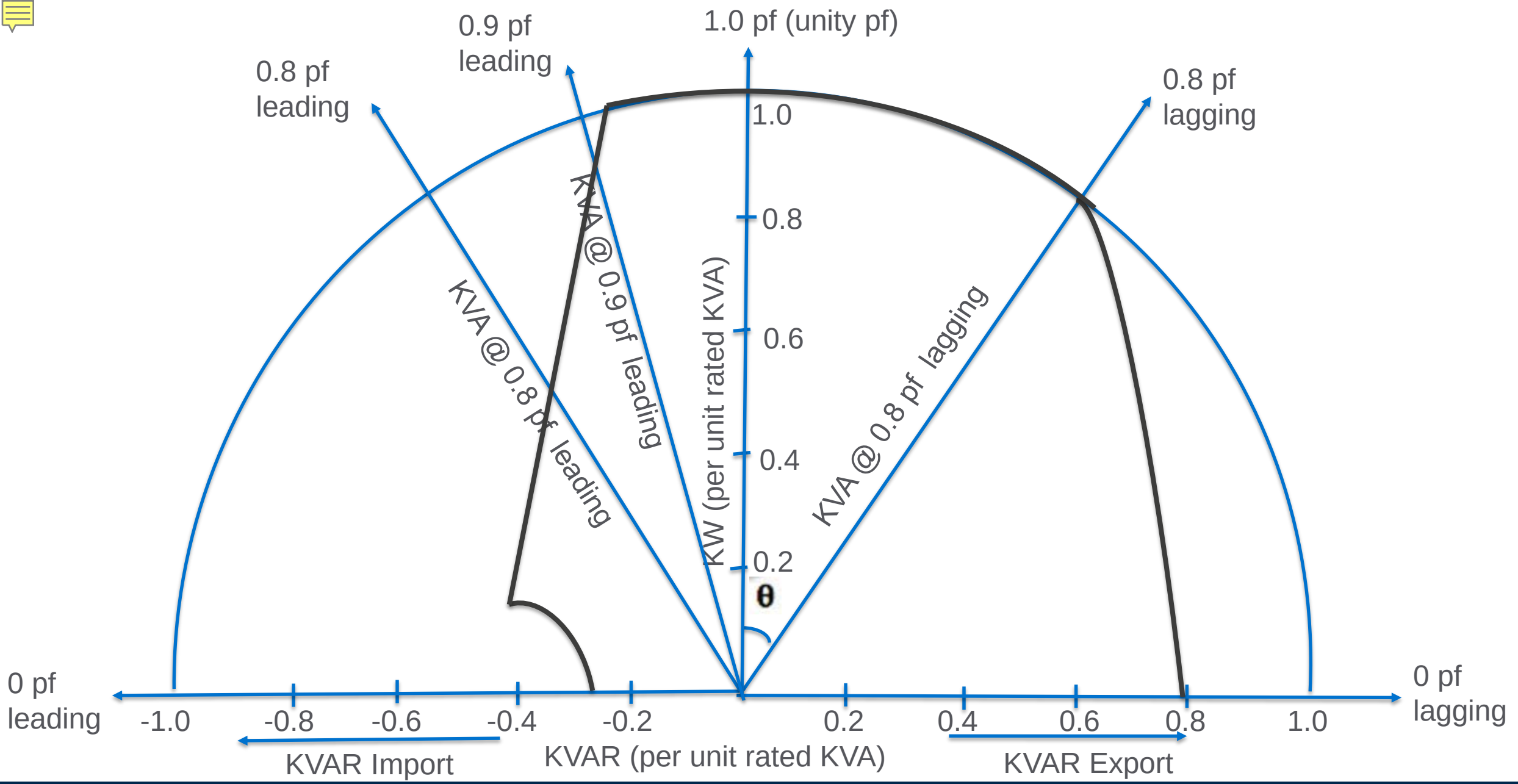

1.0 pf (unity pf)
0.8 pf
lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.8 pf lagging
θ
0 pf
leading
0 pf
lagging
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
KVAR (per unit rated KVA)

