Power Distribution System Losses

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Tao Hong

- Experience
  - *Analytical Consultant,* SAS Institute Inc.
    - Revenue optimization, retail forecasting, demand response
  - *Business Knowledge Series Instructor,* SAS Institute Inc.
    - SAS for Electric Load Forecasting
  - *Engineer, Sr. Engineer, Principal Engineer,* Quanta Technology, LLC.
    - Load forecasting, T&D planning, system loss evaluation, system reliability analysis, load modeling, renewable energy
- Education
  - Ph.D. E.E., O.R., NC State University, Raleigh
  - M.S. E.E., I.E., O.R., NC State University, Raleigh
  - B.Eng, Automation, Tsinghua University, Beijing

Outline

- Overview
- Fundamentals
- Transformer Losses
- Line Losses
- Capacitor Application

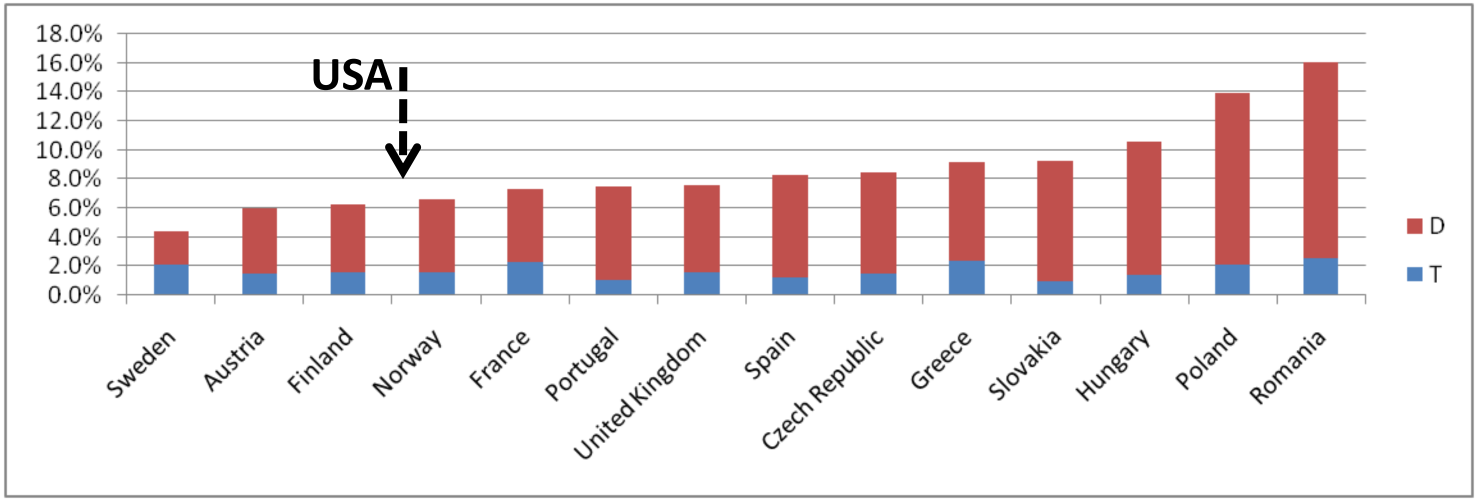
This presentation can be downloaded from the course webpage:
http://courses.DrHongTao.com/pdsl

Why Do We Study Losses?

- Cost of energy and capital
- Difficulties in siting new generation
- Pressure from regulators
- Better understanding of customer behaviors
- More defensible load forecasting
- System planning

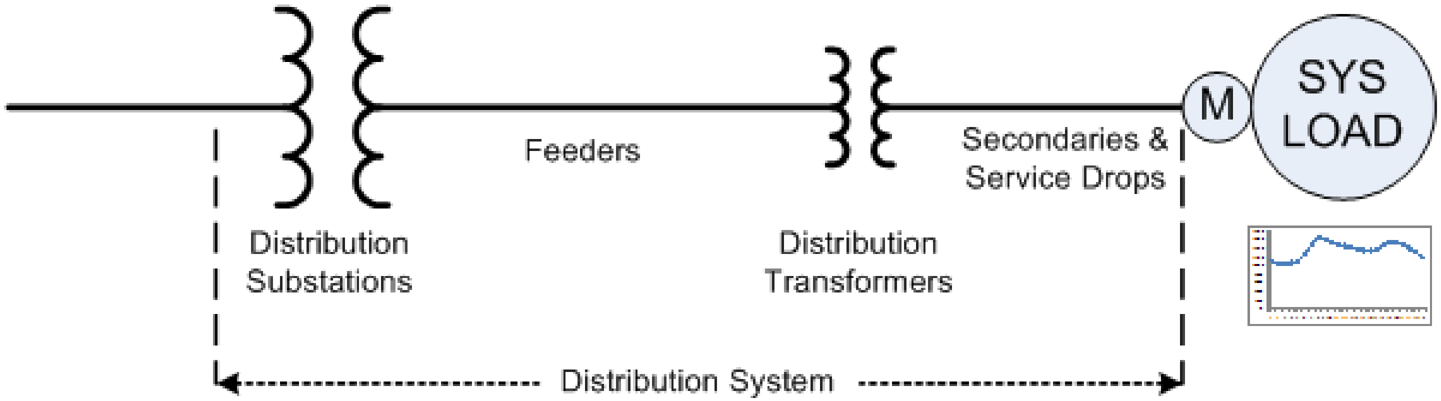
T&D Losses

- A tentative definition
  - "Energy Produced minus Energy Sold"
- T&D losses in USA
  - 6.6% (1997), 6.5% (2007)
- T&D losses in Europe

