Workshop

Design of Industrial Power Distribution Systems:
Shortcut Methods, Quick Estimation and Application Guidelines

[2012]

IEEE IAS Distinguished Lecture Series
Pune, Hyderabad, Chennai, and Delhi: India

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Design of Industrial Power Distribution Systems:
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Dr. P.K. Sen, PE, Fellow IEEE
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This (multiple days) workshop has been designed for all practicing engineers (young or experienced), managers, operation and plant maintenance personnel, advanced students interested in “power and energy engineering” career and technical personnel interested in different aspects of Power Distribution Systems Design as applied to Electric Power and Energy industry. The main objective of the workshop is to introduce the “basic” tools required and utilized in designing industrial power distribution systems. The primary focus of this course is on the medium voltage (MV) and low voltage (LV) power systems with some references to the sub-transmission system. It is assumed that participants have some basic knowledge of fundamentals of electric power systems and electric machinery. Practical experience is preferable, but not required. Emphasis is given on hand calculations and estimations. Numerous real world design problems will be solved during the entire workshop. The workshop will be divided into “multiple” modules. Extensive handouts will be provided at the workshop. This introductory workshop is must for all power systems engineers, utility and no-utility alike, consulting firms, manufacturing and process plant, and designed to facilitate in educating advanced students in power and energy engineering profession.

(Tentative) Course Outline

Day (Part) 1:

1) Logistics, Introduction, Background and Prerequisites, Expectations etc.
3) Power System Fundamentals, Understanding “Load” and “Key” Design Tools:
   - 3-Ph Power, Voltage-Current Calculations;
   - Active, Reactive Power, Apparent Power, Power Factor and Power Triangle;
   - Power Factor Correction and Shunt Capacitor Compensation;
   - Voltage Drop and Voltage Regulation
   - Load Characterization;
   - Understanding Electricity Bill;
   - Induction Motor Load, Torque-Speed Characteristics, Losses and Efficiency;
   - Selection of Plant Distribution Voltage;
   - Transformer Sizing; and
   - Motor Starting and Voltage Drop
4) Transformer Engineering, Basics and Procurement:
   - Equivalent Circuit and Design Fundamentals;
   - Performance Evaluation: Efficiency and Losses; % Impedance and Voltage Regulation;
   - Transformer Procurement, Specification Writing and Loss Evaluation; Testing;
   - Overloading, Life Assessment and Asset Management
5) Design of Industrial Power Distribution Systems and Problems:
   - Simplified Design Calculations, Transformer Sizing, Selection of Voltage;
   - Motor Starting;
   - One-line Diagram; Quick Cost Estimate

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Day (Part) 2: (When Applicable)

1) Recap of Day 1, Questions and Answers
2) Induction Motor Performance and Procurement
   • Design Fundamentals, Equivalent Circuit and Performance Evaluation;
   • Torque-Speed Characteristics;
   • Motor Starting and Voltage Drop;
   • Variable Frequency Drive;
   • Testing, Specification and Applications Guidelines.
3) 3-Phase Fault (Short-Circuit) Calculations
   • Per-Unit Methods of Calculations;
   • Sub-transient Reactance;
   • Source Reactance;
   • Shortcut Methods of Calculations for Industrial Power Systems;
   • Fault Current Distributions.
4) Design of an Industrial Power Distribution System and Problems
   • Selection of Breakers and Switchgears;
   • Motor Control Center - Specification and Evaluation;
   • System Grounding;
   • Reliability, Safety and Design;
   • Quick Cost Estimate.
5) Protection Design Philosophy
6) Emergency Power and Uninterruptible Power Supply (UPS)
7) Design Problems: Simplified Calculations, Guidelines and Techniques

Day (Part) 3: (When Applicable)

1) Recap of Days 1 and 2, Questions and Answers
2) Power Systems Protection:
   • Symmetrical Components and Unsymmetrical Faults;
   • Instrument Transformers;
   • Grounding of Power Systems and Ground Fault Protection;
   • Utility – Industry Interface;
   • Design of Protection Scheme;
   • Power Systems Protection:
     o Transformer
     o Induction Motor
     o Distribution Feeder
3) Step-by-Step Procedure in Protection Coordination and Design
4) Case Studies and Design Problems
Dr. P.K. Sen, PE, Fellow IEEE has over 45 years of combined teaching, administrative, research, and consulting engineering experience. Prior to joining Colorado School of Mines, Golden, Colorado in 2000, Dr. Sen taught for 21 years at the University of Colorado, Colorado. His industrial experience includes power plants and substation engineering design, system & feasibility studies, protection and relaying, training technical personnel at all level and solving various aspects of power systems engineering application problems. He has published over 140 technical papers on a variety of subjects related to Power Systems, Protection / and Relaying, Electric Machines, Renewable Energy and Energy Policy, Power Quality, Engineering Education and Arc Flash and Safety. Dr. Sen has supervised and mentored over 150 graduate students (including non-traditional students, and practicing engineers from the Utility Industries, Rural Electric Company’s, Consulting Engineers, and others). He is an IEEE Fellow and a Registered Professional Engineer (Electrical) in the State of Colorado. Currently Dr. Sen is a Professor of Electrical Engineering and the Site Director for the (Originally NSF funded) Industry University Cooperative Research Center (IUCRC) Power Systems Engineering Research Center (www.pserc.org) at Colorado School of Mines, Golden, Colorado. His current research interests include application problems (safety, protection, equipment life, energy economics, asset management and policy issues, etc.) in power systems engineering, renewable energy applications and distributed generation, and engineering education. Dr. Sen is a very active member of a number of Professional Societies including IEEE PES & IAS, Rocky Mountain Electrical League (RMEL) and has been instrumental in providing seminars, short courses, conduct workshops, and provide training for technical personnel in the Rocky Mountain Region and nationwide (USA) and internationally for the past 34 years.

Dr. Sen is known in the industry, locally, nationally and internationally for providing educational opportunities for practicing engineers at all level, and for both undergraduate and graduate students. He is an inspiring and prolific teacher with passion. He has authored numerous prize winning papers at the IEEE Conferences and IAS Magazine.
Design of Industrial Power Distribution Systems: Shortcut Methods, Quick Estimation and Application Guidelines

Presentation Outline

Part 1

- Introduction, and Scope of Electric Power Distribution Systems Engineering

- Characteristics of Power Distribution Systems: Utility and Industrial/Commercial Users Perspective

- Power System Fundamentals & Design Tools:
  - (Review) 1-Phase and 3-Phase Power
  - (Review) Power, Reactive Power, Power Factor
  - Power Triangle
  - Losses and Efficiency

- Selection of Voltage

- Power Factor Correction

- Percentage Impedance, Voltage Regulation and % Voltage Drop

- Understanding Electricity Bill

- Transformer
  - Procurement and Specification Writing
  - Losses and Efficiency
  - Bid Evaluation
  - Application Guidelines
  - Protection Basics

- Quick Cost Estimate

- Design Problems: Transformer Sizing, Power Factor Correction, Voltage Drop and Voltage Regulation
Design of Industrial Power Distribution Systems:
Shortcut Methods, Quick Estimation and Application Guidelines

Presentation Outline

Part 2

- Induction Motor: Characteristics, Performance Evaluation, Specification
- Quick and Simplified 3-Phase Short Circuit (Hand) Calculations for Radial System
  - Volt-Ampere Method
  - Per-Unit Method
- Power System Grounding
- Application Guidelines -
  - Motor Starting and Voltage Drop
  - Sizing Transformers
  - Capacitor Selection
  - Simplified Transformer Protection Considerations
- Conclusions, Questions and Answers
Design of Industrial Power Distribution Systems: Shortcut Methods, Quick Estimation and Application Guidelines

Presentation Outline
Part 3

1) Recap of Day 1 and 2, Questions and Answers

2) Power Systems Protection
   • Symmetrical Components and Unsymmetrical Faults;
   • Instrument Transformers;
   • Grounding of Power Systems and Ground Fault Protection;
   • Utility – Industry Interface;
   • Design of Protection Scheme;
   • Power Systems Protection:
     o Transformer
     o Induction Motor
     o Distribution Feeder

3) Step-by-Step Procedure in Protection Coordination and Design;

4) Case Studies

Problems and Solutions!!
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Note: Word of Caution!!

The following lecture notes, numerical examples and problems are designed for the US Electric Power Systems which is 60Hz system (compared to 50Hz system in India). The voltages are also different, as an example 12.47kV or 13.8kV is used as the primary distribution voltage in USA (compared to 11kV in India). The Low Voltage (LV) induction motors are designed at 3-phase, 460V, 60Hz connected to the 480V Bus (compared to 3-phase, 400V, 50Hz). However, references will be made to these values and differences during the entire workshop.

