Better Plants®
U.S. DEPARTMENT OF ENERGY

# Power Factor

U.S. DEPARTMENT OF ENERGY

# Why Care About Power Factor?

- **Low power factor:**
  - Increases the current flow in your electrical system
  - Higher current flows increase resistive losses in conductors and transformer losses
  - Causes penalty charges if below some threshold
  - Power factor is a measure of your electrical system efficiency in handling power
  - Increases system voltage drop
- **Low power factor can cost you $$$$$$**

# Three Phase Power

## First -

Real power, or kW, for a 3-phase system can be calculated as:

$$kW = Volts_{RMS} \times Amps_{RMS} \times Pf \times \sqrt{3} / 1{,}000$$

where the power factor is 1.0 for purely resistive loads and less than 1.0 and lagging for inductive loads such as induction motors, transformers, induction furnaces and magnetic ballasts. For capacitive loads the power factor is leading and less than 1.0

# Resistive Electrical Load

***A purely resistive electrical load has no inductance or capacitance***

***Good examples are electric space heaters and incandescent light bulbs***

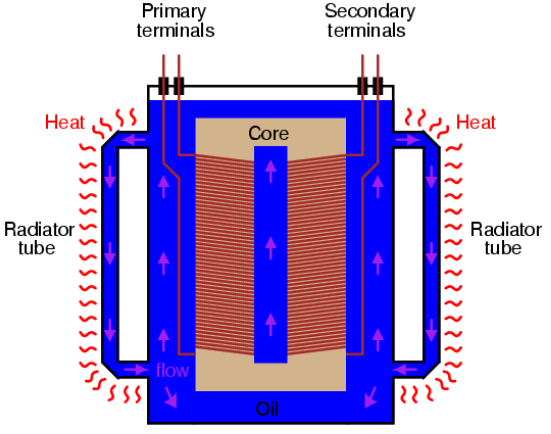
The Power Factor is 1.0 for purely resistive loads!

# Inductive Electrical Loads

## *An electrical load with iron core coils is an inductive type of load*

***Good examples are electric motors, transformers, induction furnaces, and old magnetic light ballasts***

The Power Factor is less than 1.0 for inductive loads!



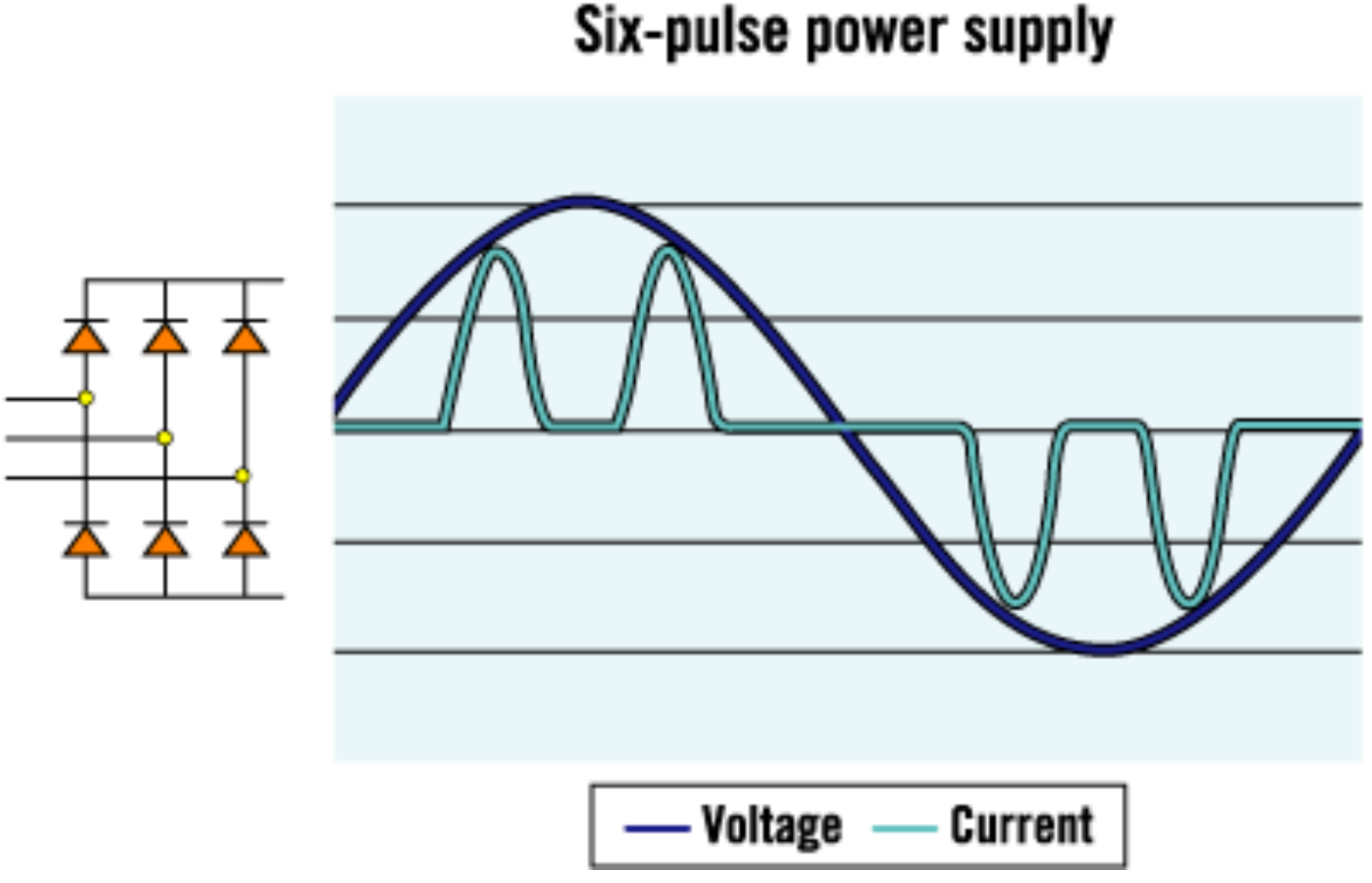
# High Harmonic Loads

***Power electronic devices often cause distorted voltage and current waveforms which cause a low power factor***

***Devices such as variable speed drives, switched mode power supplies and discharge lighting can create harmonics on your electrical system***

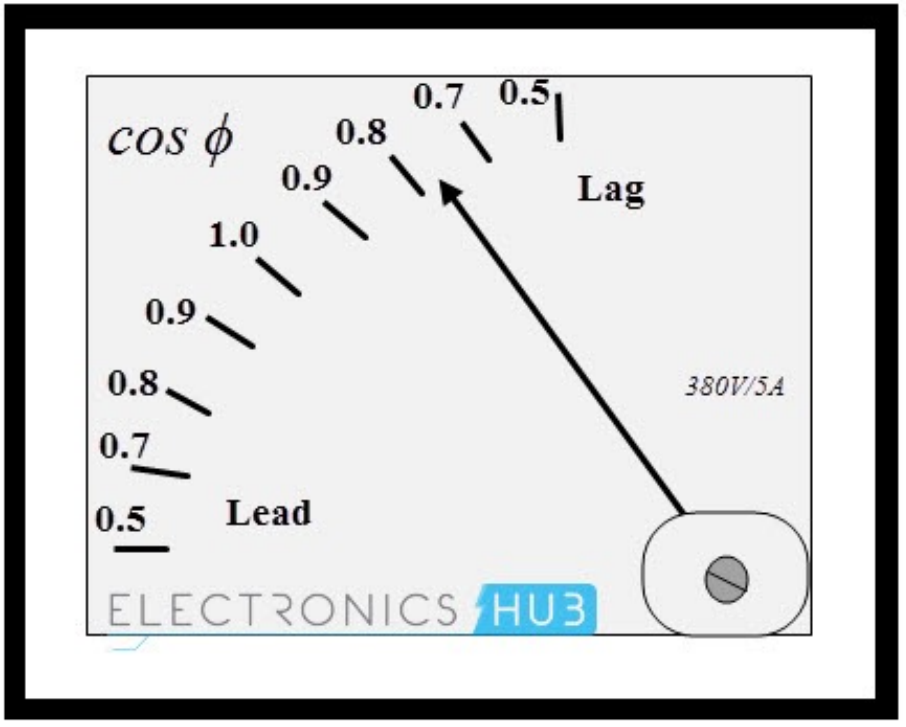
***Power factor correction for harmonic distortion requires electronic filtration – consult a specialist***

# High Harmonic Loads



# Why Are Power Factors Low?

*Why do some plants experience problems with low power factors and others don't?*

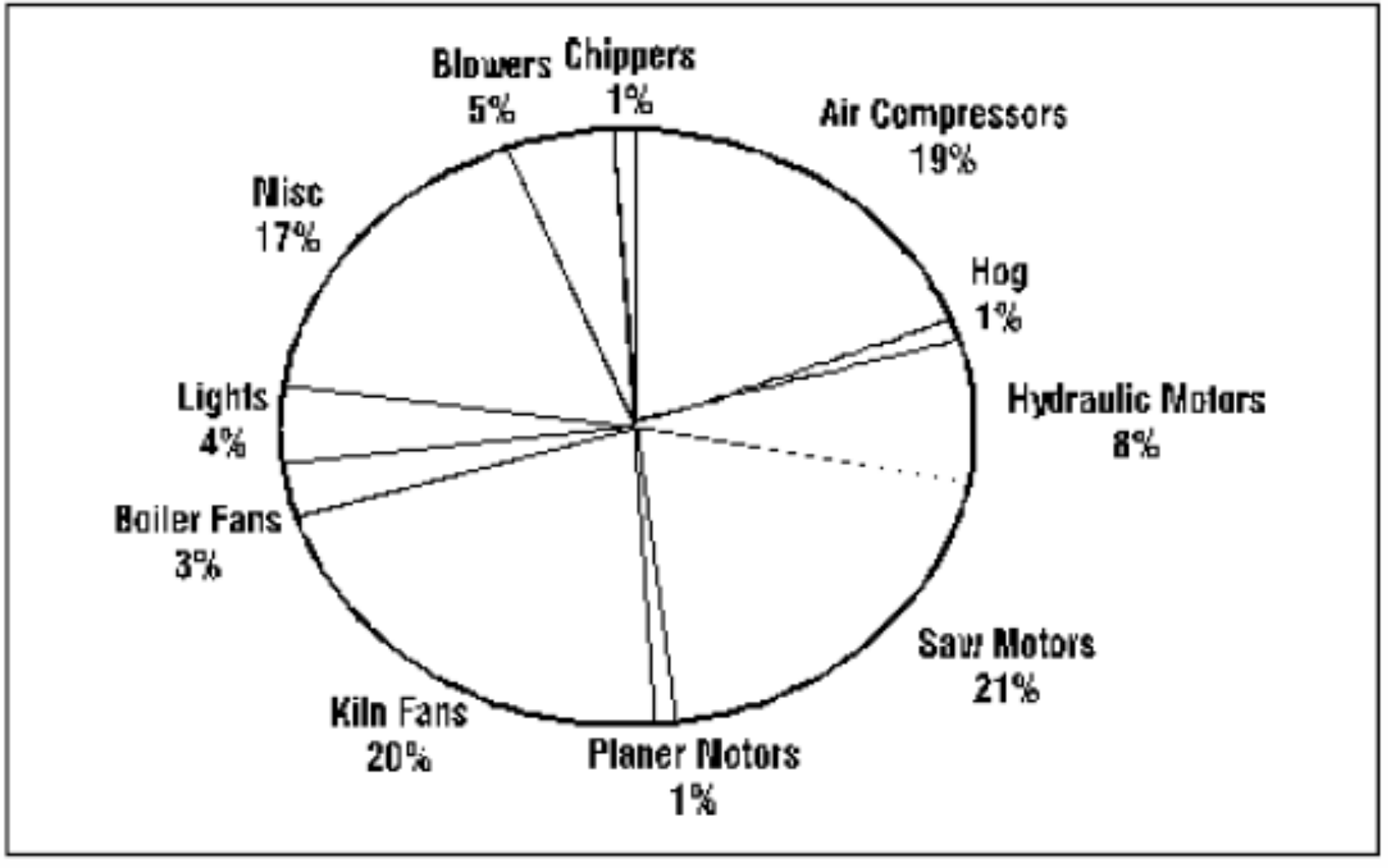


# Typical Industries Affected

**Typical uncorrected power factor by industry type**

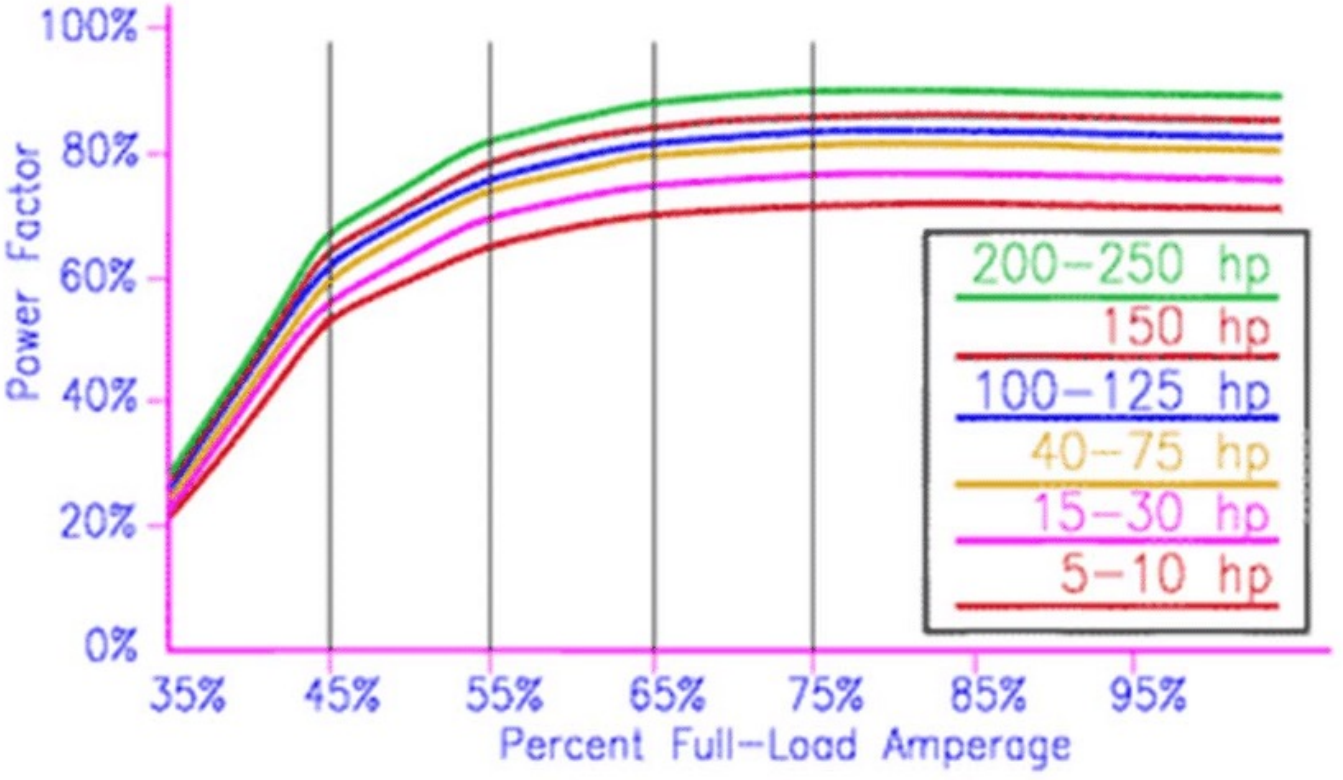
| Industry | Percent Uncorrected PF |
|---|---|
| Brewery | 76-80 |
| Cement | 80-85 |
| Chemical | 65-75 |
| Coal Mine | 65-80 |
| Clothing | 35-60 |
| Electroplating | 65-70 |
| Foundry | 75-80 |
| Forge | 70-80 |
| Hospital | 75-80 |
| Machine manufacturing | 60-65 |
| Metal working | 65-70 |
| Office building | 80-90 |
| Oil-field pumping | 40-60 |
| Paint manufacturing | 55-65 |
| Plastic | 75-80 |
| Stamping | 60-70 |
| Steelworks | 65-80 |
| Textile | 65-75 |