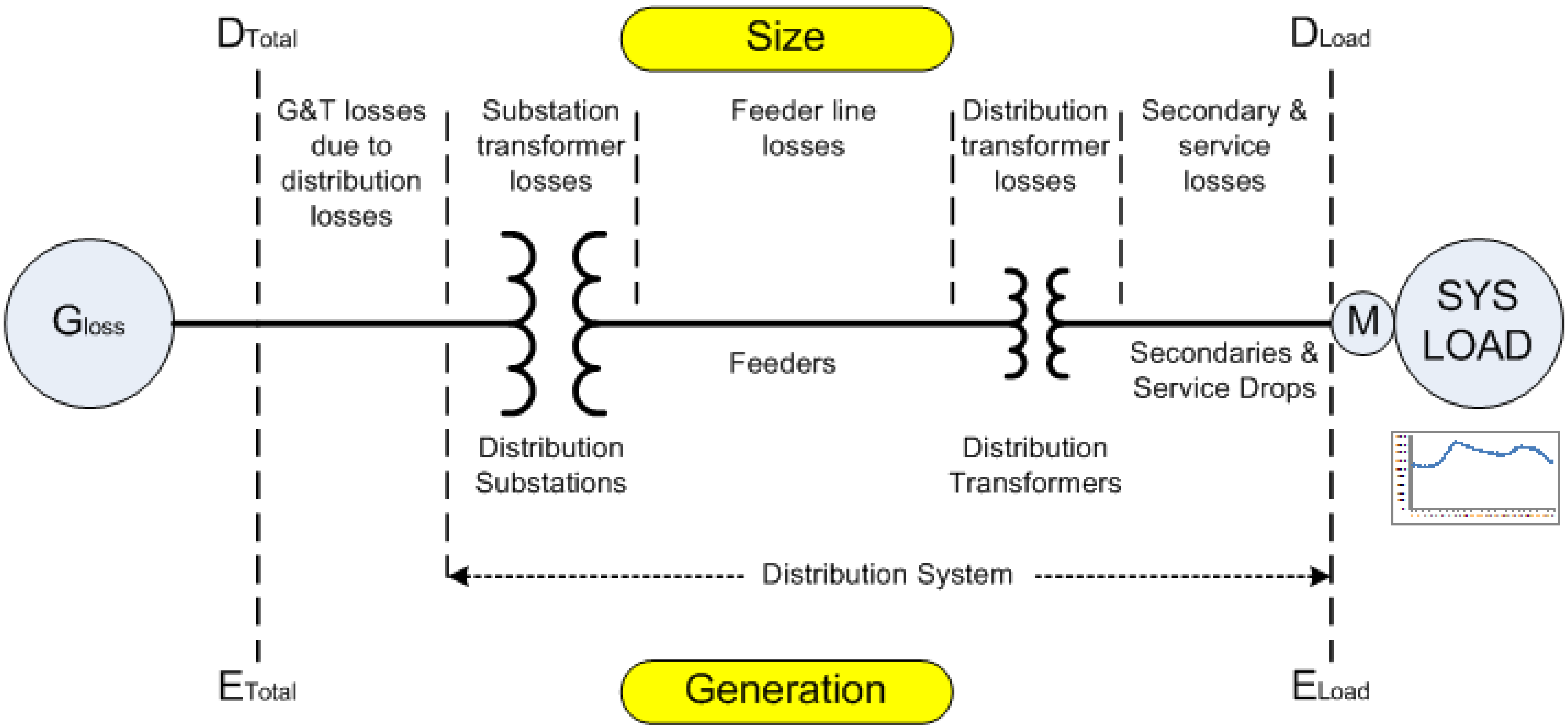


A Simplified Distribution System

- Distribution system
  - Daily load
  - System peak

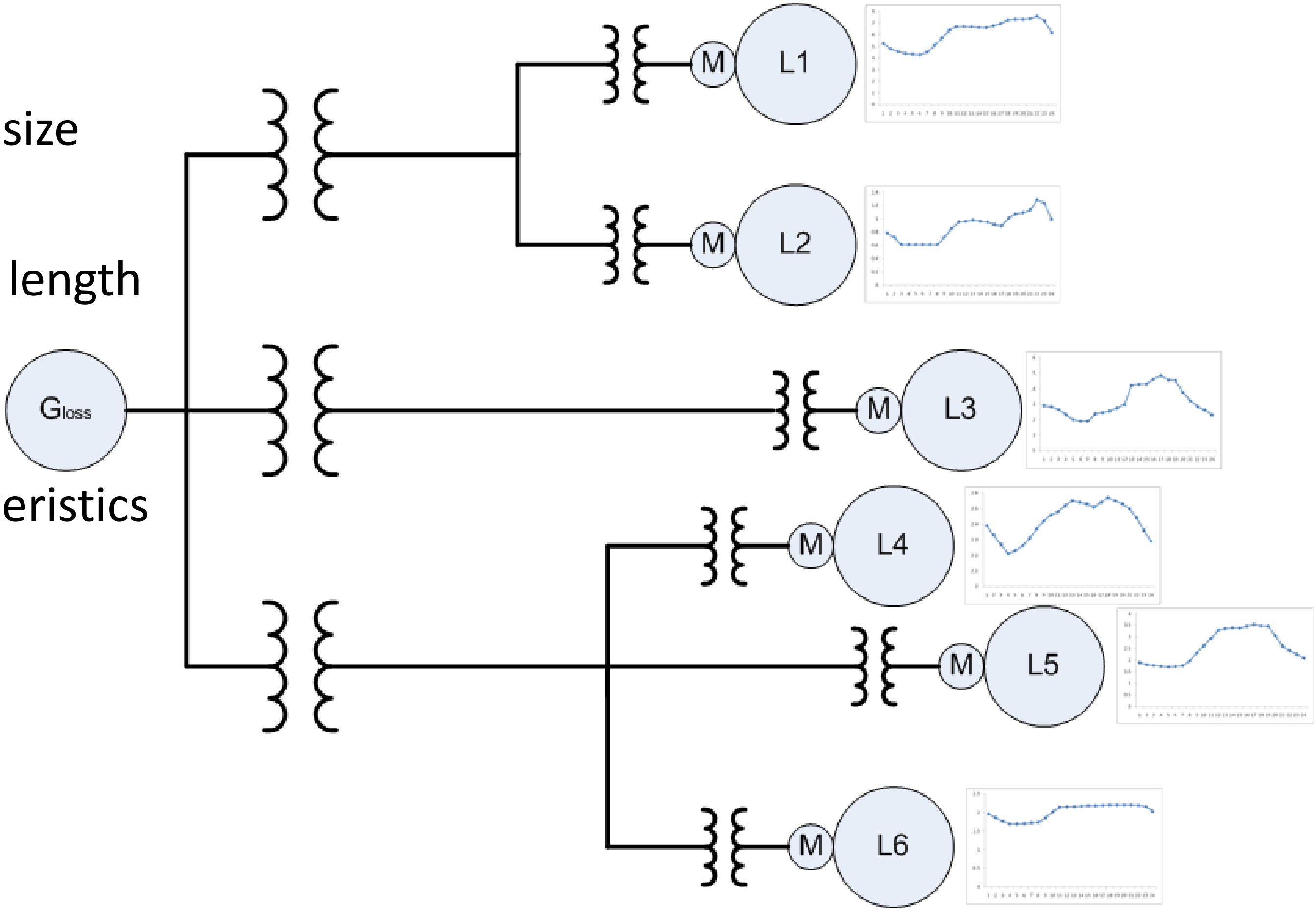


Loss Generator



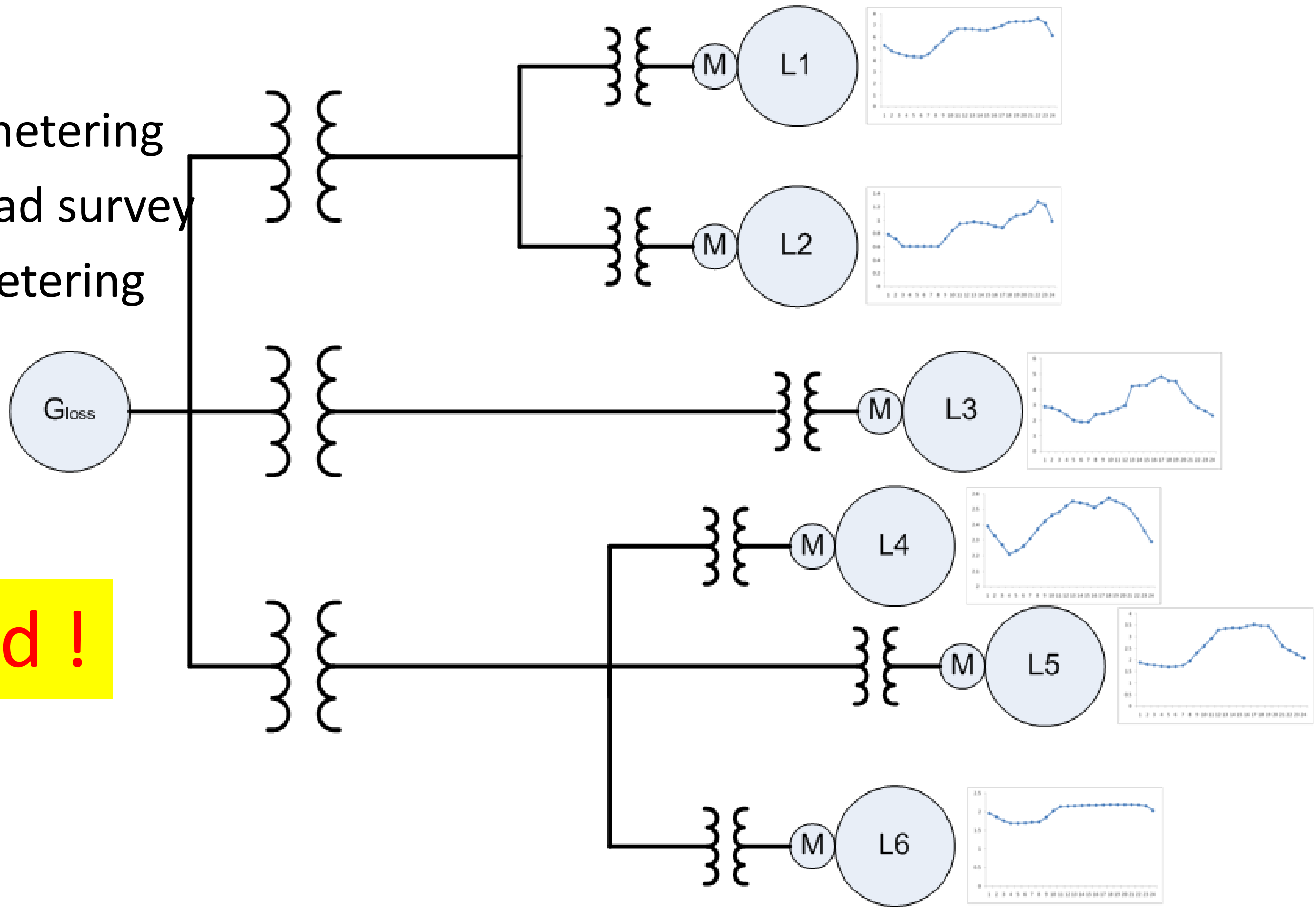
A Realistic Distribution System

- Variables
  - Transformer size
  - Line length