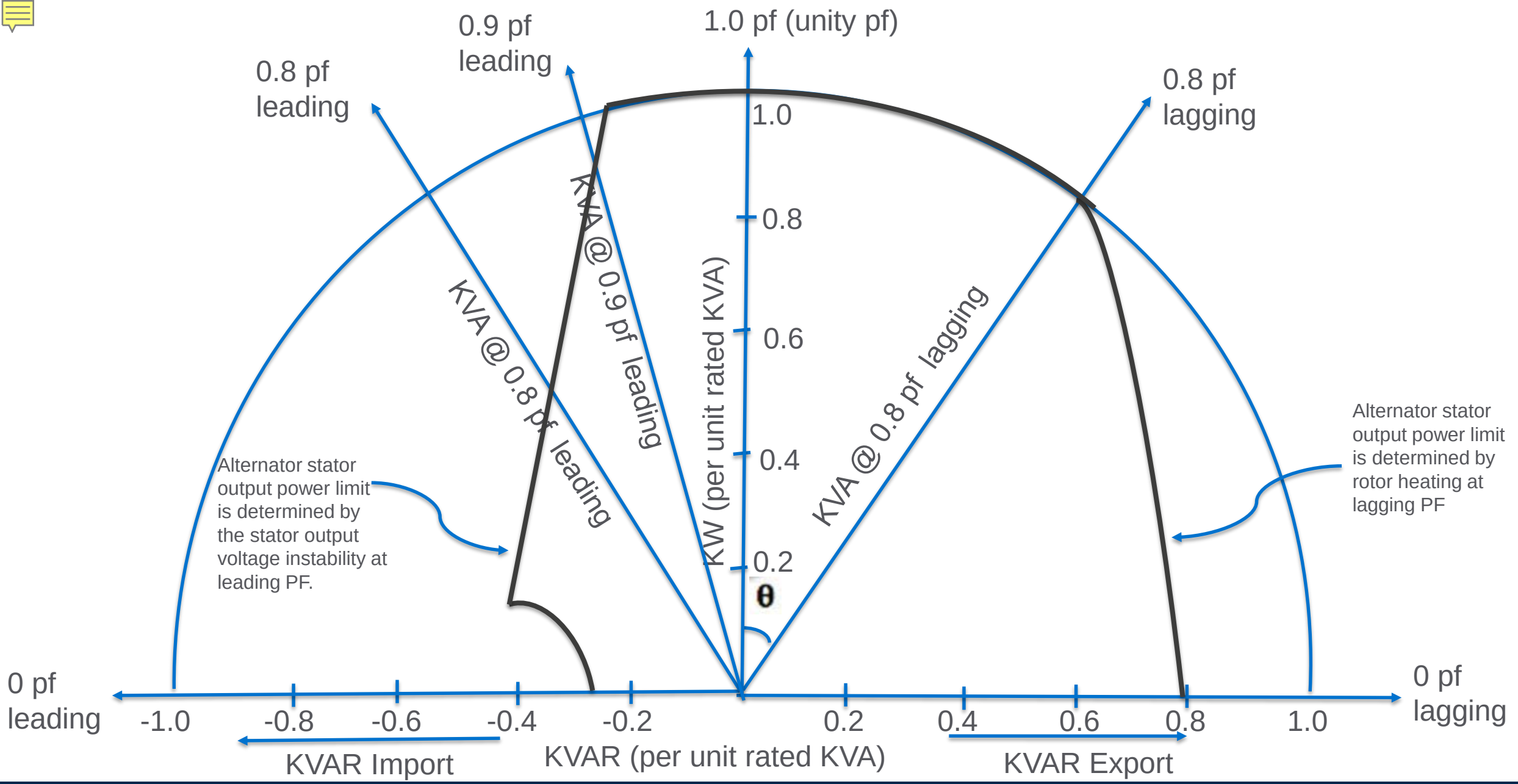

1.0 pf (unity pf)
0.9 pf leading
0.8 pf leading
0.8 pf lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.9 pf leading
KVA @ 0.8 pf leading
KVA @ 0.8 pf lagging
θ
0 pf leading
0 pf lagging
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
KVAR (per unit rated KVA)

