Selection & Applications
Of
Power Factor Correction Capacitor
For
Industrial and Large Commercial Users

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Power Quality Solution Group
Agenda

- Power Factor Fundamental
- The Need for Power Factor Correction
- Effects of Harmonics: TPF & DPF
- Correction Alternatives & Capacitor Locations
- PF Rate, Capacitor Sizing, & ROI
- Capacitor Applications To Motors
- Capacitor Switching Equipment
- Other Application Issues
  * Steady State VAR Correction
  * Dynamic VAR Correction
- Standards & Codes
Power Factor Fundamentals
Most plant loads are *Inductive* and require a magnetic field to operate:

- Motors
- Transformers
- Florescent lighting

The magnetic field is necessary, but produces no useful work.

The utility must supply the power to produce the magnetic field and the power to produce the useful work: You pay for all of it!

These two types of current are the *ACTIVE* and *REACTIVE* components.
Power Factor Fundamental

• Definitions:
  – **Working /Active Power**: Normally measured in kilowatts (kW). It does the "work" for the system--providing the motion, torque, heat, or whatever else is required.
  – **Reactive Power**: Normally measured in kilovolt-amperes-reactive (kVAR), doesn't do useful "work." It simply sustains the electromagnetic field.
  – **Apparent Power**: Normally measured in kilovolt-amperes (kVA). Working Power and Reactive Power together make up apparent power.
Power Factor: The Beer Analogy

Mug Capacity = Apparent Power (KVA)
Foam = Reactive Power (KVAR)
Beer = Real Power (kW)

\[
\text{Power Factor} = \frac{\text{Beer (kW)}}{\text{Mug Capacity (KVA)}}
\]

Capacitors provide the Foam (KVAR), freeing up Mug Capacity so you don’t have to buy a bigger mug and/or so you can pay less for your beer!
Power Factor: A measure of efficiency. The ratio of Active Power (output) to Total Power (input)

Power Factor = \frac{\text{Active (Real) Power}}{\text{Total Power}} = \frac{\text{kW}}{\text{kVA}} = \cos(\theta) = \text{DISPLACEMENT POWER FACTOR}

A power factor reading close to 1.0 means that electrical power is being utilized effectively, while a low power factor indicates poor utilization of electrical power.
LEADING AND LAGGING

\[ \begin{align*}
I_C & \quad V \\
I_R & \quad I_R \\
I_L & \quad KVAR_C \\
KVAR_L & \quad KW \\
L & \quad I_{LOAD}
\end{align*} \]
LEADING AND LAGGING

**INDUCTION MOTOR**

**OVER-EXCITED SYN. MOTOR**
## Typical Uncorrected Power Factor

(Use only as a Guide)

<table>
<thead>
<tr>
<th>By Industry</th>
<th>Power Factor</th>
<th>By Operation</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto parts</td>
<td>75-80</td>
<td>Air compressor:</td>
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<tr>
<td>Brewery</td>
<td>76-80</td>
<td>External motors</td>
<td>75-80</td>
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<td>Cement</td>
<td>80-85</td>
<td>Hermetic motors</td>
<td>50-80</td>
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<tr>
<td>Chemical</td>
<td>65-75</td>
<td>Metal working:</td>
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<tr>
<td>Coal mine</td>
<td>65-80</td>
<td>Arc welding</td>
<td>35-60</td>
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<tr>
<td>Clothing</td>
<td>35-60</td>
<td>Arc welding with standard capacitors</td>
<td>40-60</td>
</tr>
<tr>
<td>Electroplating</td>
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<td>Resistance welding</td>
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<td>40-65</td>
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<tr>
<td>Forge</td>
<td>70-80</td>
<td>Melting:</td>
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<tr>
<td>Hospital</td>
<td>75-80</td>
<td>Arc furnace</td>
<td>75-90</td>
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<td>Machine manufacturing</td>
<td>60-65</td>
<td>Inductance furnace 60Hz</td>
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<tr>
<td>Metalworking</td>
<td>65-70</td>
<td>Stamping:</td>
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<td>Office building</td>
<td>80-90</td>
<td>Standard speed</td>
<td>60-70</td>
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<td>Oil-field pumping</td>
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<tr>
<td>Plastic</td>
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<td>Weaving:</td>
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<tr>
<td>Stamping</td>
<td>60-70</td>
<td>Individual drive</td>
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<td>65-80</td>
<td>Multiple drive</td>
<td>70</td>
</tr>
<tr>
<td>Textile</td>
<td>65-75</td>
<td>Brind</td>
<td>70-75</td>
</tr>
<tr>
<td>Tool, die, jig</td>
<td>60-65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From IEEE Std 141-1993
WHY DO WE CARE ABOUT POWER FACTOR
MOTOR LOAD CHARACTERISTICS

