Power Delivery Systems Tutorial

University of California, Berkeley
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Sonoma State University

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Questions about power systems in general

Power distribution systems

Human factors and other complexities associated with technological innovation, especially human factors

Questions about power systems

How to visualize the grid?
Why are grids large and interconnected?
Why transmit power at high voltages?
Why use alternating current?
Why use three phases?
What is reactive power?
How to predict power flow?
How to balance supply and demand?
How to assess performance?

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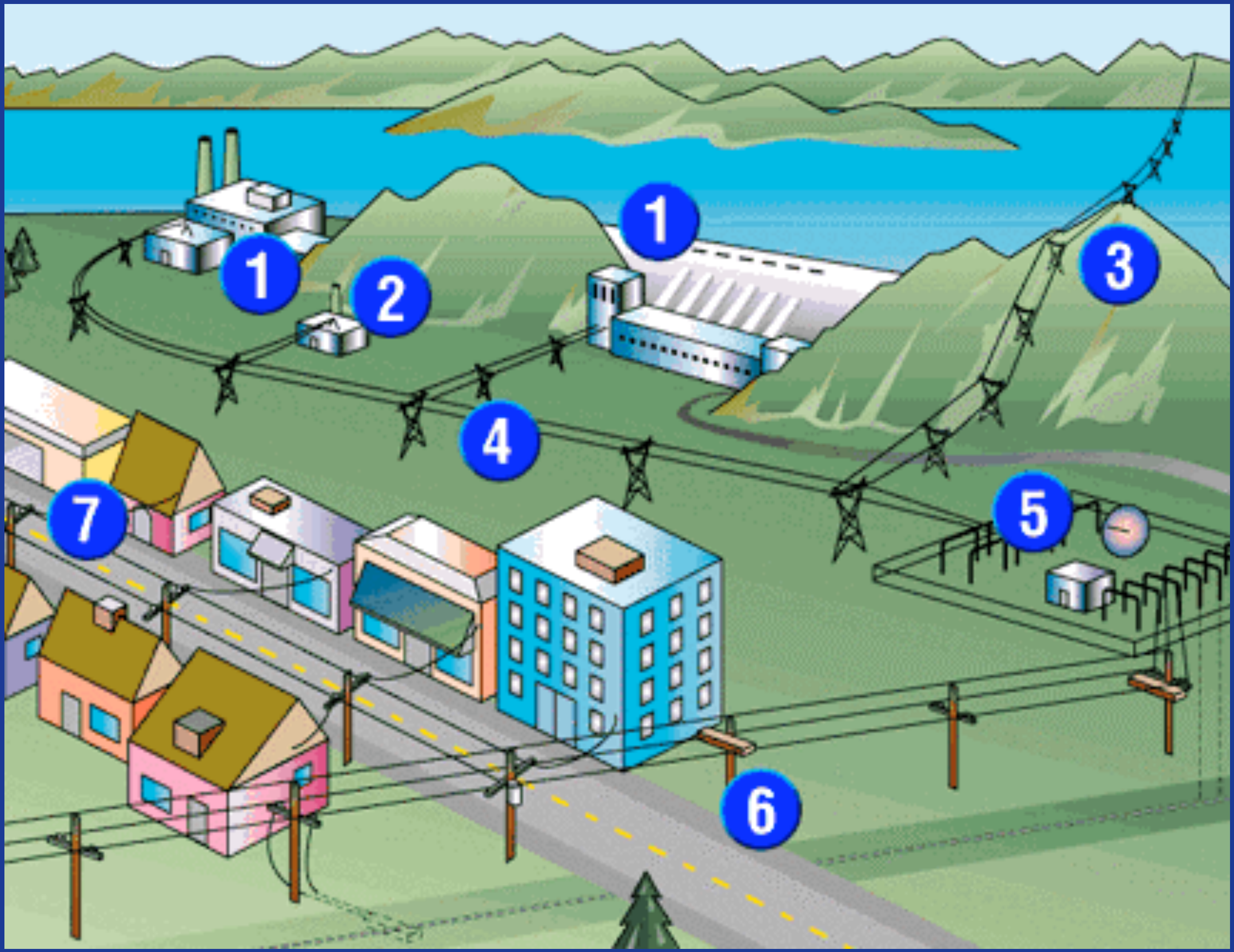


