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Distribution System Planning

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Distribution System Planning

Acknowledgement:
The slides are developed based in part on Electric Power and Energy Distribution Systems, Models, Methods and Applications, Subrahmanyan S. Venkata, Anil Pahwa, IEEE Press & Wiley, 2022

1. Overview

- Distribution system planning: Meeting future electricity needs of customers.
- Complex and capital-intensive process due to changing loads (population, technology, habits).
- Multiple objectives considered simultaneously, while meeting technical constraints.
- Goal: Minimize total cost, ensure adequate capacity to supply the load for the future with adequate reliability and acceptable voltage quality.
- Plans address both short-term (1-2 years) and long-term (5-10 years) needs.
- First stage: Load forecasting for future, identifying growth areas.
- Second Stage: Determine location & capacity of substations; number & size of transformers; and reinforce existing or build new substations based on planning results.
- Last Stage: Feeder design to deliver power from substations to customers.

1. Overview

- Feeder design includes both primary and secondary systems.
- Decisions: Number of primary feeders, size and routing of conductors.
- Secondary level decisions: Location, size of distribution transformers.
- Most of the secondary construction in US has been overhead so far.
- There is a trend toward making new secondary construction underground.
- Underground system can be more expensive (5-10 times) than overhead system, but underground secondary system is preferred by some localities for greater reliability and aesthetics.

2. Traditional vs. Modern Approaches to Planning

Legacy distribution systems:

- Only loads on substation transformers and feeders are measured.
- Little information beyond the feeder.
- Rely on customer billing data and total distribution transformer capacity for load estimates.
- As part of the load research activity, utilities installed recording devices at selected customer locations to record loads at a predetermined interval (5 minutes, 15 minutes, 30 minutes, or 1 hour) to get an idea of the daily load profiles for different classes of customers. These load profiles, especially the peak demands, are also useful for planning purposes.
- Diversity factor, maximum non-coincident demand, maximum diversified demand
- Limited data led to ad hoc distribution planning, often resulting in overdesigned systems.

2. Traditional vs. Modern Approaches to Planning

- Modern systems: More metering capabilities thanks to distribution automation and advanced metering infrastructure. Increased automation provides accurate data, eliminating some assumptions in planning.

- Traditional approach: Design to meet peak demand.

- Modern approach:

  - Uses risk analysis.

  - Requires data on hours spent at different load levels to determine the risk of insufficient capacity to meet the demand over a period of time.

  - Specifically, the number of hours under peak conditions is very important for risk assessment.

  - System reliability, resiliency, aging assets, equipment loading, regulatory environment considered in modern planning.

3. Long – Term Load Forecasting

- Load forecasting: Determining future load in an area, short-term forecasts are needed (hours to days) for operation, while long-term (1 year or more) forecasts are needed for planning.
- Knowledge of future loads is crucial for designing distribution system facilities and ensure the reliability.
- Planners need to know peak load and its timing.
- In addition to temporal forecasts, spatial forecasts are important because they tell the locations of load growth locations in addition to quantity of load growth.
- Load forecasts depend on local and national trends.
  - At local level, population growth, new industrial or commercial facilities planned.
  - At national level, high efficiency appliances.
- Appliance manufacturers and consumer organizations conduct regular surveys to keep track of consumer behaviors to determine these trends.

3. Long – Term Load Forecasting

- Another approach to forecasting is based on end-use modeling in which loads of different end uses, such as lightning, water heater, and AC, for different customers are added in a hierarchical manner to obtain the composite load.

3. Long – Term Load Forecasting

- Composite load in a utility service area shows a gradual increase in load over years.
- Composite load in small areas follow an "S" curve with three parts: dormant, growth, saturation periods as shown in figure (a).
- Combining the composite loads of all small areas in within a utility exhibits linear characteristics, reflecting overall load growth for a utility service area as shown in figure (b).
- Breaking a utility service area into smaller areas is useful for spatial load forecasting.

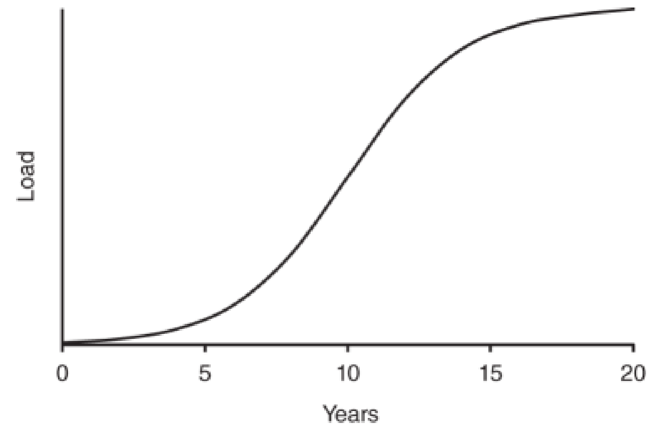


Fig. a: S-curve showing load growth in a small area.

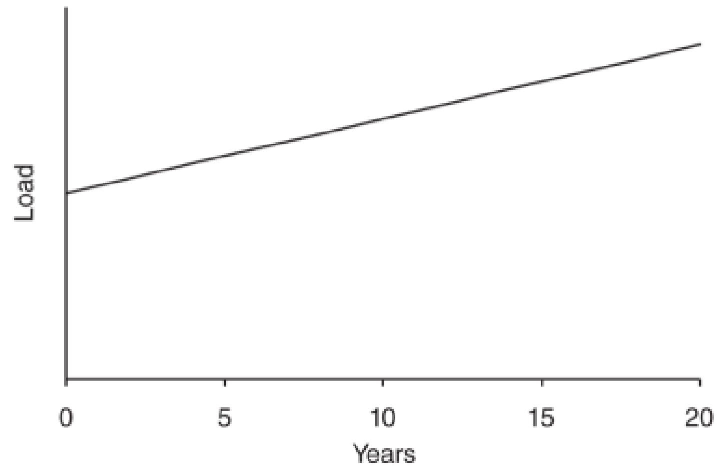
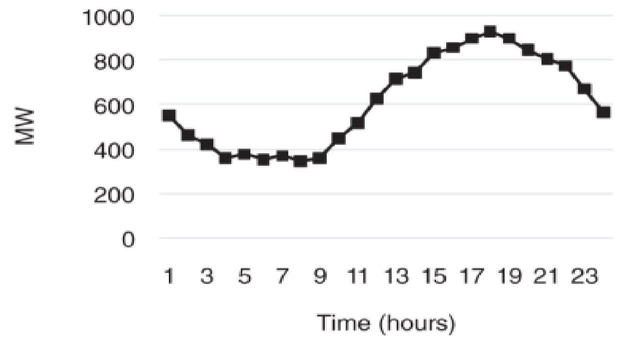


Fig. b: Load growth of a service area over the years.

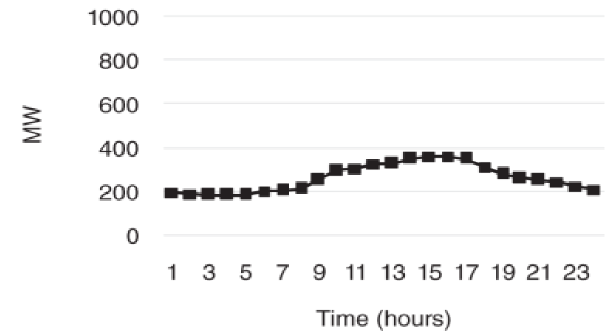
4. Load Characteristics

4.1 Customer Classes

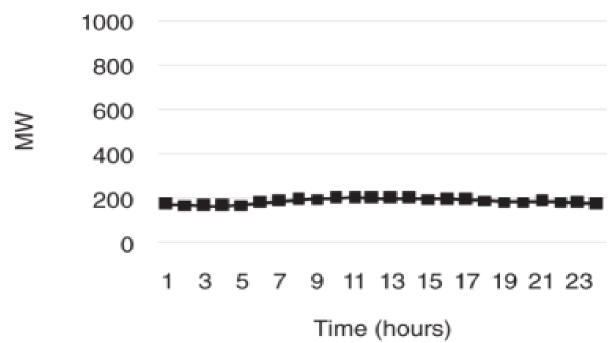
- Utilities serve various customer classes: residential, commercial, industrial, agricultural.
- Different classes have distinct electricity usage patterns, leading to varying load demands.
- Within a class, customers exhibit similar load patterns.
- For example, residential load is low at night, rises in morning, peaks during the day, declines in the evening.
- Commercial and industrial loads: High during the day, low at night.
- Commercial load variation larger due to extended operating hours for some industries.



Residential load



Commercial load

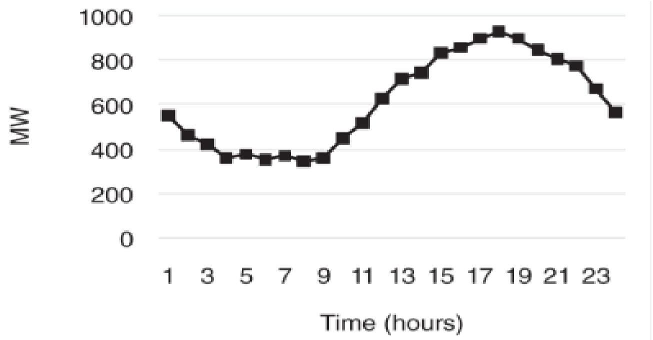


Industrial load

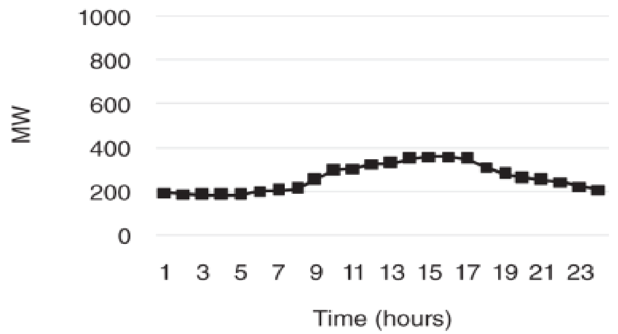
4. Load Characteristics

4.1 Customer Classes

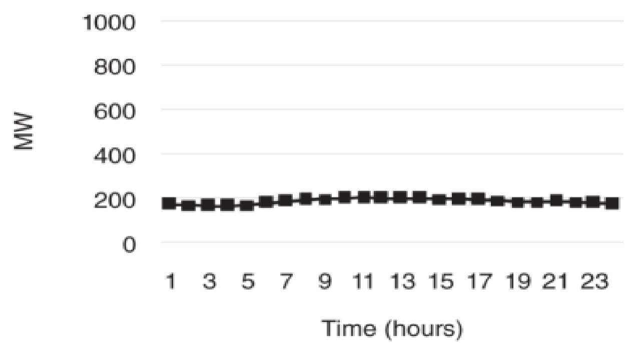
- Industrial loads: Some industries operate 24/7, contributing to relatively steady demand.
- Agricultural load demands vary based on irrigation needs for different crops.
- Load demands within each class also have seasonal fluctuations.
- Utilities maintain load demand databases for each class to be used in planning.