Motor characteristics for a typical medium-size and speed induction motor.
Why do we care about Power Factor?

- In Industrial Facilities, Mostly Induction Motor loads
- Energy Efficient Motors not optimized for PF
- Low power factor is caused by oversized or lightly loaded induction motors
- Low power factor results in:
  - Poor electrical efficiency!
  - Higher utility bills **
  - Lower system capacity
  - On the Supply Side, Generation Capacity & Line Losses
- Power Factor Correction Capacitors (PFCC) provide an economical means for improving Energy utilization
Why do we install Capacitors?

Before

After

- In this example, demand was reduced to 8250 kVA from 10000 kVA.

- 1750KVA Transformer Capacity Release.

- The power factor was improved from 80% to 97%
Harmonics

- Displacement Power Factor
- Total Power Factor
- Effects of Harmonics on Capacitors
Until recently, most electrical equipment drew current in a “linear” fashion:

- Current (i) & Voltage (v) are both “Sinusoidal”

Today, many electrical loads draw current in a “non-linear” fashion:

- Current (i) is periodic, but not “sinusoidal”
What produces “Non-linear” Current?

- Computers
- Fax Machines
- Copiers
- Variable Frequency Drives
- Electronic Ballasts
- Almost anything electronic

What produces “Non-linear” Current?
**Time vs Frequency**

**Time Domain**

- $f_1 = 60 \text{ Hz}$
- $f_3 = 3 \times 60 \text{ Hz} = 180 \text{ Hz}$
- $f_5 = 5 \times 60 \text{ Hz} = 300 \text{ Hz}$
- $f_7 = 7 \times 60 \text{ Hz} = 420 \text{ Hz}$

**Frequency Domain**

- $f_1 = 60 \text{ Hz}$
- $f_3 = 3 \times 60 \text{ Hz} = 180 \text{ Hz}$
- $f_5 = 5 \times 60 \text{ Hz} = 300 \text{ Hz}$
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**Distorted Wave**

$$= f_1 + f_3 + f_5 + f_7$$
Total Harmonic Current Distortion Is Same As Total Demand Distortion (TDD)

\[ I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots}}{I_1} \times 100 \% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100 \% \]
Total or True Power Factor (TPF)

TPF = (DPF) \times (\text{Harm Coefficient})

\begin{align*}
\text{DPF} &= \frac{KW}{KVA} = \cos \phi \\
\text{Harm Coefficient} &= \frac{1}{\sqrt{1 + TDD^2}}
\end{align*}

TPF = \text{Total or true power factor} \\
\text{DPF} = \text{Displacement power factor} \\
\text{Harm coefficient} = \text{Harmonic power factor} = \cos \delta
Total Power Factor Example

- VFD (Six Pulse)
- DPF = .95
- TDD = 90% (No Line Reactor)

Harm coefficient = \( \sqrt{\frac{1}{1 + .9^2}} = .7433 \)

- TPF = .95 x .7433 = .7061
Applying Capacitors:

- Caps at Motors or at SWBD / MCC:

  **Disadvantage:**
  - If Drives are present anywhere, the harmonic currents they produce can flow back to the point of lowest impedance: the capacitor!
  - This will cause premature failure of the capacitor.
How Harmonics Affect Capacitors

• Capacitors are naturally a **low impedance** to high frequencies:
  – **Caps absorb harmonics**
  – **Caps do not generate harmonics**