  - Service drop length
  - Load curves
  - Load levels
  - Load characteristics



Metering and Data

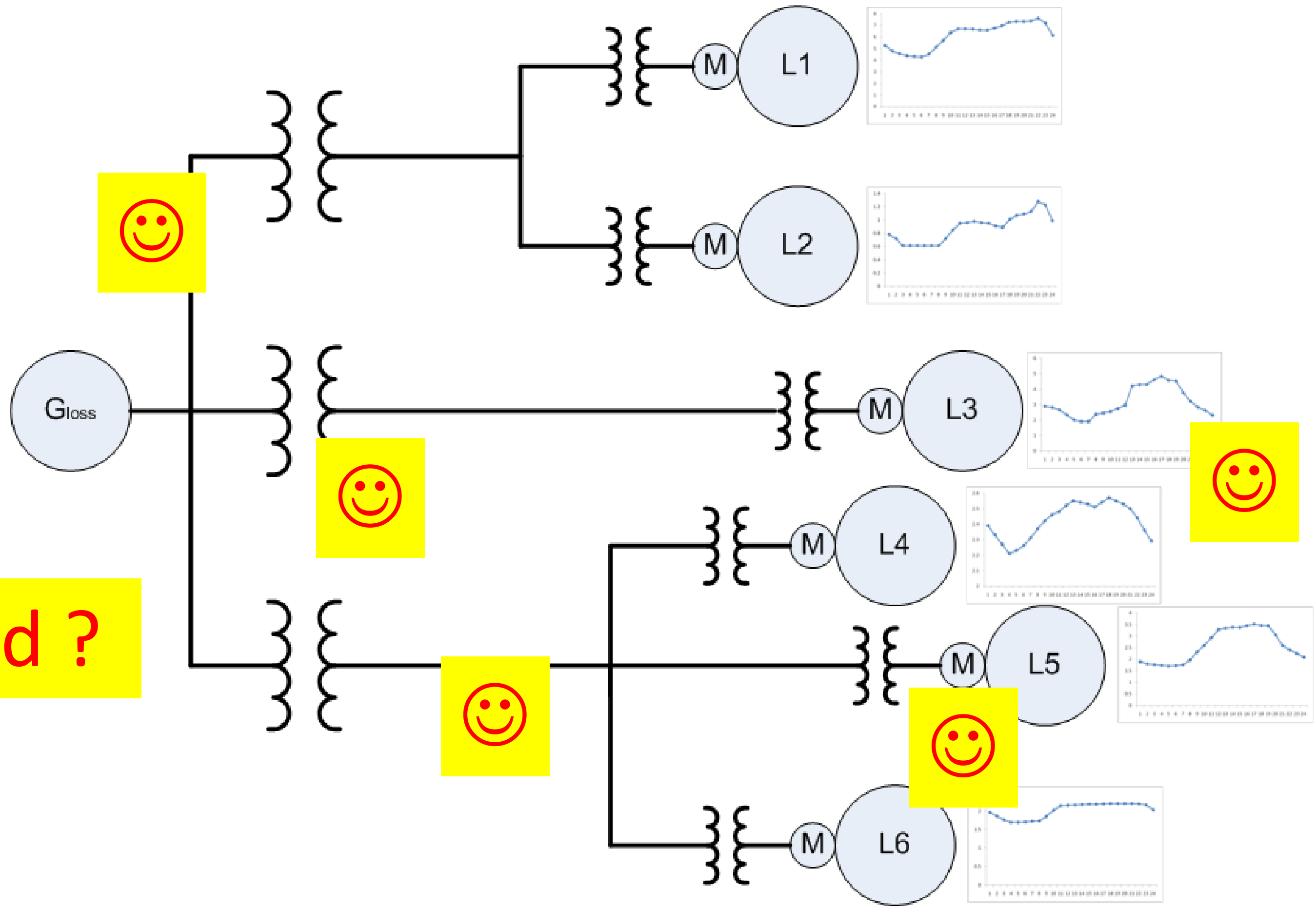
- Sources
  - Substation metering
  - Customer load survey
  - Customer metering
  - TLM
  - …



Smart Grid !

Loss Management

- Analyze…
- Optimize…



Smart Grid ?

