Iowa State University

Real Distribution System Modeling and Analysis using OpenDSS

GRA: Fankun Bu

Advisor: Dr. Zhaoyu Wang

Department of Electrical and Computer Engineering

Iowa State University

Utility I

These slides have been edited to remove business-sensitive information.

Outline

- A Real Distribution System
  - System Information
  - Raw AMI Data
- Steps of Developing the OpenDSS Model
  - Process the Raw Data
  - Develop the OpenDSS Model
- Power Flow Analysis
- Matlab-OpenDSS Interface
- Numerical Results

A Real Distribution System

- Overview of System Information and Raw Data

This is a real distribution grid located at Midwest U.S, and it belongs to a municipal utility and it is a fully observable network with smart meters installed at all customers.

System Information

- 2 substations
- 4 load tap changing substation transformers (69/13.8 kV)
- 14 feeders (83 miles)
- 1489 overhead line sections
- 2582 underground cable sections
- 5 capacitor banks
- 361 switching devices
- >1000 distribution transformers
- 5212 customers

AMI Data

- Time period: >4 year (2015-2018)
- 4321 residential customers
- 696 small commercial customers
- 146 large commercial customers
- 17 industrial customers
- 32 other customers
- Time resolution:
  - Hourly – residential, small commercial
  - 15-min – large commercial, industrial

A Real Distribution System

- Overview of System Information and Raw Data

https://www.milsoft.com/utility-solutions/upgrades/engineering-analysis-windmil

System Model 1-- Map

- Geographic information
- Overhead line
- Underground cable
- Circuit breaker
- Switch
- Fuse
- Capacitor bank
- Distribution transformer

System Model 2 -- Milsoft model

- Geographic information
- Equivalent voltage source
- Substation transformer
- Tap changer
- Circuit breaker
- Switch
- Fuse
- Capacitor bank
- Overhead line
- Underground cable

A Real Distribution System

- Overview of System Information and Raw Data

Hourly energy & instantaneous voltage

Time

one Acct.

Account		time	kWH or V	time	kWH or V	time	kWH or V	time	kWH or V
100000001	KWH	201704000000	0.392	201704000000	0.257	201704000000	0.215	201704000000	0.239
100000001	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240
100000002	KWH	201704000000	0.245	201704000000	0.204	201704000000	0.252	201704000000	0.342
100000002	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	240
100000003	KWH	201704000000	1.479	201704000000	0.417	201704000000	0.816	201704000000	0.414
100000003	VOLTS	201704000000	240	201704000000	239	201704000000	239	201704000000	240
100000004	KWH	201704000000	1.009	201704000000	0.555	201704000000	0.39	201704000000	0.382
100000004	VOLTS	201704000000	241	201704000000	237	201704000000	237	201704000000	239
100000005	KWH	201704000000	0.798	201704000000	0.809	201704000000	0.87	201704000000	0.692
100000005	VOLTS	201704000000	239	201704000000	238	201704000000	238	201704000000	240
100000006	KWH	201704000000	0.109	201704000000	0.188	201704000000	0.205	201704000000	0.148
100000006	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	242
100000007	KWH	201704000000	1.199	201704000000	1.512	201704000000	1.759	201704000000	1.474
100000007	VOLTS	201704000000	241	201704000000	240	201704000000	239	201704000000	241
100000008	KWH	201704000000	0.422	201704000000	0.419	201704000000	0.43	201704000000	0.537
100000008	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240
100000009	KWH	201704000000	2.288	201704000000	2.278	201704000000	2.335	201704000000	2.297
100000009	VOLTS	201704000000	243	201704000000	242	201704000000	242	201704000000	242
100000010	KWH	201704000000	0.223	201704000000	0.257	201704000000	0.292	201704000000	0.25
100000010	VOLTS	201704000000	242	201704000000	241	201704000000	241	201704000000	241

…

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Raw AMI data

A Real Distribution System

- System Information

What is distribution system map?

A distribution system map contains all the electric devices in a distribution grid, as well as geographic information. The map makes a foundation for utility's normal operation and future planning.

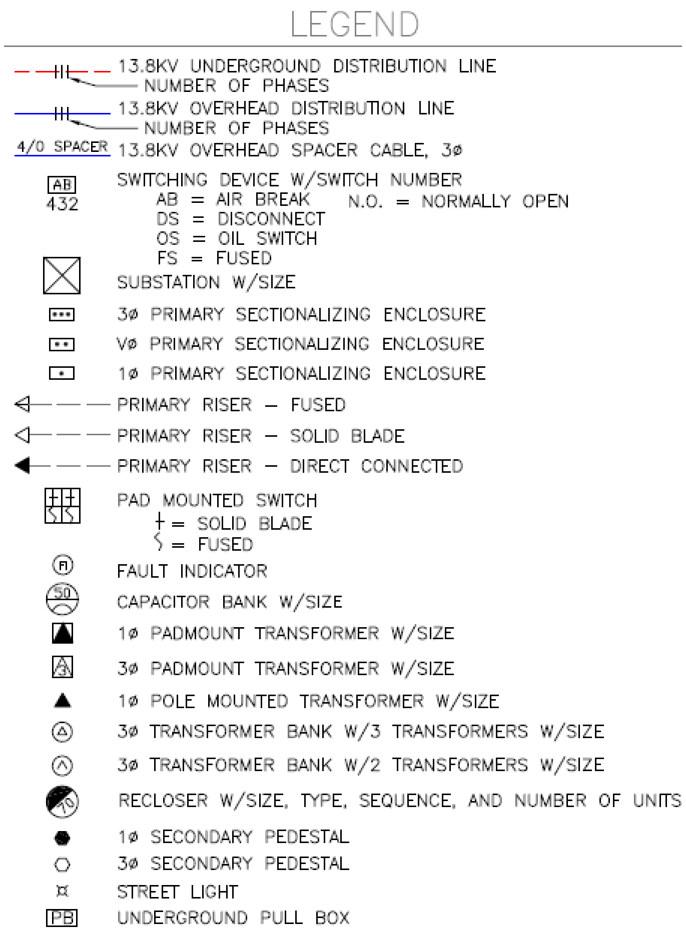
Distribution system map of the IEEE-123 Node test feeder

This map contains most of the following information:

1. Lines
   a. Location
   b. Distances
   c. Conductor sizes
   d. Phasing
2. Distribution transformers
   a. Location
   b. kVA rating
   c. Phase connection
3. In-line transformers
   a. Location
   b. kVA rating
   c. Connection
4. Shunt capacitors
   a. Location
   b. kvar rating
   c. Phase connection
5. Voltage regulators
   a. Location
   b. Phase connection
   c. Type
      i. Single-phase
      ii. Three-phase
6. Switches
   a. Location
   b. Normal open/close status

A Real Distribution System

- System Information



A Real Distribution System

- System Information
  - What is Milsoft?

The Milsoft System is an Engineering and Operations System for electric utility planning, analysis, operations and management.

It enables an electric utility to achieve optimum economy, efficiency, productivity, reliability, safety and customer service. The System is founded upon a detailed model of a utility's as-built, as-energized electric network.

The primary functions include

- Geographic Information System (GIS)
- Engineering Analysis (EA)
- Outage Management System (OMS)
- Communications (IVR)

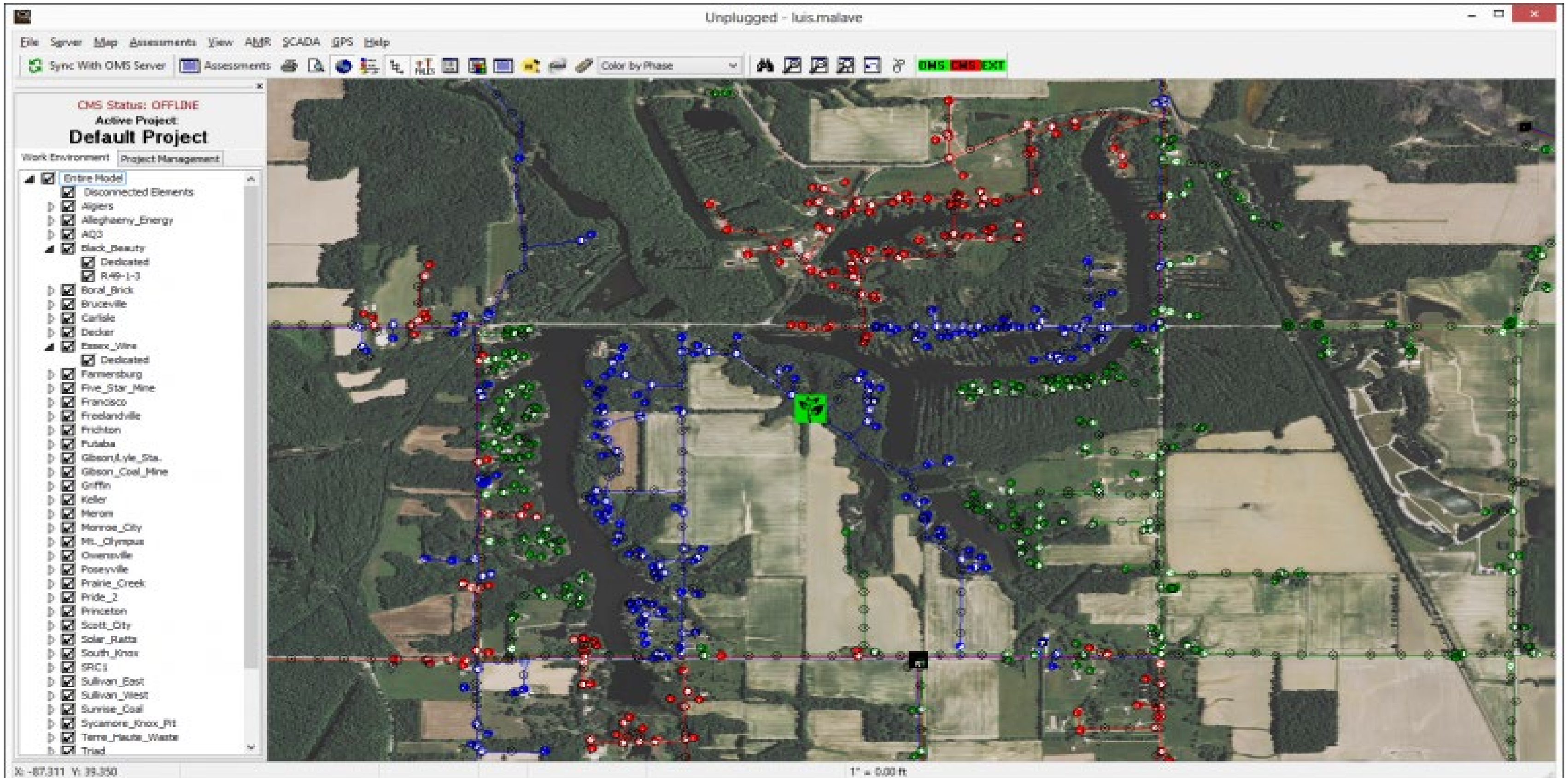
MILSOFT
Utility Solutions
Engineering Analysis • Outage Management
GIS & Field Engineering • Communications

[1] https://www.milsoft.com/about

A Real Distribution System

- System Information

  Geographic Information System (GIS) can utilize detailed geographical information of a practical network to build the consistent system in the software.



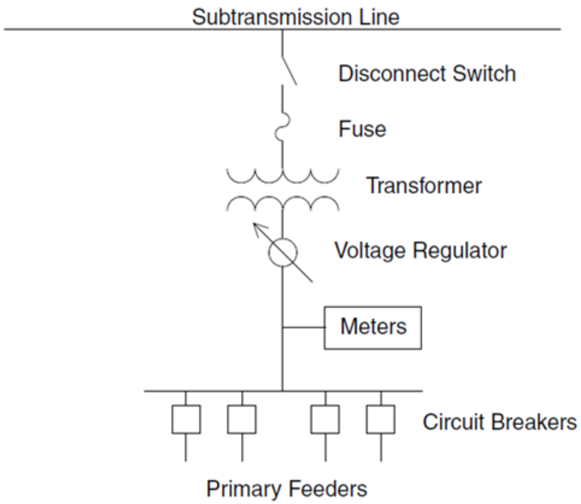
A Real Distribution System

- System Information

Substations	2
Substation Transformers	4
Regulators	4
Feeders	14
Total Feeder Length	83 miles
# of Overhead Line Sections	1489
# of Underground Cable Sections	2582
Capacitor Banks	5
Switches	361

A Real Distribution System

- System Information
  - Substation



https://www.qualitrolcorp.com/grid-applications/transmission-distribution/

The function of a distribution substation is to 'step down' high voltage electricity from the transmission or sub-transmission system to lower voltage electricity, so it can be easily supplied to homes and businesses through the distribution lines.

Devices:

- Substation transformer
- Voltage Regulator
- Disconnect Switch
- Circuit breaker
- Fuse

A Real Distribution System

- System Information
  - Substation

    There are four main functions of a distribution substation:

    1) Voltage transformation:
       - One or more transformers will always be located within the substation to step down the voltage to the primary distribution voltage level.
       - These transformers will normally be three-phase banks, or they will be three single-phase banks connected in a three-phase configuration.
       - Generally, the voltage levels of incoming lines are 69 kV, 115 kV and 138 kV. The output voltage levels include 4.16kV, 7.2kV, 12.47kV, 13.2kV, 14.4kV, 23.9kV, and 34.5kV.

http://home.eng.iastate.edu/~jdm/index.htm

A Real Distribution System

- System Information
  - Substation

2) Switching and protection: Different kinds of switchgear will be located at the substation, including switches, circuit breakers, reclosers, and fuses.

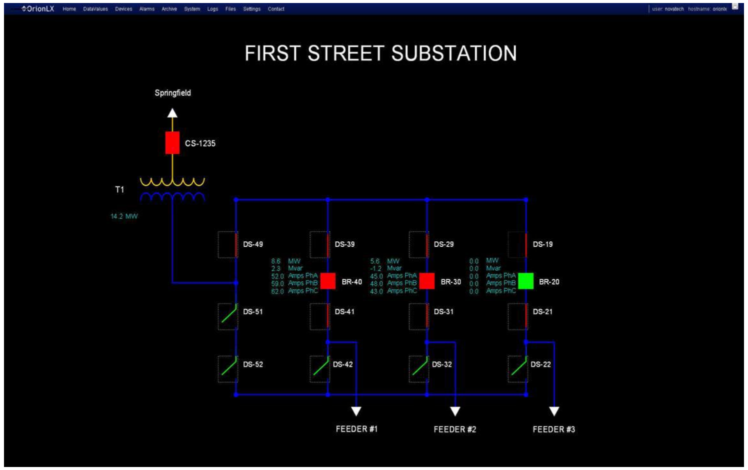
3) Voltage regulation: Because the current flows from source to load along the feeder, and because the feeder has some amount of impedance, the feeder will cause a voltage drop. As a result, we must regulate the voltage along the feeder as the load varies. Ways to do this include substation load tap-changing transformers (LTCs), voltage regulators, and fixed or switched shunt capacitors.

http://home.eng.iastate.edu/~jdm/index.htm

A Real Distribution System

- System Information
  - Substation

    4) <u>Metering:</u> Most substations have some sort of metering devices that record currents, voltages and powers of some specific electric devices. Digital recording is also heavily used and capable of recording a large amount of substation operational information.

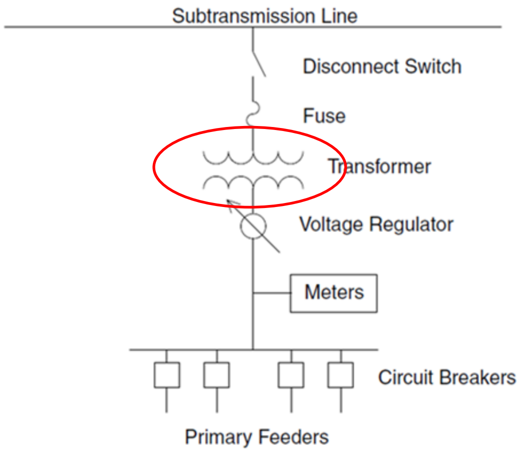


http://www.myerspowerproducts.com/index.php?option=com_content&view=category&id=167&Itemid=378&lang=en

https://www.novatechweb.com/substation-automation/web-server-hmi/

A Real Distribution System

- System Information
  - Substation transformer (Ch. 8)



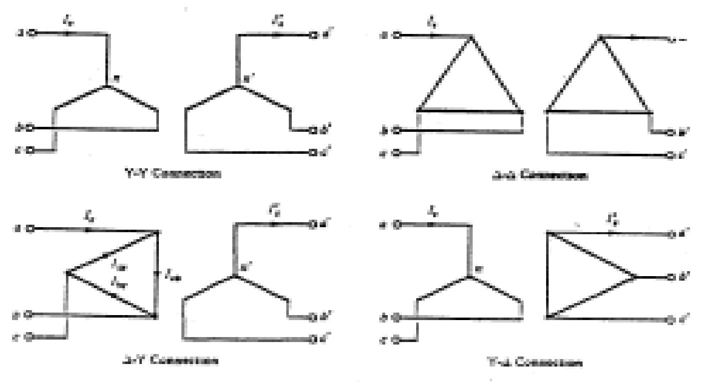
- Substation transformers provide the conversion from sub-transmission circuits to the distribution primary. Most substation transformers are connected as delta – grounded wye, to provide a *ground source* for the distribution neutral and to isolate the distribution ground system from the sub-transmission system.

- Substation transformers are *always* three-phase installations. They are *always* in the step-down configuration.

https://electrical-engineering-portal.com/distribution-substation

A Real Distribution System

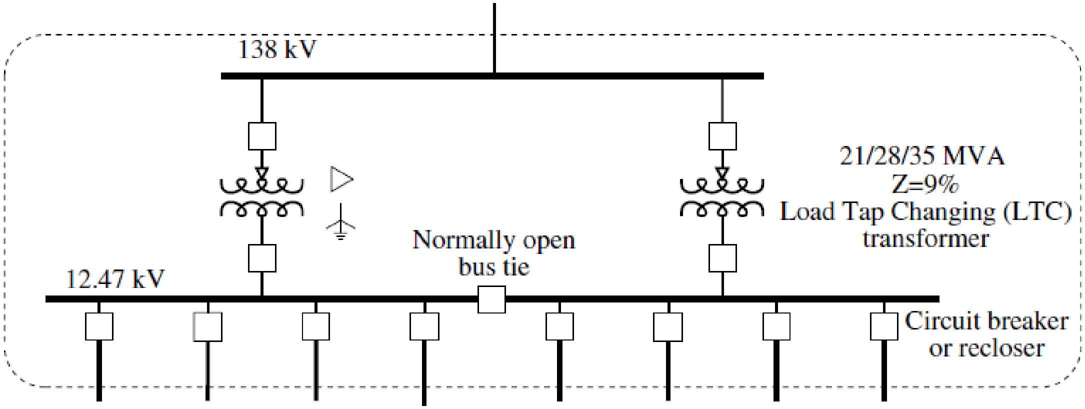
- System Information
  - Substation transformer
    - The ratings of substation tranformers generally fall within the range of 500 kVA (5 MVA) in smaller rural substations to over 8000 kVA (80 MVA) at urban substations.
    - There are two basic transformer designs: three interconnected single phase transformers and one three-phase transformer.
    - Four type of connections: Y-Y, Δ-Δ, Δ-Y, Y-Δ

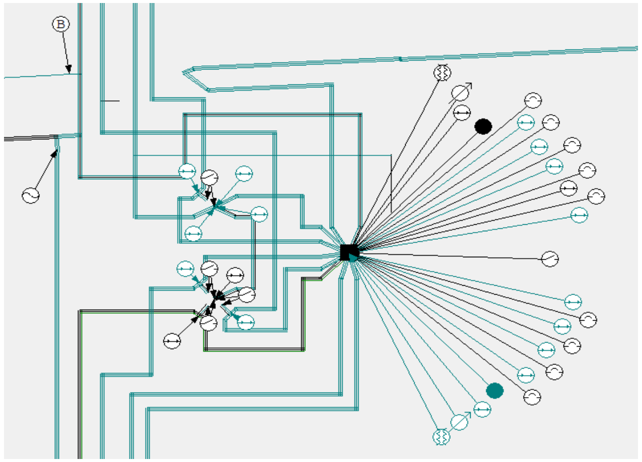


	Substation 1		Substation 2	
	Transformer 1	Transformer 2	Transformer 1	Transformer 2
kV rating	69/13.8 kV	69/13.8 kV	69/13.8 kV	69/13.8 kV
kVA rating	10,000 kVA	10,000 kVA	10,000 kVA	10,000 kVA
Connection	Delta-Wye	Delta-Wye	Delta-Wye	Delta-Wye
% Imp	6.39%	7.71%	7.59%	7.67%
X/R	5	5	5	5

A Real Distribution System

- System Information
  - Substation transformer
    - Generally, to achieve high reliability, the design in the figure below is implemented.

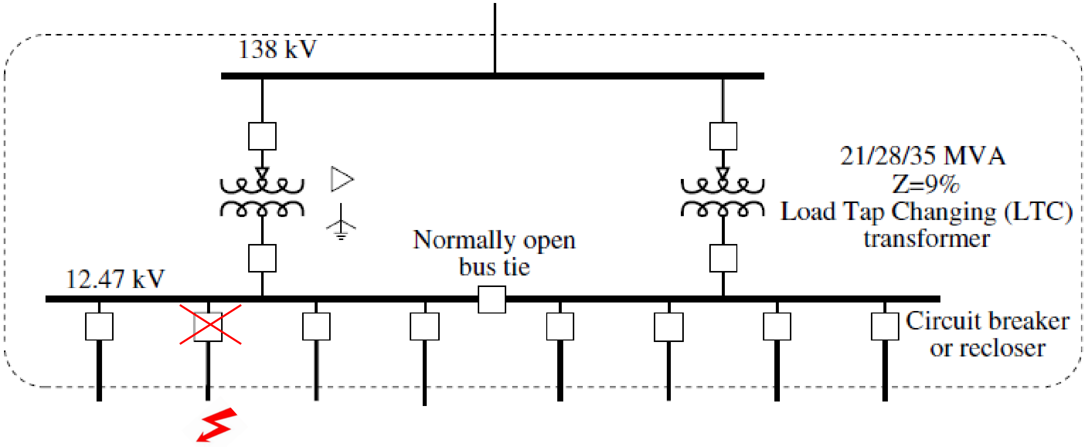


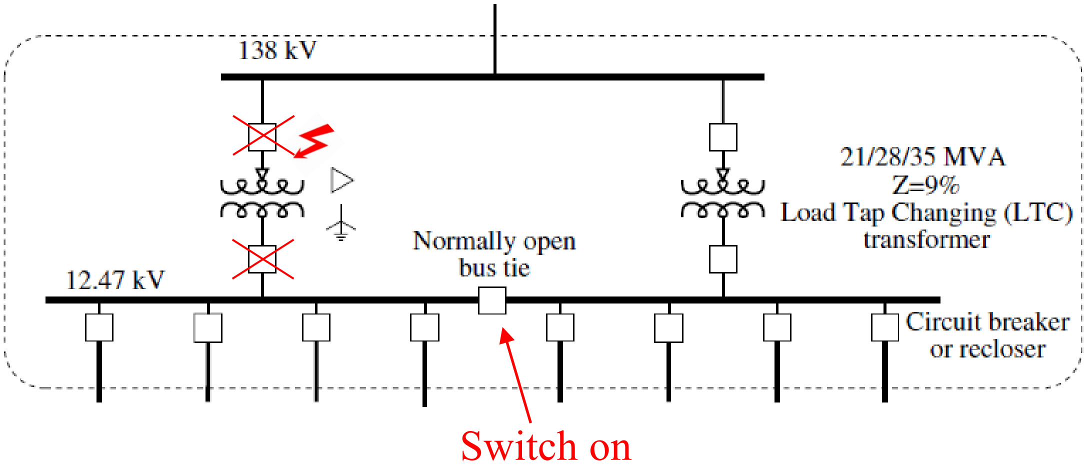


    - This type of design provides that all feeders can remain supplied for a transformer outage (caused by maintenance or fault), by switching on certain normally-open switches or circuit breakers.
    - Momentary parallel operation during switching is often permissible but must be avoided for the extended operation time due to the high secondary currents.

A Real Distribution System

- System Information
  - Substation transformer

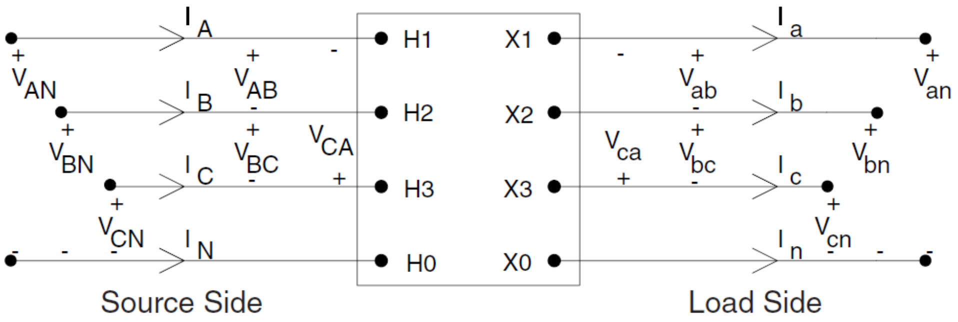




A Real Distribution System

- System Information
  - Substation transformer

    General transformer model:



- The figure above defines the various voltages and currents for all transformer banks connected between the source side *Node* n and the load side *Node m*. This model can represent a step-down or a step-up transformer bank.
- The generalized matrix equations for computing the voltages and currents at *Node* n as a function of the voltages and currents at *Node m* are given by:

$$[VLN_{ABC}] = [a_t] \cdot [VLN_{abc}] + [b_t] \cdot [I_{abc}]$$

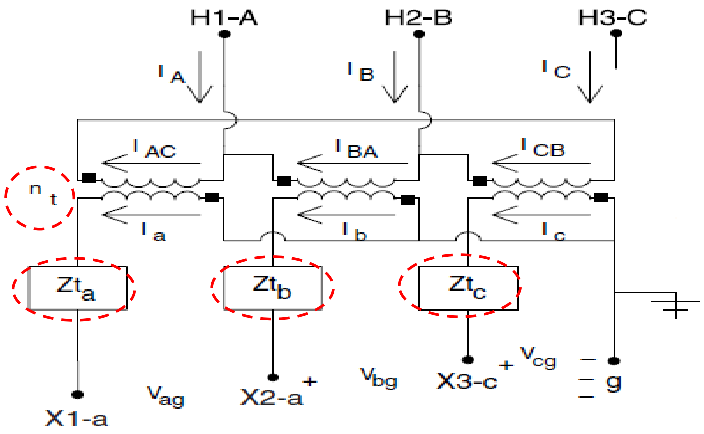
$$[I_{ABC}] = [c_t] \cdot [VLN_{abc}] + [d_t] \cdot [I_{abc}]$$

A Real Distribution System

- System Information
  - Substation transformer

$$[VLN_{ABC}] = [a_t] \cdot [VLN_{abc}] + [b_t] \cdot [I_{abc}]$$
$$[I_{ABC}] = [c_t] \cdot [VLN_{abc}] + [d_t] \cdot [I_{abc}]$$

For a specific delta-grounded wye step-down connection transformer, we have the following model and parameters



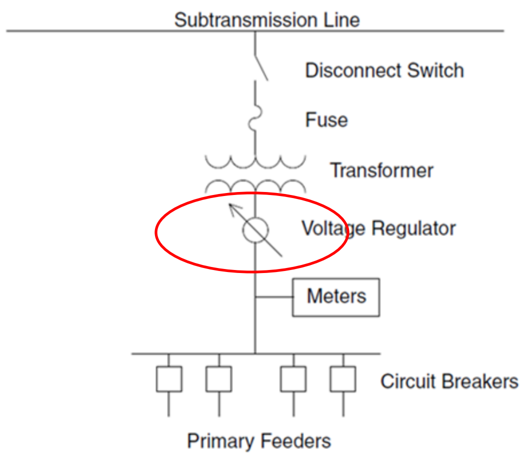
$$[a_t] = \frac{-n_t}{3} \cdot \begin{bmatrix} 0 & 2 & 1 \\ 1 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} \qquad [b_t] = \frac{-n_t}{3} \cdot \begin{bmatrix} 0 & 2 \cdot Zt_b & Zt_c \\ Zt_a & 0 & 2 \cdot Zt_c \\ 2 \cdot Zt_a & Zt_b & 0 \end{bmatrix}$$

$$[c_t] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [d_t] = \frac{1}{n_t} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

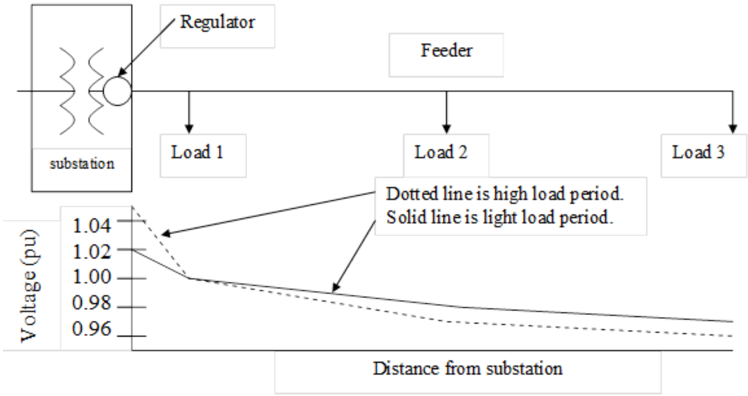
n_t is the turns ratio. Zt_a, Zt_b, and Zt_c are the impedances of phase A, phase B and phase C, respectively.
It can be seen that a_t, b_t, c_t and d_t depend on n_t, Zt_a, Zt_b, Zt_c, i.e., depend on the specific winding connection, impedance and rating of a transformer.

A Real Distribution System

- System Information
  - Voltage Regulator (Ch. 7)



- The purpose of a voltage regulator is to keep the voltage in a circuit relatively close to a desired value.
- As mentioned earlier, the voltage along a radial feeder decreases with the distance from the substation, because of the feeder voltage drop caused by the load current. That's why we need voltage regulation.



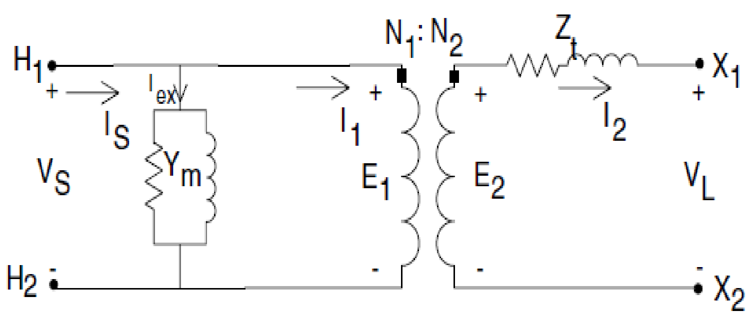
A Real Distribution System

- System Information
  - Voltage Regulator

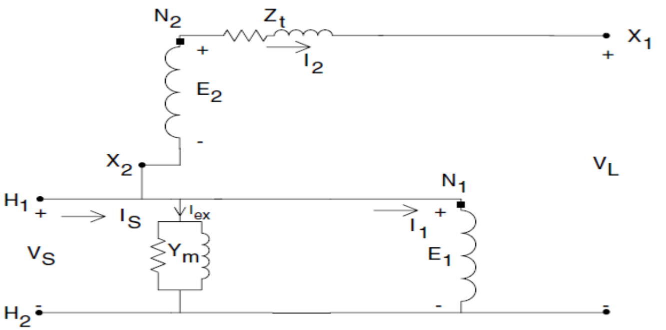
Generally, there are two types of voltage regulators:

- Step voltage regulator: It is a special transformer called an autotransformer, which has the ability to automatically change its turns ratio. It can be placed anywhere along the feeder.
- Load tap changer: it is similar to a step voltage regulator, but it is always in the substation.

A step-voltage regulator consists of an autotransformer and a load tap changing mechanism. First, let’s talk about the autotransformer. A two-winding transformer can be connected as an autotransformer, by changing its connection. For example, connecting the high-voltage terminal H1 to the low-voltage terminal X2 can create a “step-up” autotransformer.



A two-winding transformer

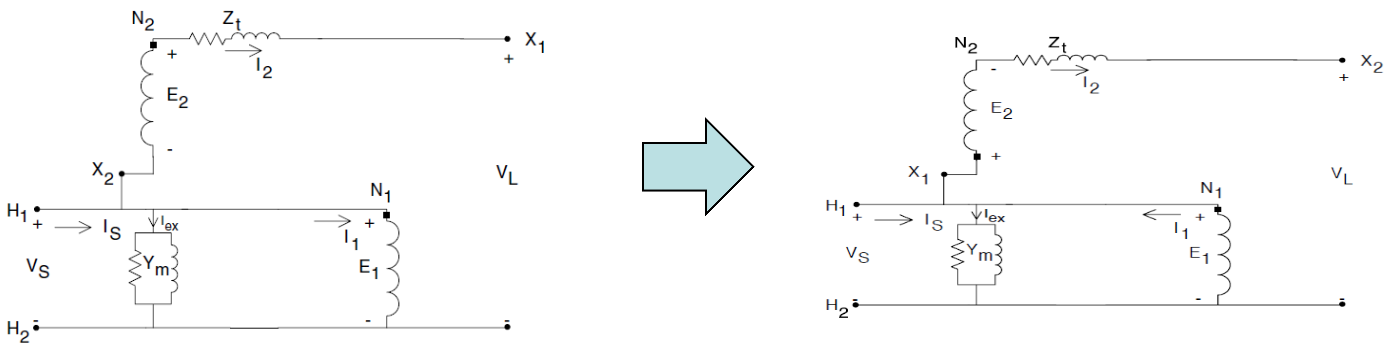


Step-up autotransformer

A Real Distribution System

- System Information
  - Voltage Regulator

A step-down autotransformer can be created by reversing the connection between the shunt and series winding in a step-up auto-transformer.



