Module 2:

Planning and operation of distribution network

Lecture 1: Introduction to distribution networks

Modelling and tools for the planning and operation of distribution network

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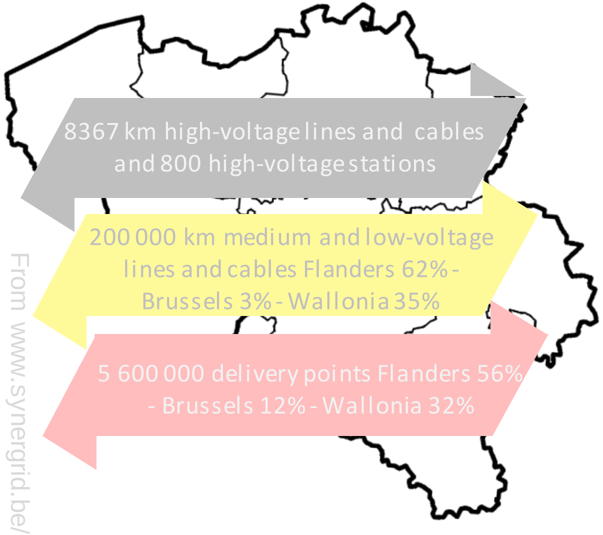
Content

1

Distribution network structure

A general view of substations, networks and components

Distribution network structure



8367 km high-voltage lines and cables and 800 high-voltage stations

200 000 km medium and low-voltage lines and cables Flanders 62% - Brussels 3% - Wallonia 35%

5 600 000 delivery points Flanders 56% - Brussels 12% - Wallonia 32%

From www.synergrid.be/

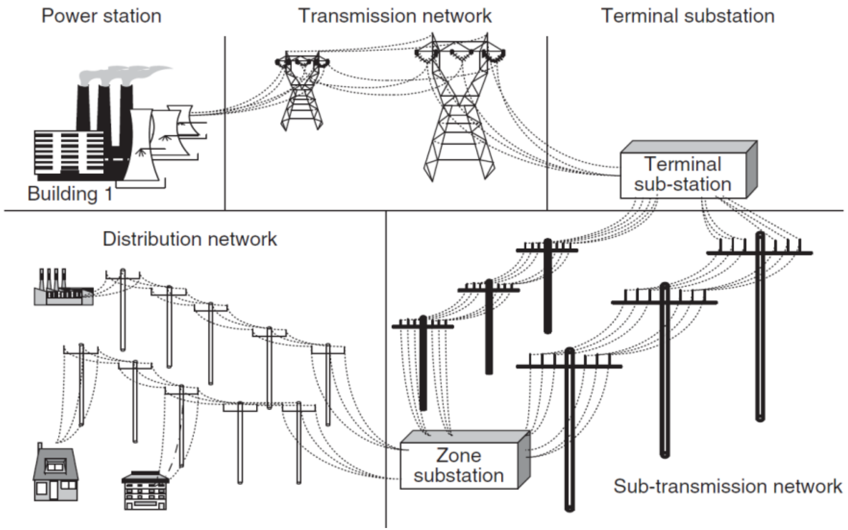


Fig.1. Electricity supply system [1]

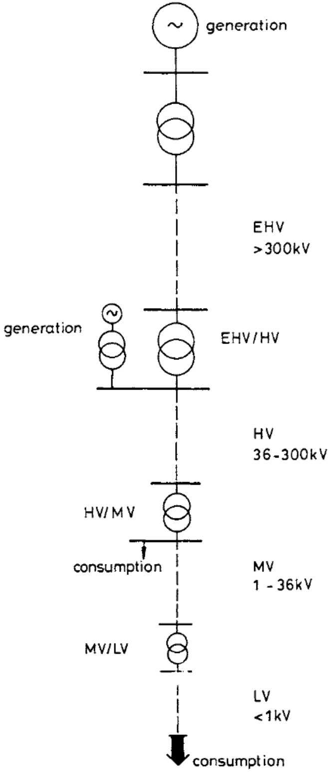
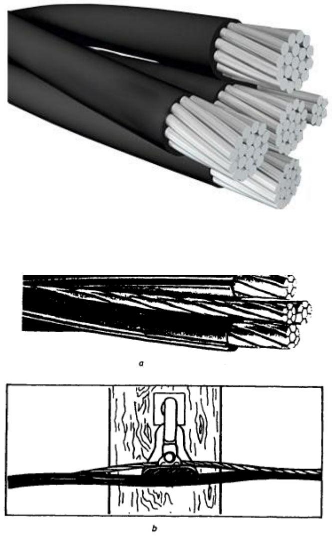
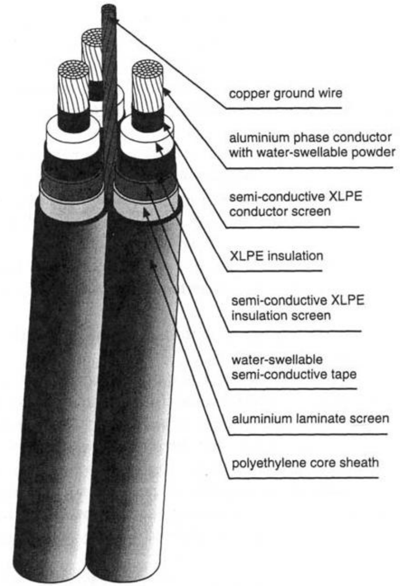


Fig.2. Voltage levels [2]

Equipment



LV aerial bunched and cable [2]
[a] self-supporting overhead cable
[b] Cable suspended from a pole



MV underground cable [2]

Pole mounted distribution transformer

20 kV overhead line with ACSR conductors

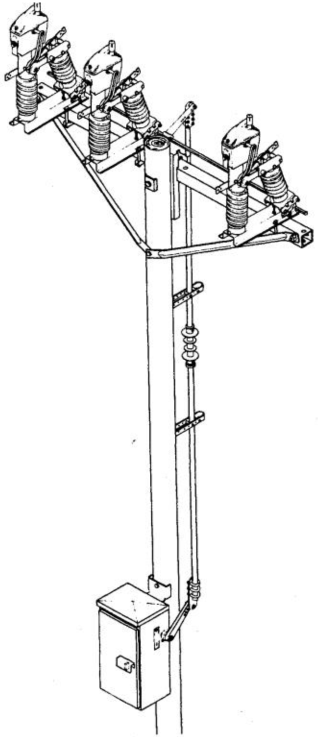
Fig.3. Distribution network typical equipment

Equipment

Three phase 15 KV outdoor ircuit breaker
From ABB.com

Fuse cutout in pole-top style

EHV disconnector
From Siemence.com



Pole-mounted load-breaking disconnector [2]

Fig.3. Distribution network typical equipment (continued)

Three-phase automatic circuit recloser
From ABB.com

Three-phase sectionalizer
From ABB.com

Fig.3. Distribution network typical equipment (continued)

General layout

- There is no international standard for the realization and the modes of customer connection
- Each distributor has its own methods and its own experiences
- Despite the differences, there is a convergence around some basic rules

Table 1. Comparison of overhead and undeground networks in Finland and England [2]

(a) England	EHV	HV	MV	LV	Total
Overhead lines, %	1·2	3·4	27·5	9·8	41·9
Underground cables, %	0·1	0·5	20·0	37·5	58·1
Ratio overhead/underground	16	7	1·4	0·3	0·7
(b) Finland	**EHV > 300 kV**	**HV 36–300 kV**	**MV 1–36 kV**	**LV < 1 kV**	**Total**
Overhead lines, %	1·0	5·2	33·1	43·4	82·7
Underground cables, %	0·0	0·1	2·8	14·4	17·3
Ratio overhead/underground	> 100	> 50	11·7	3·0	4·8

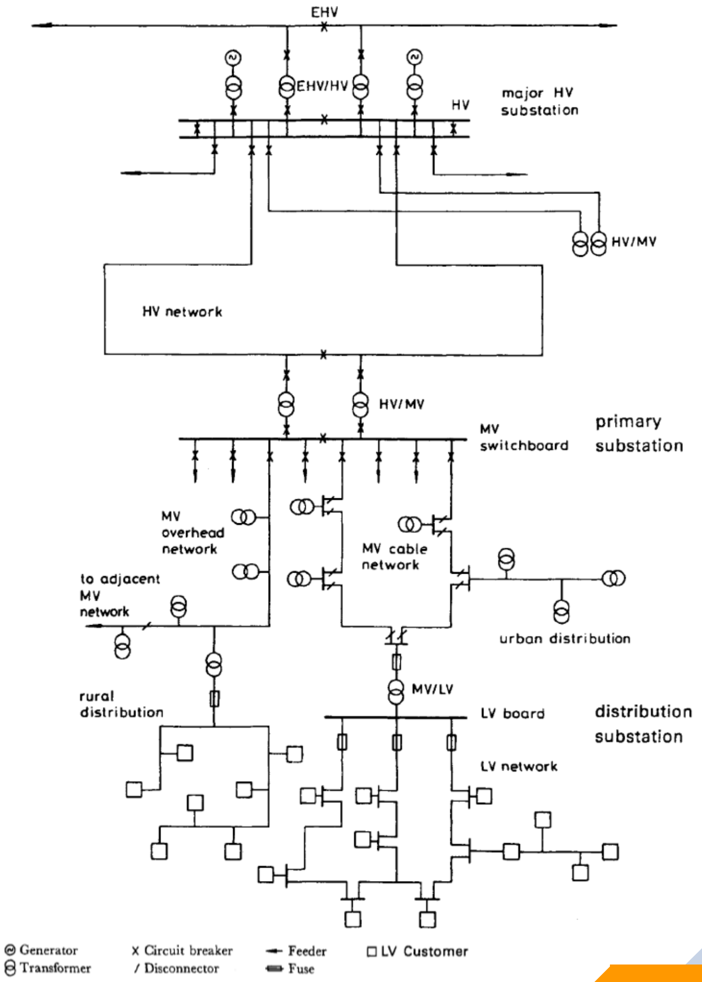


Fig.4. EHV/HV/MV/LV network arrangements [2]