Rendition of a power system from PG&E's website

www.pge.com

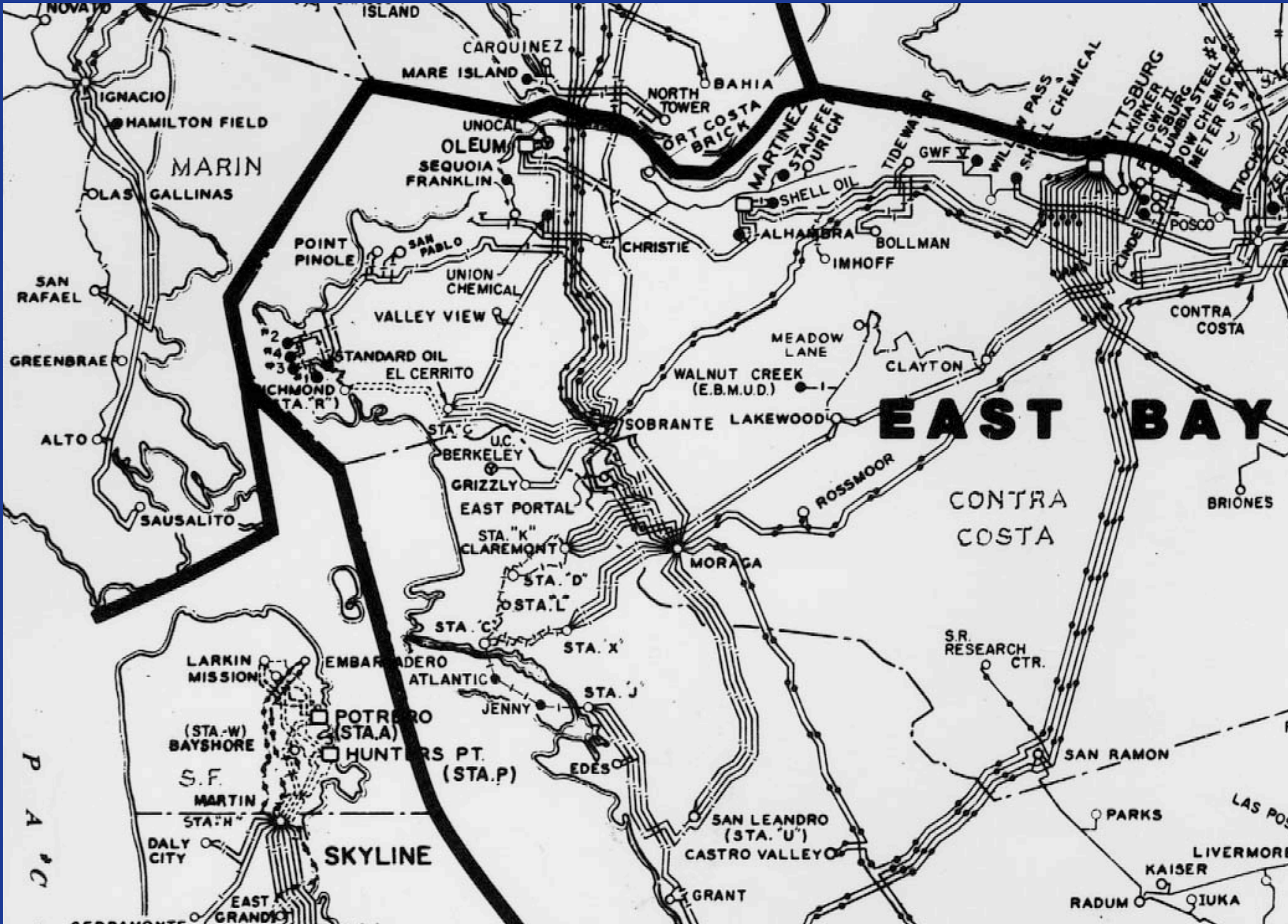
My PG&E service entrance


PG&E
Cotati
Substation

Transmission lines (230 kV)

