ELE 789 Special Topics in Electrical and Electronics Engineering: Electrical Power Quality

Dr. H. Bilge Mutluer
Course Outline

1. Power Quality (PQ) Definitions and Objectives
2. Power System Modeling and Simulation for PQ Analyses
3. Voltage Quality
4. Harmonics and Harmonic Elimination
5. Reactive Power Compensation
6. EMI, Grounding and Wiring
Reactive Power Compensation

- Power Factor
- Conventional Compensation Techniques
- Power Factor Correction of Unsymmetrical Loads and Phase Balancing
- Static Compensation Systems
  - FACTS Devices
  - Thyristor Controlled Reactor (TCR)
  - Thyristor Switched Capacitor (TSC)
  - Static Synchronous Compensator (STATCOM)
  - Other Static Compensation Systems
Load Compensation

• **Load Compensation**: management of reactive power to improve quality of the supply
  – Power factor correction
  – Improvement of voltage regulation
  – Load balancing
Power Factor Correction

- Generating reactive power as close as possible to the load rather than supplying it from a remote station.
Improvement of Voltage Regulation

• Achieved by the control of reactive power
  – Reduction and elimination of flicker
  – Increased efficiency
  – Indirect regulation of current
Load Balancing

- Reduction and elimination of negative sequence by using reactive power control
- Unbalanced operation leads to:
  - Additional losses
  - Undesired torque and oscillations in the motors
  - Increased ripple in rectifiers
  - Malfunction of several equipment
Power Factor

- Power factor is defined as the ratio of the active power $P$ to the apparent power $S$.
- In an ideal balanced case (no harmonics) it corresponds to the cosine of the displacement angle between phase voltage and phase current.
- In this ideal case, reactive power $Q$ can be defined as the sine of the displacement angle between phase voltage and phase current.
Power Factor (Single Phase)

\[ S_l = VI_1^* = V^2 G_l - jV^2 B_l = P_l + Q_l \]

\[ \text{Cos}\phi \text{ is the fraction of apparent power which can be usefully converted into other forms of energy} \]
Polyphase Systems

• In a polyphase system, which has $k$ phases that may also be unbalanced,

$$S = \sum_k \sqrt{\left((P_k^2 + Q_k^2)\right)}$$
Power Assessment with Distorted Waveforms

- According to Budenau:

\[ S^2 = P^2 + Q_B^2 + D^2 \]

\[ Q_B = \sum_{l=1}^{n} V_l I_l \sin(\varphi_l) \]

\[ P_c = \sqrt{S^2 - P^2} \]

(complementary power)
Power Assessment with Distorted Waveforms

• According to Fryze, current is separated into orthogonal components:

\[ i = i_a + i_b \]

\[ Q_F = V I_b = \sqrt{S^2 - P^2} \]
Power Assessment with Distorted Waveforms

• Shepherd and Zakikhani proposed:

\[ S^2 = S_R^2 + S_X^2 + S_D^2 \]

\[ S_R^2 = \sum_{1}^{n} V_n^2 \sum_{1}^{n} I_n^2 \cos^2(\varphi_n) \]  
active apparent power

\[ S_X^2 = \sum_{1}^{n} V_n^2 \sum_{1}^{n} I_n^2 \sin^2(\varphi_n) \]  
reactive apparent power

\[ S_D^2 = \sum_{1}^{n} V_n^2 \sum_{1}^{p} I_p^2 + \sum_{1}^{m} V_m^2 \left( \sum_{1}^{n} I_n^2 + \sum_{1}^{p} I_p^2 \right) \]  
distortion apparent power
Power Assessment with Distorted Waveforms

- Sharon proposed:

\[ S^2 = P^2 + S_Q^2 + S_C^2 \]

\[ P \sim \text{active power} \]

\[ S_Q = V \sqrt{\sum_{1}^{n} I_n^2 \sin^2(\varphi_n)} \sim \text{a reactive power in quadrature} \]

\[ S_C \sim \text{a complementary reactive power} \]
Power Assessment with Distorted Waveforms

• Emanuel proposed:

\[ Q_1 = V_1 I_1 \sin(\varphi_1) \]

\[ P_C^2 = S^2 - P^2 - Q_1^2 \]
Power Assessment with Distorted Waveforms

• Based on Fryze’s theory, Kusters and Moore proposed:

\[ S = P^2 + Q_i^2 + Q_{ir}^2 = P^2 + Q_c^2 + Q_{cr}^2 \]

\[ i_{qr} = i - i_p - i_q \]

- **Inductive case**: an active component with a waveform identical to that consumed in an ideal resistance

- **Capacitive case**: a reactive component, corresponding to either a coil or a capacitor

- **Residual reactive component**: a residual reactive component, the remaining current after removing the active and reactive, i.e.