Fundamentals of Electric Power System
# Commonly Used - SI Systems (and Practical) Units

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (I)</td>
<td>Ampere</td>
<td>A</td>
</tr>
<tr>
<td>Voltage or (V or E)</td>
<td>Volts</td>
<td>V</td>
</tr>
<tr>
<td>Potential Difference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work or (W)</td>
<td>Newton.meter</td>
<td>N.m</td>
</tr>
<tr>
<td>Energy (E)</td>
<td>Joules</td>
<td>J</td>
</tr>
<tr>
<td></td>
<td>Watt.sec</td>
<td>W.s or kWh</td>
</tr>
<tr>
<td>Power (P)(^1)</td>
<td>Watt</td>
<td>W, kW, MW</td>
</tr>
</tbody>
</table>

\[
P = \text{Rate of Work Done}
\]
\[
(1\text{HP} = 746\text{W})
\]
\[
= \text{Force x Velocity (Translation)}
\]
\[
= \text{Torque x Angular Velocity (Rotation)}
\]
\[
P = VI \quad (\text{DC System})
\]
\[
P = VI \cos \theta \quad (1\text{-Phase AC System})
\]

| Apparent Power (S)         | Volt.Ampere | VA, kVA, MVA |
|                           |             |              |
| Reactive Power (Q)         | VAmperes    | VAR, kVAR, MVAR |
|                           |             |              |
| Resistance (R)             | Ohm         | \Omega        |
| Reactance (X)              |             |              |
| Impedance (Z)              |             |              |
| Inductance (L)             | Henry       | H, mH (mili-Henry) |
| Capacitance (C)            | Farad       | F, \mu F (micro-Farad) |
| Flux (\phi)                | Weber       | Wb            |
| Flux Density (B)            | Weber/m^2   | T ( = Tesla)  |

\(^1\) It is still very common to use the unit HP instead of W, which is the standard SI unit.
Figure 1. Basic Structure of Electric Power Grid and Power System
Basic Power Systems (US):

1. Large Power **Generation**
   (4kV – 25kV) say, between 1MVA - 1,000MVA

2. **Transmission**: Primary and Secondary
   
   Primary and Bulk Power:
   - 161kV (not used any longer);
   - 230kV, 345kV, 500kV and 765kV;
   - 1,000kV or 1,200kV (future) or (more!) HVDC
   
   Secondary (also referred as “Transmission” voltage by smaller utilities):
   - 69kV, 115kV, 138kV (not very common anymore)

3. **Distribution**: Primary and Secondary
   
   Primary:
   - 25kV, 34.5kV, 46kV, 69kV and 115kV (primary distribution and secondary transmission overlaps)
   
   Secondary (or Medium Voltage: “MV”):
   - 4.16kV, 6.9kV, 12.47kV, and 13.8kV

4. **Utilization or Customer Use**
   
   Medium Voltage (MV):
   - 2.3kV (not used anymore),
   - 4.16kV, 6.9kV, 12.47kV and 13.8kV
   
   Low Voltage (LV):
   - 3-Phase, 4-Wire:
     - 120V (LN)/208V (LL),
     - 277V (LN)/480V (LL)
   - 1-Phase, 3-Wire: 120-240V
## Low Voltage (Utilization)

120/240 V, 1-Phase, 3-Wire

3-Phase, 4-Wire
120 V (LN)/208 V (LL)
277 V (LN)/480 V (LL)

### Medium Voltage (Distribution)

3-Phase (LL)
- 2.44 kV
- 4.16 kV
- 6.9 kV
- 12.47 kV**
- 13.8 kV

### Primary (Distribution) Voltage (LL)

- 25 kV
- 34.5 kV
- 44 kV

### Sub-Transmission Voltage (HV) (LL)

- 69 kV**
- 115 kV**
- 138 kV

### Extra High Voltage (EHV) (Bulk Power)

- 161 kV
- 230 kV**
- 345 kV**

### Ultra High Voltage (UHV) (Bulk Power)

- 500 kV**
- 765 kV

---

2 Very popular voltages in USA
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### Comparison of Voltages Between USA (60Hz) and India (50Hz)

<table>
<thead>
<tr>
<th>Voltages in USA (V, kV)</th>
<th>Voltages in India (V,kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120V</td>
<td>240V</td>
</tr>
<tr>
<td>480V</td>
<td>400V</td>
</tr>
<tr>
<td>4.16kV</td>
<td></td>
</tr>
<tr>
<td>6.9kV</td>
<td>6.6kV</td>
</tr>
<tr>
<td>12.47kV, 13.8kV</td>
<td>11kV</td>
</tr>
<tr>
<td>25kV</td>
<td>22kV</td>
</tr>
<tr>
<td>34.5kV</td>
<td>33kV</td>
</tr>
<tr>
<td>69kV</td>
<td>66kV</td>
</tr>
<tr>
<td>115kV</td>
<td>110kV</td>
</tr>
<tr>
<td>230kV</td>
<td>220kV</td>
</tr>
<tr>
<td>345kV, 500kV</td>
<td>400kV</td>
</tr>
</tbody>
</table>
Functional Classification of Power Systems:
Major Power Systems Elements:

- Generators and Bus Ducts
- Power Transformers
- Transmission and Distribution Lines (Overhead and Underground)
- Capacitors, Reactors, Voltage Regulators and Static VAR Compensators
- Circuit Breakers, Reclosers and Sectionalizers
- Disconnecting Devices: Motor Operating, Gang Operated, etc.
- Motors and Motor Starters
- Unit Substations
- Motor Control Centers (MCCs)
- Power Distribution Panel
- Instrument Transformers (Current “CT” and Potential “PT”)
- Protective Devices, Relays
- SCADA, Control, Monitoring, etc.

Power Systems Elements (Typical) in Different Plants:

1.0 Industrial Power Systems: Transformers; MV and LV Circuit Breakers; Disconnecting Devices; Motors and Drives; MCCs; Capacitors; Protection, Control and Monitoring Devices; Panels, etc.

2.0 Commercial Power Systems: Transformers; Bus Duct or Risers; LV Motors, Starters, and MCCs; LV Circuit Breakers; Power panels; Unit Substations; Protection, Control and Monitoring Devices, etc.

Note: Not included in this category, Power Generation Plant, Substation and Switching Station, Large Heavy Industrial Plant (Steel Mill, Petroleum and Chemical Plant), Wind Farms, etc.
Figure 2. Basic Scope of Power Distribution System and Interface with Utility
Questions Routinely Asked??

(1) What is the Best Plant Distribution Voltage?
(2) What is the Transformer Size?
(3) How can we Reduce the Electricity Bill?
(4) How much is it going to Cost for the Electrical Design?

Short Questions!!! Let’s Discuss!!

(1) You are the “electrical” engineer in-charge of the design and procurement, production, operation and maintenance, testing, etc. of a large Chemical Plant. There are a large number of low voltage motors ranging from 1HP\(^3\) – 300HP rating. You noticed that the low voltage motors in the plant are routinely failing at an alarming rate. So much so that you are losing millions of dollars for loss in production. Your General Manager (GM) is not too thrilled!! You decided do to some internal investigation and did some quick and simple testing. The voltmeter readings in a 400V switchgear (and MCC) are consistently below (say, 380V range) the nominal voltage of 400 V and there is a considerable amount of discrepancy (say over 7%) in the three line voltages. Would you worry about it? In your estimate, is it a “Power Quality” problem? Explain why or why not? You called your favorite expert “test” engineering firm “P.K. Sen Testing Company” who is charging you a lot of money. What type of conversations are you planning to have? Could you think of some possible solutions and mitigation techniques? Discuss!!

(2) You have a “Neutral Conductor” connected to 3-phase, 400V “Star” connected system (continuous current rating of 1.2kA). An ammeter connected to the neutral circuit reads a pretty substantial value (say, 400 A). Explain how such a high value of current (the possibility) in the neutral conductor. Do you see any problem? Discuss in detail.

\(^3\) HP is still routinely used as the unit of the motor output. Standard SI unit is W.
“System Studies” Performed Routinely in Power Distribution System

(1) Check (or Select) Major Equipment Rating -
   ▪ Normal
   ▪ Abnormal (Fault) Operating Conditions
(2) Power-Flow Studies and Power Factor Correction
(3) 3-Phase Short-Circuit Studies (or Fault Calculations)
(4) Unbalanced Fault Calculations (Symmetrical Components)
(5) Protection Coordination and Relay Settings Studies
(6) Motor Starting and Voltage Drop
(7) System Grounding and Ground Fault Protection
(8) Other Studies -
   ▪ Outage and Power Restoration
   ▪ Reliability
   ▪ Lighting Design
   ▪ Energy Management Study
   ▪ Harmonic Analysis and Power Quality
   ▪ Transient Studies
   ▪ Voltage Collapse and Transient Stability Studies
   ▪ Rate Structure, etc.