Residential load



Commercial load



Industrial load

4. Load Characteristics

4.2 Loads in a Modern House

- Changes in residential loads:
  - More efficient appliances.
  - New types of loads: computers, entertainment devices.
  - Transformation in lighting: incandescent to CFLs to LED lamps.
- 2015 Energy Information Administration (EIA) survey data:
  - Average monthly electric energy consumption for US residential customers: 901 kWh.
  - Average monthly bill: $114.03.
  - Average price: $0.1265/kWh.
  - State variations: Washington (lowest) $0.0909/kWh, Hawaii (highest) $0.296/kWh, Connecticut (lowest 48 states) $0.2094/kWh.
  - Highest consumption: Louisiana (1286 kWh), lowest: Maine (556 kWh).
  - Louisiana: High AC use due to hot, humid climate. Maine: Low electricity consumption due to gas-based heating.

4. Load Characteristics

4.2 Loads in a Modern House

- Energy consumption breakdown (2015):
  - Electricity: 47%, natural gas: 44%.
  - Half of home energy consumption is heating, cooling, ventilation.
- Key energy-consuming uses (2015):
  - Air conditioning: largest energy consumption, followed by space cooling, water heating.
  - Lighting: 10%, refrigerators: 7%, TVs: 7%, clothes dryers: 5%.
  - Miscellaneous appliances (12%): freezers, dishwashers, washers, cooking ranges, microwaves, etc.
  - Other appliances (13%): computers, home audio, coffee makers, etc.
- Specific appliances:
  - HVAC: 1-6 kW
  - Refrigerator: about 600 W, cycles on/off for temperature maintenance.
  - Stand-alone freezer: typical rating of 500 W.

4. Load Characteristics

4.2 Loads in a Modern House

- Clothes washer: about 500 W, dishwasher: about 1.2 kW, clothes dryer: about 4 kW.

- Trends over years:
  - Increase in electronics portion (large flat screen TVs, computers).
  - Decrease in lighting portion (proliferation of LED lighting).

- Following table illustrates the energy usage in the US homes in 2015. *Source: Data from U.S. Energy Information Administration*

Usage	Percentage of energy used
Air conditioning	17
Space heating	15
Water heating	14
Lighting	10
Refrigerators	7
Television and related equipment	7
Clothes dryer	5
Miscellaneous	12
Other	13

4. Load Characteristics

4.3 Time Aggregation

- Instantaneous power: Voltage × current, not useful for planning due to large fluctuations.
- Demand (in kW): Average power over selected time period, used for planning.
- Typical utility time periods: 1 min, 5 min, 15 min, 30 min, 1 hour.
- Calculate demand: Energy consumed (kWh) divided by time period (hours).
- Example: Load consumes 2 kWh in 15 min (0.25 h), demand = 2/0.25 = 8 kW.
- Another example: Load consumes 7.5 kWh in 1 hour, demand = 7.5/1 = 7.5 kW.
- Reported demand at a given time is average load for the previous time period.
- Example: Demand reported at 2:00 a.m. (one-hour basis) is average load between 1:00 a.m. and 2:00 a.m.
- For 15-minute reporting: Reported value at 2:00 a.m. is average load between 1:45 a.m. and 2:00 a.m.

4. Load Characteristics

4.3 Time Aggregation

- Single-house demand characteristics within a short time period (Figure: a) show significant fluctuations.
- Fluctuations result from random switching of loads: automatic or by occupants.
- Automatic switches: AC, central heating, refrigerators, water heaters.
- Occupant-controlled switches: lighting, cooking appliances, washer, dryer, computers, entertainment loads.
- Loads may vary in power consumption even when on.
- Load demand smoothens with longer time periods, such as the load demand characteristics on 30-minute basis (Figure: b).

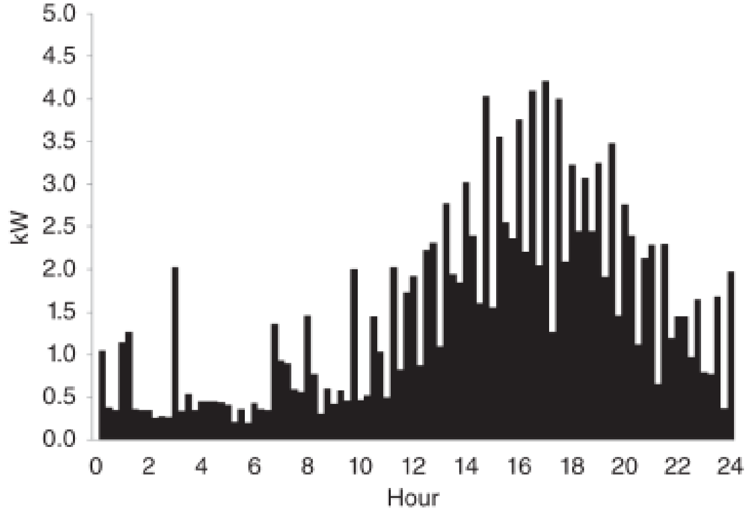


Fig. a: Demand of a house on 15-minute basis.

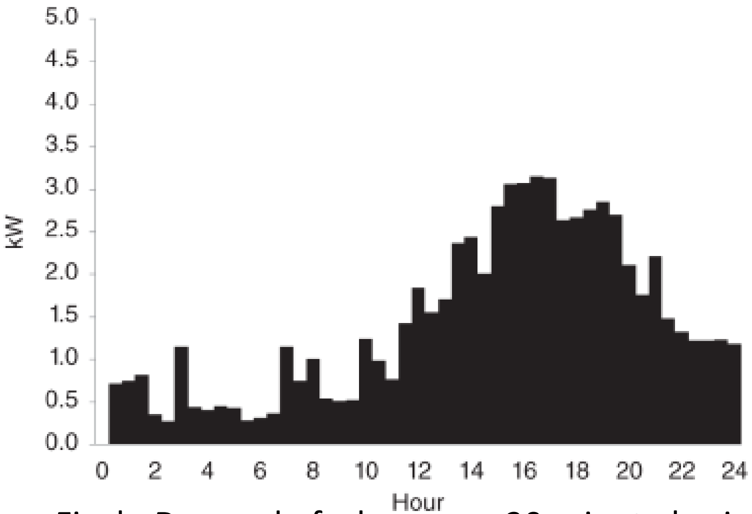


Fig. b: Demand of a house on 30-minute basis.

4. Load Characteristics

4.3 Time Aggregation

- Load demand characteristics on 1-hour basis (Figure: c).
- Time interval larger than 1 hour is not used to determine the load demand characteristics of the for planning purposes.
- Notice that time aggregation reduces peak load demand value.

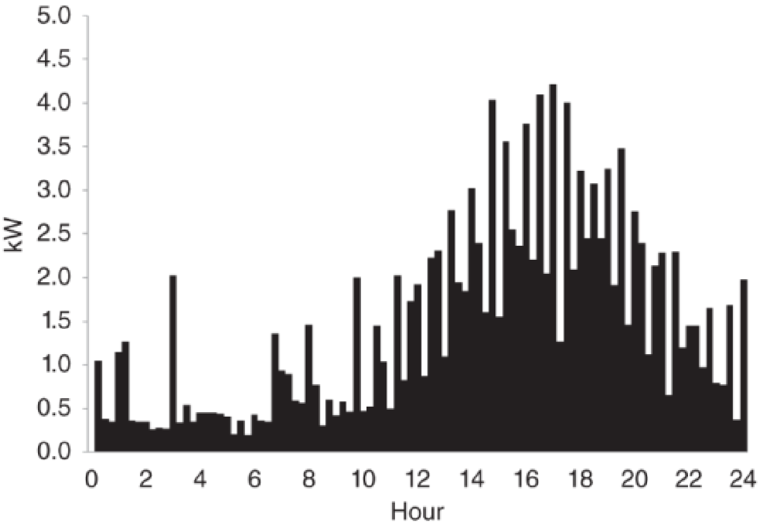


Fig. c: Demand of a house on 15-minute basis.

Diversity Factor

By definition, diversity factor (DF) is the ratio of the maximum noncoincident demand of a group of customers to the maximum diversified demand of the group. With reference to the transformer serving four customers, the DF for the four customers would be:

$$\text{Max\_noncoincident\_demand} = 6.18 + 6.82 + 4.94 + 7.05 = 24.98\text{kW}$$

$$\text{Diversity\_factor} = \frac{\text{Max.\_noncoincident\_demand}}{\text{Max.\_diversified\_demand}} = \frac{24.98}{16.16} = 1.5458$$