\[ i_{qr} / i_{qc} \]

\[ i_{ql} / i_{qc} \]
Power Assessment with Distorted Waveforms

- Also based on Fryze’s definition, Emanuel proposed:

\[ S^2 = (P_1 + P_H)^2 + Q_F^2 \]

\[ Q_F^2 = Q_B^2 + D^2 \]

\[ S^2 = (P_1 + P_H)^2 + Q_1^2 + Q_H^2 \]

- fundamental
- harmonics
- fundamental
- harmonics

\[ Q_H^2 = Q_F^2 - Q_1^2 \]
## Illustrative Example

<table>
<thead>
<tr>
<th>Case</th>
<th>$V_1 \angle \alpha_1$</th>
<th>$V_3 \angle \alpha_3$</th>
<th>$V_5 \angle \alpha_5$</th>
<th>$V_7 \angle \alpha_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$v_A$ 113.65$\angle 0^\circ$</td>
<td>$i_A$ 15$\angle -30^\circ$</td>
<td>5.8$\angle 0^\circ$</td>
<td>2$\angle 0^\circ$</td>
</tr>
<tr>
<td>B</td>
<td>$v_B$ 105$\angle 0^\circ$</td>
<td>$i_B$ 15$\angle 0^\circ$</td>
<td>5$\angle 0^\circ$</td>
<td>21$\angle 0^\circ$</td>
</tr>
<tr>
<td>C</td>
<td>$v_C$ 105$\angle 0^\circ$</td>
<td>$i_C$ 15$\angle -30^\circ$</td>
<td>5$\angle -90^\circ$</td>
<td>3$\angle -150^\circ$</td>
</tr>
<tr>
<td>D</td>
<td>$v_D$ 105$\angle 0^\circ$</td>
<td>$i_D$ 15$\angle -30^\circ$</td>
<td>40.82$\angle 180^\circ$</td>
<td>5.44$\angle -60^\circ$</td>
</tr>
</tbody>
</table>
Illustrative Example

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
<th>Case D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>$P(W)$</td>
<td>1476</td>
<td>1845</td>
<td>1282</td>
</tr>
<tr>
<td>Budeanu</td>
<td>$Q_B(Var)$</td>
<td>852</td>
<td>0</td>
<td>978</td>
</tr>
<tr>
<td>Shepherd</td>
<td>$S_X(VA)$</td>
<td>852</td>
<td>0</td>
<td>1046</td>
</tr>
<tr>
<td>Sharon</td>
<td>$Q_S(Var)$</td>
<td>852</td>
<td>0</td>
<td>1046</td>
</tr>
<tr>
<td>Emanuel</td>
<td>$Q_I(Var)$</td>
<td>852</td>
<td>0</td>
<td>788</td>
</tr>
<tr>
<td>Fryze</td>
<td>$Q_F(Var)$</td>
<td>1107</td>
<td>0</td>
<td>1327</td>
</tr>
<tr>
<td>Budeanu</td>
<td>$D(VA)$</td>
<td>707</td>
<td>0</td>
<td>897</td>
</tr>
<tr>
<td>Apparent</td>
<td>$S(VA)/PF$</td>
<td>1845/0.80</td>
<td>1845/1</td>
<td>1845/0.695</td>
</tr>
</tbody>
</table>

In general:

$Q_1 \leq Q_B \leq S_X \leq Q_S \leq Q_F$
Power Factor

- **Displacement Power Factor:**
  \[
  S_1 = \sqrt{(P_1^2 + Q_1^2)} \Rightarrow DPF = \frac{P_1}{S_1}
  \]

- **Total Power Factor:**
  \[
  S = \sqrt{(P_{total}^2 + Q_{total}^2 + D^2)} \Rightarrow TPF = \frac{P_{total}}{S_{total}}
  \]

  \[
  P_{total} = V_a I_a + \sum_{h=1}^{\infty} V_h I_h \cos(\theta_h - \theta_h^t),
  \]

  \[
  Q_{total} = \sum_{h=1}^{\infty} V_h I_h \sin(\theta_h - \theta_h^t),
  \]

  \[
  S_{total} = \sqrt{(\sum_{h=0}^{\infty} I_h^2)(\sum_{h=0}^{\infty} V_h^2)},
  \]

  \[
  D = \sqrt{S_{total}^2 - P_{total}^2 - Q_{total}^2},
  \]
Advantages of Reactive Power Compensation

• Reduce electric utility bill
• Reduce $\rho R$ losses and, therefore, heating in lines and transformers
• Increase the voltage at the load, increasing production and/or the efficiency of the operation
• Reduce current in the lines and transformers, allowing additional load to be served without building new circuits
Power Factor Correction Example