Step-up autotransformer $\frac{V_L}{V_S} = \frac{N_2 + N_1}{N_1} = 1 + \frac{N_2}{N_1}$

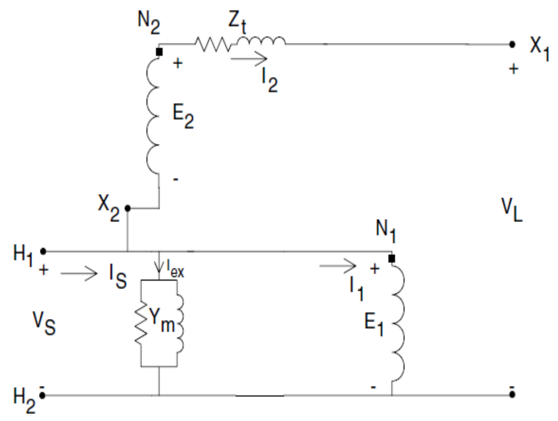
Step-down autotransformer $\frac{V_L}{V_S} = \frac{-N_2 + N_1}{N_1} = 1 - \frac{N_2}{N_1}$

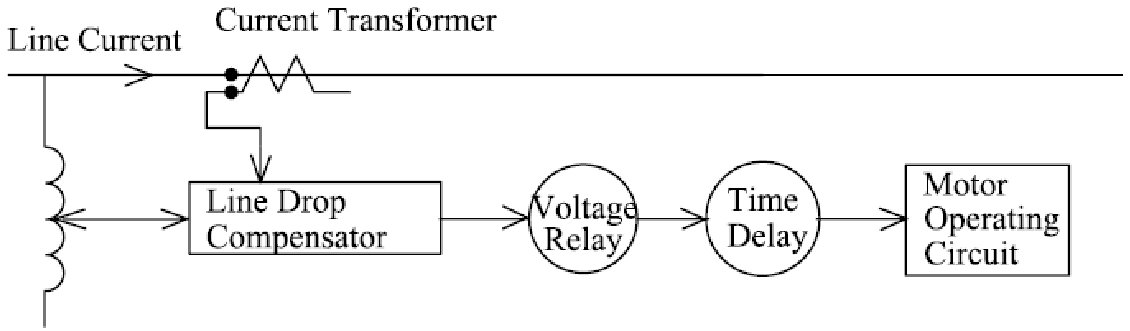
The generalized equations of substation transformers also applies to autotransformers.

$$[VLN_{ABC}] = [a_t] \cdot [VLN_{abc}] + [b_t] \cdot [I_{abc}]$$
$$[I_{ABC}] = [c_t] \cdot [VLN_{abc}] + [d_t] \cdot [I_{abc}]$$

A Real Distribution System

- System Information
  - Voltage Regulator
    - As mentioned earlier, a step-voltage regulator consists of an autotransformer and a load tap changing mechanism. The voltage change is obtained by changing the taps of the series winding of the autotransformer. The position of the tap is determined by a control circuit (line drop compensator).
    - The block diagram below shows the circuit that controls tap changing on a step-voltage regulator.





Step-voltage regulator control circuit.

A Real Distribution System

- System Information
  - Voltage Regulator
    - *Voltage Level*: the desired voltage (on a 120-V base) to be held at the load center.
    - *Bandwidth*: the allowed variance of the load center voltage from the set voltage level. The voltage held at the load center will be ± one half the bandwidth.
    - *Time Delay*: length of time that a raise or lower operation is called for before the actual execution of the command. This prevents taps changing during a transient or short time change in current.
    - *Line Drop Compensator*: Set to compensate for the voltage drop (line drop) between the regulator and the load center. The settings consist of R and X settings in volts, which are corresponding to the equivalent impedance between the regulator and the load center. This setting may be zero if the regulator output terminals are the load center.

    - Generally, standard step-voltage regulators contain a reversing switch enabling a ±10% regulator range.
    - Note that the required rating of a step-voltage regulator is based upon the *kVA transformed*, not the kVA rating of the line. In general, this will be 10% of the line rating since rated current flows through the series winding which represents the ±10% voltage change.

A Real Distribution System

- System Information
  - Voltage Regulator

Two types of step voltage regulators:

(1) Type A

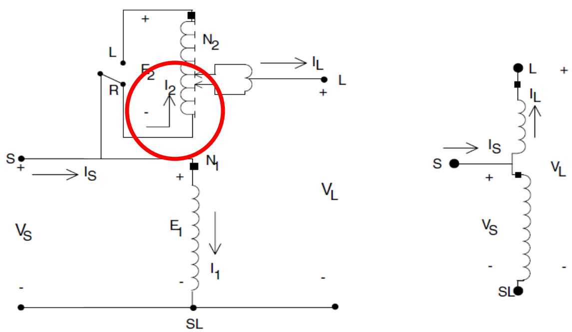


FIGURE 7.7
Type A step-voltage regulator in the raise position.

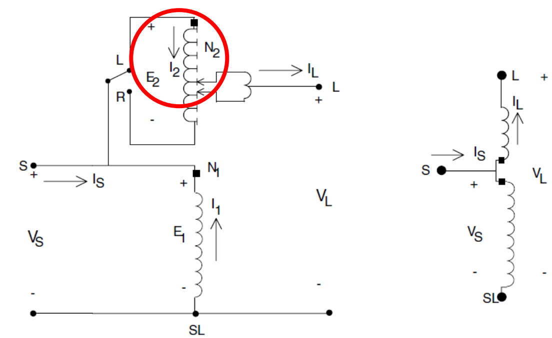


FIGURE 7.8
Type A step-voltage regulator in the lower position.

(2) Type B

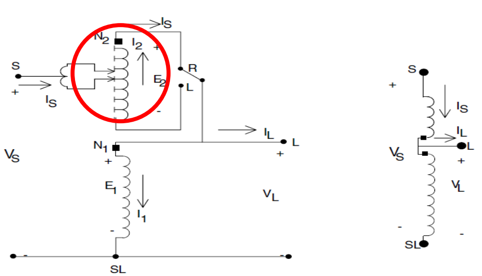


FIGURE 7.9
Type B step-voltage regulator in the raise position.

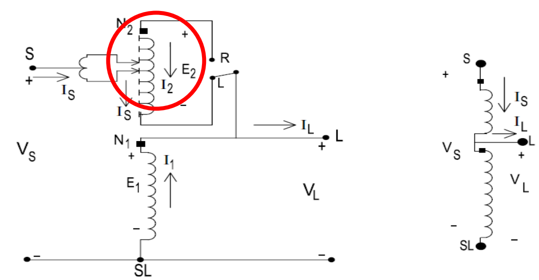


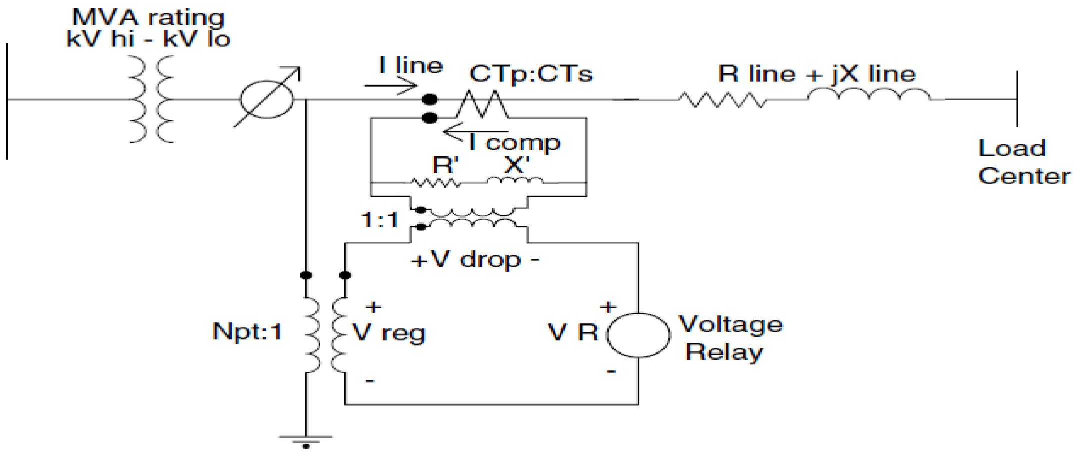
FIGURE 7.10
Type B step-voltage regulator in the lower position.

A Real Distribution System

- System Information
  - Voltage Regulator

    The line drop compensator:

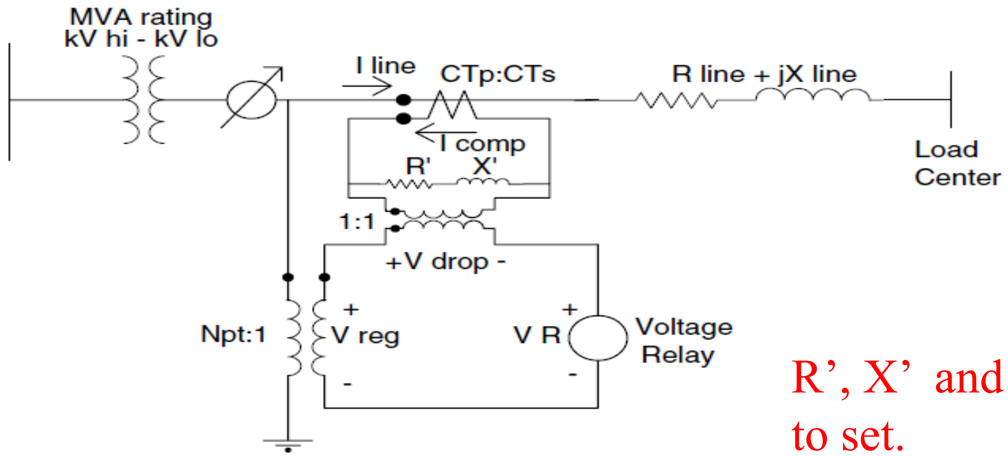
    - The changing of taps on a volatge regulator is controlled by the line drop compensator.
    - This figure shows a simplified sketch of a compensator circuit and how it is connected to the distribution line through a potential transformer and a current transformer.
    - The purpose of the line drop compensator is to model the voltage drop of the distribution line from the regulator to the load center.



Line drop compensator circuit.

A Real Distribution System

- System Information
  - Voltage Regulator



R', X' and VR are needed to set.

Line drop compensator circuit.

- *CTp:* primary current rating, typically be the rated current of the feeder,
- *CTs*: secondary rated current of the current transformer, usually 5 A
- *CTp*:*CTs*: the current transformer turns ratio,
- *R'*: R settings in volts,
- *X'*: X settings in volts,
- *Npt*: the turns ratio of the potential transformer,
- *Vreg:* the input voltage to the compensator,
- V_R : desired voltage.

A Real Distribution System

- System Information
  - Voltage Regulator

Generally, R and X setting of the line volatge drop are in terms of volts (R' and X'), to estimate them, first, calculate the base impedance values both in the line and in the compensator

Base	Line Circuit	Compensator Circuit
Voltage	V_{LN}	$\frac{V_{LN}}{N_{PT}}$
Current	CT_P	CT_S
Impedance	$Zbase_{\text{line}} = \frac{V_{LN}}{CT_P}$	$Zbase_{\text{comp}} = \frac{V_{LN}}{N_{PT} \cdot CT_S}$

With the computed base values, the compensator *R* and *X* settings in ohms can be calculated by first computing the per-unit line impedance:

$$R_{pu} + jX_{pu} = \frac{Rline_{\Omega} + jXline_{\Omega}}{Zbase_{\text{line}}} = (Rline_{\Omega} + jXline_{\Omega}) \cdot \frac{CT_P}{V_{LN}}$$

The compensator impedance in ohms is computed by multiplying the per-unit impedance by the base compensator impedance:

$$Rcomp_{\Omega} + jXcomp_{\Omega} = (R_{pu} + jX_{pu}) \cdot Zbase_{\text{comp}} = (Rline_{\Omega} + jXline_{\Omega}) \cdot \frac{CT_P}{N_{PT} \cdot CT_S} \quad \Omega$$

A Real Distribution System

- System Information
  - Voltage Regulator

The compensator R and X settings in volts are determined by multiplying the compensator R and X in ohms times the rated secondary current in amps (CT_S) of the current transformer:

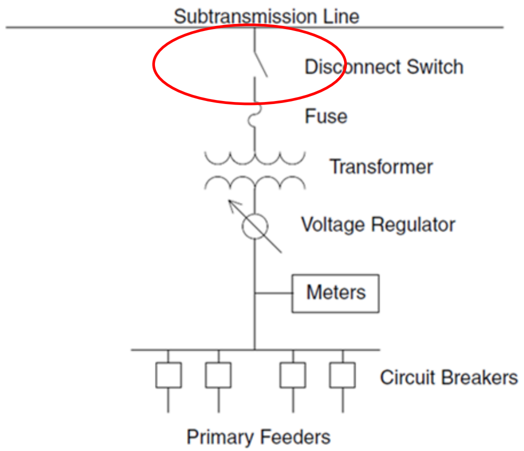
$$R' + jX' = (Rcomp_\Omega + jXcomp_\Omega) \cdot CT_S = (Rline_\Omega + jXline_\Omega) \cdot \frac{CT_P}{N_{PT}} \text{ V}$$

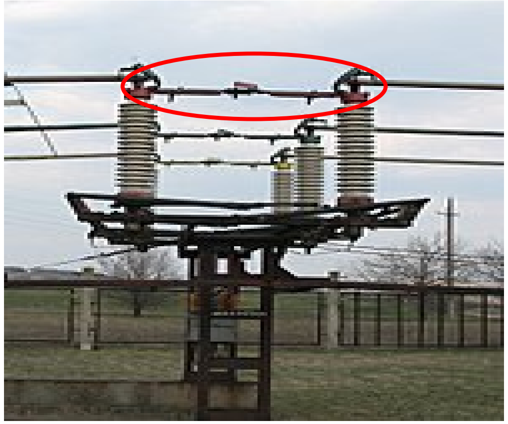
Parameters of the load tap changer:

	Substation 1		Substation 2	
	LTC 1	LTC 2	LTC 1	LTC 2
kV rating	13.8 kV	13.8 kV	13.8 kV	13.8 kV
kVA rating	10.5 MVA	10.5 MVA	10.5 MVA	10.5 MVA
Connection	Wye-Wye	Wye-Wye	Wye-Wye	Wye-Wye
% Boost	10.00%	10.00%	10.00%	10.00%
Number of steps	16	16	16	16
Voltage bandwdith (volt)	2	2	2	2
CTp (A)	439	439	439	439

A Real Distribution System

- System Information
  - Disconnect Switch



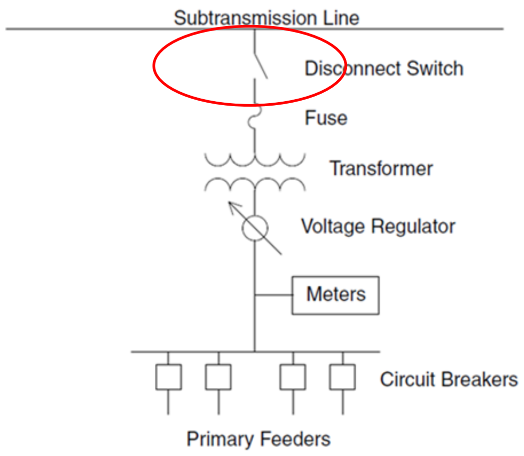


- Disconnect switch is one type of switching devices.
- Switching devices are used to close or open electrical circuits. The types of switching devices include:
  - Circuit breaker -- makes and breaks all currents, including normal currents and ***short-circuit*** currents
  - Switch -- makes and breaks currents that are ***smaller*** than the rated normal current
  - Disconnect switch (disconnector) – used for ***no-load*** closing and opening operation
  - Switch disconnector -- the combination of a switch and a disconnector
  - Fuse -- consists of a fuse base and a fuse link. The fuse link is used for ***one single breaking*** of a short circuit current.

https://electrical-engineering-portal.com/medium-voltage-switchgear-basics-of-switching-devices

A Real Distribution System

- System Information
  - Disconnect Switch



- The purpose of disconnect switches in substations is to allow ***isolation*** of apparatus such as circuit breakers, transformers, and transmission lines, for maintenance.
- The disconnect switch is usually not intended for normal control of the circuit, but only for ***safety isolation***, since it lacks a mechanism for suppression of electric arcs, which occurs when conductors carrying high currents are electrically interrupted.
- Thus, they are ***off-load*** devices, with very low breaking capacity, intended to be opened only after current has been interrupted by some other control devices, such as circuit breaker.

While *opening* a circuit, the below sequence should be followed

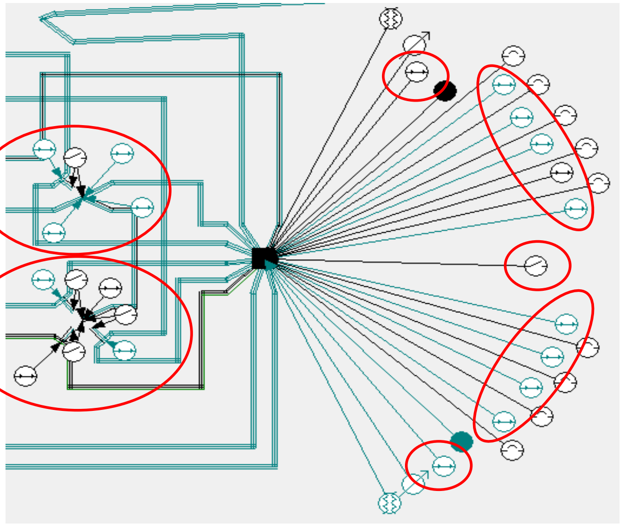
Open the circuit breaker → Open the disconnect switch

While *making* a circuit, the below sequence should be followed

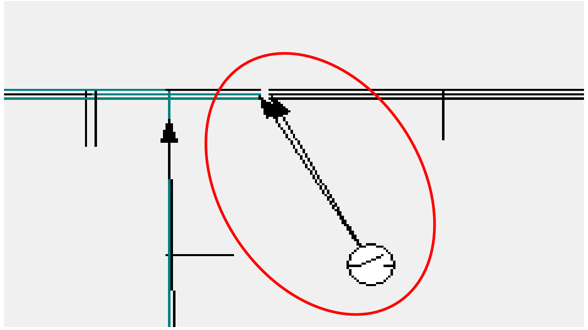
Close the disconnect switch → Close the circuit breaker

A Real Distribution System

- System Information
  - Disconnect Switch



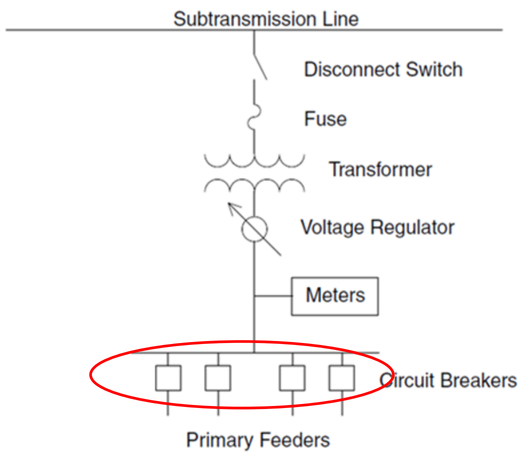
- In the real distribution system, there are *24* disconnect switches in substation 1.
- Some are normally open, some are normally closed.
- In general, circuit breaker-disconnect switch pairs are used for making or opening circuits.

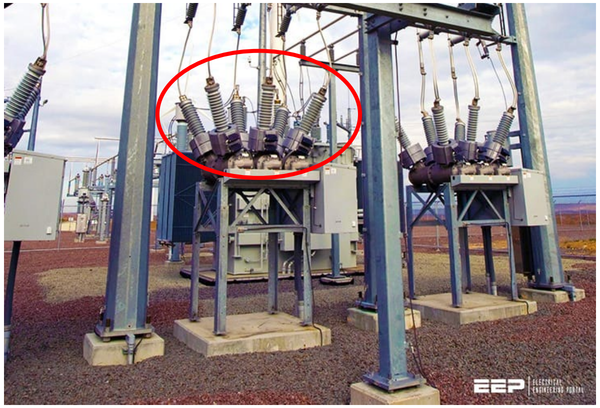


- There are also some in-line switches (e.g. circuit breakers), which are used for system protection and re-configurations.

A Real Distribution System

- System Information
  - Circuit Breaker



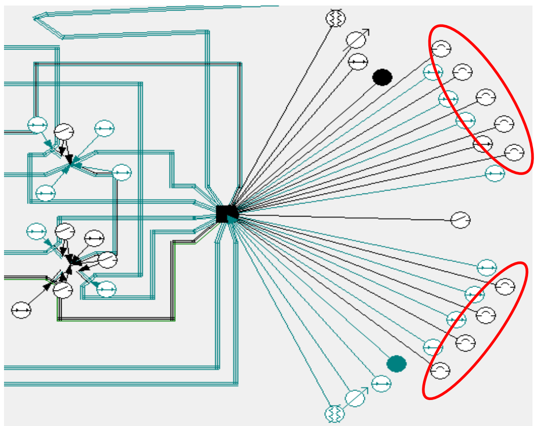


- Circuit breakers are often used in the substation on the bus and on each feeder.
- Circuit breakers are available with very high interrupting and continuous current ratings.
- The interrupting medium in circuit breakers can be any of vacuum, oil, or air, etc. Oil and vacuum breakers are most common in distribution substations.
- Circuit breakers are always ***paired*** with relays which sense short-circuit condition using potential transformers (PTs) and current transformers (CTs). The relays provide the brains to control the ***opening*** or ***closing*** of the circuit breaker, so the circuit breaker coordinates with other devices. While closing a circuit breaker, the relays perform reclosing functions.

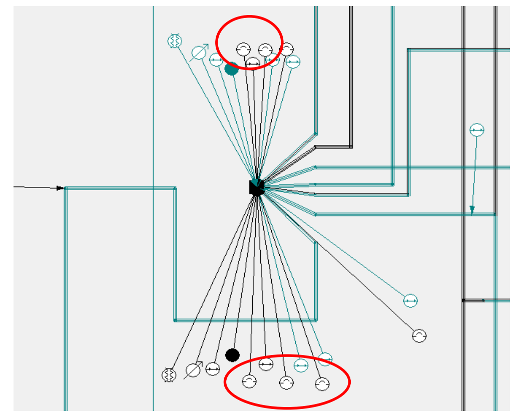
https://electrical-engineering-portal.com/substation-basics#circuit-breakers

A Real Distribution System

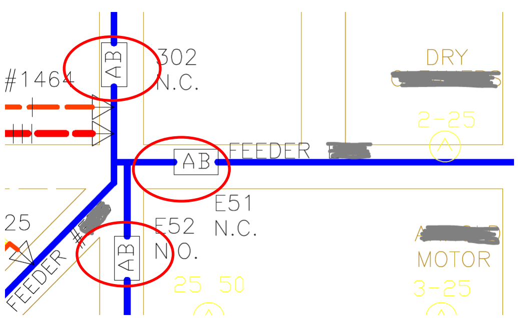
- System Information
  - Circuit Breaker



- In substation 1, there are 9 feeder circuit breakers.



- In substation 2, there are 5 feeder circuit breakers.



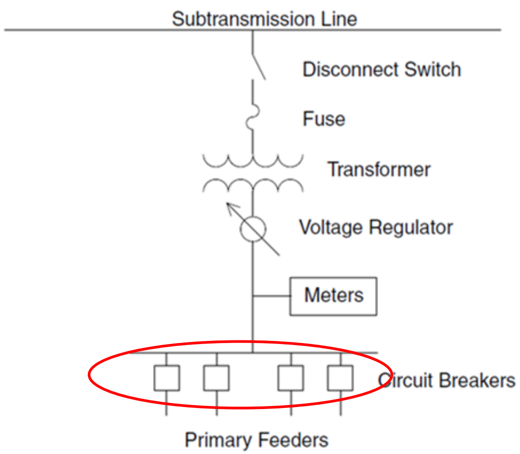
AB
432

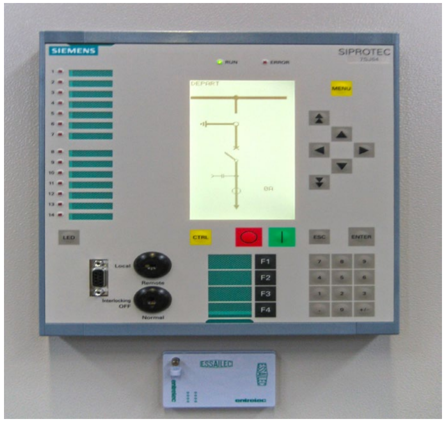
SWITCHING DEVICE W/SWITCH NUMBER

AB = AIR BREAK N.O. = NORMALLY OPEN
DS = DISCONNECT
OS = OIL SWITCH
FS = FUSED

A Real Distribution System

- System Information
  - Relay





https://en.wikipedia.org/wiki/Digital_protective_relay

- Relays are used for ***controlling*** distribution circuit breakers. The basic idea is that if the short-circuit current (or other measurements) exceeds a preset value and remains higher for longer than the delay time set, the relay will trip the circuit breaker.

- Distribution circuits are almost always protected by ***overcurrent*** relays that use ***inverse time-current*** characteristics. Also, instantaneous relay trip is implemented by utilities, although not common.

- The main types of relays include
  - Electromechanical relay
  - Static relay
  - Digital relay — A most modern relay technology which is fully digital based on microprocessor components.

A Real Distribution System

- System Information
  - Relay
    - An ***inverse time-current*** characteristic means that the relay will operate faster with increased current.
    - Inverse time-current characteristic is expressed as

$$t = TD\left(\frac{A}{M^p - 1} + B\right)$$

where

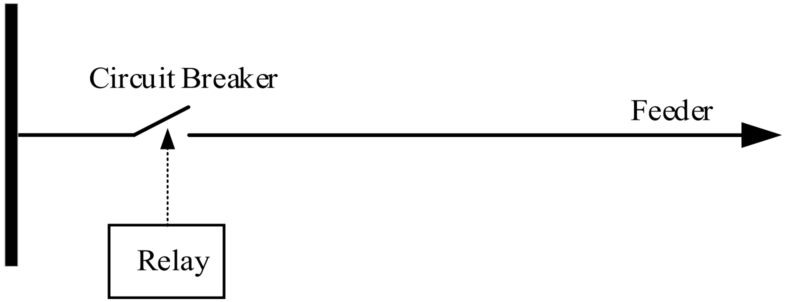
t = trip time, sec

M = multiple of pickup current ($M > 1$)

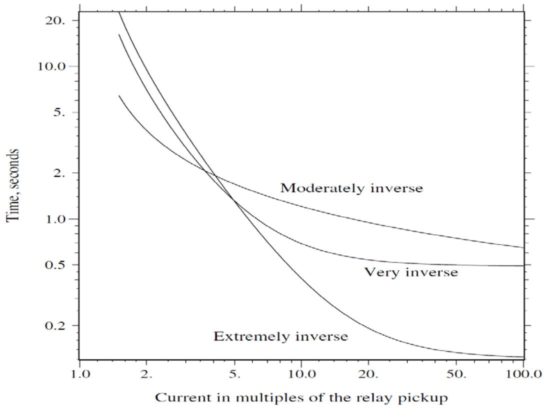
TD = time dial setting

A, B, p = curve shaping constants

M = short-circuit current/current setting

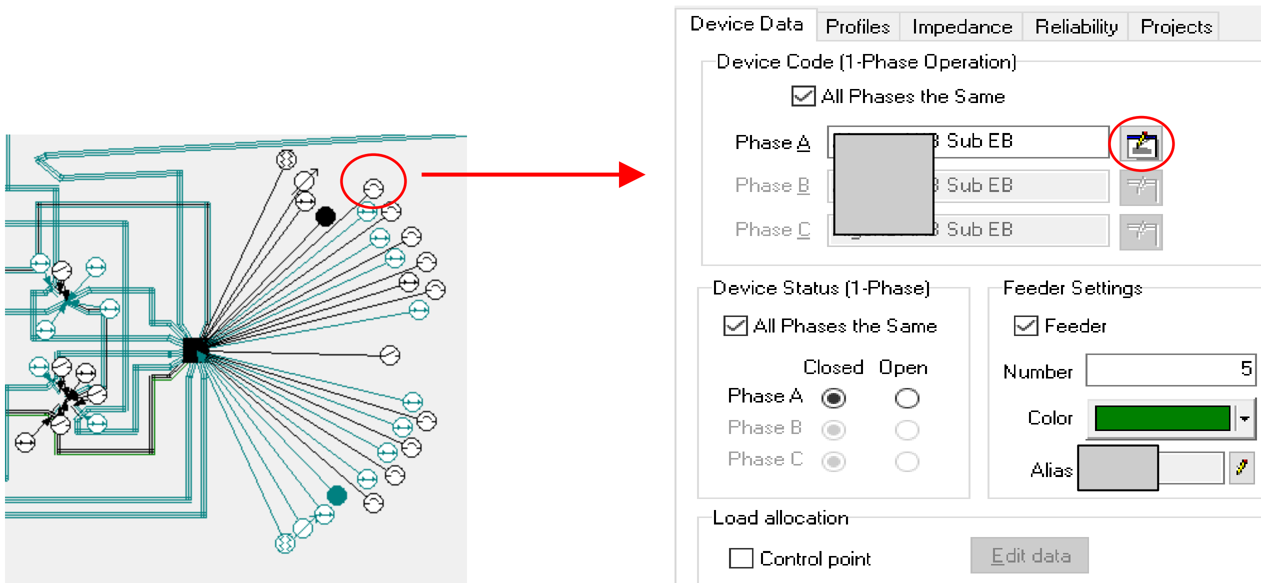


The higher the short-circuit current, the faster a relay trips.



A Real Distribution System

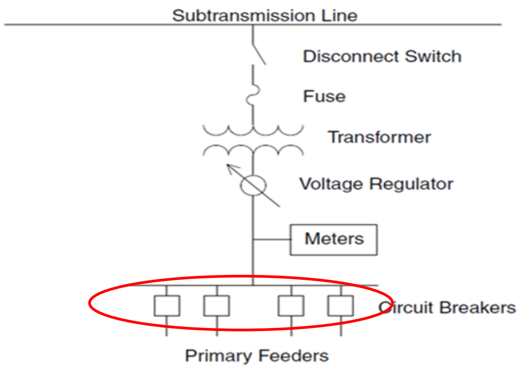
- System Information
  - Relay



In the real distribution system, there is no separate relay devices for the circuit breakers, the functions of relays are performed by reclosers.

A Real Distribution System

- System Information
  - Recloser



- Recloser is a ***self-controlled*** device for automatically interrupting and reclosing an AC circuit, with a predetermined sequence of opening and reclosing.

- Like a circuit breaker, a recloser can be used for ***interrupting*** currents. The interrupting medium of a recloser is most commonly vacuum or oil.

- The recloser control can be electronic, electromechanical or hydraulic. A hydraulic recloser uses springs and hydraulic systems for timing and actuation.

- In short, a recloser is a circuit breaker which is integrated with a relay and a reclosing control element.

A fault occurs → The recloser opens the circuit → The recloser reclose the circuit

- Temporary fault → Success, keep closed
- Permanent fault → Reopen, reclose, until finally open the circuit

https://www.arteche.com/en/reclosers-and-switches

A Real Distribution System

- System Information
  - Recloser

Why do we need the function of reclosing?

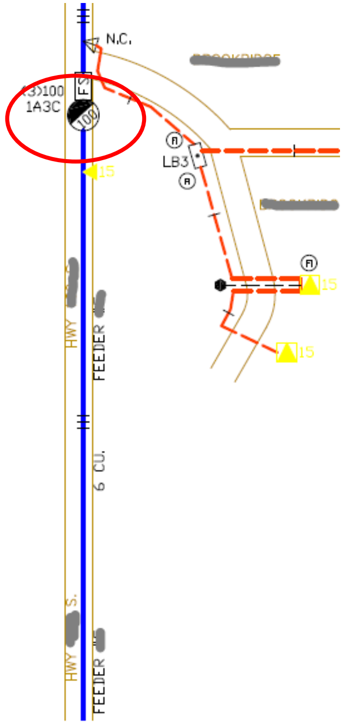
Automatic reclosing is motivated by the fact that about ***60-80%*** of all overhead distribution faults are temporary and last only a few cycles or a few seconds. For example, a branch may blow against a circuit and then fall to the ground. As a result, it becomes very attractive to reclose following an initial opening of the protection device.

Reclosers have many distribution applications.

- It can be used in the substation as feeder interrupters instead of circuit breakers. Reclosers are used more in ***smaller stations*** and circuit breakers more in larger stations.
- Three-phase reclosers can be used on the main feeder to provide necessary protection coverage on ***longer*** circuits, along with improved reliability.
- Reclosers are available as ***single-phase*** units, so they can be used on single-phase taps (laterals) instead of fuses.
- Another common application is in ***auto-loop automation*** schemes to automatically sectionalize customers after a fault.
- Three-phase reclosers are available that can operate each phase ***independently*** (so a single-phase fault will only open one phase).