General layout

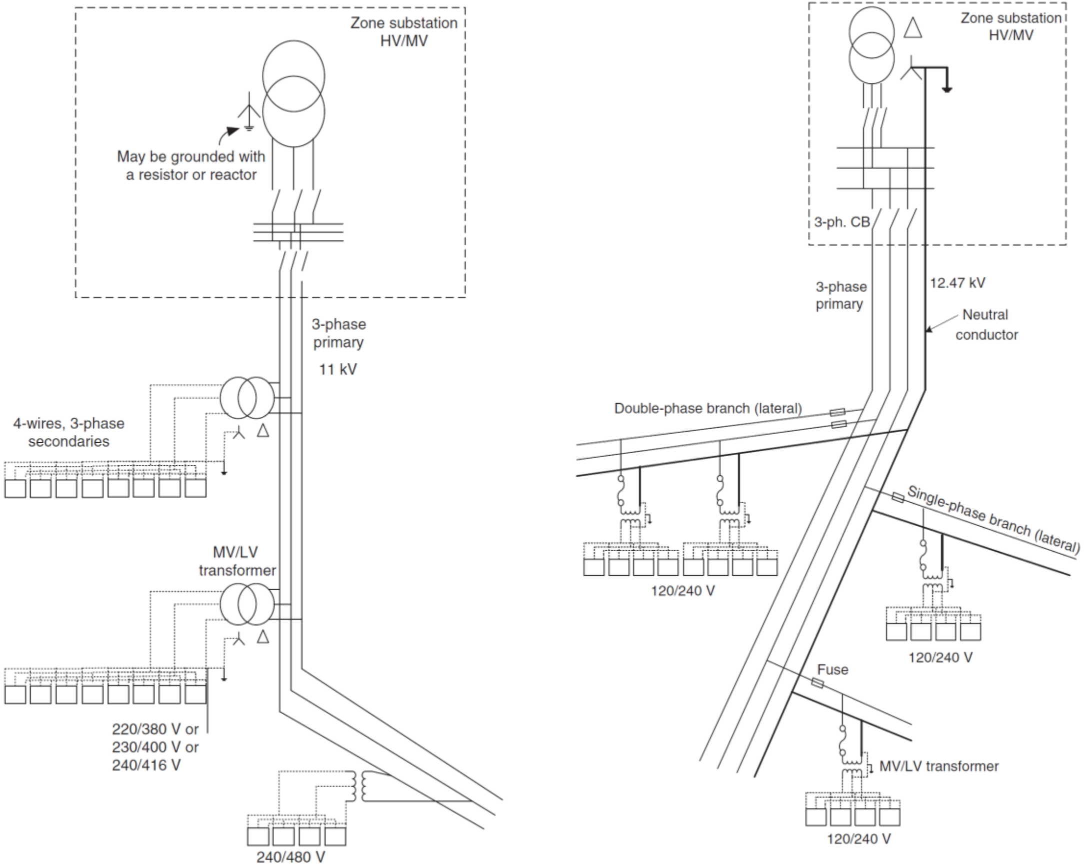


Fig.5. North American vs European distribution systems [1]

HV/MV substations

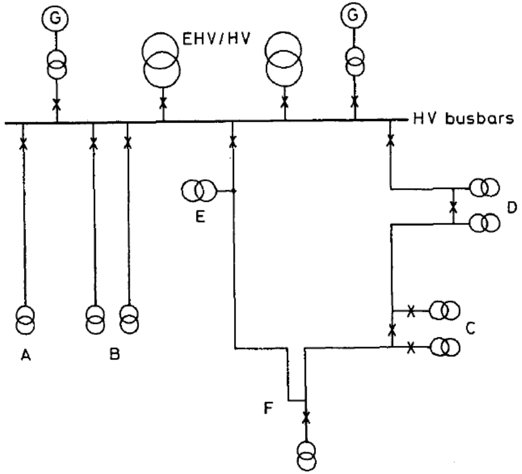


Fig.6. Different arrangements of HV/MV substations [2]

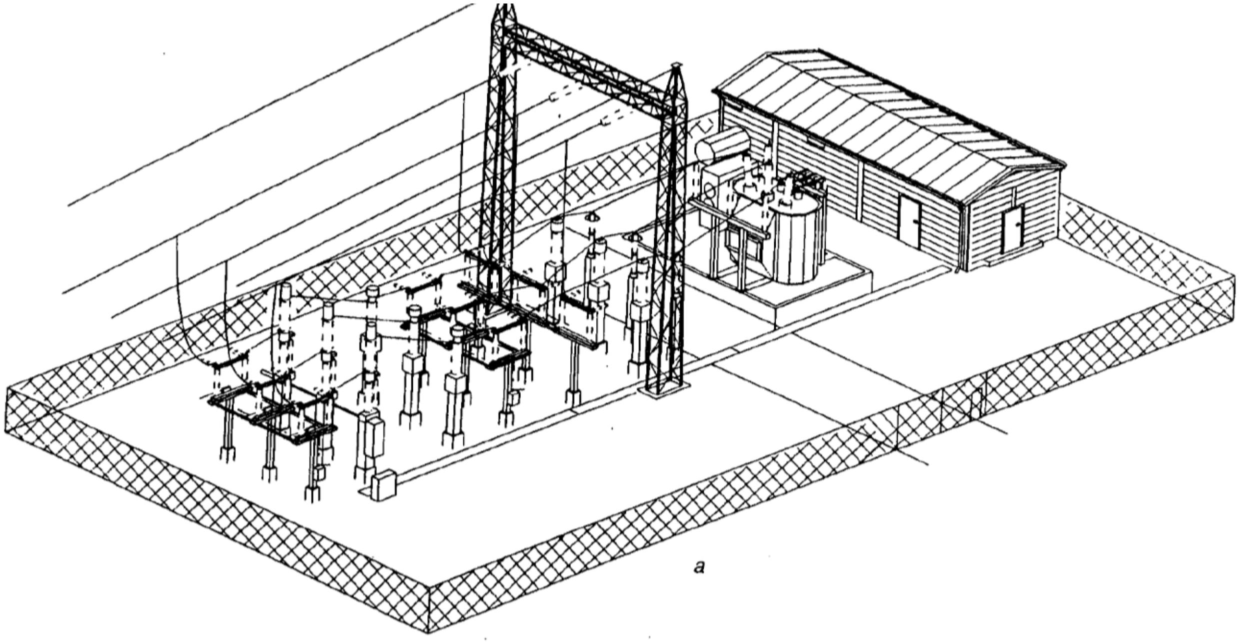


Fig.7. Layout of simple one transformer substation [2]

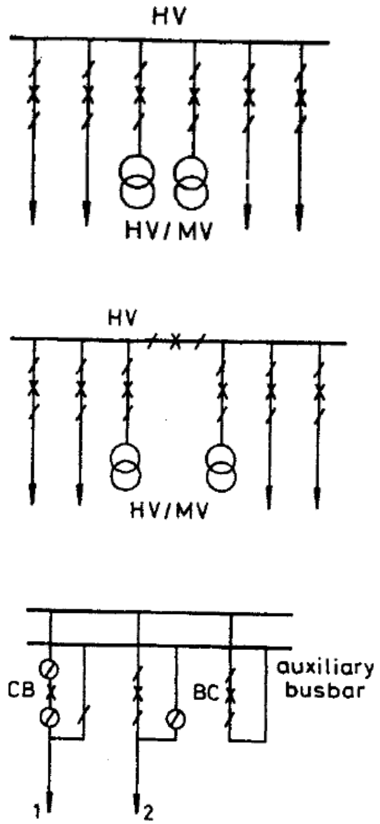


Fig.8. HV single busbar arrangement [2]

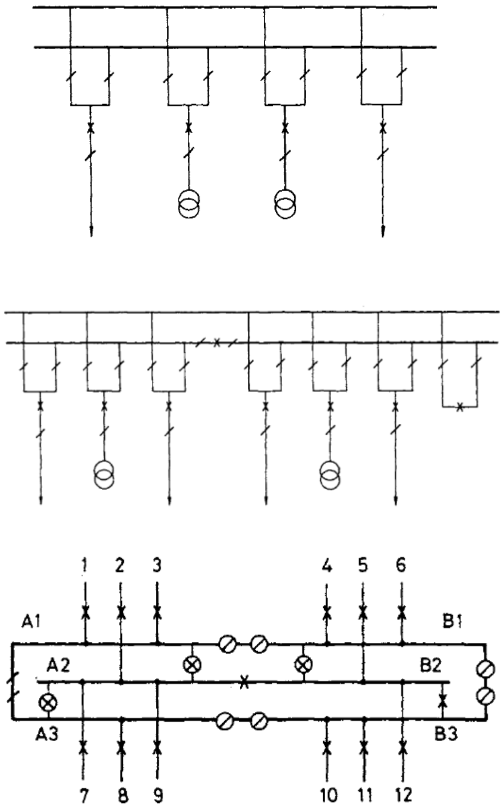


Fig.9. HV duble busbar arrangement [2]

X circuit breaker (closed)
⊗ circuit breaker (open)
/ disconnector (closed)
⊘ disconnector (open)
automatic motorised disconnector
HV/MV transformer

MV network

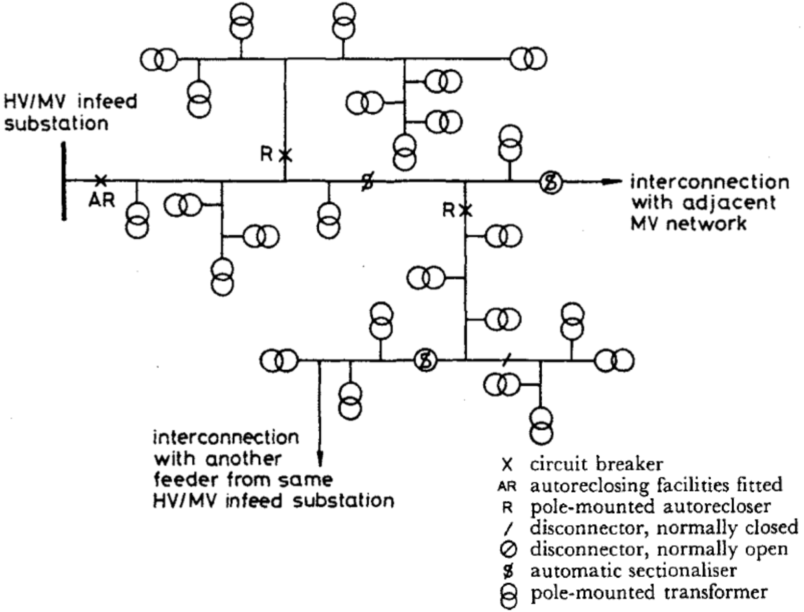


Fig.10. Schematic of typical MV overhead radial feeder [2]