Definitions

- System losses
  - Demand losses
  - Energy losses
- Equipment losses

- No load losses
- Load Losses

Calculation

- Substation transformers
- Feeders
- Distribution transformers
- Secondary losses
- Capacitors
- Unmetered load and theft

Causes

- Poor power factor on the distribution feeder
- Conductor sizing and arrangement
- Load imbalance between feeders
- Imbalance between phase A, B, C
- Load/no-load losses in distribution transformers
- Improper Volt/VAR control (regulator/LTC settings, line cap controls, blown fuses on cap banks, etc.)
- Extremely long distribution lines

Mitigation

- Increase conductor size
- Proper distribution transformer size and design (no load and load)
- Balance currents in phases
- Share loads equally between circuits
- Optimize feeder configuration at each voltage level
- Add feeder capacitors
- Reduce harmonics
- High efficiency loads

Mitigation (*Continued*)

- Higher primary voltages
- Lower secondary voltages (usually)
- Proper distribution substation design and operation
- Capacitor bank inspection of fuses
- Primary selective systems as opposed to secondary network systems
- Eliminate transformations, where possible
- Replace low efficiency and overloaded transformers
- Proper capacitor control

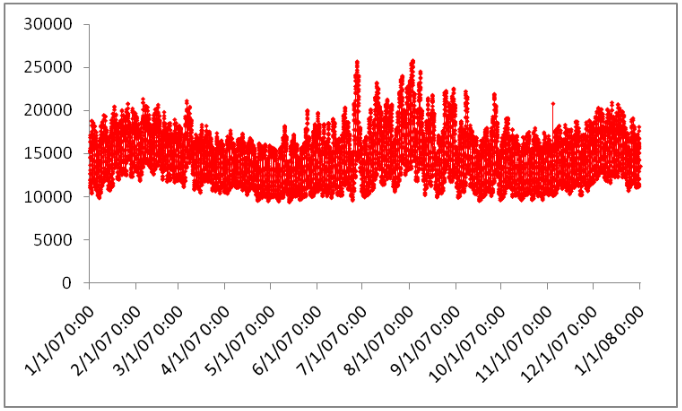
Mitigation (*Continued*)

- Load control (demand side management)
- Amorphous steel transformers
- Reduce load factor by reducing peak loads
- Retire low efficiency cable
- Open tie at substations, with multiple transformers, to reduce circulating currents or match transformer impedances

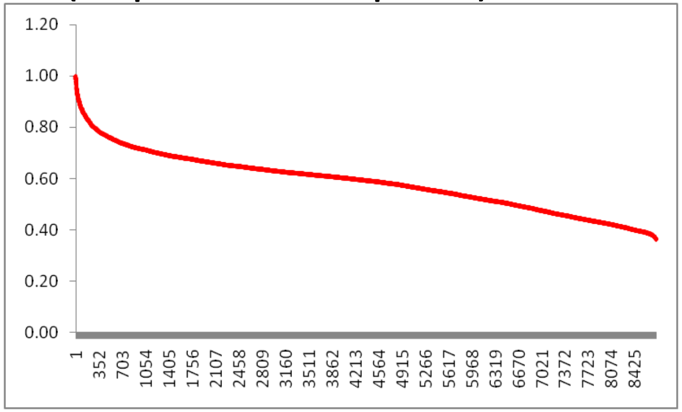
Q/A

Load Duration Curve

- Load curve



- Load duration curve
  - Descending order of load (in per unit of peak)



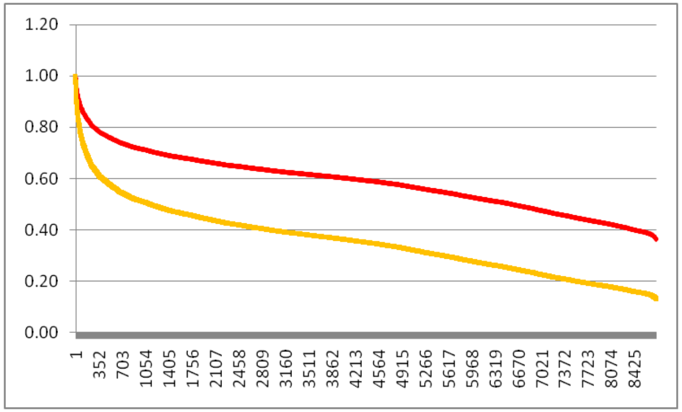
Load Factor

- Average load, in per unit of peak, over a predetermined period of time

$$\text{Load Factor} = \frac{\text{kWh of Load During a Specified Time Period}}{\text{(Hours in Time Period)(Peak kW Load)}}$$

Loss Duration Curve

- Load losses are proportional to the square of the loading
  - ~~Average losses are proportional to the square of average load~~
  - ~~Average losses are proportional to the square of load factor~~
- Loss duration curve
  - Square of load duration curve



Loss Factor

- Average loss, in per unit of peak, over a predetermined period of time

$$\text{Loss Factor} = \frac{\text{kWh of Loss During a Specified Time Period}}{(\text{Hours in Time Period})(\text{Peak kW Loss})}$$

Loss Factor

- Empirical formula

$$\text{Loss Factor} = C(\text{Load Factor}) + (1-C)(\text{Load Factor})^2$$
$$C \in [0.15, 0.3]$$

Coincidence Factor

- The ratio of the maximum demand of a set of users to the sum of the set's individual maximum demands

$$\text{Coincidence Factor} = \frac{\left\| \sum_{i=1}^{N} D_i \right\|_\infty}{\sum_{i=1}^{N} \left\| D_i \right\|_\infty}$$

Coincidence Factor

- Empirical formula

$$\text{Coincidence Factor} = 0.5 \times (1 + \frac{5}{2N+3})$$

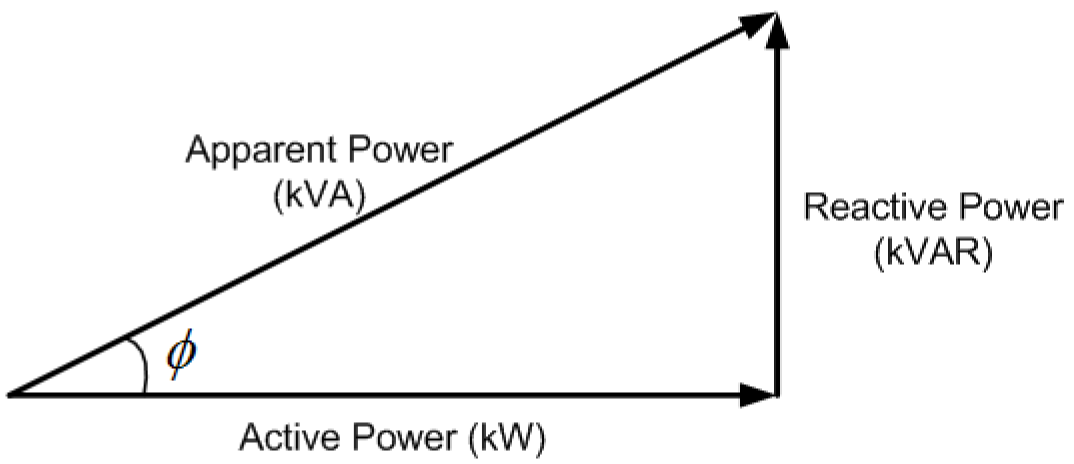
Diversity Factor

- The inverse of coincidence factor

$$\text{Diversity Factor} = \frac{\sum_{i=1}^{N} \left\| D_i \right\|_\infty}{\left\| \sum_{i=1}^{N} D_i \right\|_\infty}$$

Power Factor

- The ratio of active power to apparent power
  - cosϕ
- 0.85 to 0.98



Peak Responsibility Factor

- Peak load losses occur at peak load on a component
  - May not occur at system peak
  - Only a "fraction" of the individual peak losses contribute to system peak demand

$$\text{System Peak Responsibility Factor} = \frac{\text{Component kW Load at System Peak}}{\text{Component kW Peak Load}}$$

Question: "Fraction" = SPRF?