A Real Distribution System

- System Information
  - Recloser



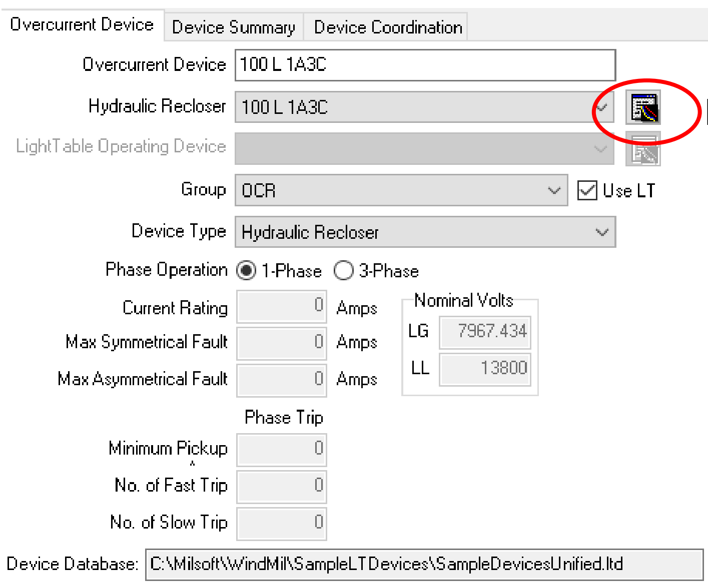
The real corresponding picture from Google Map

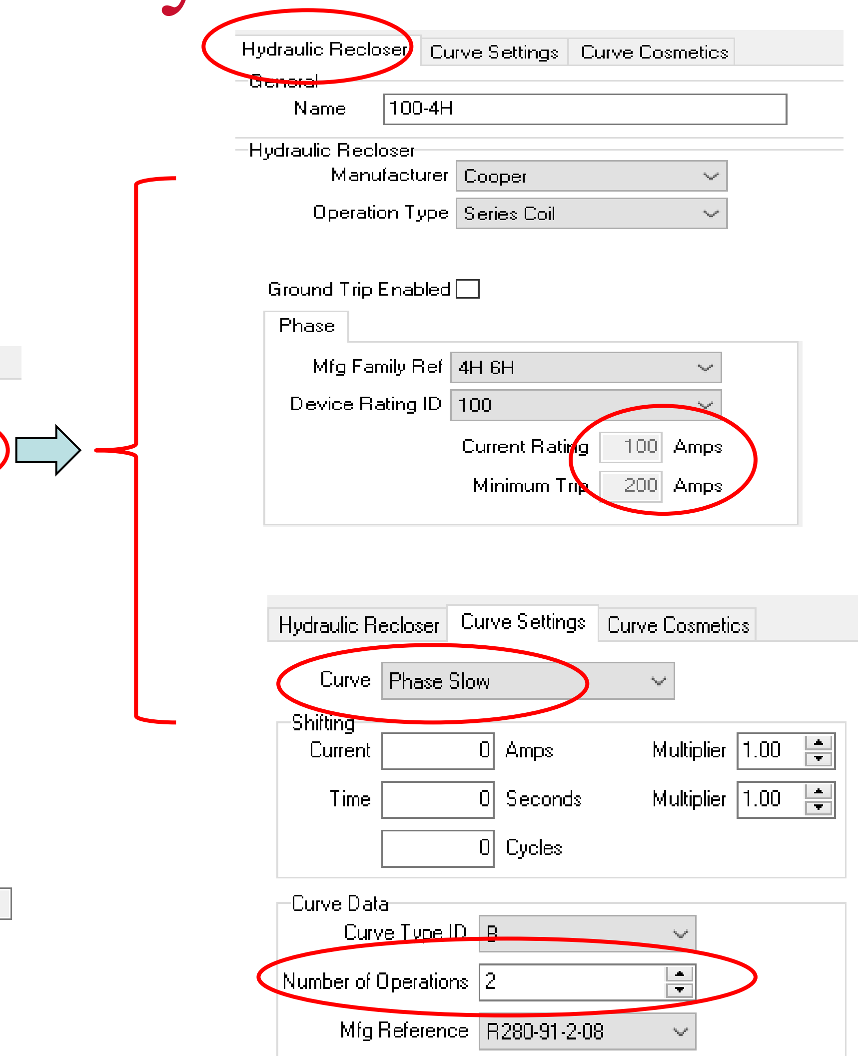
RECLOSER W/SIZE, TYPE, SEQUENCE, AND NUMBER OF UNITS

Current rating

A Real Distribution System

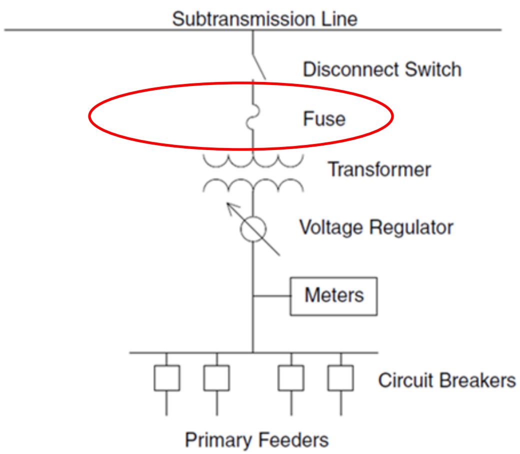
- System Information
  - Recloser



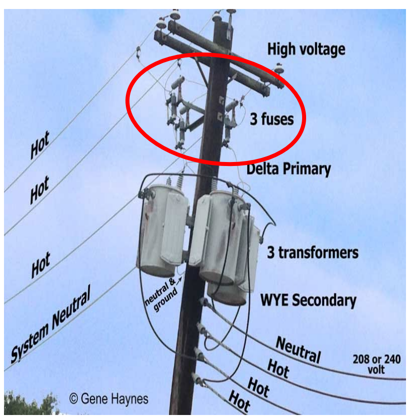


A Real Distribution System

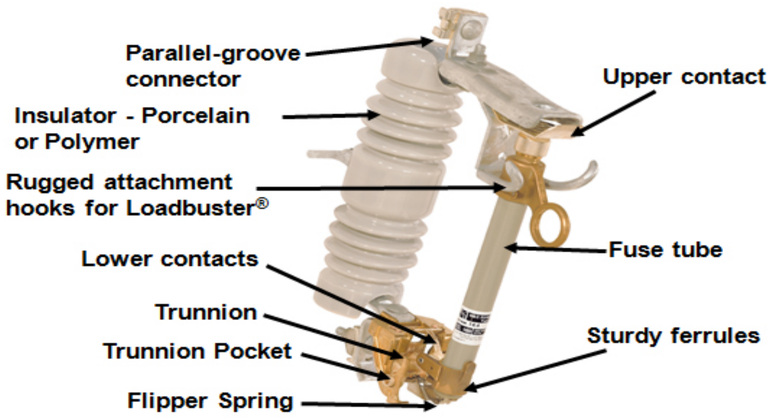
- System Information
  - Fuse



- Fuses have elements that melt if enough current flows through it for enough time.
- They are inexpensive, and can open very fast for high currents.
- The most common type of fuses is the expulsion type within a cutout. A cutout is used to support the fuse and enable efficient replacement when it is blown.



https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/substation_equipment/high_voltage_fuses.html



https://www.eng-tips.com/viewthread.cfm?qid=442197

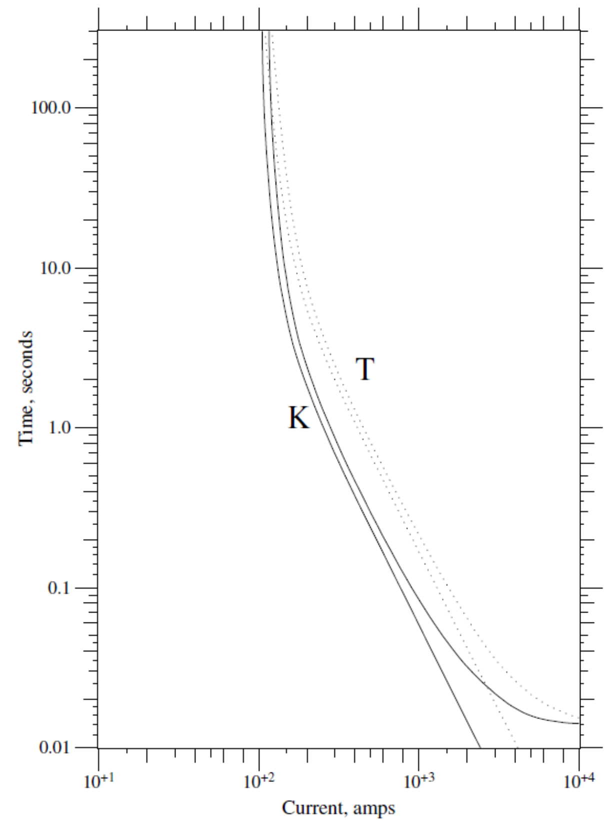
A Real Distribution System

- System Information
  - Fuse

    Some characteristics of the fuse:
    - Interruption is relatively ***fast*** and can occur in a half of a cycle for large currents.
    - The I^2t value of a fuse is often needed to ***coordinate*** between fuses. For the same current, fuses with larger I^2t value melt slower than fuses with smaller I^2t value.
    - Industry standards specify two types of expulsion fuses.
      - **K-type**: fast fuse with speed ratio of 6-8
      - **T-type**: slower fuse with speed ratio of 10-13
    - The speed ratio is the ratio of
      - The melting current at 0.1 second to
      - the melting current at X seconds, where X is 300 for fuse ratings below 100 amps and X is 600 for fuse ratings above 100 amps.

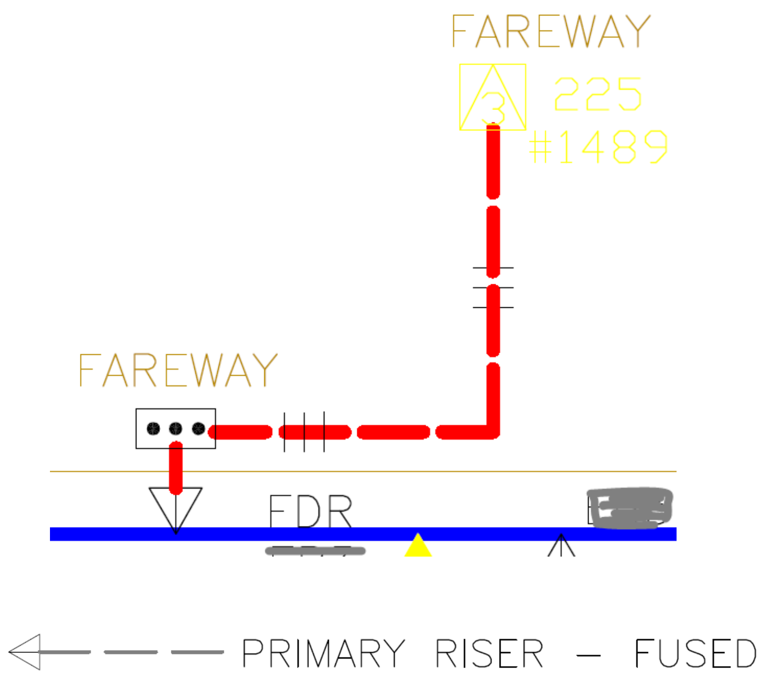
      The current rating is the level of current the fuse can safely carry for an indefinite period of time.

The higher the short-circuit current, the faster a fuse melts.



A Real Distribution System

- System Information
  - Fuse



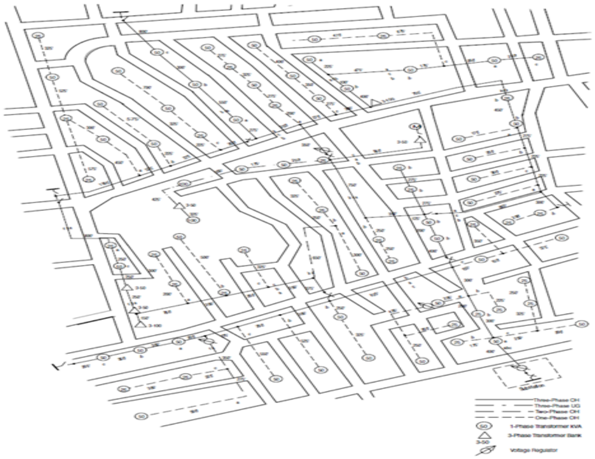
A lateral supplying a Fareway market. Fuses are installed at the head of the lateral for protection.

Real corresponding picture from Google Map

A Real Distribution System

- System Information
  - Primary Distribution System

https://www.gegridsolutions.com/multilin/resource/Feeder/UniFlip_Publication/document.pdf



The primary distribution system consists of the ***feeders*** emanating from the substation and supplying power to one or more secondary distribution systems. Normally, primary feeders are 3-phase circuits.

Feeders are almost ***always*** radial from substation to loads (i.e., one way flow of power) in rural areas, ***usually*** radial in residential neighborhoods, and they are ***often*** radial even in urban areas. In densely populated urban areas, particularly commercial and business districts where reliability is critical, feeders may be ***looped***.

A Real Distribution System

- System Information
  - Primary Distribution System -- Overhead Line

There are ***two*** types of primary feeders, overhead line and underground cable.
Overhead line:

- Along streets, alleys, through woods, and in backyards, many of the distribution lines that feed customers are overhead structures.
- Because overhead lines are exposed to trees and animals, to wind and lightning, and to cars and kites, they are a ***critical component*** in the reliability of distribution circuits.

Some typical constructions:

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(a) Three-phase 34.5-kV armless construction with covered wire.

(b) Single-phase circuit, line-to-ground 7.2 kV.

(c) Single-phase circuit, 4.8-kV.

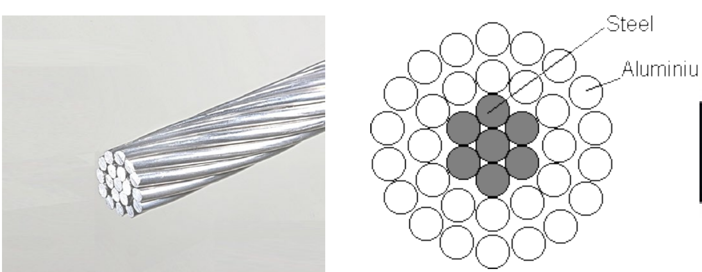
A Real Distribution System

- System Information
  - Primary Distribution System -- Overhead Line

Conductor:

Definition of wire: A wire is metal drawn or rolled to long lengths, normally understood to be a solid wire. Wires may or may not be insulated. A conductor is one or more wires suitable for carrying electric current. Often the term conductor is used to mean wire.

Most conductors are either ***aluminum*** or ***copper***. Utilities use aluminum for almost all new overhead installations. Aluminum is lighter and less expensive for a given current-carrying capability. Copper was installed more in the past, so significant lengths of copper are still in service on overhead circuits.



Aluminum conductor steel-reinforced cable(ACSR)

Copper

https://www.okonite.com/product-catalog/section-2/

Size	Material	Resistance (Ω/mile)	Diameter (inch)	GMR (feet)	Capacity (A)
4/0	ACSR	0.592	0.563	0.00814	340
1/0	ACSR	1.12	0.355	0.00446	230
4	ACSR	2.55	0.257	0.00452	140
2	ACSR	1.65	0.316	0.00504	180
6	CU	2.41	0.201	0.00568	130
2	CU	0.87	0.3	0.0083	200
4/0	AA	0.554	0.512	0.0167	326
1/0	AA	1.114	0.362	0.0111	228

A Real Distribution System

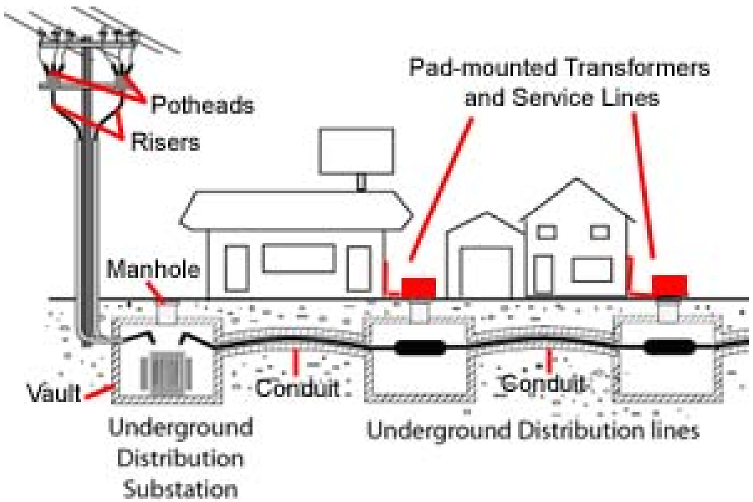
- System Information
  - Primary Distribution System -- Underground Cable

Underground cable:

- Much new distribution is underground. Underground cable is much more hidden from view than overhead circuits, and is ***more reliable***.
- However, an underground circuit typically costs anywhere from 1 to 2.5 times the equivalent overhead circuit.

There are seven distinguishing features with regards to cable construction:

- Single phase vs. polyphaser
- Neutral
- Conductor
- Insulation
- Shielding
- Jackets
- Burial

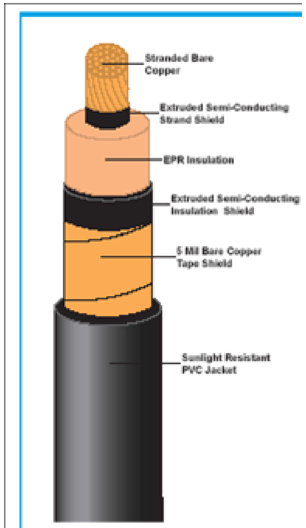


https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/substation.html

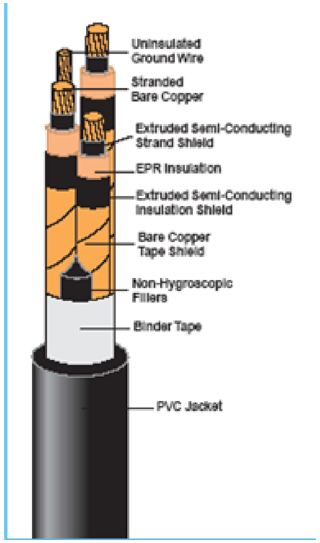
A Real Distribution System

- System Information
  - Primary Distribution System -- Underground Cable
    - Single phase vs. polyphaser

Cables may have 1, 2, 3, or 4 conductors. Use of multiple conductors saves money, as only 1 shield and 1 jacket is needed and they are easier to install.



single phase cable



3 phase cable

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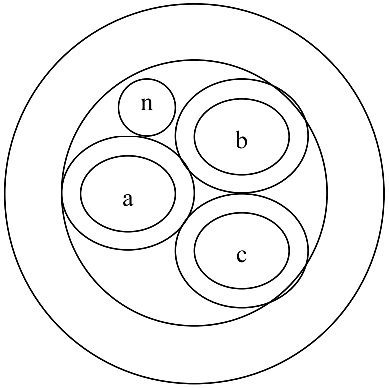
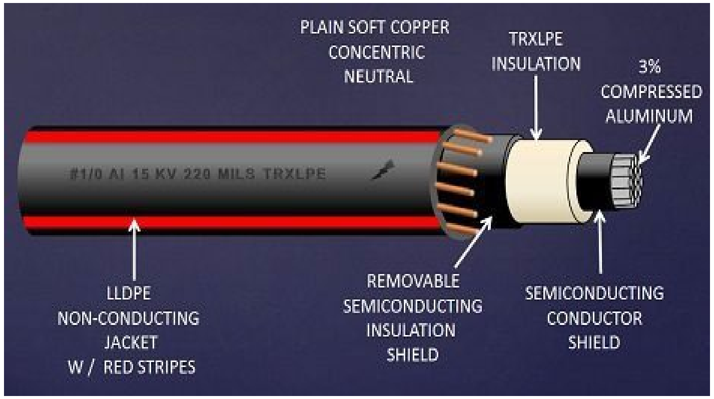
A Real Distribution System

- System Information
  - Primary Distribution System -- Underground Cable
    - Neutral

The neutral may be ***non-concentric*** or ***concentric***. The non-concentric neutral typically has only a single neutral wire. Concentric neutrals, on the other hand, have neutral wires wound helically around the insulation shield.



non-concentric



concentric

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https://solutions.borderstates.com/whats-the-difference-between-epr-and-tr-xlp-cable/

A Real Distribution System

- System Information
  - Primary Distribution System -- Underground Cable
    - Conductor

      Like the overhead lines, conductors may be copper or aluminum for underground cables. Copper is a slightly better conductor than aluminum (lower resistivity) and therefore the same ampacity can be achieved with a lower diameter cable.
    - Insulation

      There are three basic types of cable insulation in use today: paper, plastic compounds, rubber or rubber-like compounds.
    - Shielding

      The shield is a conducting layer surrounding another part of the cable.
    - Jackets

      The jacket is also referred to as the armor, and like this latter name suggests, its function is to provide physical protection from environmental and installation conditions.

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A Real Distribution System

- System Information
  - Primary Distribution System -- Underground Cable

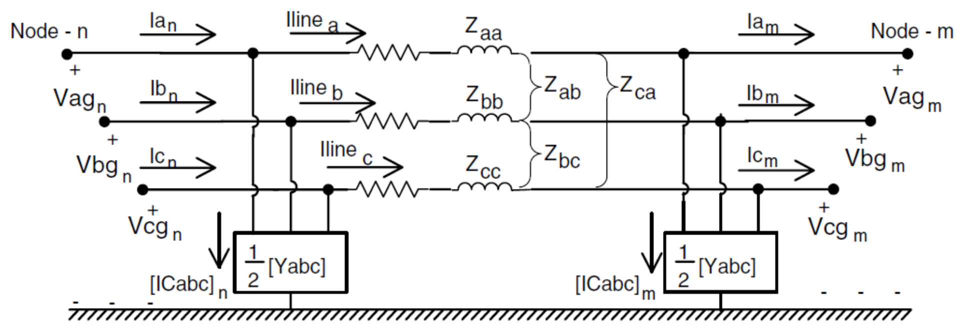
Overhead vs. Underground: Advantages of Each

Overhead	Underground
Cost — Overhead's number one advantage. Significantly less cost, especially initial cost.	*Aesthetics* — Underground's number one advantage. Much less visual clutter.
Longer life — 30 to 50 years vs. 20 to 40 for new underground works.	*Safety* — Less chance for public contact.
Reliability — Shorter outage durations because of faster fault finding and faster repair.	*Reliability* — Significantly fewer short and long-duration interruptions.
Loading — Overhead circuits can more readily withstand overloads.	*O&M* — Notably lower maintenance costs (no tree trimming).
	Longer reach — Less voltage drop because reactance is lower.

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:



- The figure above shows an exact model of a three-phase, two-phase, or single-phase overhead or underground line. When a line segment is two-phase (V-phase) or single-phase, some of the impedance and admittance values will be zero.
- The two equations relating the input (*Node n*) voltages and currents to the output (*Node m*) voltages and currents are as follows:

$$[VLG_{abc}]_n = [a]\cdot[VLG_{abc}]_m + [b]\cdot[I_{abc}]_m$$

$$[a] = [U] + \frac{1}{2}\cdot[Z_{abc}]\cdot[Y_{abc}]$$

$$[b] = [Z_{abc}]$$

U – Identity matrix

$Zabc$ – Series impedance matrix

$$[Z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$$

$$[I_{abc}]_n = [c]\cdot[VLG_{abc}]_m + [d]\cdot[I_{abc}]_m$$

$$[c] = [Y_{abc}] + \frac{1}{4}\cdot[Y_{abc}]\cdot[Z_{abc}]\cdot[Y_{abc}]$$

$$[d] = [U] + \frac{1}{2}\cdot[Z_{abc}]\cdot[Y_{abc}]$$

$Yabc$ – Shunt admittance matrix

$$[Y_{abc}] = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}$$

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

To calculate Zabc matrix, first, we calculate the self and mutual impedances of all conductors, using the ***conductor*** and ***construction*** information. The two equations for calculating self and mutual impedances are as follows

$$\begin{cases} \widehat{z_{ii}} = r_i + 0.09530 + j0.12134(\ln \frac{1}{GMR_i} + 7.93402)\ \Omega/\text{mile} & (4.41) \\ \widehat{z_{ij}} = 0.09530 + j0.12134(\ln \frac{1}{D_{ij}} + 7.93402)\Omega/\text{mile} & (4.42) \end{cases}$$

Then, a primitive impedance matrix is built using the calcualted self- and mutual-impedances:

$$[\hat{z}_{\text{primitive}}] = \begin{bmatrix} \hat{z}_{aa} & \hat{z}_{ab} & \hat{z}_{ac} & | & \hat{z}_{an1} & \hat{z}_{an2} & \hat{z}_{anm} \\ \hat{z}_{ba} & \hat{z}_{bb} & \hat{z}_{bc} & | & \hat{z}_{bn1} & \hat{z}_{bn2} & \hat{z}_{bnm} \\ \hat{z}_{ca} & \hat{z}_{ca} & \hat{z}_{cc} & | & \hat{z}_{cn1} & \hat{z}_{cn2} & \hat{z}_{cnm} \\ --- & --- & --- & --- & --- & --- & --- \\ \hat{z}_{n1a} & \hat{z}_{n1b} & \hat{z}_{n1c} & | & \hat{z}_{n1n1} & \hat{z}_{n1n2} & \hat{z}_{n1nm} \\ \hat{z}_{n2a} & \hat{z}_{n2b} & \hat{z}_{n2c} & | & \hat{z}_{n2n1} & \hat{z}_{n2n2} & \hat{z}_{n2nm} \\ \hat{z}_{nma} & \hat{z}_{nmb} & \hat{z}_{nmc} & | & \hat{z}_{nmn1} & \hat{z}_{nmn2} & \hat{z}_{nmnm} \end{bmatrix} \quad (4.45)$$

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

$$[\hat{z}_{\text{primitive}}] = \begin{bmatrix} \hat{z}_{aa} & \hat{z}_{ab} & \hat{z}_{ac} & | & \hat{z}_{an1} & \hat{z}_{an2} & \hat{z}_{anm} \\ \hat{z}_{ba} & \hat{z}_{bb} & \hat{z}_{bc} & | & \hat{z}_{bn1} & \hat{z}_{bn2} & \hat{z}_{bnm} \\ \hat{z}_{ca} & \hat{z}_{ca} & \hat{z}_{cc} & | & \hat{z}_{cn1} & \hat{z}_{cn2} & \hat{z}_{cnm} \\ --- & --- & --- & --- & --- & --- & --- \\ \hat{z}_{n1a} & \hat{z}_{n1b} & \hat{z}_{n1c} & | & \hat{z}_{n1n1} & \hat{z}_{n1n2} & \hat{z}_{n1nm} \\ \hat{z}_{n2a} & \hat{z}_{n2b} & \hat{z}_{n2c} & | & \hat{z}_{n2n1} & \hat{z}_{n2n2} & \hat{z}_{n2nm} \\ \hat{z}_{nma} & \hat{z}_{nmb} & \hat{z}_{nmc} & | & \hat{z}_{nmn1} & \hat{z}_{nmn2} & \hat{z}_{nmnm} \end{bmatrix} \quad (4.45)$$

After that, the primitive impedance matrix is partitioned into four matrices:

$$[\hat{z}_{\text{primitive}}] = \begin{bmatrix} [\hat{z}_{ij}] & [\hat{z}_{in}] \\ [\hat{z}_{nj}] & [\hat{z}_{nn}] \end{bmatrix} \quad (4.46)$$

Finally, the primitive impedance matrix is reduced to a 3*3 phase frame matrix consisting of the self and mutual equivalent impedances for the three phases

$$[z_{abc}] = [\widehat{z_{ij}}] - [\widehat{z_{in}}] \cdot [\widehat{z_{nn}}]^{-1} \cdot [\widehat{z_{nj}}] \quad (4.53)$$

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

To calculate Yabc matrix of an overhead line, first, we calculate the self and mutual potential coefficients using ***conductor*** and ***construction*** information. The two equations used for calculating self and mutual potential coefficients are as follows:

$$\hat{P}_{ii} = 11.17689 \cdot \ln \frac{S_{ii}}{RD_i} \text{ mile}/\mu\text{F}$$

$$\hat{P}_{ij} = 11.17689 \cdot \ln \frac{S_{ij}}{D_{ij}} \text{ mile}/\mu\text{F}$$

Then, the primitive potential coefficient matrix is built as

$$[\hat{P}_{\text{primitive}}] = \begin{bmatrix} \hat{P}_{aa} & \hat{P}_{ab} & \hat{P}_{ac} & \bullet & \hat{P}_{an} \\ \hat{P}_{ba} & \hat{P}_{bb} & \hat{P}_{bc} & \bullet & \hat{P}_{bn} \\ \hat{P}_{ca} & \hat{P}_{cb} & \hat{P}_{cc} & \bullet & \hat{P}_{cn} \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \hat{P}_{na} & \hat{P}_{nb} & \hat{P}_{nc} & \bullet & \hat{P}_{nn} \end{bmatrix}$$

S_{ii} = distance from Conductor i to its image i' (ft.)
S_{ij} = distance from Conductor i to the image of Conductor j (ft.)
D_{ij} = distance from Conductor i to Conductor j (ft.)
RD_i= radius of Conductor i in ft.

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

Then, the primitive potential coefficient matrix is partitioned into four matrices

$$[\hat{P}_{\text{primitive}}] = \begin{bmatrix} [\hat{P}_{ij}] & [\hat{P}_{in}] \\ [\hat{P}_{nj}] & [\hat{P}_{nn}] \end{bmatrix}$$

After that the primitive coefficient matrix is reduced using the Kron reduction method to a 3*3 phase potential coefficient matrix

$$[P_{abc}] = [\hat{P}_{ij}] - [\hat{P}_{in}] \cdot [\hat{P}_{nn}]^{-1} \cdot [\hat{P}_{nj}]$$

The inverse of the potential coefficient matrix will give us the ***capacitance matrix***

$$[C_{abc}] = [P_{abc}]^{-1}$$

The ***admittance matrix*** is given by multiplying Cabc with 2 πf

$$Y_{abc} = 2\pi f \; C_{abc}$$

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

For underground cables, the calculation of shunt admittance matrix is slightly different from that of overhead lines.

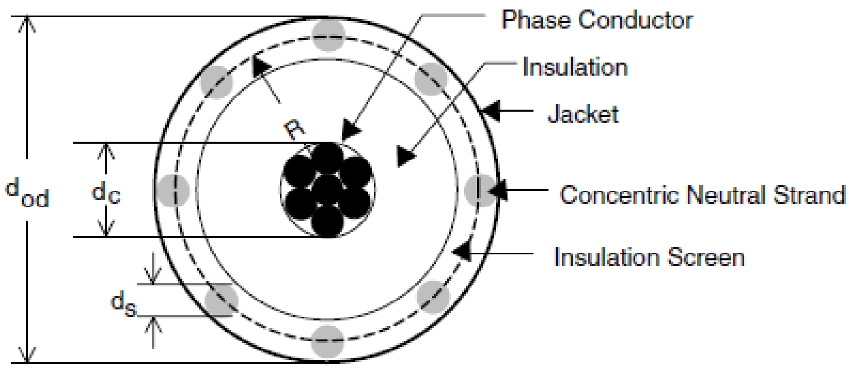


FIGURE 4.9
Concentric neutral cable.

dc = diameter of phase conductor
ds = diameter of neutral conductor
dod = overall diameter of cable

A Real Distribution System

- System Information
  - Primary Distribution System

Line Model:

First, the radius of the phase conductor is calculated by dividing the diameter of phase conductor by 2: $RD_c = d_c\ /2$

Then, the radius of the strand conductor is calculated by diving the diameter of the strand conductor by 2 : $RD_s = d_s\ /2$

Then, the radius of the cable is calculated using the overall diameter of the cable and the diameter of strand conductor: $R = (d_{od} - d_s)\ /2$

After that, the capacitance from phase to ground for a concentric neutral cable, Cpg, is calculated:

$$C_{pg} = \frac{2\pi\varepsilon}{\ln(R/RD_c) - (1/k)\ln(k*RD_s/R)}$$

Then, the phase admittance for a concentric neutral cable is given by multiplying the capacitance with $2\pi f$: $y_{pg} = 2\pi f C_{pg}$

Finally, the shunt admittance matrix for this three-phase underground cable is obtained by putting the three phase admittances together:

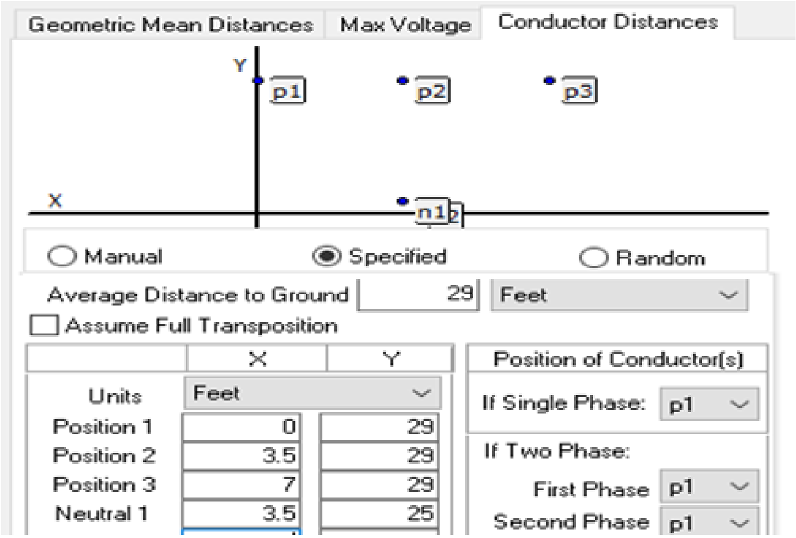
$$y_{abc} = \begin{bmatrix} y_{ag} & 0 & 0 \\ 0 & y_{bg} & 0 \\ 0 & 0 & y_{cg} \end{bmatrix}$$

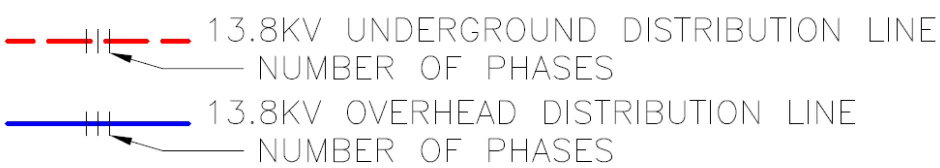
ε = permittivity of the medium
k = number of strands
dc = diameter of phase conductor
ds = diameter of neutral conductor
dod = overall diameter of cable

A Real Distribution System

- System Information
  - Primary Distribution System -- Underground Cable

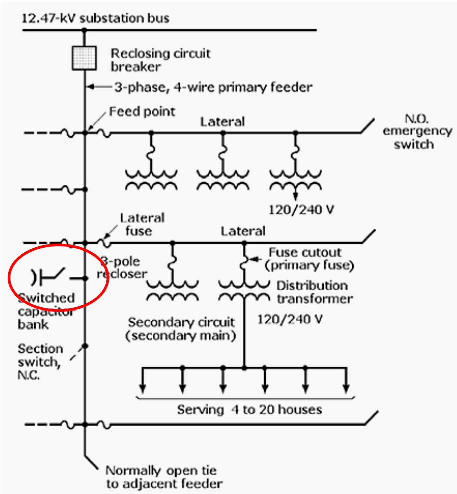
Size	Material	Resistance (Ω/mile)	Diameter (inch)	GMR (feet)	Capacity (A)
4/0	ACSR	0.592	0.563	0.00814	340
1/0	ACSR	1.12	0.355	0.00446	230
4	ACSR	2.55	0.257	0.00452	140
2	ACSR	1.65	0.316	0.00504	180
6	CU	2.41	0.201	0.00568	130
2	CU	0.87	0.3	0.0083	200
4/0	AA	0.554	0.512	0.0167	326
1/0	AA	1.114	0.362	0.0111	228





A Real Distribution System

- System Information
  - Capacitor Bank (Ch. 9)



Capacitors provide tremendous benefits to distribution system performance.