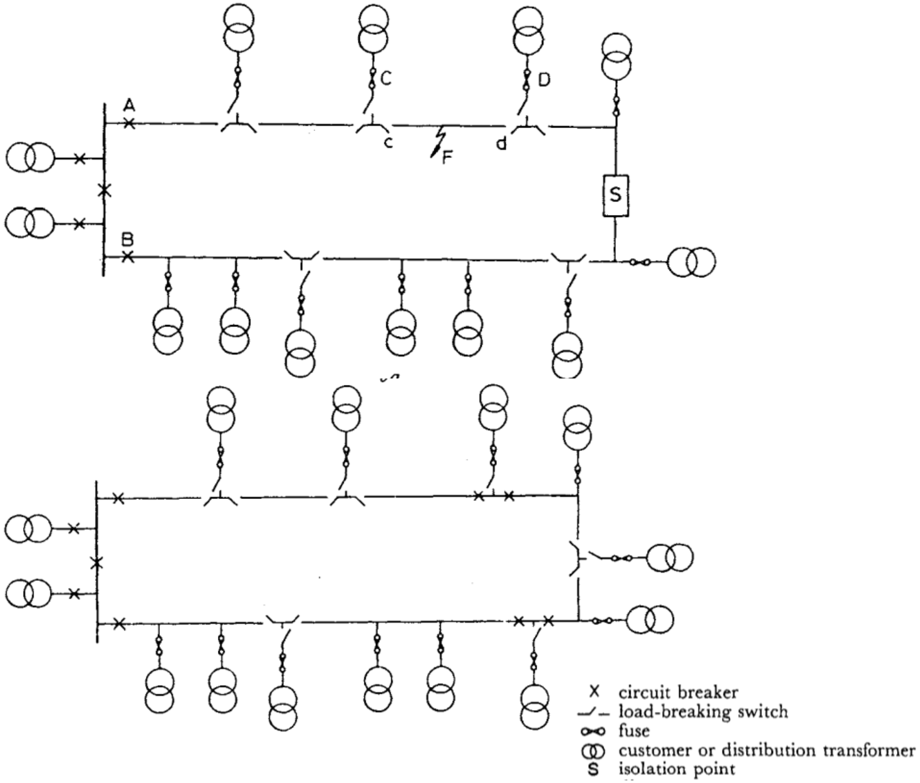


Fig.11. MV underground loop arrangements [2]

MV/LV substations

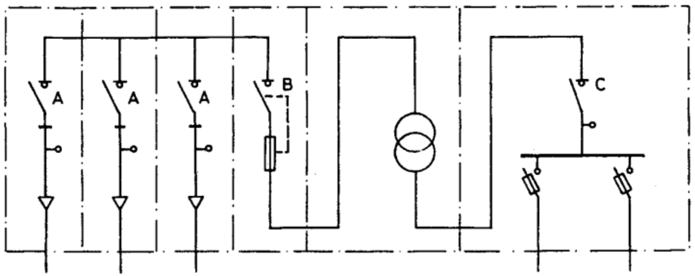
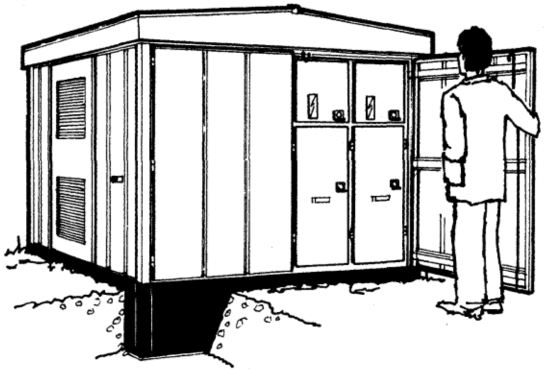


Fig.12. Schematic of an urban single-transformer MV/LV substation [2]



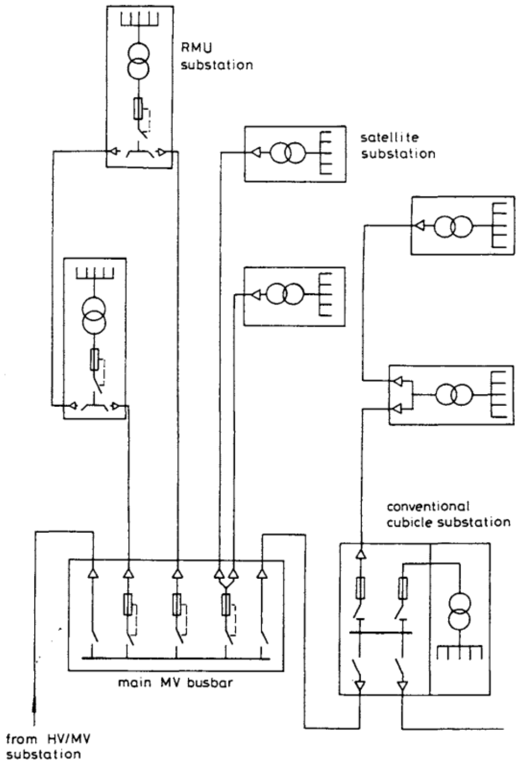


Fig.13. Urban MV/LV substation arrangements [2]

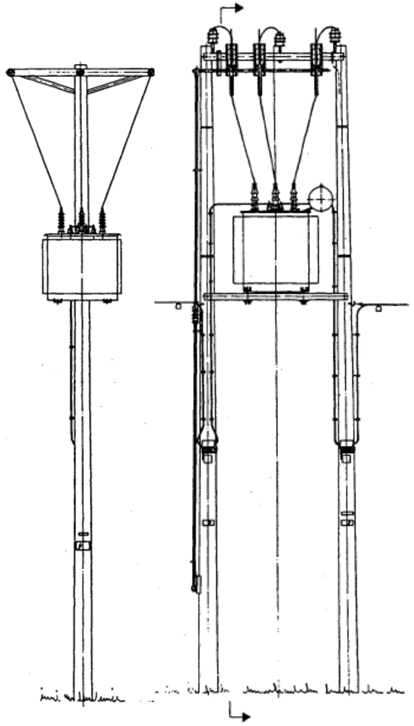


Fig.14. Various methods of supporting transformers on poles [2]

LV network

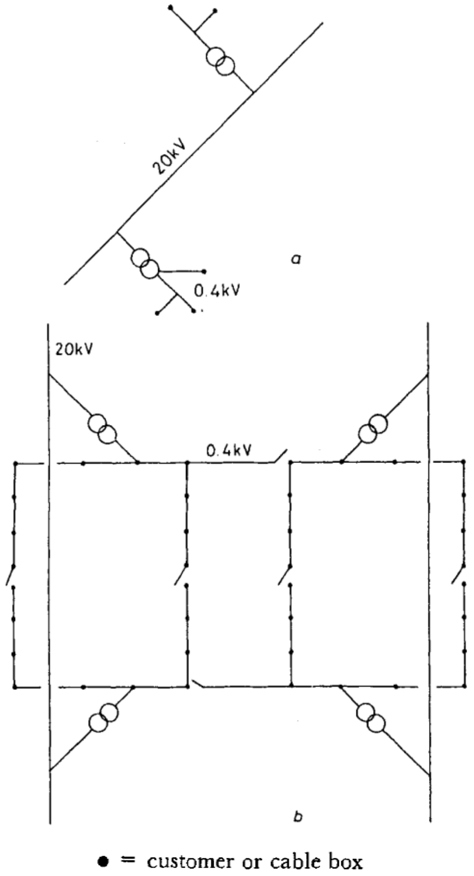


Fig.15. Typical LV systems
a. Rural, b. Urban [2]

Service connection

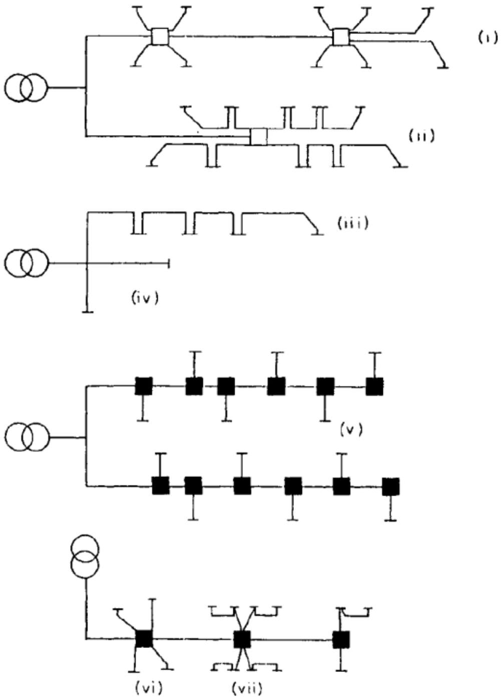
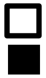


Fig.16. Some service cable arrangements [2]



cable disconnection boxes or cabinets
fixed underground joints

2

Distribution network loads

Load profiles, descriptive factors,
and special loads

Distribution network loads

- The present and estimated future demand levels influence the sizes of individual lines and cables and other equipment, and also the optimum system configuration as a whole, e.g. substation density.

- It determines among several other factors the network design and timing of major reinforcements.