Peak Responsibility Factor

- Fraction = SPRF?
  - SPRF is a ratio of loads
  - Losses are proportional to the square of loads
  - Losses are function of $SPRF^2$
- Example
  - 1kW losses at its peak load
  - SPRF = 0.8
  - 0.64kW losses at system peak
  - Need additional 0.64kW generation and equipment to supply losses

Peak Responsibility Factor

- Typical peak responsibility factor for transformers

Type	SPRF	$SPRF^2$
Generator Step-up	1	1
Transmission substation	0.9	0.81
Distribution substation	0.8	0.64
Distribution	0.75	0.56

Peak Responsibility Factor

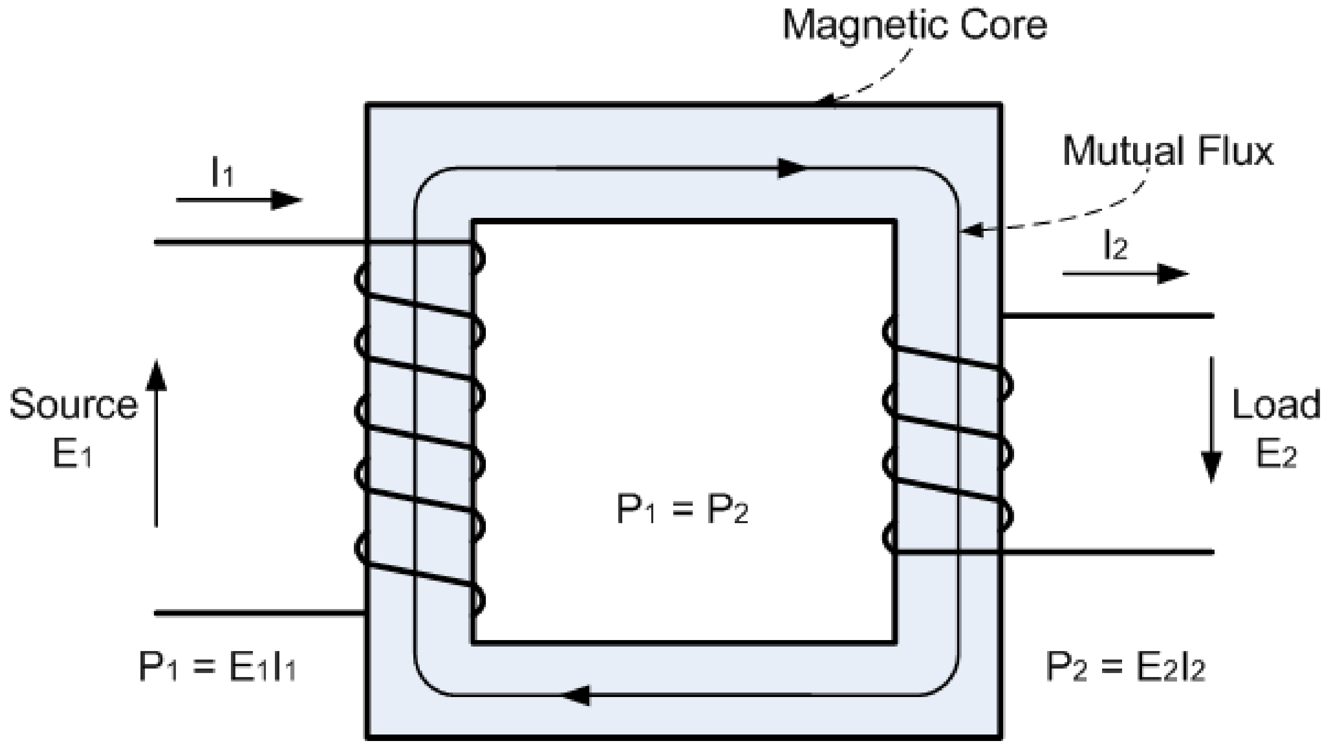
- Peak responsibility factors of one utility

	Distribution Sub	Feeder
Min	0.83	0
Q1	0.92	0.58
Average	0.93	0.71
Median	0.95	0.76
Q3	0.96	0.85
Max	0.98	1