Capacitors can ***reduce losses***, ***free up capacity***, and ***reduce voltage drop***.

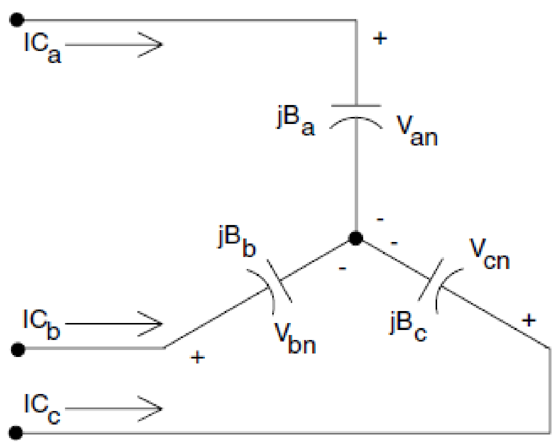
- Losses; Capacity — By canceling the reactive power to motors and other loads with low power factor, capacitors decrease the line current. Reduced current frees up capacity, i.e., the same circuit can serve more load. Reduced current also significantly lowers the I^2R line losses.
- Voltage drop — Capacitors provide a voltage boost, which cancels part of the voltage drop caused by system loads.

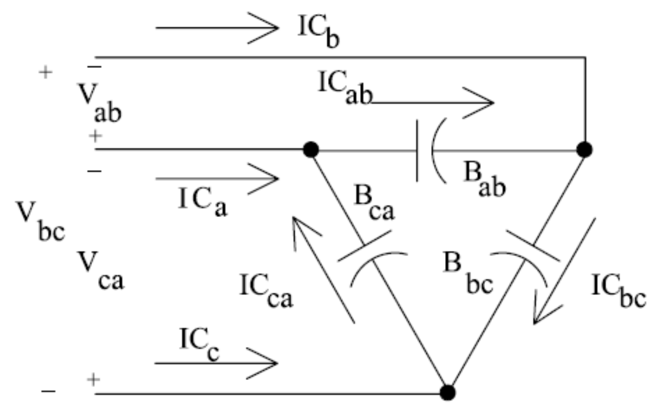
https://www.eaton.com/us/en-us/catalog/medium-voltage-power-distribution-control-systems/pole-mounted-capacitor-banks.html

A Real Distribution System

- System Information
  - Capacitor Bank (Ch. 9)

Two types of connection: wye and delta.





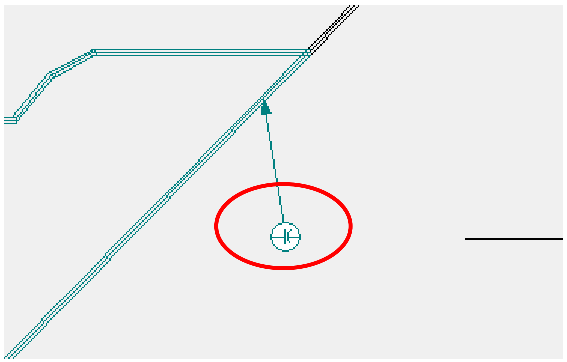
$$B_c = \frac{kvar}{kV_{LN}^2 \cdot 1000} \text{ S}$$

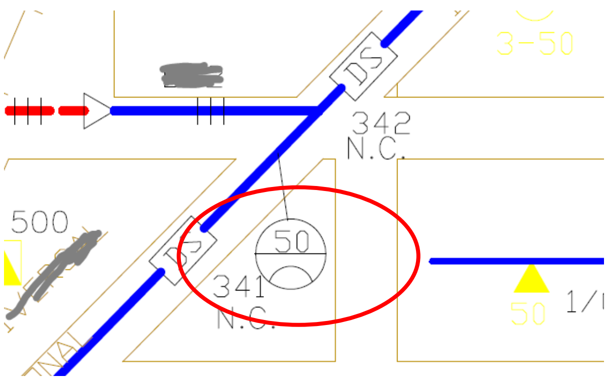
$$B_c = \frac{kvar}{kV_{LL}^2 \cdot 1000} \text{ S}$$

A Real Distribution System

- System Information
  - Capacitor Bank (Ch. 9)

    In the real distribution system, there are 5 capacitor banks.

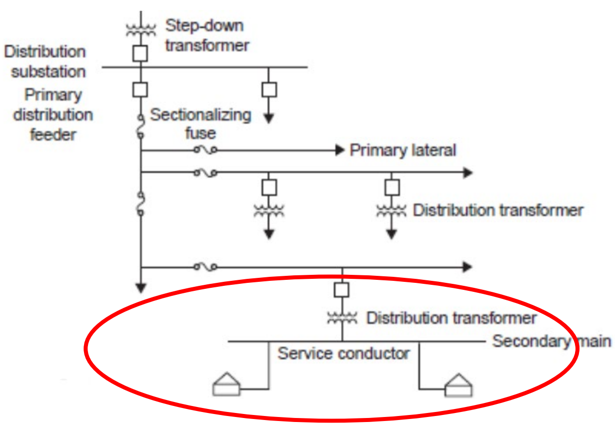




Real corresponding picture from Google Map

A Real Distribution System

- System Information
  - Secondary Distribution System (Ch. 11)



Tony Samaritano, Power Systems, Rowan University 2012

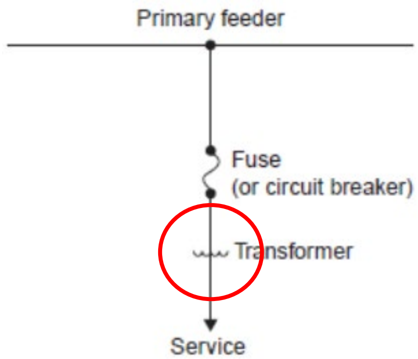
Secondary distribution system is an AC power distribution system in which customers are served.

The secondary circuit is supplied by distribution transformers. The standard secondary voltage levels are

- 120/240 single-phase
- 120/208 three-phase
- 277/480 three-phase

A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer



https://metglas.com/distribution-transformer-electrical-steel/three-white-distribution-transformers-on-pole-with-light-blue-sky/

- The distribution transformer normally serves as the ***final transition*** to the customers and often provides a local grounding reference. Most distribution circuits have hundreds of distribution transformers.

- Distribution feeders may also have other transformers: voltage regulators, feeder step banks, and grounding banks.

A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - From a few kVA to a few MVA, distribution transformers ***convert*** primary voltage to low voltage that customers can use. In North America, more than *40* million distribution transformers are in service.

Standard Distribution Transformer Sizes

Distribution Transformer Standard Ratings, kVA	
Single phase	5, 10, 15, 25, 37.5, 50, 75, 100, 167, 250, 333, 500
Three phase	30, 45, 75, 112.5, 150, 225, 300, 500

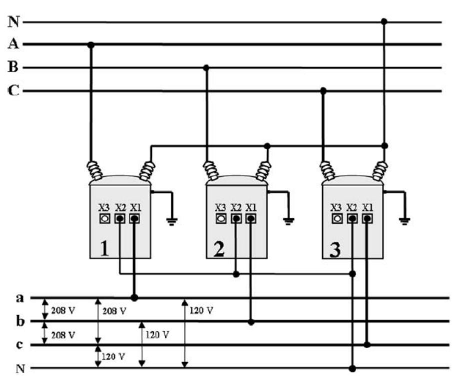
- Distribution transformers are available in several ***standardized sizes*** as shown in Table below.

Voltage	# Phases	# Wires	Application
120/240 V	Single-phase	Three	Residential
208Y/120 V	Three-phase	Four	Residential/Commercial
480Y/277 V	Three-phase	Four	Commercial/Industrial/High Rise

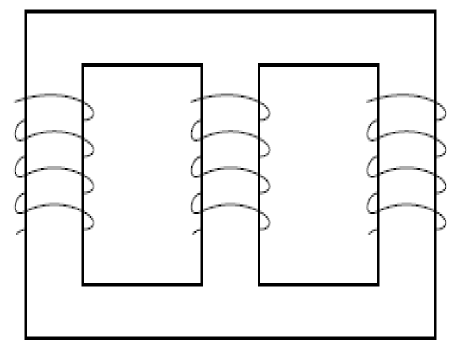
- Most installations are single phase. The most common overhead transformer is the 25-kVA unit; pad-mounted transformers tend to be slightly larger where the 50-kVA unit is the most common.

A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - ➢ Three-phase Transformer



Three-phase overhead transformer banks are normally constructed from three single-phase units. Three-phase pad-mounted distribution transformer is a three-phase transformer with one single unit.

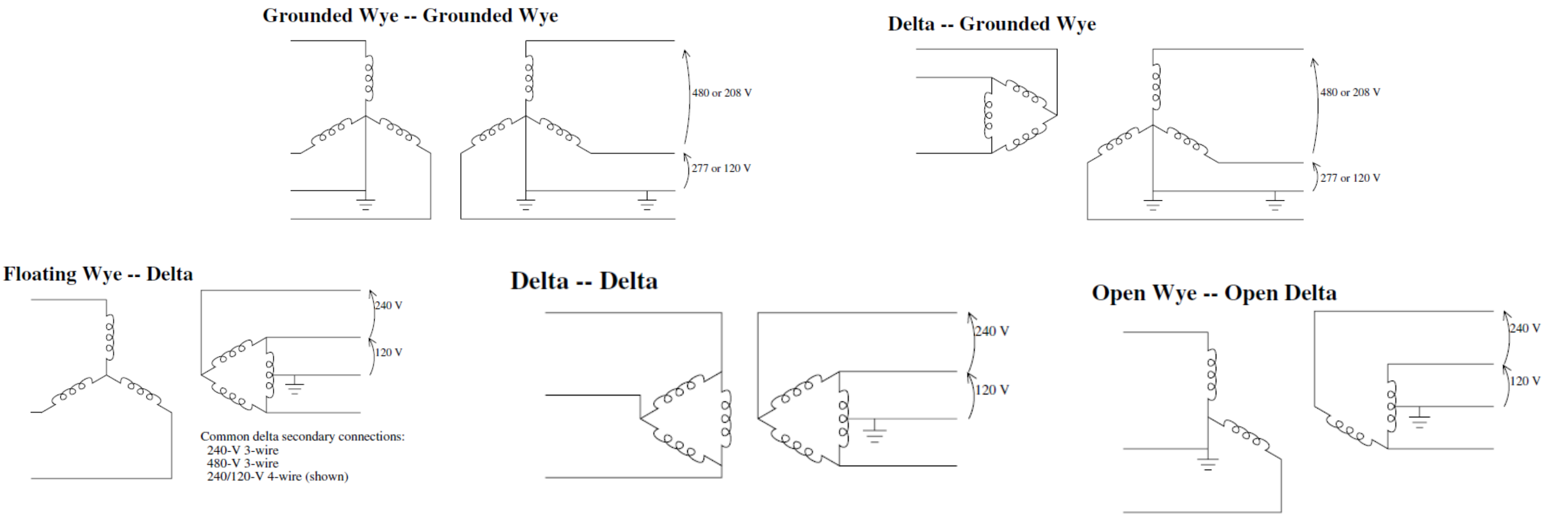


https://metglas.com/distribution-transformer-electrical-steel/three-white-distribution-transformers-on-pole-with-light-blue-sky/

https://www.larsonelectronics.com/product/150677/500-kva-pad-mount-transformer-12470v-delta-primary-480grdy-277-wye-n-secondary-oil-cooled

A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Three-phase Transformer
      - There are many types of three-phase ***connections*** used to serve three-phase load in distribution systems. Both the primary and secondary windings may be connected in different ways: delta, floating wye, or grounded wye.



A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Three-phase Transformer
    - For the primary winding of three-phase distribution transformers, utilities need to ***choose proper connections*** according to the configuration of primary feeders.
      - The delta and floating-wye primary connections are suitable for ungrounded and grounded primary distribution systems.
      - The grounded-wye primary connection is only suitable on four-wire grounded primary distribution systems.
    - ***Customer needs*** play a role in the selection of the secondary configuration. The delta configuration and the grounded-wye configuration are the two most common secondary configurations.
      - A ***grounded-wye*** secondary adeptly handles single-phase loads on any of the three phases with less concerns about unbalances.
      - An ***ungrounded*** secondary system like the delta can supply three-wire ungrounded service. Some industrial facilities prefer an ungrounded system, so they can continue to operate with line-to-ground faults.

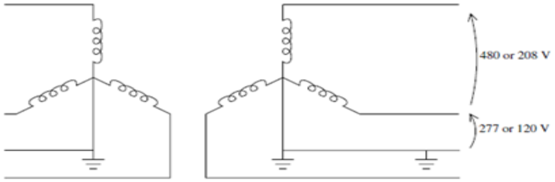
A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Three-phase Transformer

      The most common three-phase distribution transformer supply connection is the ***grounded wye*** – ***grounded wye*** connection. Its main characteristics are:

      - Supply — The supply must be a grounded 4-wire system
      - Service — It supplies grounded-wye service, normally either 480Y/277 V or 208Y/120 V. It does not supply ungrounded service.
      - Zero sequence — All zero-sequence currents — harmonics, unbalance, and ground faults — transfer to the primary. It also acts as a high-impedance ground source to the primary.
      - Coordination — Because ground faults pass through to the primary, larger transformer services and local protective devices should be coordinated with utility ground relays.

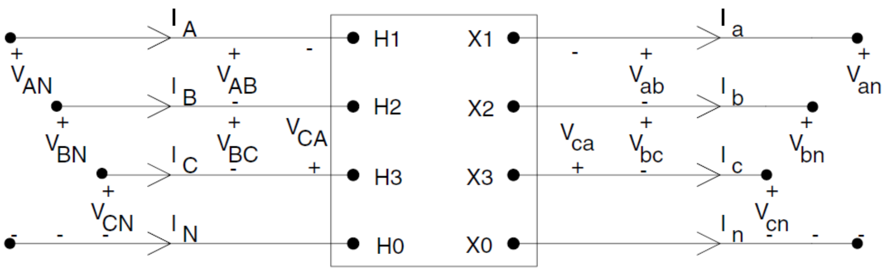
Grounded Wye -- Grounded Wye



A Real Distribution System

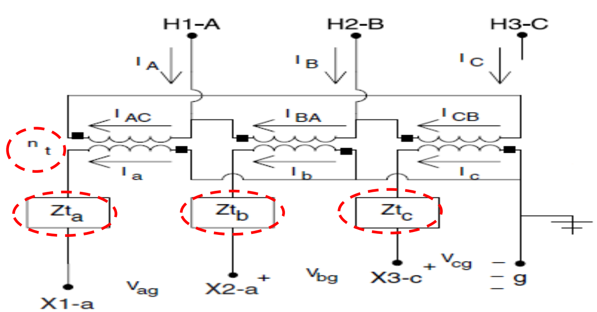
- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Three-phase Transformer

      For the three-phase distribution transformer, the model of the three-phase substation transformer also applies.



$$[VLN_{ABC}] = [a_t]\cdot[VLN_{abc}] + [b_t]\cdot[I_{abc}]$$
$$[I_{ABC}] = [c_t]\cdot[VLN_{abc}] + [d_t]\cdot[I_{abc}]$$

a_t, b_t, c_t and d_t depend on the specific winding connection, impedance and rating of a transformer. For example, for a delta-grounded wye step-down connection transformer,



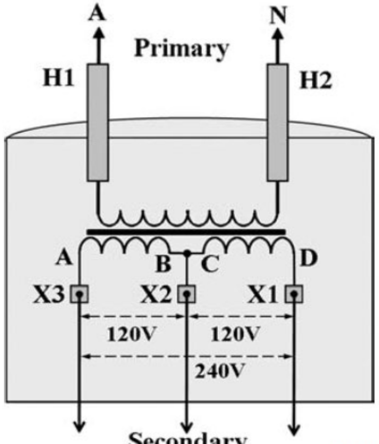
$$[a_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2 & 1\\ 1 & 0 & 2\\ 2 & 1 & 0\end{bmatrix} \qquad [b_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2\cdot Zt_b & Zt_c\\ Zt_a & 0 & 2\cdot Zt_c\\ 2\cdot Zt_a & Zt_b & 0\end{bmatrix}$$

$$[c_t] = \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \qquad [d_t] = \frac{1}{n_t}\cdot\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ -1 & 0 & 1\end{bmatrix}$$

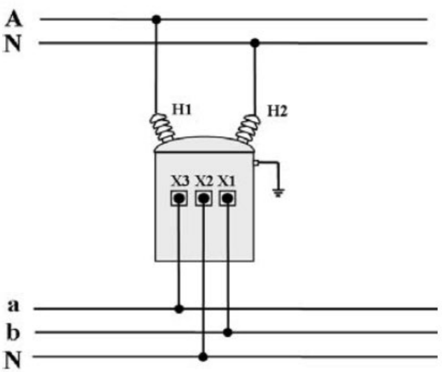
A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Single-phase Center-tapped Transformer
      - Single-phase transformers supply ***single-phase*** service.
      - The standard secondary load service is a ***120/240-V three-wire*** service.
      - This configuration has two secondary windings in series with the midpoint grounded. The secondary terminals are labeled X1, X2, and X3 where the voltage X1-X2 and X2-X3 are each 120 V. X1-X3 is 240 V.

https://en.wikipedia.org/wiki/Distribution_transformer



(Blume)



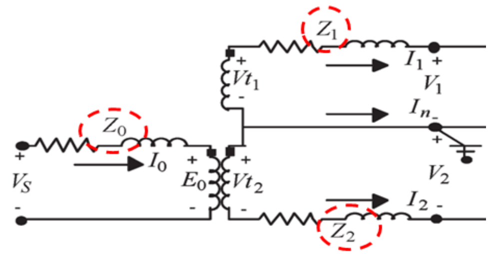
Secondary Voltage 240/120 Vac

(Blume)

A Real Distribution System

- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Single-phase Center-tapped Transformer

The single-phase center-tapped transformer model is shown in the figure below.



When the secondary terminal voltages and secondary currents are known, the primary source voltage and current are calculated using these two equations(backward sweep):

$$[V_{ss}] = [a_t] \cdot [V_{12}] + [b_t] \cdot [I_{12}]$$

$$[I_{00}] = [c_t] \cdot [V_{12}] + [d_t] \cdot [I_{12}]$$

$$[V_{ss}] = \begin{bmatrix} V_s \\ V_s \end{bmatrix} \quad [a_t] = [av] = n_t \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$[I_{00}] = \begin{bmatrix} I_0 \\ I_0 \end{bmatrix} \quad [c_t] = n_t \cdot \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$[b_t] = \begin{bmatrix} n_t \cdot Z_1 + \frac{1}{n_t^2} \cdot Z_0 & -\frac{1}{n_t^2} \cdot Z_0 \\ \frac{1}{n_t^2} \cdot Z_0 & -(n_t \cdot Z_2 + \frac{1}{n_t^2} \cdot Z_0) \end{bmatrix}$$

$$[d_t] = \frac{1}{n_t} \begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix}$$

a_t, b_t, c_t and d_t depend on n_t, Z_0, Z_1, Z_2, i.e., depend on the specific impedance and winding ratings of a transformer.

A Real Distribution System

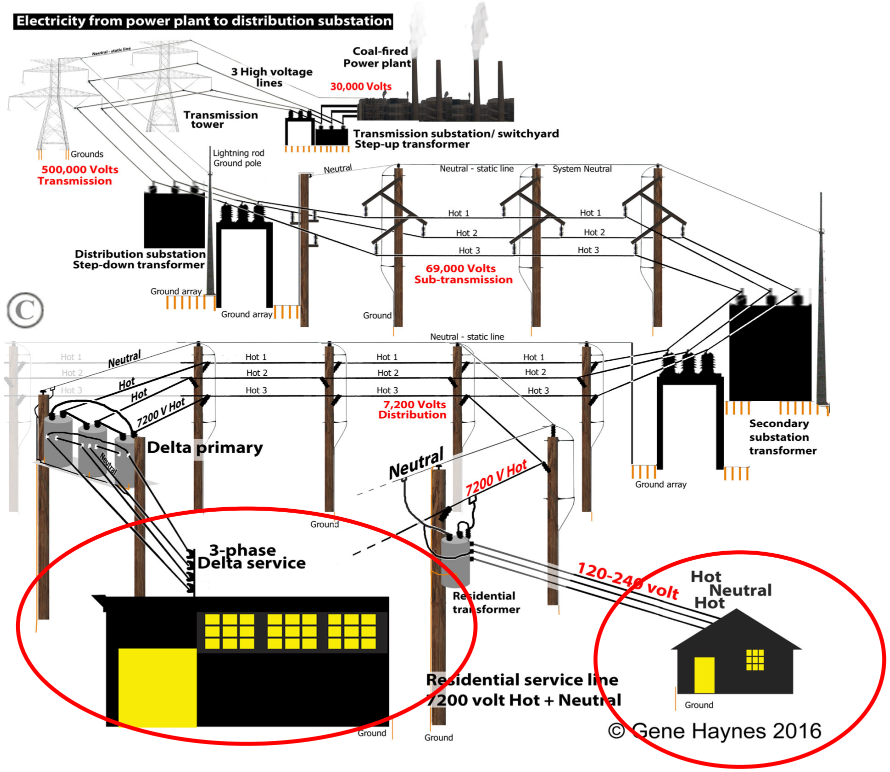
- System Information
  - Secondary Distribution System -- Distribution Transformer
    - Single-phase Center-tapped Transformer

1ø PADMOUNT TRANSFORMER W/SIZE
3ø PADMOUNT TRANSFORMER W/SIZE
1ø POLE MOUNTED TRANSFORMER W/SIZE
3ø TRANSFORMER BANK W/3 TRANSFORMERS W/SIZE
3ø TRANSFORMER BANK W/2 TRANSFORMERS W/SIZE

Number of Phases	Capacity	R (%)	X (%)
3 phases	45 kVA	2.52	1.73
3 phases	75 kVA	2.27	1.91
3 phases	112.5 kVA	2.43	3.87
3 phases	225 kVA	1.15	5.5
3 phases	300 kVA	1.8	4.5
3 phases	500 kVA	1.6	5.9
1 phase	15 kVA	1.6	2.02
1 phase	25 kVA	1.4	2.3
1 phase	37.5 kVA	3.6	2.7
1 phase	50 kVA	3.1	2.8
1 phase	100 kVA	2.12	3.55

A Real Distribution System

- System Information
  - Load (Ch. 9)



- Distribution systems obviously exist to supply electricity to end users, so loads and their characteristics are important.
- Utilities supply a broad range of loads, from rural areas to urban areas with different load densities.
- A utility may feed houses with a 10- to 20-kVA peak load, as an industrial customer peaking at 5 MW.
- Customer loads have many common characteristics. Load levels vary through the day, peaking in the afternoon or early evening.

http://waterheatertimer.org/Names-of-parts-on-electric-pole.html

A Real Distribution System

- System Information
  - Load

According to the load types, load models can be classified into:

- Constant impedance
- Constant current
- Constant active and reactive power
- Any combination of the above

According to the load phase configuration, we have

- Single-phase load
- Two-phase load
- Three-phase load

According to the load connection, we have

- Wye-connected load
- Delta-connected load

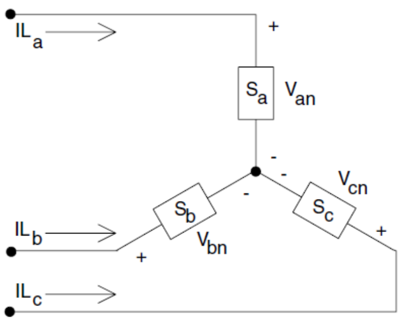


FIGURE 9.1
Wye-connected load.

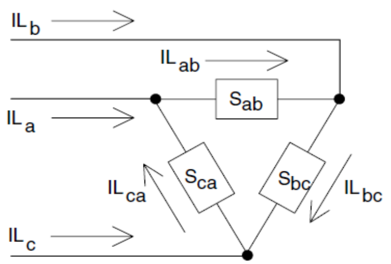


FIGURE 9.2
Delta-connected load.

A Real Distribution System

- System Information
  - Load

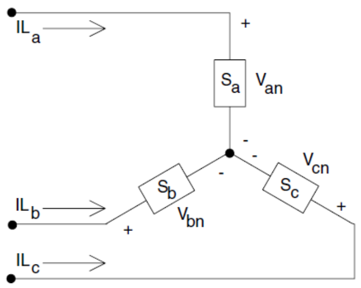
Two examples:

- For a constant active and reactive power, wye-connected load, the line currents are given by

$$IL_a = \left(\frac{S_a}{V_{an}}\right)^* = \frac{|S_a|}{|V_{an}|}\underline{/\delta_a - \theta_a} = |IL_a|\underline{/\alpha_a}$$

$$IL_b = \left(\frac{S_b}{V_{bn}}\right)^* = \frac{|S_b|}{|V_{bn}|}\underline{/\delta_b - \theta_b} = |IL_b|\underline{/\alpha_b}$$

$$IL_c = \left(\frac{S_c}{V_{cn}}\right)^* = \frac{|S_c|}{|V_{cn}|}\underline{/\delta_c - \theta_c} = |IL_c|\underline{/\alpha_c}$$

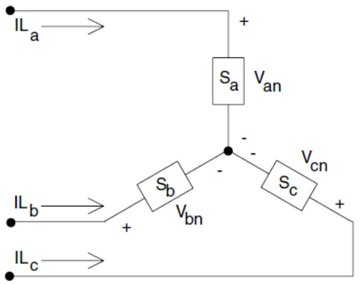


- For a constant impedance, wye-connected load, the line currents are given by

$$IL_a = \frac{V_{an}}{Z_a} = \frac{|V_{an}|}{|Z_a|}\underline{/\delta_a - \theta_a} = |IL_a|\underline{/\alpha_a}$$

$$IL_b = \frac{V_{bn}}{Z_b} = \frac{|V_{bn}|}{|Z_b|}\underline{/\delta_b - \theta_b} = |IL_b|\underline{/\alpha_b}$$

$$IL_c = \frac{V_{cn}}{Z_c} = \frac{|V_{cn}|}{|Z_c|}\underline{/\delta_c - \theta_c} = |IL_c|\underline{/\alpha_c}$$



A Real Distribution System

- Raw AMI Data
  - What is AMI?

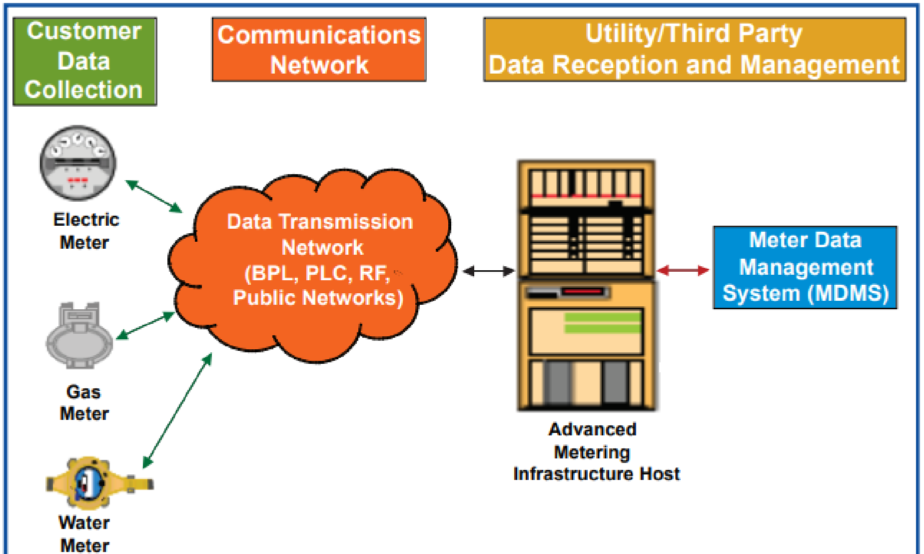


Figure 1: AMI Building Blocks[1]

AMI is the abbreviation of Advanced Metering Infrastructure, which typically refers to the full measurement and collection system that includes

- meters at the customer site,
- communication networks between the customer and a service provider, such as an electric, gas, or water utility, and
- data reception and management systems that make the information available to the service provider.

The customers are equipped with advanced solid state and electronic meters that collect time-based demand data, which is we are interested in.

https://www.ferc.gov/CalendarFiles/20070423091846-EPRI%20-%20Advanced%20Metering.pdf

A Real Distribution System

- Raw AMI Data
  - Overview of AMI Collection

	Substation 1									Substation 2				
	Transformer 1				Transformer 2					Transformer 1		Transformer 2		
Feeder Name	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5	Feeder 6	Feeder 7	Feeder 8	Feeder 9	Feeder 1	Feeder 2	Feeder 3	Feeder 4	Feeder 5
Total Number of Customers	61	790	238	383	159	0	120	6	1	207	141	804	806	1496
# of Residential Customers	30	739	154	346	129	0	91	0	0	105	85	622	631	1389
# of Small Commerical Customers	29	41	68	30	21	0	24	1	0	72	34	141	145	90
# of Large Commerical Customers	1	10	14	1	8	0	3	4	0	22	19	30	22	12
# of Industrial Customers	0	0	1	1	1	0	2	1	1	4	1	0	3	2
Time Period	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year	4 year
Residential Demand Time Resolution	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly
Small Commerical Demand Time Resolution	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly	Hourly
Large Commerical Record Time Resolution	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min
Industrial Record Time Resolution	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min	15-min
Total Number of Residential customers	1489									2832				
Total Number of Small Commercial customers	214									482				
Total Number of Large Commercial Customers	41									105				
Total Number of Industrial Customers	7									10				

A Real Distribution System

- Raw AMI Data
  - Original AMI Data

Hourly energy & instantaneous voltage

0.257 = Energy Consumed from 04/01/2017 00:00 AM to 04/01/2017 01:00 AM

one Acct.