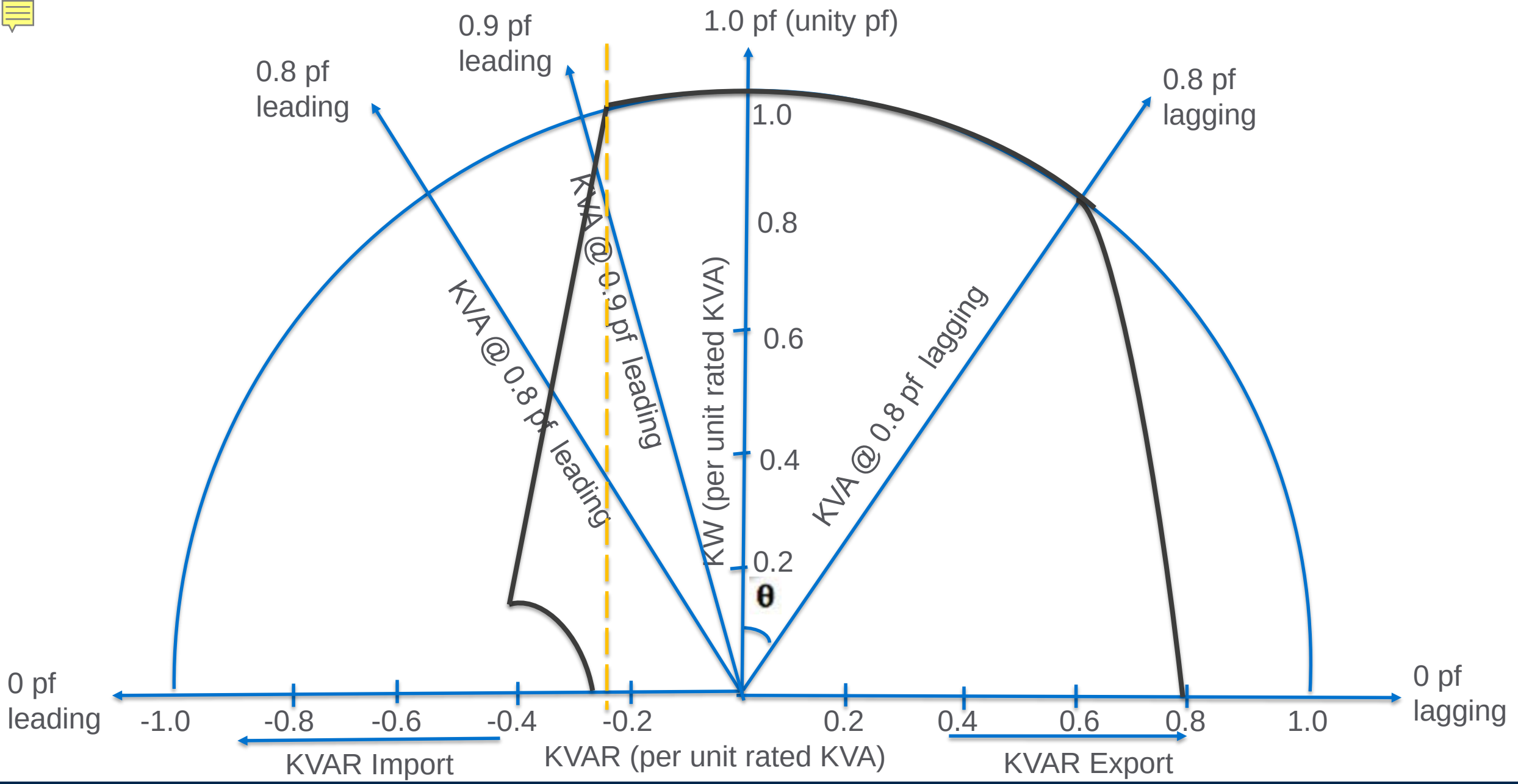

1.0 pf (unity pf)
0.9 pf leading
0.8 pf leading
0.8 pf lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.9 pf leading
KVA @ 0.8 pf leading
KVA @ 0.8 pf lagging
θ