• As capacitor absorbs harmonics, the capacitor heats up
  – **Reduced life expectancy**

• Voltage harmonics stress the capacitor dielectric
  – **Reduced life expectancy**

• **Parallel combination of capacitors with motor or transformer can cause resonance** condition
The installation of standard capacitors can magnify harmonic currents on the network.
How Harmonics Affect Capacitors:

- **Resonance:**

  \[ X_L = 2\pi f_l \]

  \[ X_C = \frac{1}{2\pi f_C} \]

  \[ fr = f \sqrt[1]{\frac{X_L}{X_C}} \quad \text{Resonance} \]
Resonant Point likely to amplify dominant harmonic (typically 5th)

Magnification of Harmonic Current when Standard Capacitor are Added to the Network
Power Factor Correction With Harmonics:

- **De-tuning a network:**
  - “Force” the resonant point away from naturally occurring harmonics

4.2 Harmonic (252 Hz)

We control the impedance of these two elements
UTILITY RATE & PFCC
1 If the consumer does not correct the power factor, the utility may have to
   3 Build more power plants
   3 Install New/Large transformers
   3 Use larger utility cables/Wires, Switchgear, etc.

1 Many different rate structures across the country. Typically, penalties are imposed for PF < 95%.

1 *Thousands of Customers across the country are currently unaware that they are being penalized for low power factor***!
How do utilities charge for Power Factor?

• Utilities recoup the cost of providing reactive power in different ways…..
  – **kVA billing**: utility measures and bills every ampere of current including reactive current.
  – **kW demand** billing with Power factor adjustment: utility charges according to kW demand and adds a surcharge for power factor, typically in the form of a multiplier applied to kW demand.
  – **kVAR Reactive Demand charge**: A direct charge for use of magnetizing power. (example: $4.50/kVAR)

1 Two utilities recently introduced substantial Power Factor Penalties
  - TXU (Texas)  $3.50 - $5.50 per kW Demand to 95% pf
  - TVA (Tennessee)  $1.46 per kVAR lagging, $1.14 per kVAR leading (April 1, 2004)
MOST COMMON POWER FACTOR RATE CLAUSE

BILLING KW DEMAND =

ACTUAL KW DEMAND \times \frac{\text{BASE PF}}{\text{ACTUAL PF}}
Penalty Calculation From Utility Bills In TX

BILLING DEMAND (apfa) = KW2 & ACTUAL DEMAND = KW1

Due to PF Adjustment, KW2 > KW1

*Distribution System Charge = (KW2-KW1) x $3.55 / apfa = M1
*Nuclear Decommission Charge = (KW2-KW1) x $0.044/apfa = M2
*Transition Charge-1 = (KW2-KW1) x $0.177/ apfa = M3
*Transition Charge-2 = (KW2-KW1) x $0.272 / apfa = M4
*Transmission Service Charge = (KW2-KW1) x $1.19 / apfa = M5
*Transmission Cost Recov Factor = (KW2-KW1) x $0.27103 /apfa = M6

Total / Month = M1+M2+M3+M4+M5+M6 = $ / Month
CAPACITOR LOCATION & TYPE
Three Options for Applying Power Factor Capacitors:

A) Fixed capacitors @ individual motors or @ MCC
B) Automatic Banks at Main Switch Board
C) De-tuned Automatic Capacitor Bank at Main Switch Board

Harmonic Source e.g. Variable Speed Drive
Fixed Capacitors - Low Voltage

- **Main Benefit**
  - pf correction

- **Side Benefit**
  - voltage support
  - Small $I^2R$ reduction

- **Usage**
  - Correcting pf on individual loads such as motors

- **Disadvantages**
  - Overcompensation (correct past unity)
  - Not to be used on non-linear loads
  - Unable to track minute by minute load changes occurring on non-compensated feeders
Standard Automatic Capacitor Systems

- **Main Benefit**
  - \( pf \) correction

- **Side Benefit**
  - Voltage support
  - Small \( I^2R \) reduction

- **Usage**
  - Correcting \( pf \) on entire MCC’s or substations

- **Application alert**
  - Not to be used on non-linear loads
Anti-Resonant Automatic Cap. Bank