Account		time	kWH or V	time	kWH or V	time	kWH or V	time	kWH or V
100000001	KWH	201704000000	0.392	201704000000	0.257	201704000000	0.215	201704000000	0.239
100000001	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240
100000002	KWH	201704000000	0.245	201704000000	0.204	201704000000	0.252	201704000000	0.342
100000002	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	240
100000003	KWH	201704000000	1.479	201704000000	0.417	201704000000	0.816	201704000000	0.414
100000003	VOLTS	201704000000	240	201704000000	239	201704000000	239	201704000000	240
100000004	KWH	201704000000	1.009	201704000000	0.555	201704000000	0.39	201704000000	0.382
100000004	VOLTS	201704000000	241	201704000000	237	201704000000	237	201704000000	239
100000005	KWH	201704000000	0.798	201704000000	0.809	201704000000	0.87	201704000000	0.692
100000005	VOLTS	201704000000	239	201704000000	238	201704000000	238	201704000000	240
100000006	KWH	201704000000	0.109	201704000000	0.188	201704000000	0.205	201704000000	0.148
100000006	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	242
100000007	KWH	201704000000	1.199	201704000000	1.512	201704000000	1.759	201704000000	1.474
100000007	VOLTS	201704000000	241	201704000000	240	201704000000	239	201704000000	241
100000008	KWH	201704000000	0.422	201704000000	0.419	201704000000	0.43	201704000000	0.537
100000008	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240
100000009	KWH	201704000000	2.288	201704000000	2.278	201704000000	2.335	201704000000	2.297
100000009	VOLTS	201704000000	243	201704000000	242	201704000000	242	201704000000	242

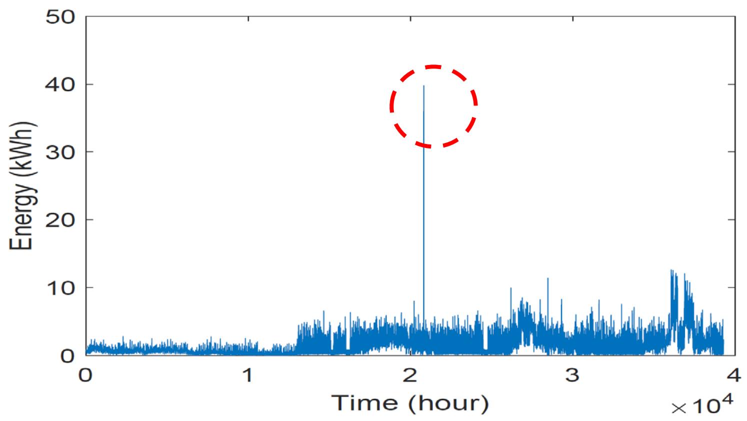
…

…

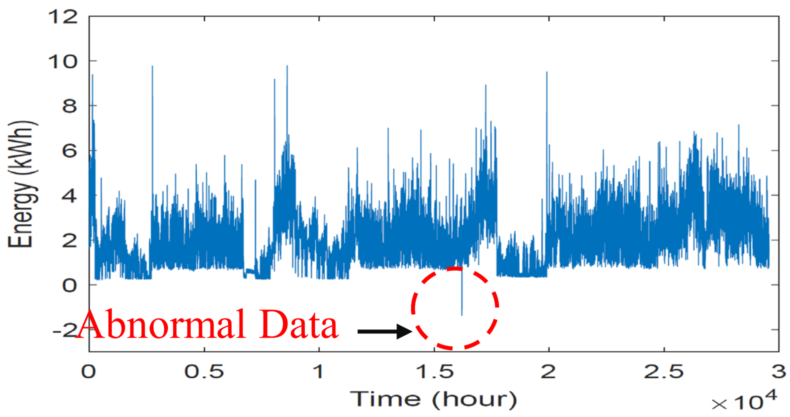
201704010100 = 04/01/2017 01:00 AM

A Real Distribution System

- Raw AMI Data
  - Original AMI Data Preprocessing
    - ✓ Common Smart Meter Data Problems:
      - Outliers/Bad Data
      - Communication Failure
      - Missing Data



    - ✓ Solutions:
      - Engineering intuition (data inconsistency)
      - Conventional Statistical Tools (e.g. Z-score)
      - Robust Computation (e.g. relevance vector machines)
      - Anomaly Detection Algorithms

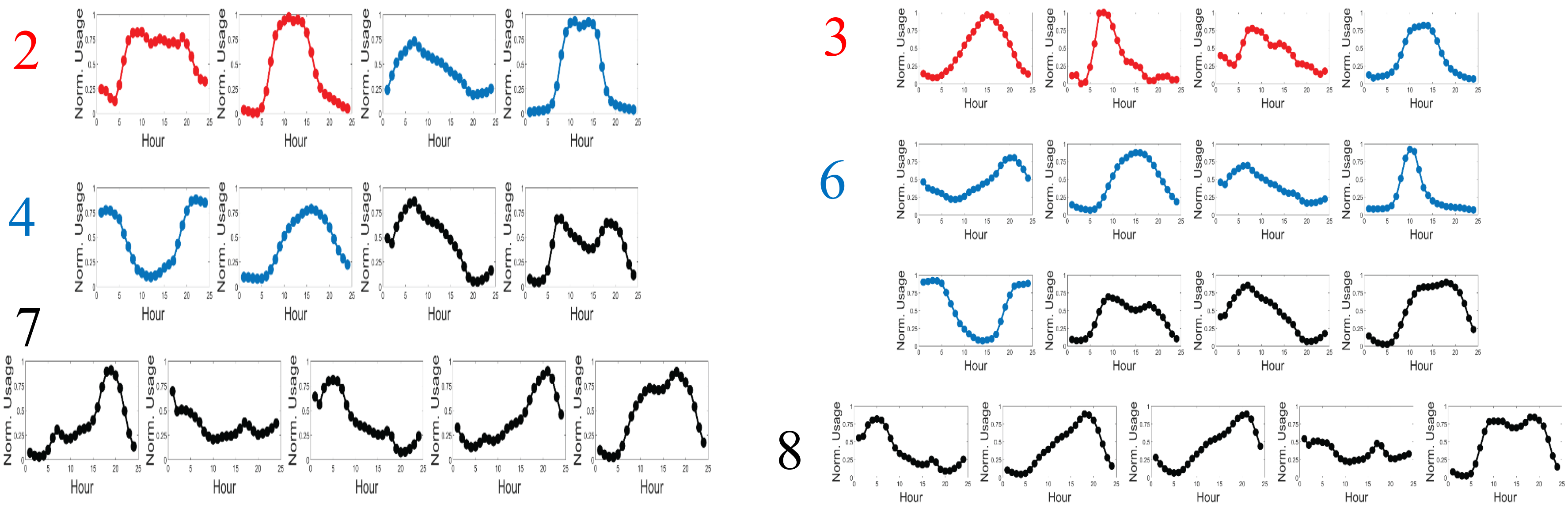


A Real Distribution System

- Raw AMI Data
  - Typical Load Profiles

Typical Load Patterns on Weekdays

Typical Load Patterns on Weekends



- Industrial - Commercial - Residential

https://ieeexplore.ieee.org/abstract/document/8616827

Steps of Developing OpenDSS Model

- Overall steps

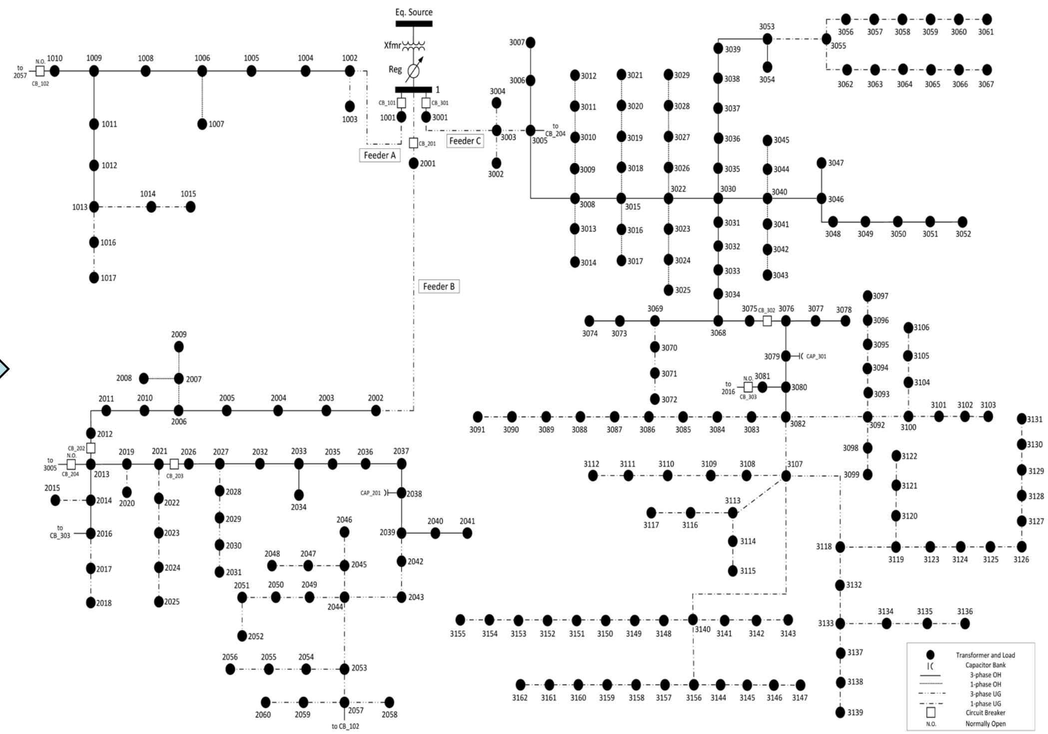
Step I -- Extract the topology based on the provided distribution system map and Milsoft model,
Step II -- Determine the connection between customers and distribution transformers using geographic information, and aggregate individual loads to spot loads,
Step III -- Collect device information based on the provided distribution system map and Milsoft model, and built models for all devices using OpenDSS,
Step VI-- Build the Matlab-OpenDSS interface,
Step V -- Perform time-series power flow analysis.

* We choose three typical feeders to develop a distribution system model using OpenDSS.

Steps of Developing OpenDSS Model

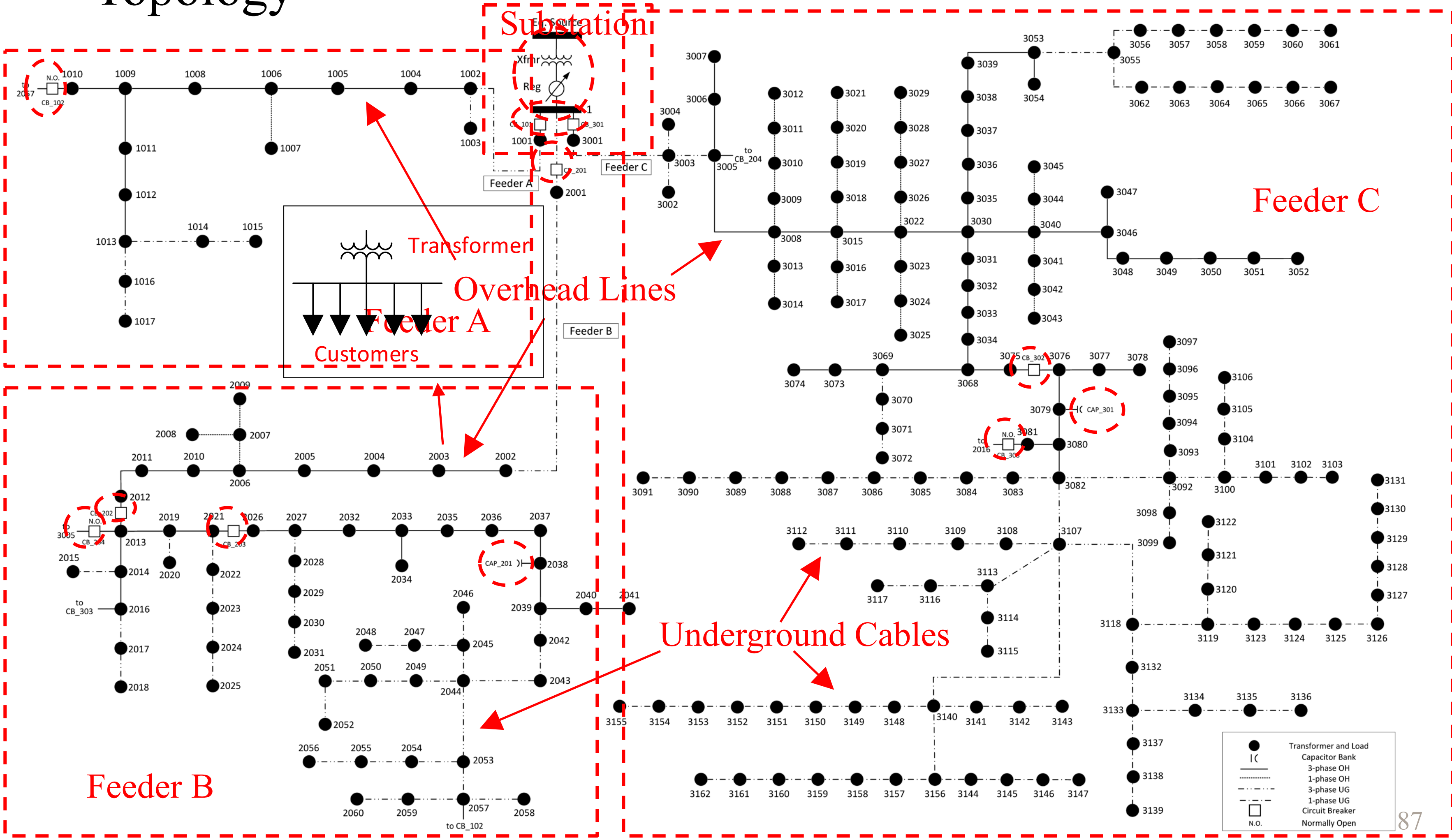
- Topology

Choose 3 typical feeders



Steps of Developing OpenDSS Model

- Topology



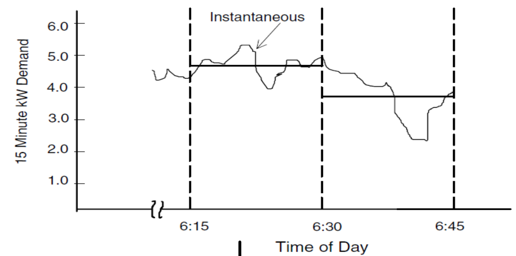
Steps of Developing OpenDSS Model

- Aggregating Individual Loads

Calculate P and Q for Individual Customer

Account		time	kWH or V	time	kWH or V	time	kWH or V	time	kWH or V	time	kWH or V
100000001	KWH	201704000000	0.392	201704000000	0.257	201704000000	0.215	201704000000	0.239	201704000000	0.172
100000001	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240	201704000000	240
100000002	KWH	201704000000	0.245	201704000000	0.204	201704000000	0.252	201704000000	0.342	201704000000	0.3
100000002	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	240	201704000000	239
100000003	KWH	201704000000	1.479	201704000000	0.417	201704000000	0.816	201704000000	0.414	201704000000	0.409
100000003	VOLTS	201704000000	240	201704000000	239	201704000000	239	201704000000	240	201704000000	240
100000004	KWH	201704000000	1.009	201704000000	0.555	201704000000	0.39	201704000000	0.382	201704000000	0.517
100000004	VOLTS	201704000000	241	201704000000	237	201704000000	237	201704000000	239	201704000000	239
100000005	KWH	201704000000	0.798	201704000000	0.809	201704000000	0.87	201704000000	0.692	201704000000	0.69
100000005	VOLTS	201704000000	239	201704000000	238	201704000000	238	201704000000	240	201704000000	238
100000006	KWH	201704000000	0.109	201704000000	0.188	201704000000	0.205	201704000000	0.148	201704000000	0.294
100000006	VOLTS	201704000000	241	201704000000	240	201704000000	240	201704000000	242	201704000000	241
100000007	KWH	201704000000	1.199	201704000000	1.512	201704000000	1.759	201704000000	1.474	201704000000	1.555
100000007	VOLTS	201704000000	241	201704000000	240	201704000000	239	201704000000	241	201704000000	241
100000008	KWH	201704000000	0.422	201704000000	0.419	201704000000	0.43	201704000000	0.537	201704000000	0.587
100000008	VOLTS	201704000000	239	201704000000	239	201704000000	238	201704000000	240	201704000000	240
100000009	KWH	201704000000	2.288	201704000000	2.278	201704000000	2.335	201704000000	2.297	201704000000	2.163
100000009	VOLTS	201704000000	243	201704000000	242	201704000000	242	201704000000	242	201704000000	242

Raw energy data



Assumption

Extract energy data from Excel files

Average hourly energy

Assumption: P = average hourly energy

P

$Q = P \times \tan(\arccos(pf))$

pf : 0.9 to 0.95

P.mat

3	4	5
15.2900	6.8920	4.9160
14.9010	6.6720	5.3350
15.7720	7.0130	4.5630
15.7570	6.4520	4.7820
15.2920	6.3560	4.4820
15.8140	6.8610	4.9630
16.0440	8.4220	4.7000

Q.mat

3	4	5
3.8320	3.3379	1.9429
4.8977	3.0399	2.4307
5.1840	2.0455	1.8034
7.1791	3.1248	1.3948
5.0262	1.8538	1.4732
4.6124	1.7195	1.9615
5.2734	4.0790	1.3708

Steps of Developing OpenDSS Model

- Aggregating Individual Loads

Calculate Nodal P and Q

Customer Location

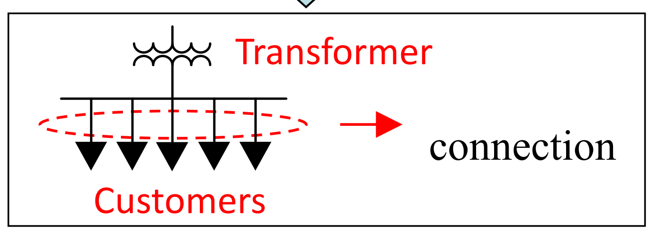
Meter Account	Latitude	Longitude	FeederNumber
10000001	12.0686754	-124.244348	Feeder_A
10000002	12.066563	-124.228338	Feeder_B
10000003	12.068427	-124.2255	Feeder_A

+

Transformer Location

Transformer	Latitude	Longitude	FeederNumber
T_1003	12.081288	-124.21749	Feeder_A
T_1004	12.073812	-124.24075	Feeder_B
T_1005	12.0735614	-124.24048	Feeder_A

Determine the connection between distribution transformers and customers



$$\text{Nodal P} = \sum \text{customer P}$$

$$\text{Nodal Q} = \sum \text{customer Q}$$

Test System Description

- Aggregating Individual Loads

Final Nodal P and Q

1. Active Power

Time \ P (kW) \ Node Name	Node 1001	Node 1002	Node 1003	Node 1004	Node 1005	Node 1006	Node 1007	Node 1008	Node 1009	…
1/1/17 1:00 AM	0	0	15.29	6.892	4.916	5.04	4.163	14.096	17.081	
1/1/17 2:00 AM	0	0	14.901	6.672	5.335	4.76	3.07	14.937	12.786	
1/1/17 3:00 AM	0	0	15.772	7.013	4.563	5.04	3.507	14.789	10.209	
1/1/17 4:00 AM	0	0	15.757	6.452	4.782	4.8	3.143	14.761	10.04	
1/1/17 5:00 AM	0	0	15.292	6.356	4.482	5	3.147	15.156	10.147	
1/1/17 6:00 AM	0	0	15.814	6.861	4.963	4.36	3.336	11.145	9.678	

…

2. Reactive Power

Time \ Q (kVar) \ Node Name	Node 1001	Node 1002	Node 1003	Node 1004	Node 1005	Node 1006	Node 1007	Node 1008	Node 1009	…
1/1/17 1:00 AM	0	0	3.83203522	3.3379479	1.9429275	2.2962918	2.01623292	6.42232734	6.75084317	
1/1/17 2:00 AM	0	0	4.89772185	3.039853	2.4306978	0.9665592	0.43745131	5.90348015	3.72925	
1/1/17 3:00 AM	0	0	5.18400571	2.0454583	1.803413	1.47	0.71212672	7.16263961	2.55861658	
1/1/17 4:00 AM	0	0	7.17910129	3.1248462	1.39475	2.0447914	1.33891239	5.3575276	4.86259393	
1/1/17 5:00 AM	0	0	5.02623734	1.8538333	1.4731622	0.7124614	1.03436888	2.15961304	4.62310978	
1/1/17 6:00 AM	0	0	4.61241667	1.7195287	1.9615031	1.8573522	0.67740369	4.04509485	1.37904031	

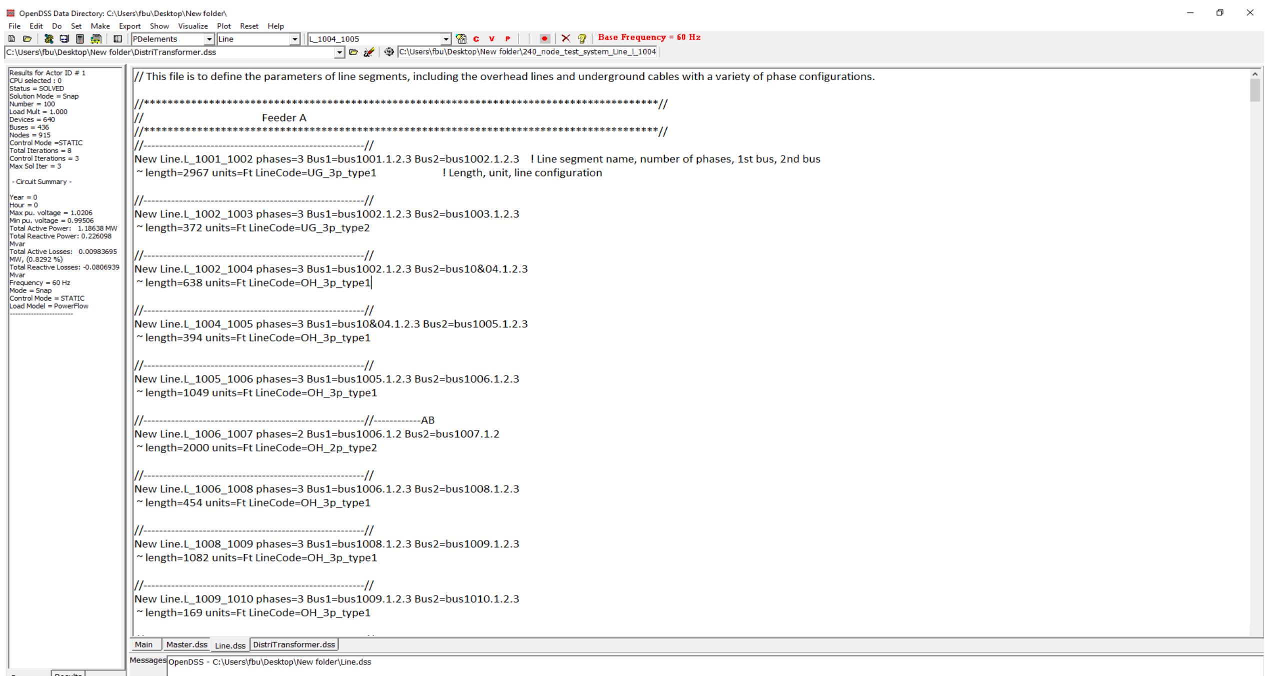
…

Steps of Developing OpenDSS Model

- What is OpenDSS ?

The Open Distribution System Simulator (OpenDSS, or simply, DSS) is a comprehensive electrical system simulation tool for electric utility **distribution systems**.

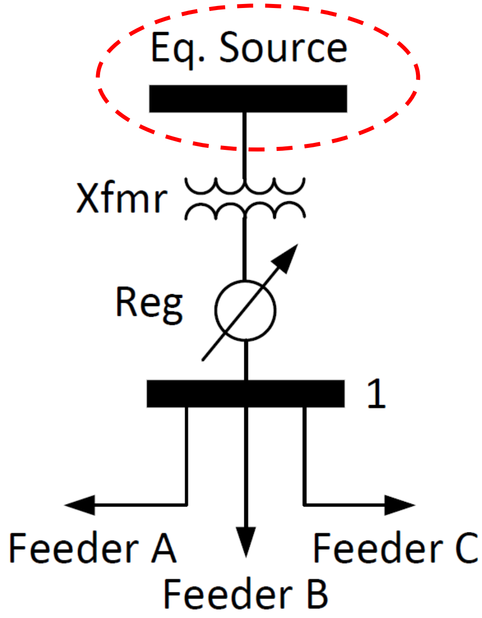
- Open → Open Source
- DSS → Distribution System Simulator



Steps of Developing OpenDSS Model

- Electric Devices

Equivalent Swing Bus



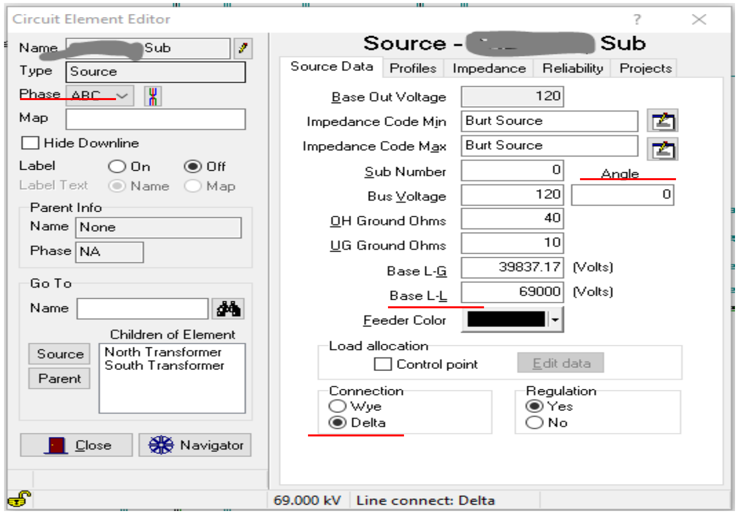
- The 69 kV sub-transmission system in real system is equivalent to a swing bus in the OpenDSS model.

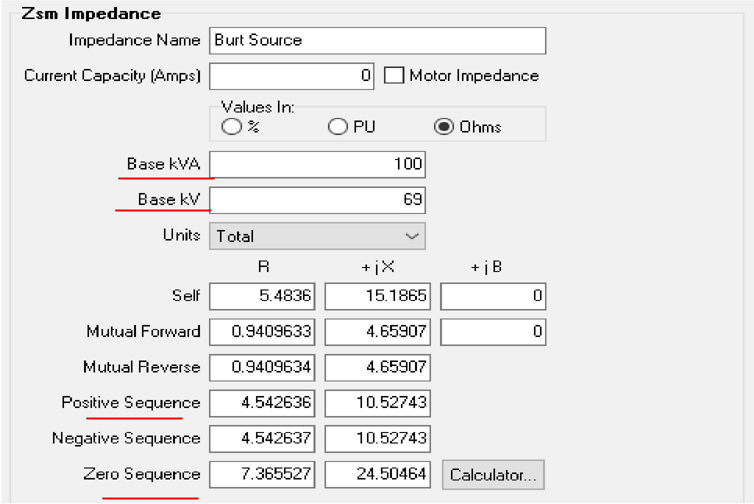
https://www.qualitrolcorp.com/grid-applications/transmission-distribution/

Steps of Developing OpenDSS Model

- Electric Devices

  Equivalent Swing Bus



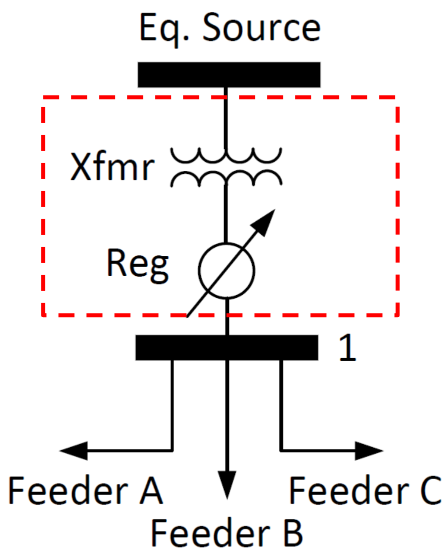


Edit "Vsource.source" Bus1= eq_source_bus.1.2.3 Phases=3 Angle=0.00000 Pu=1.00000 BaseKv=69.00000 R1=4.54263687 X1=10.52743053 R0=7.36552668 X0=24.50463867

Steps of Developing OpenDSS Model

- Electric Devices

Substation Transformer



- The substation transformer in the real distribution system is a 69/13.8 kV step-down three-phase transformer, which has an on-load tap changing mechanism.

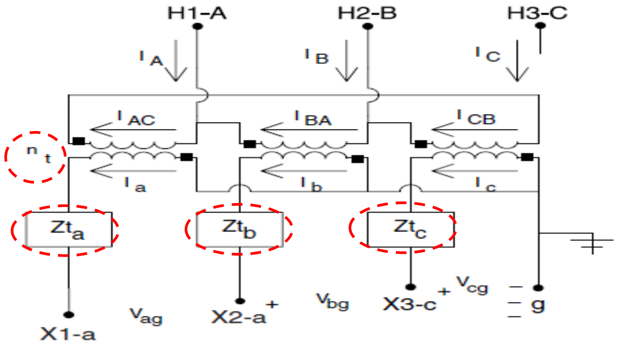
- In OpenDSS, a three-phase transformer object, three single-phase regulator objects, and one regulator control object are used to model this substation transformer with a load tap changing mechanism.

Steps of Developing OpenDSS Model

- Electric Devices

Three-phase transformer model

$$[VLN_{ABC}] = [a_t]\cdot[VLN_{abc}] + [b_t]\cdot[I_{abc}]$$
$$[I_{ABC}] = [c_t]\cdot[VLN_{abc}] + [d_t]\cdot[I_{abc}]$$



$$[a_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2 & 1\\ 1 & 0 & 2\\ 2 & 1 & 0\end{bmatrix} \qquad [b_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2\cdot Zt_b & Zt_c\\ Zt_a & 0 & 2\cdot Zt_c\\ 2\cdot Zt_a & Zt_b & 0\end{bmatrix}$$

$$[c_t] = \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \qquad [d_t] = \frac{1}{n_t}\cdot\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ -1 & 0 & 1\end{bmatrix}$$

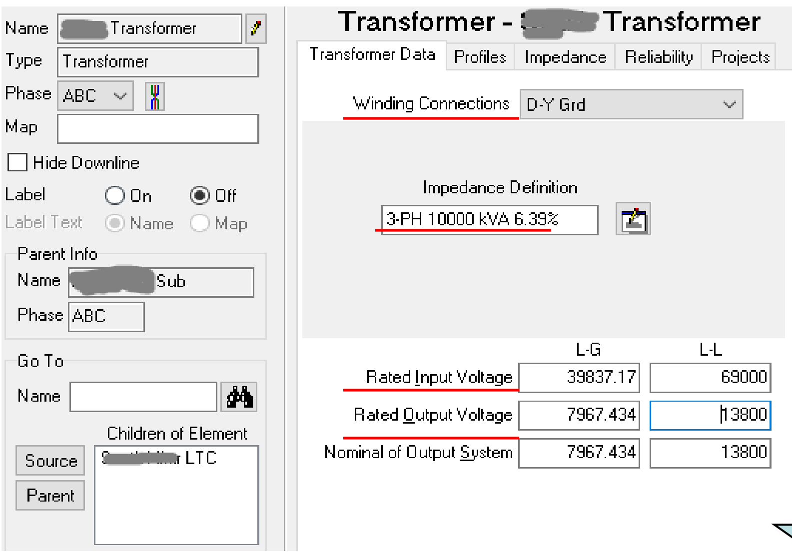
a_t, b_t, c_t and d_t depend on n_t, Zt_a, Zt_b, Zt_c, i.e., depend on the specific winding connection, impedance and rating of a transformer.

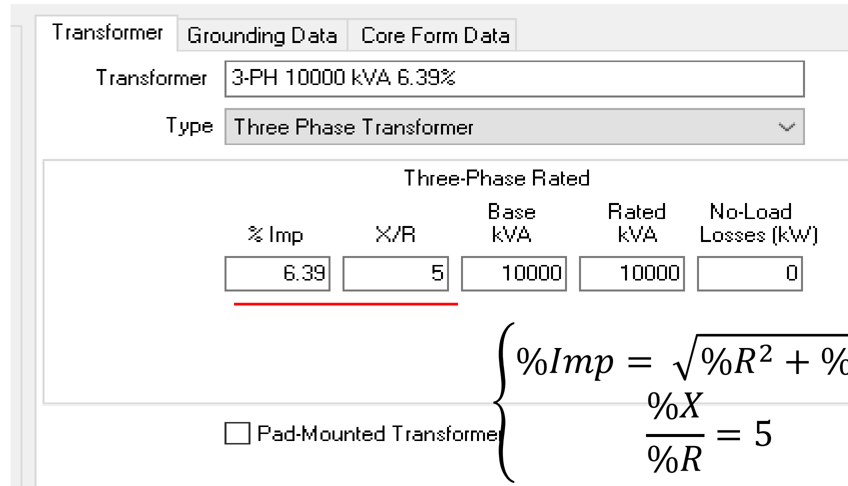
To build a transformer model, we need to know kV rating, kVA rating, number of phases, number of windings, connection, percent resistance, and percent reactance.

Steps of Developing OpenDSS Model

- Electric Devices

  Substation transformer information





$$\begin{cases} \%Imp = \sqrt{\%R^2 + \%X^2} \\ \dfrac{\%X}{\%R} = 5 \end{cases}$$

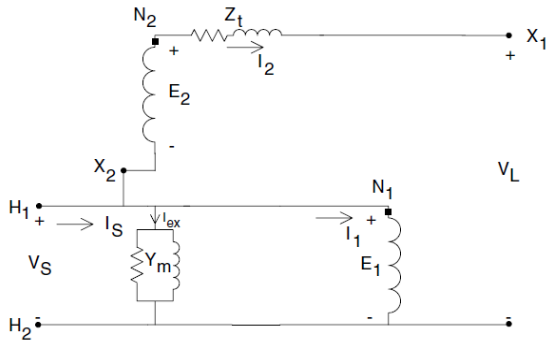
OpenDSS code:

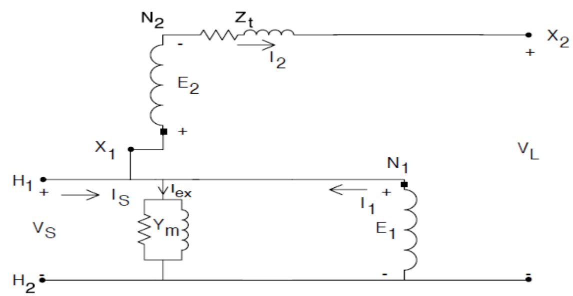
```
New Transformer.Sub_Xfmr      Phases=3          Windings=2      XHL=6.26591063
~ wdg=1 bus=eq_source_bus.1.2.3   conn=delta kV=69   kva=10000 %R=0.62659091
~ wdg=2 bus=bus_Xfmr.1.2.3        conn=wye  kV=13.8 kva=10000 %R=0.62659091
```

Steps of Developing OpenDSS Model

- Electric Devices

Tap changer model (voltage regulator)





Step-up autotransformer $\frac{V_L}{V_S} = \frac{N_2 + N_1}{N_1} = 1 + \frac{N_2}{N_1}$

Step-down autotransformer $\frac{V_L}{V_S} = \frac{-N_2 + N_1}{N_1} = 1 - \frac{N_2}{N_1}$

The generalized equations of substation transformers also applies to autotransformers.

$$[VLN_{ABC}] = [a_t] \cdot [VLN_{abc}] + [b_t] \cdot [I_{abc}]$$

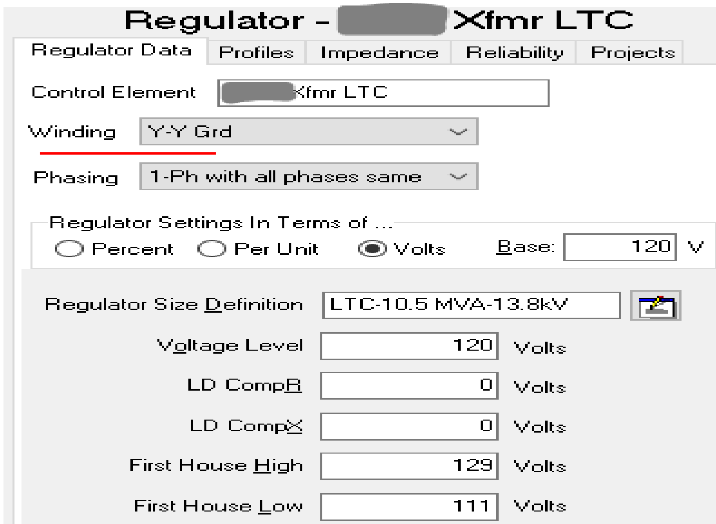
$$[I_{ABC}] = [c_t] \cdot [VLN_{abc}] + [d_t] \cdot [I_{abc}]$$

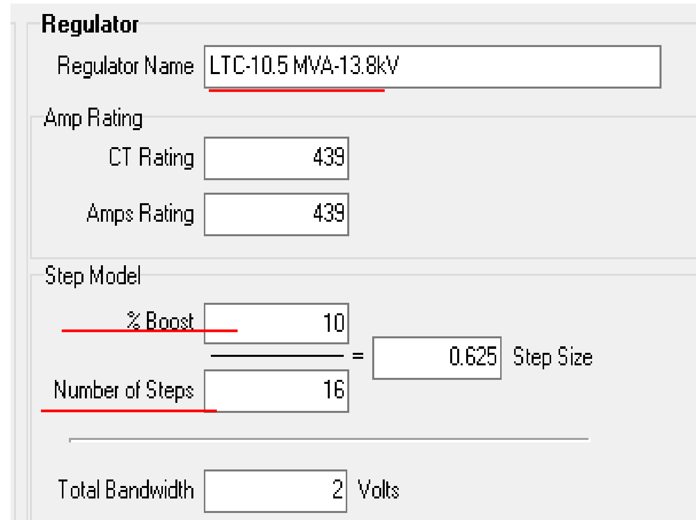
To build a tap changer, we need to specify the number of phases, number of windings, percent resistance and reactance, winding connection, kV rating, kVA rating, number of taps, maximum and minimum tap.