# Typical Sawmill Load



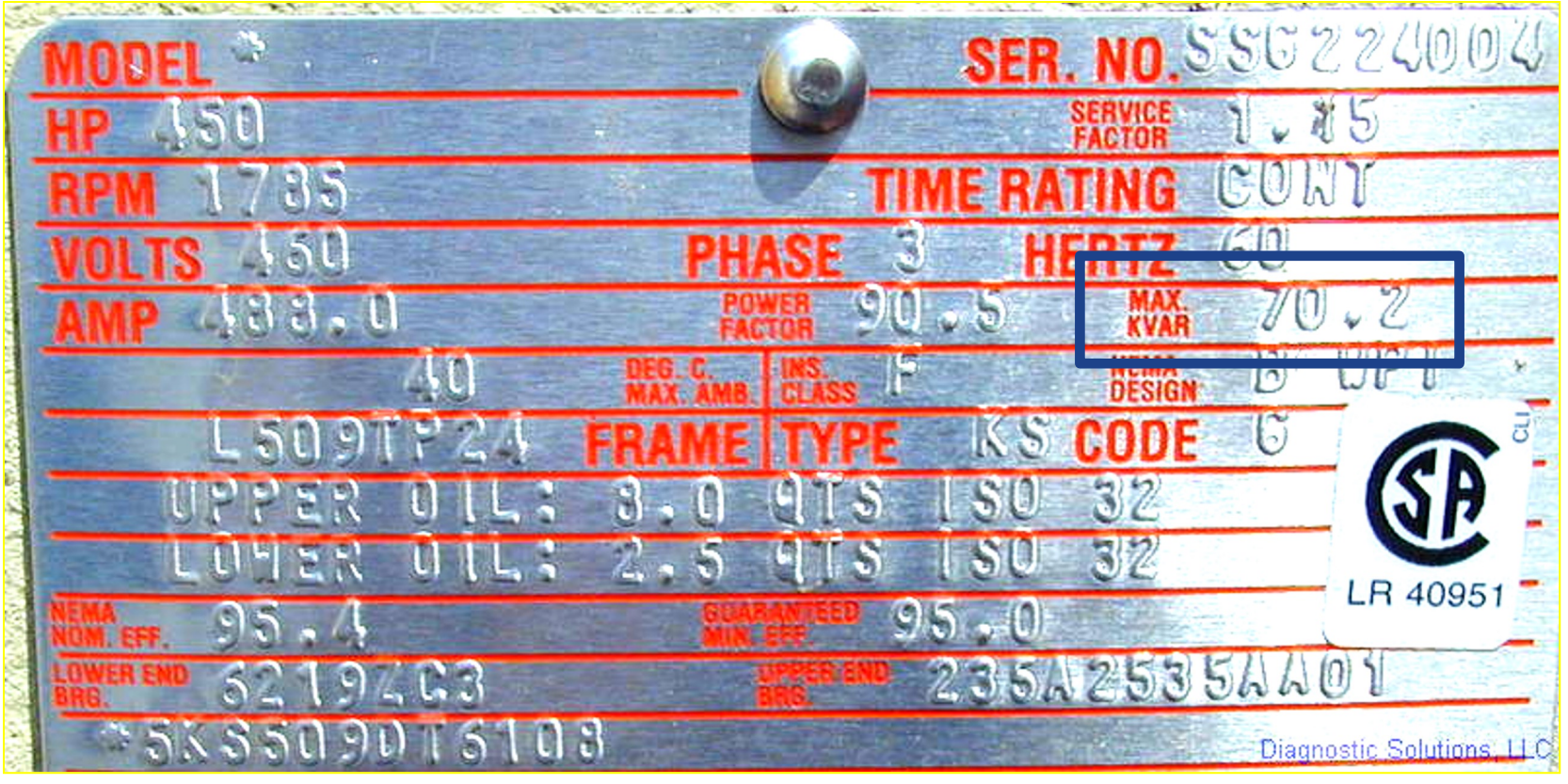
# Induction Motor Power Factor

- Data is without pf correction
- Motors can be purchased with pf correction capacitors



# Induction Motor Power Factor

Motor nameplates typically indicate maximum capacitive correction



# What is Power Factor?

***Power factor (pf) is a term used to express the relationship between the Real Power (kW) required for a load and the Total or Apparent Power (kVa) supplied.***

***In totally resistive loads the Real Power is equal to the Apparent Power.***

$$kW = kVa$$

$$kW = Volts_{RMS} \times Amps_{RMS} \times Pf \times \sqrt{3} / 1{,}000$$

# Apparent Power

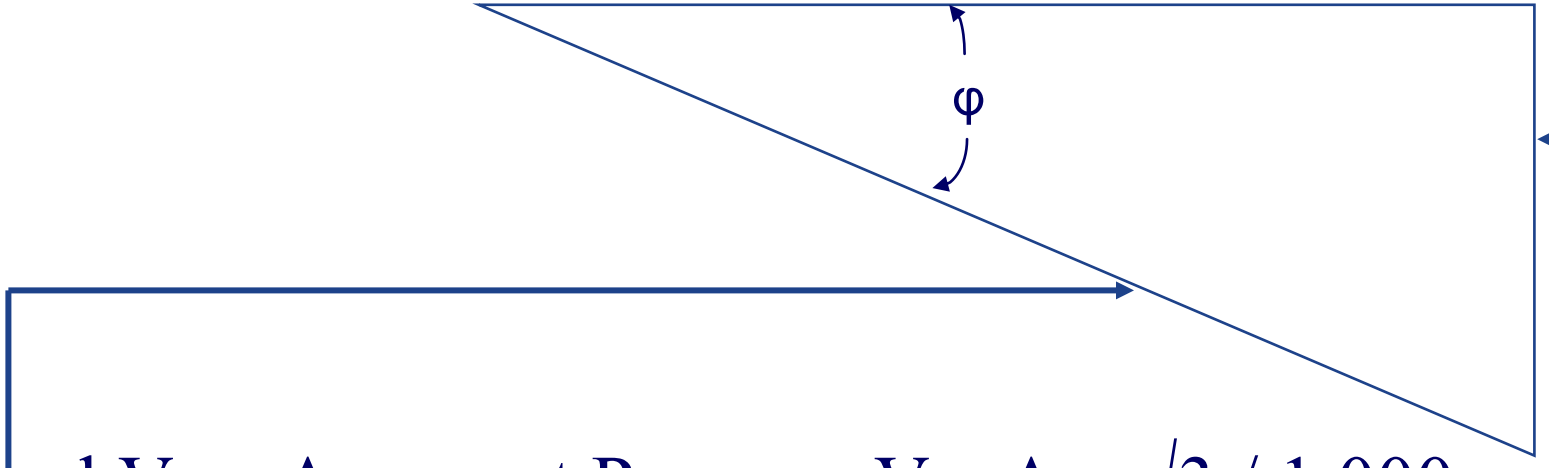
***Apparent power, or kVa, for a 3-phase system can be calculated as:***

$$kVa = Volts_{RMS} \times Amps_{RMS} \times \sqrt{3}/1{,}000$$

***For a purely resistive circuit, kW and kVa are equal because the power factor is 1.0. If the circuit contains an electric induction motor or other inductive load, then the power factor is less than 1.0 and kVa will be greater than kW***

# Power Triangle

kW = Real Power (3-phase) = V x A x pf x √3 / 1,000




kVa = Apparent Power = V x A x √3 / 1,000

Power Factor is the cosine of the angle between the Real Power and the Apparent Power; kW/kVa

$$pf = kW/kVa = \cos(\varphi)$$

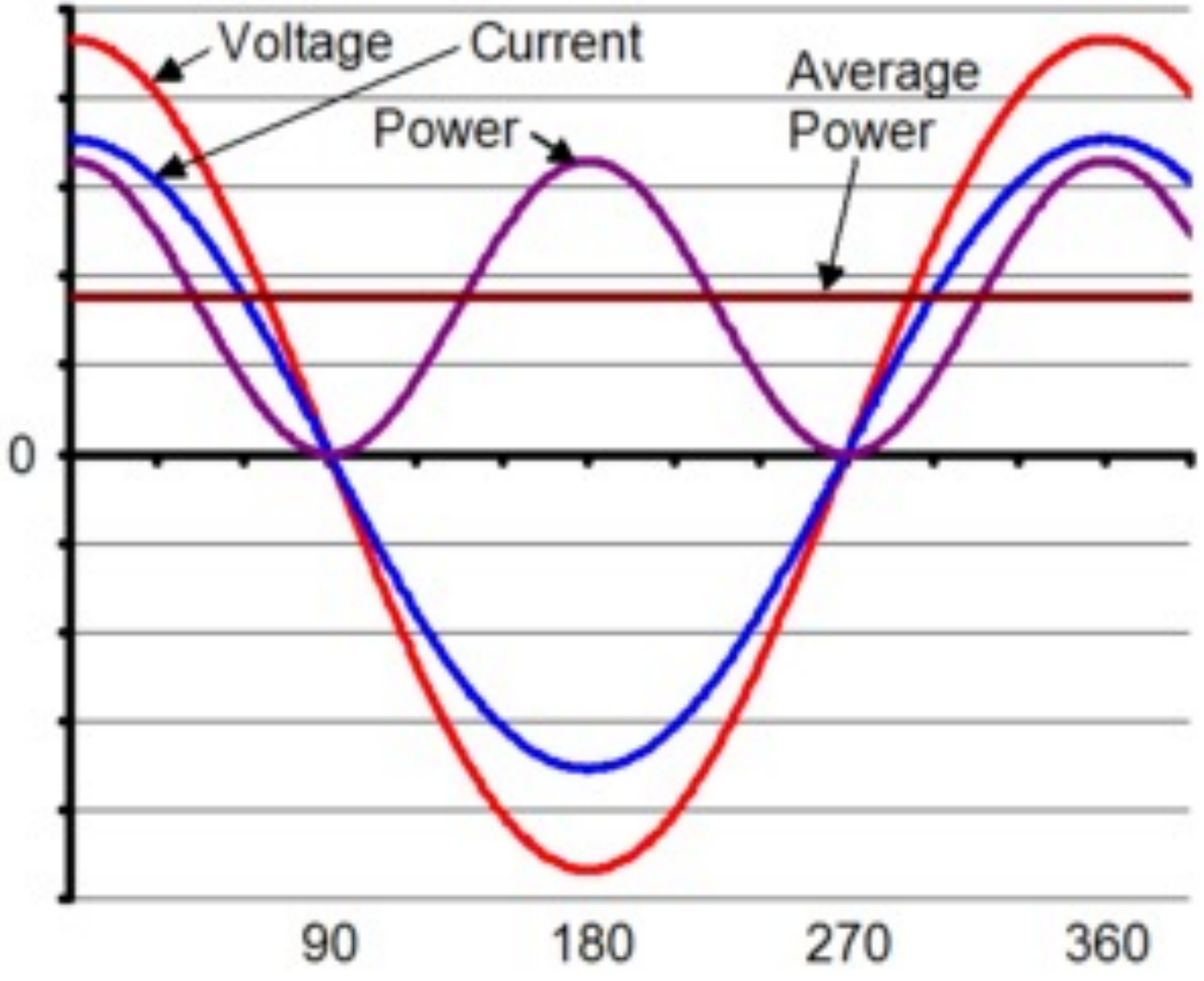
$$kVa^2 = kW^2 + kVar^2$$

# Power Factor

***With inductive loads, Reactive Power (kVar) is required, and additional magnetizing current is supplied to operate the load. This non-working power causes a shift in timing of the current and voltage waveforms, thereby increasing the amount of Apparent Power (kVa) necessary.***

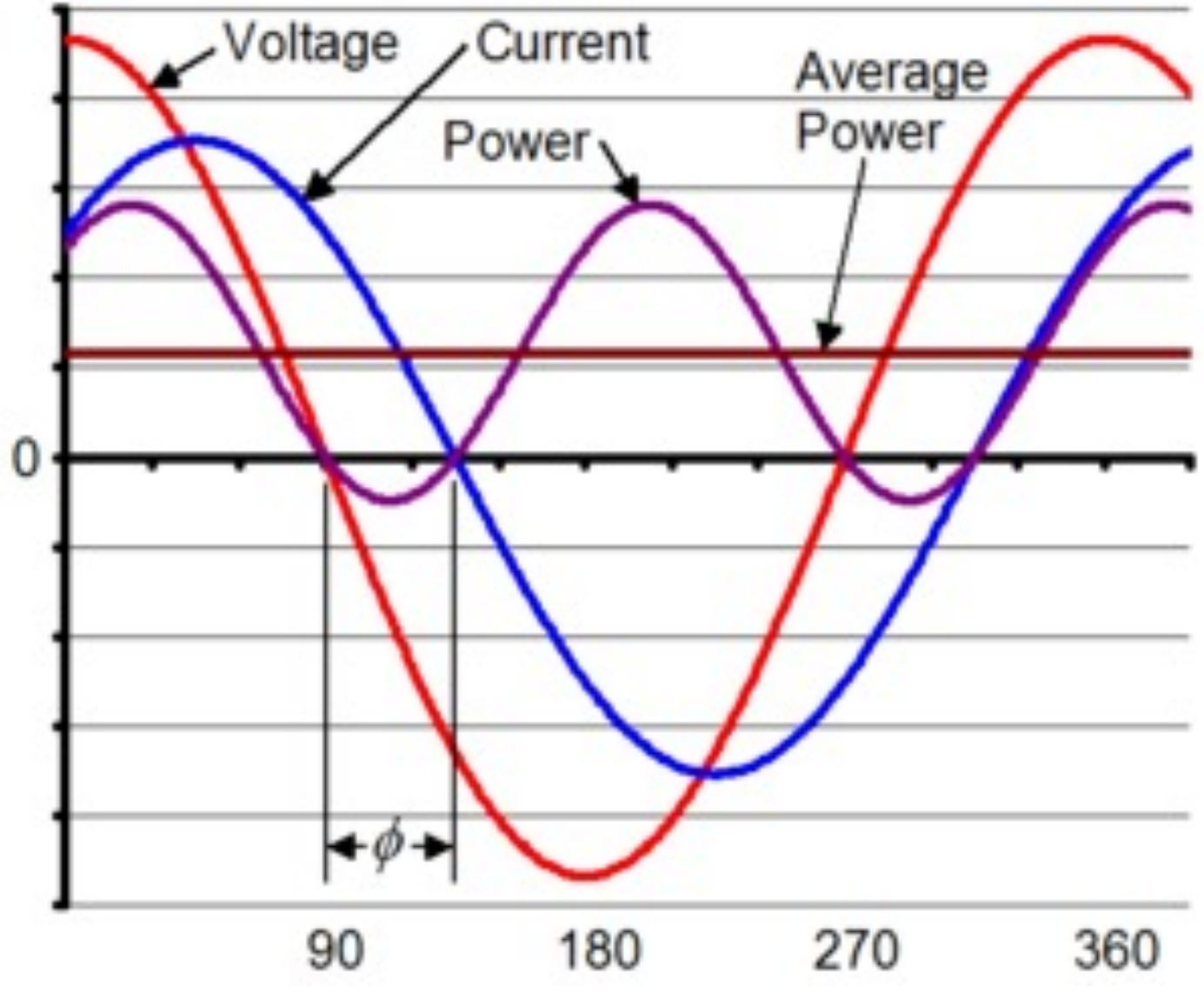
The current supplied by the power company increases!