- Undervoltages and losess at peak demands and undervoltages

Load profile

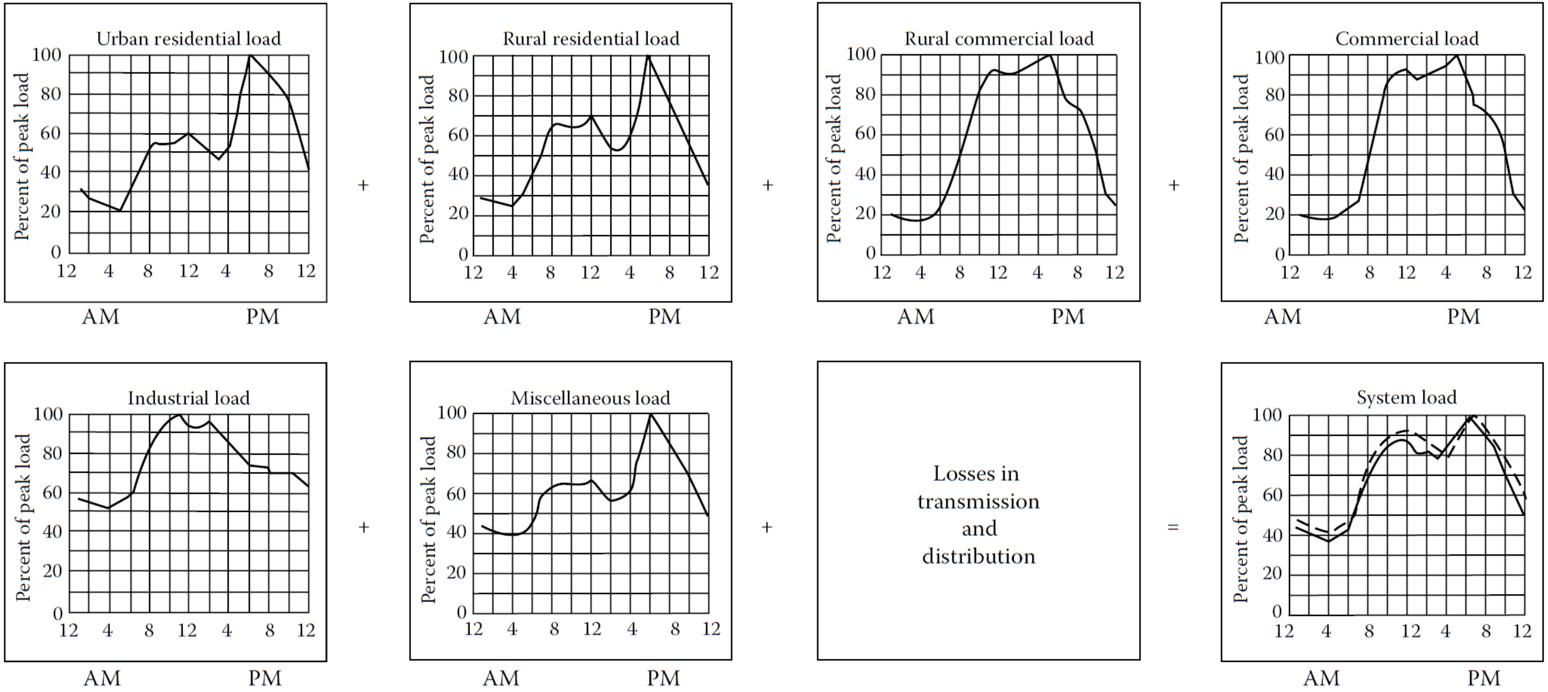


Fig 17. Development of aggregate load curves for winter peak period. Miscellaneous load includes street lighting and sales to other agencies [3]

Load profile

Table 2. Daily load data of a primary feeder for a typical winter day [3]

Time	Load, kW		
	Street Lighting	Residential	Commercial
12 AM	100	200	200
1	100	200	200
2	100	200	200
3	100	200	200
4	100	200	200
5	100	200	200
6	100	200	200
7	100	300	200
8		400	300
9		500	500
10		500	1000
11		500	1000
12 noon		500	1000
1		500	1000
2		500	1200
3		500	1200
4		500	1200
5		600	1200
6	100	700	800
7	100	800	400
8	100	1000	400
9	100	1000	400
10	100	800	200
11	100	600	200
12 PM	100	300	200

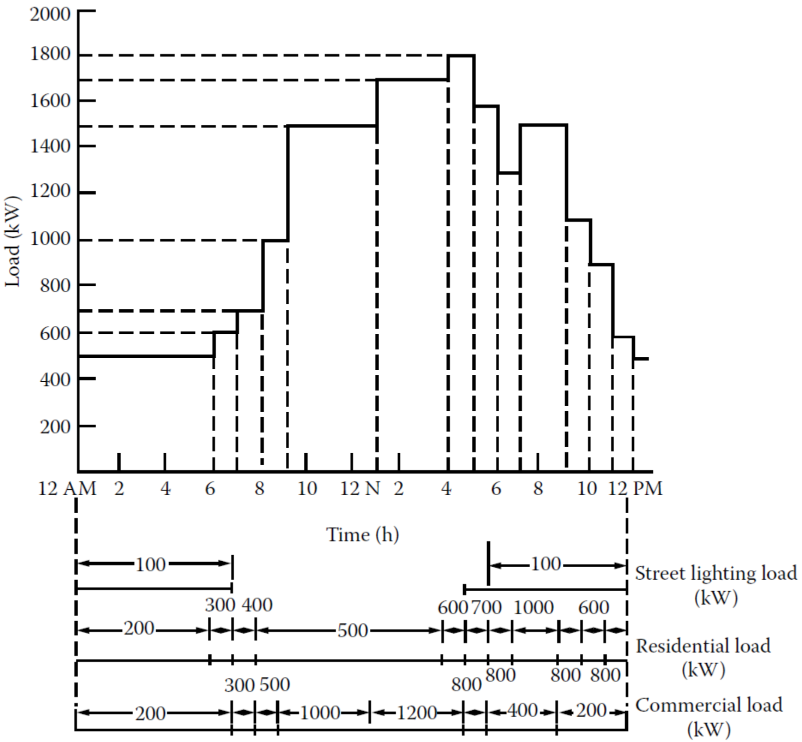


Fig.18. Daily load curve of a primary feeder for a typical winter day [3]

Load factors

$$\mathrm{DF} = \frac{\text{Maximum demand}}{\text{Total connected demand}}$$

$$F_u \triangleq \frac{\text{Maximum demand}}{\text{Rated system capacity}}$$

$$F_{\mathrm{LD}} \triangleq \frac{\text{Average load}}{\text{Peak load}}$$

$$\text{Annual load factor} = \frac{\text{Total annual energy}}{\text{Annual peak load} \times 8760}$$

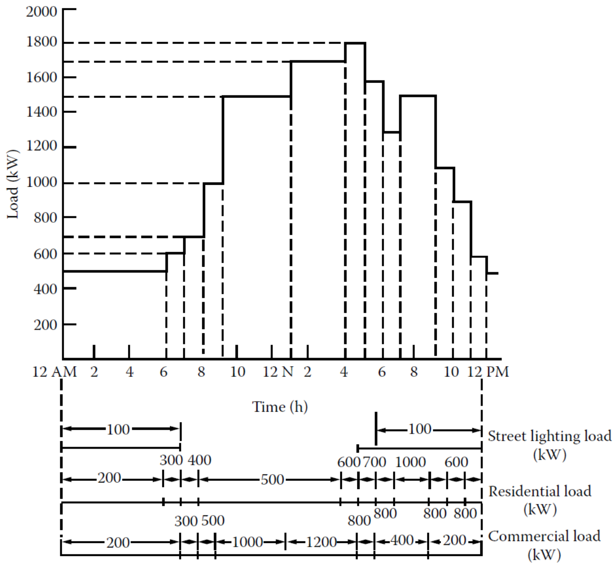
$$F_D \triangleq \frac{\text{Sum of individual maximum demands}}{\text{Coincident maximum demand}} = \frac{\sum_{i=1}^{n} D_i}{D_g}$$

$$c_i \cong \frac{\text{Class demand at time of system (i.e., group) peak}}{\text{Class noncoincident maximum demand}}$$

$$D_g \triangleq c_1 \times D_1 + c_2 \times D_2 + c_3 \times D_3 + \cdots + c_n \times D_n$$

$$F_c = \frac{\text{Coincident maximum demand}}{\text{Sum of individual maximum demands}} = \frac{1}{F_D}$$

Load factors



$$c_{\text{street}} = \frac{0\ \text{kW}}{100\ \text{kW}} = 0$$

$$c_{\text{residential}} = \frac{600\ \text{kW}}{1000\ \text{kW}} = 0.6$$

$$c_{\text{commercial}} = \frac{1200\ \text{kW}}{1200\ \text{kW}} = 1.0$$

$$F_D = \frac{\sum_{i=1}^{3} D_i}{\sum_{i=1}^{3} c_i \times D_i}$$

$$= \frac{100 + 1000 + 1200}{0 \times 100 + 0.6 \times 1000 + 1.0 \times 1200}$$

$$= 1.278$$

$$F_c = \frac{1}{F_D}$$

$$= \frac{1}{1.278}$$

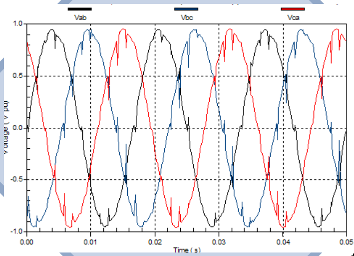
$$= 0.7825$$

Calculate the load factor.

Special loads

Customers expect an electricity supply of good quality. Consequently it is necessary to give special consideration to loads which may produce various irregularities on the supply voltage, resulting in interference with the correct operation of customer appliances or utility equipment.

Steel making arc furnaces, induction furnaces, welding equipment, rolling mills and railway traction

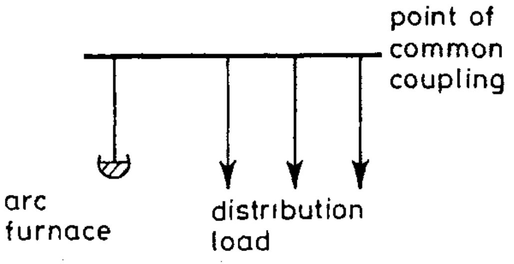


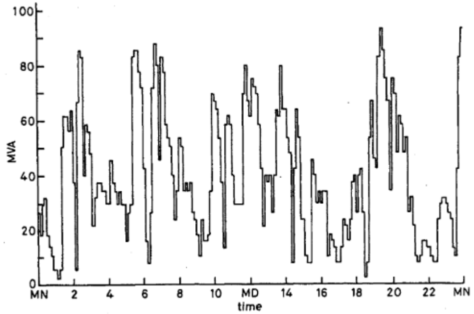
severe voltage distortion (6-8% THD) on the secondary bus of a customer that has a large amount of nonlinear (UPSs) loads. From http://www.pqsoft.com/

Items which does not causing problems individually, but can collectively affect the quality of supply

- ✓ Electric power quality is the degree to which the voltage, frequency, and waveform of a power supply system conform to established specifications.
- ✓ An electric arc furnace (EAF) is a furnace that heats charged material by means of an electric arc.
- ✓ An induction furnace is an electrical furnace in which the heat is applied by induction heating of metal.
- ✓ Welding joins materials by using high heat to melt the parts together and allowing them to cool, causing fusion.