0 pf leading
0 pf lagging
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
KVAR Import
KVAR (per unit rated KVA)
KVAR Export

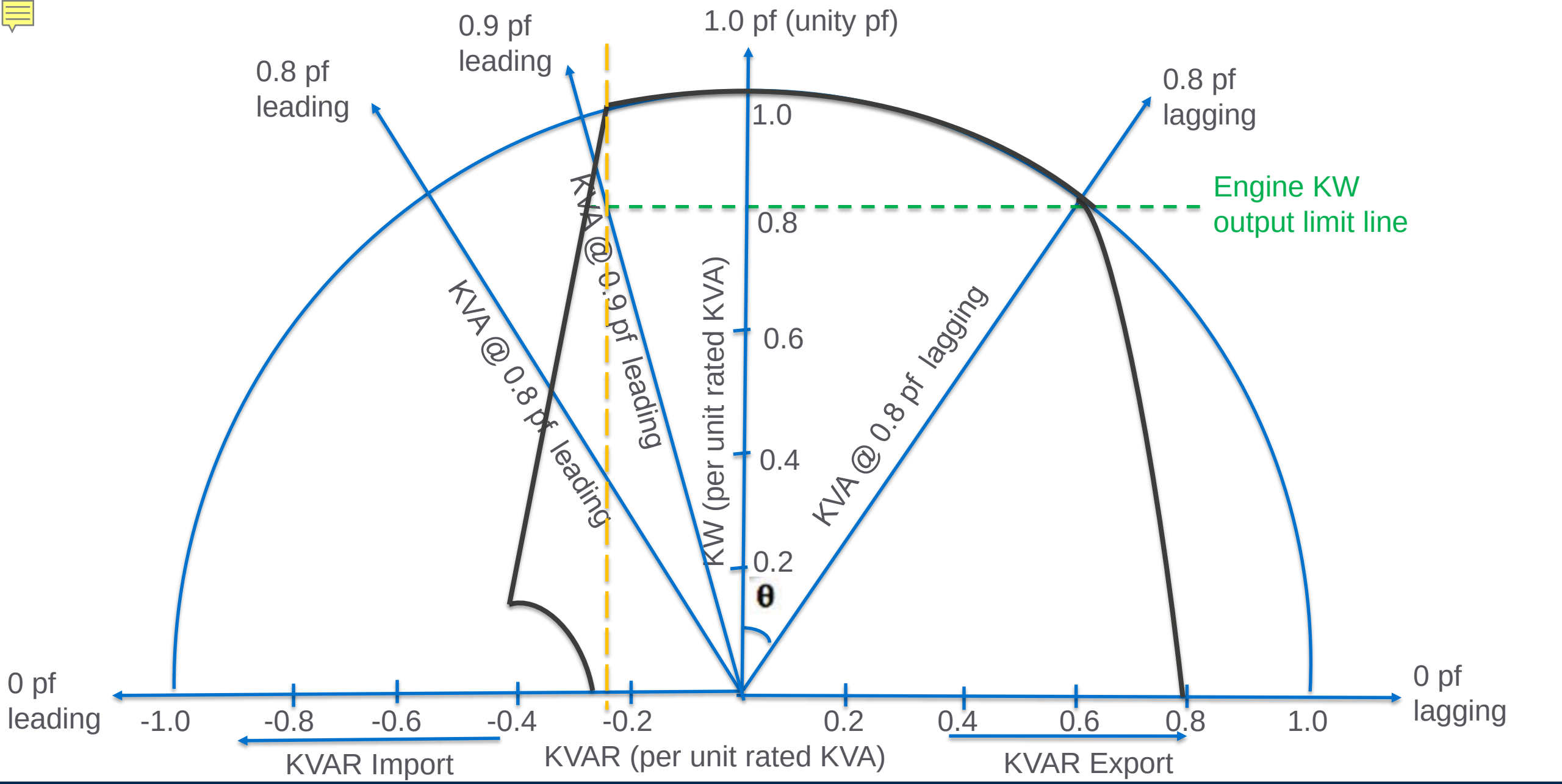
Alternator Capability Curve – sample diagram