Computer Programs Vs. "Quick Estimate - Hand Calculations"
"Preliminary Design"
Basic Tools in Design!!
1-Phase Circuit

Please see “Appendix A” for Additional Information
Complex Power and Power Triangle:

In electric power system studies, the so-called “Complex Power” constitutes a very simple and extremely valuable computational aid. Mathematically, Complex Power is defined as:

\[ S = \vec{V} \cdot \vec{I}^* = P + jQ \]  
\[ = |V| \angle 0^\circ \cdot |I| \angle +\phi, \text{ taking the voltage as reference} \]
\[ = |V| \cdot |I| \angle +\phi \]
\[ S = |V| |I| \cos \phi + j |V| |I| \sin \phi \]  

Complex Power (S) can be depicted in a complex plane (as a Power Triangle) as shown in Figure 3. The real (P), reactive (Q) and the apparent power (S) corresponds to the three sides of a right-angle triangle, referred as “Power Triangle”. This is used extensively and quite conveniently in solving many power systems problems related to “Power Factor Improvement” as will be seen later.

![Power Triangle](image)

Figure 3. Power Triangle

The trigonometric relationships between P, Q and S are simple but very useful. Complex Power or (Power Triangle) also fixes the convention\(^4\) of reactive power:

For any electrical load:
(+) Q “lagging” VAR (or inductive load), and
(-) Q leading VAR (or capacitive load).

**In other words, it is easy to remember, inductive load absorbs (needs) VAR, while a capacitive load generates (deliver) VAR.**

\[ P = S \cos \phi \]  
\[ Q = S \sin \phi = P \tan \phi \]  

\(^4\) Will be discussed in the class.
Power Factor, Reactive Power Compensation
Power factor Improvement

Fundamental:

Power Factor (Cos $\phi$) = P/S
Where, Power factor Angle ($\phi$)$^5$ is the angle between the Voltage and Current or between the Power and Apparent Power.

Lagging Power Factor: Current lags the voltage. They are “Inductive” loads, and “absorbs” reactive (or lagging) VAR. (e.g. Induction Motor).

Leading Power Factor: Current leads the voltage. It is “Capacitive” load, and “generates” reactive power. (e.g., Capacitor).

Ideal and Most Desirable Condition:
Power Factor = 1.00
(Net) Reactive Power (Q) = 0.00
Power Factor Angle ($\phi$) = 0°

Easiest way to calculate “Power Factor Improvement Problems” is by using phasor diagram and “Power Triangle (P,Q, and S)” and applying simple trigonometric relationships.

Benefits of Power Factor Improvement:

1) Lower Purchase Power Costs$^6$, if the utility enforces a “Power Factor Clause.”
2) Release of System Electrical Capacity allows expansion without replacement of equipment like transformers, cables, etc.
3) Improve Voltage Regulation or Reduce the Voltage Drop
4) Lower System Losses

$^5$ Sometimes $\theta$ has been used also.
$^6$ Will be discussed later
Power Factor Improvement

Voltage-Current (V-I) Phasor Diagram

- Typical Overall Plant Power Factor after Compensation is ≈ 0.95 lag
- Typical Plant Power Factor before Compensation is ≈ 0.8 - 0.85 lag

- Release System Capacity
- Smaller Equipment Rating
- Reduced Energy Loss
- Lower Purchased Price and Cost Savings
- Improved Voltage Regulation

Power Triangle
Design Considerations of Reactive Power Supply

The reactive power compensation should in general be installed as close to the load as practical to get the highest benefit. The following illustration shows four possible capacitor locations in an industrial plants. The most desirable location is $C_1$ followed by $C_2$, $C_3$ and $C_4$.

Economics must be considered when determining the location and size. Cost should also include the switching device. Study carefully the option of distributed vs. lumped capacitors.

The expression "release of capacity" means that as the power factor is improved, the current in the existing system will be reduced, permitting additional load to be served by the same system. Equipment such as transformers, cables, generators, buses, etc. may not have to be replaced or overloaded.

"Voltage improvement" or better voltage regulation is an additional benefit of improved power factor operation. This can be very easily explained using the following phasor diagram and a simple expression.

Possible Shunt Capacitor Location

![Diagram showing possible shunt capacitor locations](image)
Capacity Release by Power Factor Improvement

\[ Q_0 \Rightarrow \text{load in MVA} \]

Power Factor = \( \cos \theta_1 \) (initial poor p.f.)

\[ AB \Rightarrow \text{load MVAR (lag)} \]

\[ BC \Rightarrow \text{Capacitor MVARC (lead), } Q_c \]

\( \cos \theta_2 = \text{New Improved Power Factor} \)

Released Capacity,

\[ T_c = \text{MVA} \left[ \frac{\text{MVARC} \cdot \sin \theta_1}{\text{MVA}} - 1 + \sqrt{1 - (\cos \theta_1)^2 \left(\frac{\text{MVARC}}{\text{MVA}}\right)^2} \right] \]
Practice Problems: No. 1
Sharpen Your Knowledge

Problem No. 1
In a 1-phase power measurement experiment, the meters read 120V, 4A, and 400W. The load is known to be inductive. Calculate the series equivalent impedance \((R_s + j X_s)\) or the parallel values \((R_p || j X_p)\)

**Ans:** (a) \(R_s + j X_s = 25 + j 16.6\ \Omega\), (b) \(R_p = 36\ \Omega\) and \(X_p = 54.3\ \Omega\)

Problem No. 2
A coil with an impedance of 64.1\(\angle 51.4^\circ\)\(\Omega\) is connected in series with a resistance of 22.5\(\Omega\). The combination is supplied by a 120V source. Determine the coil and resistor voltages and the overall power factor. Draw the phasor diagram for these voltages.

**Ans.** \(V_R = 33.8V\); \(V_C = 96.2V\); 0.78 (lag)

Problem No. 3
A coil is placed in series with a resistance of 30\(\Omega\). When the combination is connected to a 220V, 60Hz source, the current is 4.2A and the power drawn by the circuit is 670W. Determine the circuit power factor and draw the impedance phasor and power triangle diagrams. Also calculate the coil impedance, coil inductance and voltage across the coil.

**Ans.** 0.73 (lag)

Problem No. 4
In a 1-phase circuit calculation, the voltage and current waves are given by the following equations: \(v(t) = 141.4 \sin (377t + 10^\circ)\)\(V\) and \(i(t) = 7.07 \sin (377t – 20^\circ)\)\(A\), respectively. Sketch the waves and draw the corresponding phasor diagrams. Calculate the power factor, (real) power (\(P\)), reactive power (\(Q\)) and the apparent power (\(S\)). Also find the equivalent impedance, and the corresponding real (resistive) and imaginary (reactive) components. Identify whether the reactive part is an inductor or a capacitor, and find the corresponding inductance or capacitance values.

**Ans.** 0.866 (lag)
Checking Concepts and Basics
Brain Tinker - (Practice) Quiz No. 1

1. **Circle all the Appropriate Answers**:

   - **Unit of (Real) Power**: kVAR, kW, N.m/s, kVA, J/s, HP
   - **Induction Motor Power Factor**: lagging, unity, leading
   - **Unit of Energy**: rad/sec, kWh, N (Newton), N.m, J
   - **Unit of Impedance**: Ohm, Henry, Farad, Hertz, Siemens
   - **Typical Voltage for a 100HP Motor**: 120V, 11.0kV, 400V, 66kV

2. **Fill in the Blanks**:

   - For a pure inductance the current _____________ the voltage by 90°.
   - Power Factor is defined as the ___________ of the angle between voltage and current.
   - Power output of a 2,000kVA, 0.8 power factor (lag) load is __________ kW.
   - In an industrial plant, power factor is improved by adding ___________ to the system.
   - The line-to-neutral voltage in a 400V, 3-phase, 4-wire power system is __________ V.

3. **Enumerate the Benefits of “Power Factor Improvement” in power system**:
   
   a.
   b.
   c.
   d.
   e.