- Automatic Cap. Bank with a reactors in series
- Reactors tuned to 4.2 or 4.4
- Use where Non-Linear Loads less than 50% of total loads.
Transient Free De-Tuned Automatic Cap. Banks

- For sensitive networks
- Similar to Anti-resonant Automatic Capacitor System except solid state switching
- Reactor tuned to 4.2 or 4.4
- Response time < 5 sec
- Use where Non-Linear Loads < 50% of Total Loads.
Electronic Switch – Transient Free

- Fuses
- SCR-Diode
- De-tuned Inductor

Diagram showing connections for L1, L2, L3 with components labeled accordingly.
Rule Of Thumb For PFCC Applications

* When Non-Linear Loads < 15% Of Total Loads
  Select Standard Automatic Cap. Bank

* When Non-linear Loads >15% But < 50% Of Total Loads
  Select Anti-Resonant (Detuned) Auto. Cap. Bank

* When Non-Linear Loads > 50% Of Total Loads
  Select Active Harmonics Filter For VAR Correction

* When Transformer KVA To Cap. KVAR Ratio < 3
  Select Anti-Resonant (Detuned) Auto. Cap. Bank

* When Soft-Starters are present, select Detuned Auto. Cap. Bank
ACTIVE FILTER in VAR Correction Mode
Cyclical Loads & Loads With Dynamic VARMovements

**CAUSES**
- WELDING OPERATIONS
- LARGE HP MOTOR STARTING
- PROCESS LOADS (i.e. MIXERS, CRUSHERS, CHIPPERS, SHREDDERS)
- ARC FURNACES

**RESULTING IN**
- VOLTAGE FLICKER
- VOLTAGE SAGS
- POOR POWER FACTOR
- INABILITY TO START MOTORS
Active Filter (AHF)

- For Power Factor Correction For System where Non-Linear Loads > than 50% of Total Loads.
- When Fast VAR Movements Necessary
- AHF-New breed of power quality product
  - Harmonics cancellation
  - Power factor correction
  - VAR compensation
  - Resonance elimination
- Independent or simultaneous modes of operation
Active Harmonics Filter

- Electronic filtering up to the 50th harmonic
Hybrid Filters

- Combination of passive & active technologies
MV HVC Banks – General Layout
HVC Banks – General

- Marriage of two technologies
- Fixed capacitor banks and AHF
- Auxiliaries: MV/LV SWGR

![Graph showing HVC banks performance](image)
## Cyclical Loads & Loads With Dynamic VAR Movements

### Causes
- WELDING OPERATIONS
- LARGE HP MOTOR STARTING
- PROCESS LOADS (i.e. MIXERS, CRUSHERS, CHIPPERS, SHREDDERS)
- ARC FURNACES

### Solutions
**Application of:**
- HYBRID VAR COMPENSATION (HVC)
  - DYNAMIC VAR INJECTION ON PER CYCLE BASIS
  - PASSIVE/ACTIVE SYSTEM ARRANGEMENT
  - WITH INRUSH OR DE-TUNED REACTORS
  - CUSTOM-ENGINEERED FOR SPECIFIC SITE, NETWORK, LOAD CHARACTERISTIC NEEDS

**Resulting In**
- VOLTAGE FLICKER
- VOLTAGE SAGS
- POOR POWER FACTOR
- INABILITY TO START MOTORS
CAPACITOR APPLICATIONS
AT
MOTOR TERMINAL

> Motor Overload Protection

> Re-closure Issue – Jogging, Reversing, Inching, Plugging Applications
Capacitor At Motor Terminal
Motor Over Load Protection Issue
Motor Self-Excitation Voltage Influenced By Capacitor Ratings

Typical characteristic data showing how motor voltage due to self-excitation is influenced by capacitor rating.
Reclosed Breaker & Net Voltage

Equivalent circuit of simple system showing system quantities that control transient currents upon circuit-breaker reclosure.