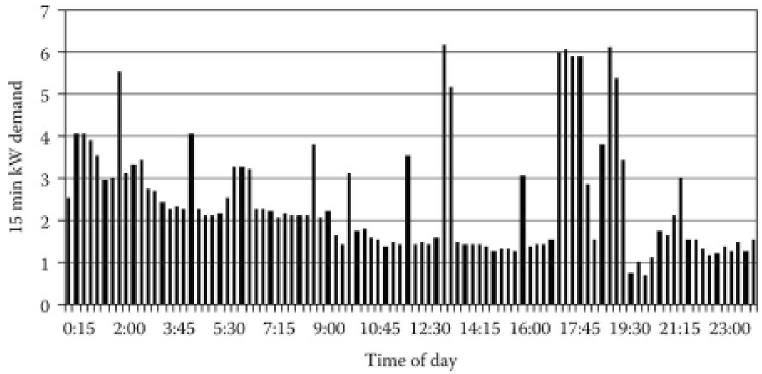


Fig.1 24-hour demand curve for customer#1

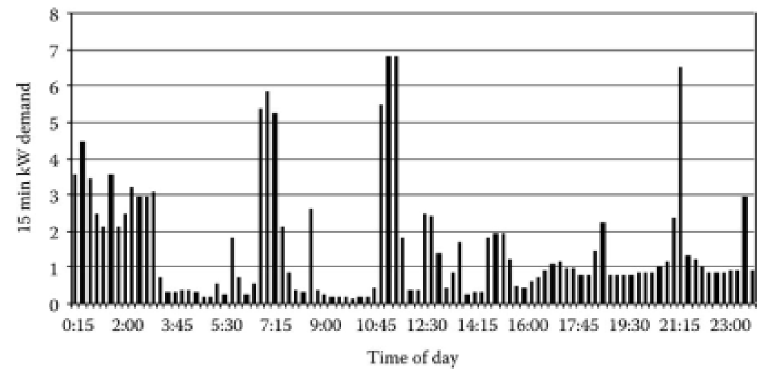


Fig.2 24-hour demand curve for customer#2

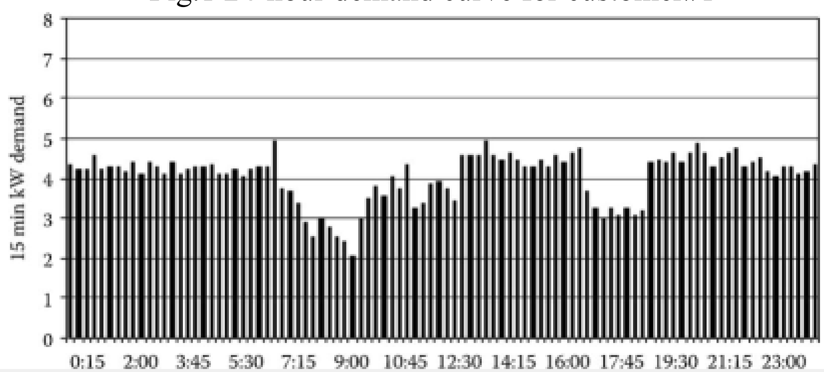


Fig.3 24-hour demand curve for customer#3

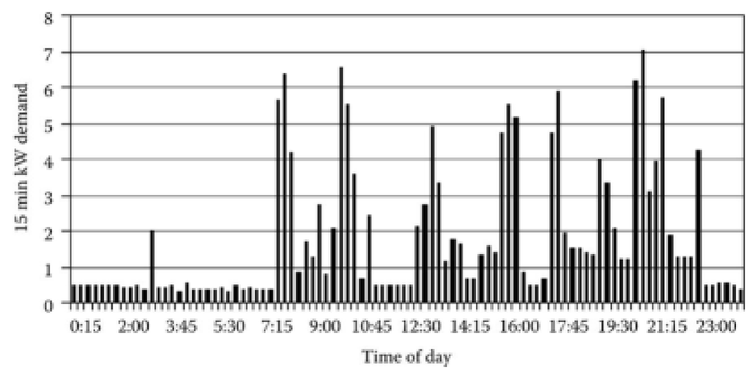


Fig.4 24-hour demand curve for customer#4

Diversity Factor

Table 1 is an example of the DFs for the number of customers ranging from 1 up to 70. The table was developed from a different database than the four customers that have been discussed previously.

Table 1 Diversity Factors

N	DF	N	DF	N	DF	N	DF	N	DF	N	DF	N	DF
1	1.0	11	2.67	21	2.90	31	3.05	41	3.13	51	3.15	61	3.18
2	1.60	12	2.70	22	2.92	32	3.06	42	3.13	52	3.15	62	3.18
3	1.80	13	2.74	23	2.94	33	3.08	43	3.14	53	3.16	63	3.18
4	2.10	14	2.78	24	2.96	34	3.09	44	3.14	54	3.16	64	3.19
5	2.20	15	2.80	25	2.98	35	3.10	45	3.14	55	3.16	65	3.19
6	2.30	16	2.82	26	3.00	36	3.10	46	3.14	56	3.17	66	3.19
7	2.40	17	2.84	27	3.01	37	3.11	47	3.15	57	3.17	67	3.19
8	2.55	18	2.86	28	3.02	38	3.12	48	3.15	58	3.17	68	3.19
9	2.60	19	2.88	29	3.04	39	3.12	49	3.15	59	3.18	69	3.20
10	2.65	20	2.90	30	3.05	40	3.13	50	3.15	60	3.18	70	3.20

Diversity Factor

A graph of the DFs is shown in Fig.5.

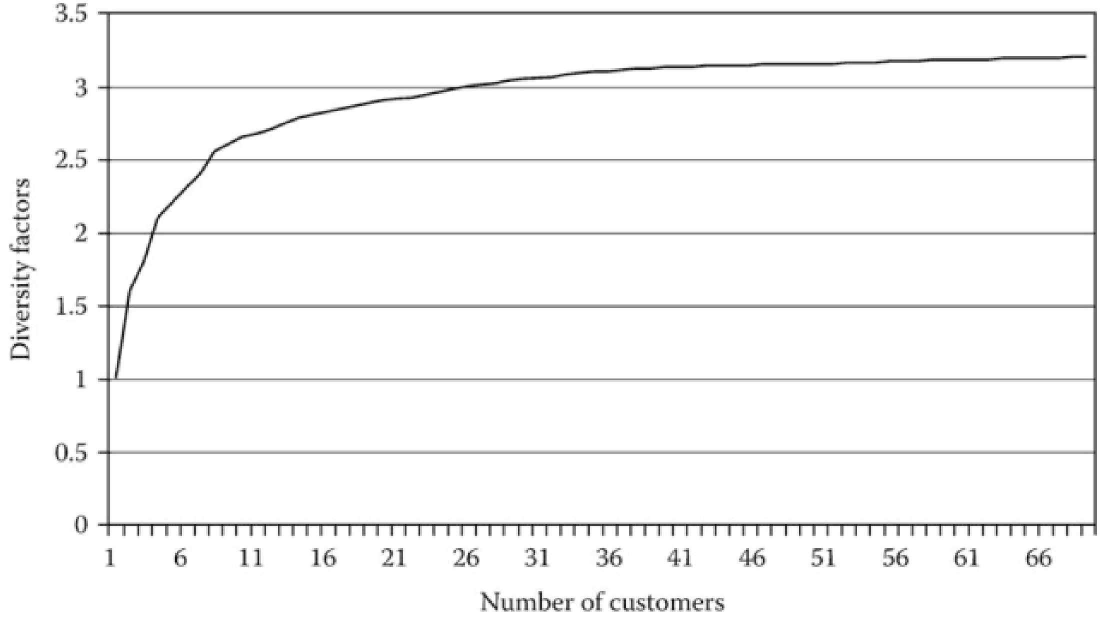


Fig.5 Diversity Factor

Note that, in Table 1 and Fig. 5, the value of the DF basically leveled out when the number of customers reached 70. This is an important observation because it means, at least for the system from which these DFs were determined, that the DF will remain constant at 3.20 from 70 customers and above. In other words as viewed from the substation, the maximum diversified demand of a feeder can be predicted by computing the total noncoincident maximum demand of all of the customers served by the feeder and dividing by 3.2.

Application of Diversity Factors

The definition of the DF is the ratio of the maximum noncoincident demand to the maximum diversified demand. DFs are shown in Table 2. When such a table is available, then it is possible to determine the maximum diversified demand of a group of customers such as those served by a distribution transformer. That is, the maximum diversified demand can be computed by:

$$\text{Diversity\_factor} = \frac{\text{Max.\_noncoincident\_demand}}{\text{Max.\_diversified\_demand}}$$

$$\text{Max.\_diversified\_demand} = \frac{\text{Max.\_noncoincident\_demand}}{DF_n}$$

But how could we know peak demand? (w/o demand mtr)

Many times the maximum demand of individual customers will be known either from metering or from knowledge of the energy (kWh) consumed by the customer. Some utility companies will perform a load survey of similar customers in order to determine the relationship between the energy consumption in kWh and the maximum kW demand. Such a load survey requires the installation of a demand meter at each customer's location.

Relate energy consumption to peak demand through study:

- Similar type of customers (residential)
- Metering on each customer for study

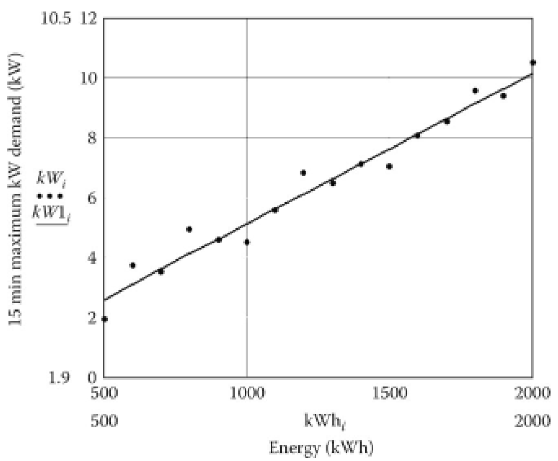


Fig.6 kW demand versus kWh for residential customers

The plot of points for 15 customers along with the resulting equation derived

$$\text{Max.\_kW\_demand} = 0.1058 + 0.005014 * kWh$$

4. Load Characteristics

4.4 Diversity and Coincidence

- Temporal aggregation reduces peak demand by averaging over a selected time duration.
- Aggregating demands of multiple houses smoothens out load demand characteristics (Figures (a-f) shown in the next slide).
- Load diversity (LD) in utility terminology: Houses have different load on/off timings.
- Peak demand of a group of houses at any time is lower than an individual house's peak.
- For conductor sizing, use peak value of combined demand on hottest (or coldest) day.
- Transformer sizing considers how many houses are served, using typical load demand characteristics.
- Coincidence factor adjusts aggregated and maximum loads of houses for coincident peak demand. Mathematically,

$$C = \frac{D_{mG}}{\sum_{i=1}^{n} D_{mi}}$$

where, D_{mi} is the peak demand of the i^{th} load in a group of n loads.

and, D_{mG} is the Coincident peak demand of the group.

4. Load Characteristics

4.4 Diversity and Coincidence

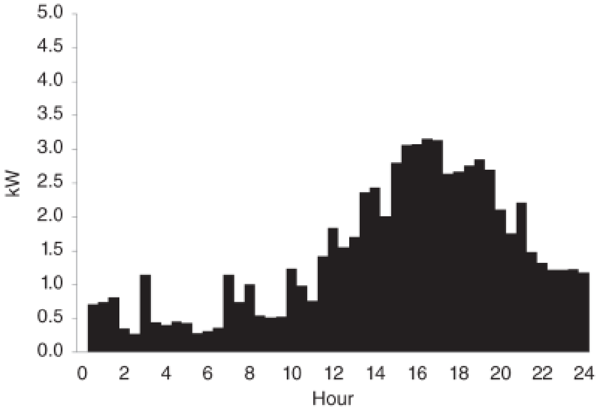


Fig. a: Demand of a house on 30-minute basis..