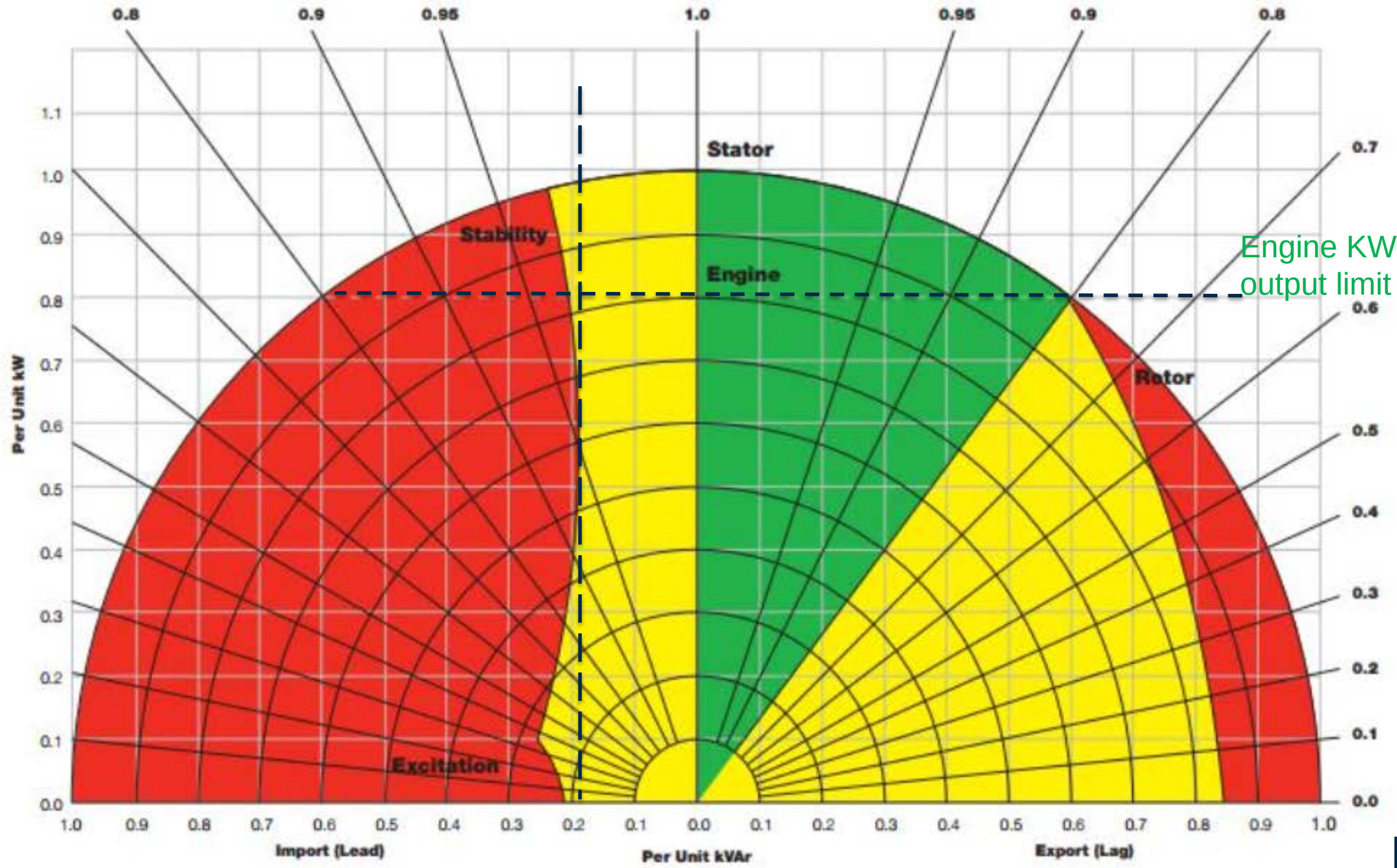



1.0 pf (unity pf)
0.9 pf leading
0.8 pf leading
0.8 pf lagging
1.0
0.8
0.6
0.4
0.2
KVA @ 0.9 pf leading
KVA @ 0.8 pf leading
KW (per unit rated KVA)
KVA @ 0.8 pf lagging
θ
0 pf leading
0 pf lagging
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
KVAR Import
KVAR (per unit rated KVA)
KVAR Export


1.0 pf (unity pf)
0.9 pf leading
0.8 pf leading
0.8 pf lagging
1.0
0.8
0.6
0.4
0.2
KW (per unit rated KVA)
KVA @ 0.9 pf leading
KVA @ 0.8 pf leading
KVA @ 0.8 pf lagging
θ
Alternator stator output power limit is determined by the stator output voltage instability at leading PF.
Alternator stator output power limit is determined by rotor heating at lagging PF
0 pf leading
0 pf lagging
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
KVAR Import
KVAR (per unit rated KVA)
KVAR Export