4. **Write the time domain and phasor equations of the following two sine waves. Draw the phasor quantities. Also calculate the frequency in Hz, power factor, power, reactive power and the apparent power.**
3-Phase Circuit

&

Power Measurements

Please see “Appendix B” for Additional Information
3-Phase Circuit Calculations:

\[ P_{3\phi} = \sqrt{3} V_l I_l \cos \theta \quad (W, \text{kW, MW}) \quad (1) \]
\[ Q_{3\phi} = \sqrt{3} V_l I_l \sin \theta \quad (\text{VAR, kVAR, MVAR}) \quad (2) \]
\[ S_{3\phi} = P_{3\phi} \pm jQ_{3\phi} \quad (\text{VA, kVA, MVA}) \quad (3) \]
\[ S_{3\phi} = \sqrt{P_{3\phi}^2 + Q_{3\phi}^2} \quad (4) \]

Where,
- \( V_l \) = Line Voltage in Volts (V)
- \( I_l \) = Line Current in Amps (A)
- \( \cos \theta \) = Power Factor
- \( \theta \) = Phase Angle Between the Phase-Voltage and Phase-Current

Depending on the connection (and more!!), it can be shown (from the phasor diagram) that in a 2-wattmeter method of 3-phase power measurements the, two wattmeter reads the following quantities:

One wattmeter reads: \( W_1 = V_l I_l \cos (\theta + 30^\circ) \) \quad (5)
The Second one reads: \( W_2 = V_l I_l \cos (\theta - 30^\circ) \) \quad (6)

From algebraic manipulation, it can be shown that:

\[ P_{3\phi} = W_1 + W_2 = \sqrt{3} V_l I_l \cos \theta \quad (7) \]

Also, \( \tan \theta = \sqrt{3} \left[ \frac{W_1 - W_2}{W_1 + W_2} \right] \) \quad (8)

Hence, the power factor \( \cos \theta \) of the load can be calculated. In order to find out, whether the load is "inductive" or "capacitive," this is tricky and requires the full knowledge of the phasor diagram, and which wattmeter is designated as \( W_1 \) or \( W_2 \). Also in a two-wattmeter power measurements, wattmeter readings could be positive or negative. One must always carry the sign while performing calculations. Please read any book that describes this in detail (This is beyond the scope of this note and lecture.)

---

7 Beyond the scope of this presentation

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3-Phase Motor Load (US System)
(Examples)

(1) Medium Voltage (MV) Motor:

\[
P_t = \sqrt{3} V_L I_L \cos \theta
\]

\[
1 \text{ HP} = 746 \text{ W} = 0.746 \text{ kW}
\]

\[
P_0 = 2,000 \times 0.746 = 1,492 \text{ kW}
\]

\[
P_t = 1,604.3 \text{ kW}
\]

Efficiency \(\eta = P_t/P_0\) (say 0.93)

Power Factor = 0.93 (lag)

\[
I_L = \frac{P_t}{\sqrt{3} V_L \cos \theta} = 249 \text{ A}
\]

Rounded Current

(2) Low Voltage (LV) Motor:
Power Factor Improvement Capacitor Calculations

\[
P_t = \frac{300 \times 0.746}{0.88} = 254.3 \text{ kW}
\]

\[
Q_C = 53.9 \text{ kVAR}
\]
## Typical (US) Motor Data Information

<table>
<thead>
<tr>
<th>Induction Motor (HP)</th>
<th>Bus Voltage (kV)</th>
<th>Rated Motor Voltage (kV)</th>
<th>Typical Efficiency and Power Factor (lag): Same Value (Without PF Improvement Capacitor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less Than 1 HP (Fractional HP - FHP)</td>
<td>1-Ph, 120 V</td>
<td>1-Ph, 460 V</td>
<td>0.6-0.75 (lag)</td>
</tr>
<tr>
<td></td>
<td>1-Ph, 240 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-Ph, 208 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less Than 1 HP</td>
<td>3-Ph, 480 V</td>
<td>3-Ph, 460 V</td>
<td>≈ 0.75 (lag)</td>
</tr>
<tr>
<td>1 - 400 HP</td>
<td>3-Ph, 480 V</td>
<td>3-Ph, 460 V</td>
<td>0.82 - 0.9 (lag)</td>
</tr>
<tr>
<td>300 – 3,000 HP</td>
<td>3-Ph, 4.16 kV</td>
<td>3-Ph, 4.0 kV</td>
<td>0.85 - 0.94 (lag) or Higher!!</td>
</tr>
<tr>
<td>2,000 – 8,000 HP</td>
<td>3-Ph, 6.9 kV</td>
<td>3-Ph, 6.6 kV</td>
<td>0.9 - 0.95 (lag) or Higher!!</td>
</tr>
<tr>
<td>6,000 HP - Above</td>
<td>3-Ph, 13.8 kV</td>
<td>3-Ph, 13.2 kV</td>
<td>0.9 - 0.96 (lag) or Higher!!!</td>
</tr>
</tbody>
</table>

Note:

Quite often, power factor improvement capacitors are added at the motor terminals. Power Factor is improved typically to about 0.95-0.96 (lag) at full-load operating point.

---

8 See the overlap.
Selection of Voltage (US)

For “Distribution Systems” most commonly used voltages are:

**Medium Voltages:**
(a) 13.8 kV, 3-Phase, 3-Wire (or 4-Wire)
(b) 12.47 kV (LL)/7.2 kV (LN), 3-Phase, 3-Wire (or 4-Wire)
(c) 6.9 kV, 3-Phase, 3-Wire (or 4-Wire)
(d) 4.16 kV (LL)/2.3 kV(LN), 3-Phase, 3-Wire (or 4-Wire)

**Low Voltages:**
(a) 480 V Grd (Y) / 277 V, 3-Phase, 4-Wire (Wye Connected)
(b) 480 V or 240 V, 3-Phase, 3-Wire (Delta Connected)
(c) 240 V / 120 V, 3-Phase, 4-Wire (Delta Connected)
(d) 208 V Grd (Y) / 120 V, 3-Phase, 4-Wire (Wye Connected)
(e) 120 V / 240 V, 1-Phase, 3-Wire (Mid-Point Grounded)
Selection of “Plant” Distribution Voltage
Major Considerations

- Availability of Utility Voltage
- Utility Interconnection Requirements and Rate Structures
- Largest “Single” Motor Load
- Acceptable % Voltage Regulation, Voltage Drop or Power Quality
- Equipment Rating Limitations
  - Short Circuit Rating
  - Motor Starting Voltage Drop
- Cost
- Operation and Maintenance
- Etc.
Practice Problems: No. 2
Sharpen Your Knowledge

Problem No. 1:
In a single phase power measurement for an inductive load, the voltmeter reads 120V (rms), the ammeter reading is 5A (rms), and the wattmeter reading is 480W. Calculate the power factor, and the circuit elements. If the frequency is 60 Hz, calculate the inductance of the circuit. Also draw the power triangle, impedance diagram, and the voltage-current phase relationship.

Ans. Power Factor = 0.8 (lag); Z = \[24\angle36.8^\circ\] \[\Omega\] = 19.2+j 14.4 \[\Omega\]; L= 0.038 H

Problem No. 2
A large industrial plant receives 3-phase electric power from the local utility. The following loads are being fed in the plant at 11.0 kV (line) / 6.35 kV (phase).

(a) 1.2 + j 1.2 MVA,
(b) 2.0 MW at 0.8 (lag) power factor,
(c) 800 kW of pure heating and lighting (negligible reactive power) load, and
(d) A number of induction motors: power output total of 3,000 HP, with a composite efficiency of 0.85 and power factor of 0.88 (lag) respectively.

Calculate the total (composite) load power factor, power, reactive power and apparent power. Also calculate the full-load current. If you want to improve the plant power factor to 0.95 lag, calculate the capacitive VAR requirements. Draw the simplified one-line diagram and phasor diagram (power triangle).

Ans. (Selected) Power = 6.63 MW; Power Factor = 0.85 (lag); \[Q_C = 1.94 \text{ MVAR}\]

Problem No. 3
The following loads are being fed from a 3-phase, 4.16 kV (US) system. Calculate the total line current, power factor, power, reactive power and apparent power.

(a) 2 MVA at 0.8 lag power factor,
(b) 1 MW at 0.9 lag power factor, and
(c) 700 kW + j 700 kVAR.

It is proposed that the power factor of the combined load be improved to 0.95 lag. Calculate the reactive power compensation required. Draw the phasor diagram.