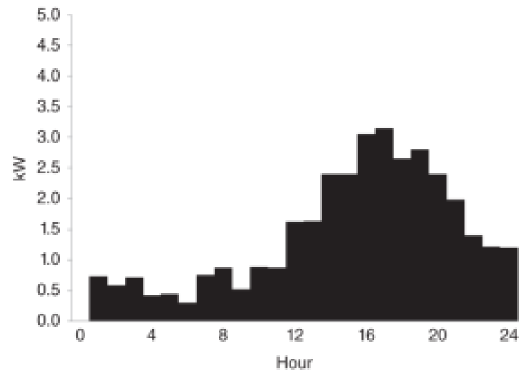


Fig. b: Demand of a house on one-hour basis.

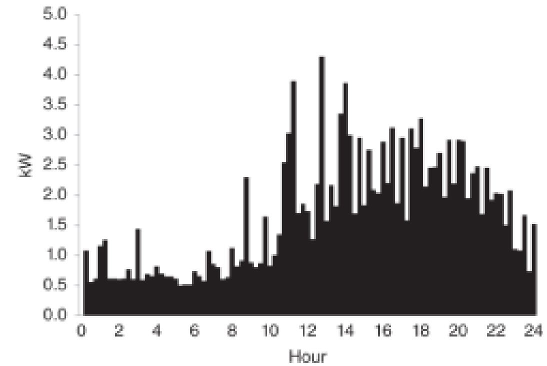


Fig. c: Fifteen-minute average load of two houses.

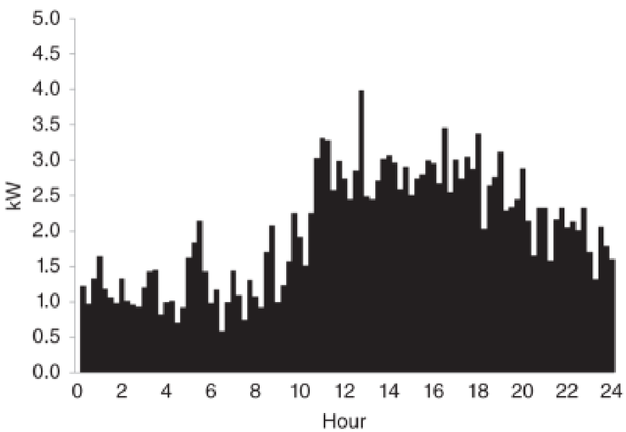


Fig. d: Fifteen-minute average load of 5 houses.

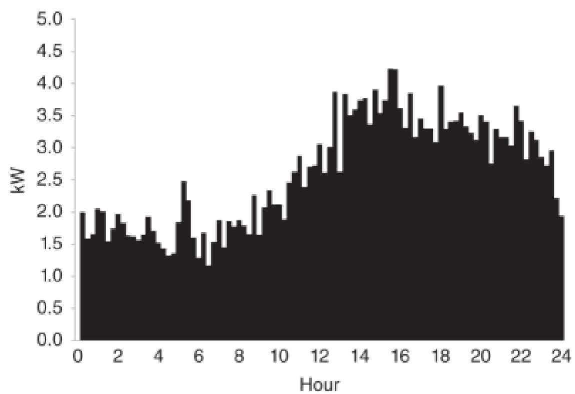


Fig. e: Fifteen-minute average load of 10 houses.

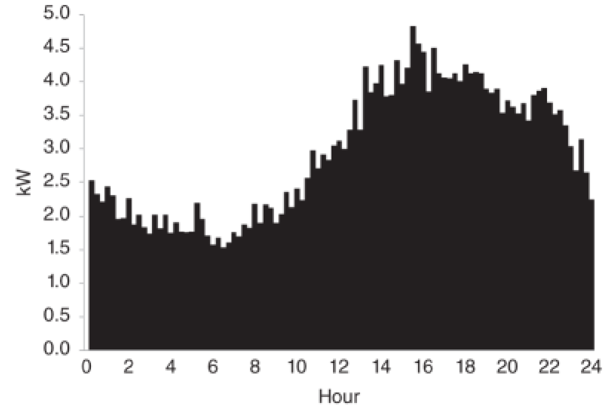


Fig. f: Fifteen-minute average load of 20 houses.

4. Load Characteristics

4.4 Diversity and Coincidence

- Coincidence factor (CF) ranges from 0 to 1.
- CF decreases as the number of houses in a group increases.
- Common range for CF: 0.3–0.6 for larger groups.
- CF graph (similar to Figure on the right) shows CF variation based on the number of houses (*n*).
- CF decreases quickly for lower n values, then saturates.
- Saturation point typically reached around *n* = 15–20.

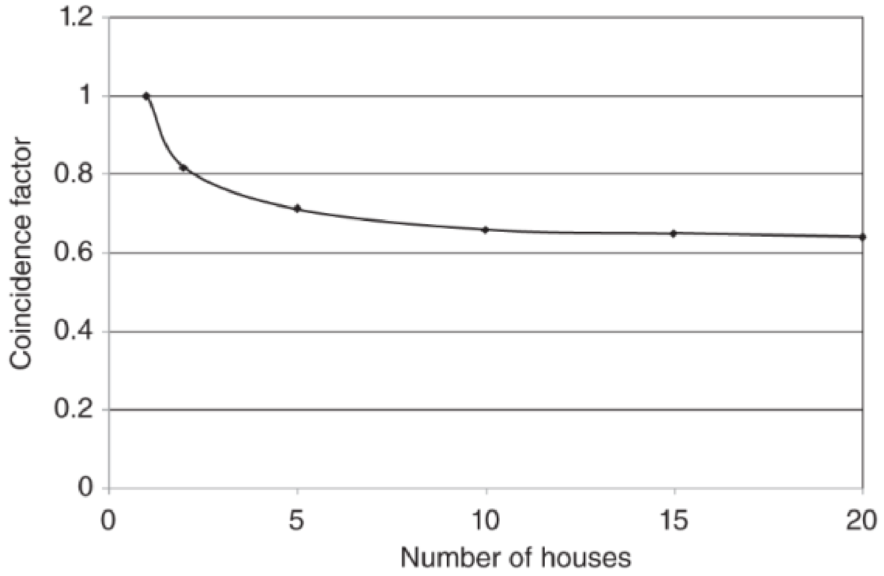


Fig. Coincidence factor as a function of number of houses.

4. Load Characteristics

4.4 Diversity and Coincidence

- The inverse of the coincidence factor is defined as the diversity factor (D).
- Diversity Factor gives an indication of the separation in individual house's peak demands in comparison to the peak demand of the group. Mathematically,

$$D = \frac{1}{C}$$

- Further, the difference between the sum of the individual peak demands and the coincident peak demand of the group is defined as LD,

$$LD = \sum_{I=1}^{n} D_{mi} - D_{mG}$$

- The concept of coincidence can also be applied to loads of different types. For example, if a feeder has to serve residential, commercial, and industrial loads with given load demand characteristics, these characteristics can be used to find the coincident peak demand. This and other factors are then used to find the size of the feeder that would be adequate to serve the combined load.

4. Load Characteristics

4.5 Demand Factor

- The ratio of the maximum load demand over a period to the connected load for any load or class of load is defined as the demand factor (DemandF).

$$DemandF = \frac{Maximum\ Load\ Demand}{Connected\ Load}$$

- Connected load: Sum of rated values of all loads in a house.
- Not all loads used simultaneously; only a portion used at once.
- Example with light bulbs: Total ratings ~2 kW, simultaneous operation ~600 W.
- Diversity Factor for lighting load: 0.3 (0.6/2 =0.3).
- Example with air conditioner: Rated 6 kW, runs 30 min on hottest day. Average hourly demand: 3 kW; Air conditioner's DemandF: 0.5 (3/6).
- DemandF applies to individual loads or a group of loads.

4. Load Characteristics

4.6 Load Duration Curve

- Load in a distribution system changes over time. Examination of hourly loads for short durations (e.g., a day) provides highest, lowest loads, their occurrence times, and load fluctuation pattern.
- For longer durations (e.g., a year), examining hourly load for each day is a tedious task.
- Load duration curve simplifies this by graphing *load vs. time* for which the load is higher than the specified value.
- We can easily obtain the two extreme ends of the load duration curve by looking at the highest and the lowest values of the load over a period of time.
- Load is never higher than the peak load (L_p), so the load > L_p for 0% of the time.
- Load is always ≥ lowest load (L_l), so the load ≥ L_l for 100% of the time.
- Intermediate points obtained by quantizing load in equal steps.
- Steps' size is crucial: Too large provides few data points; too small provides too many data points.

4. Load Characteristics

4.6 Load Duration Curve

- Load duration curve effectively summarizes load behavior over an extended period.
- For example: In figure (a), we see that L_p = 17 MW and L_l = 4 MW
- Illustration using 2 MW steps for load duration curve.
- Count hours load is higher than selected load (e.g., >10 MW for 10 h).

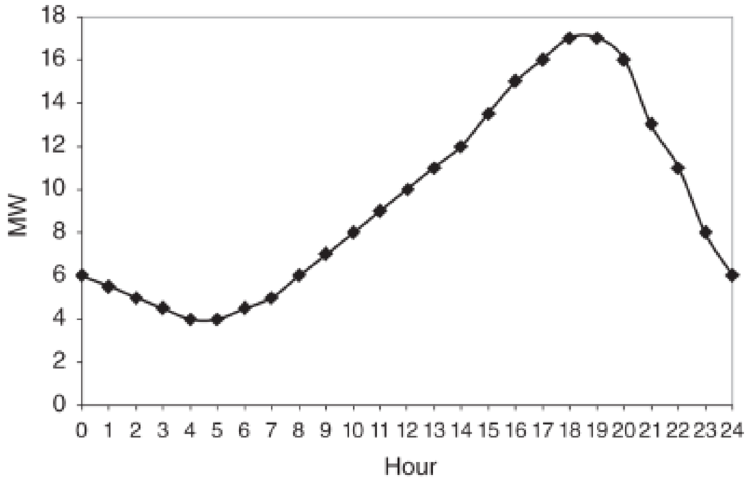


Fig. a: Hourly load at a substation.