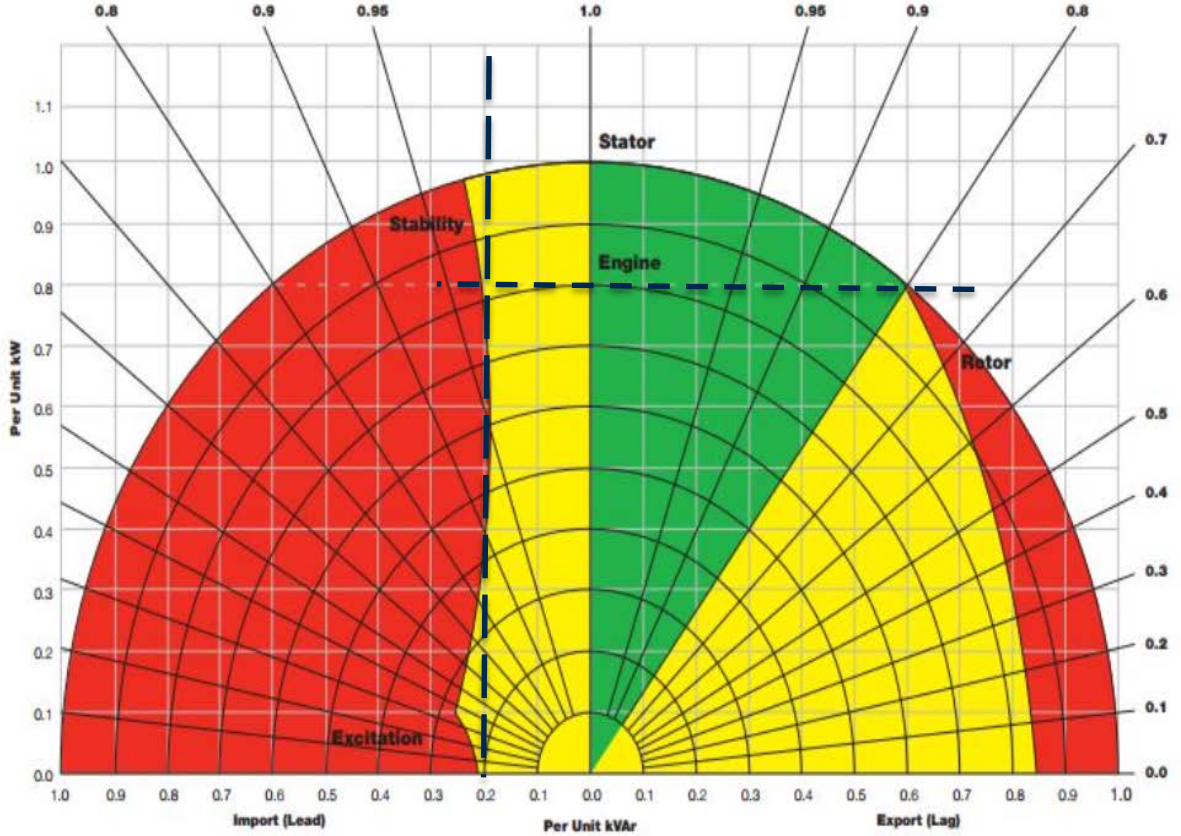

0.9 pf
leading
1.0 pf (unity pf)
0.8 pf
leading
0.8 pf
lagging
1.0
0.8
0.6
0.4
0.2
KVA @ 0.9 pf leading
KW (per unit rated KVA)
KVA @ 0.8 pf leading
KVA @ 0.8 pf lagging
θ
0 pf
leading
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
0 pf
lagging
KVAR Import
KVAR (per unit rated KVA)
KVAR Export


0.9 pf leading
1.0 pf (unity pf)
0.8 pf leading
0.8 pf lagging
1.0
Engine KW output limit line
0.8
KVA @ 0.9 pf leading
KW (per unit rated KVA)
0.6
KVA @ 0.8 pf leading
KVA @ 0.8 pf lagging
0.4
0.2
θ
0 pf leading
-1.0
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1.0
0 pf lagging
KVAR Import
KVAR (per unit rated KVA)
KVAR Export


0.8
0.9
0.95
1.0
0.95
0.9
0.8
Stator
Stability
Engine
Rotor
Excitation
Engine KW
output limit line
Per Unit kW
Per Unit kVAr
Import (Lead)
Export (Lag)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

When an alternator is subjected to the Leading PF loads! - Summary

- Reverse KVAR (Leading out of phase current component)
- Stator output voltage rises
- AVR decreases the excitation
- Too much reverse KVAR can cause the AVR completely turn off and lose control
- The voltage overshoots uncontrollably
- Result:
  - The generator shuts down
  - Damage to the loads
  - The UPS goes into the by-pass mode or switches to the battery



Facts to Remember

- Loads with the Leading out of phase current component (leading power factor) produce reverse KVAR
- The alternator has limited capability of absorbing the reverse KVAR
- A blanket statement: The KVAR absorption capability of an alternator is XYZ irrespective of the leading power factor value of the load.
- The KVAR absorption capabilities of alternators are different amongst the manufacturers.
- The harmonics limiting filters, when sized to the rated capacity of the UPS can cause leading power factor on the power source.
    - Lightly loaded UPS
    - UPS ramping up from no load

Recommendations: Open to discussion

- The expected reverse KVAR from the load should be calculated in the design phase of the project.
  - The leading PF value is not important!
  - Alternator Capability caurve in the submittal pacakge
- Specify lower temperature rise Alternator (larger KVA)
  - Lower sub transient reactance
- While loading a GenSet, care should be taken to not generate reverse KVAR to the unacceptable level.
  - Add inductive loads first
  - Add inductive loads along with the leading PF loads in smaller steps
- While on the GenSet, turn off or limit the operation of the UPS filters until other types of loads are connected.
  - If acceptable by other loads
  - Today's advance excitation systems and other contemporary features on the GenSet contribute to provide stable voltage as well

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