Ans: \[I = 565 \text{ A}; P = 3.3 \text{ MW}; Q = 2.384 \text{ MVAR}; Cos \theta = 0.81 \text{ (lag)}\]
\[S = 4.071 \text{ MVA}\]
Checking Concepts and Basics
Brain Tinker - (Practice) Quiz No. 2

1) Determine the current drawn from a 3-phase, 400 V line by a 3-phase 10 HP motor operating at full load, 85% efficiency, and 80% power factor lagging. Find the values of P and Q drawn from the line.
   Ans. 15.84 A, 8.8k W, 6580 VAR

2) A 3-phase load draws 200 kW at a power factor of 0.707 lagging from a 400V line. In parallel with this load is a 3-phase capacitor bank which draws 50kVA. Find the total current and resultant power factor.
   Ans. 360.8 A, 0.8 (lag)

3) A 3-phase motor draws 10 kVA at 0.6 power factor lagging from a 220 V source. Determine the kVA rating of capacitors to make the combined power factor 0.85 lagging, and determine the line current before and after the capacitors are added.
   Ans. 18.5 A, 4.28 kVAR (Cap)
Understanding Electrical Load Requirements
“Load Profile & Load Study“

(Typical) Daily Load Curve

- Connected Load
- Maximum Demand
- Demand Factor
- Load Factor
- Diversity Factor
- Coincidence Factor
- Plant Utilization Factor
Load Characteristics

Types of Loads:
- Residential
- Commercial
- Industrial

Connected Load:
The connected load is the sum of the continuous ratings of the load consuming apparatus connected to the system or any part.
**Units:** kW (P), kVA (S), kVAR (Q)

Demand:
The demand of an installation or system is the load at receiving terminals averaged over a specified interval time (usually 15 mins.).
**Units:** kW (P), kVA (S), kVAR (Q)

Maximum Demand:
The maximum demand of an installation or system is the greatest of all demands which have occurred during the specified period of time (15 mins. duration).
**Units:** kW, kVA, kVAR

Demand Factor:
The demand factor is the ratio of the maximum demand of a system to the total connected load of the system. **Note:** The demand factor of a part of the system may be similarly defined applicable to that part only.
**Unit:** None

Utilization Factor:
The utilization factor is the ratio of the maximum demand of a system to the rated “capacity” of the system.
**Unit:** None

Load Factor:
The load factor is the ratio of the average load over a designated period of time to the peak load occurring in that period.
**Unit:** None
**Diversity Factor, Coincidence Factor and Load Diversity:**

The “diversity factor” is the ratio of the sum of the individual maximum demands of the various subdivisions of a system to the maximum demand of the whole (composite) system. Usually, this factor is always greater than or equal to (≥) 1.0. Diversity Factor of 1.0 means, the maximum demand of the individual (or sub-groups) loads are all happening at the same time. This is a measure of combined maximum demand of a composite load compared to the individual maximum demands.

**Unit:** None

Mathematically,

\[
F_D = \frac{D_1 + D_2 + D_3 + \ldots + D_n}{D_1 + 2 + 3 + \ldots + n} = \frac{\sum D_s}{s = 1} = \frac{1}{F_c}
\]

Where, \( F_c \) is called the “Coincidence Factor”.

“Coincidence Factor: is the reciprocal of the “diversity factor”.

**Unit:** None

“Load Diversity” is the difference between the sum of the peaks and the peak of the combined load.

**Unit:** kW

Mathematically,

\[
\text{Load Diversity} = (D_1 + D_2 + D_3 + \ldots + D_n) - (D_{1+2+3+\ldots+n}) = \sum_{s=1}^{n} D_s - (D_{1+2+3+\ldots+n})
\]

Where, \( D_1, D_2, \ldots \ldots D_n \) are the maximum demand of load nos. 1, 2, etc. and \( (D_{1+2+\ldots+n}) \) is the maximum demand of the group of loads.

**Loss Factor:**

The loss factor is the ratio of the average power loss to the peak load power loss, during a specified period of time.

**Unit:** None
Checking Concepts and Basics
Brain Tinker - (Practice) Quiz No. 3

Fill in the blanks and/or discuss very briefly (one or two short sentences, precise). Draw any sketch, phasor diagram, etc., if appropriate.

1) Most commonly used utility distribution voltage(s) (kV) _______________.
   Future trends in utility distribution voltage(s) ___________________.

2) Define Complex Power (S) : ____________________.
   Explain why we use this concept using the examples of an “inductor” and a “capacitor”.

3) What is a “synchronous condenser”? _______________________________

4) What is “shunt compensation”? Discuss.

4) Typical Induction Motor Voltage:
   100kW _______ 500kW _______ 6,000kW _______ 20,000kW _______

6) Name the Major Factors that determine the Cost of Electricity
   __________________________________________________________
   __________________________________________________________

7) Name the different losses in a Power Transformer and discuss whether they are constant or variable.

8) What is a “Radial (System) Feeder”?
Sample Design Problems
Power Factor Improvement & Transformer Sizing
(Design) Problem No. 1

A typical distribution substation transformer rated at 110kV (Grounded Wye\(^9\)) - 11.0kV (Grounded Wye) is supplying the following four feeder of (composite) loads as specified. Calculate (a) total power, (b) reactive power, (c) apparent power, (d) overall power factor, (e) current on the low side, (f) current on the high side of the transformer. Select a proper size of the transformer. If the overall power factor has to be improved to 0.95 (lag), calculate the amount of Capacitor VAR requirement. Also calculate the transformer Released Capacity for the improved power factor condition. Find a suitable overhead conductor size for both the high side and the low side of the substation. (Partial Solution)

(i) 5 MVA @ 0.8 (lag) power factors
(ii) 2 MW @ 0.9 (lag) power factors
(iii) Pure Heating Load of 1 MW, and
(iv) 707 kW + j 707 kVAR

Load (i) \(\Rightarrow 4.0 + j 3.0\) MVA
Load (ii) \(\Rightarrow 2.0 + j 0.97\) MVA
Load (iii) \(\Rightarrow 1.0 + j 0.0\) MVA
Load (iv) \(\Rightarrow 0.7 + j 0.7\) MVA
Total Load \((S_t)\) \(\Rightarrow 7.7 + j 4.67\) MVA
\(= 9.0 \angle 31.2^\circ\) MVA

Select a 10/12.5MVA (ONAN/ONFA)\(^{10}\) Transformer

(a) Total Power \((P_t) = 7.7\) MW
(b) Total Reactive Power \((Q_t) = 4.67\) MVAR (lag)
(c) Total Apparent Power \((S_t) = 9.0\) MVA
(d) Overall Power Factor \((\cos \theta_t) = \cos 31.2^\circ = 0.855\) (lag)

---

\(^9\) Also called “Star”
\(^{10}\) Will be discussed later
From simple geometry:

Power Factor Improvement Capacitor Rating \( (Q_C) \)

\[
P = P (\tan \theta_1 - \tan \theta_2)
= 7.7 (\tan 31.2^o - \tan 18.2^o)
= 2.14 \text{ MVAR}
\]

(Select: 2 MVAR Cap Bank!!)

Currents can be calculated by using the following equation:

Power \( (P_{3-Ph}) = \sqrt{3} V_1 I_1 \cos \theta \)

Algebraic summation of MVA loads will yield a higher transformer rating (typically 10-15% higher than actual demands).
Power Distribution Systems Engineering
Design Project No. 1

Instructions: Please work in a group of two or three.

A small industrial plant has the following loads:

i) Twenty (20), 200HP motors (only half of them are running at any given time).

ii) Ten (10), 50 HP motors (8 motors are running at the same time).

iii) 500 kW of heating and process loads.

iv) Two (2), 50 kVA lighting transformers, and

v) 100 HP of small (mostly fractional HP) motors.

You have been asked to perform a “preliminary conceptual design and feasibility study with cost estimate.” Design a simple power system, draw (neatly hand drawn) the one-line diagram, and calculate the transformer rating(s). Also provide an alternate design to choose from. The one-line diagram must include all the relevant information necessary to check the design feasibility. The plant receives power from a local utility at 22.0kV. Use reasonable future expansion plan, and diversity factor. Also utilize in your design a number of low-voltage MCC’s and lightning panels. Also provide a cost estimate\(^\text{11}\) for the entire project. Make any reasonable assumptions. Provide a list of questions, you may wish to ask and would like to know to refine your preliminary design at a later date.

\(^{11}\) Class participation
Voltage Drop and % Voltage Regulation Calculations

Short (Radial) Distribution Feeder, a Transformer or Combination

% Voltage Regulation

\[ \frac{|V_2|_{no\ load} - |V_2|_{load}}{|V_2|_{load}} \times 100 \]

Per-Phase or “Equivalent Y” Calculations

This is one of the most important calculations done in designing any electrical power system. Depending on the accuracy requirement and applications, and data availability, there are a number of different ways, one can calculate this. However, it is very important to know the limitations and accuracy of different techniques. Either per-unit methods or volt-ampere method could be utilized. It is very important to remember, the voltage drop calculations when done in volta-ampere method is always “per-phase”. However, on per-unit method of calculations, it really doesn’t matter.

\[
\overline{V_1} = \overline{V_2} + \overline{I} \cdot \overline{Z} = V_2 \angle 0^\circ + I \angle -\theta \cdot Z \angle \phi
\]
Approximate Voltage Drop,
\[ |\Delta V| \approx I R \cos \theta \pm I X \sin \theta \quad \text{(Volt/Phase)} \]

\[ \approx \frac{PR}{V} \pm \frac{QX}{V} \quad \text{(Volt/Phase)} \]

% Voltage Regulation

\[ |\Delta V| \]
\[ = \frac{---}{V_2 \text{ load}} \times 100 \]

\[ \approx [ (\%) \cos \theta \pm (\%) \sin \theta ] \cdot I_{pu} \quad \text{(Loading)} \]
(+) Lagging Power Factor
(-) Leading Power Factor
Voltage Drop Calculations
(Design) Problem No. 2

An 18km (~11.2mi), 60Hz single-circuit, 3-phase line is composed of “Partridge” conductors equilaterally spaced with 1.6m (~5.25ft) between centers. The line impedance is 0.3792 + j 0.6662 Ω/mile/phase. The line delivers 2.5MW at 11 kV to a balanced load. What must be the sending-end voltage and the corresponding voltage regulation when the power factor is (a) 80% lagging, (b) unity, and (c) 90% leading? Assume a wire temperature of 50°C. Verify your calculations by volt-amp method, per-unit method and graphically. Also check your answers using exact solution method and approximate method.