Steps of Developing OpenDSS Model

- Electric Devices

Tap changer information (voltage regulator)





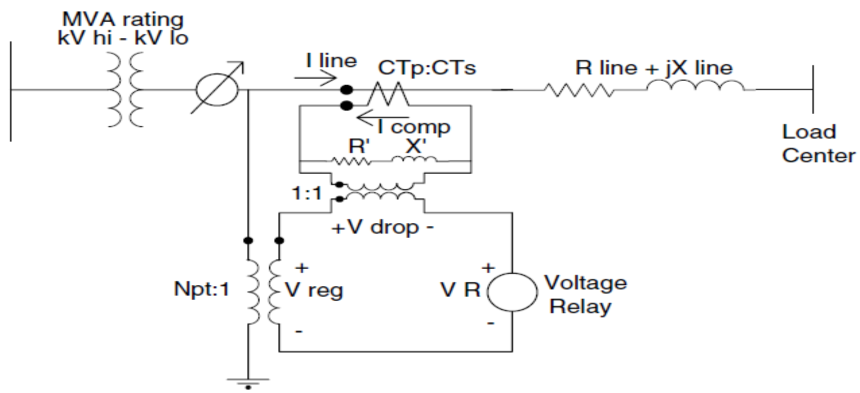
OpenDSS code:

New Transformer.sub_regulator_A Phases=1 bank=Reg1 Windings=2 XHL=0.01
~ wdg=1 bus=bus_Xfmr.1 conn=wye kV=7.9677 kva=3500 %R=0.001
~ wdg=2 bus=bus1.1 conn=wye kV=7.9677 kva=3500 %R=0.001 NumTaps=16
MaxTap=1.1000 MinTap=0.9000

Steps of Developing OpenDSS Model

- Electric Devices

In OpenDSS, a regulator control object is necessary to be defined for controlling a regulator.



Regulator control circuit.

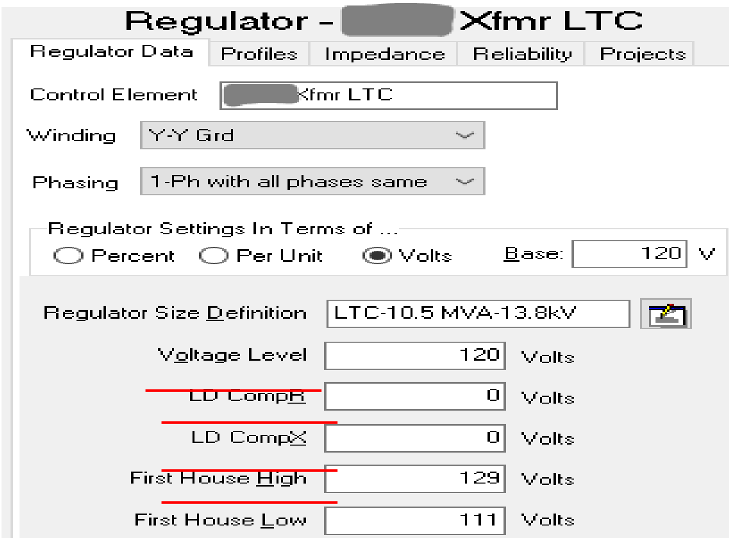
For a regulator control model, we need to specify the regulator to be controlled, the bus to be monitored, number of windings, the desired voltage, R and X setting on the line drop compensator, voltage bandwidth, potential transformer turns ratio, and voltage limit.

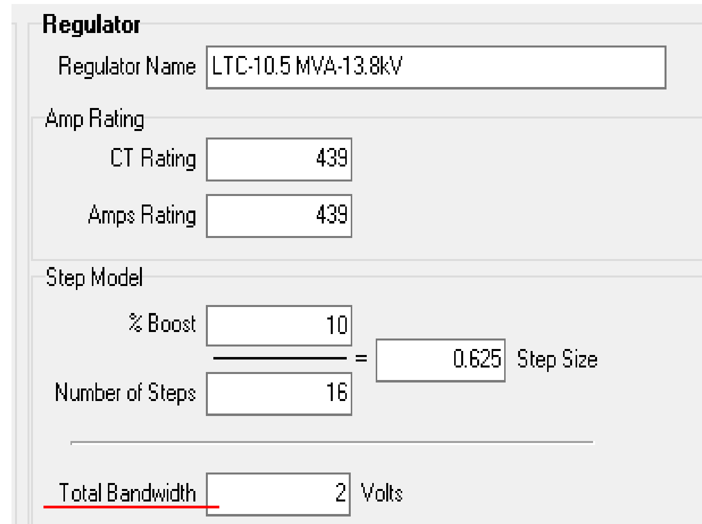
- *CTp*:*CTs*: the current transformer turns ratio,
- *CTp:* primary current rating, typically be the rated current of the feeder,
- *CTs*: secondary current rating of the current transformer,
- *R'*: R settings in volts,
- *X'*: X settings in volts,
- *Npt*: the potential transformer turns ratio,
- *Vreg:* the input voltage to the compensator,
- V_R : desired voltage.

Steps of Developing OpenDSS Model

- Electric Devices

  Tap changer information





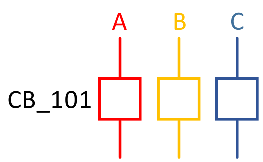
OpenDSS code:

New RegControl.Reg_contr_A Transformer=sub_regulator_A bus=bus1.1 Winding=2 vReg=123.00000 R=0.00000 X=0.00000 Band=2 PTratio=66.395279 vLimit=129.00000

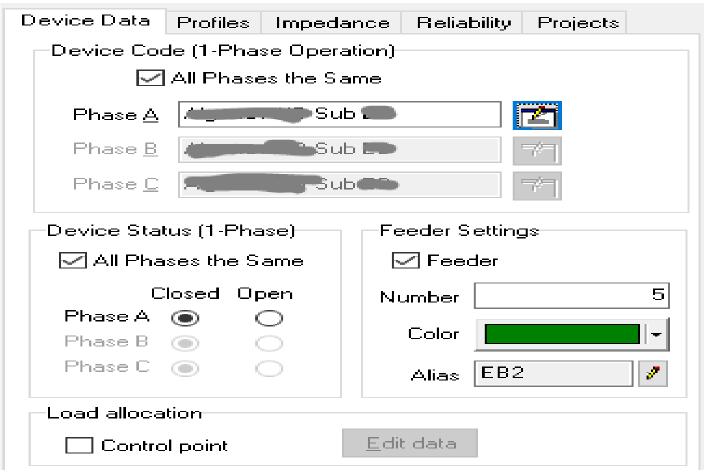
Steps of Developing OpenDSS Model

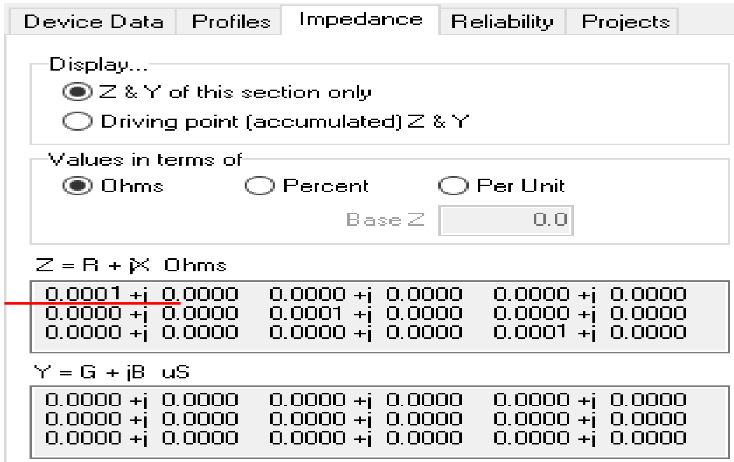
- Electric Devices

  Circuit breaker model



- 9 circuit breakers, 6 of which are normally-closed and the remaining 3 are normally-open





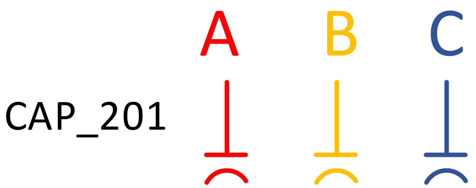
OpenDSS code:

New Line.CB_201 Phases=3 Bus1=bus1.1.2.3 Bus2=bus2001.1.2.3 Switch=y r1=1e-4 r0=0 x1=0 x0=0 c1=0 c0=0

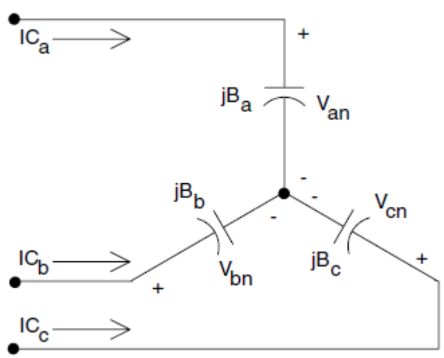
Steps of Developing OpenDSS Model

- Electric Devices

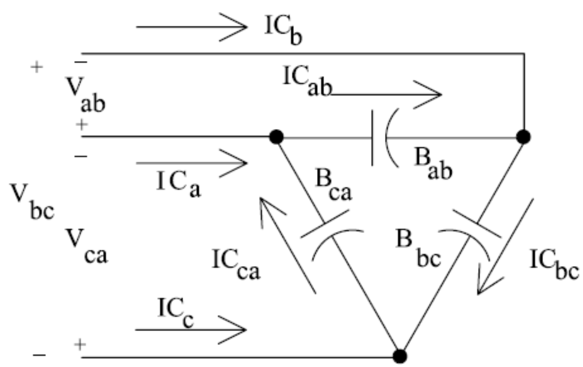
Capacitor bank model



- Two shunt capacitor banks for voltage regulation, which are located on Feeder B and Feeder C, respectively
- Capacitor banks are switched on in normal operation to provide reactive power support



$$B_c = \frac{kvar}{kV_{LN}^2 \cdot 1000} \ \mathrm{S}$$



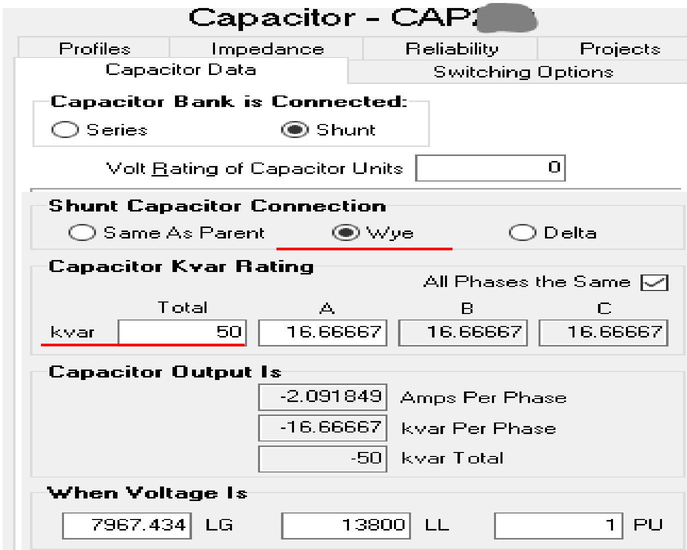
$$B_c = \frac{kvar}{kV_{LL}^2 \cdot 1000} \ \mathrm{S}$$

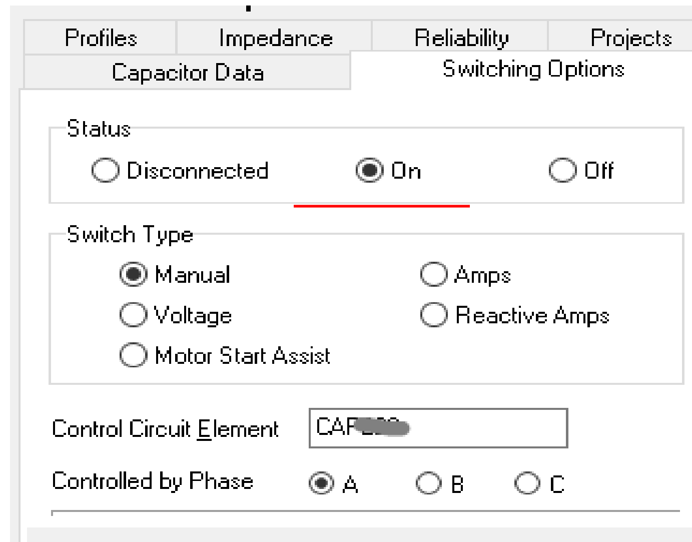
For a capacitor bank, we need to specify the number of phases, kV rating, kVar rating, the connection, and the normal state.

Steps of Developing OpenDSS Model

- Electric Devices

Capacitor bank information





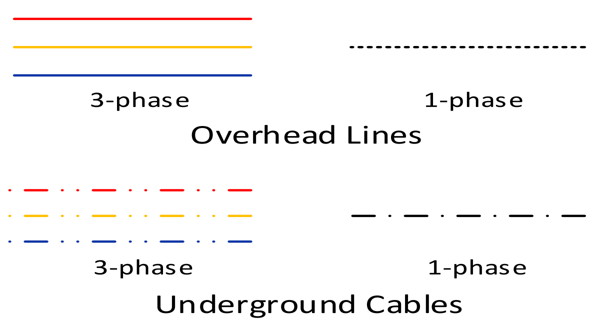
OpenDSS code:

New Capacitor.CAP_201 phases=3 bus1=bus2038.1.2.3 kV=13.8 kvar=50 enabled=Yes

Steps of Developing OpenDSS Model

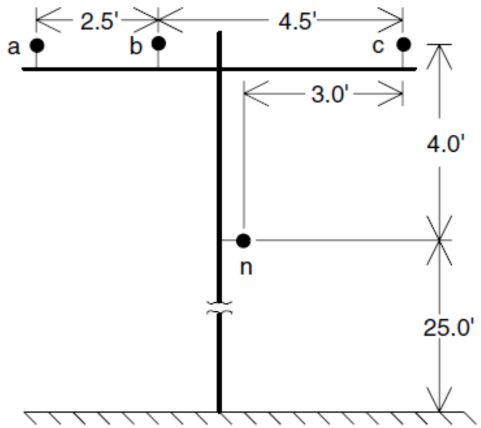
- Electric Devices

Overhead lines and underground cable model



- In OpenDSS, to build a line model, first, we should build linecode models corresponding to different conductors and construction structures.
- The lincode models are defined in terms of series-impedance matrix per-unit length and shunt admittance matrix per-unit length.

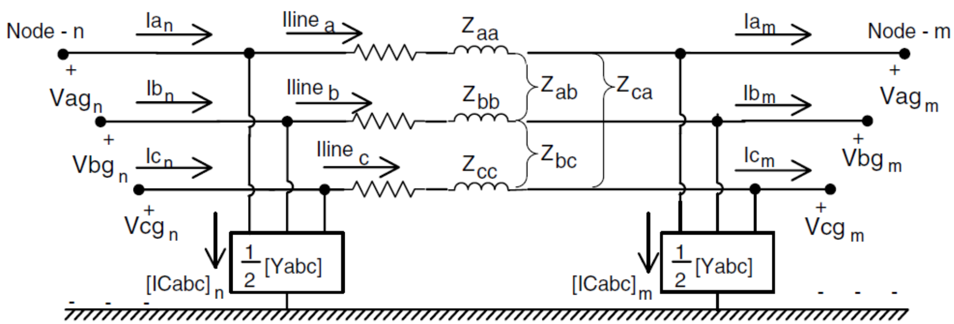
Size	Material	Resistance (Ω/mile)	Diameter (inch)	GMR (feet)	Capacity (A)
4/0	ACSR	0.592	0.563	0.00814	340
1/0	ACSR	1.12	0.355	0.00446	230
4	ACSR	2.55	0.257	0.00452	140
2	ACSR	1.65	0.316	0.00504	180
6	CU	2.41	0.201	0.00568	130
2	CU	0.87	0.3	0.0083	200
4/0	AA	0.554	0.512	0.0167	326
1/0	AA	1.114	0.362	0.0111	228



Steps of Developing OpenDSS Model

- Electric Devices

Overhead Lines and Underground Cables



$$[VLG_{abc}]_n = [a] \cdot [VLG_{abc}]_m + [b] \cdot [I_{abc}]_m$$

$$[a] = [U] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[b] = [Z_{abc}]$$

U – Identity matrix

$Zabc$ – Series impedance matrix $[Z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$

$$[I_{abc}]_n = [c] \cdot [VLG_{abc}]_m + [d] \cdot [I_{abc}]_m$$

$$[c] = [Y_{abc}] + \frac{1}{4} \cdot [Y_{abc}] \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[d] = [U] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}]$$

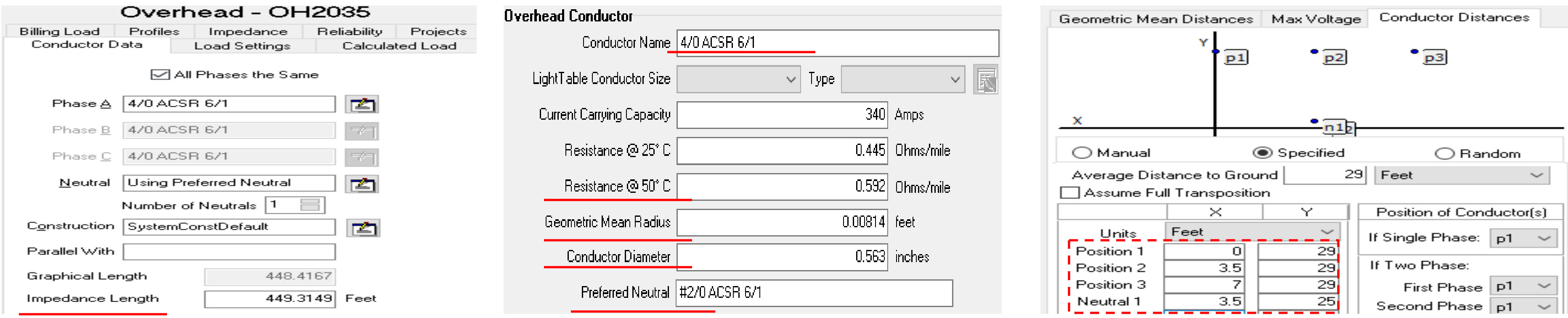
$Yabc$ – Shunt admittance matrix $[Y_{abc}] = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}$

To build line models, we need to calculate Zabc and Yabc matrices.
To calculate Zabc and Yabc matrices, we need to know the conductor and construction information.

Steps of Developing OpenDSS Model

- Electric Devices

Series impedance matrix



- Conductor information:
  Geometric mean radius: $GMR_p = 0.00814$ ft, $GMR_n = 0.0051$ ft
  Resistance per unit length: $r_p = 0.592$ ohms/mile, $r_n = 0.895$ ohms/mile
- Distances between conductors;
  $D_{ab} = 3.5$ ft, $D_{bc} = 3.5$ ft, $D_{ca} = 7$ ft, $D_{an} = 5.315$ ft, $D_{bn} = 4$ ft, $D_{cn} = 5.315$ ft

Steps of Developing OpenDSS Model

- Electric Devices

Series impedance matrix

- Conductor information:
  Geometric mean radius: $GMR_p = 0.00814$ ft, $GMR_n = 0.0051$ ft
  Resistance per unit length: $r_p = 0.592$ ohms/mile, $r_n = 0.895$ ohms/mile
- Distances between conductors;
  $D_{ab} = 3.5$ ft, $D_{bc} = 3.5$ ft, $D_{ca} = 7$ ft, $D_{an} = 5.315$ ft, $D_{bn} = 4$ ft, $D_{cn} = 5.315$ ft

+

$$\widehat{z_{ii}} = r_i + 0.09530 + j0.12134(\ln\frac{1}{GMR_i} + 7.93402)\ \Omega/\text{mile} \quad (4.41)$$

$$\widehat{z_{ij}} = 0.09530 + j0.12134(\ln\frac{1}{D_{ij}} + 7.93402)\Omega/\text{mile} \quad (4.42)$$

$$[\hat{z}_{\text{primitive}}] = \begin{bmatrix} [\hat{z}_{ij}] & [\hat{z}_{in}] \\ [\hat{z}_{nj}] & [\hat{z}_{nn}] \end{bmatrix}$$

$$[z_{abc}] = [\widehat{z_{ij}}] - [\widehat{z_{in}}] \cdot [\widehat{z_{nn}}]^{-1} \cdot [\widehat{z_{nj}}]$$

OpenDSS code:

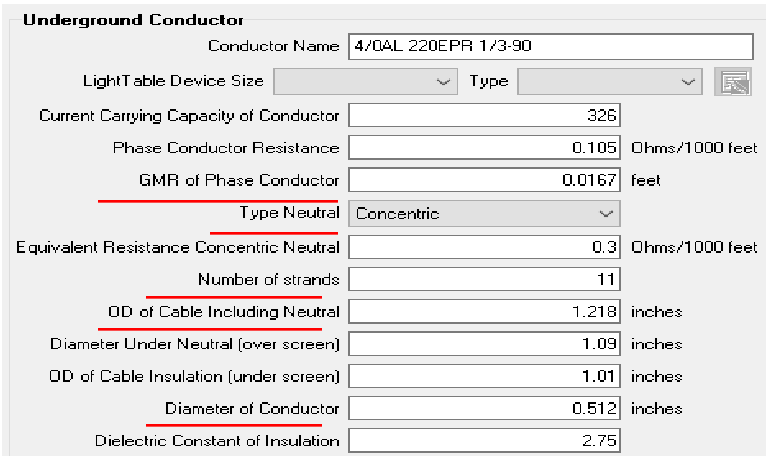
```
New LineCode.OH_3p_type1 nphases= 3 Units= mi
~ Rmatrix= (0.615927 | 0.170927 0.615927 | 0.170927 0.170927 0.615927 )
~ Xmatrix= (1.209389 | 0.433188 1.209389 | 0.433188 0.433188 1.209389 )

New Line.L_2006_2010 phases=3 Bus1=bus2006.1.2.3 Bus2=bus2010.1.2.3
~ length=170 units=Ft LineCode=OH_3p_type1
```

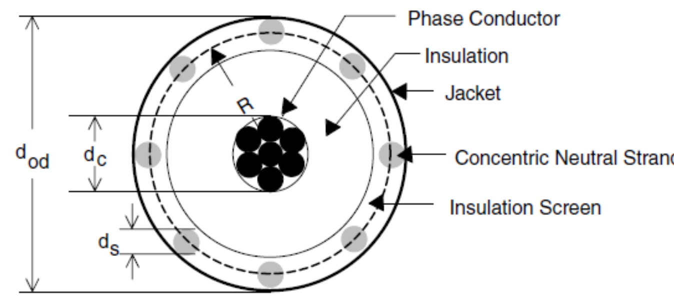
Steps of Developing OpenDSS Model

- Electric Devices

Shunt admittance matrix


Underground Conductor

Conductor Name	4/0AL 220EPR 1/3-90	
LightTable Device Size		Type
Current Carrying Capacity of Conductor	326	
Phase Conductor Resistance	0.105	Ohms/1000 feet
GMR of Phase Conductor	0.0167	feet
Type Neutral	Concentric	
Equivalent Resistance Concentric Neutral	0.3	Ohms/1000 feet
Number of strands	11	
OD of Cable Including Neutral	1.218	inches
Diameter Under Neutral (over screen)	1.09	inches
OD of Cable Insulation (under screen)	1.01	inches
Diameter of Conductor	0.512	inches
Dielectric Constant of Insulation	2.75	



- Conductor information:
  Underground cable type: concentric
  Number of strands: k = 11
  Diameter of neutral: $d_s = 1.218 - 1.09 = 0.128$ inch
  Diameter of conductor: $d_c = 0.512$ inch
  The radius of a circle passing through the centers of the neutral strands: R = (1.218-0.128)/2= 0.545 inch

Steps of Developing OpenDSS Model

- Electric Devices

Shunt admittance matrix

- Conductor information:
  Underground cable type: concentric
  Number of strands: k = 11
  Diameter of neutral: d_s = 1.218 – 1.09 = 0.128 inch
  Diameter of conductor: d_c = 0.512 inch
  The radius of a circle passing through the centers of the neutral strands: R = (1.218-0.128)/2= 0.545 inch

+

$$\begin{cases} RD_c = d_c/2, \ RD_s = d_s/2 \\ C_{pg} = \dfrac{2\pi\varepsilon}{\ln(R/RD_c) - (1/k)\ln(k*RD_s/R)} \end{cases} \quad (5.30)$$

$$y_{pg} = 2\pi f C_{pg}$$

$$y_{abc} = \begin{bmatrix} y_{ag} & 0 & 0 \\ 0 & y_{bg} & 0 \\ 0 & 0 & y_{cg} \end{bmatrix}$$

OpenDSS code:

```
New LineCode.UG_3p_type1 nphases= 3 Units= mi
~ Cmatrix= (286.101593 | 0.000000 286.101593 | 0.000000 0.000000 286.101593 )
```

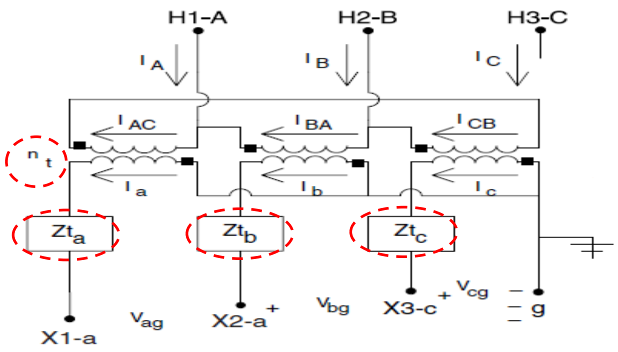
Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer -- 3-phase

For a three-phase distribution transformer, its model is

$$[VLN_{ABC}] = [a_t]\cdot[VLN_{abc}] + [b_t]\cdot[I_{abc}]$$
$$[I_{ABC}] = [c_t]\cdot[VLN_{abc}] + [d_t]\cdot[I_{abc}]$$



$$[a_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2 & 1\\ 1 & 0 & 2\\ 2 & 1 & 0\end{bmatrix} \qquad [b_t] = \frac{-n_t}{3}\cdot\begin{bmatrix}0 & 2\cdot Zt_b & Zt_c\\ Zt_a & 0 & 2\cdot Zt_c\\ 2\cdot Zt_a & Zt_b & 0\end{bmatrix}$$

$$[c_t] = \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \qquad [d_t] = \frac{1}{n_t}\cdot\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ -1 & 0 & 1\end{bmatrix}$$

a_t, b_t, c_t and d_t depend on n_t, Zt_a, Zt_b, Zt_c, i.e., depend on the specific winding connection, impedance and rating of a transformer.

To build a transformer model, we need to know kV rating, kVA rating, number of phases, number of windings, connection, percent resistance, percent reactance.

Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 3-phase

From the distribution system map, we can obtain the kV rating, kVA rating, connection for the three-phase distribution transformers. We also have the measured percent impedances of distribution transformers as shown in this table.

Note that %R should be split into the primary winding percent impedance and secondary winding impedance.

These measured parameters are obtained by performing short circuit tests on transformers.

kVA	Single-Phase		kVA	Three-phase	
	%X	%R		%X	%R
5	1.68	2.94	6	1.72	2.72
7.5	1.84	2.42	9	1.16	2.31
10	1.92	2.04	15	1.82	2.1
15	2.02	1.6	30	1.37	3.8
25	2.3	1.4	45	1.73	2.52
37.5	2.7	3.6	75	1.91	2.27
50	2.8	3.1	112.5	3.87	2.43
75	3.7	2.48	150	5	2.35
100	3.55	2.12	225	5.5	1.15
167	3.25	1.6	300	4.5	1.8
			500	5.9	1.6

*0.5 Assuming $R_S = R_L$

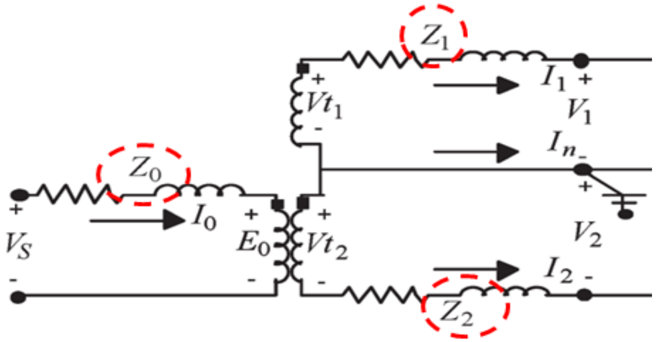
OpenDSS code:

```
New Transformer.T_1004 Phases=3 Windings=2 XHL=1.91
~ wdg=1 bus=bus1004.1.2.3.0         conn=wye kV=13.8   kva=75 %R=1.135
~ wdg=2 bus=T_bus1004_L.1.2.3.0 conn=wye kV=0.208 kva=75 %R=1.135
```

Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 1-phase center-tapped



$$[V_{ss}] = [a_t]\cdot[V_{12}] + [b_t]\cdot[I_{12}] \qquad [I_{00}] = [c_t]\cdot[V_{12}] + [d_t]\cdot[I_{12}]$$

$$[V_{ss}] = \begin{bmatrix} V_s \\ V_s \end{bmatrix} \quad [a_t] = [av] = n_t\cdot\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad [I_{00}] = \begin{bmatrix} I_0 \\ I_0 \end{bmatrix} \quad [c_t] = n_t\cdot\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$[b_t] = \begin{bmatrix} n_t\cdot Z_1+\frac{1}{n_t^2}\cdot Z_0 & -\frac{1}{n_t^2}\cdot Z_0 \\ \frac{1}{n_t^2}\cdot Z_0 & -(n_t\cdot Z_2+\frac{1}{n_t^2}\cdot Z_0) \end{bmatrix} \qquad [d_t] = \frac{1}{n_t}\begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix}$$

$$\begin{cases} Z_0 = 0.5 * \%R + \text{j } 0.8 * \%X \\ Z_1 = \%R + \text{j } 0.4 * \%X \\ Z_2 = \%R + \text{j } 0.4 * \%X \end{cases}$$

a_t, b_t, c_t and d_t depend on n_t, Z_0, Z_1, Z_2, i.e., depend on the specific impedance and winding ratings of a transformer.

To build a 1-phase center-tapped distribution transformer model, we need to know kV rating, kVA rating, number of phases, number of windings, connection, percent resistance, percent reactance.

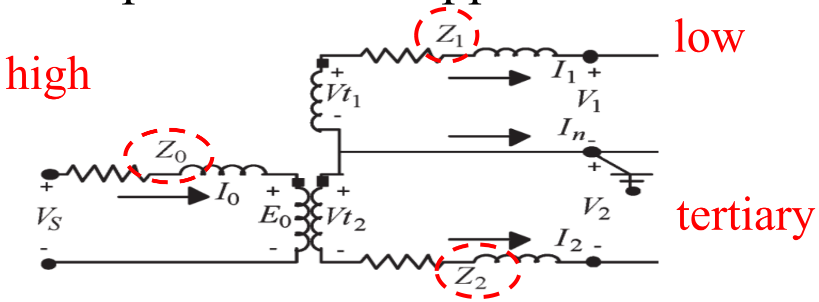
Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 1-phase center-tapped

kVA	Single-Phase		kVA	Three-phase	
	%X	%R		%X	%R
5	1.68	2.94	6	1.72	2.72
7.5	1.84	2.42	9	1.16	2.31
10	1.92	2.04	15	1.82	2.1
15	2.02	1.6	30	1.37	3.8
25	2.3	1.4	45	1.73	2.52
37.5	2.7	3.6	75	1.91	2.27
50	2.8	3.1	112.5	3.87	2.43

+



$$\begin{cases} Z_0 = 0.5 * \%R + j\,0.8 * \%X \\ Z_1 = \%R + j\,0.4 * \%X \\ Z_2 = \%R + j\,0.4 * \%X \end{cases} \Rightarrow \begin{cases} Z_{01} = 1.5 * \%R + j\,1.2 * \%X \\ Z_{02} = 1.5 * \%R + j\,1.2 * \%X \\ Z_{12} = 2 * \%R + j\,0.8 * \%X \end{cases}$$

OpenDSS code:

```
New Transformer.T_1014 Phases=1 Windings=3 XHL=2.76  XHT=2.76  XLT=1.84
~ wdg=1 bus=bus1014.2.0        conn=wye kV=7.9677   kva=25  %R=0.7
~ wdg=2 bus=T_bus1014_L.1.0 conn=wye kV=0.120       kva=25  %R=1.4
~ wdg=3 bus=T_bus1014_L.0.2 conn=wye kV=0.120       kva=25  %R=1.4
```


W. H. Kersting, "Center-Tapped Transformer and 120-/240-V Secondary Models," IEEE Trans. Ind. Appl., vol. 45, pp. 575–581, Mar./Apr. 2009.