Special loads





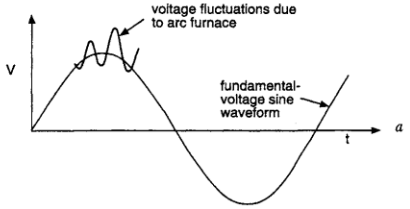


Fig . 19. Voltage fluctuation impressed on fundamental voltage waveform on point of common coupling with electric arc-furnaces [2]

If excessive voltage fluctuations are impressed on the system and are adversely affecting the customers

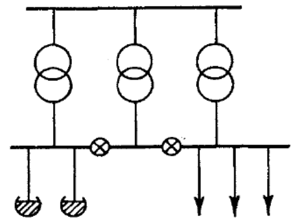


Fig. 20. Re-arrangement of supply connection [2]

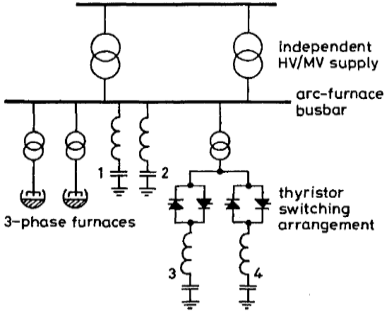


Fig. 21.Thyristor-switched capacitor compensation [2]

The use of heavy-current rectifiers and inverters has contributed significantly to the development of variable-speed DC and AC motor drives, which have many applications in industry and rail traction. However, these installations can be sources of harmonic distortion affecting other customers.

The harmonic currents cause:

- increased losses, thus decreasing the capacity of a network.
- cause errors in energy meters and system protection
- serious problems can occur if the frequency of one harmonic coincides with the resonant frequency of the network, resulting in overvoltages
- increased vibration in transformers and motors.

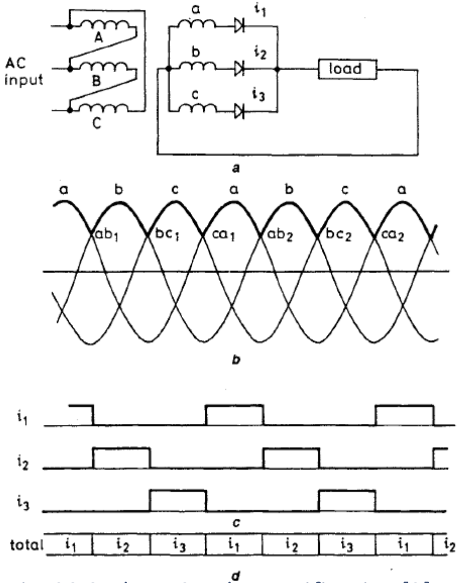


Fig. 23.3-phase 3 pulse rectification [2]
a Schematic of connections
b Input voltage/current waveforms
c Ideal input-current waveforms
d Ideal output-current waveforms

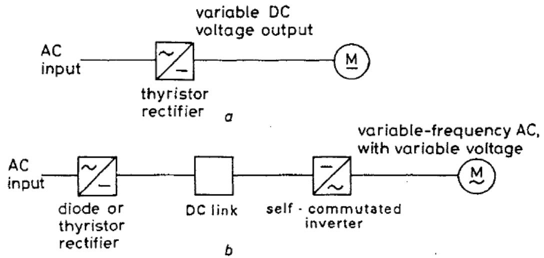


Fig. 22.Speed control of motors [2]

$$N = kp \pm 1$$

p = pulse number
k = any integer from 1 to infinity
N = harmonic number

$$\frac{I_N}{I_f} = \frac{1}{N}$$

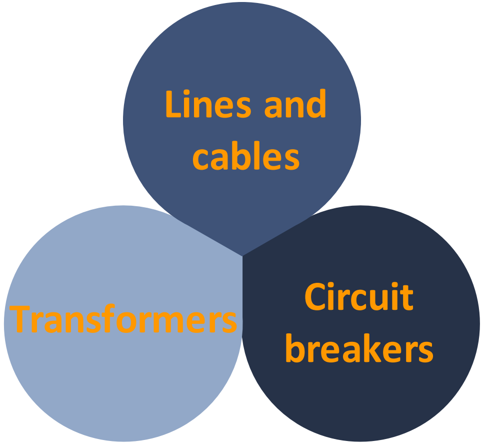
3

Components modelling

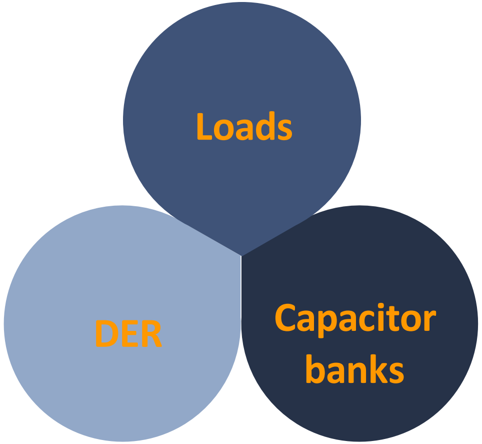
Models for most common network elements suitable for power flow analysis

Components modelling

A model, in power system analysis is a mathematical model as a set of equations or relations, which appropriately describes the interactions between different variables in the time frame studied and with the desired accuracy of a component or system.



Series components



shunt components

$$\frac{\partial V(x)}{\partial x} = -(R + j\omega L)\, I(x)$$

$$\frac{\partial I(x)}{\partial x} = -(G + j\omega C)\, V(x) \ .$$

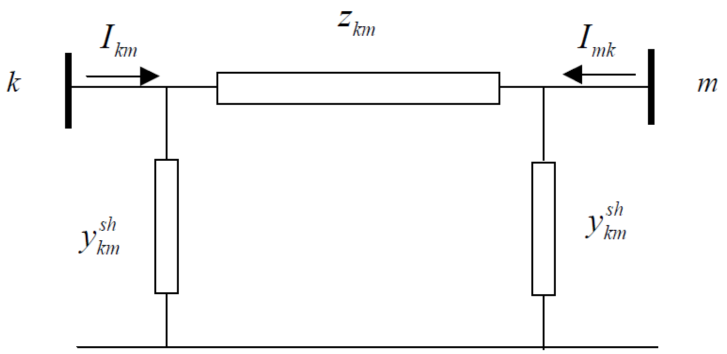


Fig. 24. Lumped-circuit model (-model) of a transmission line between nodes k and m [5]

$$Z_{km} = R_{km} + jX_{km} = \text{series impedance } (\Omega)$$

$$Y_{km}^{sh} = G_{km}^{sh} + jB_{km}^{sh} = \text{shunt admittance (siemens)}$$

$$y_{km} = z_{km}^{-1} = g_{km} + jb_{km}$$

$$g_{km} = \frac{r_{km}}{r_{km}^2 + x_{km}^2}$$

$$b_{km} = -\frac{x_{km}}{r_{km}^2 + x_{km}^2}$$

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} y_{km} + y_{km}^{sh} & -y_{km} \\ -y_{km} & y_{km} + y_{km}^{sh} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix}$$

Example

For a 138 kV transmission line section

$$z = r + jx = 0.0062 + j0.0360 \text{ p.u.}$$

$$b^{sh} = 0.0105 \text{ p.u.}$$

$$b = -\frac{x}{r^2 + x^2} = -\frac{0.0360}{0.0062^2 + 0.0360^2} = -27.0 \text{ p.u.}$$

$$g = \frac{r}{r^2 + x^2} = \frac{0.0062}{0.0062^2 + 0.0360^2} = 4.64 \text{ p.u.}$$

$$b/b^{sh} = \frac{-27.0}{0.0105} = -2596 \qquad x/r = \frac{0.036}{0.0062} = 5.8$$

Carson's Equations

$$\overline{Z}_{ii} = r_i + 9.8696\times10^{-4}\cdot f + j1.2566\times10^{-3}\cdot f.(\ln\frac{1}{GMR_i} + 6.4905 + \frac{1}{2}\ln\frac{\rho}{f}) \text{ , } (\Omega/km)$$

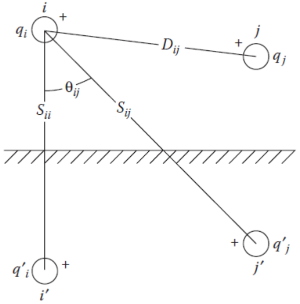
$$\overline{Z}_{ij} = 9.8696\times10^{-4}\cdot f + j1.2566\times10^{-3}\cdot f.(\ln\frac{1}{D_{ij}} + 6.4905 + \frac{1}{2}\ln\frac{\rho}{f}) \text{ , } (\Omega/km)$$

Primitive potential coefficients

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

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

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

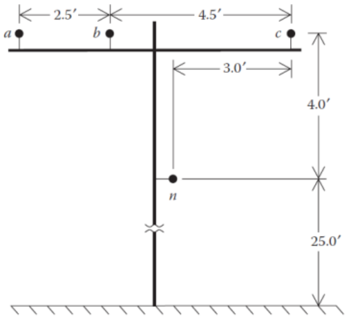


Example

An overhead three-phase distribution line is constructed as shown. Determine the phase impedance and admittance matrices of the line. The phase conductors are 336,400 26/7 ACSR (Linnet), and the neutral conductor is 4/0 6/1 ACSR.