“Equivalent Y” Calculations

Z = (0.3792+j 0.6662) • 18 • 0.6214 Ω
= 8.57 ∠ 60.4° Ω
\[ V_1 = V_2 + I \cdot Z \]
\[ = 7,660 \angle 4.2^\circ \text{ V/phase} \]

\[ V_1 \text{ (line)} = \sqrt{3} \cdot 7,660 \text{ V} = 13,268 \text{ V (Exact Solution)} \]

**Approximate Solution:**

\[ |\Delta V| \approx I \cdot R \cos \theta + I \cdot X \sin \theta \]
\[ = 1,289.1 \text{ V/phase} \]

**Phasor Diagram (Graphical Solution)**

\[ V_2 \approx 6,351 + 1,289.1 \text{ V/phase} \]
\[ = 7,640.1 \text{ V/phase} \]

\[ V_1 \text{ (line)} = \sqrt{3} \cdot 7,640.1 = 13,232 \text{ V} \]
(Compare this number with the exact solution of 13,268 V)

\[ \% \text{ Difference (Error)} = 0.27\% \text{ (Negligible)} \]

**Line Losses**

\[ (3) \ I_1^2 \cdot (R) = 3 \cdot 164^2 \cdot 4.24 = 342 \text{ kW} \]

**Reactive Power Loss**

\[ (3) \ I_1^2 \cdot (X) = 3 \cdot 164^2 \cdot 7.45 = 601 \text{ kVAR} \]
\[ \text{Efficiency} = \frac{(2,500)}{(2,500 + 342)} \times 100\% \]

\[ = 88\% \]

\[ \% \text{ Voltage Regulation} = \frac{|\Delta V|}{V_2} \times 100 \]

\[ = \frac{1,289.1}{6,351} \times 100 \]

\[ = 20.3\% \]

\[ \text{Efficiency} = 88.0\% \]

\[ \% \text{ VR} = 20.3\% \]

\[ \textbf{Poor Design}!!! \]
Quick (Simplified) Estimation of Plant Load, Selection of Transformer Size, Simplified Calculations & More

Some simplified guidelines (at random order) and design procedures

- 1HP ≈ 1kVA for 400V Motor Loads.

- For large MV Motors, calculate the kVA input by using power factor and efficiency values. This will produce better and more realistic design (otherwise it will be over-designed). If efficiency and power factor values are not known, use a multiplier of 0.9. (As an example, a 2,000HP motor will draw at full-load approx. 0.9 x 2,000 = 1,800kVA load).

- 1 kW ≈ 1 kVA for Heating & Lighting Load (Power Factor = 1.0).

- Algebraic additions of kVA’s will result in conservative (higher) number for the Transformer Size, hence, the design. Typical error in calculations is within 10% or below. For quick estimate and “preliminary” design (conservative) this is fine.

- Neglect the value of resistance R for all simplified calculations (X/R Ratio ≥ 10), except for the loss evaluation, cost of energy calculations, efficiency evaluation, etc. where $ value and the loss value is involved.

- Value of (R) is important for the low voltage (220V and sometimes 400V) calculations. (X/R ratio is less than 1.0, means resistance value is higher than the reactance value)

- For the 400V Secondary Voltage systems, Transformer Ratings should be limited to approx. 2,000kVA (2,500 kVA max.) in order to limit the fault current on the LV side. (You will learn this in Part 2).
Identify the Largest (Single) Motor. For a typical 400V, 3-phase distribution system, motors rated up to 250kW (or 300HP range) and below will not normally produce unusually high voltage drop during starting (direct-on-line or full-voltage), provided the transformer size is about 5 times the motor kVA rating.

Quickly estimate the overall plant power factor of the composite load under normal running (operating) conditions. Do not ignore (or forget) the power factor improvement capacitors provided with each individual motors (when applied). Also make sure that you have considered the diversity factor, demand factor, load redundancy, standby motors, etc. Always consider the abnormal (worst) mode of operation before sizing the transformer.

Check the “Utility Power Factor Clause” and make a “Preliminary” decision whether you need to provide shunt compensation (power factor improvement capacitor) and the amount of kVAR (or MVAR). Also quickly identify the possible location(s) of the capacitors.

Based on load data, known operating procedures and requirements, and physical aspects of the design, typically draw two alternate designs. Please take into account any Emergency (or Standby) power requirements and the need for Uninterruptible Power Supply (UPS) system. Quite often this is not mentioned by the client.

Using the simplified formula, quickly estimate the % Voltage Drop through the transformer(s) and the secondary bus-voltage under normal operating conditions (with or without compensation). This is usually within 3-4%. If it is higher, you may have to change the design. Plan to adjust the “No-load” (or sometimes called “Off-load” or “De-energized”) tap changer (NLTC) (provided with the transformer at no additional cost, ± 2 x 2.5% is the normal or default values) to compensate for the voltage. This is the least expensive way to maintain the voltage and improve on voltage regulation.

Identify the largest motor on various busses (study), which could create potential voltage drop during full-voltage (or direct-on-line) starting. Also it

---

12 Common practice

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is very important, that you know the frequency of starting (like no. of starts/hr). We will discuss the “voltage flicker” problem in the class.

- In order to avoid excessive voltage drop during starting (direct-on-line or full-voltage starting), try to limit the rating of the largest single motor to about 20% (no more than 25%) of the transformer rating. Otherwise, you have to use “soft start” devices. They are not cheap!!

- Criteria (good and preferred design) used commonly in the industry limits the % (momentary) voltage drop during the largest motor starting to about 12%. Anything larger than that requires further understanding of the mechanical load, motor rotor and mechanical load inertia, calculations of time of acceleration, motor heating curve, and many more things. We will discuss this in the third day when we have the time.
Transformer

Please see “Appendix C” for Additional Information
Fig 2.1 Transformer Core Configuration
[Reference ANSI/IEEE Standard C57.105-1978]
Checking Concepts and Basics
Brain Tinker - (Practice) Quiz No. 4

1) Name the principal component parts of a (two-winding) transformer, and discuss the materials of construction.

2) Discuss the simple (input-output) power and flux (or MMF) balance relationships. [voltage ratio, current ratio and turns ratio relationship.] What is the difference between the voltage ratio and turns ratio in a 3-phase Wye (Star)-Delta Transformer?

3) Write Faraday’s Law and explain.

4) Write the equation for induced voltage (E) in a winding due to a sinusoidal (time varying) field.

5) What is the difference between the leakage flux and the mutual flux? Discuss the physical significance in applications.

6) Draw a simplified transformer equivalent circuit and discuss the physical significance of the key elements. Draw the most simplified equivalent circuit of a transformer. What is the efficiency of this model?

7) Enumerate the various losses in a transformer and discuss. Define transformer efficiency.

8) Draw a “typical” transformer efficiency curve and explain the design and the maximum efficiency point.

9) Why do you laminate the transformer core?

10) What does limit the transformer output?
Selection of Transformer Size
(Design) Problem No. 3

A single-phase source supplies power to the following three loads connected in parallel:

(a) 25kVA @ 0.8 lag power factor,
(b) an electric heater drawing 50A @ 200 V, and
(c) an ideal capacitor drawing 10kVA.

Draw power triangle of individual load. Also calculate the total power, reactive power, apparent power and power factor. If the load voltage is 200 V, calculate the total current. Also select a suitable size of a 1-phase transformer.

[Ans. 30kW, 5kVAR (lag), 0.986 (lag), 152.1A]
Typical Bus Arrangements

Figure 1
Simple radial System (Typical)

Figure 2
Expanded Radial System (Typical)
Comments:
Duplicate Feed for each Unisub
Normal & alternative source
Higher reliability
Little or no interruption cost
Higher cost

Figure 3
Primary Selective system (Typical)

Comments:
Primary selective
Fault isolation by sectionalizing
Costs less than Fig. 3

Figure 4
Primary Loop System (Typical)
Fig. 2: Simplest Form of Distribution Substations

Fig. 3: Alternate Subtransmission Supply

Fig. 4: Duplicate Supply to Eliminate Service Interruptions Due to Subtransmission Outages

Fig. 5: Spot-Network Type Distribution Substations

Fig. 6: Duplicate Transformers and Subtransmission Circuits

Fig. 7: Automatic Throwover Switching for Rapid Service Restoration

Fig. 8: Distribution Substations with Elaborated Busing Arrangements

Ref: Westinghouse, "Distribution Systems: Vd. 3" Reference Book.
Checking Concepts and basics
(Final) Brain Tinker

(1) A small industrial plant (receiving power at 11.0kV) has the following loads:
   (a) 3 x 100 HP Induction Motors
   (b) 2 x 50 HP Induction Motors, and
   (c) 300 kW of lighting, heating and other small plant loads
Estimate the total plant load, typical running power factor, and size (specify) a transformer. Discuss the protection philosophy for such a plant. Provide a quick cost estimate for the entire electrical system including lighting, motors, and construction.