# Purely Resistive Load




Power is determined from AC voltage and current with a power factor ($\varphi=0^{o}$), $\cos\varphi=1.0$ (Note: voltage and current waves are in phase)

# Inductive Load




Power determined from AC voltage and current with a lagging power factor ($\varphi=45^{o}$, $\cos\varphi=0.7071$); Current wave lags voltage wave

# Power Factor (two 100 kW loads)

## Consider the following example:

*Case #1 –*

*Have 100 kW electric resistance heating load with pf = 1*

*Case #2 –*

*Have a large partially loaded induction motor pulling 100 kW, but with pf = 70.4 %*

*(250 hp motor operating at 127 hp load @ 95% eff)*

# Power Factor – Case #1

## Case #1 -

Real Power = 100 kW = 460 V x 125.5 A x 1.0 x √3 / 1,000

Amps = 125.5 (Power Factor = 100 kW/100 kVa = 1.0000)

Apparent Power = 100 kVa

Volts = 460, 3-phase

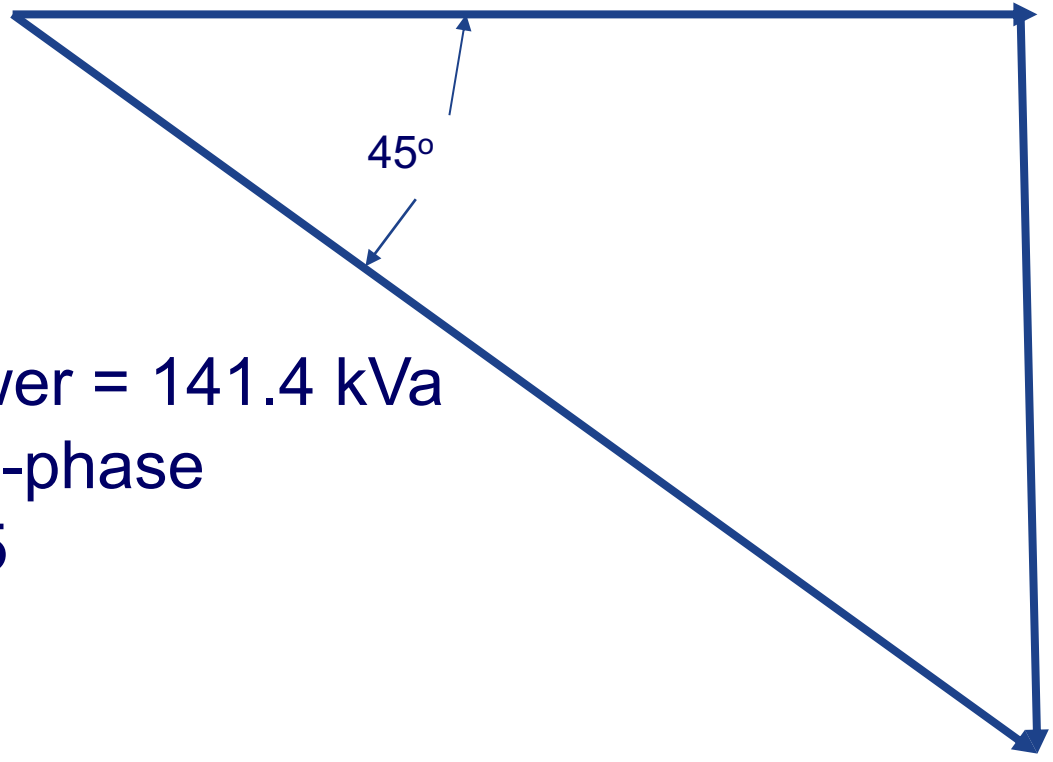
Amps = 125.5

Reactive Power = 0.0 kVar

Since Pf = 1.0, the kW = kVa and the kVar = 0.0

# Power Factor – Case #2

Real Power = 100 kW = 460 V x 177.5 A x 0.7071 x √3 / 1,000
Amps = 177.5 (Power Factor = 100/141.4 = 0.7071)




Reactive Power = 100.0 kVar

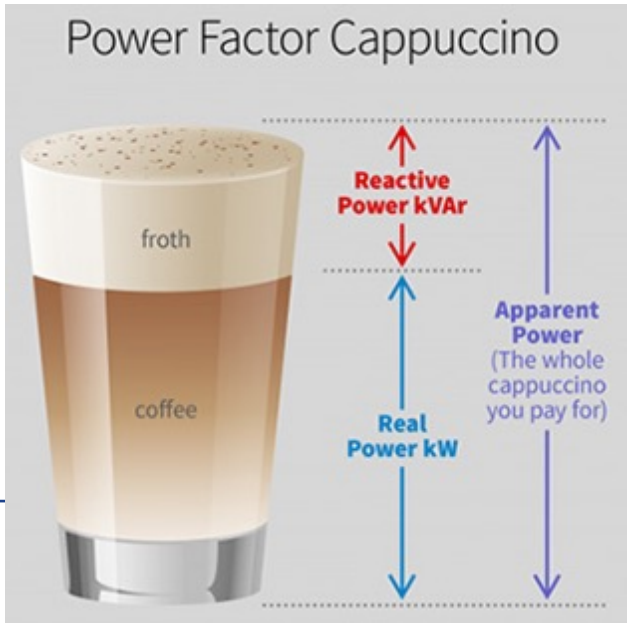
Apparent Power = 141.4 kVa
Volts = 460, 3-phase
Amps = 177.5

We need 177.5 – 125.5 = 52.0 additional amps because the power factor is 0.7071 and not 1.0 (purely resistive load)

# Low Power Factor

*There are an additional 52.0 amps of current with the inductive load that:*

- *Does not change the kW used by the load (the energy usage is the same except for the additional $I^2R$ line losses)*
- *Causes the utility to provide 52.0 non-productive amps of current to the load*
- *Increases $I^2R$ line losses*
- *Loads plant electrical circuits*



# Power Factor

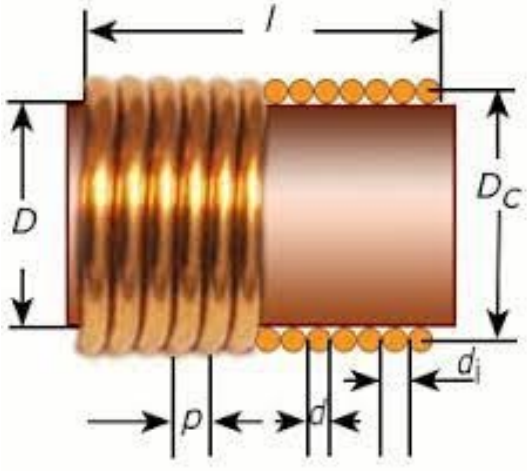
*Reasons to Improve Plant Power Factor*

- *Avoid penalty charges from the utility*
- *Reduce current flows on the electrical system*
- *Reduce $I^2R$ line losses*
- *Possibly unload circuits, transformers, etc. and allow for additional electrical loads to be added*

# Power Factor

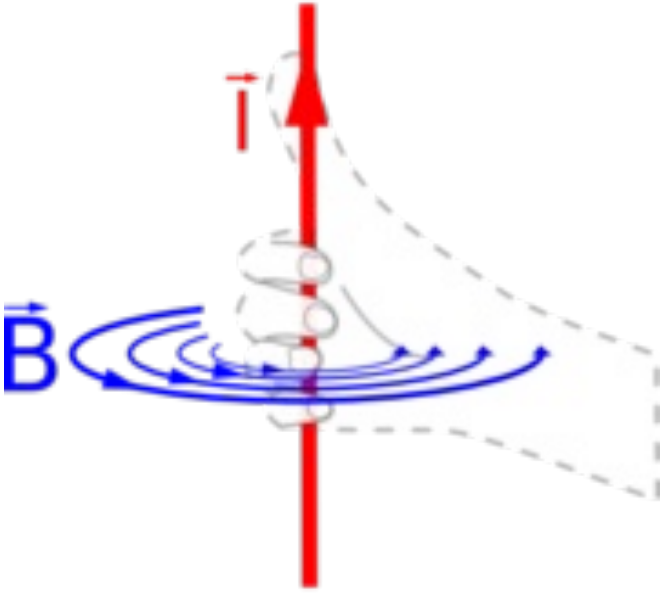
## What causes a lagging Power Factor?

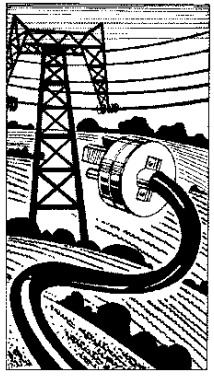
## Inductance!!!



# Inductance

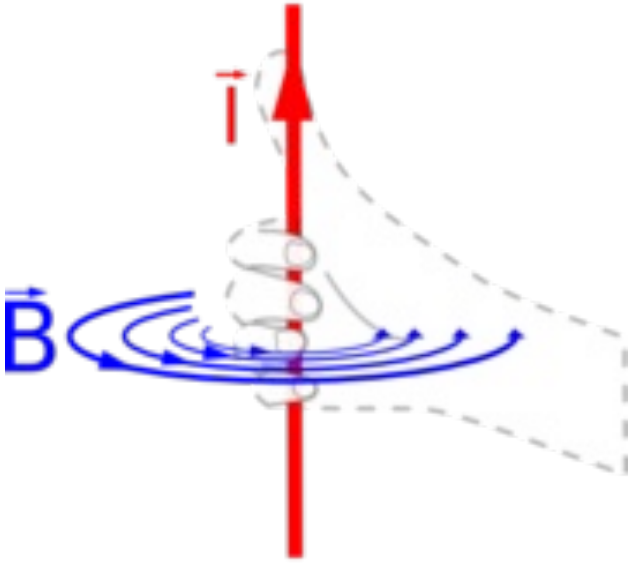
- *Inductance in an electrical circuit is caused by the magnetic field around the conductor*
- *Energy is stored in the magnetic field produced by a current flowing through a conductor described by the right-hand rule*



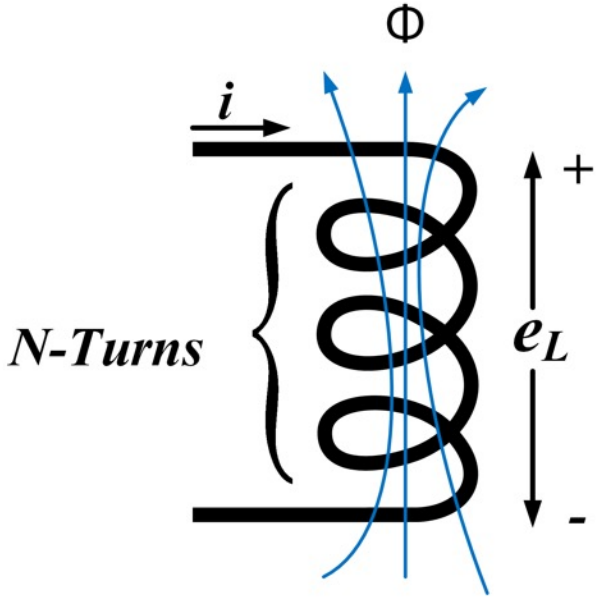
# Power Factor

- *The strength of the magnetic field is determined by the amount of current flow*
- *The polarity (direction) of the magnetic field is determined by the direction of the current flow*



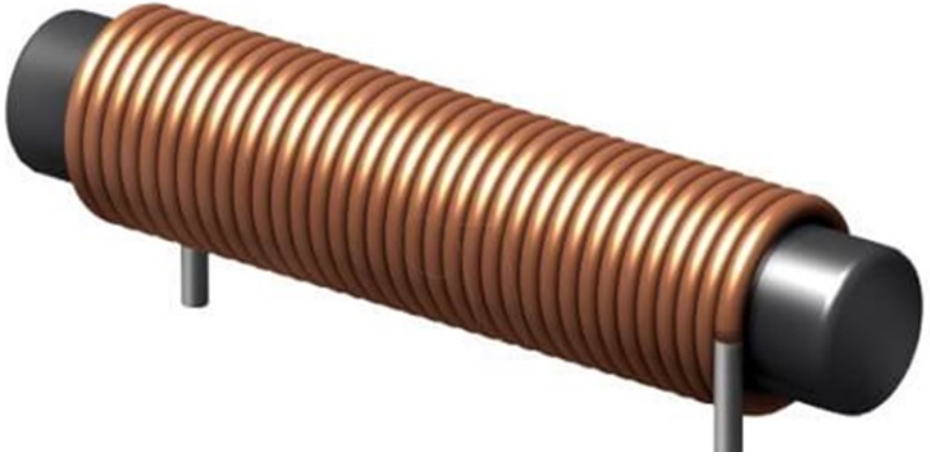
# Power Factor

- *The amount of energy stored in a magnetic coil in air is very small and will not affect the phase relationship between the current and voltage in a circuit*



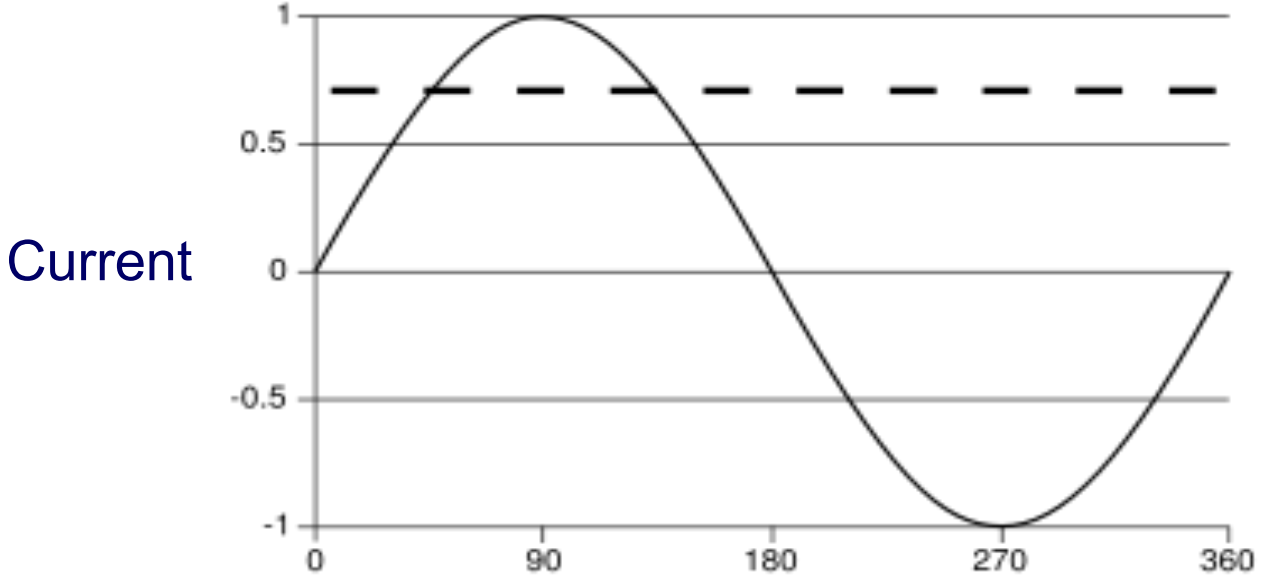
# Power Factor

- *However, when the wire is wrapped around an iron core, as in a motor or transformer, the amount of energy stored in the magnetic field is large*
- *When this energy is returned to the circuit the effect it has is to cause the current waveform to lag the voltage waveform; i.e. cause a lagging power factor*