Table: Data for load duration curve obtained from Fig. a

Load (MW)	Number of hours for which load is higher than this value	% of time for which load is higher than this value
17	0	0
16	2	8.33
14	5	20.83
12	7	29.17
10	10	41.67
8	12	50.00
6	15	62.50
4	24	100.00

4. Load Characteristics

4.6 Load Duration Curve

- From the table, we can get the load duration curve as shown in figure (b).
- Load duration curves, especially for a year are:
  - Vital for planning studies.
  - Used to plan required system equipment.
  - Used to estimate losses.
- Load duration curves provide valuable insights for effective system planning and resource allocation.

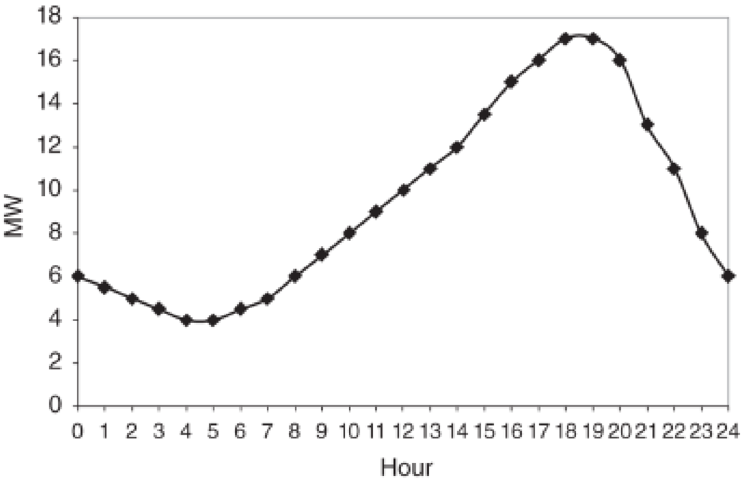


Fig. a: Hourly load at a substation.

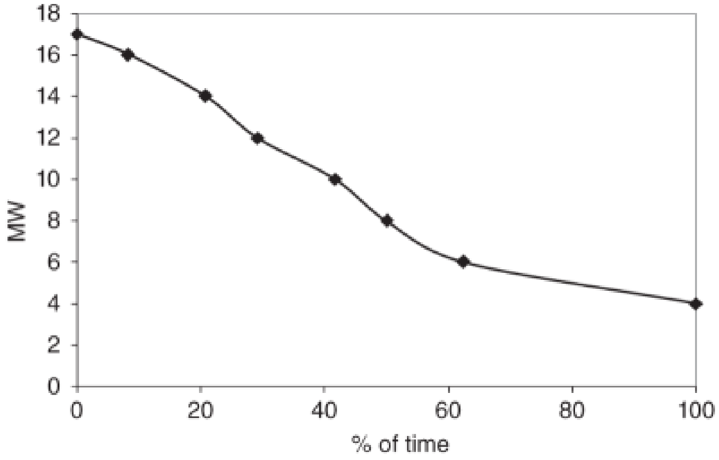


Fig. b: Load Duration Curve corresponding to the Load Characteristic.

4. Load Characteristics

4.7 Load Factor

- Load Factor: Relates load changes over a time period to the peak load.
- Measures how closely load aligns with peak load.
- High load factor: Load consistently near peak load for a significant portion of the time.
- Mathematically, it is the average load over a period of time divided by the peak load within that time duration,

$$LF = \frac{L_a}{L_p} = \frac{\frac{\sum_{i=0}^{n} L_i}{N}}{L_p}$$

where, L_i is the hourly load at hour *i*, *N* is the total number of hours in the time period under consideration, and L_i is the peak load in that time period.

4. Load Characteristics

4.8 Loss Factor

- Loss Factor (*LsF*): Ratio of average hourly losses to peak hourly losses in the system.
- Very useful for calculating total losses over a period if losses at the peak load are known.
- For load characteristics in which peak load exists for a very short duration, an approximate value for the *LsF*: can be obtained by taking the square of the load factor.
- Consider a discrete version of load duration curve as shown in Fig. a, where *Lp* is the peak load, and *L1, L2, L3* are the other load levels for specified durations. The total time duration is *T* hours.

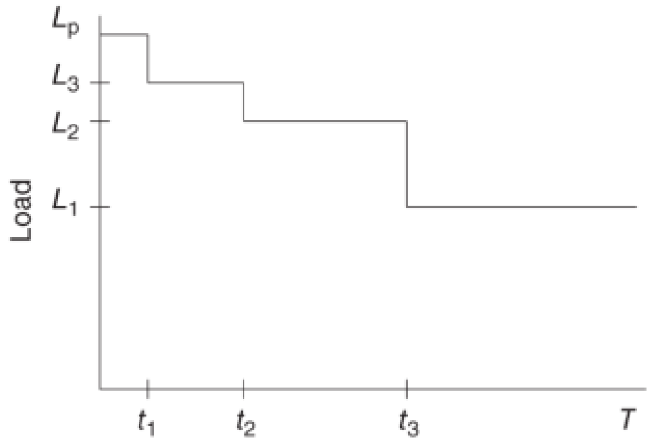


Fig. a: Discrete load duration curve

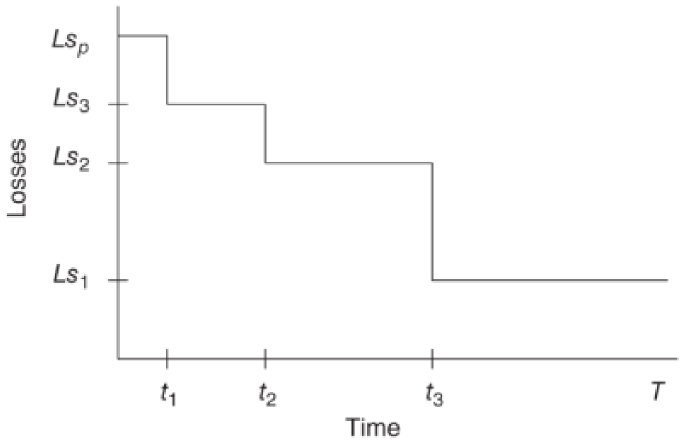


Fig. b: Discrete loss duration curve.

4. Load Characteristics

4.8 Loss Factor

- Resistive losses (predominant in distribution systems) proportional to square of current.
- Assuming fixed voltage, losses proportional to square of load.
- Loss characteristics for the same duration (Fig.b):

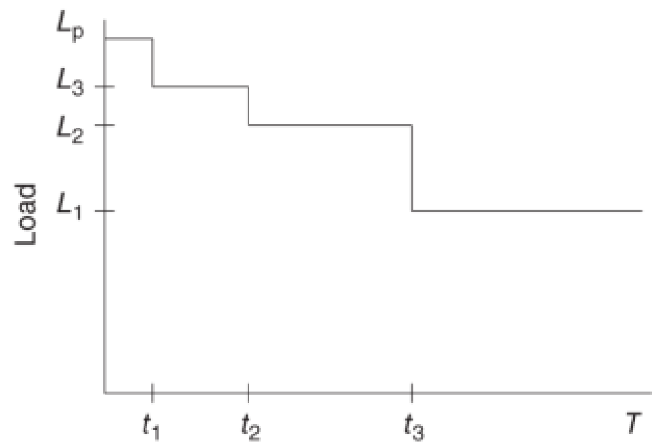


Fig. a: Discrete load duration curve

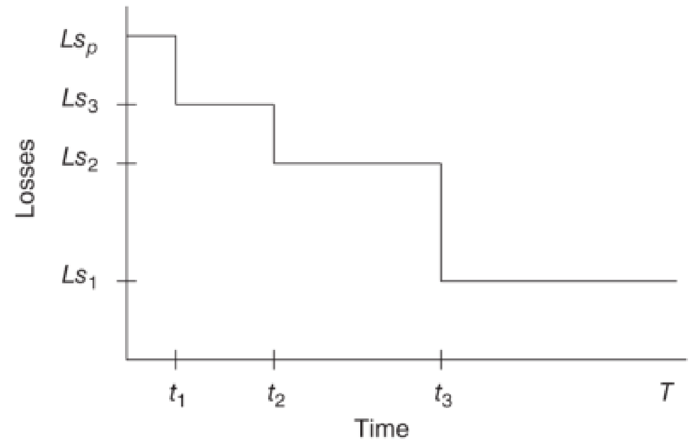


Fig. b: Discrete loss duration curve.

4. Load Characteristics

4.8 Loss Factor

- In figure b, the notations are defined as,
  - *Lsp*: Average hourly losses at peak load.
  - *Ls1, Ls2, Ls3*: Losses at other load levels.
- Loss factor and loss characteristics provide insights into distribution system losses and efficiency.
- From fig. a, we get,

$$\mathrm{LF} = \frac{L_p t_1 + L_3(t_2 - t_1) + L_2(t_3 - t_2) + L_1(T - t_3)}{T L_p}$$

- Similarly,

$$LsF = \frac{Ls_p t_1 + Ls_3(t_2 - t_1) + Ls_2(t_3 - t_2) + Ls_1(T - t_3)}{T Ls_p}$$

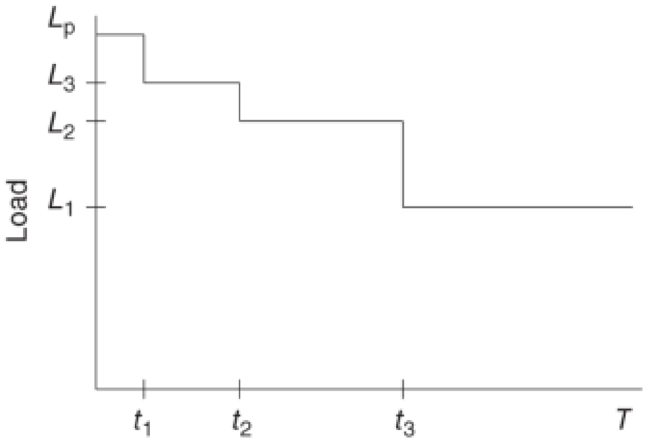


Fig. a: Discrete load duration curve

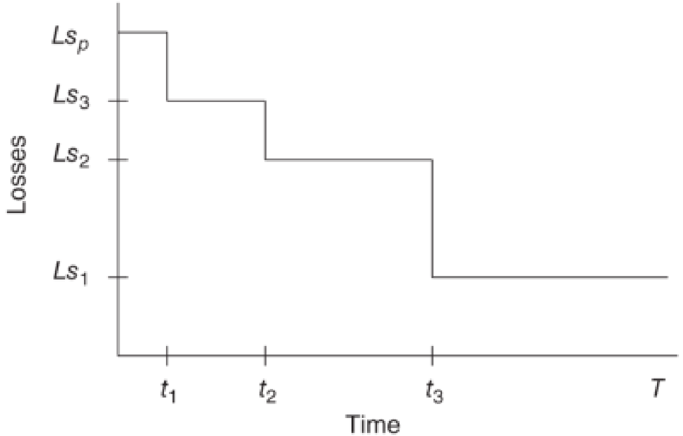


Fig. b: Discrete loss duration curve.