Busbars, transformers and circuit breakers at Cotati substation

Lakeville Transmission Substation



NOVATO
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CARQUINEZ
MARE ISLAND
NORTH TOWER
BAHIA
IGNACIO
HAMILTON FIELD
MARIN
UNOCAL
OLEUM
SEQUOIA
FRANKLIN
LAS GALLINAS
MARTINEZ
SHELL OIL
GWF V
ALHAMBRA
BOLLMAN
IMHOFF
CHRISTIE
POINT PINOLE
SAN PABLO
UNION CHEMICAL
SAN RAFAEL
VALLEY VIEW
STANDARD OIL
EL CERRITO
GREENBRAE
MEADOW LANE
WALNUT CREEK (E.B.M.U.D.)
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EAST BAY
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U.C. BERKELEY
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EAST PORTAL
ROSSMOOR
CONTRA COSTA
BRIONES
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IUKA
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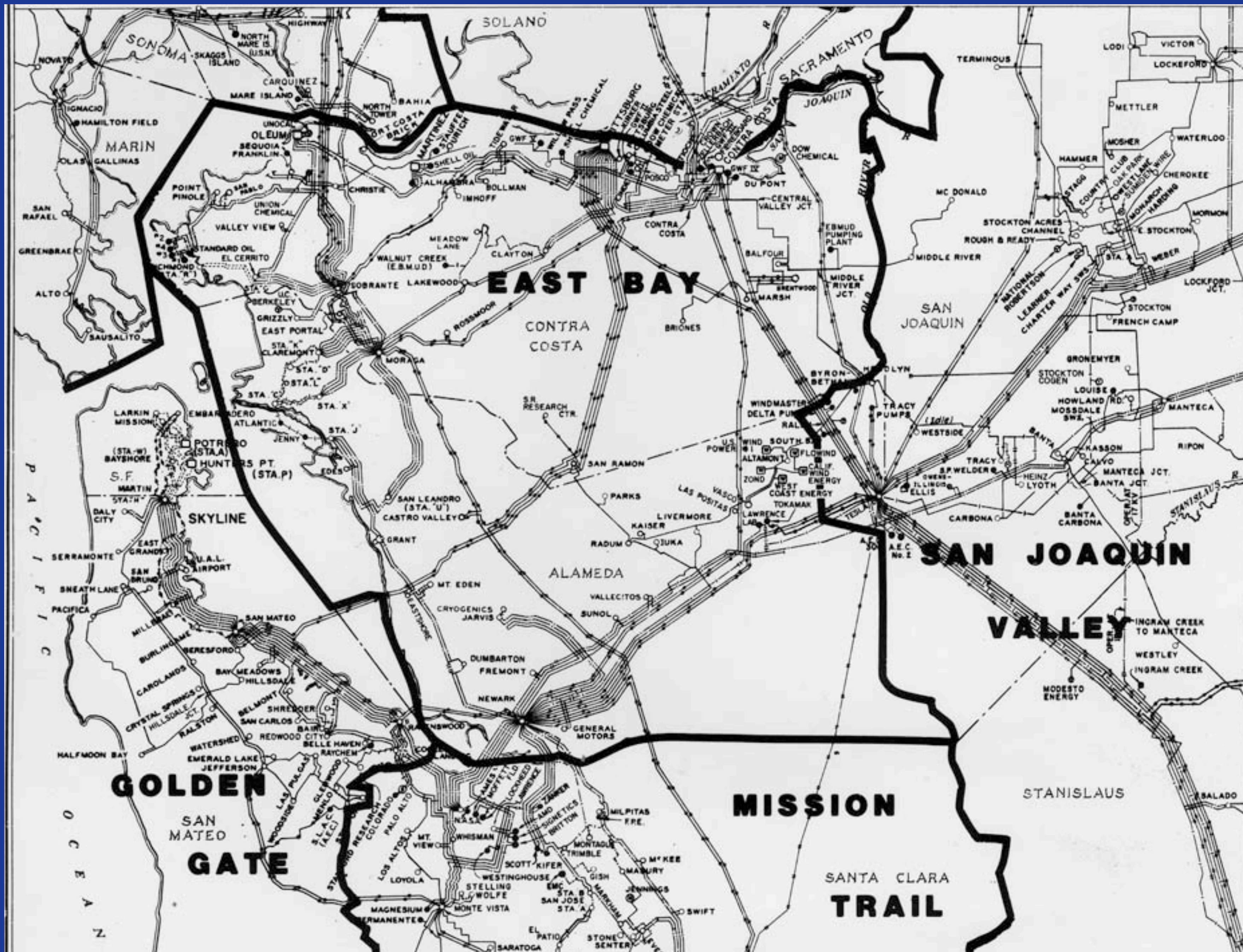
POSCO
PITTSBURG