Steps of Developing OpenDSS Model

- Electric Devices

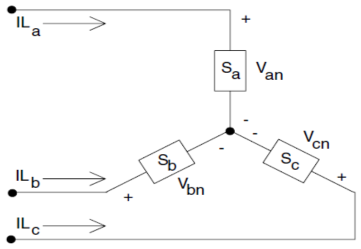
Load

In this OpenDSS model, constant active and reactive power load models are selected. For a constant P and Q, wye-connected load, the line currents are given by

$$IL_a = \left(\frac{S_a}{V_{an}}\right)^* = \frac{|S_a|}{|V_{an}|}\underline{/\,\delta_a - \theta_a} = |IL_a|\,\underline{/\,\alpha_a}$$

$$IL_b = \left(\frac{S_b}{V_{bn}}\right)^* = \frac{|S_b|}{|V_{bn}|}\underline{/\,\delta_b - \theta_b} = |IL_b|\,\underline{/\,\alpha_b}$$

$$IL_c = \left(\frac{S_c}{V_{cn}}\right)^* = \frac{|S_c|}{|V_{cn}|}\underline{/\,\delta_c - \theta_c} = |IL_c|\,\underline{/\,\alpha_c}$$



Using the calculated nodal P and Q, together with the phasing of customers, we can develop load models in OpenDSS as follows:

OpenDSS code:

3-phase
```
New  Load.Load_1005  phases=3  conn=wye  bus1=T_bus1005_L.1.2.3.0
kV=0.208  kW=4.916000000000000   Kvar=1.942927521885772
```

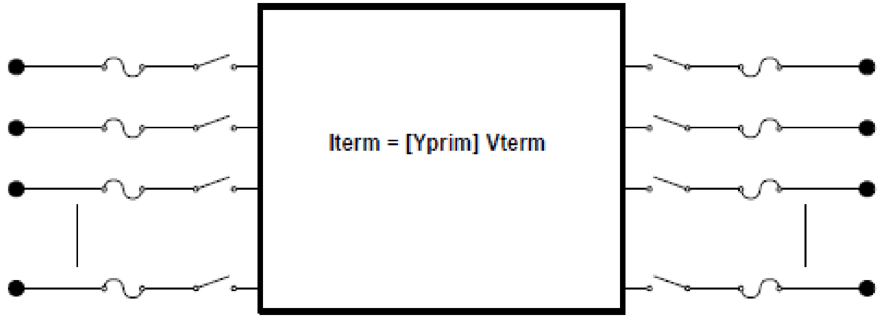
1-phase
```
New  Load.Load_1006  phases=1  conn=delta  bus1=T_bus1006_L.1.2
kV=0.208  kW=5.040000000000000   Kvar=2.296291839688011
```

Power Flow Analysis

Typically, a power-flow analysis can determine the following variables by phase and total three-phase:

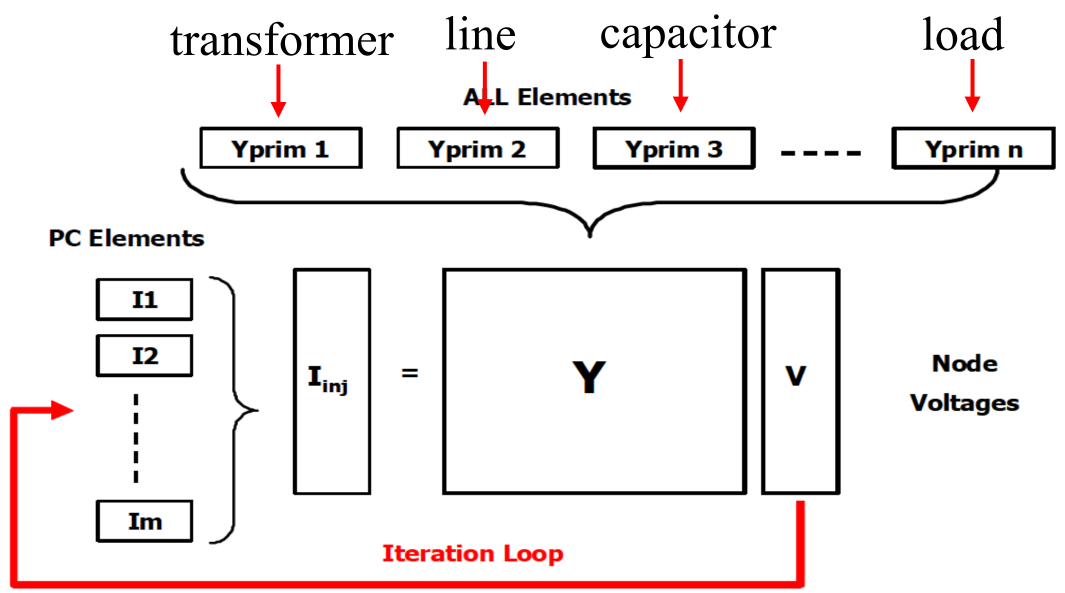
- Voltage magnitudes and angles at all nodes of the feeder
- Line flow in each line section specified in kW and kVar, amps and degrees, or amps and power factor
- Power loss in each line section
- Total input kW and kVar
- Total power losses
- Load kW and kVar based upon the specified model for the load

In OpenDSS, each element is denoted as a 2-terminal element.



Power Flow Analysis

- A primitive admittance matrix, Yprim, is computed for each circuit element in the model.
- Then, these small nodal admittance matrices are used to construct the main system admittance matrix (**Y**).
- By setting initial value of nodal voltages, an iterative procedure is performed to solve the power flow.



Matlab-OpenDSS Interface

```
clear;

%% Read load data
load FeederA_P;      % Active powers correpsonding to Feeder A's buses
load FeederA_Q;      % Reactive powers correpsonding to Feeder A's buses
load FeederB_P;      % Active powers correpsonding to Feeder B's buses
load FeederB_Q;      % Reactive powers correpsonding to Feeder B's buses
load FeederC_P;      % Active powers correpsonding to Feeder C's buses
load FeederC_Q;      % Reactive powers correpsonding to Feeder C's buses

%% Build the Matlab-OpenDSS COM interface
DSSObj=actxserver('OpenDSSEngine.DSS');               % Register the COM server (initialization)
if ~DSSObj.Start(0)                                   % Start the OpenDSS, and if the registration is unsuccessful,
                                                        stop the program and remind the user
    disp('Unable to start OpenDSS Engine');
    return
end
DSSText = DSSObj.Text;                                % Define a text interface variable
DSSCircuit = DSSObj.ActiveCircuit;                    % Define a circuit interface variable
DSSText.Command='Compile "C:\Users\fbu\Desktop\Project\Test system
1\Matlab_OpenDSS_Interface\0813\Code\Master.dss"';    % Specify the directory of OpenDSS master file

%% Define variables to collect the power flow results
bus_voltages_rect = [];                   % Bus voltage in rectangular coordinate
bus_voltage_magni_pu = [];                % Bus voltage magnitude in per unit.
currents_line = [];                       % Line current
powers_line = [];                         % Line power
elem_names = [];                          % Element names
elem_losses = [];                         % Element loss
total_power = [];                         % System total power
i_notconverged = 0;                       % Define a variable to record the number of unconverged snapshot power
                                            flow solutions
Tap_position_collect = [];                % Tap changer position
```

Load the calculated P and Q

Build the connection between Matlab and OpenDSS

Define variables to collect power flow result

Matlab-OpenDSS Interface

```
%% Specify load buses (buses with load)
FeederA_bus_with_load = 1003:1017;          % Buses of Feeder A that have loads
FeederB_bus_with_load = [2002:2003, 2005, 2008:2011, 2014:2018, 2020, 2022:2025, 2028:2032, 2034:2035, 2037,
2040:2043, 2045:2056, 2058:2060];           % Buses of Feeder B that have loads
FeederC_bus_with_load = [3002, 3004, 3006:3007, 3009:3014, 3016:3021, 3023:3029, 3031:3039, 3041:3045, 3047:3052,
3054, 3056:3067, 3070:3074, 3077:3078, 3081, 3083:3091, 3093:3099, 3101:3106, 3108:3112, 3114:3117, 3120:3132,
3134:3138, 3141:3155, 3157:3162];           % Buses of Feeder C that have loads

%% Solve quasi-static time-series power flow via Matlab-OpenDSS interface and collect results
n = length(FeederA_P(:, 1));                          % Number of hours in one year, i.e., 8760
for i = 1:n
      %% For each load of Feeder A, set kW and kVar
      for k = 1:length(FeederA_bus_with_load)            % From the 1st bus with load to the last bus with load
          bus_num = FeederA_bus_with_load(1,k);          % Bus No.
          DSSText.command=[[char('load.Load_'), num2str(bus_num), char('.kW=')]  num2str(FeederA_P(i,
          bus_num-1000)) ' kvar='  num2str(FeederA_Q(i, bus_num-1000)) ''];
         % Build bus name and set corresponding kW and kVar
         %  bus_num-1000 specifies the column number that the power corresponds to
      end


      %% For each load of Feeder B, set kW and kVar
      for k = 1:length(FeederB_bus_with_load)           % From the 1st bus with load to the last bus with load
          bus_num = FeederB_bus_with_load(1,k);         % Bus No.
          DSSText.command=[[char('load.Load_'), num2str(bus_num), char('.kW=')]  num2str(FeederB_P(i,
          bus_num-2000)) ' kvar='  num2str(FeederB_Q(i, bus_num-2000)) ''];
          % Build bus name and set corresponding kW and kVar
          %  bus_num-2000 specifies the column number that the power corresponds to
      end
```

Specify the nodes with loads

solve snapshot power flow over a one-year period

Edit the "kW" and "kVar" using the loaded calculated P and Q, Feeder A

Edit the "kW" and "kVar" using the loaded calculated P and Q, Feeder B

Matlab-OpenDSS Interface

```
for i = 1:n
    . . .

  %% For each load of Feeder C, set kW and kVar
    for k = 1:length(FeederC_bus_with_load)          % From the 1st bus with load to the last bus with load
        bus_num = FeederC_bus_with_load(1,k);        % Bus No.
        DSSText.command=[[char('load.Load_'), num2str(bus_num), char('.kW=')] num2str(FeederC_P(i,
        bus_num-3000)) ' kvar=' num2str(FeederC_Q(i, bus_num-3000)) ''];
        % Build bus name and set corresponding kW and kVar
        %  bus_num-3000 specifies the column number that the power corresponds to
    end


    %% Solve snapshot power flow
    DSSText.Command='solve';


    %% Convergence checking and record the number of uncoverged snapshot power flow
    DSSSolution = DSSCircuit.Solution;              % Obtain solution information from the interface
    if ~DSSSolution.Converged                       % Check whether the power flow computation converges
        fprintf('The Circuit did not converge. \n');
        i_notconverged = i_notconverged + 1;        % calculate the total number of unconverged power flow
                                                    computations
        continue;
    end

  %% Collect power flow results
    % Collect bus names
    bus_names = DSSCircuit.AllNodenames;

    % Collect all bus voltages in rectangular coordinate
    bus_voltage_temp = DSSCircuit.AllBusVolts;  % Obtain rectangular voltage in each snapshot power flow solution
    bus_voltages_rect = [bus_voltages_rect; bus_voltage_temp]; % Collect rectangular voltages in all snapshot
                                                                power flow solutions
```

Edit the "kW" and "kVar" using the loaded calculated P and Q, Feeder C

solve snapshot power flow

Collect the convergence information checked by OpenDSS

Collect the solved bus voltage

Matlab-OpenDSS Interface

```
for i = 1:n
    . . .

      % Collect all bus voltage magnitude in p.u.
      bus_voltage_magni_pu_temp = DSSCircuit.AllBusVmagPu; % Obtain V in p.u. in each snapshot power flow olution
      bus_voltage_magni_pu = [bus_voltage_magni_pu; bus_voltage_magni_pu_temp]; % Collect voltages in p.u. in all
                                                                                  snapshot power flow solutions

      % Collect element names and losses
      elem_names = DSSCircuit.AllElementNames; % Obtain element names
      elem_loss_temp = DSSCircuit.AllElementLosses; % Obtain element losses in each snapshot power flow solution
      elem_losses = [elem_losses; elem_loss_temp]; % Collect element losses in all snapshot power flow solutions

      % Collect total power of the entire system
      total_power_temp = DSSCircuit.TotalPower; % Obtain total system power in each snapshot power flow solution
      total_power = [total_power; total_power_temp]; % Collect total power of the entire system in all snapshot
                                                       power flow solutions

      % Collect currents and powers of all lines
       currents_DSS_Lines = []; % Define a variable to collect line currents in each snapshot power flow solution
       Powers_DSS_Lines = []; % Define a variable to collect line powers in each snapshot power flow solution
       DSSLines = DSSObj.ActiveCircuit.Lines; % Specify that the currently activated objects are lines
       DSSActiveCktElement = DSSObj.ActiveCircuit.ActiveCktElement; % Returns an interface to the active circuit
                                                                      element (lines).
```

Collect element loses

Collect total power of the entire system

Matlab-OpenDSS Interface

```
for i = 1:n
    . . .

       line_names = {}; % Names of lines
       line_I_points_nums = []; % For each line, define a variable to collect the number of current (or power) variables in rectangular coordinate, e.g., a single phase line has 4 current variables, i.e., real and image parts of the current which flows into the head of the line, real and image parts of the current which flows out the end of the line
       i_Line = DSSLines.First; % Initializing line NO. as the first line
       while i_Line > 0        % From the 1st line to the last line
            currents_DSS_Lines = [currents_DSS_Lines, DSSActiveCktElement.Currents]; % Collect line currents in each snapshot power flow solution

            Powers_DSS_Lines= [Powers_DSS_Lines, DSSActiveCktElement.Powers]; % Collect line powers in each snapshot power flow solution

            line_names{i_Line, 1} = DSSActiveCktElement.NAME; % Collect line names in each snapshot power flow solution

            line_I_points_nums = [line_I_points_nums; length(DSSActiveCktElement.Currents)]; % Collect the total number of variables correponsing to each line in each snapshot power flow solution
            i_Line = DSSLines.Next; % Move to next line in each snapshot power flow solution

       end

      currents_line = [currents_line; currents_DSS_Lines];%Collect line current in all snapshot power flow solutions
      powers_line = [powers_line; Powers_DSS_Lines]; % Collect line powers in all snapshot power flow solutions
```

Collect line currents and powers

Matlab-OpenDSS Interface

```
for i = 1:n
    . . .

 % Collect tap positions
     DSSCircuit.RegControls.Name = 'Reg_contr_A';            % Specify the name of tap changer contoller from which
                                                             we want to get tap postion
     TapChanger1_temp = DSSCircuit.RegControls.TapNumber;    % Obtain tap position of tap changer (Phase A)
     DSSCircuit.RegControls.Name = 'Reg_contr_B';            % Specify the name of tap changer contoller from which
                                                             we want to get tap postion
     TapChanger2_temp = DSSCircuit.RegControls.TapNumber;    % Obtain tap position of tap changer (Phase B)
     DSSCircuit.RegControls.Name = 'Reg_contr_C';            % Specify the name of tap changer contoller from which
                                                             we want to get tap postion
     TapChanger3_temp = DSSCircuit.RegControls.TapNumber;    % Obtain tap position of tap changer (Phase C)
     Tap_position_collect = [Tap_position_collect; [TapChanger1_temp, TapChanger2_temp, TapChanger3_temp]];
                                                % Collect tap changers positions in all snapshot power flow solutions

End

fprintf('The number of snapshot power flow soultions that do not converge is: %d. \n', i_notconverged);
% Print the total number of unconverged power flow solutions
```

Collect tap position of tap changers

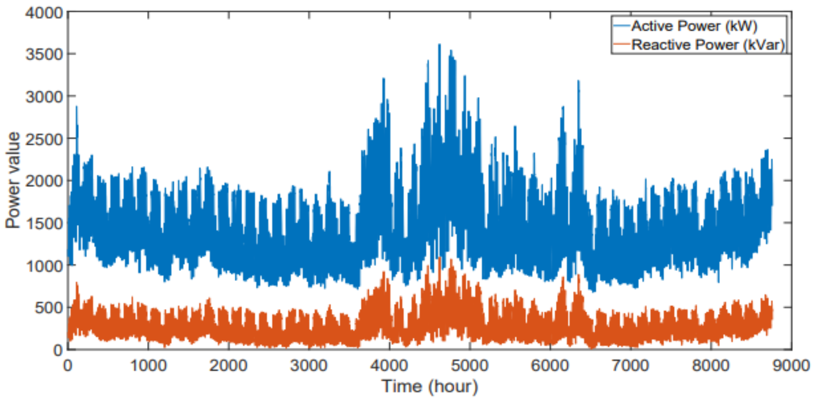
Numerical Results

- Files

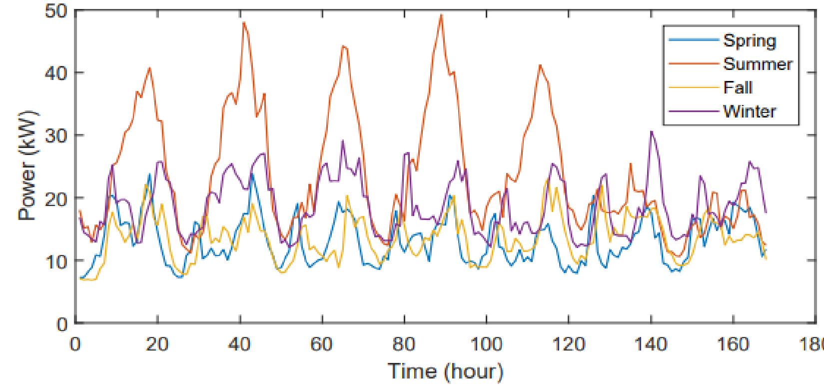
	Name	Date modified	Type	Size
OpenDSS Model	Capacitor.dss	5/26/2019 11:04 PM	DSS File	1 KB
	CircuitBreaker.dss	8/14/2019 10:03 AM	DSS File	2 KB
	DistriTransformer.dss	6/9/2019 11:52 AM	DSS File	84 KB
	Line.dss	5/28/2019 3:40 PM	DSS File	43 KB
	Linecode.dss	5/26/2019 10:56 PM	DSS File	4 KB
	Load.dss	5/26/2019 11:36 AM	DSS File	42 KB
	Master.dss	5/28/2019 3:43 PM	DSS File	2 KB
	RegControl.dss	5/26/2019 10:52 PM	DSS File	1 KB
	SubTransformer.dss	5/27/2019 2:48 PM	DSS File	2 KB
	Vsource.dss	5/21/2019 11:33 AM	DSS File	1 KB
Matlab-OpenDSS Interface	Matlab_OpenDSS_interface.m	8/21/2019 11:33 AM	MATLAB Code	13 KB
One-year Load Data	FeederA_P.mat	5/28/2019 4:18 PM	MATLAB Data	398 KB
	FeederA_P_Q_Header.mat	5/28/2019 4:21 PM	MATLAB Data	11 KB
	FeederA_Q.mat	5/28/2019 4:19 PM	MATLAB Data	949 KB
	FeederB_P.mat	5/28/2019 4:19 PM	MATLAB Data	1,287 KB
	FeederB_P_Q_Header.mat	5/28/2019 4:21 PM	MATLAB Data	29 KB
	FeederB_Q.mat	5/28/2019 4:19 PM	MATLAB Data	2,842 KB
	FeederC_P.mat	5/28/2019 4:19 PM	MATLAB Data	3,988 KB
	FeederC_P_Q_Header.mat	5/28/2019 4:21 PM	MATLAB Data	69 KB
	FeederC_Q.mat	5/28/2019 4:19 PM	MATLAB Data	8,632 KB

Numerical Results

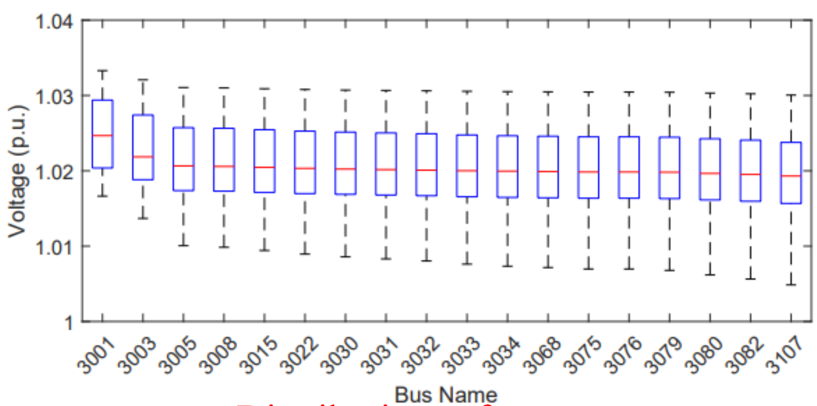
- Time-series Results



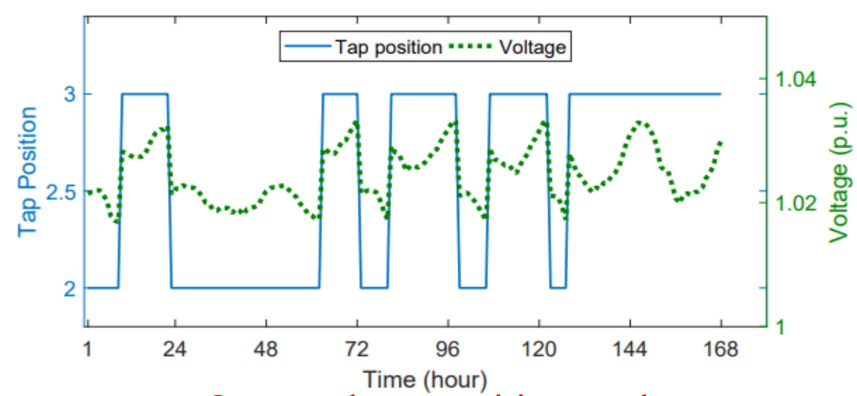
One-year active and reactive power consumption at the substation transformer



One week load profiles of a selected primary node in different seasons



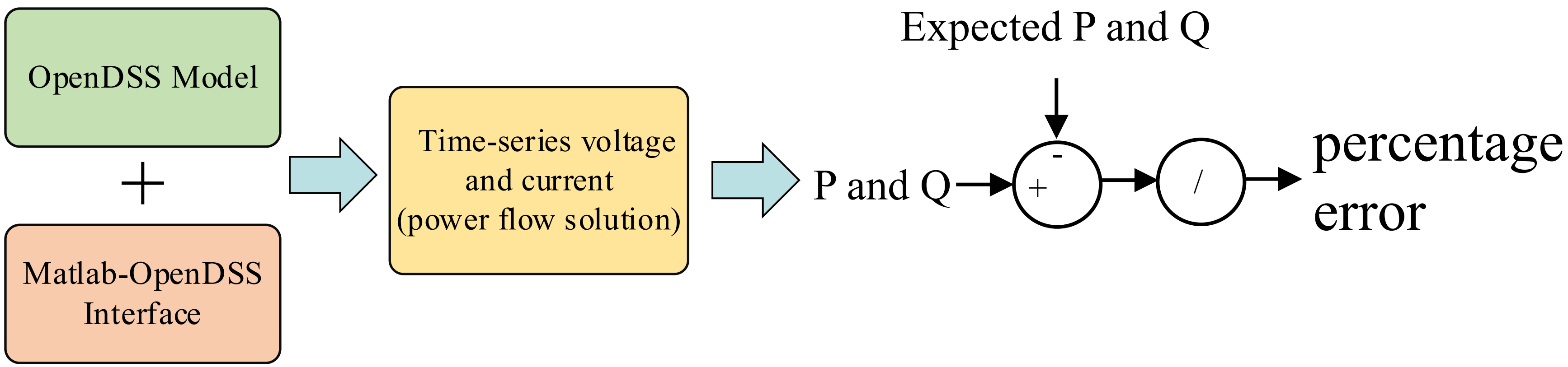
Distributions of one-year nodal voltages of Feeder C (phase A)

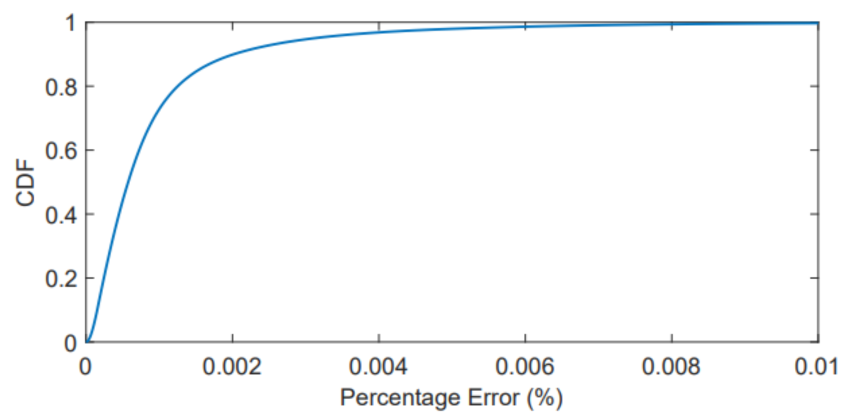


One-week tap positions and voltage magnitudes at Bus 1 (phase A)

Numerical Results

- Convergence validation





Cumulative distribution function of the power flow solution error

Utility II

These slides have been edited to remove business-sensitive information.

Outline

- A Real Distribution System
  - System Information
  - Raw Data

- Steps of Developing the OpenDSS Model
  - Process the Raw Data
  - Develop the OpenDSS Model

A Real Distribution System

- Overview of System Information and Raw Data

This system is a real distribution grid located at Midwest U.S, and it belongs to a municipal utility and it is installed with Automatic Meter Reading (AMR) system.

System Information

- 1 substation
- 2 substation transformers (~/2.4 kV)
- 8 feeders
- 22 miles overhead wire
- 3 miles underground wire
- 1787 poles
- 517 distribution transformers
- 1 PV plant

SCADA Data

- Substation energy recording
  - Time period: 6 years (2013 to 2018)
  - Time resolution: one-hour
  - Historical Peak: 7,700 kW
- PV generation recording
  - Time period: 1 year (June, 2018 to May 2019)
  - Time resolution: one-hour
  - Historical peak: 1,600 kW

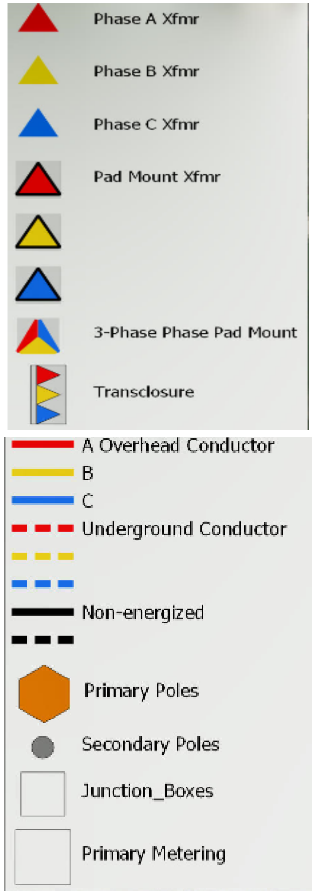
AMR Data

- Type: monthly billing data
- Time period: 16 months (Feb. 2018-May 2019)
- 1329 customers

A Real Distribution System

- Overview of System Information and Raw Data
  - System Information (Map)

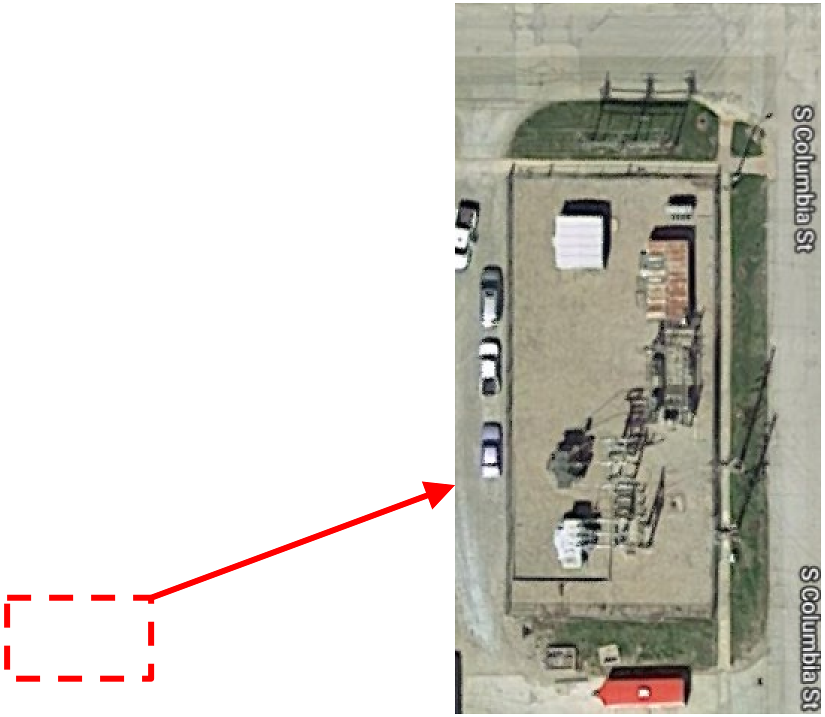
legend



A Real Distribution System

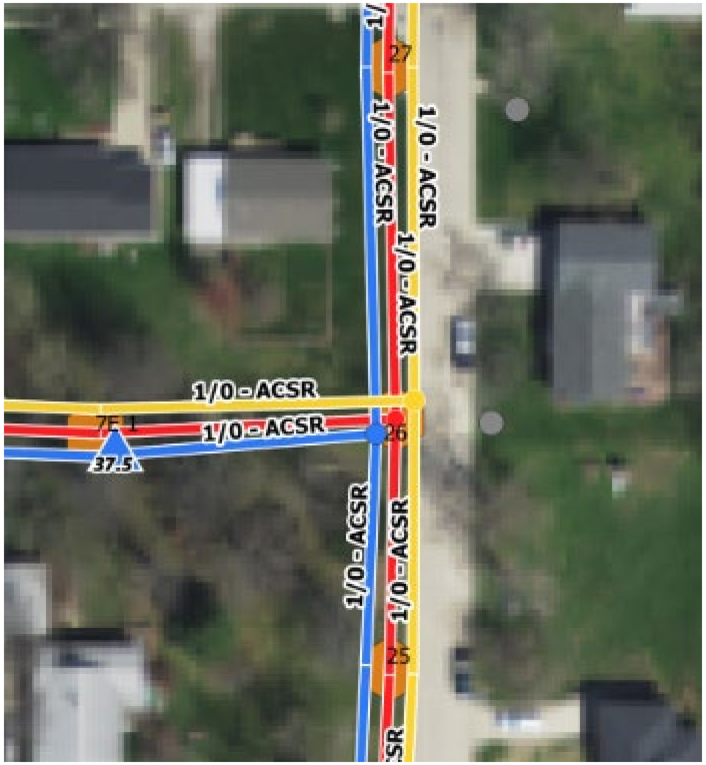
- Overview of System Information and Raw Data
  - System Information (Map)

Substation



A Real Distribution System

- Overview of System Information and Raw Data
  - System Information (Map)



- Geographic information of poles and distribution transformers.
- Line: overhead or underground, conductor information, phasing
- Distribution transformer: kVA capacity, number of phases, phasing

A Real Distribution System

- Overview of System Information and Raw Data
  - System Information (Device)

Overview of distribution transformers and capacitor banks

	Transformer 1				Transformer 2				
Feeder Name	Feeder 1	Feeder 6	Feeder 8	Feeder 9	Feeder 3	Feeder 4	Feeder 5	Feeder 7	∑
Total number of distribution tranformer	56	65	66	58	82	38	114	38	517
1-phase distribution transformer	55	62	62	55	80	35	111	34	494
3-phase distribution transformer	1	3	4	3	2	3	3	4	23
Pole-mounted distribution transformer	38	46	49	44	69	30	94	30	400
Pad-mounted distribution transformer	18	19	17	14	13	8	20	8	117
Capacitor bank	1	2	1	2	1	2	2	1	12
Capacitor bank kVar	150	525	300	300	225	450	450	300	2700

* Each distribution transformer and capacitor is installed with a fuse for protection.

A Real Distribution System

- Overview of System Information and Raw Data
  - System Information (Distribution transformer)

latitude	longitude	pole_number	number_of_transformers	number_of_phases	transformer_size_kva
20.750511	-102.412681	1A-2	0		
20.749581	-102.412363	1B-1	1	Single Phase	25
20.749613	-102.412793	1BA-1	0		
20.74958	-102.413235	1BA-2	0		
20.74937	-102.412245	1B-2	0		
20.749166	-102.415888	1BC-7	0		
20.749138	-102.41545	1BC-6	1	Single Phase	25
20.74916	-102.414866	1BC-5	0		
20.749148	-102.414313	1BC-4	1	Single Phase	25
20.749098	-102.413785	1BC-3	0		
20.749083	-102.413178	1BC-2	1	Single Phase	37.5
20.74893	-102.413203	1BC-2A	0		
20.749133	-102.412815	1BC-1	0		
20.748876	-102.412696	1BC-1A	0		
20.749131	-102.41226	1B-3	0		
20.749	-102.411913	1BB-1A	0		
20.749148	-102.411788	1BB-1	1	Single Phase	37.5
20.74918	-92.411513	1BB-2	0		
20.749151	-92.411168	1BB-3	1	Single Phase	37.5
20.749316	-92.410606	1BB-3B	0		

…

…

Pole and distribution transformer information

*The pad-mounted wire connecting point is defined as a underground pole.

A Real Distribution System

- Overview of System Information and Raw Data
  - System Information (Capacitor bank)

	latitude	longitude	pole_number	feeder_number	number_of_capacitors	capacitor_1_size_kvar	capacitor_2_size_kvar	capacitor_3_size_kvar
1	20.7506	-102.40228	1G-4	1	3	50	50	50
2	20.7565	-102.41276	3D-2	3	3	75	75	75
3	20.7595	-102.41649	4I-6	4	3	100	100	100
4	20.7588	-102.41638	4IC-3	4	3	50	50	50
5	20.748	-102.42886	5H-8	5	3	100	100	100
6	20.7514	-102.42799	5-35	5	3	50	50	50
7	20.7457	-102.42637	6G-11	6	3	100	100	100
8	20.7444	-102.42763	6JC-1	8	3	100	100	100
9	20.745	-102.42459	6-39	6	3	75	75	75
10	20.7522	-102.41338	7-16	7	3	100	100	100
11	20.7487	-102.40978	9-43	9	3	50	50	50
12	20.7511	-102.41074	9A-3	9	3	50	50	50

Pole and capacitor bank information

A Real Distribution System

- Overview of System Information and Raw Data
  - Raw Data (SCADA)

Time → kWh ↓ kVarh ↓

RECORDER ID	DATE	HOUR	DELKWH	DELKVARH
SUB	10114	1	1817.16	86.64
SUB	10114	2	1760.48	83.64
SUB	10114	3	1718.32	81.56
SUB	10114	4	1741.32	82.76
SUB	10114	5	1755.84	83.4
SUB	10114	6	1817.68	86.52
SUB	10114	7	1864.88	89
SUB	10114	8	1900.92	91.16
SUB	10114	9	2002.44	97.4
SUB	10114	10	2181.24	108.2
SUB	10114	11	2241.56	112.16
SUB	10114	12	2307.92	116.72
SUB	10114	13	2321.4	117.8
SUB	10114	14	2267.68	114.16
SUB	10114	15	2243.28	112.32
SUB	10114	16	2228.16	111.28
SUB	10114	17	2309.08	116.72
SUB	10114	18	2518.92	131.56

. . .