# Power Factor

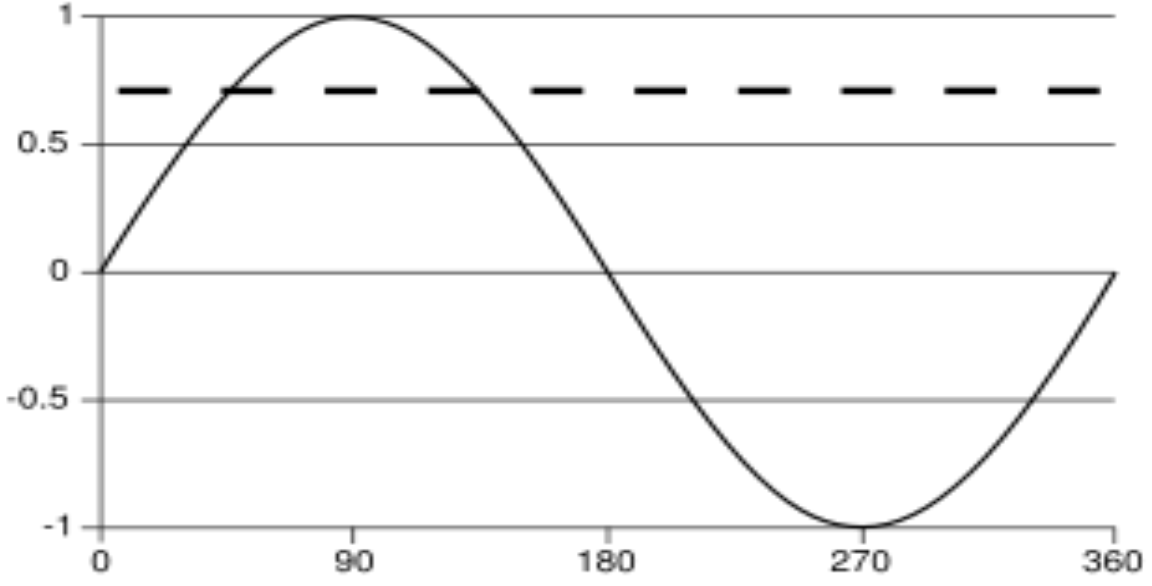
- *With an AC circuit, the current polarity (direction) changes every ½ cycle*
- *Therefore, the polarity of the magnetic field changes every ½ cycle*

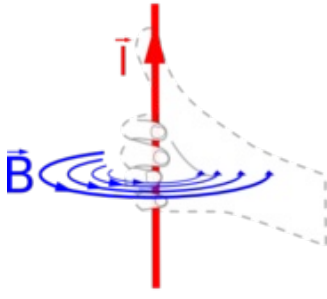


# Power Factor

- *With a sine wave of AC current, the current rises during the first ¼ cycle from 0 to the peak positive value*
- *As the current rises, the magnetic field gets stronger with more energy being stored*

Current

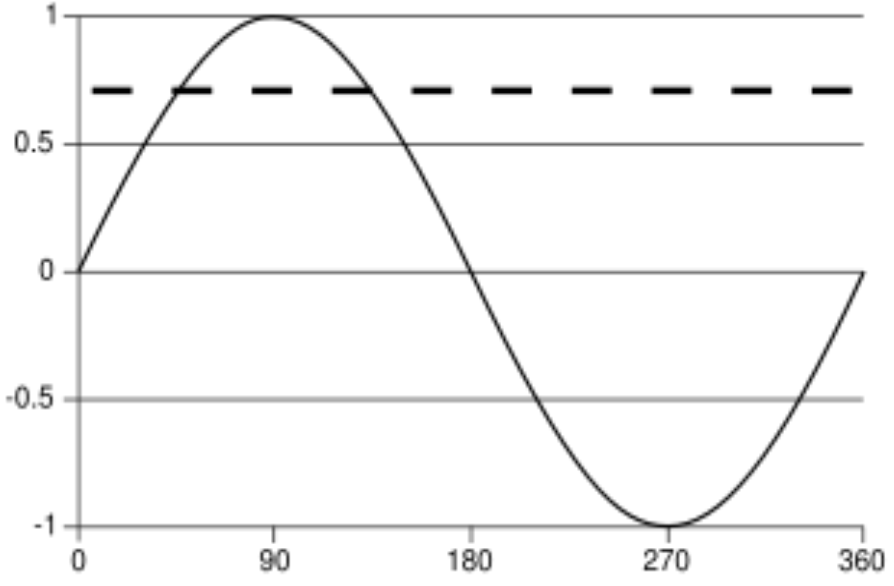


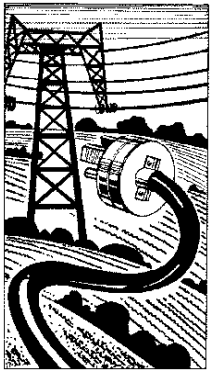



# Power Factor

- *The maximum magnetic energy storage occurs when the current peaks at the end of the first ¼ cycle*
- *During the second ¼ cycle the current starts trying to decrease from its peak*

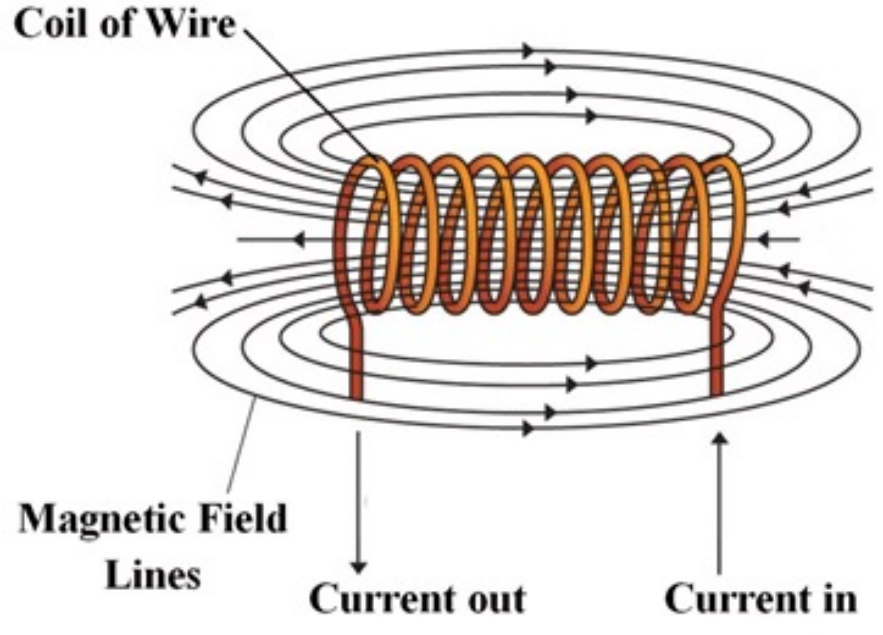
Current



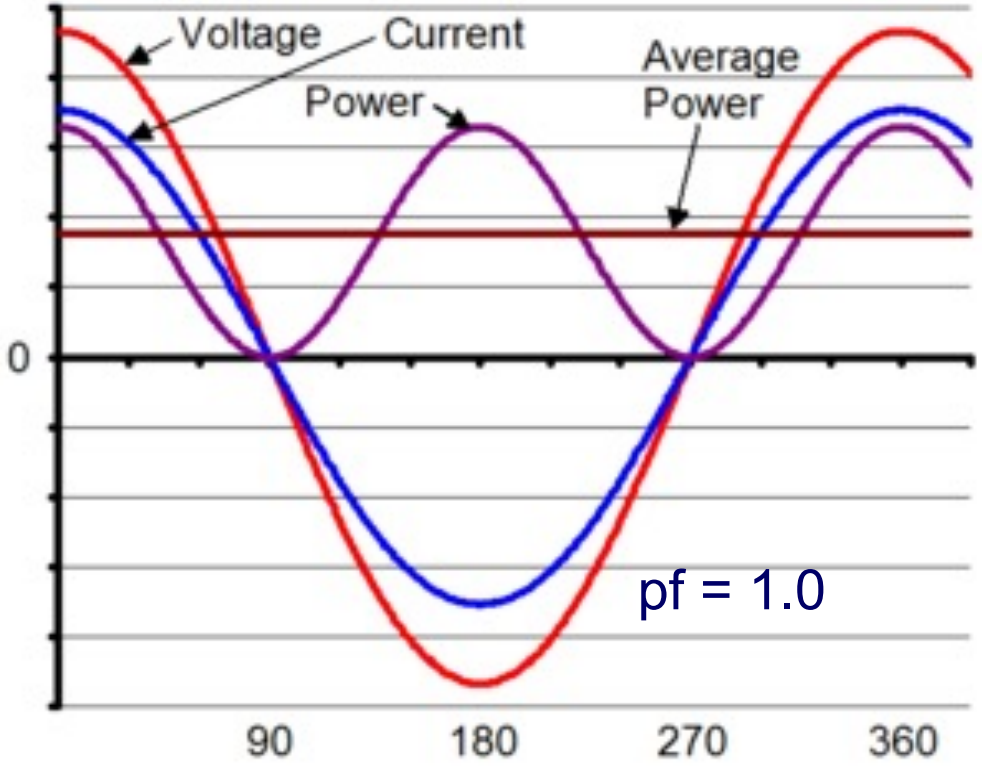
# Power Factor

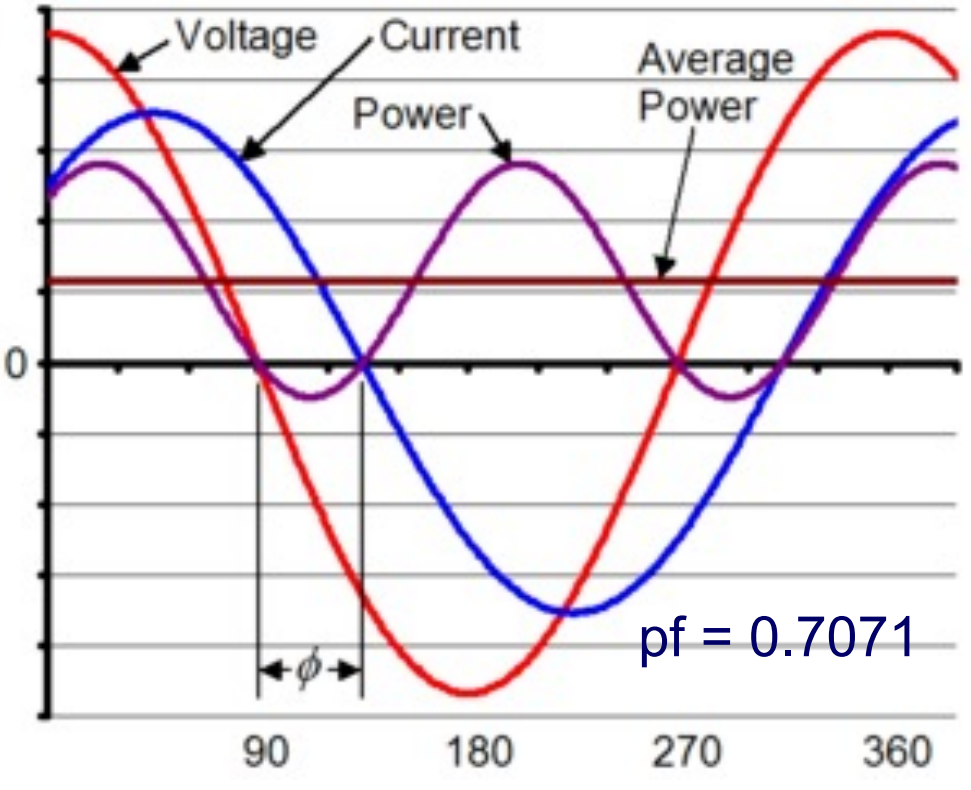
- *The magnetic field resists the decrease in current by returning energy to the circuit, attempting to maintain the current level*
- *This returning energy causes the current wave to lag the voltage wave*



# Power Factor

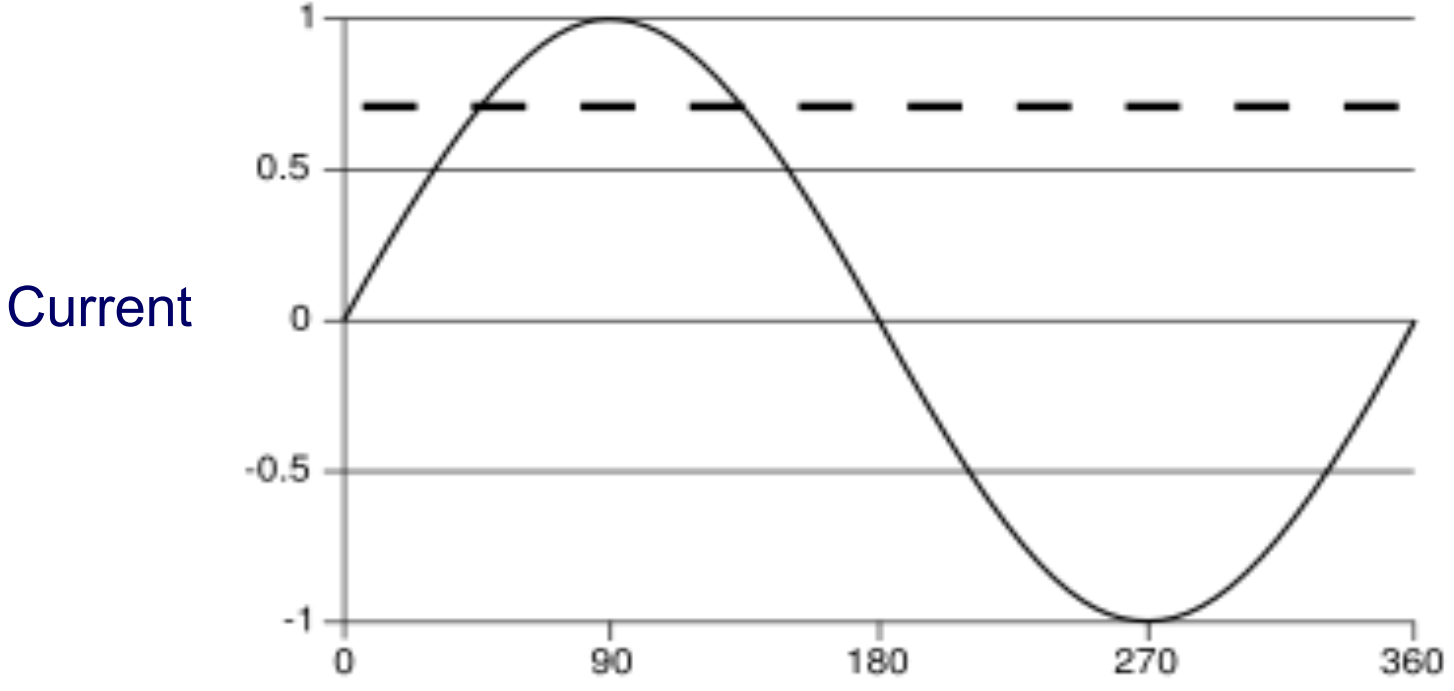
- *On the left we see voltage and current in phase with pf=1; on the right the voltage wave peaks before the current wave with pf=0.7071*