4. Load Characteristics

4.8 Loss Factor

- For a special case where L_1, L_2, and L_3 are equal, we get

$$\text{LF} = \frac{t_1}{T} + \frac{L_1(T - t_1)}{L_p T}$$

and

$$\text{LsF} = \frac{t_1}{T} + \frac{Ls_1(T - t_1)}{Ls_p T}$$

- Now, if we consider the peak load of a very short duration or $t_1 \ll T$,

$$\frac{t_1}{T} \rightarrow 0 \text{ and } \frac{(T - t_1)}{T} \rightarrow 1$$

- Hence,

$$\text{LF} = \frac{L_1}{Lp} \text{ and } \text{LsF} = \frac{Ls_1}{Ls_p}.$$

- With $Ls_1 = k(L_1)^2$ and $Ls_p = k\left(L_p\right)^2$, we get

$$\mathbf{LsF} = (\mathbf{LF})^2$$

4. Load Characteristics

4.8 Loss Factor

- Approximation improves as time duration (T) increases, e.g., for a year.
- Peak load usually exists for a short period (1-2 hours).
- Square relationship between *load factor* and *LsF* is an extreme simplification.
- Reality: off-peak loads vary.
- Despite simplifications, this relationship is acceptable for planning purposes.
- Other approximations are also available in literature.

5. Design Criteria and Standards

- Planning engineer's role: Minimize distribution system equipment cost, ensure design criteria and standards are met.
- Key issues in distribution system planning and design:
  - Voltage and service quality.
  - Equipment loading.
  - Safety.
- Design criteria and standards set by:
  - Equipment manufacturers.
  - Standards organizations.
  - Utilities (often more stringent).
- Equipment loading:
  - Manufacturers specify limits to prevent equipment damage.
- Safety:
  - Involves insulation, clearance between equipment.
- Voltage and service quality:
  - Directly affect customers' experience.

5.1 Voltage Standards

- ANSI C84.1 standard specifies service voltage for U.S. utilities:
  - Range A: 114–126 V (on a 120-V nominal), preferred range.
  - Range B (emergency): 110–127 V.
  - Building wiring drop allowed: 4 V.
  - Utilization voltage for customers: 110–126 V under normal operation.
- Equipment manufacturers design within ANSI range; operation outside this range shortens equipment life.
- Utilities aim to keep service voltage ≥ 120 V for a larger safety margin.
- Providing ANSI-specified voltage to customers is a challenge due to:
  - Voltage drop over conductors from substation to customers.
  - Voltage drop fluctuates with load changes.
  - Proximity to substation affects voltage drop.
- Utilities use tools like load tap changers, line regulators, capacitors to
  - Maintain service voltage within ANSI range;
  - Ensure proper system design and voltage control.

5.2 Conservation Voltage Reduction

- Lowering voltage reduces real and reactive power demand, energy consumption.
- Utilities can operate within lower ANSI range (e.g., 114 V) for energy savings.
- Utilities conducted experiments (1970s-1980s) on voltage reduction's effects.
- Some success in energy reduction, peak power control.
- Voltage control for conservation (CVR) and peak power reduction practiced by a few utilities.
- Challenges include load reduction uncertainty, voltage-related complaints.
- Recent interest grows due to:
  - National energy conservation focus.
  - Environmental concerns and carbon emission reduction efforts.
  - Positive impact on utility's "green image."
- Studies show real load-to-voltage sensitivities vary (0.4 - 2.5), average: 0.8 - 1.0.
- Reactive load-to-voltage sensitivity range: 3 - 5, average around 4.
- Energy sensitivity over 24 hours: 0.6 - 1.237.

6. Distribution System Design

6.1 Substation Design

- Distribution substation marks transition from transmission/sub-transmission to distribution.
- Power enters at 34.5 - 230 kV, reduced to 2.4 - 34.5 kV in distribution substation.
- Distribution voltage determined by load density, power delivery distance.
- Substations often positioned for uniform service area coverage, except rural settings.
- Example substation layout shown in the figure.
- Three 115-kV incoming lines connected to 115-kV bus.
- 115-kV bus normally operates as contiguous bus with 4 NC switches.
- Different configurations possible in emergencies.
- Each incoming line equipped with circuit breaker.

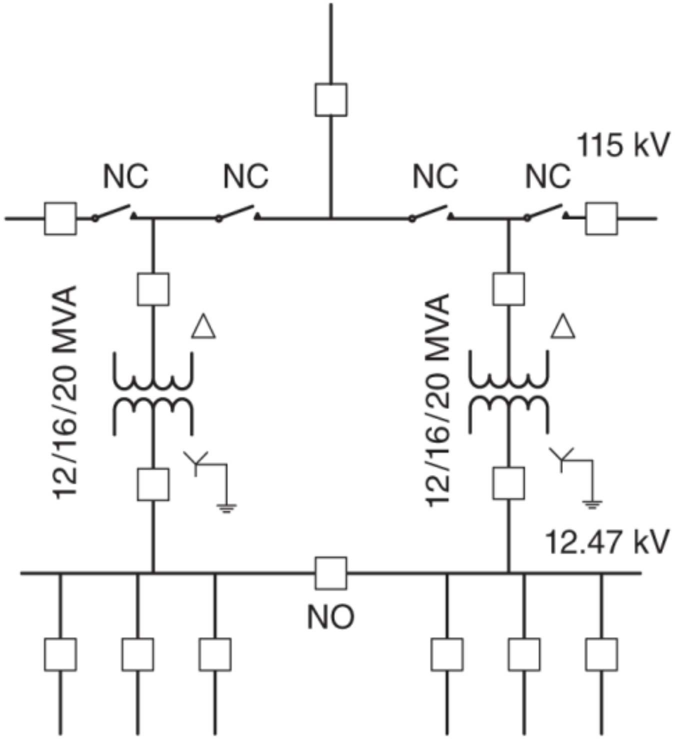


Fig: Typical Layout of a Substation
(NC, normally closed and NO, normally open)

6. Distribution System Design

6.1 Substation Design

- Various bus arrangements (main & transfer bus, ring bus, breaker-and-a-half bus schemes) for reliability enhancement. Complex arrangements more expensive, can complicate protection systems.
- Distribution substations can have 1 to 3 transformers.
- Example substation (Figure) has two 12/16/20 MVA transformers, 115kV-Δ/12.47kV-Y-grounded.
- Equal capacity transformers preferred based on substation's total load.
- Tie breaker on 12.47 kV bus normally open to avoid parallel operation of transformers.
- Transformers loaded to 50% of highest rating during peak load for redundancy.
- If 3 transformers, loaded to 67% for load sharing on failure.

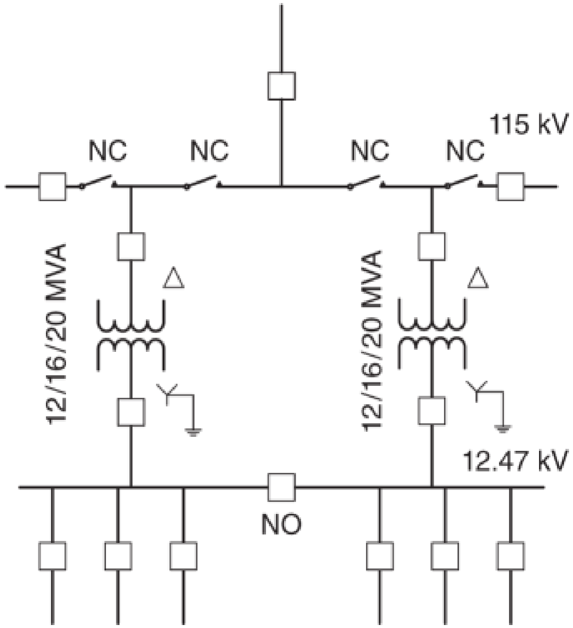


Fig: Typical Layout of a Substation
(NC, normally closed and NO, normally open)

6. Distribution System Design

6.1 Substation Design

- Multiple transformers enhance loading and reliability.
- Automation and switch operation enable load transfer during failures.
- Distribution substation transformers usually have Δ/Y configuration to provide neutral on the low-voltage side for distribution of single-phase power to customers using one of the phases and the neural.
- The rule of keeping Y-connection on the high-voltage side of the Δ/Y transformers is overruled in this case to make the neutral available on the low-voltage side.

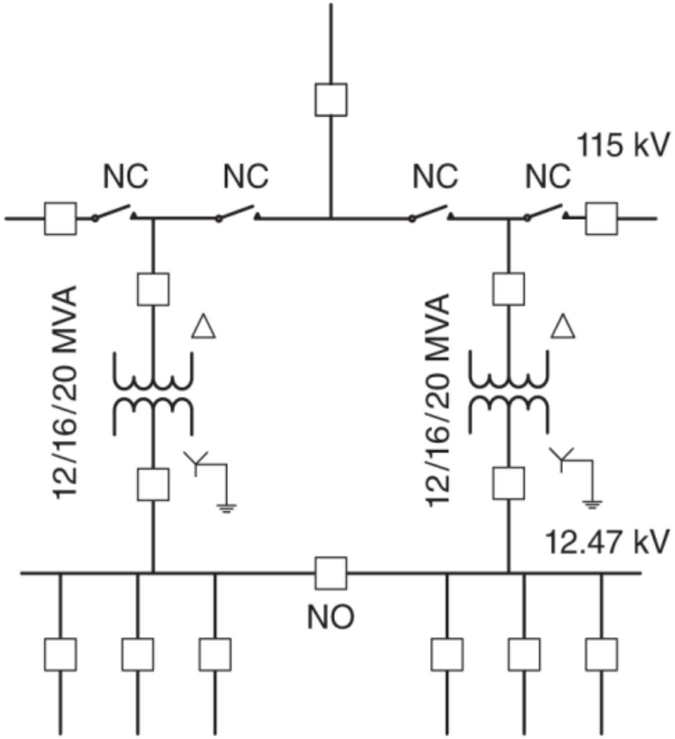


Fig: Typical Layout of a Substation
(NC, normally closed and NO, normally open)

6. Distribution System Design

6.1 Substation Design

- 12.47 kV bus on low-voltage side split into two segments with NO switch.
- Each segment has 1 to 4 feeders based on load and transformer capacity.
- Typical feeder designed for 4-8 MVA.
- Example substation (Figure) has three feeders per transformer, a total of six feeders.