<table>
<thead>
<tr>
<th>Description</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Power</td>
<td>1200 W</td>
<td>1200 W</td>
</tr>
<tr>
<td>p.f.</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Apparent Power</td>
<td>1200 VA</td>
<td>2400</td>
</tr>
<tr>
<td>Line Current (rms)</td>
<td>5A</td>
<td>10A</td>
</tr>
<tr>
<td>Distribution Losses (i^2R)</td>
<td>15 W</td>
<td>60 W</td>
</tr>
<tr>
<td>Increase in the efficiency:</td>
<td>3.57%</td>
<td></td>
</tr>
</tbody>
</table>
Reactive Power Regulations

Distribution Penalty limits according to EPDK MHY, Installed Power is >50kVA

2001 - 2007

2008 -
Load Identification

Data Acquisition system

Monthly electrical energy bills

Denis Open Cast Mine 34.5kV Bus, Energy Consumption, Year 1999

- Active consumption, MWh
- Inductive Reactive consumption, MVArh
- Capacitive Reactive consumption, MVArh

Inductive reactive energy Penalty Limit

Capacitive reactive energy Penalty Limit
Load Identification

• Load Cycle:
  – Fixed loads
  – Intermittent loads (>1min)
  – Fast varying loads (<1min)

• Voltage Level
  – LV (<1kV)
  – MV (Distribution HV)
  – HV (Transmission)

• Reactive Power
  – Inductive
  – Capacitive
  – Both

• Active Power
  – Consumption
  – Consumption + Regeneration
Load Identification

(a)
Conventional Reactive Power Compensation Techniques

• The opposite of the load reactive power is applied (magnitude is determined by penalty limits) to reduce the average Q, thus increasing $\cos \phi$ above penalty limits.
Location of the Installation

- **CLOSER TO THE SUPPLY**
  - Installation Costs decrease
  - Special attention due to low X/R ratio

- **CLOSER TO THE LOADS**
  - Reduction of distribution losses
  - Precise control
Conventional Shunt Compensation (Inductive Load)

• Select Shunt Capacitor (Group)
• Determine the no-load voltage rise to make sure that the voltage will not rise above 110 percent when the load is minimum.
• Determine the impact of the capacitors on harmonics
  – Consider filter design
  – Consider changing the impedance
Selection of Shunt Capacitor Size

\[
kvar = kW \left( \tan \theta_{\text{orig}} - \tan \theta_{\text{new}} \right) \sqrt{\frac{1}{PF_{\text{orig}}^2} - 1} - \sqrt{\frac{1}{PF_{\text{new}}^2} - 1}
\]

where
- \(kvar\) = required compensation in kvar
- \(kW\) = real power in kW
- \(\theta_{\text{orig}}\) = original power factor phase angle
- \(\theta_{\text{new}}\) = desired power factor phase angle
- \(PF_{\text{orig}}\) = original power factor
- \(PF_{\text{new}}\) = desired power factor
Feeder Voltage Rise due to Capacitors

Shunt Connection

Series Connection

\[
\% \Delta V = \frac{100}{V_{\text{with cap}}} \left( V_{\text{with cap}} - V_{\text{no cap}} \right)
\]
Voltage Rise by Capacitors

\[ \%\Delta V = \frac{kvar_{cap} \times Z_{tx} \, (\%) \, \%}{kVA_{tx}} \]

where \( \%\Delta V \) = percent voltage rise
\( kvar_{cap} \) = capacitor bank rating
\( kVA_{tx} \) = step-down transformer rating
\( Z_{tx} \) = step-down transformer impedance, \( \% \)

Reduction of Current

\[ \%\Delta I = 100 \left[ 1 - \left( \frac{\cos \theta_{before}}{\cos \theta_{after}} \right) \right] \]

Reduction of Losses

\[ \% \text{loss}_{\text{reduction}} = 100 \left[ 1 - \left( \frac{pf_{\text{original}}}{pf_{\text{corrected}}} \right)^2 \right] \]
Capacitive Impedance

- Capacitive reactance $X_C$ decreases proportionately

$$X_C = \frac{1}{2\pi fC}$$

- At the fundamental frequency:

$$X_C = \frac{kV^2}{Mvar}$$
Load Balancing

Three phase unbalanced load

\[ Y_{l}^{ab} = \frac{1}{Z_{l}^{ab}} \]

\[ Y_{l}^{ab} \neq Y_{l}^{bc} \neq Y_{l}^{ca} \]
Eliminating the susceptance, thus eliminating the reactive power

\[ Y_{l}^{ab} = G_{l}^{ab} + jB_{l}^{ab} \]

\[ B_{\gamma}^{ab} = -B_{l}^{ab} \]
Load Balancing

Unbalanced load with unity power factor

By using delta / wye transformation

Single phase unbalanced load with unity power factor (Repeated for all three phases)
Load Balancing