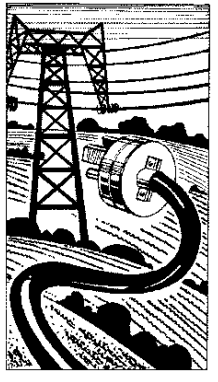


# Power Factor

- *At the ½ cycle point, the current is zero and the polarity is reversing as the direction of the current is changes*

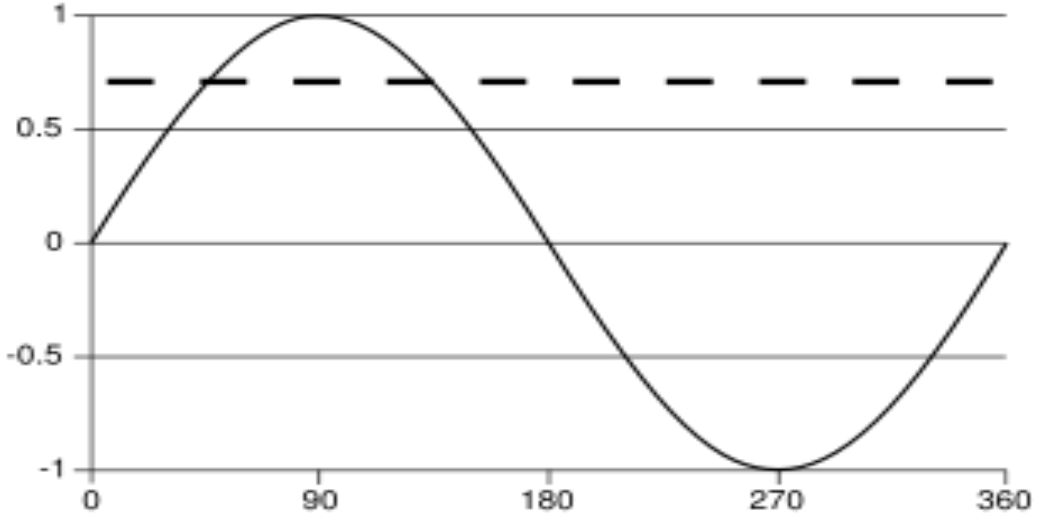


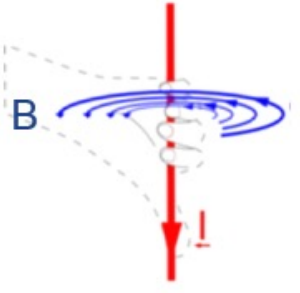



# Power Factor

- *During the portion of the cycle from ½ to ¾ of the waveform, the current builds to its maximum value in the opposite direction as it did during the 0 to ¼ portion of the cycle*
- *The magnetic field strength also builds with the current level in the opposite direction*

Current

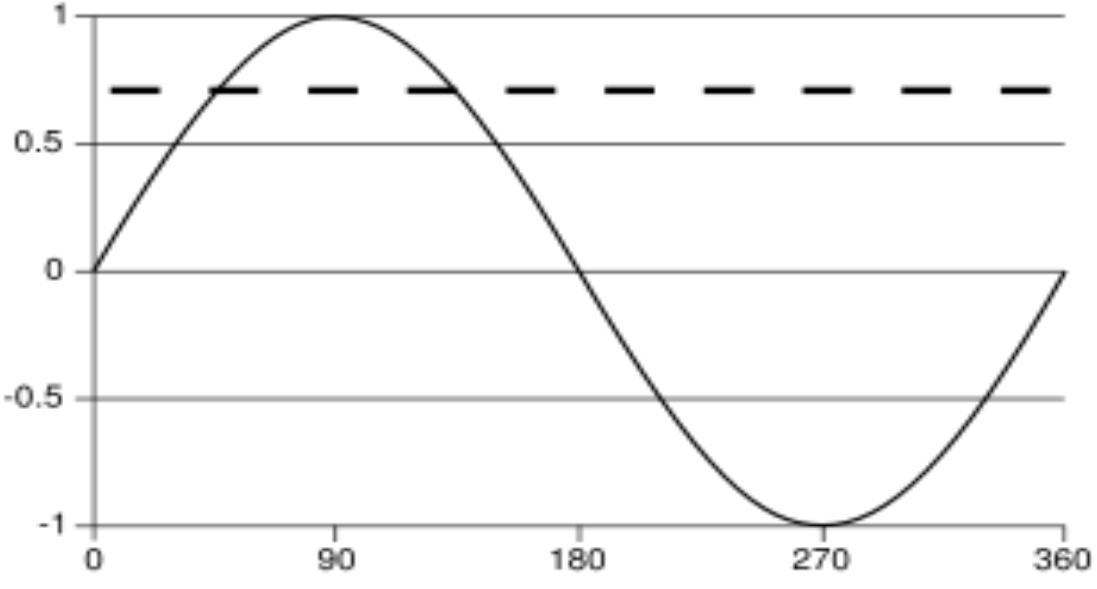


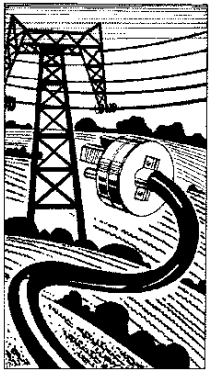



# Power Factor

- *During the last portion of the cycle, from ¾ to the completion of the sine wave, the current again attempts to collapse and the magnetic field tries to maintain its value by feeding energy back into the circuit*

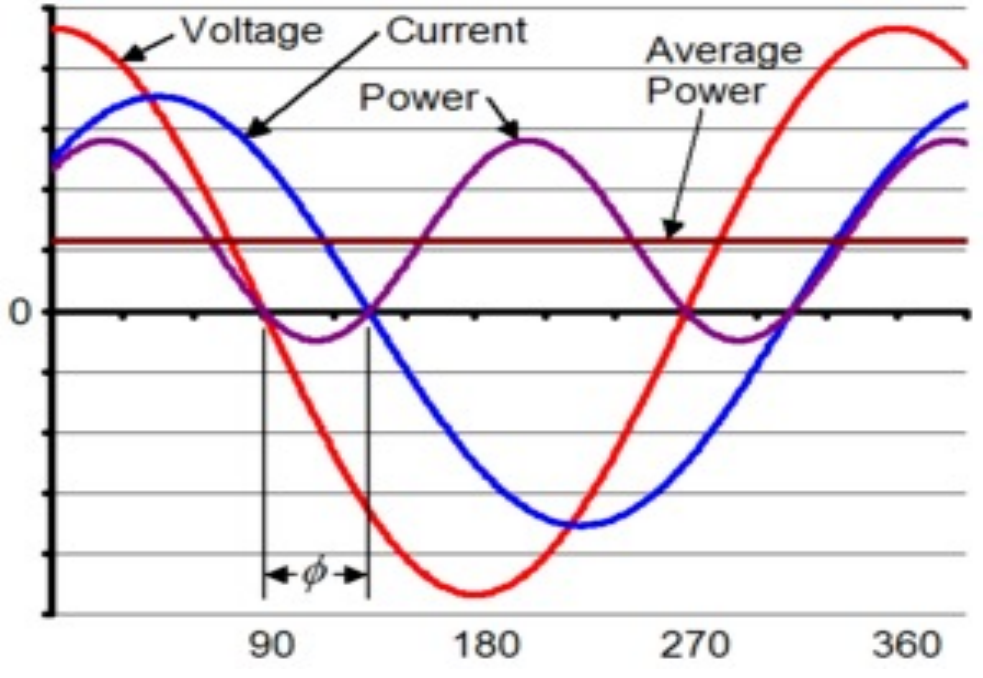
Current



# Power Factor

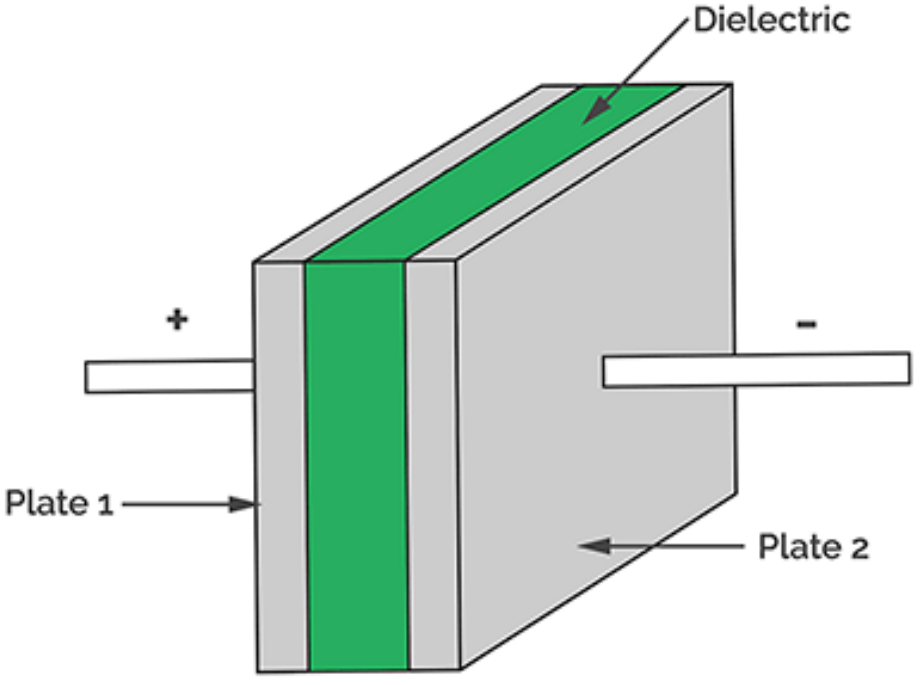
- *All this time the voltage waveform was not impeded in executing its sine wave*
- *Thus, the overall impact of inductance in a circuit to cause the current waveform to lag the voltage waveform*



# Power Factor Correction

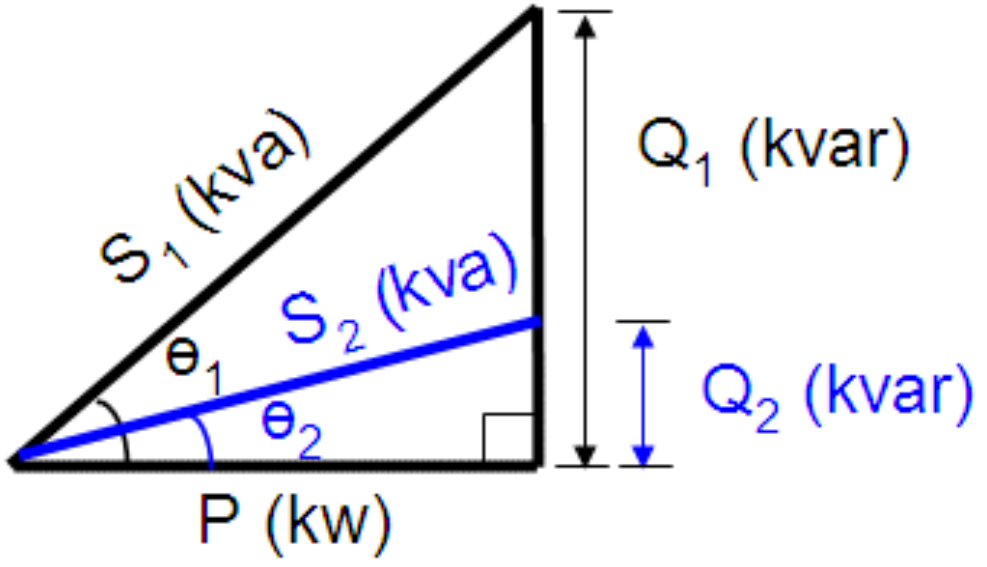
- *Capacitance is to voltage as inductance is to current*

- *In other words, the effect of capacitance in a circuit is to retard the voltage waveform relative to the current waveform*



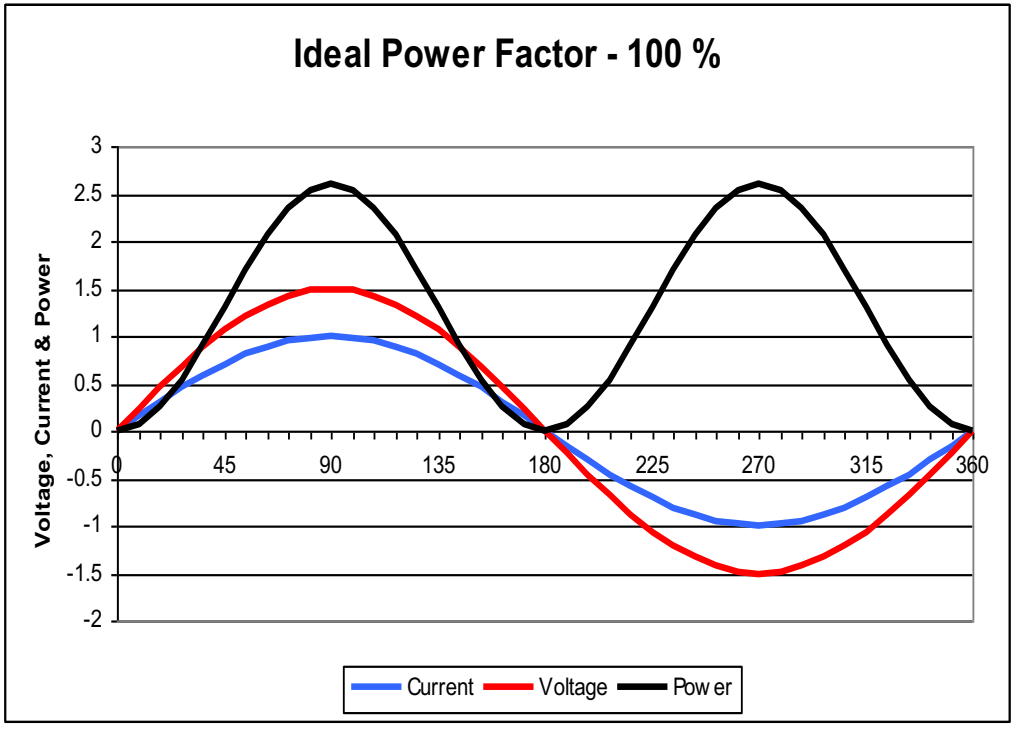
# Power Factor Correction

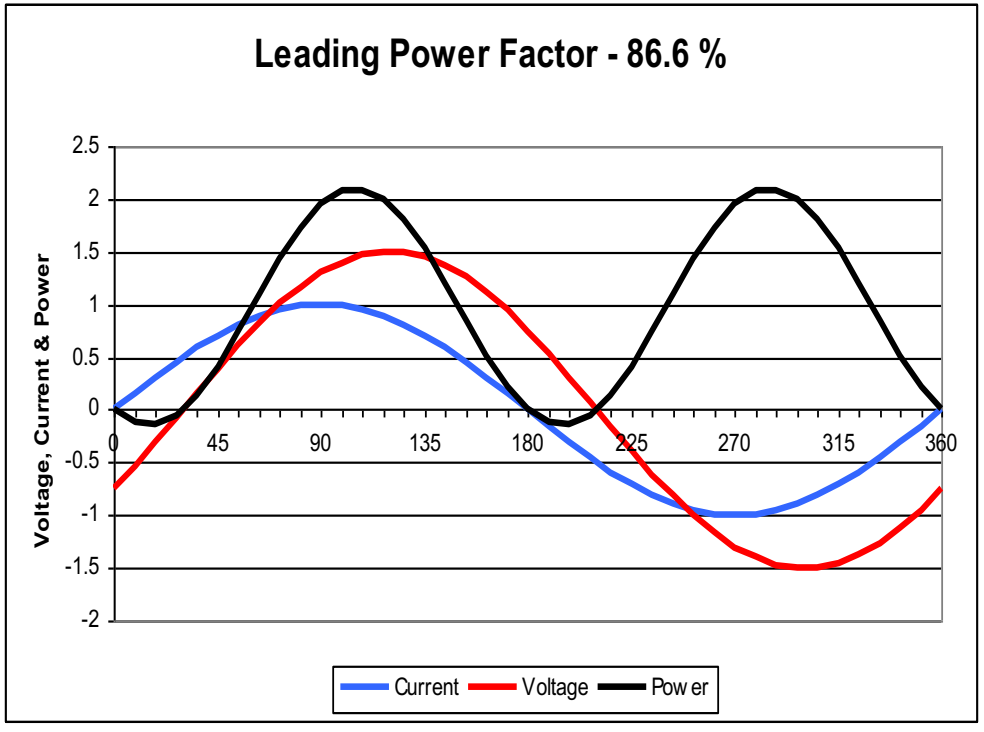
- *Thus, the addition of capacitors to a circuit with inductance can reduce the phase difference between the voltage and current waveforms, i.e. improve the power factor*