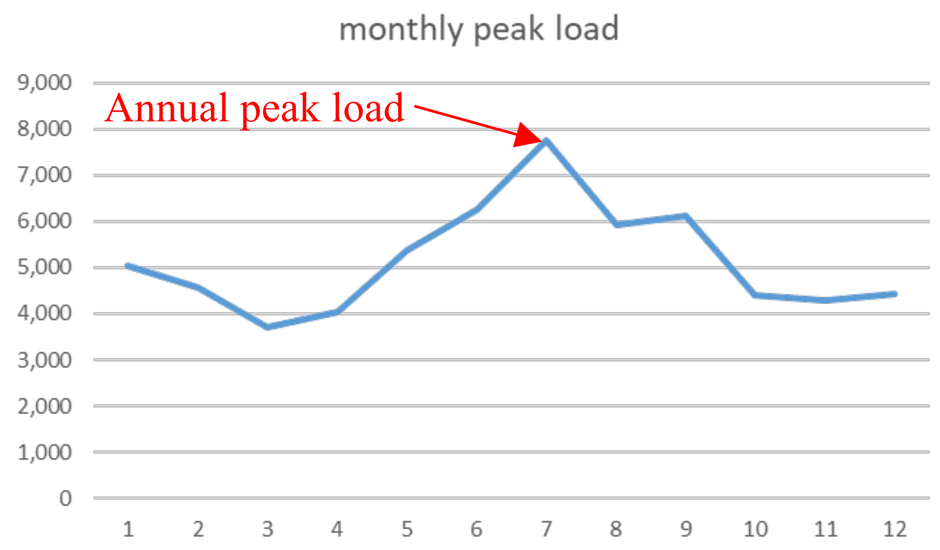
SCADA data

A Real Distribution System

- Overview of System Information and Raw Data
  - Raw Data (SCADA)

Monthly peak consumptions with a time period of one year

Peak	Peaking Time
5,050	Monday - January 1, 2018 at 07:00 PM
4,576	Tuesday - February 6, 2018 at 08:00 AM
3,718	Wednesday - March 7, 2018 at 08:00 PM
4,030	Thursday - April 19, 2018 at 08:00 AM
5,379	Monday - May 28, 2018 at 07:00 PM
6,267	Monday - June 18, 2018 at 06:00 PM
7,769	Thursday - July 12, 2018 at 02:00 PM
5,919	Friday - August 3, 2018 at 05:00 PM
6,131	Thursday - September 20, 2018 at 04:00 PM
4,397	Wednesday - October 3, 2018 at 05:00 PM
4,282	Tuesday - November 27, 2018 at 08:00 AM
4,422	Friday - December 7, 2018 at 09:00 AM



SCADA data

A Real Distribution System

- Overview of System Information and Raw Data
  - Raw Data (AMR)

Location | Account | kWh | Recording Time | Monthly kWh

Longitude, latitude	account	unit	02/20/2018	03/20/2018	04/20/2018	05/20/2018	06/20/2018	07/20/2018	08/20/2018	09/20/2018
POINT (-102.424463 20.743974)	100001	kWh	488	342	345	348	546	654	1052	919
POINT (-102.4092902243 20.7538538797)	100002	kWh	769	526	527	642	1254	1325	1938	1237
POINT (-102.4124532193 20.7569480306)	100003	kWh	2542	2371	2455	2494	3124	3114	3480	3810
POINT (-102.4198587984 20.7442916548)	100004	kWh	134	86	93	69	79	90	70	60
POINT (-102.4300806969 20.744413582)	100005	kWh	980	732	732	886	959	1227	1352	1109
POINT (-102.4245234951 20.7499153148)	100006	kWh	1870	1264	1264	990	805	1097	1198	863
POINT (-102.4078213796 20.7528298295)	100007	kWh	548	388	388	359	360	543	663	521
POINT (-102.424463 20.743974)	100008	kWh	744	541	541	513	728	1065	1230	996
POINT (-102.4279925972 20.7439799774)	100009	kWh	867	557	496	514	546	945	784	590
POINT (-102.4281327426 20.7484378166)	100010	kWh	687	552	655	608	1175	1803	1719	1473
POINT (-102.424463 20.743974)	100011	kWh	643	487	489	551	491	718	907	762

. . .

. . .

AMR data

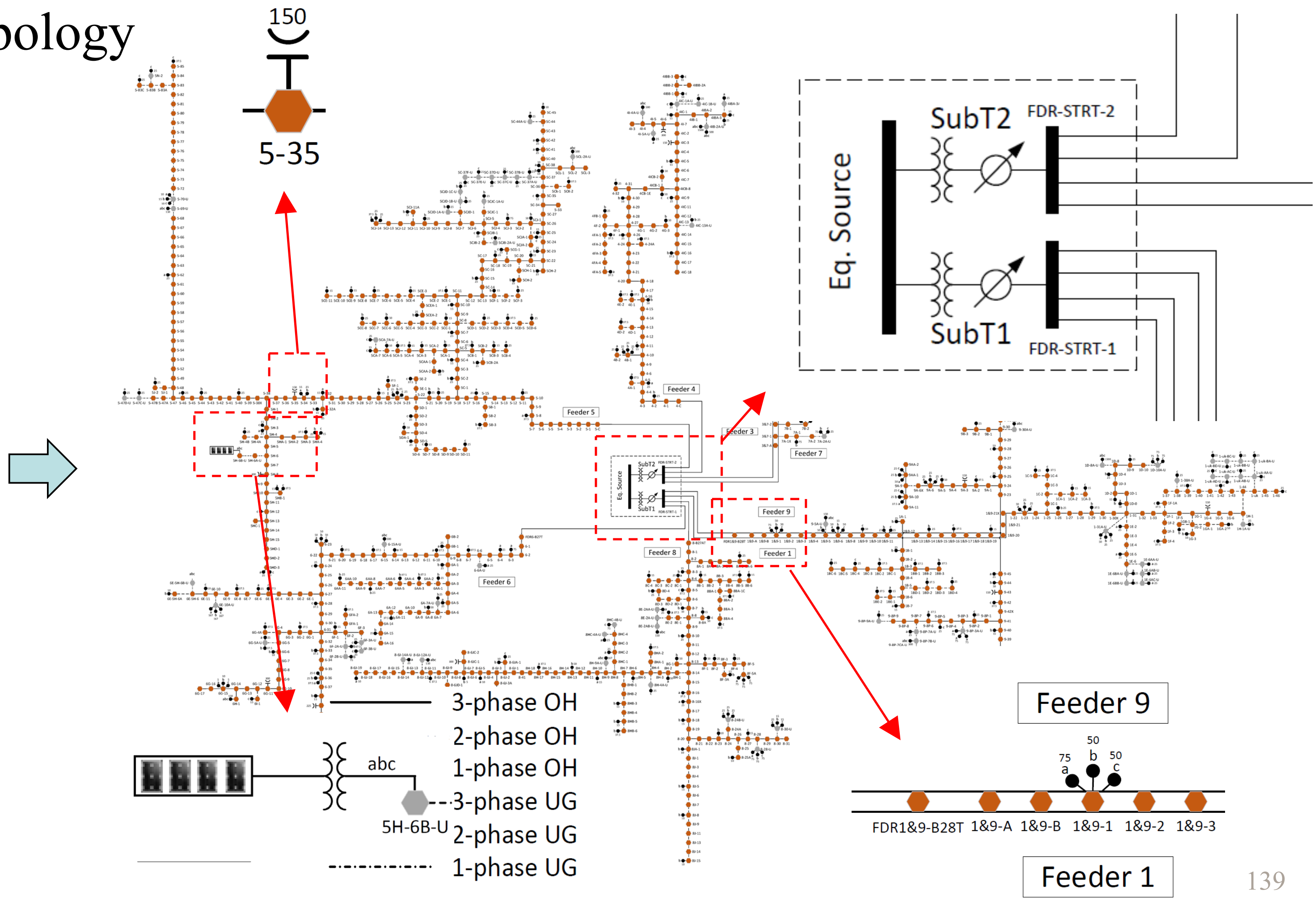
Steps of Developing OpenDSS Model

- Overall steps

Step I -- Extract the topology based on the provided distribution system map,
Step II -- Determine the connection between customers and distribution transformers using geographic information, then infer hourly energy consumption from monthly billing data, calculate customer-level P and Q, and aggregate individual customer powers to obtain spot loads,
Step III -- Build electric device models in OpenDSS, using provided device information and calculated loads,
Step VI-- Build the Matlab-OpenDSS interface,
Step V -- Perform time-series power flow analysis.

Steps of Developing OpenDSS Model

- Topology



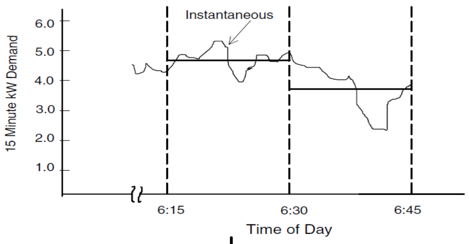
Steps of Developing OpenDSS Model

- Aggregating Individual Loads

Calculate P and Q for Individual Customer

Raw monthly billing data

Longitude, latitude	account	unit	02/20/2018	03/20/2018	04/20/2018	05/20/2018	06/20/2018	07/20/2018	08/20/2018	09/20/2018
POINT (-102.424463 40.743974)	100001	kWh	488	342	345	348	546	654	1052	919
POINT (-102.4092902243 40.7538538797)	100002	kWh	769	526	527	642	1254	1325	1938	1237
POINT (-102.4124532193 40.7569480306)	100003	kWh	2542	2371	2455	2494	3124	3114	3480	3810
POINT (-102.4198587984 40.7442916548)	100004	kWh	134	86	93	69	79	90	70	60
POINT (-102.4300806969 40.744413582)	100005	kWh	980	732	732	886	959	1227	1352	1109
POINT (-102.4245234951 40.7499153148)	100006	kWh	1870	1264	1264	990	805	1097	1198	863
POINT (-102.4078213796 40.7528298295)	100007	kWh	548	388	388	359	360	543	663	521
POINT (-102.424463 40.743974)	100008	kWh	744	541	541	513	728	1065	1230	996
POINT (-102.4279925972 40.7439799774)	100009	kWh	867	557	496	514	546	945	784	590
POINT (-102.4281327426 40.7484378166)	100010	kWh	687	552	655	608	1175	1803	1719	1473
POINT (-102.424463 40.743974)	100011	kWh	643	487	489	551	491	718	907	762
POINT (-102.4174401164 40.7600544813)	100012	kWh	10	1	0	0	0	0	0	0
POINT (-102.4245519936 40.7459381613)	100013	kWh	675	471	528	549	651	880	831	779



Assumption

Typical load profiles

Hourly energy data

Assumption: P = average hourly energy

P

Q = P×tan(arccos(pf))

pf: 0.9~0.95

P.mat

3	4	5
15.2900	6.8920	4.9160
14.9010	6.6720	5.3350
15.7720	7.0130	4.5630
15.7570	6.4520	4.7820
15.2920	6.3560	4.4820
15.8140	6.8610	4.9630
16.0440	8.4220	4.7000

Q.mat

3	4	5
3.8320	3.3379	1.9429
4.8977	3.0399	2.4307
5.1840	2.0455	1.8034
7.1791	3.1248	1.3948
5.0262	1.8538	1.4732
4.6124	1.7195	1.9615
5.2734	4.0790	1.3708

https://ieeexplore.ieee.o mp.jsp?tp=&arnumber=

Steps of Developing OpenDSS Model

- Aggregating Individual Loads

Calculate Nodal P and Q

Longitude, latitude	account
POINT (-102.424463 20.743974)	100001
POINT (-102.4092902243 20.7538538797)	100002
POINT (-102.4124532193 20.7569480306)	100003
POINT (-102.4198587984 20.7442916548)	100004

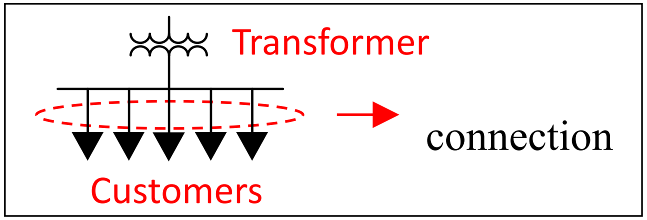
Customer Location

+

latitude	longitude	pole_number	number_of_phases	transformer_size_kva
20.750511	-102.412681	1A-2		
20.749581	-102.412363	1B-1	Single Phase	25
20.749613	-102.412793	1BA-1		
20.74958	-102.413235	1BA-2		
20.74937	-102.412245	1B-2		
20.749166	-102.415888	1BC-7		

Transformer Location

Determine the connection between distribution transformers and customers



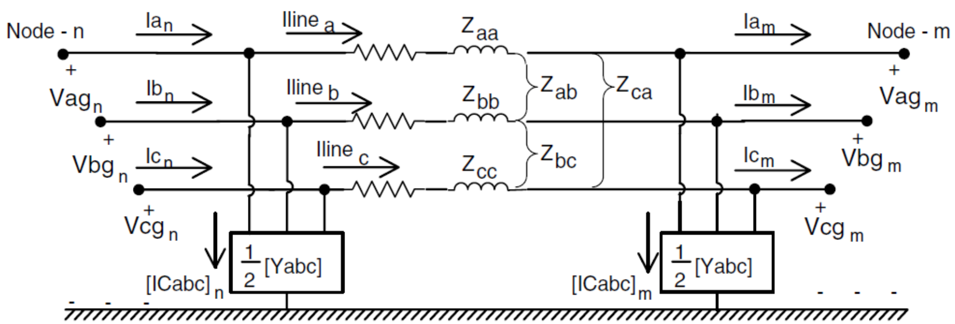
Nodal P = ∑ customer P

Nodal Q = ∑ customer Q

Steps of Developing OpenDSS Model

- Electric Devices

Overhead Lines and Underground Cables



$$[VLG_{abc}]_n = [a] \cdot [VLG_{abc}]_m + [b] \cdot [I_{abc}]_m$$

$$[a] = [U] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[b] = [Z_{abc}]$$

U – Identity matrix

$Zabc$ – Series impedance matrix $[Z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$

$$[I_{abc}]_n = [c] \cdot [VLG_{abc}]_m + [d] \cdot [I_{abc}]_m$$

$$[c] = [Y_{abc}] + \frac{1}{4} \cdot [Y_{abc}] \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$$[d] = [U] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}]$$

$Yabc$ – Shunt admittance matrix $[Y_{abc}] = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}$

In short, to build line models, we need to calculate Zabc and Yabc matrices. To calculate Zabc and Yabc matrices, we need to know the conductor and construction information. In OpenDSS, Zabc and Yabc are defined in terms of linecode.

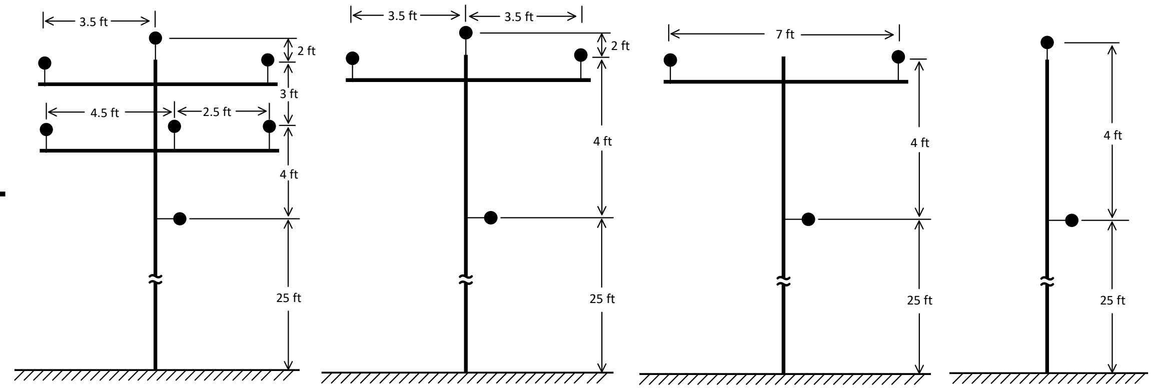
Steps of Developing OpenDSS Model

- Electric Devices

Linecode -- Series impedance

Size	Material	Resistance (Ω/mile)	Diameter (inch)	GMR (feet)	Capacity (A)
4/0	ACSR	0.592	0.563	0.00814	340
1/0	ACSR	1.12	0.355	0.00446	230
4	ACSR	2.55	0.257	0.00452	140
2	ACSR	1.65	0.316	0.00504	180
8	CU	3.8	0.1285	0.00416	90
6	CU	2.41	0.201	0.00568	130
4	CU	1.503	0.204	0.00663	170
2	CU	0.87	0.3	0.0083	200
1/0	Cu	0.607	0.368	0.0113	310

+



- Conductor information:
  GMR_p, GMR_n
  Resistance per unit length: r_p, r_n
- Distances between conductors;
  D_{ab}, D_{bc}, D_{ca}, D_{an}, D_{bn}, D_{cn}

Steps of Developing OpenDSS Model

- Electric Devices

Linecode -- Series impedance

- Conductor information:
  GMR_p, GMR_n
  Resistance per unit length: r_p, r_n
- Distances between conductors;
  D_{ab}, D_{bc}, D_{ca}, D_{an}, D_{bn}, D_{cn}

$$+ \begin{cases} \widehat{z_{ii}} = r_i + 0.09530 + j0.12134(\ln\frac{1}{GMR_i} + 7.93402)\ \Omega/\text{mile} & (4.41) \\ \widehat{z_{ij}} = 0.09530 + j0.12134(\ln\frac{1}{D_{ij}} + 7.93402)\Omega/\text{mile} & (4.42) \end{cases}$$

$$[\hat{z}_{\text{primitive}}] = \begin{bmatrix} [\hat{z}_{ij}] & [\hat{z}_{in}] \\ [\hat{z}_{nj}] & [\hat{z}_{nn}] \end{bmatrix}$$

$$[z_{abc}] = [\widehat{z_{ij}}] - [\widehat{z_{in}}] \cdot [\widehat{z_{nn}}]^{-1} \cdot [\widehat{z_{nj}}]$$

OpenDSS code:

```
New LineCode.1/0ACSR_#2ACSR7/1_3ph_OH nphases=3 Units=mi
~ Rmatrix= ( 1.350475 | 0.227405 1.344401 | 0.230475 0.227405 1.350475 )
~ Xmatrix= ( 1.412199 | 0.589906 1.419390 | 0.519317 0.589906 1.412199 )

New Line.FDR1_MF_7      Phases=3   Bus1=1-27.1.2.3       Bus2=1-28.1.2.3
~ LineCode=1/0ACSR_#2ACSR7/1_3ph_OH   Length=0.11  units=kft
```

Steps of Developing OpenDSS Model

- Electric Devices

Linecode – Shunt admittance

To obtain shunt admittance matrix of overhead lines, first, we should calculate the self and mutual potential coefficients of each conductor:

Size	Material	Resistance (Ω/mile)	Diameter (inch)	GMR (feet)	Capacity (A)
4/0	ACSR	0.592	0.563	0.00814	340
1/0	ACSR	1.12	0.355	0.00446	230
4	ACSR	2.55	0.257	0.00452	140
2	ACSR	1.65	0.316	0.00504	180
8	CU	3.8	0.1285	0.00416	90
6	CU	2.41	0.201	0.00568	130
4	CU	1.503	0.204	0.00663	170
2	CU	0.87	0.3	0.0083	200
1/0	Cu	0.607	0.368	0.0113	310

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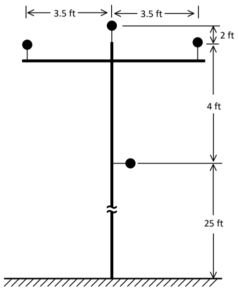


+

$$\hat{P}_{ii} = 11.17689 \cdot \ln \frac{S_{ii}}{RD_i} \text{ mile}/\mu\text{F}$$

$$\hat{P}_{ij} = 11.17689 \cdot \ln \frac{S_{ij}}{D_{ij}} \text{ mile}/\mu\text{F}$$

$$[\hat{P}_{\text{primitive}}] = \begin{bmatrix} \hat{P}_{aa} & \hat{P}_{ab} & \hat{P}_{ac} & \bullet & \hat{P}_{an} \\ \hat{P}_{ba} & \hat{P}_{bb} & \hat{P}_{bc} & \bullet & \hat{P}_{bn} \\ \hat{P}_{ca} & \hat{P}_{cb} & \hat{P}_{cc} & \bullet & \hat{P}_{cn} \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \hat{P}_{na} & \hat{P}_{nb} & \hat{P}_{nc} & \bullet & \hat{P}_{nn} \end{bmatrix}$$

Sii – the distance from conductor *i* to its image *i'* (ft)
Sij – the distance from conductor *i* to the image of conductor *j* (ft)
Dij – the distance from conductor *i* to conductor *j* (ft)
RDi – the radius of conductor *i* (ft)

Steps of Developing OpenDSS Model

- Electric Devices

Shunt admittance matrix

Then, the primitive potential coefficient matrix is partitioned as follows

$$[\hat{P}_{\text{primitive}}] = \begin{bmatrix} \hat{P}_{aa} & \hat{P}_{ab} & \hat{P}_{ac} & \bullet & \hat{P}_{an} \\ \hat{P}_{ba} & \hat{P}_{bb} & \hat{P}_{bc} & \bullet & \hat{P}_{bn} \\ \hat{P}_{ca} & \hat{P}_{cb} & \hat{P}_{cc} & \bullet & \hat{P}_{cn} \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \hat{P}_{na} & \hat{P}_{nb} & \hat{P}_{nc} & \bullet & \hat{P}_{nn} \end{bmatrix} \Rightarrow [\hat{P}_{\text{primitive}}] = \begin{bmatrix} [\hat{P}_{ij}] & [\hat{P}_{in}] \\ [\hat{P}_{nj}] & [\hat{P}_{nn}] \end{bmatrix}$$

Then, the primitive matrix can be reduced using the Kron reduction method to an n*n phase potential coefficient matrix

$$[P_{abc}] = [\hat{P}_{ij}] - [\hat{P}_{in}] \cdot [\hat{P}_{nn}]^{-1} \cdot [\hat{P}_{nj}]$$

Finally, the inverse of the potential coefficient matrix will give the n*n capacitance matrix as follows

Capacitance matrix → $[C_{abc}] = [P_{abc}]^{-1}$

OpenDSS code:

```
New LineCode.1/0ACSR_#2ACSR7/1_3ph_OH nphases=3 Units=mi
~ Rmatrix= ( 1.350475 | 0.227405 1.344401 | 0.230475 0.227405 1.350475 )
~ Xmatrix= ( 1.412199 | 0.589906 1.419390 | 0.519317 0.589906 1.412199 )
~ Cmatrix= ( 13.111582 | -3.100145 13.428192 | -1.706202 -3.100145 13.111582  )
```

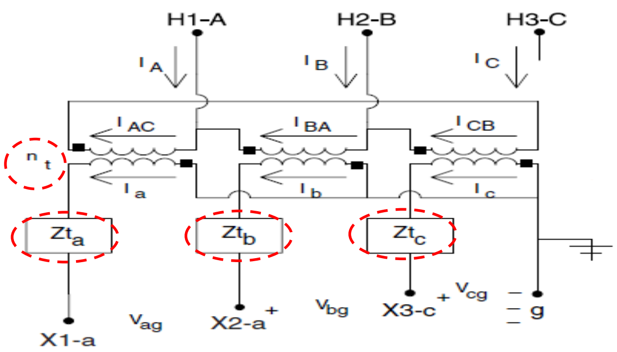
Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 3-phase

For a three-phase distribution transformer, its model is

$$[VLN_{ABC}] = [a_t]\cdot[VLN_{abc}] + [b_t]\cdot[I_{abc}]$$
$$[I_{ABC}] = [c_t]\cdot[VLN_{abc}] + [d_t]\cdot[I_{abc}]$$



$$[a_t] = \frac{-n_t}{3}\cdot\begin{bmatrix} 0 & 2 & 1 \\ 1 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} \qquad [b_t] = \frac{-n_t}{3}\cdot\begin{bmatrix} 0 & 2\cdot Zt_b & Zt_c \\ Zt_a & 0 & 2\cdot Zt_c \\ 2\cdot Zt_a & Zt_b & 0 \end{bmatrix}$$

$$[c_t] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad [d_t] = \frac{1}{n_t}\cdot\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

a_t, b_t, c_t and d_t depend on n_t, Zt_a, Zt_b, Zt_c, i.e., depend on the specific winding connection, impedance and rating of a transformer.

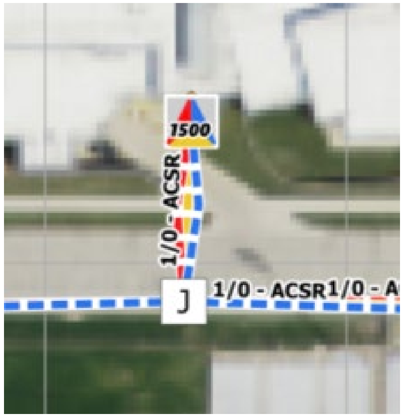
Similar with the substation transformer model, to build a distribtuion transformer model in OpenDSS, we need to know kV rating, kVA rating, number of phases, number of windings, connection, percent resistance, percent reactance.

Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 3-phase

From the distribution system map and Milsoft model, we can obtain the kV rating, kVA rating, connection for the three-phase distribution transformers. We also know the measured percent impedances of a variety of distribution transformers, as shown in this table.



+

kVA	Single-Phase		kVA	Three-phase	
	%X	%R		%X	%R
5	1.68	2.94	6	1.72	2.72
7.5	1.84	2.42	9	1.16	2.31
10	1.92	2.04	15	1.82	2.1
15	2.02	1.6	30	1.37	3.8
25	2.3	1.4	45	1.73	2.52
37.5	2.7	3.6	75	1.91	2.27
50	2.8	3.1	112.5	3.87	2.43
75	3.7	2.48	150	5	2.35
100	3.55	2.12	225	5.5	1.15
167	3.25	1.6	300	4.5	1.8
			500	5.9	1.6

Parameters obtained from short circuit tests

Note that %R should be split into the primary winding percent impedance and secondary winding impedance.

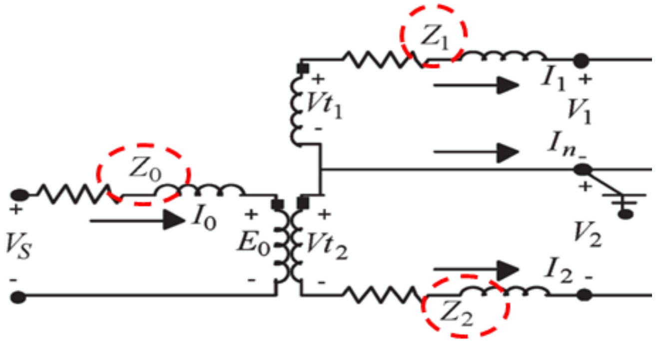
*0.5 Assuming $R_S = R_L$

OpenDSS code:

```
New Transformer.T-1-35 Phases=3 Windings=2 XHL=5.5
~ wdg=1 bus=1-35.1.2.3.0        conn=wye kV=13.8  kva=225 %R=0.575
~ wdg=2 bus=T-1-35-L.1.2.3.0    conn=wye kV=0.208 kva=225 %R=0.575
```

Steps of Developing OpenDSS Model

- Electric Devices



$$[V_{ss}] = [a_t] \cdot [V_{12}] + [b_t] \cdot [I_{12}] \qquad [I_{00}] = [c_t] \cdot [V_{12}] + [d_t] \cdot [I_{12}]$$

$$[V_{ss}] = \begin{bmatrix} V_s \\ V_s \end{bmatrix} \quad [a_t] = [av] = n_t \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad [I_{00}] = \begin{bmatrix} I_0 \\ I_0 \end{bmatrix} \quad [c_t] = n_t \cdot \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$[b_t] = \begin{bmatrix} n_t \cdot Z_1 + \frac{1}{n_t^2} \cdot Z_0 & -\frac{1}{n_t^2} \cdot Z_0 \\ \frac{1}{n_t^2} \cdot Z_0 & -(n_t \cdot Z_2 + \frac{1}{n_t^2} \cdot Z_0) \end{bmatrix} \qquad [d_t] = \frac{1}{n_t} \begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix}$$

$$\begin{cases} Z_0 = 0.5 * \%R + \text{j } 0.8 * \%X \\ Z_1 = \%R + \text{j } 0.4 * \%X \\ Z_2 = \%R + \text{j } 0.4 * \%X \end{cases}$$

a_t, b_t, c_t and d_t depend on n_t, Z_0, Z_1, Z_2, i.e., depend on the specific impedance and winding ratings of a transformer.

Similar with 3-phase distribution transformers, to build a 1-phase center-tapped distribution transformer model in OpenDSS, we need to know kV rating, kVA rating, number of phases, number of windings, connection, percent resistance, and percent reactance.

Steps of Developing OpenDSS Model

- Electric Devices

Secondary Distribution Transformer – 1-phase center-tapped

kVA	Single-Phase		kVA	Three-phase	
	%X	%R		%X	%R
5	1.68	2.94	6	1.72	2.72
7.5	1.84	2.42	9	1.16	2.31
10	1.92	2.04	15	1.82	2.1
15	2.02	1.6	30	1.37	3.8
25	2.3	1.4	45	1.73	2.52
37.5	2.7	3.6	75	1.91	2.27
50	2.8	3.1	112.5	3.87	2.43

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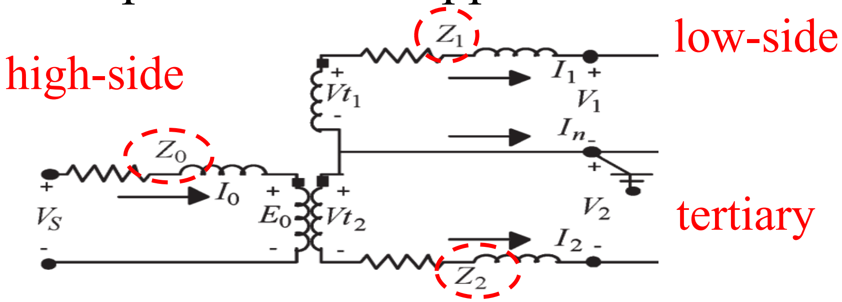


$$\begin{cases} Z_0 = 0.5 * \%R + j\,0.8 * \%X \\ Z_1 = \%R + j\,0.4 * \%X \\ Z_2 = \%R + j\,0.4 * \%X \end{cases} \Rightarrow \begin{cases} Z_{01} = 1.5 * \%R + j\,1.2 * \%X \\ Z_{02} = 1.5 * \%R + j\,1.2 * \%X \\ Z_{12} = 2 * \%R + j\,0.8 * \%X \end{cases}$$

OpenDSS code:

```
New Transformer.T-9-45 Phases=1 Windings=3 XHL=2.76  XHT=2.76  XLT=1.84
~ wdg=1 bus=9-45.1.0       conn=wye kV=1.3856    kva=25 %R=0.7
~ wdg=2 bus=T-9-45-L.1.0    conn=wye kV=0.120     kva=25 %R=1.4
~ wdg=3 bus=T-9-45-L.0.2    conn=wye kV=0.120     kva=25 %R=1.4
```


W. H. Kersting, "Center-Tapped Transformer and 120-/240-V Secondary Models," IEEE Trans. Ind. Appl., vol. 45, pp. 575–581, Mar./Apr. 2009.

Steps of Developing OpenDSS Model

- Electric Devices

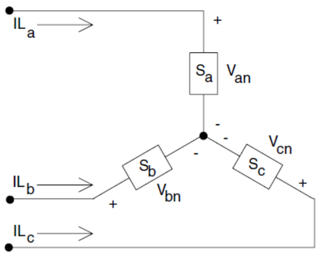
Load

When building the models of loads, constant active and reactive power load models are selected. The figure on the right shows a constant P and Q, wye-connected load model.

$$IL_a = \left(\frac{S_a}{V_{an}}\right)^* = \frac{|S_a|}{|V_{an}|}\underline{/\delta_a - \theta_a} = |IL_a|\underline{/\alpha_a}$$

$$IL_b = \left(\frac{S_b}{V_{bn}}\right)^* = \frac{|S_b|}{|V_{bn}|}\underline{/\delta_b - \theta_b} = |IL_b|\underline{/\alpha_b}$$

$$IL_c = \left(\frac{S_c}{V_{cn}}\right)^* = \frac{|S_c|}{|V_{cn}|}\underline{/\delta_c - \theta_c} = |IL_c|\underline{/\alpha_c}$$



Using the calculated nodal P and Q, together with the phasing of customers, we can develop load models in OpenDSS as follows:

OpenDSS code:

3-phase

```
New  Load.L-7-43A-U phases=3  conn=wye  bus1=T-7-43A-U-L.1.2.3.0
kV=0.208  kW=24.916000000000000    Kvar=11.942927528857772
```

1-phase

```
New  Load. L-9-45  phases=1  conn=delta  bus1=T-9-45-L.1.2  kV=0.208
kW=5.040000000000000    Kvar=2.296291839688011
```