336,400 26/7 ACSR:	$GMR = 0.0244$ ft	
$RD_c = 0.03004$ ft	Resistance $= 0.306\ \Omega$/mile	
4/0 6/1 ACSR:	$GMR = 0.00814$ ft	
$RD_s = 0.02346$ ft	Resistance $= 0.5920\ \Omega$/mile	

$d_1 = 0 + j29$ $d_2 = 2.5 + j29$ $d_3 = 7.0 + j29$ $d_4 = 4.0 + j25$



$$[z_{abc}] = \begin{bmatrix} 0.4576 + j1.0780 & 0.1560 + j.5017 & 0.1535 + j0.3849 \\ 0.1560 + j0.5017 & 0.4666 + j1.0482 & 0.1580 + j0.4236 \\ 0.1535 + j0.3849 & 0.1580 + j0.4236 & 0.4615 + j1.0651 \end{bmatrix} \Omega/\text{mile}$$

$$[y_{abc}] = j\cdot376.9911\cdot[C_{abc}] = \begin{bmatrix} j5.6711 & -j1.8362 & -j0.7033 \\ -j1.8362 & j5.9774 & -j1.169 \\ -j0.7033 & -j1.169 & j5.3911 \end{bmatrix} \mu\text{S/mile}$$

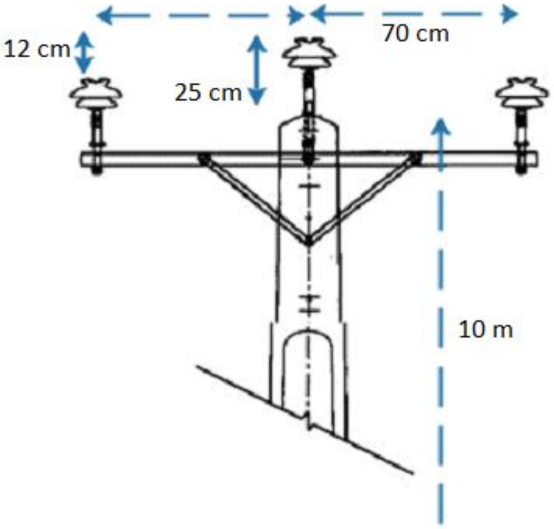


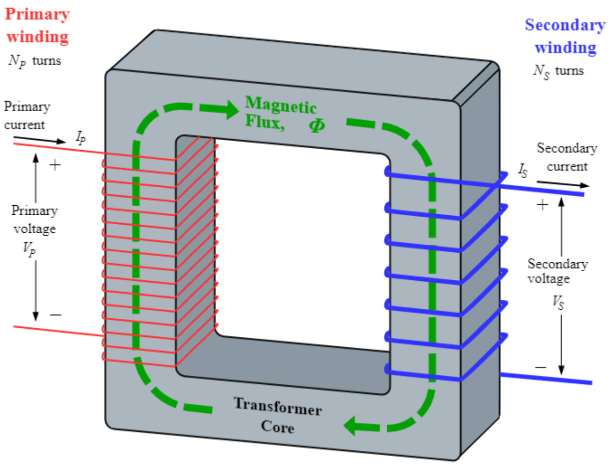
Table. 3. Typical ACSR conductor data

name	Cross section (mm2)	GMR (cm)	AC resistance (/km)
Fox	42.77	0.323	0.799
Mink	73.65	0.424	0.463
Dog	118.5	0.495	0.279
Hyena	126.43	0.563	0.277

Fox

$$Z_{Fox} = \begin{bmatrix} 0.83235 + 0.78992i & 0.049348 + 0.45107i & 0.049348 + 0.40843i \\ 0.049348 + 0.45107i & 0.83235 + 0.78992i & 0.049348 + 0.45107i \\ 0.049348 + 0.40843i & 0.049348 + 0.45107i & 0.83235 + 0.78992i \end{bmatrix}$$

Transformers



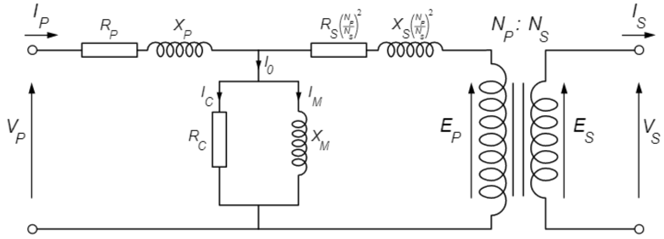


Fig. 25. In-phase transformer model

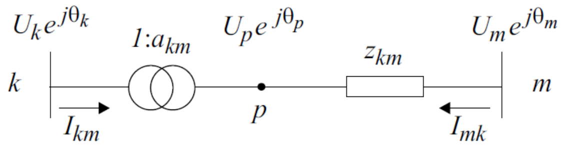


Fig. 26. In-phase transformer approximate model [5]

$$\frac{U_p}{U_k} = a_{km}$$

$$\frac{I_{km}}{I_{mk}} = -\frac{|I_{km}|}{|I_{mk}|} = -a_{km}$$

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} a_{km}^2 y_{km} & -a_{km} y_{km} \\ -a_{km} y_{km} & y_{km} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix}$$

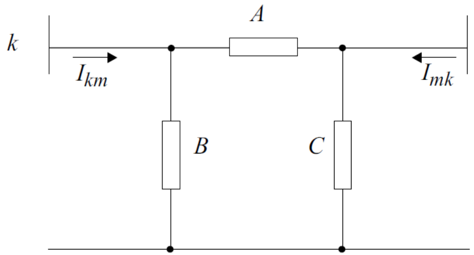


Fig. 27. Equivalent model for in-phase transformer [5]

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} A+B & -A \\ -A & A+C \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix}$$

$$A = a_{km} y_{km}$$

$$B = a_{km}(a_{km} - 1) y_{km}$$

$$C = (1 - a_{km}) y_{km}$$

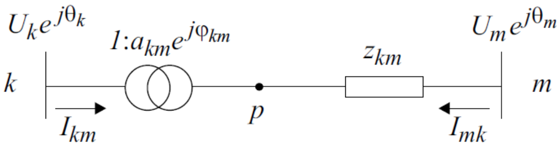


Fig. 28. Phase shifting transformer approximate model [5]

$$\frac{E_p}{E_k} = t_{km} = a_{km}e^{j\varphi_{km}}$$

$$\frac{I_{km}}{I_{mk}} = -t_{km}^{*} = -a_{km}e^{-j\varphi_{km}}$$

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} a_{km}^2 y_{km} & -t_{km}^{*} y_{km} \\ -t_{km} y_{km} & y_{km} \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix}$$

Unified Branch Model

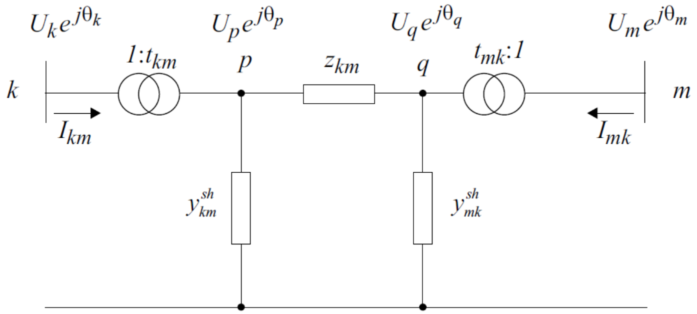


Fig. 29. Unified branch model [5]

- if $t_{km} = t_{mk} = 1$ is assumed, the result is an equivalent -model of a transmission line
- if the shunt elements are ignored, and $t_{km} = 1$ and $t_{mk} = a_{mk} e^{-j\varphi_{mk}}$ is assumed, then the result is a phase shifting transformer with the tap located on the bus *m* side
- if the shunt elements are ignored, and $t_{mk} = 1$ and $t_{km} = a_{km}$ is assumed, then the result is an in-phase transformer with the tap located on the bus *k* side

$$\begin{pmatrix} I_{km} \\ I_{mk} \end{pmatrix} = \begin{pmatrix} a_{km}^2 (y_{km} + y_{km}^{sh}) & -t_{km}^* t_{mk} y_{km} \\ -t_{mk}^* t_{km} y_{km} & a_{mk}^2 (y_{km} + y_{km}^{sh}) \end{pmatrix} \begin{pmatrix} E_k \\ E_m \end{pmatrix}$$

There are other types such as as three winding transformer, and etc.

Due to negligible variations in the frequency, loads are traditionally modelled by the following model:

$$P = P_n \left(\frac{U}{U_n}\right)^{k_{pu}}$$
$$Q = Q_n \left(\frac{U}{U_n}\right)^{k_{qu}}$$

- Constant power model: When both exponents are equal to 0
- Constant current model: When both exponents are equal to 1
- Constant impedance model: When both exponents are equal to 2

Proof mathematically

The ZIP model:

$$P = P_n\left[p_1 \left(\frac{U}{U_n}\right)^2 + p_2 \left(\frac{U}{U_n}\right) + p_3\right]$$
$$Q = Q_n\left[q_1 \left(\frac{U}{U_n}\right)^2 + q_2 \left(\frac{U}{U_n}\right) + q_3\right]$$

Example

For a real-world 10kV substation

$$P = 1.12 - 2.032U + 1.912U^2,$$
$$Q = 7.486 - 16.27U + 9.784U^2$$

4

Distribution network analysis

Load flow and state estimation formulation

Distribution network analysis

Distribution load flow

The inputs

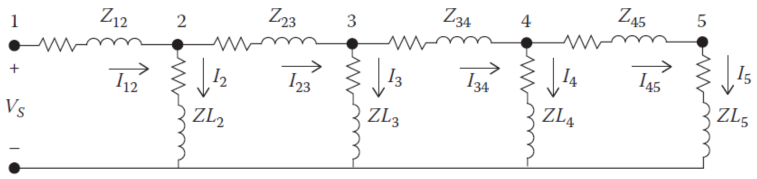
- Main substation voltage
- Load data and their models
- Network data including the topology, lines impedance, etc.