# Power Factor Correction

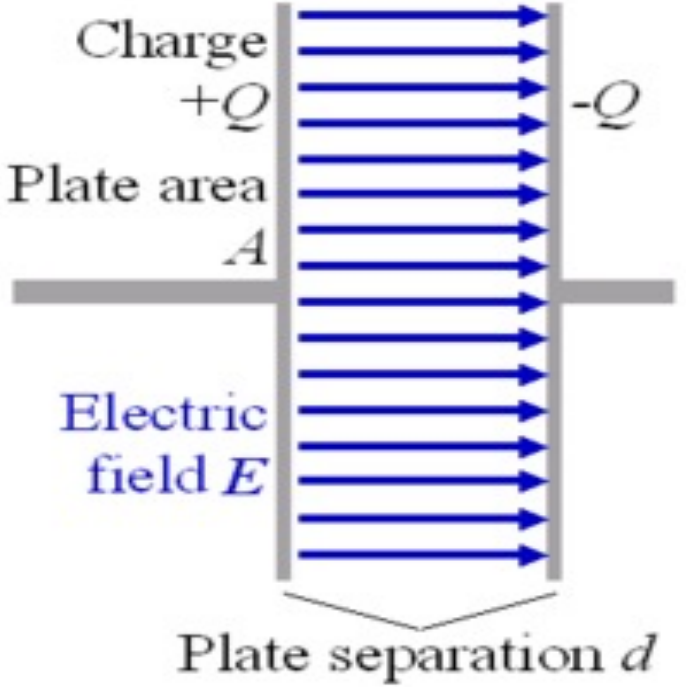
- *If capacitors are added to a purely resistive circuit, the current wave will lead the voltage, giving rise to a leading power factor*

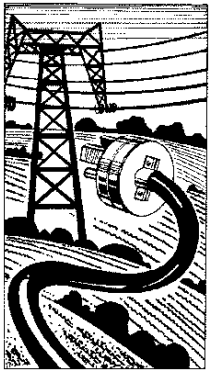


# Power Factor Correction

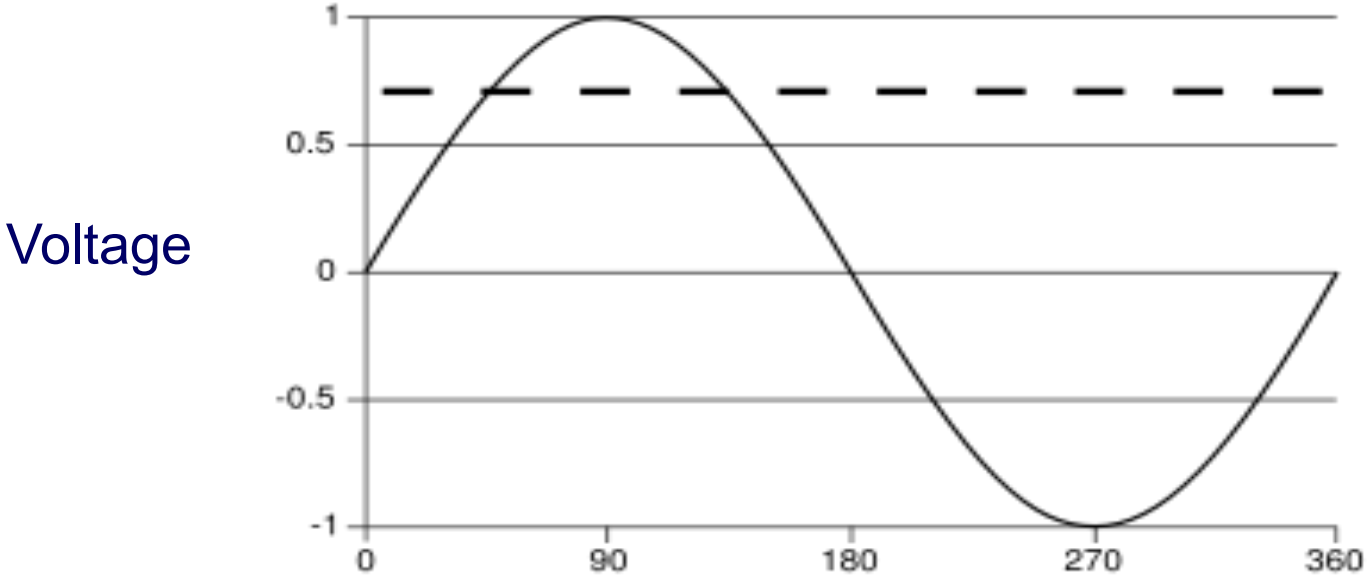
- *A capacitor is made with two electrical plates separated by an insulating layer*
- *A capacitor stores electrons*



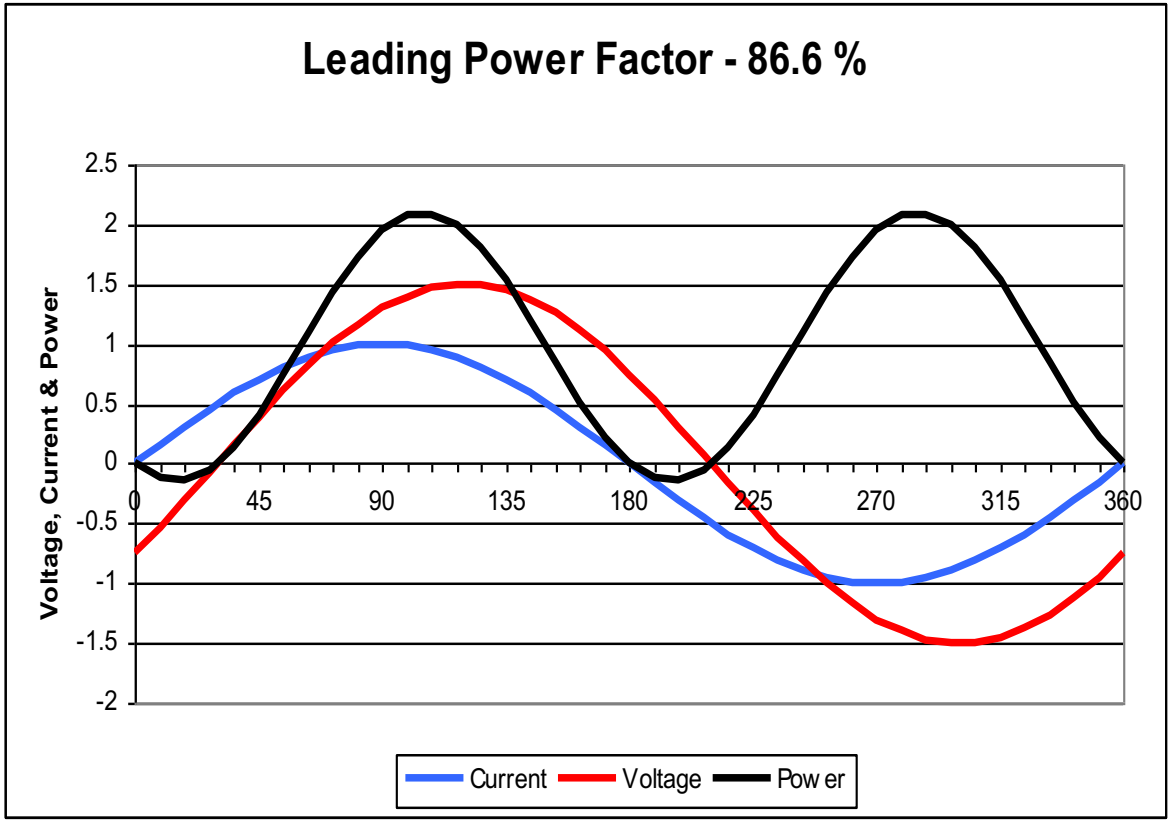
# Power Factor Correction

- *As voltage rises during the first ¼ cycle, electrons are stored on one of the capacitor plates*
- *The peak storage occurs at the ¼ cycle point as the voltage reaches a peak*



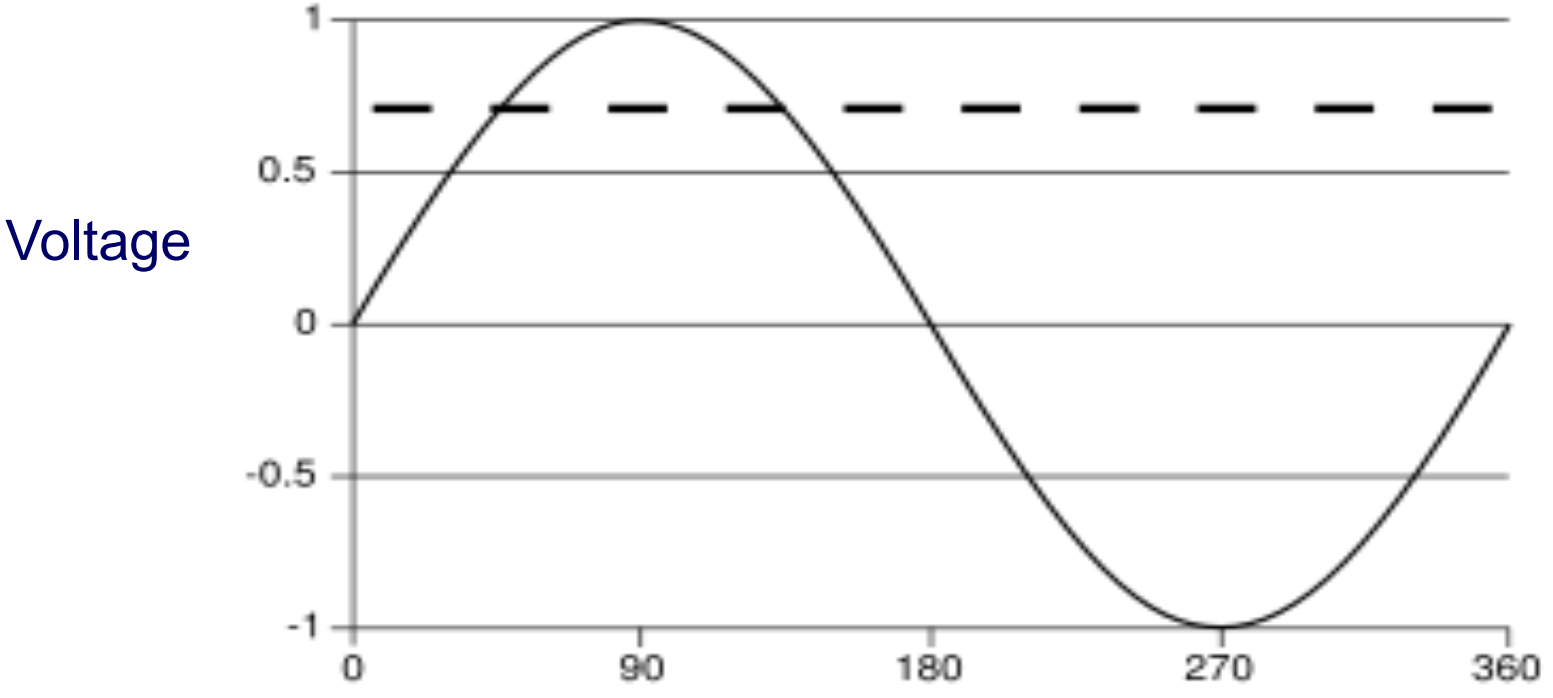
# Power Factor Correction

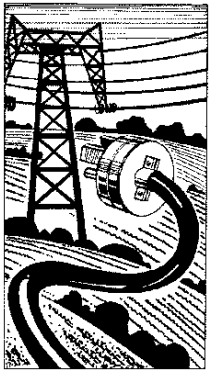
- *As the voltage tries to fall, the capacitor returns electrons to the circuit holding the voltage higher than it would be without the capacitor*



# Power Factor

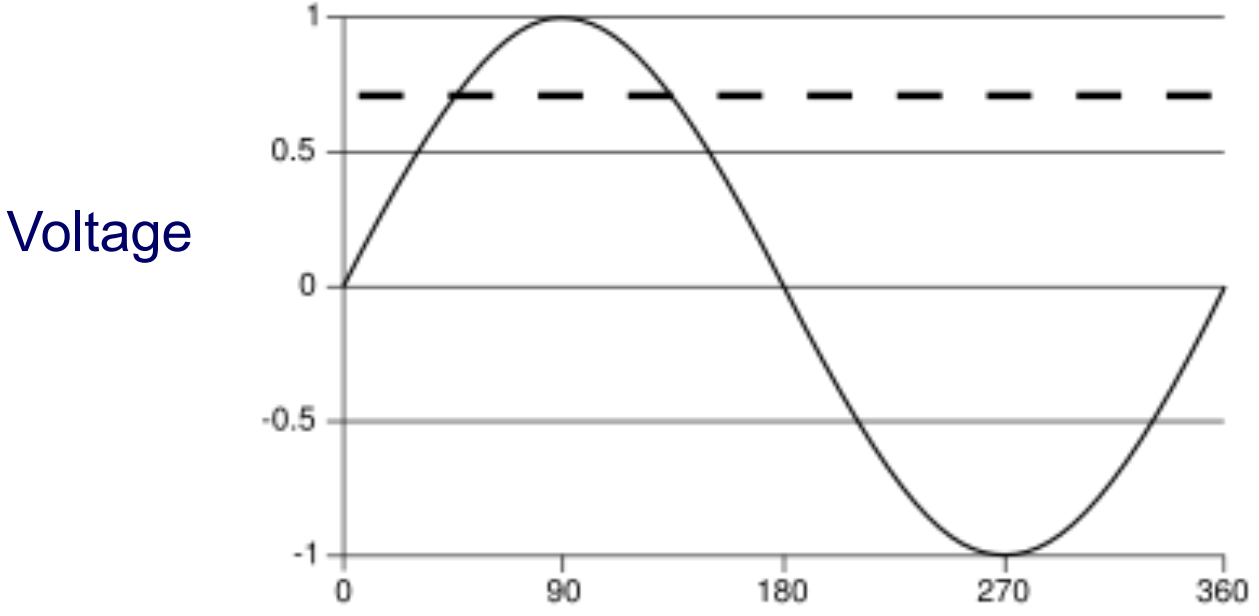
- *During the second ¼ cycle the capacitor discharges, returning the stored electrons to the circuit*