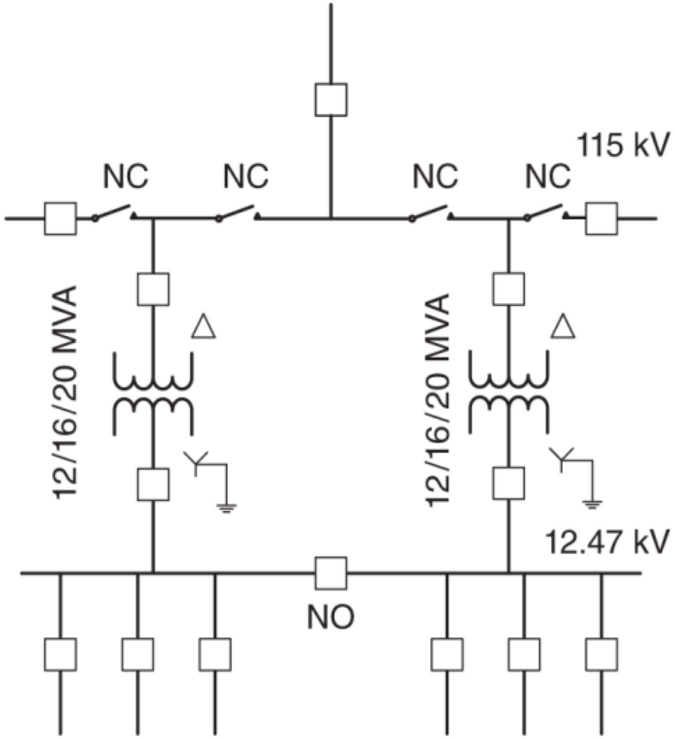
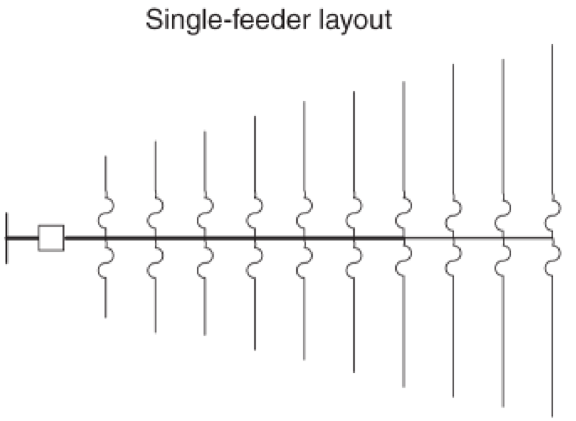


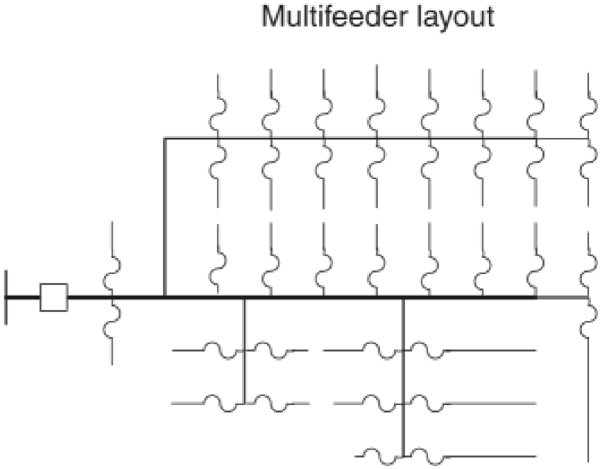
Fig: Typical Layout of a Substation
(NC, normally closed and NO, normally open)

6. Distribution System Design

6.2 Design of Primary Feeders

- Primary feeders are crucial for distributing power from substations to customers.
- Distribution systems typically have a radial structure, except in densely populated areas.
- Radial structures have power flowing in one direction, aiding simplicity.
- Radial systems are cost-effective, easier to operate, and simpler to protect.
- Distribution systems mainly use radial configuration with tree-like feeder arrangement.
- Substation is the root of the feeder tree, with main three-phase primary feeder or trunk.
- Primary feeder may split into sub-feeders or rema as one throughout service area.
- Single and multi-feeder layouts are depicted in Figures on the right, respectively.





6. Distribution System Design

6.2 Design of Primary Feeders

- Load on primary feeders decreases as distance from substation increases.
- Conductor sizes for primary feeders can be tapered based on radial load distribution.
- Primary main feeders in distribution systems often have a N.O. (Normally Open) switch or circuit breaker called the tie switch at their ends.
- Tie switches are closed during permanent faults to restore power to some customers on faulted feeders.
- The feeder on the other side of the tie switch could be connected to the same transformer, or to a different transformer from the same substation, or to a transformer from a different substation, each of them provides a different level of reliability and has different costs.
- Feeding arrangements impact backup possibilities in case of transformer or feeder failures.
- Primary lateral feeders are single-phase, phase and neutral conductors branching off primary mains.

6. Distribution System Design

6.2 Design of Primary Feeders

- Connected to the primary main feeders are the primary lateral feeders, which are usually single phase, with phase and neutral conductors.
- Primary lateral feeders carry power from primary mains to customers.
- Primary main feeders are commonly along city streets, but the lateral feeders are mostly in the utility easement behind houses in residential subdivisions.
- Phase selection for lateral feeders maintains rough balance among the three phases.
- Figure on the right illustrates feeders and streets in a typical US city.

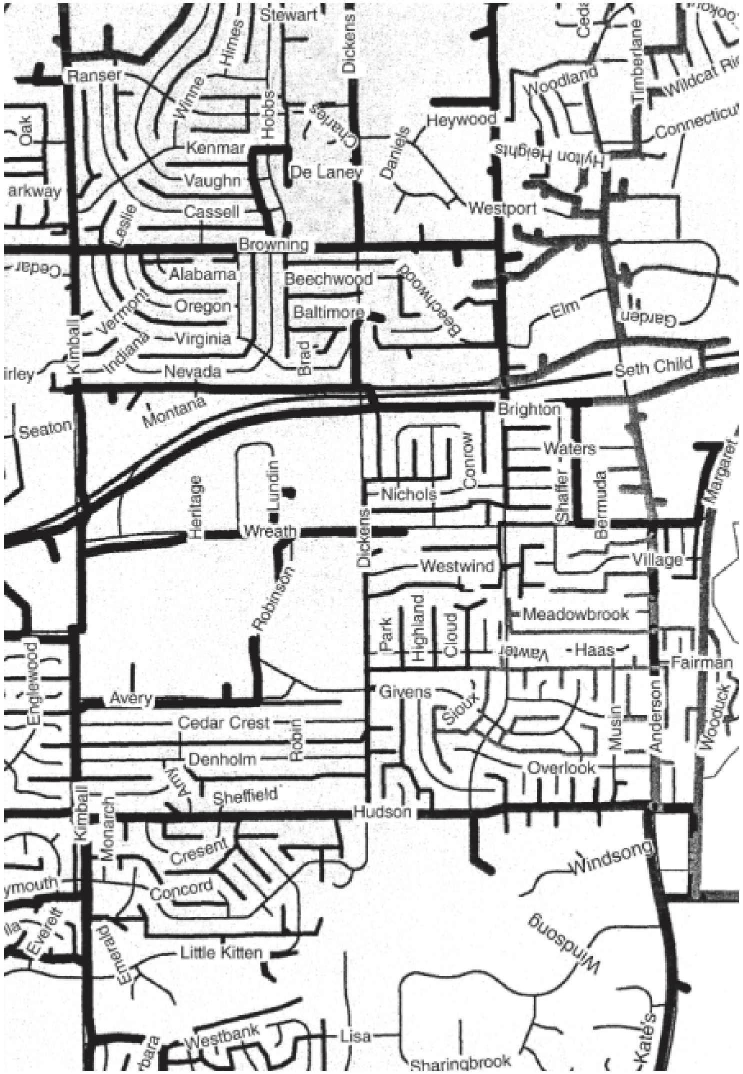


Fig. Feeders along with the roads in a typical distribution system in the United States.

6. Distribution System Design

6.3 Design of Secondary Systems

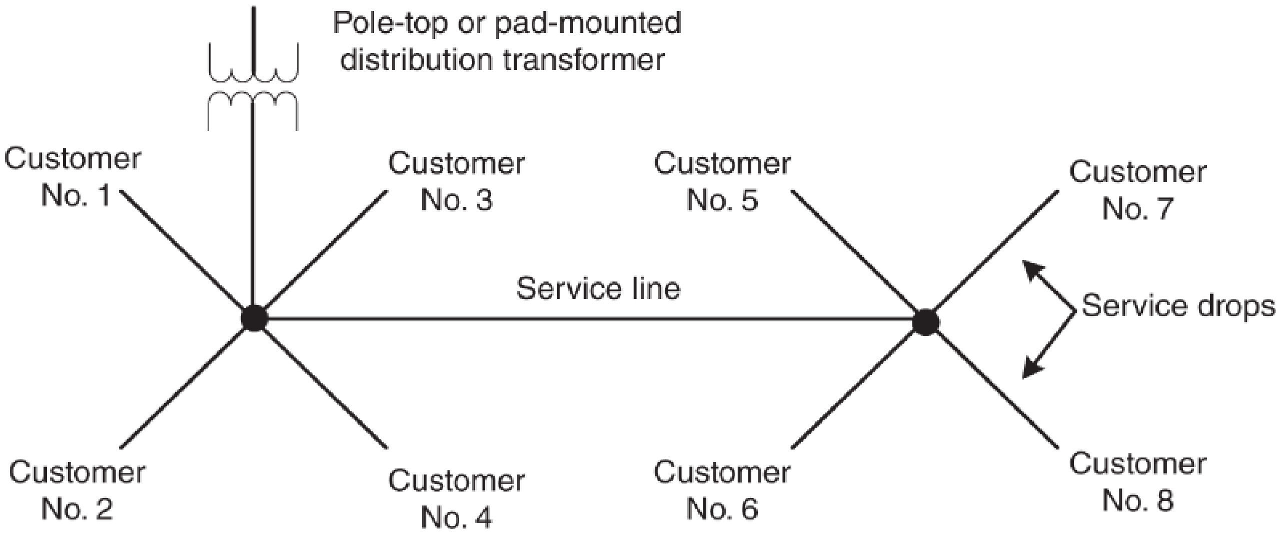


Fig. Illustration of a secondary system for service to eight customers.