The outputs

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

- Distribution systems are radial or weakly meshed network structures
- They have high X/R ratios in the line impedances
- They may have of many single-phase or two-phase loads and laterals

Bkward-forward load flow (ladder method)



$$V_2 = V_3 = V_4 = V_5 = V_S$$

$$I_i = \frac{V_i}{Z_{Li}}$$

$$I_{45} = I_5, I_{34} = I_4 + I_{45}, I_{23} = I_3 + I_{34}, I_{12} = I_{23} + I_2$$

$$V_j = V_i - Z_i I_{ij}$$

$$\sum_{i=1}^{n} (|V_i^k| - |V_i^{k-1}|)$$

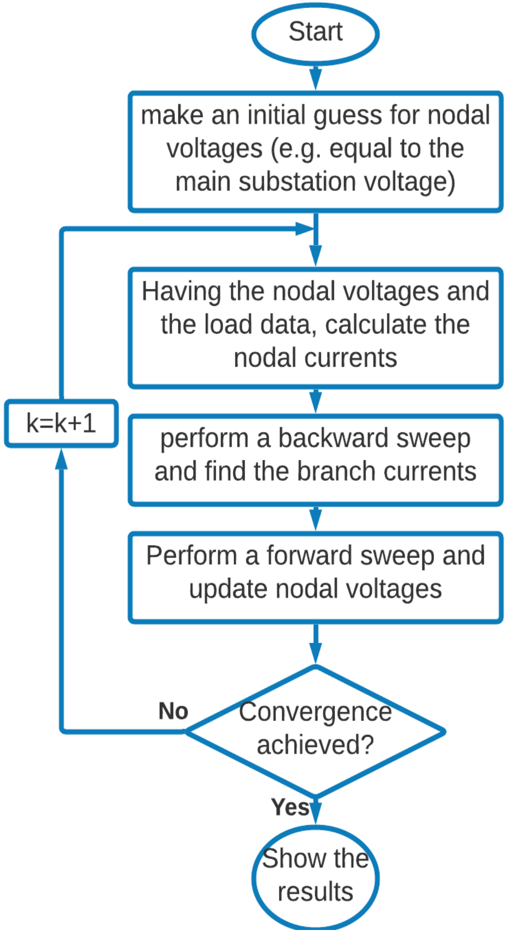


Fig. 30.backward-forward load flow flowchart

- ✓ **Distribution networks are unbalanced and asymmetrical**
- ✓ **In underground networks shunt susceptance may not be negligible**

1. **Make an initial guess for nodal voltages**
2. **Calculate the currents of shunt elements (loads, line shunt susceptance, capacitor banks, and etc.)**

$$\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix} = \begin{bmatrix} Y_{L_{aa}} & Y_{L_{ab}} & Y_{L_{ac}} \\ Y_{L_{ba}} & Y_{L_{bb}} & Y_{L_{bc}} \\ Y_{L_{ca}} & Y_{L_{bc}} & Y_{L_{cc}} \end{bmatrix} \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix}$$

3. **Perform a backward sweep and find the branch currents**
4. **Update the nodal voltages using the three-phase branch admittance matrix**

$$\begin{bmatrix} V_{ja} \\ V_{jb} \\ V_{jc} \end{bmatrix} = \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} - \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_{a} \\ I_{b} \\ I_{c} \end{bmatrix}$$

5. **Repaeat until convergence in nodal voltages is achieved**

Distribution state estimation

In any distribution network with a set of measurements (Z), the relation between network state variables (x) and the measurements can be described as follows:

$$z = h(x) + e$$

where h represents the relation between the measurements and the state variables and e is the measurement error.

For example in the following figure which presents a portion of a distribution network, assume that the line suceptance is negligible, the line impedances are known, and the lines currents and the voltages of nodes 1 and 3 are measured. To obtan the voltage of node 2 we have:

$$V_2 = V_1 - Z_1 I_1$$
$$V_2 = V_3 + Z_2 I_2$$

Considering the errors in measurements, the obtained values will not be equal

State estimators (SE) determine the most likely state of a power system from sets of measurements

- Most likely values of states (even better than measurement)
- Bad data detection
- Remote measurement inspection
- Topology identification and etc.

The WLS technique:

The estimate of the unknown state vector *X* can be obtained by minimizing the least-squares function below:

$$j(x) = \sum_{i=1}^{m} w_i (z_i - h_i(x))^2 = [z - h(x)]^T W [z - h(x)] \qquad W = \begin{bmatrix} \sigma_1^2 & 0 & \cdots \\ 0 & \sigma_2^2 & \vdots \\ \vdots & \cdots & \ddots \end{bmatrix}^{-1}$$

The diagonal elements of W determine the influence of measurements based on their variances σ_j^2

In order to minimise *j(x)* with respect to the state vector, the first-order optimality conditions need to be satisfied:

$$g(x) = \frac{\partial j(x)}{\partial x} = -H^T(x)W[z - h(x)] = 0$$

$$H(x) = \partial h(x)/\partial x$$

The estimate is obtained by solving the non-linear optimality conditions through an iterative process:

$$x^{k+1} = x^k - [G(x^k)]^{-1} g(x^k)$$

where *G(x)* is the gain matrix:

$$G(x) = \frac{\partial g(x)}{\partial x} = H^T(x)WH(x)$$

Starting from an initial guess, the state estimation algorithm iteratively updates the state variables for $k = 1,2,3...$ until appropriate convergence is attained

State estimation has been exploited for many years for transmission systems. The same framework could, in principle, be also used for SE in distribution systems. However, the problem of SE in distribution networks has to be approached in a different way, due to the inherent differences between the two types of networks:

Imbalance. This is due to the presence of widespread nonsymmetrical loads and consequently, of non-symmetrical three-phase electrical quantities.

Radial or weakly meshed topology. These topologies allow the use of the branch currents as possible primary state variables.

Low number of measurement devices. The observability of the network can only be obtained by exploiting the so-called pseudo-measurements. Besides, because of the lack of redundancy, the available measurements are critical

Low X/R ratio. This leads to the impossibility of adopting simplifications commonly used in the estimators developed for transmission systems, as for example, neglecting resistances because of dominant inductive terms. As a further consequence, decoupled versions of the estimators are not so easily obtained.

High number of nodes. This (along with the need of developing three-phase estimators) leads to very large systems, resulting in the explosion of execution times of the algorithms.

Network model uncertainty. In the SE framework, line impedances of the network are generally assumed to be known. Actually, the knowledge of network model parameters has large uncertainty due to network aging and lack of accurate measurement campaigns. This can lead to a degradation of SE performance.

Observability and measurements

If the set of measurements is sufficient to make state estimation possible, we say the network is observable (an estimation of internal states of a system can be inferred from the knowledge of its external outputs). Observability depends on the number of measurements available and their geographic distribution.

Real measurements vs pseudo measurements

MV level measurements

LV Level measurements

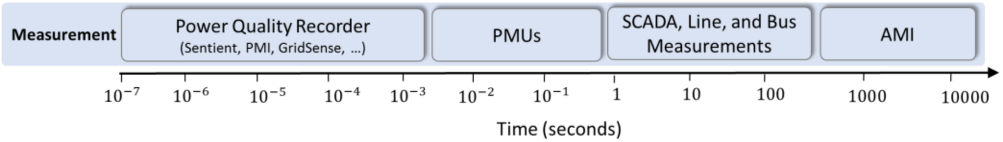


Fig. 31. Distribution measurements resolution [6]

Choose of state variable

Table. 4. Approaches to State Variable Formulation [6]

State Vector	Coordinate	Advantages	Drawbacks
Bus (Node) Voltage	Polar	• Direct estimation of voltage magnitude and phase • Suitable for meshed networks	• Many non-linear measurement functions • High computational burden
	Rectangular	• Linearization of many measurement functions • High computational speed • Suitable for meshed networks	• Difficult treatment of current magnitude measurements
Branch (Line) Current	Polar	• Easy handling of current magnitude measurements • Easier handling of single-phase laterals branching from feeder	• Many non-linear measurement functions • High computational burden • Only practical for radial/weakly meshed grids
	Rectangular	• Linearization of many measurement functions • Sparse system matrices • High computational speed	• Only practical for radial/weakly meshed grids
Power	Rectangular	• Practical for underdetermined systems • Linear line flow measurements	• Computational burden for calculating relevant states