Q/A

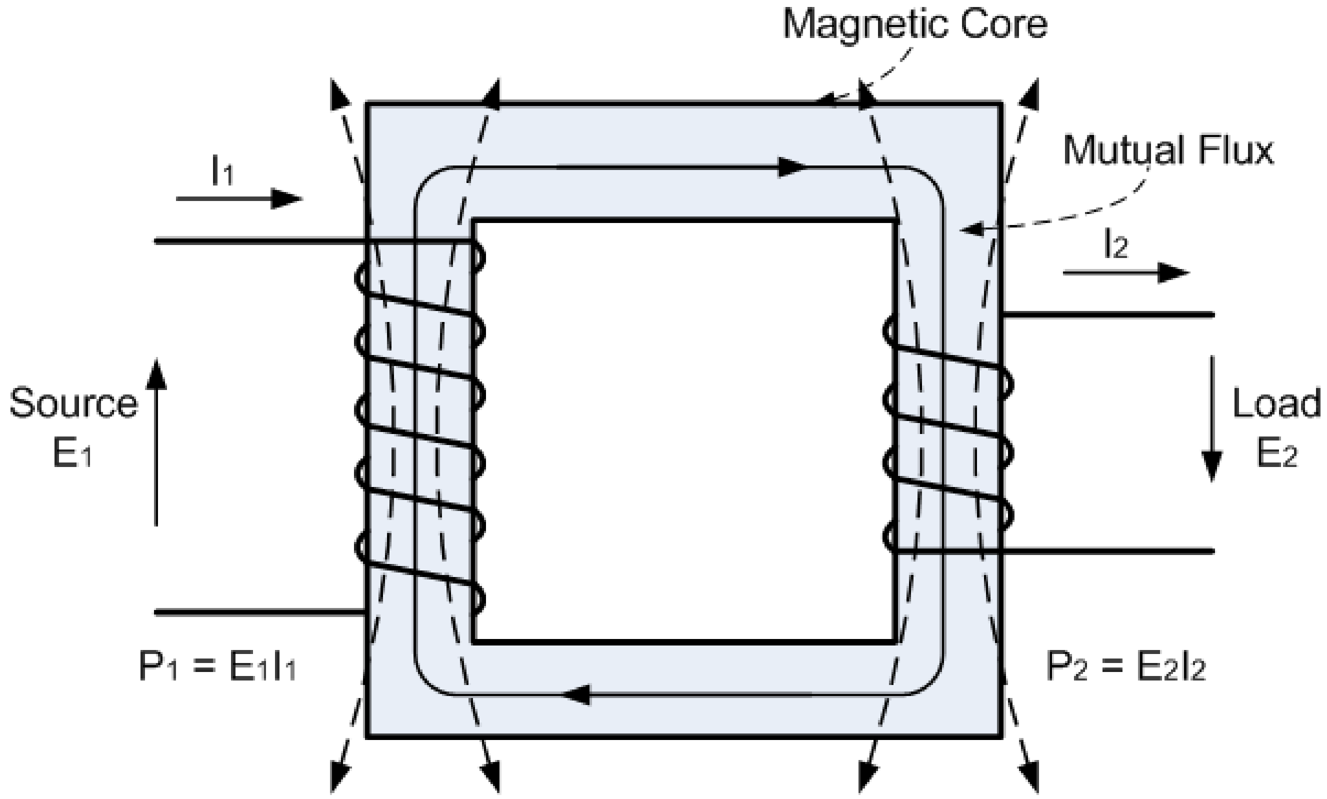
A Basic Transformer

- Lossless transformer



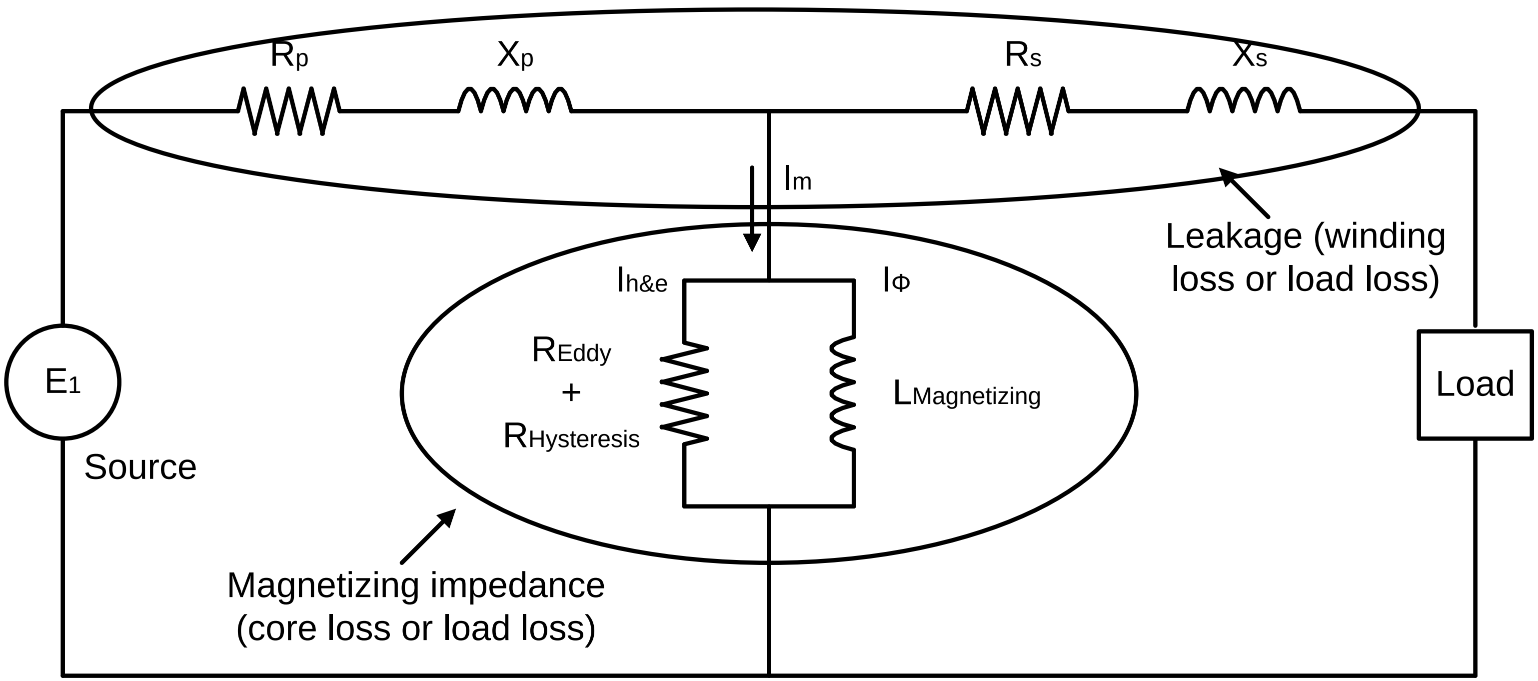
A Basic Transformer

- Flux relations



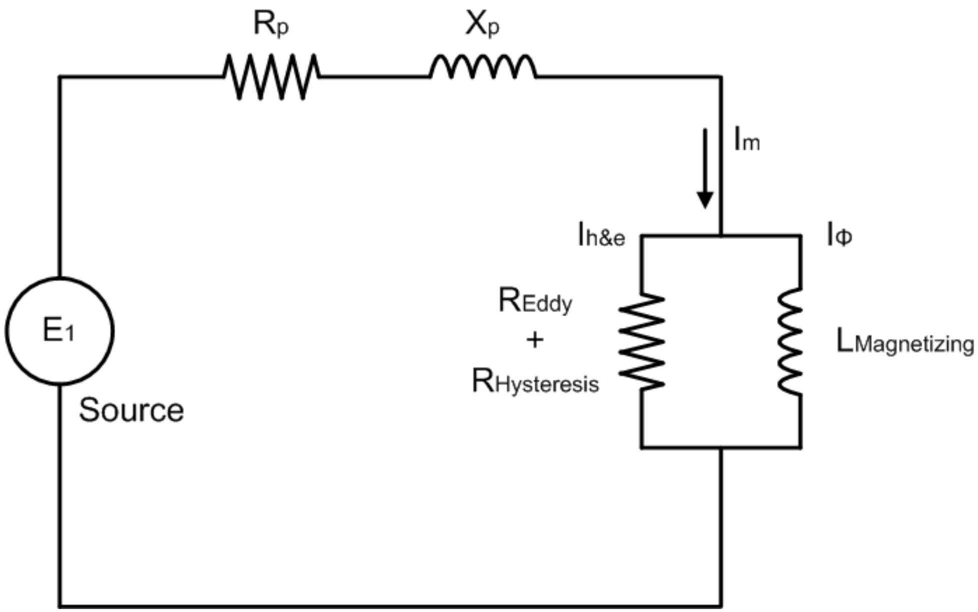
Transformer Model

- Leakage impedance
- Magnetizing impedance



No-load Losses

- Primary circuit



No-load Losses

- No-load losses of a transformer
  - Eddy-current loss
  - Hysteresis loss
  - I^2R loss caused by exciting current
  - Dielectric losses
- Due to the iron in the transformer core
  - Iron losses
  - FE losses

No-load Losses

- Transformer no-load demand losses (TNLDL)
  - From data sheet
- Transformer no-load energy losses (TNLEL)

Transformer No-Load Energy Losses =
Transformer No-Load Demand Losses × 8760

Load Losses

- Transformer load demand losses (TLDL)

Transformer Load Demand Losses =
Transformer Peak Load Demand Losses × $SPRF^2$

Load Losses

- Transformer load energy losses (TLEL)

Transformer Load Energy Losses = Transformer Peak Load Demand Losses × Annual Loss Factor × 8760

