WESTERN MINING
ELECTRIC ASSOCIATION

Power Factor Considerations
At
Open Pit Coal Mines
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By:
*Electrical Systems Consultants, Inc.*
Jerry Hager, P.E.
Mark Galey, P.E.
DEFINITION OF POWER FACTOR

- Power Factor = is the ratio of real power (kW) to apparent power

\[
\text{Power Factor} = \frac{\text{kW}}{\text{kVA}} = \cos \theta
\]
UNCORRECTED POWER FACTOR

REAL POWER (KW)

θ POWER FACTOR ANGLE THETA

APPARENT POWER (KVA)

REACTIVE COMPONENT (KILOVARS OR KVAR)
POWER FACTOR TRIANGLE ILLUSTRATING THE EFFECTS OF CAPACITOR INSTALLATION

REAL POWER (KW)

ORIGINAL POWER FACTOR = \( \frac{100}{125} = 80\% \)

AFTER INSTALLATION OF 50 KVAR OF CAPACITORS

\[ \frac{100}{103.07} = 97.02\% \]

NEW APPARENT POWER
103.07 KVAR

APPARENT POWER (KVA)
125 KVA

50 KVAR CAPACITOR

UNCORRECTED REACTIVE KVAR

REACTIVE COMPONENT LOAD KVAR = 75 KVAR
BENEFITS OF POWER FACTOR CORRECTION

There are just two benefits from power factor improvement -

- Reduced losses or reduced kVA loading (not both)
- Voltage support (reduced voltage drop)
REDUCED KVA LOADING

• Most facilities are amp or kVA limited
• Increasing power factor reduces kVA loading and increases voltage thus reducing amp loading or resistive losses.

\[ I^2R \]
VOLTAGE DROP

% Voltage Drop =

\[
\frac{kVA \ (R \ \cos \ \theta + X \ \sin \ \theta)}{10 \ (kV)^2}
\]
VOLTAGE DROP

• Note:
• Voltage drop is caused by kW real power flowing through the resistance to electric source (generator) and
• Reactive (lagging pf) load flowing through reactance back toward electric source.
VOLTAGE DROP

- Per Unit Voltage Drop Through Transformer
- Transformers are almost all reactive.
- Thus voltage drop due to reactive load.
VOLTAGE DROP

- Percent drop through transformer = \[
\frac{(\text{kVAR})(X_L)}{10(\text{kV})^2}\]

- Where:
  - \(X_L\) = %percent impedance of transformer
  - \(\text{kVAR}\) = reactive load
  - \(\text{kV}\) = line-to-line voltage
Transformer = 10 MVA at 6% Impedance

Load = 8 MW and 6 MVAR at 10 MVA

Voltage Drop = \( R \times P + Q \times X \)\( \text{V} \)

\[
R = \frac{0.06}{11} = 0.00545 \text{ pu} \quad X = 0.06 \times \cos 85^\circ = 0.05229 \text{ pu}
\]

Voltage Drop = \( 0.00545 \times 0.8 + 0.05229 \times 0.6 \)

\[
= 0.00436 + 0.03137 \text{ pu}
\]

\[
= 0.0357 \text{ or } 3.157\%
\]
LIGHT LOAD CONDITION
WITHOUT CAPACITOR

REAL (WORKING) CURRENT
20 AMPS

MAGNETIZING (REACTIVE) CURRENT - 55 AMPS

INDUCTION MOTOR

POWER FACTOR = \frac{20}{58.5} = .34 \text{ OR } 34.2\%
LIGHT LOAD CONDITION
WITH CAPACITOR

REAL (WORKING) CURRENT
20 AMPS

MAGNETIZING (REACTIVE) CURRENT - 5 AMPS

CAPACITOR

INDUCTION MOTOR

POWER FACTOR = $\frac{20}{20.6} = .97$ OR 97%
Transformer Excitation

- 2% to 4% of Transformer Rating
- Hysteresis and Eddy Currents – Core
- Core Loss (kW) ~0.6% of Rating
- Magnetizing (kVAR) ~2% to 4%
- 20% Magnetizing 3rd Harmonics
Transformer Winding Loss

\[ V I_{pu} = 10,000 \text{ kVA} \]

\[ I_{pu}^2 \times R_{pu} = 0.0054 \text{ pu} \quad I_{pu}^2 \times X_{pu} = 0.0523 \text{ pu} \]

MW Loss = 54 kW \quad MVAR Loss = 523 kVAR
Typical Mine
Transformer kVAR Consumption

- 12,000 kW Mine Load
- 52,000 kVA Connected Transformers
- 1,000 kVAR Magnetizing kVAR Loss
- 1,200 kVAR I^2X Loss
Typical Mine $I^2R$ & $I^2X$

Line Loss

- $I^2R$ Loss 3% to 5% of Total Load
- Typical Cost (12 MW Mine) $150,000 per Year at $0.05/kWh
- $I^2X$ Loss at 10-15% of MW Load
- Line Charging ~ $+1,000$ kVAR
AC & DC Drives