(2) A 3-phase transformer is rated at 5/7.5 MVA, 13.8 kV (Delta) – 4.16 kV (Grounded-Wye). Calculate (estimate) the full-load phase and line currents on both high-side and low-side of the transformer at maximum loading. What will be a typical % reactance and X/R ratio values? Also calculate the maximum available fault current on the low-side of the transformer. Discuss the protection philosophy for this transformer.
Transformer “key” Nameplate Rating Data

An Example

3-Phase, 60Hz
115 kV (Delta) – 12.47 kV (Grounded Wye)
20/25/30 (@ 55\(^\circ\)C) /36 MVA (@65\(^\circ\)C)
Cooling: (OA/FA/FA)
Tap Changer (No-Load and/or Load)
Bushing CT Ratios!!
HV Winding: 350 kV BIL
LV Winding: 60 kV BIL
\% r\(_t\) = 0.6\% and \% x\(_t\) = 8.0\%

(Note: \% impedance values are always based on the lowest or “base” rating)

Discuss Procurement Strategy!!

1) Initial (Capital) Cost
2) No-Load (Core) Loss
3) Load (Winding) Loss
4) Future Growth and Replacement
5) Overloading and Loss-of-Life Assessment
Appendix “A”

**Single-Phase Circuit Calculations:**
(Review)

- “Sinusoidal (Sine or Cosine) Wave” - Peak and Root-Mean-Squared (RMS) Values of Voltage and Current; Time-Varying Quantities; Frequency (f) and Angular Frequency (ω) and Phase Angle (φ)
- Phasor Notations and Diagrams
- Three Elements (RLC) – Resistance (R), Reactance (± j X) and Impedance (Z = R ± j X); Voltage-Current-Power Relationships and Phasor Diagrams
- Power (P); Reactive Power (Q), and Apparent Power (S) Complex Power and Power Triangle
- Power Factor and Power Factor Correction
- Voltage Drop and Voltage Profile
**Sinusoidal Function and Phasor Diagram**

\[ i(t) = I_m \sin (\omega t \pm \phi) \quad (A) \]
\[ I_{\text{rms}} = \frac{I_m}{\sqrt{2}} = 0.707 \, I_m \quad (A) \]

\[ I = I_{\text{rms}} \angle \pm \phi \quad (A) \]

Where,
\[ \omega = \text{Angular Frequency} \quad (= 2\pi f) \quad \text{(rad/sec)} \]
\[ \Phi = \text{Phase Angle} \quad \text{(rad)} \]
\[ f = \text{Frequency} \quad \text{(Hz)} \]

**Impedance:**

\[ Z = R \pm jX \quad (\Omega) \quad \text{Rectangular Coordinate System} \]
\[ Z = |Z| \angle \pm \theta \quad (\Omega) \quad \text{Polar Coordinate System} \]
\[ = |Z| \cos \theta \pm j|Z| \sin \theta \quad (\Omega) \]

\[ |Z| = \sqrt{R^2 + X^2} \]
\[ \theta = \tan^{-1} \left( \frac{X}{R} \right) \]
### RLC Circuit Elements

<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>L (H)</th>
<th>C (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- \( v(t) = R \cdot i(t) \)
- \( Z = R \angle 0^\circ \)
- \( v(t) = L \cdot \frac{d}{dt} i(t) \)
- \( Z = j \omega L = \omega L \angle 90^\circ \)
- \( i(t) = \frac{1}{C} \frac{d}{dt} v(t) \)
- \( Z = -j \frac{1}{\omega C} = \frac{1}{\omega C} \angle -90^\circ \)

**Current Lags**

- \( P_{av} = V_{rms} I_{rms} = VI (\omega) \)
- \( Q = 0 \)
- \( I = \frac{|V|}{R} \angle 0^\circ \)

Energy Stored = 0

**Current Leads**

- \( P_{av} = 0 \)
- \( Q = VI (\angle VAR) \)
- \( I = \frac{|V|}{1/\omega C} \angle 90^\circ \)

Energy Stored = \( \frac{1}{2} CV^2 \)

Note: Counterclockwise direction of rotation is the positive direction.
SINGLE PHASE CIRCUITS:

Complex Power  \( S = P + jQ \)

\[ = V \* I^* = V \angle 0^\circ \times I \angle \phi \]

\( S: \) Apparent Power (VA)

\( P: \) Real or Active Power (W)

\( Q: \) Reactive Power (VAR); \( Q \) is positive for inductive Load and \( Q \) is negative for capacitive Load (by convention)

\[ \frac{V}{I} = \frac{Z}{\angle \phi} \]

\[ \frac{V}{I} = \frac{Z}{\angle 0^\circ} \]

\[ V \angle 0^\circ \]

\[ I \angle \phi \]

\[ I^* = I \angle -\phi \]

\[ \frac{V}{I} = \frac{Z}{\angle 0^\circ} \]

\( jQ \) (Capacitive)

\( \begin{align*}
|S| &= \sqrt{|P|^2 + |Q|^2} \\
|S| &= |V| \times |I| \\
|P| &= |V| \times |I| \cos \phi \\
|Q| &= |V| \times |I| \sin \phi \\
\frac{|Q|}{|P|} &= \tan \phi \\
\frac{|P|}{|S|} &= \cos \phi
\end{align*} \)

V, I, P, Q & S are all in pu (or other appropriate units)

\( \phi: \) Power factor Angle and \( \cos \phi: \) Power Factor

\( \phi = \frac{V}{I} \quad \text{Inductive Load \Rightarrow Lagging PF.} \)

\( \text{Capacitive Load \Rightarrow Leading PF.} \)
Appendix “B”

Three-Phase Circuit Calculations:
(Review)

3-Phase Circuit Calculations
(Review and Problem Solving)

Balanced 3-Phase Circuits:
(1) Wye (Y) -
Connected
(2) Delta (Δ) -
Connected

(1) Wye Connection:

$$|V_l| = \sqrt{3} |V_p|$$

$$I_l = I_p$$

$$P_{3\phi} \text{(Real Power)}$$

$$= 3 |V_p| |I_p| \cos \theta$$

$$= \sqrt{3} |V_l| |I_l| \cos \theta$$

$$Q_{3\phi} \text{(Reactive Power)}$$

$$= 3 |V_p| |I_p| \sin \theta$$

$$= \sqrt{3} |V_l| |I_l| \sin \theta$$

$$|S_{3\phi}| \text{(Apparent Power)}$$

$$= 3 |V_p| |I_p|$$

$$= \sqrt{3} |V_l| |I_l|$$
(2) Delta Connection:

\[ |I_1| = \sqrt{3} |I_p| \]
\[ V_1 = V_p \]

\[ P_{3\phi} \text{ (Real Power)} \]
\[ = 3 |V_p| |I_p| \cos \theta \]
\[ = \sqrt{3} |V_1| |I_1| \cos \theta \]

\[ Q_{3\phi} \text{ (Reactive Power)} \]
\[ = 3 |V_p| |I_p| \sin \theta \]
\[ = \sqrt{3} |V_1| |I_1| \sin \theta \]

\[ |S_{3\phi}| \text{ (Apparent Power)} \]
\[ = 3 |V_p| |I_p| \]
\[ = \sqrt{3} |V_1| |I_1| \]
$\theta$ is the angle between Phase Voltage ($V_p$) and Phase Current ($I_p$) and is called the Power Factor Angle.

$\cos \theta$ is called the Power Factor.