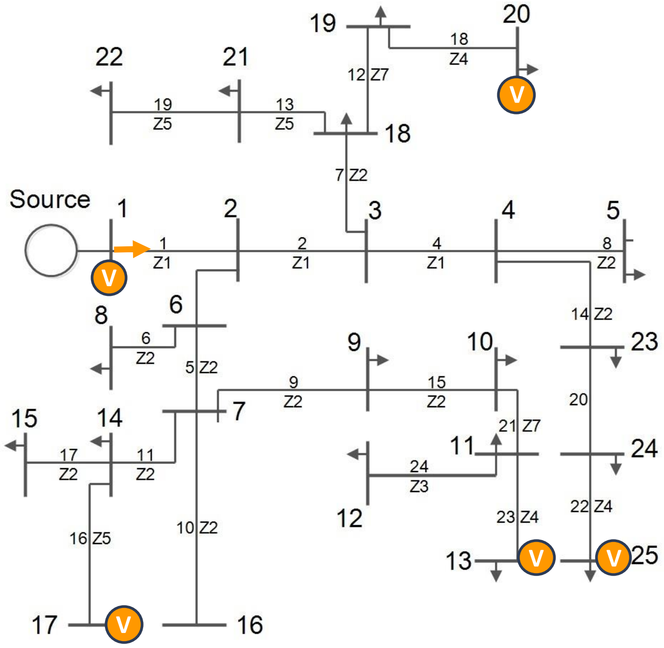


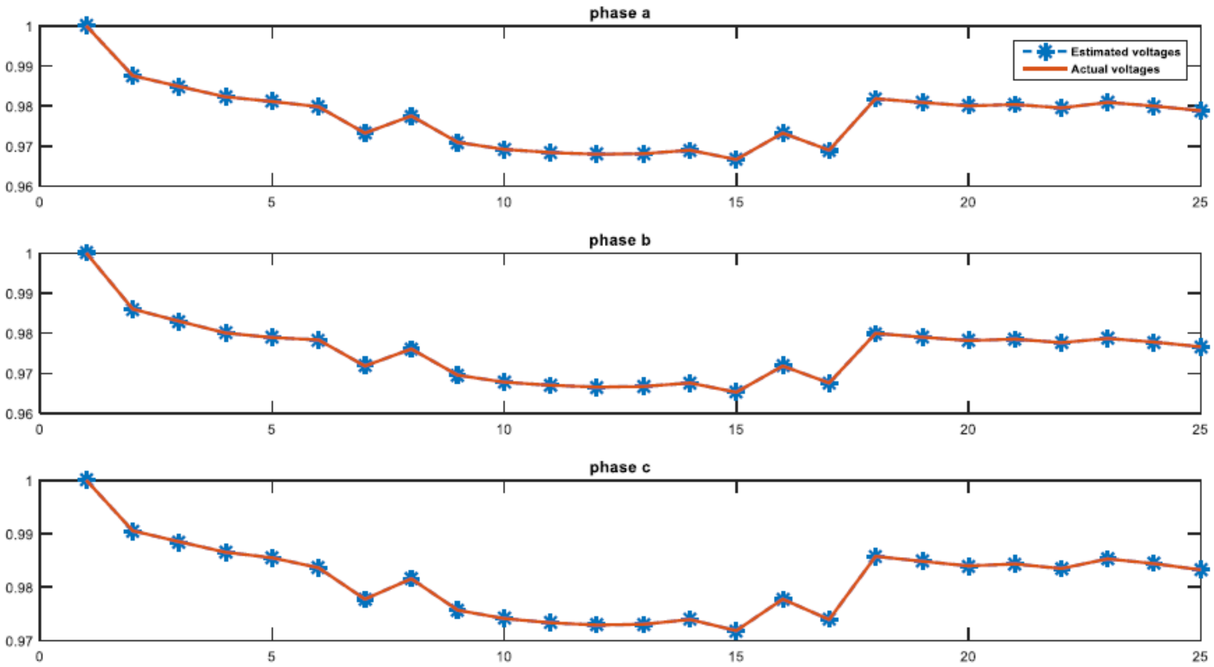
Fig. 33. Modified IEEE 25 node feeder

- **Substation voltage and current measurements have 0.5% error with random distribution**
- **Feeder voltage measurements have 1% error with random distribution**
- **MV/LV substation P and Q are estimated with 30% error with random distribution**

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\left|V_i^e\right| - \left|V_i^a\right|\right)^2}{n}}$$

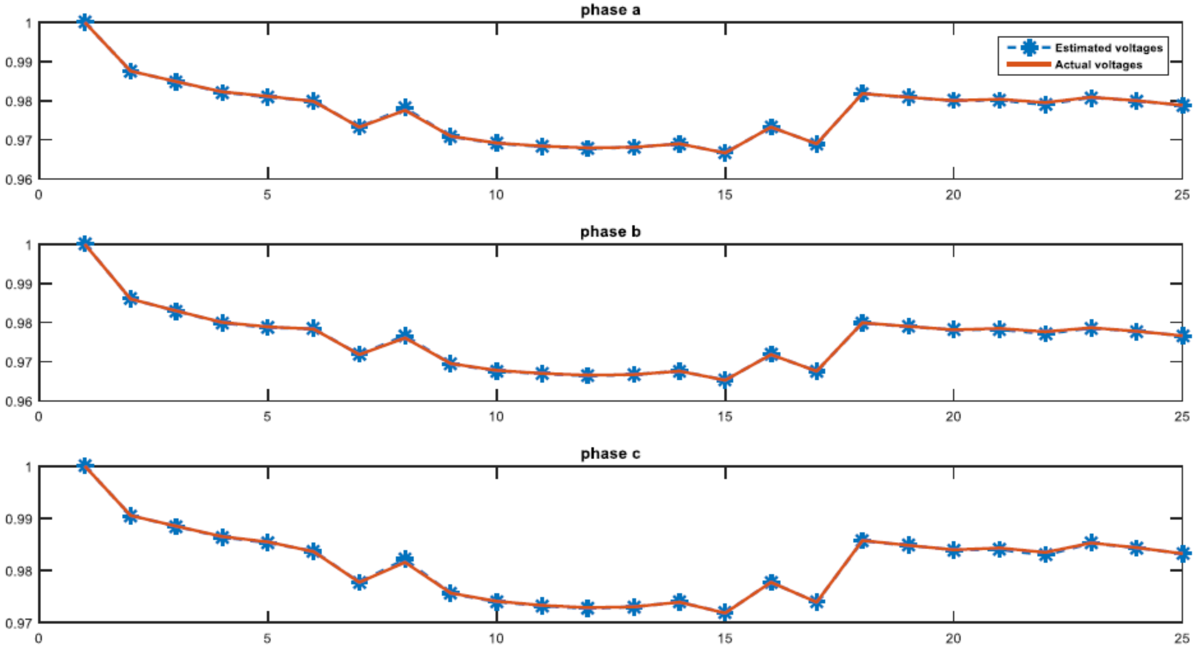
The results rae presented as RMSE per unit voltage in %

Scenario 1: Accurate load estimates and measurements



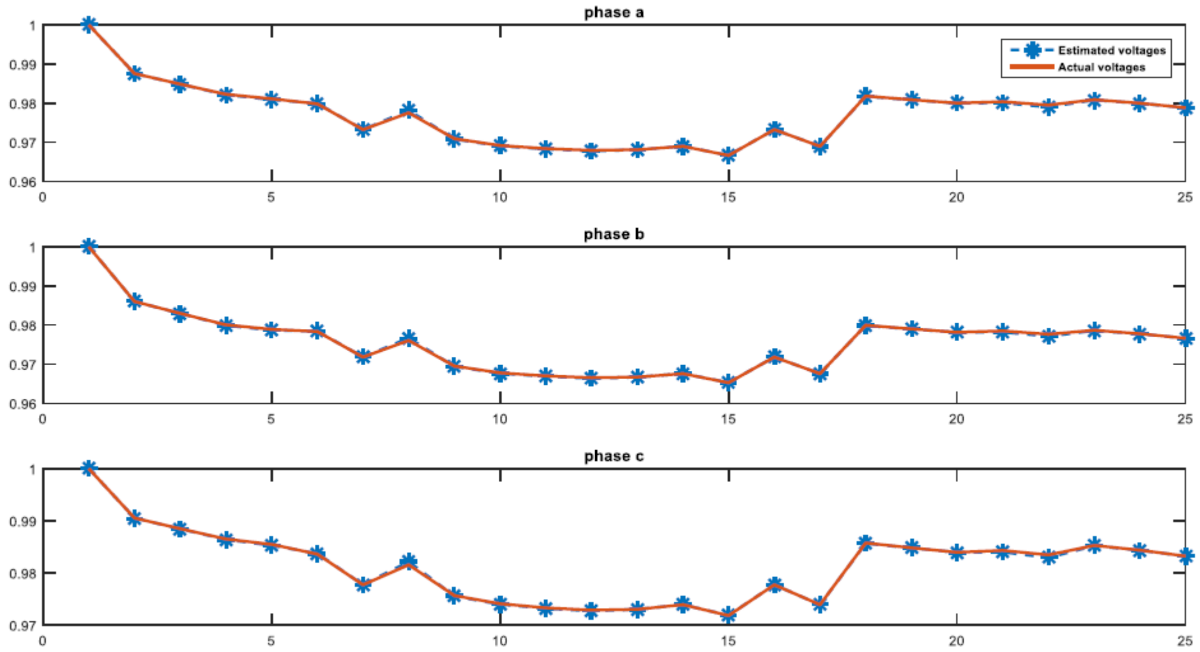
Scenario 2: Accurate measurements and inaccurate load estimates

RMSE_a= 0.019
RMSE_b= 0.02
RMSE_c= 0.019



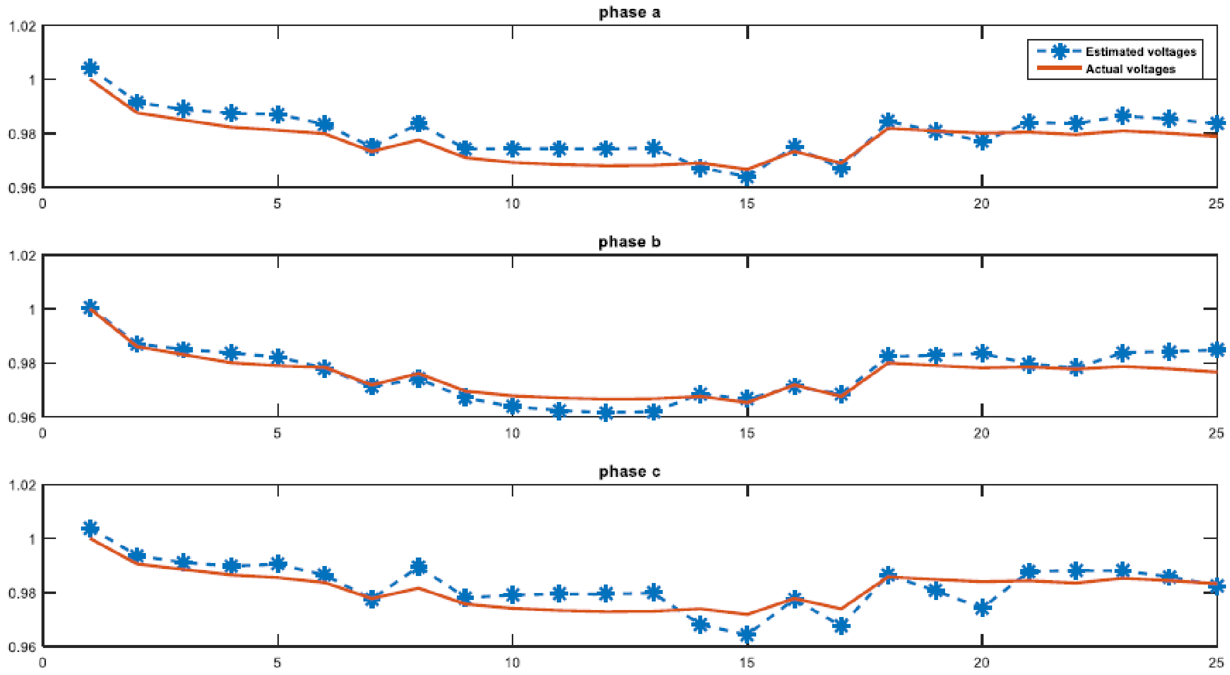
Scenario 3: Accurate measurements and inaccurate load estimates
Voltage measurements at nodes 20 and 17 are not available

RMSE_a= 0.034
RMSE_b= 0.035
RMSE_c= 0.029



Scenario 4: Inaccurate measurements and inaccurate load estimates

RMSE_a= 0.53
RMSE_b= 0.36
RMSE_c= 0.67



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Thank you

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