- The secondary system is the part of the distribution system closest to customers.
- Components of the secondary system include distribution transformers, secondary feeders, and service drops.
- Secondary system is single-phase for residential customers and three-phase for large industrial and commercial customers.

6. Distribution System Design

6.3 Design of Secondary Systems

- Distribution transformers are small (5 to 100 kVA) with 120 V/240 V secondary.
- Transformer size at a location depends on the number and class of customers it serves.
- Transformers typically serve four to eight medium-sized single-family homes.
- If homes are very large, a transformer may serve only one or two homes.
- A single transformer may serve several apartments in a complex.

6. Distribution System Design

6.4 Underground Distribution Systems

- Overhead distribution systems are predominant worldwide due to lower cost compared to underground systems.
- Underground systems are 5–10 times more expensive than overhead systems.
- Densely populated areas and business districts often use underground systems despite the higher cost.
- Some cities require underground systems in new housing developments for aesthetic reasons.
- Developers may choose underground distribution in high-cost subdivisions even without mandates. In some cases, underground systems have underground laterals and secondary systems, but the primary main remains overhead.
- Overhead distribution systems are more vulnerable to failure due to exposure to the environment.
- Overhead systems offer the advantage of easier fault location and repairs.
- Underground systems have fewer faults, but locating and repairing faults is challenging and time-consuming.

6. Distribution System Design

6.5 Rural vs. Urban Systems

- Distribution systems can be categorized into urban, semi-urban, and rural based on load density.
- Urban systems have high load density, smaller substation spacing, larger transformers, and bigger feeders.
- Urban systems are mostly thermally limited. The total load that a substation can supply is based on the thermal loading capacity of transformers and feeders. Voltage drop is usually not a problem.
- Rural systems have low load density, larger substation spacing, smaller transformers, and smaller feeders.
- Semi-urban systems fall between urban and rural systems in terms of characteristics.
- Urban systems often have multiple power transformers and sufficient NO tie points, leading to higher reliability.
- Rural systems are usually voltage drop-limited due to long feeder lengths.
- Semi-urban systems may experience a combination of thermal and voltage drop limitations based on design choices.

7. Cold Load Pickup (CLPU)

7.1 CLPU Fundamentals

- Categories of Residential Feeder Loads:
    - Thermostatically controlled devices (e.g., air conditioners, heaters, refrigerators).
    - Manually controlled loads (operated by occupants based on needs).
- Contribution of Thermostatically Controlled Devices:
    - Largest share of total load in typical houses.
    - Contribution depends occupants' lifestyle.
- Diversity Among Loads in Groups of Houses:
    - Aggregate load lower than connected load under normal conditions.
    - Impact of extended interruption: Immediate activation of thermostatically controlled devices upon power restoration.
    - Higher post-restoration load from manually controlled devices due to user demand.
- Cold Load Pickup (CLPU) Phenomenon:
    - Experienced after extended power interruption.

7. Cold Load Pickup (CLPU)

7.1 CLPU Fundamentals

  - Four phases: inrush, motor starting, motor running, and enduring.
  - First three phases <15 s, current may reach 5–15 times of pre-outage current.
  - Enduring phase until normal load diversity is restored, lasting hours.
  - Influenced by outage time, temperature, device type, and ratings.
- Historical Context of CLPU:
  - Originated in 1940s due to high inrush currents hindering reenergization.
  - Solutions include inverse characteristic relays and distribution system sectionalization.
- Increasing Presence of Thermostatically Controlled Devices:
  - Growing penetration in distribution systems.
  - CLPU restoration issues preceding serious overloading problems.
- Significance of Sustained Load After Restoration:
  - Important consideration for loading limitations of distribution equipment.

7. Cold Load Pickup (CLPU)

7.2 CLPU Models

- Main idea: develop a physically-based load model for individual loads. Then use aggregation of these loads to find the total demand.
- Aggregated load behavior can be determined based on these models using numerical techniques by solving partial differential equations or by Monte Carlo simulation.
- An example after restoration around midnight during winter is given. The load prior to interruption was 749 kW.
    - The load in the first 15-min period is 1451 kW, around two times the load prior to interruption.
    - The load returns to normal in the third interval.
- Simulations and experimental data suggest that aggregate load in distribution system during CLPU can be represented by a delayed exponential model.

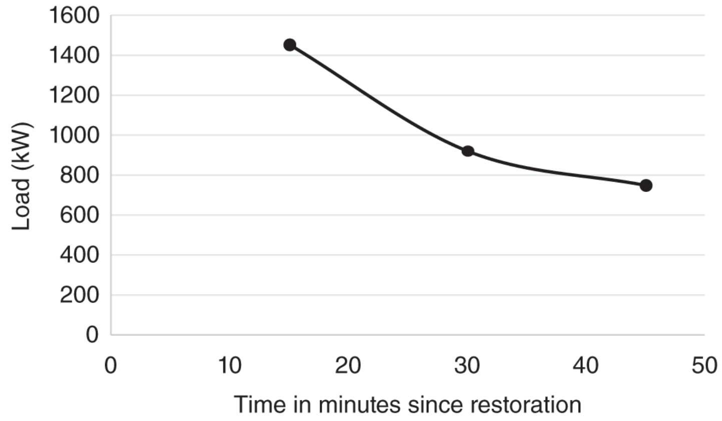


Fig. Load upon restoration following a long outage. The dots show the average load for 15 min prior to that time.

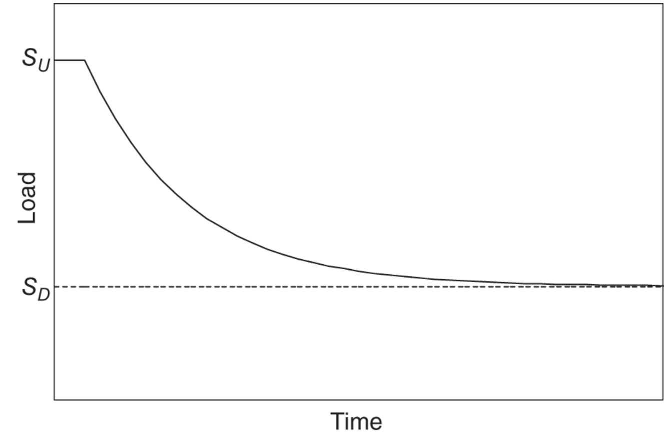


Fig. Delayed exponential model for cold load pickup. S_U is the undiversified load and S_D is the diversified load.

7. Cold Load Pickup (CLPU)

7.3 Impacts of CLPU

- Impact on Operation and Design:
  - CLPU affects operation and design of distribution systems.
  - Impacts vary based on system type.
- Overloading and Excessive Voltage Drops:
  - CLPU leads to higher load than normal.
  - Overloading of transformers and conductors.
  - Excessive voltage drops on feeders.
  - Urban systems: Overloading of transformers is critical.
  - Rural systems: Excessive voltage drops are critical.
- Step-wise Restoration Approach:
  - Full load restoration may not be possible in one step.
  - Remote sectionalizing switches on main feeder for system division.
  - Sections restored incrementally.

7. Cold Load Pickup (CLPU)

7.3 Impacts of CLPU

- Load Behavior and Restoration Sequence:
  - Load dynamics of sections are crucial.
  - Restoration sequence impacts procedure.
  - Objectives: Meeting restoration goals, limiting transformer and feeder loading, preventing voltage-drop violations.
- Restoration Objectives:
  - Minimize customer interruption duration.
  - Directly enhance system reliability.
  - Shorter interruptions lead to higher system reliability.

7. Cold Load Pickup (CLPU)

7.4 Operating Limits

ANSI/IEEE PC57.91-1994 Standard:

- Transformer Load and Loss of Life:
  - Transformer load can exceed rated load in emergencies.
  - Transformer loss of life should not exceed 4%.
- Temperature Limits for Transformer:
  - Maximum top-oil temperature: 110 °C.
  - Maximum hottest spot winding temperature: 180 °C.
  - Maximum short time loading: Up to two times the maximum normal rating.
- Short Time Emergency Loading of Conductors:
- 133% of normal full load. Voltage Limits and Voltage Drop:
  - Supply voltage to customers within ANSI C84.1 limits.
  - Voltage drop breakdown:
    - ❑ Lateral under normal operation: ~2.5%.
    - ❑ Lateral under emergency operation: 3.54%.

7. Cold Load Pickup (CLPU)

7.4 Operating Limits

ANSI/IEEE PC57.91-1994 Standard:

- Total Permissible Voltage Drop:
  - Upper end of zone at substation.
  - Main feeders:
    - Normal operation: Up to 7.5%.
    - Emergencies: Up to 10.62%.
- Voltage Drop Limit During CLPU Restoration:
  - Voltage drop should not exceed 10.62%.

8. Asset Management

- **Asset Management Overview:**
  - Optimal utilization of assets in planning and operation.
  - Balancing decisions for replacement and updating of equipment.
  - Considering age and current operating status.
  - Accounting for risk associated with actions.
- **Planning Phase:**
  - Decisions on equipment replacement or updates.
  - Balancing timing to avoid disastrous consequences.
  - Considering risk and cost-effectiveness.
- **Operation Phase:**
  - Real-time decisions on equipment loading.
  - Considering equipment conditions and status.
  - Balancing risk of overloading and curtailed service.

8. Asset Management

- **Balancing Risk and Service:**
  - Preventing equipment failure from sustained overloading.
  - Ensuring uninterrupted service to customers.
  - Risk assessment and mitigation.
- **Challenges with Aging Infrastructure:**
  - Existing distribution and transmission infrastructure is old.
  - Some equipment exceeds 40 years in age.
  - Complete replacement is cost-prohibitive.
  - A planned replacement strategy is required.

Thank You!