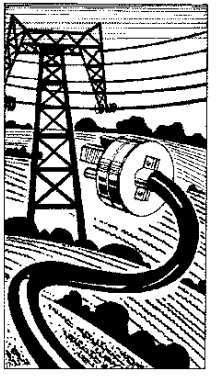


# Power Factor

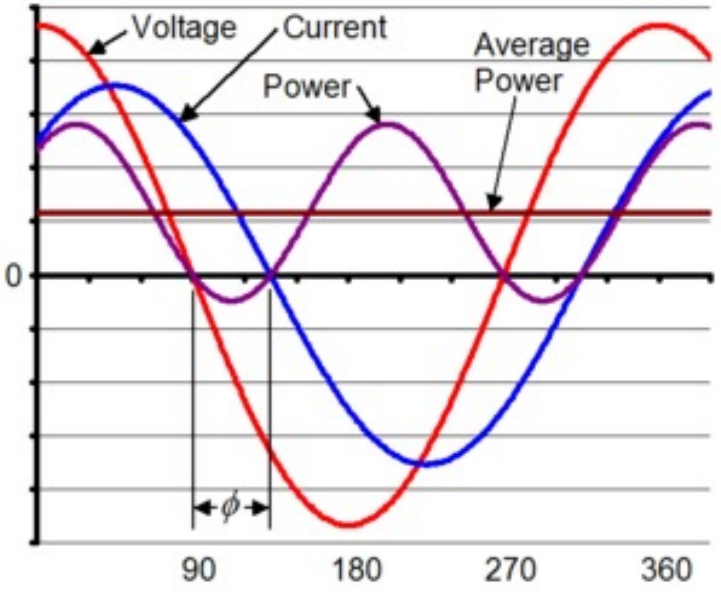
- *At the ½ cycle point the voltage polarity switches and the electrons are stored on the opposite plate as during the first ¼ cycle*
- *Thus, the capacitor charges and discharges twice during each full sine wave cycle*

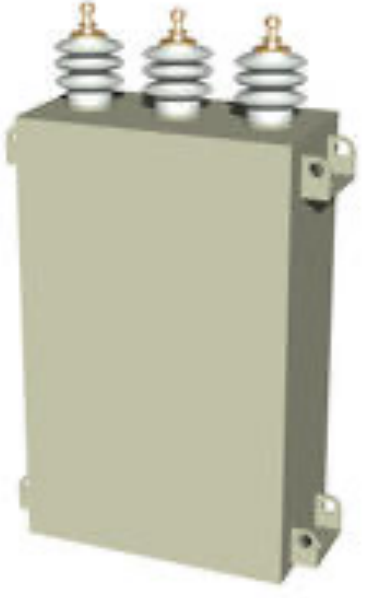


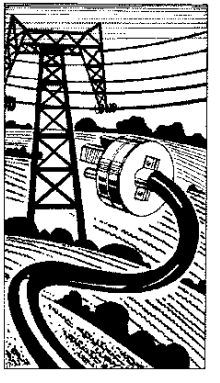



# Power Factor

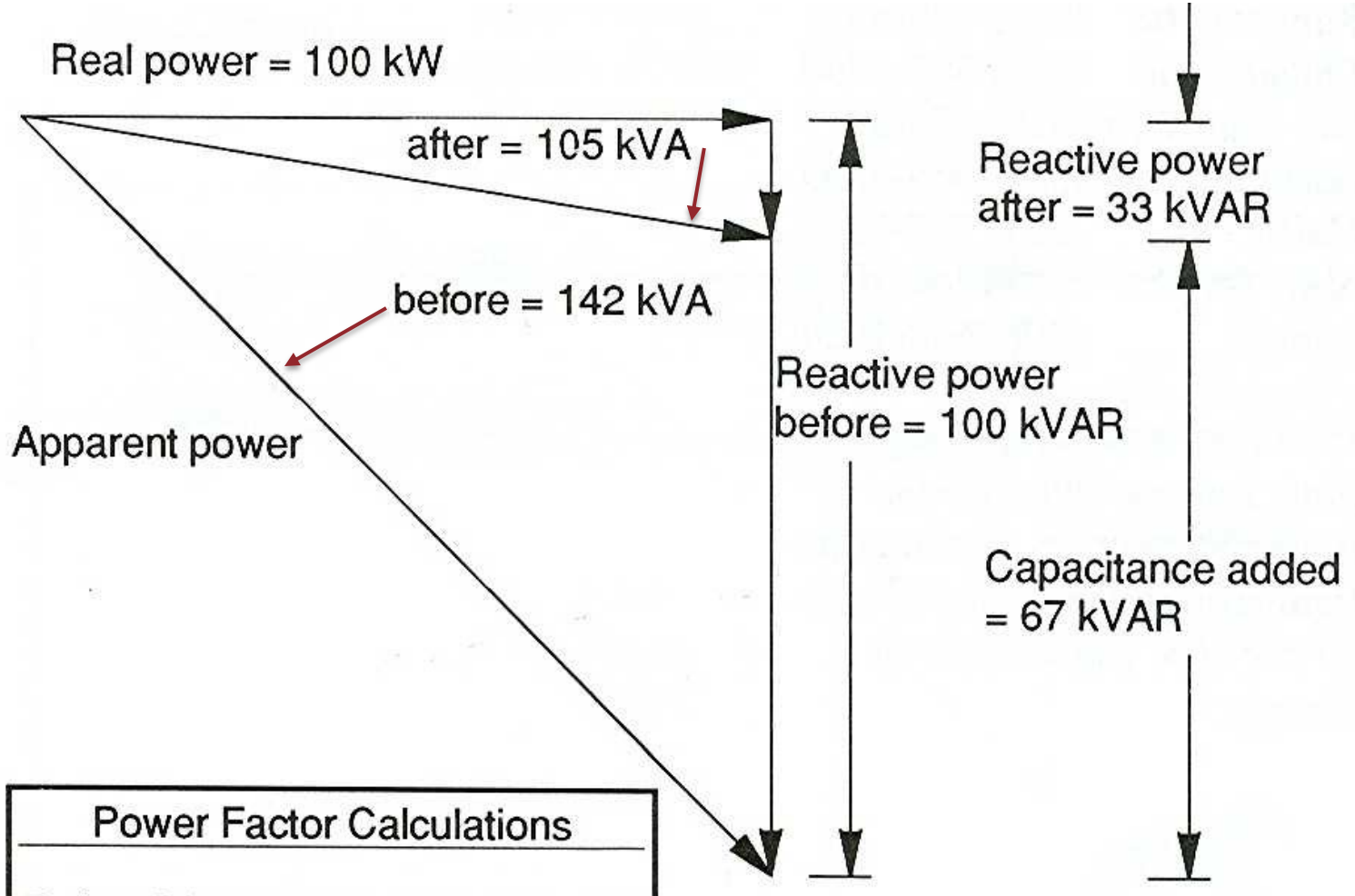
- *Thus, by adding the correct amount of capacitance to an inductive electrical circuit the power factor can be adjusted to any desired value*
- *A practical "rule of thumb" is to raise a lagging power factor enough to avoid utility company penalties*





# Correcting Low Power Factor




**Power Factor Calculations**

*Before* Pf = 100/142 = .70 or 70%
*After* Pf = 100/105 = .95 or 95%

# Correcting Low Power Factor

- A typical electrical distribution system in an industrial facility will suffer a 2% overall electrical loss as current flows through the resistance of the wires
- Power factor improvement reduces these losses and can be estimated as:

$$\% \text{ Reduction} = 100 - 100 \times (PF1/PF2)^2$$

PF1 = 80%, PF2 = 95%, % Red = 29.1%

29.1% of 2% = 0.58% Reduction in Loss

# *Correcting Low Power Factor – Tables*

Example:

100 kW load at 70% pf
Want to correct to 95% pf

100 kW x 0.691 = 69.1 Kvar

Need to install 69.1 Kvar of Capacitors

| POWER FACTOR CORRECTION TABLE | | | |
|---|---|---|---|
| ORIGINAL FACTOR % | DESIRED POWER FACTOR % | | |
| | 85 | 90 | 95 |
| 60 | 0.713 | 0.849 | 1.004 |
| 62 | 0.646 | 0.782 | 0.937 |
| 64 | 0.581 | 0.717 | 0.872 |
| 66 | 0.518 | 0.654 | 0.809 |
| 68 | 0.458 | 0.594 | 0.749 |
| 70 | 0.400 | 0.536 | 0.691 |
| 72 | 0.344 | 0.480 | 0.635 |
| 74 | 0.289 | 0.425 | 0.580 |
| 76 | 0.235 | 0.371 | 0.526 |
| 77 | 0.209 | 0.345 | 0.500 |
| 78 | 0.182 | 0.318 | 0.473 |
| 79 | 0.156 | 0.292 | 0.447 |
| 80 | 0.130 | 0.266 | 0.421 |
| 81 | 0.104 | 0.240 | 0.395 |
| 82 | 0.078 | 0.214 | 0.369 |
| 83 | 0.052 | 0.188 | 0.343 |
| 84 | 0.026 | 0.162 | 0.317 |
| 85 | 0.000 | 0.136 | 0.291 |
| 86 | | 0.109 | 0.264 |
| 87 | | 0.083 | 0.238 |
| 88 | | 0.056 | 0.211 |
| 89 | | 0.028 | 0.183 |
| 90 | | 0.000 | 0.155 |
| 91 | | | 0.127 |
| 92 | | | 0.097 |
| 93 | | | 0.066 |
| 94 | | | 0.034 |
| 95 | | | 0.000 |

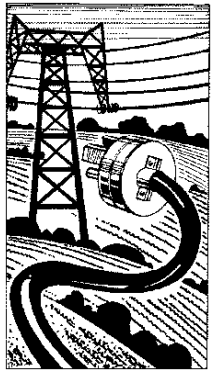
# Power Factor

- *It is possible to over correct by adding too much capacitance causing the power factor to go beyond unity (from lagging to leading)*
- *Some utility companies charge penalties for leading power factor as well as lagging power factor*
- *Generally, charges for leading power factor are smaller than those for lagging power factor*
- *Automatic switching capacitor banks are used with loads if their pf varies greatly*

# Power Factor

- *An East Tennessee Utility company charges $1.46 / Lagging kVar and $1.14 for each Leading kVar*

- *Their threshold to initiate penalty charges is 95%*



# Power Factor Example

- *A medium sized company receives a monthly bill for August with the following information:*
  - kWh = 315,500
  - Actual kW = 683.0
  - Apparent Power kVA = 882.4
  - Power factor penalty below 85%

# Power Factor Example

- Rate Structure: GSA-3

Demand Charge:

| | |
|---|---|
| Summer Period | First 1,000 kW of billing demand per month, at $19.80 per kW |
| | Excess over 1,000 kW of billing demand per month, at $19.93 per kW, plus an additional |
| | $19.93 per kW per month for each kW, if any, of the amount by which the customer's billing demand exceeds the higher of 2,500 kW or its contract demand |
| Winter Period | First 1,000 kW of billing demand per month, at $18.84 per kW |
| | Excess over 1,000 kW of billing demand per month, at $18.97 per kW, plus an additional |
| | $18.97 per kW per month for each kW, if any, of the amount by which the customer's billing demand exceeds the higher of 2,500 kW or its contract demand |
| Transition Period | First 1,000 kW of billing demand per month, at $18.84 per kW |
| | Excess over 1,000 kW of billing demand per month, at $18.97 per kW, plus an additional |
| | $18.97 per kW per month for each kW, if any, of the amount by which the customer's billing demand exceeds the higher of 2,500 kW or its contract demand |

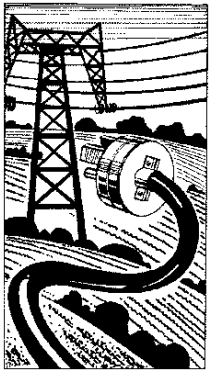
# Power Factor Example

- Rate Structure: GSA-3

| | | |
|---|---|---|
| Energy Charge: | | |
| Summer Period | First 150,000 kWh per month at | 5.810¢ per kWh |
| | Additional kWh per month at | 4.990¢ per kWh |
| Winter Period | First 150,000 kWh per month at | 5.810¢ per kWh |
| | Additional kWh per month at | 4.990¢ per kWh |
| Transition Period | First 150,000 kWh per month at | 5.810¢ per kWh |
| | Additional kWh per month at | 4.990¢ per kWh |

# Power Factor Example

- *Calculate:*
  - Electrical energy charge
  - Power factor
  - Demand charge
  - kVARs of capacitors to correct pf to 85%
  - At $75/kVAR for capacitors, the project cost to correct pf to 85%
  - Reduction in electrical current from capacitor location back to power plant (voltage = 480 V)



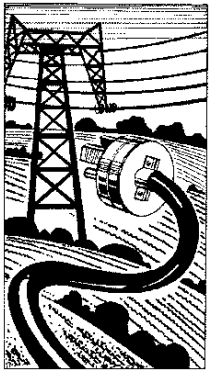
# Power Factor Example

- *Calculate:*
  - Electrical energy charge

150,000 kWh x $0.0581 = $8,715.00

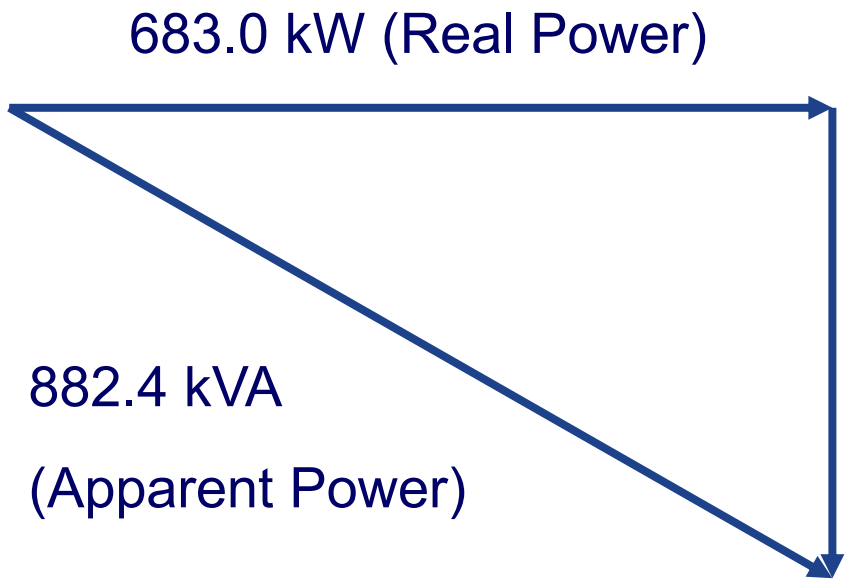
(315,500 – 150,000) kWh x $0.0499 = $8,258.45