Reactive Losses

- Reactive demand losses
  - No-load reactive losses
  - Load reactive losses

Very Small

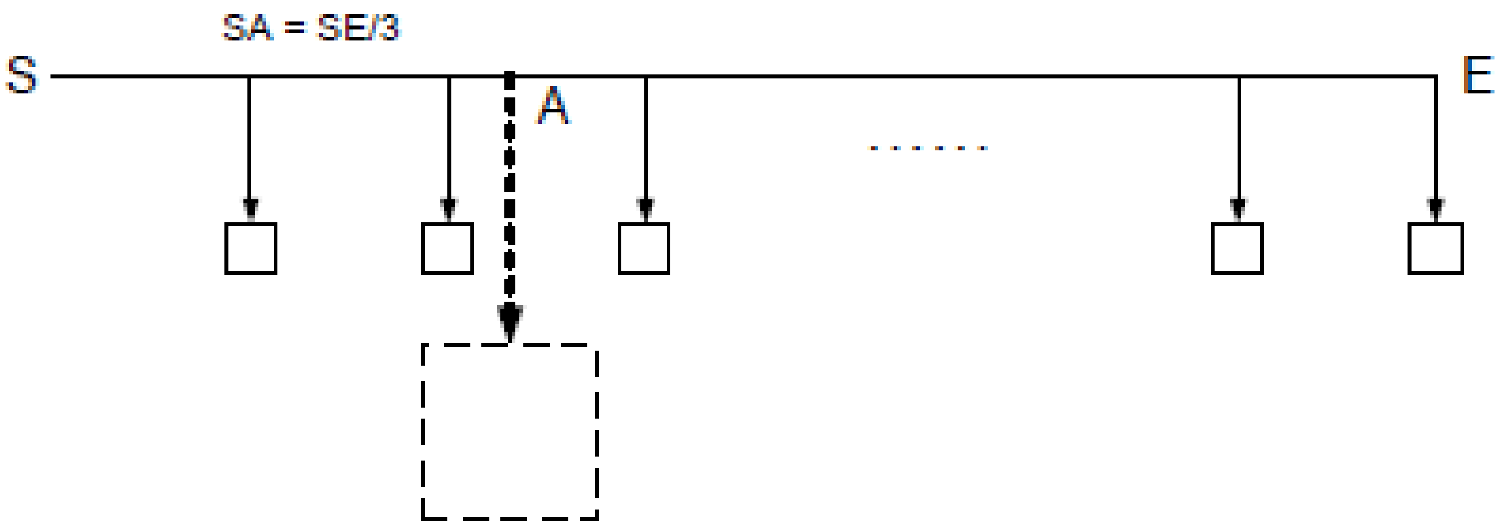
- Reactive energy losses

No Value?

Q/A

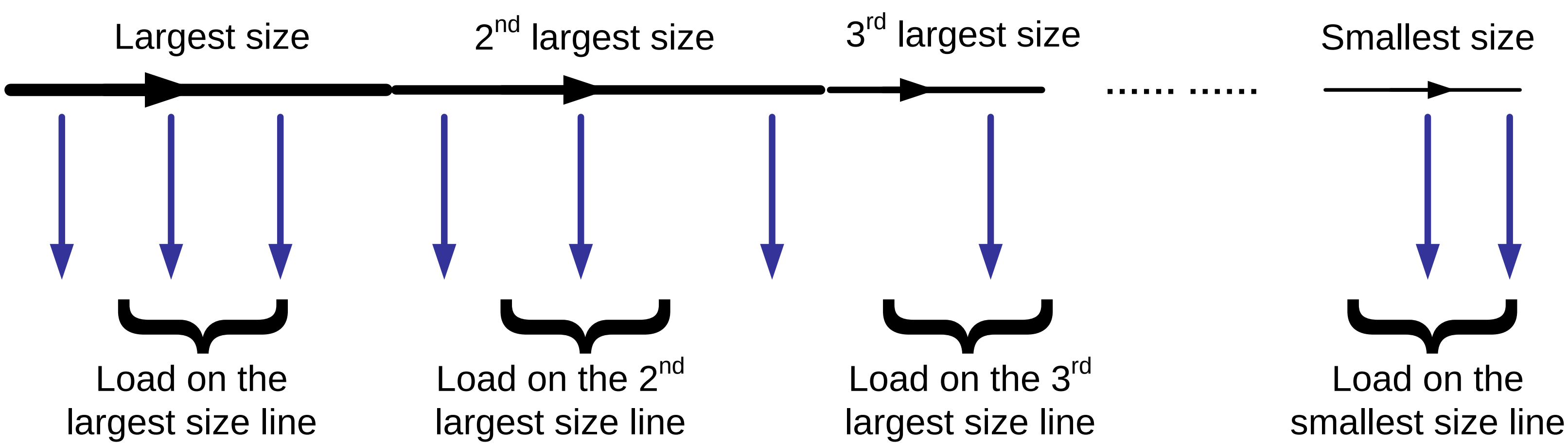
1/3 Rule

- For feeders with evenly distributed load and one conductor size
  - "1/3 Rule" for losses



Generic Line Losses

- For a generic feeder



$$P_k = \frac{(I_{\max,k})^2 + I_{\min,k} I_{\max,k} + (I_{\min,k})^2}{3} R_k$$

Primary Line Losses

- Peak load losses

Peak 3ø Load Losses = 3× Generic Line Losses

Primary Line Losses

- Energy losses

Primary Line Energy Losses = Peak 3ø Load Losses × Loss Factor × 8760

Primary Line Losses

- Demand losses

Primary Line Demand Losses = Peak 3ø Load Losses × $SPRF^2$

Lateral Line Losses

- Peakl losses on a single phase lateral (including 100% neutral return)

Peak 3ø Load Losses = 2 × Generic Line Losses

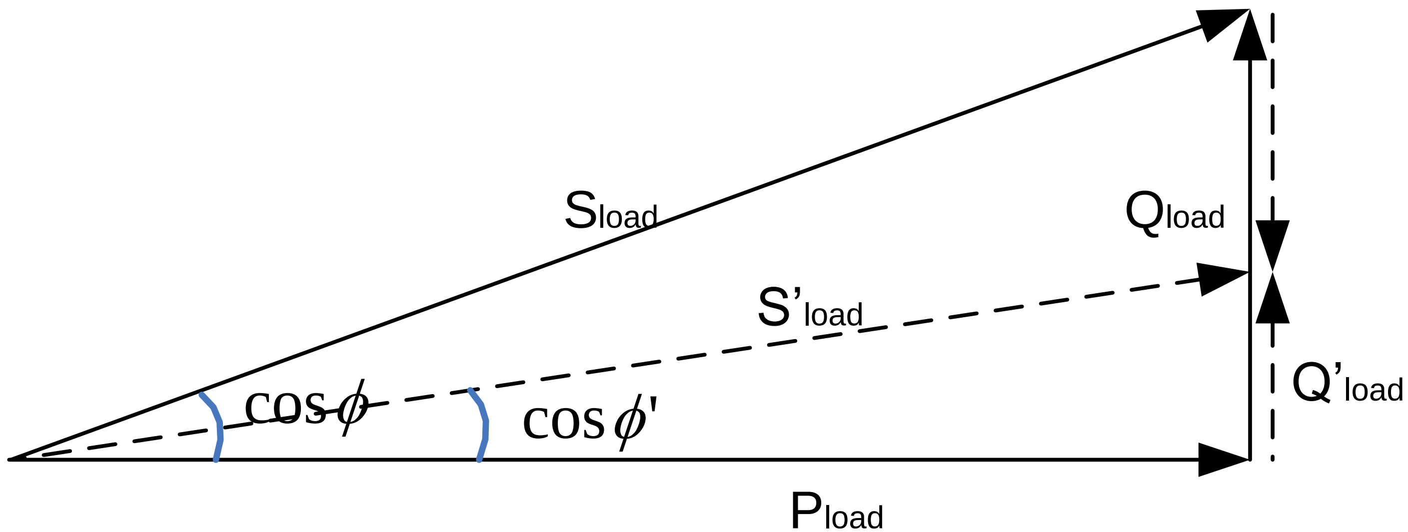
Distribution Factor

- When losses are not uniformly distributed over the circuit
  - Peak 3ø Load Losses = "I-square R" × Distribution Factor