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TERMINOUS
LODI
VICTOR
LOCKEFORD
METTLER
MOSHER
WATERLOO
HAMMER
CHEROKEE
MORMON
E. STOCKTON
STOCKTON ACRES
CHANNEL
ROUGH & READY
WEBER
LOCKFORD JCT.
STOCKTON
FRENCH CAMP
GRONEMYER
STOCKTON COGEN
LOUISE
HOWLAND RD.
MOSSDALE
MANTECA
RIPON
KASSON
CALVO
MANTECA JCT.
BANTA JCT.
BANTA CARBONA
CARBONA
TRACY
WESTSIDE
TRACY PUMPS
ELLIS
BYRON-BETHANY
WINDMASTER
DELTA PUMPS
U.S. WIND POWER
ALTAMONT
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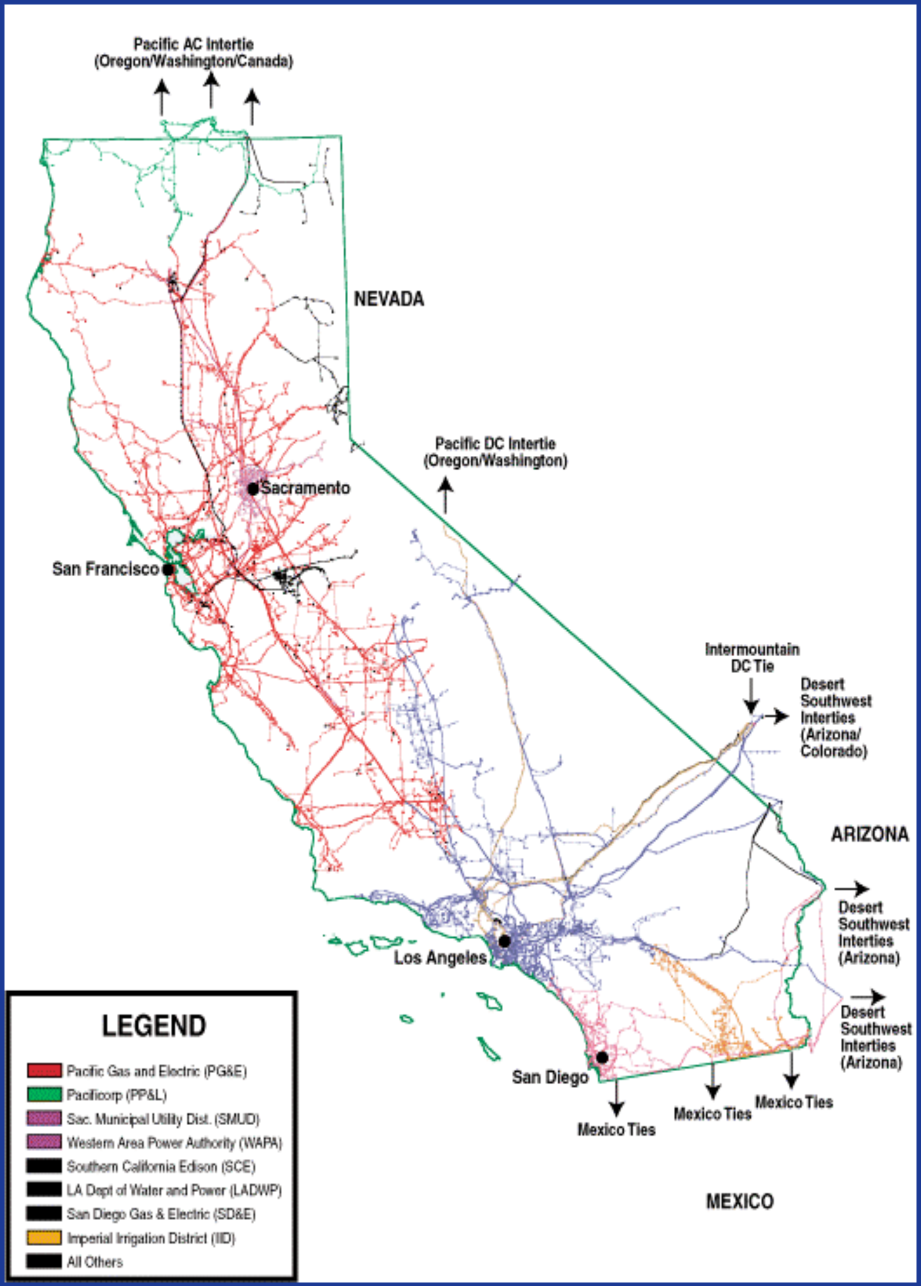
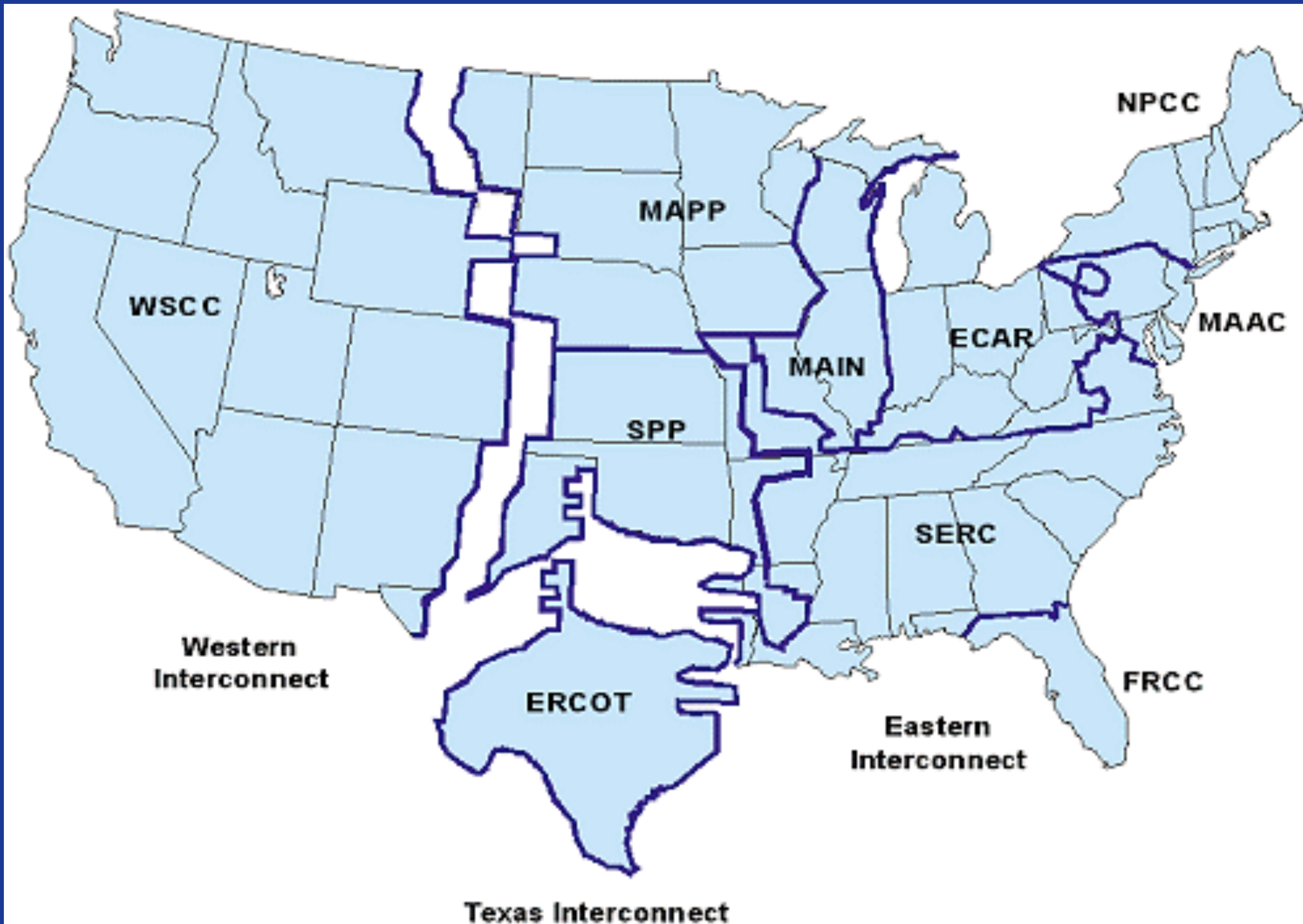
LOS ALTOS
MT. VIEW
WHISMAN
N.A.S.A.
LOYOLA
SCOTT
KIFER
MONTAGUE
TRIMBLE
MC KEE
MABURY
GISH
JENNINGS
WESTINGHOUSE
STELLING
WOLFE
MONTE VISTA
SAN JOSE STA. A
STA. B
MAGNESIUM
PERMANENTE
SARATOGA
EL PATIO
STONE
SENTER
SWIFT
INGRAM CREEK TO MANTECA
WESTLEY
INGRAM CREEK
MODESTO ENERGY
SALADO