Total energy charge = $16,973.45

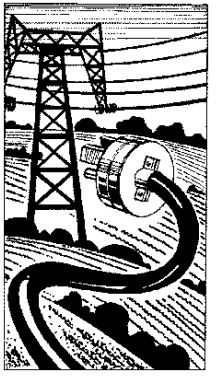


# Power Factor Example

- *Calculate:*
  - Power factor



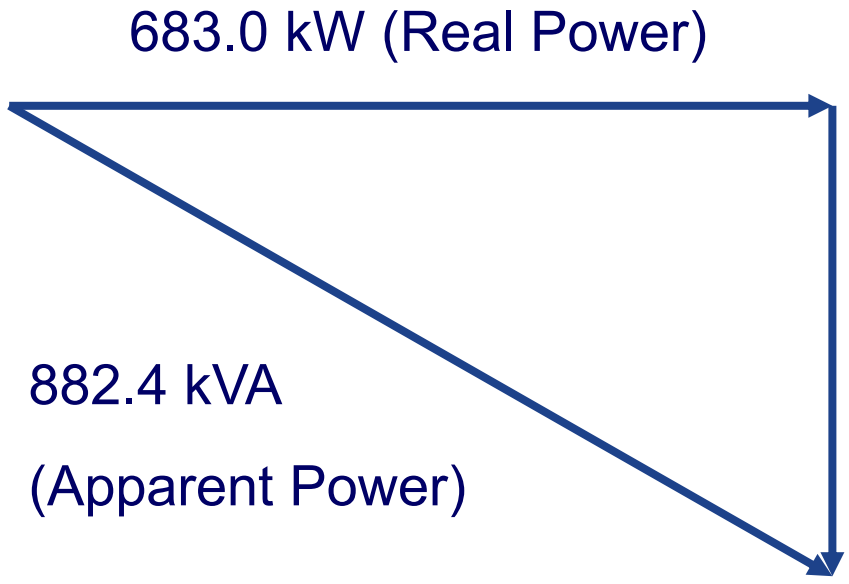

Power Factor = 683.0/882.4 = 0.774 or 77.4%
Power Factor Angle = Inverse Cosine (0.774) = 39.3 degrees



# Power Factor Example

- *Calculate:*
  - Power factor

We are paying a power factor penalty!




Power Factor = 683.0/882.4 = 0.774 or 77.4%
Power Factor Angle = Inverse Cosine (0.774) = 39.3 degrees

# Power Factor Example

- ***Calculate:***
  - **Demand charge**

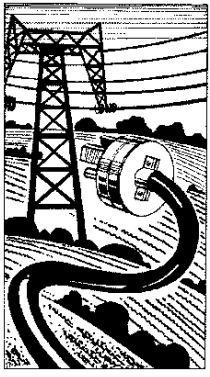
882.4 kVA x 0.85 x $19.80/kVA = $14,851

(882.4 x 0.85) = 750.0 kVA or kW

Correct power factor above to 85% and the demand charge could have been:

683.0 kW x $19.80/kW = $13,523

Potential savings = $14,851 - $13,523 = $1,328

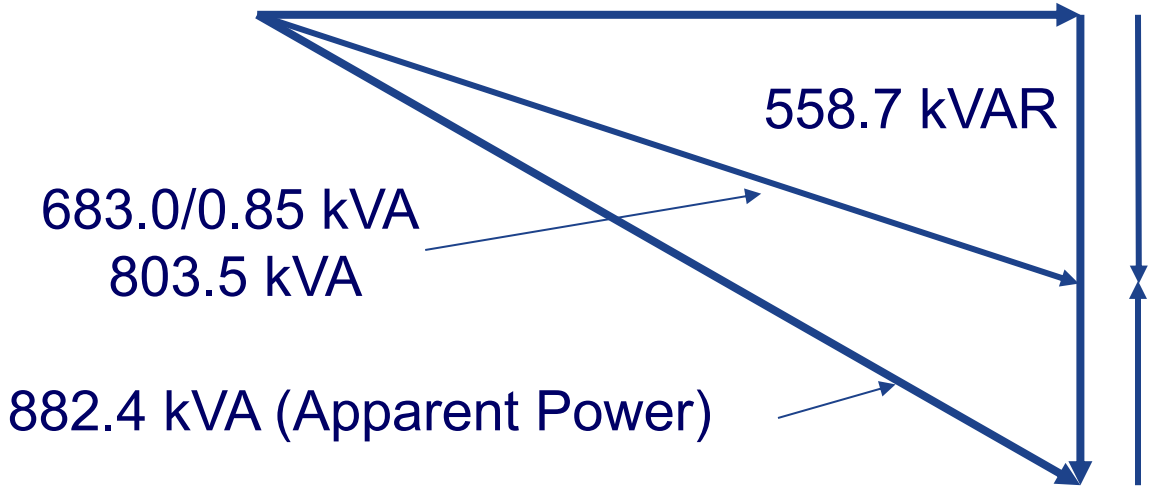


# Power Factor Example

- *Calculate:*
  - kVARs of capacitors needed to correct power factor to 85%

Pf = 0.85 = kW/kVA

kVA = 683.0/0.85 = 803.5




Power Factor = 683.0/882.4 = 0.774 or 77.4%

Power Factor Angle = Inverse Cosine (0.774) = 39.3 degrees

# Power Factor Example

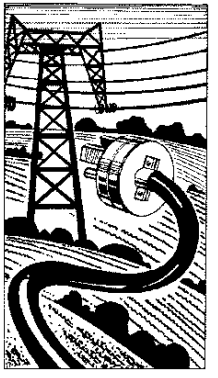
- *Calculate:*
  - Capacitor project cost

150 kVAR x $75/kVAR = $11,250

12 month savings:

12 months x $1,328/month = $15,936

Simple payback = $11,250/$15,936 = 0.71 years



# Power Factor Example

- *Calculate:*
  - *Current reduction from the point of capacitor installation back to the power plant*

Before correction -

882.4 kVA = (480 V)(Amps)$\sqrt{3}$/1000

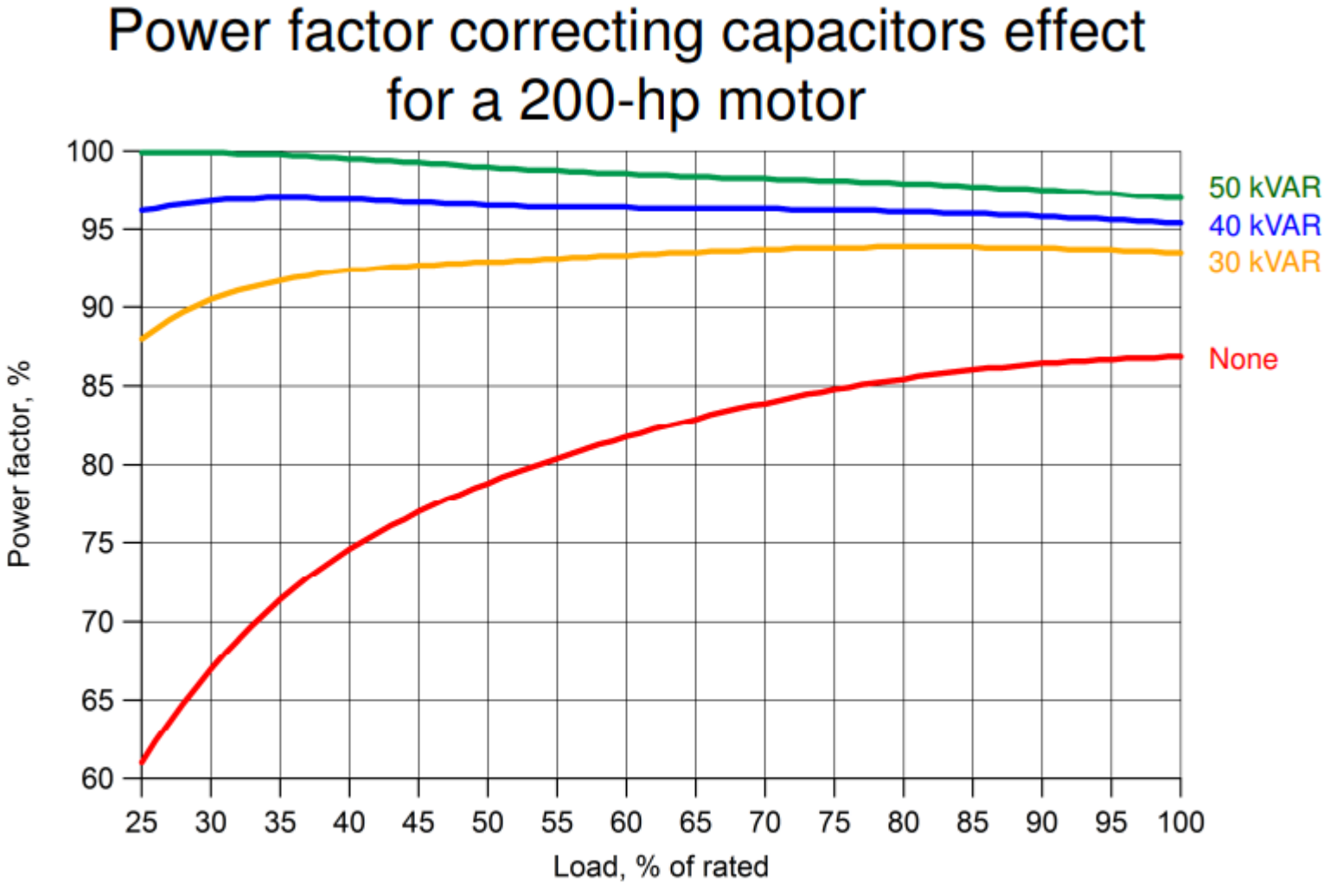
Amps = 1,061.4

After correction to 85% –

803.5 kVA = (480 V)(Amps)$\sqrt{3}$/1000

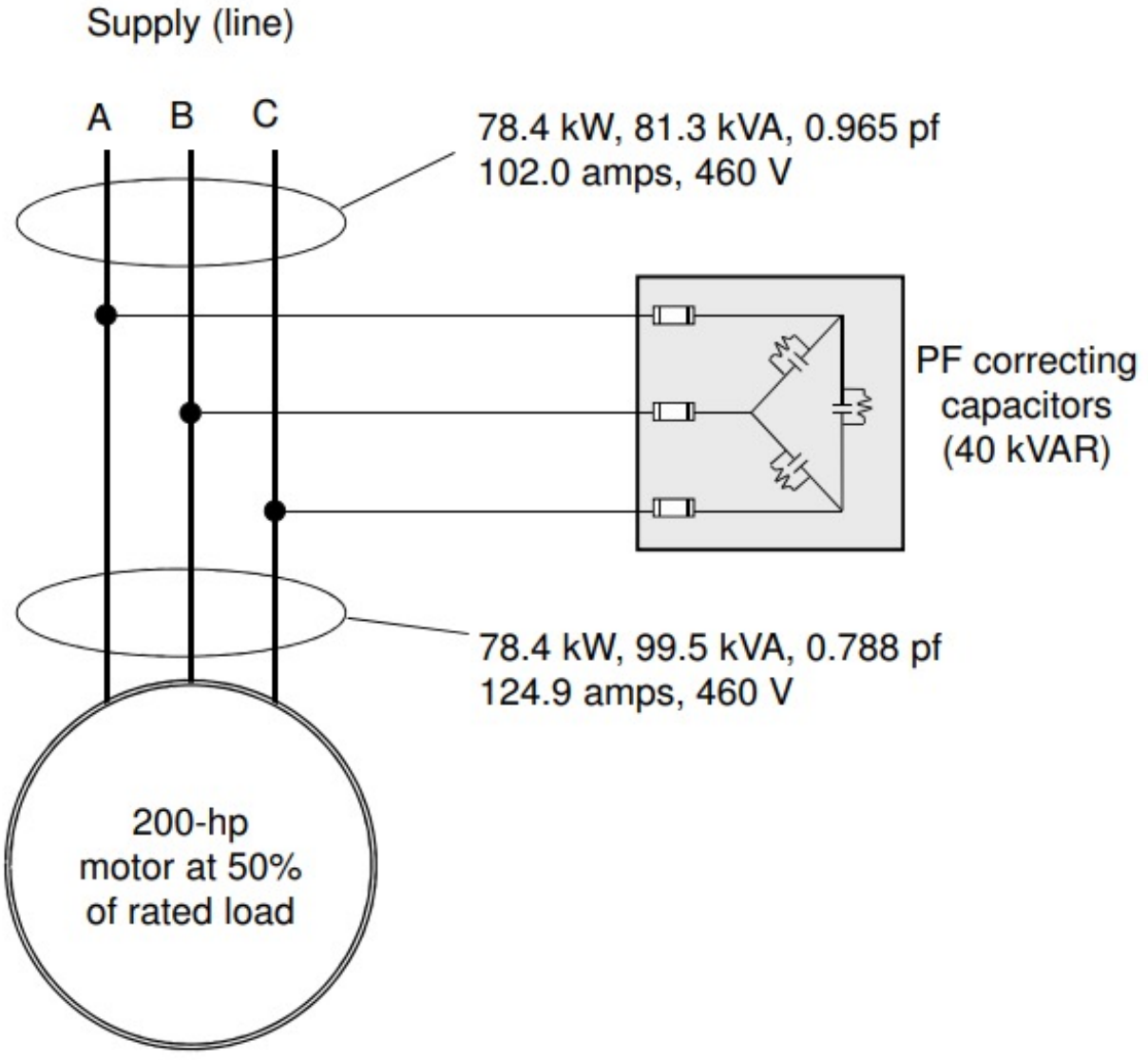
Amps = 966.5  (8.9% reduction – 94.9 amps)

# Static capacitor operation




Note: typical power factor penalty, where applicable, comes into play at about 85%

# Electrical details



# Utility company capacitors

# Variable Frequency Drives

- Cannot install capacitors to the output of a VSD – will damage the VSD & capacitors
- Capacitors installed on the inlet side of the VSD should be located at least 250 feet away from the drive

# Variable Frequency Drives

- Most VSD manufacturers quote a 0.95 power factor for the drive based on the phase angle between the voltage and current waveforms
- Considering the harmonics created, the effective power factor is usually closer to 0.70

# Solid State Soft Starter

- Cannot install capacitors to the output of a solid state soft starter – will damage the starter & capacitors
- Capacitors installed on the inlet side of the solid state soft starter should be located at least 170 feet away from the starter

# Solid State Soft Starter

- The capacitors must be controlled by a separate contactor
- Capacitors should be switched on only after the soft starter output voltage has reached line voltage

# Capacitor Selection

- Static power factor correction should neutralize no more than 80% of the magnetizing current of a motor
- Beyond that limit overcorrection can result in damage to motor and capacitors

# Capacitor Selection

- Magnetizing current is usually between 20% and 60% of full load rated current, depending on the number of poles in motor and its size
- Select capacitors for the specific motor being corrected

# Power Factor

- It is possible to over correct by adding too much capacitance causing the power factor to go beyond unity
- Some utility companies charge penalties for leading power factor as well as lagging power factor
- Generally, charges for leading power factor are smaller than those for lagging power factor

# Questions ????