$$\text{Distribution Factor} = 1 + I_r/I_s + (I_r/I_s)^2$$

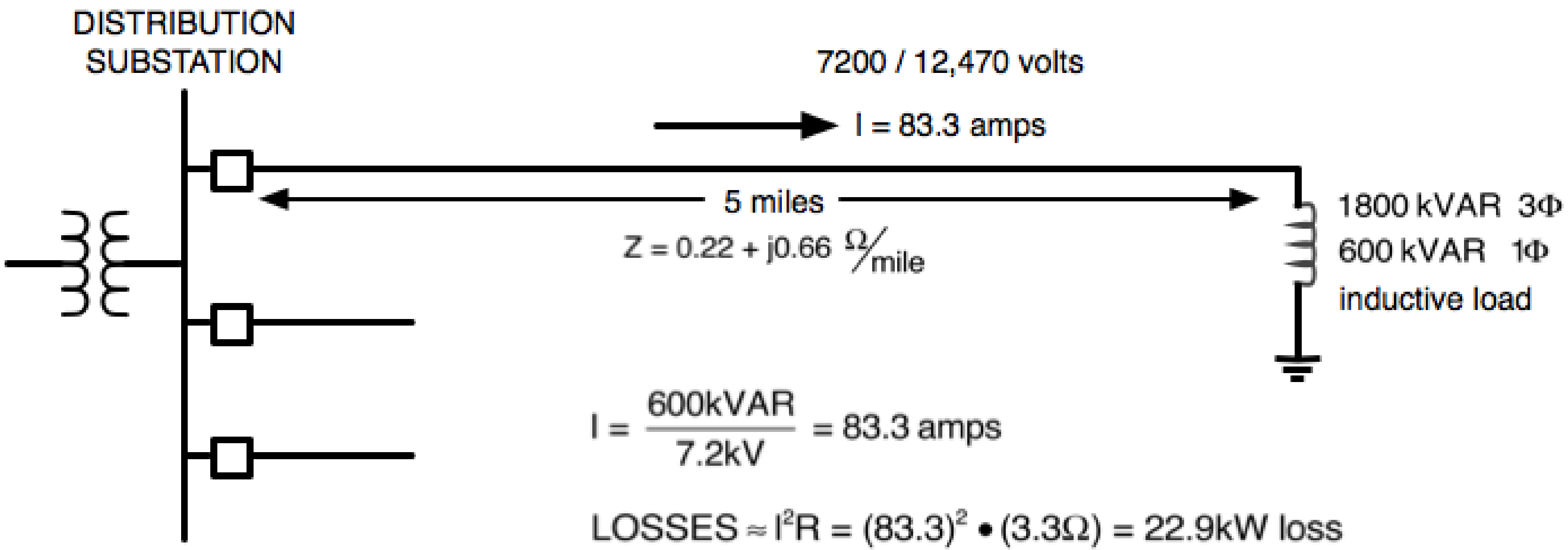
Q/A

Active and Reactive Power



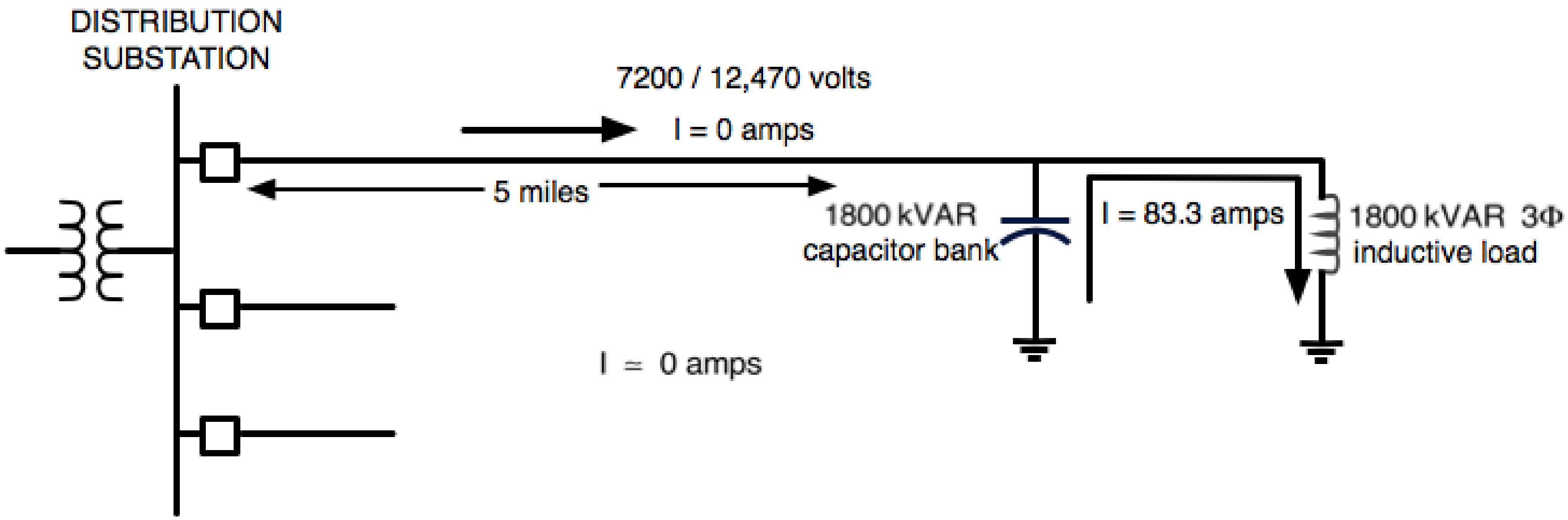
Inductive Load

- 1800 kVAR inductive load



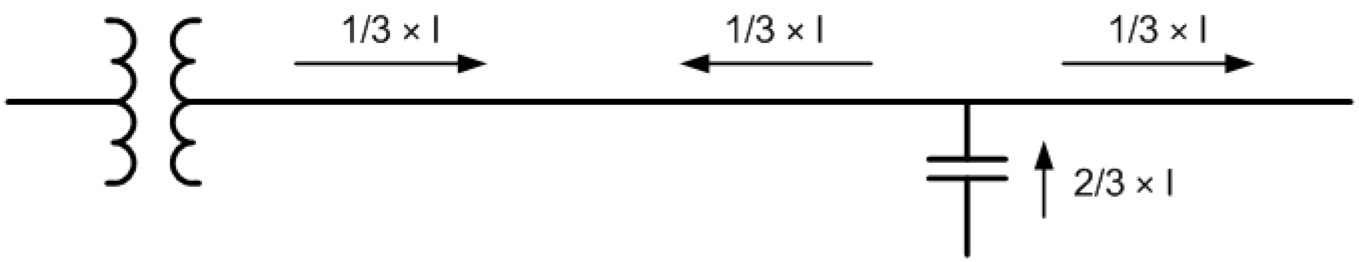
Impact of Capacitor Bank

- 1800 kVAR capacitor bank



Capacitor Placement

- 2/3 Rule



Place 2/3 of the needed kVAR 2/3 of the way down the feeder.

Fixed/Switched Capacitors

- Loads change over time
  - 24 hours of the day
  - 7 days of a week
  - 12 months of a year
- Loads change due to weather
- Loads change due to human activities
- Challenges
  - Size, location, timing
  - Minimize costs and losses
  - Transmission constrains, etc.

Capacitor Control

- Voltage
  - cheap & simple / ☹ for insignificant voltage drop
- Current
  - ☹ for high/low power factor (winter/summer) loads
- VAR
  - ☹ for multiple switched banks
- Temperature
  - cheap & simple / ☹ for special days
- Time
  - cheap & simple / ☹ for abnormal loads
- Power factor
- Automation
- Combination

Capacitor Switching

Q/A

Thank You

- Questions / comments?

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