California's electric transmission system by utility

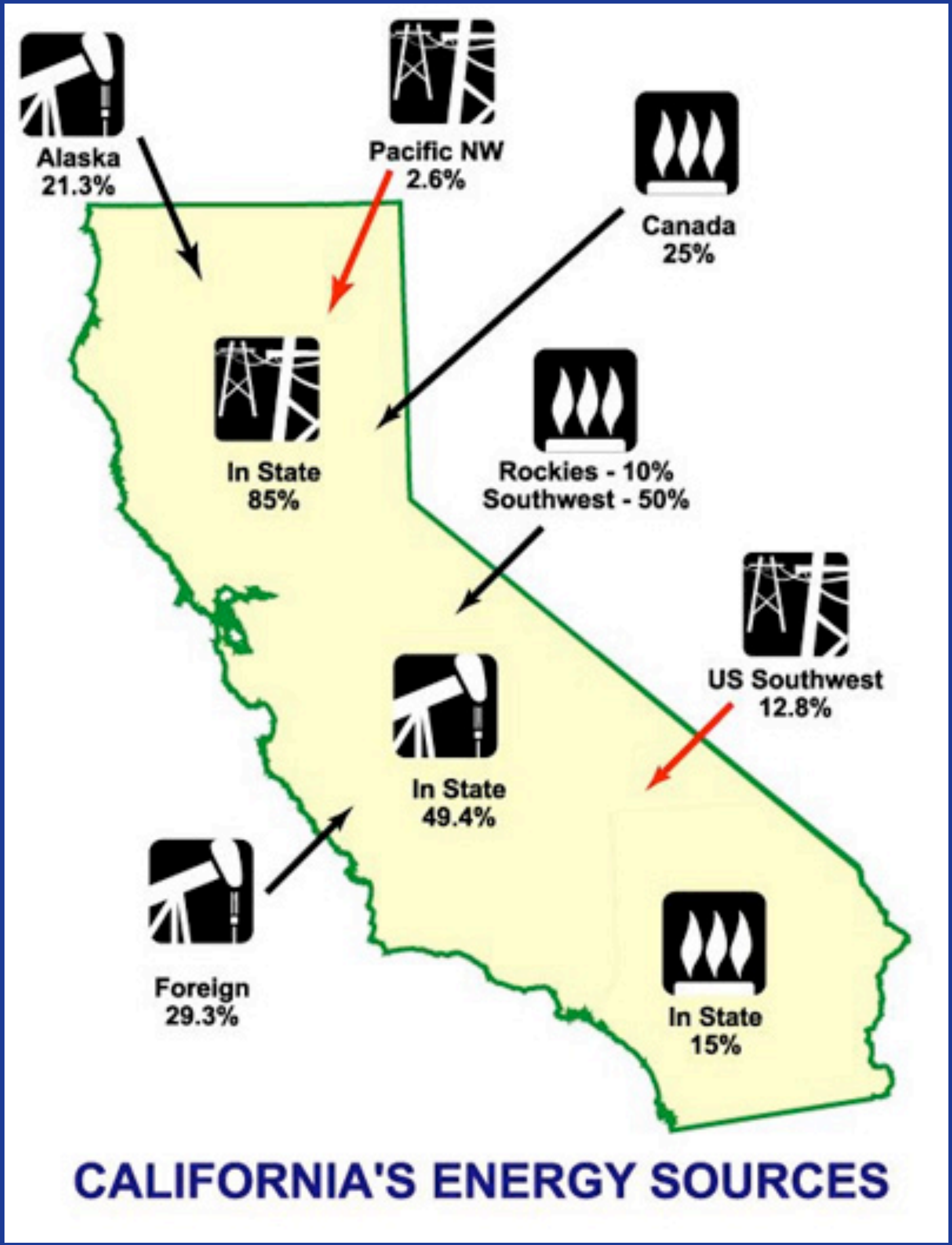
www.energy.ca.gov



Path 15 (500 kV line): California's Backbone



California within the synchronous a.c. grid of the Western Systems Coordinating Council (WSCC)