- VFD’s at 95% Lagging Power Factor
- Static DC Drives at 30-85% Lagging Power Factor
- DC Drives with Reactive Power Compensation (RPC) at 90% Lagging PF with SCR’s (Thyristers)
- Static AC Drives with PWM or CCI inverters at 95% Lagging to Power Factor
- Ward-Leonard DC at 85-94% Lagging PF
AC & DC Drives

- AC Drives with IGBT rectifier/inverter at 80% Leading to Unity Power Factor
Variable Static Capacitors

- Adaptive Var Compensator (AVC)
  $35/kVAR, $50/kVAR with Step-up Transformer and Breaker
- Static Var Compensator (SVC) up to 100 MVAR
Harmonic Problems

Adding capacitors can result in resonance

Harmonic\_Number\_of\_Resonance := \sqrt{\frac{\text{Short\_Circuit\_MVA}}{\text{Capacitor\_kVAR}}}

Typical Mine

- 480-volt 6th Harmonic 15,000 Amps
- 2.4/4.16-kV 18th Harmonic 17,000 Amps
- 4.16/7.2-kV 11th Harmonic 3,500 Amps
- 4.16/7.2-kV 14th Harmonic 5,100 Amps
Typical 12 MW Mine kVAR Requirements

- 1,200 kVAR, $I^2X$ Transformer Loss
- 1,000 kVAR Transformer Magnetizing
- 4,200 kVAR, 7,000 hp Motors
- - 1,000 kVAR Line Charging
- -2,000 kVAR Excavation Equipment

Total = 3,400 kVAR at 96% Power Factor
Mining Shovels

- Induction or synchronous motors driving DC machines 88% Lagging Power Factor
- DC Drives with SCR rectifiers and RPC’s for reactive control at 90% Lagging Power Factor
- New AC IGBT inverters used with induction motors 90% leading Power Factor
P&H 4100 Shovel VAR Input

P&H 4100 MVAR OUTPUT

-2.5  -2.0  -1.5  -1.0  -0.5  0.0  0.5  1.0  1.5  2.0

Time

MVAR

RMS VAR

Ave VAR

155 per. Mov. Avg. (MVAR)
P&H 4100 XPB - One Minute

![Graph showing load and voltage changes over time.](attachment:graph.png)

- 3.84 MW + j0.31 at Voltage = 98%
- -0.06 MW - j1.26 MVAR at Voltage = 104.2%
- -2.13 + j0.19 at Voltage = 100.8%
- -0.54 - j0.24 at Voltage = 100.9%

Voltage

Time (sec)
P&H 2300 at RMS PF 98.9% Lag
Large Draglines

- DC Motor loops provide power for hoist, drag and swing
- Synchronous motor/generator sets act as prime movers
- Synchronous machines usually set to hold 93% leading power factor
Marion 8200 Dragline

Voltage Swing = 9.5%

6.82 - j0.83 at Voltage = 95.8%

-2.75 + j2.11 at Voltage = 102.4%
BI 1570 Dragline at 95% PF
Lagging and Leading
230kV-69kV Source & Mine 69kV Voltages at 69kV

230-kV & 69-kV Substation Loads

3.4% Voltage Swing at 69 kV Source Bus Low of 230-kV

4.3% Voltage Swing 69-kV Mine Bus
230kV-69kV Source & Mine 69kV Voltages at 69kV
Capacitance Varies with Square of Voltage

- 600 kVAR at 102% Voltage produces 624 kVAR
- 600 kVAR at 105% Voltage produces 661 kVAR
- 600 kVAR at 95% Voltage produces 542 kVAR
- 600 kVAR at 90% Voltage produces 486 kVAR
## Capacitor Additions for 80% PF Mine Loss Savings

<table>
<thead>
<tr>
<th>PF</th>
<th>kVAR Load</th>
<th>Load</th>
<th>Loss</th>
<th>Cost</th>
<th>Mine Loss with Capacitors</th>
<th>Annual Savings</th>
<th>#</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.0%</td>
<td>1,687 kVAR</td>
<td>313 kW</td>
<td>$77,000</td>
<td>$41,000</td>
<td>6,000 kVAR</td>
<td>20</td>
<td>$64,000</td>
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<tr>
<td>98.0%</td>
<td>2,373 kVAR</td>
<td>320 kW</td>
<td>$78,000</td>
<td>$40,000</td>
<td>5,000 kVAR</td>
<td>17</td>
<td>$54,000</td>
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</tr>
<tr>
<td>95.0%</td>
<td>3,690 kVAR</td>
<td>340 kW</td>
<td>$83,000</td>
<td>$35,000</td>
<td>4,000 kVAR</td>
<td>13</td>
<td>$42,000</td>
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</tr>
<tr>
<td>90.0%</td>
<td>5,084 kVAR</td>
<td>379 kW</td>
<td>$93,000</td>
<td>$25,000</td>
<td>2,000 kVAR</td>
<td>7</td>
<td>$22,000</td>
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</tr>
<tr>
<td>85.0%</td>
<td>6,078 kVAR</td>
<td>425 kW</td>
<td>$104,000</td>
<td>$14,000</td>
<td>1,000 kVAR</td>
<td>3</td>
<td>$10,000</td>
<td></td>
</tr>
</tbody>
</table>