Positive sequence balancing of the single-phase unity power factor load
(Reapeated for all three phases)

\[
B_{\gamma}^{ab} = \frac{G_{l}^{ab}}{\sqrt{3}}
\]

\[
B_{\gamma}^{ca} = -\frac{G_{l}^{ab}}{\sqrt{3}}
\]
After Load Balancing

\[
\begin{bmatrix} V_+ \\ 0 \\ 0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} Z_a + Z_b + Z_c & Z_a + hZ_b + h^2 Z_c & Z_a + h^2 Z_b + hZ_c \\ Z_a + hZ_b + h^2 Z_c & Z_a + Z_b + Z_c & Z_a + hZ_b + h^2 Z_c \\ Z_a + h^2 Z_b + hZ_c & Y_1 + h^2 Y_2 + hY_3 & Z_a + Z_b + Z_c \end{bmatrix} \begin{bmatrix} I_+ \\ I_- \\ I_0 \end{bmatrix}
\]

\[
[V_+] = \frac{1}{3} \begin{bmatrix} Z_a + Z_b + Z_c & Z_a + hZ_b + h^2 Z_c & Z_a + h^2 Z_b + hZ_c \\ Z_a + hZ_b + h^2 Z_c & Z_a + Z_b + Z_c & Z_a + hZ_b + h^2 Z_c \\ Z_a + h^2 Z_b + hZ_c & Y_1 + h^2 Y_2 + hY_3 & Z_a + Z_b + Z_c \end{bmatrix} \begin{bmatrix} I_+ \\ I_- \\ I_0 \end{bmatrix}
\]

\[
V_+ = \frac{1}{3} \left[ \frac{3}{G_{l}^{ab}} + \frac{\sqrt{3}}{jG_{l}^{ab}} - \frac{\sqrt{3}}{jG_{l}^{ab}} \right] I_+
\]

\[
G_{l}^{ab} V_+ = I_+
\]
Load Balancing

Repeating the same procedure for all three phases:

\[ G = G_{l}^{ab} + G_{l}^{bc} + G_{l}^{ca} \]

Positive sequence wye equivalent of the single phase unity power factor load
Steinmetz Equations

Reactive Power Elimination

\[ B_{\gamma}^{ab} = -B_{l}^{ab} + \frac{(G_{l}^{ca} - G_{l}^{bc})}{\sqrt{3}} \]

\[ B_{\gamma}^{bc} = -B_{l}^{bc} + \frac{(G_{l}^{ab} - G_{l}^{ca})}{\sqrt{3}} \]

\[ B_{\gamma}^{ca} = -B_{l}^{ca} + \frac{(G_{l}^{bc} - G_{l}^{ab})}{\sqrt{3}} \]

Negative Sequence Elimination

Susceptance values needed for complete load balancing
Load Balancing Example

• 34.5kV bus with a 3790 MVA short circuit
• An unbalance is created by inserting a 5 Ohm resistance between phase B and C.
• The necessary inductance of 0.0276mH is calculated between A and B,
• 366.6uF capacitance is needed across C and A to balance the load.
Load Balancing Example

Unbalanced Load

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>3 phase Currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>Ia: +12, Ib: -12, Ic: -9</td>
</tr>
<tr>
<td>0.41</td>
<td>Ia: +9, Ib: -9, Ic: -6</td>
</tr>
<tr>
<td>0.42</td>
<td>Ia: +6, Ib: -6, Ic: -3</td>
</tr>
<tr>
<td>0.43</td>
<td>Ia: +3, Ib: -3, Ic: +0</td>
</tr>
<tr>
<td>0.44</td>
<td>Ia: +0, Ib: +0, Ic: +3</td>
</tr>
<tr>
<td>0.45</td>
<td>Ia: +3, Ib: +3, Ic: +6</td>
</tr>
</tbody>
</table>

Unbalanced Load After Compensation

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>3 phase Currents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>Ia: +12, Ib: +12, Ic: +12</td>
</tr>
<tr>
<td>1.41</td>
<td>Ia: +9, Ib: +9, Ic: +9</td>
</tr>
<tr>
<td>1.42</td>
<td>Ia: +6, Ib: +6, Ic: +6</td>
</tr>
<tr>
<td>1.43</td>
<td>Ia: +3, Ib: +3, Ic: +3</td>
</tr>
<tr>
<td>1.44</td>
<td>Ia: +0, Ib: +0, Ic: +0</td>
</tr>
<tr>
<td>1.45</td>
<td>Ia: +3, Ib: +3, Ic: +3</td>
</tr>
</tbody>
</table>