\[ X_s = X_{s1} + X_{s2} = \text{Total System Reactance} \]

\[ E_s = \text{Equivalent Supply Voltage at Terminals of Machine} \]

\[ X'' = \text{Reactance of } E_m = \text{Equivalent Driving Voltage} \]

\[ E_m = \text{Machine Equivalent Driving Voltage} \]

\[ E_s = \text{System Equivalent Driving Voltage} \]

\[ \Delta E = \text{Net Driving Voltage} = E_s - E_m \]

\[ \theta = \text{Electrical Angle between } E_s \text{ and } E_m \]

\[ \theta \text{ is } \theta \text{ at Instant of Reclosing} \]

Expressed as

\[ \Delta E = -E_s + E_m^2 - 2E_sE_m \cos \theta \]

When \( E_s = E_m = E \),

\[ \Delta E = 2E \sin \left( \frac{\theta}{2} \right) \]

Effect of Phase Angle between Components of Net Driving Voltage at the Instant of Circuit-breaker Reclosure.
CAPACITOR APPLICATION ISSUES
Multi-Energy Power System of the Future?

- Hospital with cogeneration (1.5 MW)
- Residential photovoltaic system (6 kW)
- Utility-owned wind turbine site (1 MW)
- Residential Fuel cell (7 kW)
- Small wind turbine (10 kW)
- Utility-owned Photovoltaic site (500 kW)
- Factory with natural gas fuel cell (100 kW to 5 MW)
Power Quality Correction

Utility & Customer Owned

Solar Power System Working In Parallel

\[ \cos \phi_2 = 0.55 \]
\[ \cos \phi_1 = 0.89 \]

1000 KW
3000 KW

1818 KVA
1537 KVA

1537 KVAR
1537 KVAR

PV
2 MW

PG & E

3 MW Load
Key Questions to ask Customer For Capacitor Applications

- Are you being charged for poor power factor by your utility (ask for a copy of their electric bill - kW, kVA, Power Factor)?
- Do you have a large number of drives, rectifiers or other harmonic generating equipment? Do you have nuisance tripping of overloads?
- Do you have welders, chippers, or other large cyclical loads?
- Do you have problems with voltage sags or “flicker”? How sensitive is your equipment to these power issues?
- Do you have capacity issues on any of your substations?
- Do you have HID lighting or critical processes with low tolerance to “brownouts”?
- Have you been experiencing poor weld quality?
- Do you have Soft Starters in the System?
- Do you have Motors subject to reversing, jogging, inching, or plugging?
Capacitor Standards

- NEMA CP-1 for Shunt Capacitors
- UL 810 Standard for Capacitors
- NFPA 70, National Electrical Code
- IEEE Standard 399, Power System Analysis
- ANSI / IEEE Standard 18, Shunt Power Capacitors
- IEEE Standard 141, Recommended Practice for Electrical Power Distribution for Industrial Plants
Other Capacitor Application Issues

**NEC & NEMA:**

* The Ampacity of Capacitor Circuit Conductors shall not be less than 135% of rated Capacitor Current
* Breaker Rating based on 135% Rated Capacitor Current
* Fuse Rating based on 165% Rated Capacitor Current for Class R Time Delay
* Fusible Switch Rating based on 165% Rated Capacitor Current
Capacitor When Properly Applied Will Have Long Life.

Conditions that affect the Life of Capacitor:

* **Ambient Temp.** < 46Deg C or 115Deg F
* **Case Temp. of Capacitor** < 55Deg C or 131 Deg F
* Shunt Capacitor designed to operate at 110% Rated Voltage.
* Avoid sustained **Over Voltage**
* **High System Harmonics**
Summary of Benefits:

- **Reduced Power Costs:**
  - Since Capacitors supply reactive power, you don’t pay the utility for it
  - Depending up on location of Cap. Bank, Line Loss can be reduced.
  - You can calculate the savings

- **Off-load transformers**
  - Defer buying a larger transformer when adding loads

- **Reduce voltage drop at loads**
  - Only if capacitors are applied at loads
  - (minimal benefit at best)
Thank You!

Questions?