**Power Triangle**

\[
\begin{align*}
Q_{3\phi} \text{ (Inductive)} & = S_{3\phi} \\
\sqrt{3} V_e I_e \text{ (VA)} & = S_{3\phi} \\
Q_{3\phi} & = \sqrt{3} V_e I_e \sin \theta \text{ (VAR)} \\
\tan \theta & = \frac{Q_{3\phi}}{P_{3\phi}} \\
P_{3\phi} & = \sqrt{3} V_e I_e \cos \theta \text{ (W)} \\
Q_{3\phi} \text{ (Capacitive)} & =
\end{align*}
\]

\[
S_{3\phi} = \sqrt{P_{3\phi}^2 + Q_{3\phi}^2}
\]
Appendix “C”

Transformer:
(Review)

In an ideal transformer:

\[ v_1(t) = e_1(t) = N_1 \frac{d\phi}{dt} \]
\[ v_2(t) = e_2(t) = N_2 \frac{d\phi}{dt} \]
\[ \frac{v_1(t)}{v_2(t)} = \frac{e_1(t)}{e_2(t)} = \frac{N_1}{N_2} \]
\[ \frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} \]

\[ \frac{V_1}{N_1} = \frac{V_2}{N_2} = \text{Volt/Turn} \]

Assume:

\[ \phi(t) = \phi_m \sin \omega t \]
\[ e_1(t) = v_1(t) = N_1 \frac{d\phi}{dt} \]
\[ = \omega N_1 \phi_m \cos \omega t \]
\[ = \omega N_1 \phi_m \sin (\omega t + 90^\circ) \]

\[ E_1 = V_1 = \omega N_1 \phi_m / \sqrt{2} = 4.44 f N_1 \phi_m \]
\[ = 4.44 f N_1 A_c B_m \]
\[ \frac{V_1}{N_1} = \frac{V_2}{N_2} = 4.44 f A_c B_m \]

When a load is connected to the secondary winding, the following will occur:

a. A continuous current will flow in the secondary coil.
b. This secondary current in turn creates an alternating magnetic field, which will tend to induce a voltage within itself of such value as to stop the current from flowing.
c. This secondary magnetic field will act on the primary in such a way as to reduce the effect of mutual coupling in the primary coil.
d. This will cause more current to flow in the primary coil, which in turn will set up a stronger magnetic field.
e. This stronger magnetic field will induce a greater voltage in the secondary coil, which will in turn tend to reduce the effect of opposing field in the secondary coil.

Thus, a state of equalization will be reached where the magnetic fields of the primary and secondary are so balanced that the ampere-turns in one match the ampere-turns in the other.

*Ampere-Turn (or Flux) Balance: Primary AT = Secondary AT*

\[ N_1 I_1 = N_2 I_2 \]
\[ N_1/N_2 = I_2/I_1 \]

[4] Power Balance:

The transformer acts automatically to regulate the flow of energy in the primary as it is demanded by the load connected to the secondary. When no load is connected to the secondary coil, no current will flow in it. In a real transformer, however, a small current will flow in the primary coil to produce the flux and supply the no-load losses. In an ideal transformer (with no losses), primary input equals to the secondary output.

For no losses in the transformer: *Primary Power = Secondary Power*

\[ V_1 I_1 = V_2 I_2 \]
\[ V_1/V_2 = E_1/E_2 = N_1/N_2 = I_2/I_1 \]
Equivalent Impedance:

\[ a = \frac{N_1}{N_2} \]

\[ V_1 = \left( \frac{N_1}{N_2} \right) V_2 \]

\[ I_1 = \left( \frac{N_2}{N_1} \right) I_2 \]

\[ Z' = \frac{N_1}{N_2} Z_2 = a^2 Z_2 \]
Transformer Equivalent Circuit

Ideal Transformer

Referred to Primary

Professor, Colorado School of Mines
Senior Consultant, NEI Electric Power Engineering, Inc.
There are two types of tap-changer:

a. **De-Energized (No-Load or Off-Load - NLTC)** tap changers are used when it is expected that the ratio will need to be changed infrequently, because of load growth of some seasonal change. The desired tap is selected by means of a ratio adjuster. This is provided as a standard design practice and available at practically no additional cost and commonly employed on the high side.

   Typical no-load tap-changer has $\pm 5\%$ variation, two taps above and two taps below the nominal voltage ($\pm 2 \times 2\frac{1}{2}\%$).

b. **Load Tap Changer (LTC)** is used when changes in ratio may be frequent or when it is undesirable to de-energize the transformer to change a tap. A large number of units, typically at 10 MVA or higher rating, are now being built with load tap changing equipment. It is used on transformers and auto-transformers for transmission tie, for bulk distribution units, and at other points of load service.

   In seldom makes much difference to the user which winding or windings are tapped. The choice is usually made by the designer on the basis of cost and good design. Both winding current and voltage must be considered when applying LTC equipment. High voltage and high current applications require special considerations to arrive at an optimum location for the LTC equipment. Step down units usually have LTC in the low-voltage winding. Typically LTC adds in the range of 20-30% to the cost of the transformer without any LTC.

   Most commonly, LTC has taps 16 above and 16 below with 5/8% each step ($\pm 16 \times 5/8\%$) giving $\pm 10\%$ voltage variation.
3.2 Real Transformer and Equivalent Circuit

No-Load Condition

\[ R_c = \text{Equivalent Resistance Corresponding to the Core Loss} \]
\[ X_m = \text{Reactance Corresponding to the Core (Mutual) Flux} \]
\[ I_{NL} = \text{No-Load Current, Very Small, (1-4\% of } I_{FL} \text{)} \]

Equivalent Circuit:
Transformer Equivalent Circuit:

\[ R_x = \text{Equivalent Resistance (Core Loss)} \]
\[ X_m = \text{Magnetizing Reactance (Core Flux)} \]
\[ r_i = \text{Winding Resistance (combined)} \]
\[ x_i = \text{Winding Leakage Reactance (combined)} \]

Open Circuit or No-Load Test Data

Short Circuit Test Data

Open Circuit (No-Load) Test:

\[ P_{OC} \]
\[ I_{OC} = I_{NL} \]
\[ V_{OC} \]

"LV" \hspace{1cm} "HV"

Short Circuit Test:

\[ P_{SC} \]
\[ I_{SC} \]
\[ V_{SC} \]

"HV" \hspace{1cm} "LV"

\[ P_{SC} = \text{Winding (Copper) Loss} \]
\[ I_e = \text{Short Circuit Current (Usually Rated)} \]
\[ V_i = \text{Input Voltage (Usually less than 10\% of Rated Voltage)} \]
3.4 3-Phase (2-Winding) Transformer

Application Considerations:

- Voltage Requirements (1-Phase v. 3-Phase Loads)
- Transformer Neutral grounding
- Unbalanced Conditions
- Ferroresonance
- Circulating Delta Currents
- neutral Voltage Shift and Stabilizing
- Saturation and Harmonic generation
- System neutral grounding
- protection and Relaying Considerations
- Ground Fault Isolation
- Utility v. Industrial Application
- Cost, BIL / Insulation

[1] Core Construction, Coils, and Physical Design

[1] Core Construction, Coils and Physical Design

Refer to Section 2 and the figures below.
3-Phase Transformer

**Standard ANSI Connection**

**Zero Phase Shift for Wye-Wye or Delta-Delta Connection.**

**30° Phase Shift for Wye-delta Connection.**
Low Voltage lags the High Voltage.

![Diagram of 3-Phase Transformer](image)

**Performance Evaluation**

\[ \text{Efficiency } (\eta) = \frac{\text{Output}}{\text{Input}} \]
\[ \text{Input} = \text{Output} + \text{Losses} \]
\[ \text{Losses} = \text{Core (Iron) Loss} + \text{Winding (Copper) Loss} \]
\[ \text{Core (Iron) Loss} = \text{Constant Loss} \]
\[ \text{Winding (Copper) Loss} = I^2 r_t, \text{ proportional to } I^2 \]

Power Input for Open Circuit Test at Rated Voltage → Core Losses

Power Input for Short Circuit Test → Winding Losses ( \( \propto I^2 \) )

\[ \% \text{Voltage Regulation or Voltage Drop} = \left[ \% r_t \cos \theta \pm \% x_t \sin \theta \right] * \text{pu Loading} \]
\[ (+) \rightarrow \text{Lagging Power Factor} \]
\[ (-) \rightarrow \text{Leading Power Factor} \]
### Various 3-Phase Transformer Connections

<table>
<thead>
<tr>
<th>Winding Connections</th>
<th>Comments</th>
</tr>
</thead>
</table>
| ![Winding Connections](image) | • Commonly used in industrial systems.  
• It provides isolation at each voltage for ground currents (ground fault isolation).  
• Neutral may be solidly grounded.  
• Provide 3-Phase, 4-Wire power system.  
• Possibility of ferroresonance exists. |
| ![Winding Connections](image) | Seldom used for new systems. |
| ![Winding Connections](image) | • When used it is usually on HV systems or required by the utility (e.g. generator transformer).  
• This may serve as a grounding bank in an ungrounded system in which case the primary must be designed for full system zero-sequence ground current. |
| ![Winding Connections](image) | • Transformer neutral may be unstable.  
• It is not recommended to use this configuration. |
| ![Winding Connections](image) | • Used in HV incoming utility service.  
• The delta winding stabilizes the neutral and protects the system transformer from excessive third harmonic voltages.  
• Can take care of unbalanced loads. |
| ![Winding Connections](image) | • Quite commonly used by utilities to serve general purpose 1-phase and 3-phase loads via 4-wire service.  
• Minimize ferroresonance.  
• Used on HV transmission systems. |