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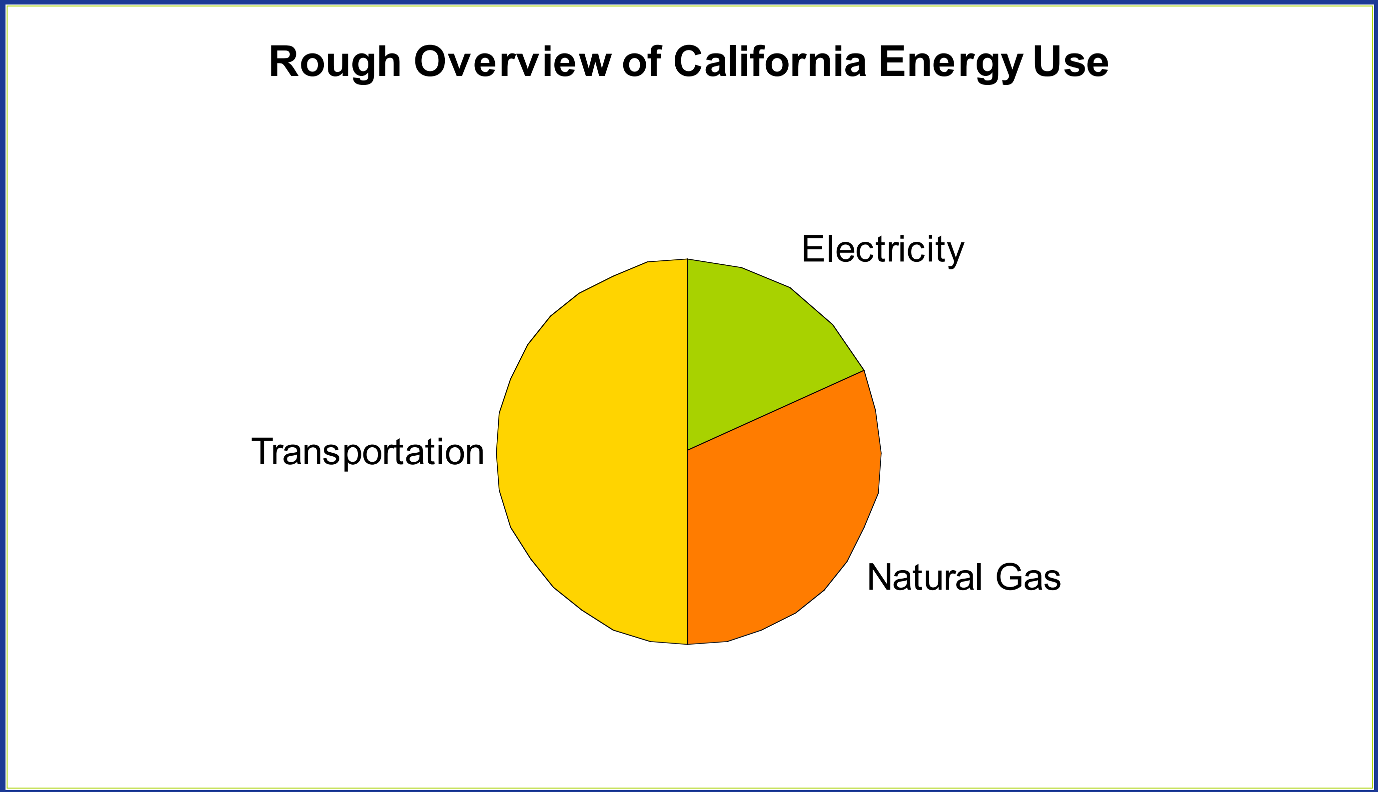

CA Electricity Consumption: 288 billion kWh in 2005

Source: California Energy Commission

www.energy.ca.gov

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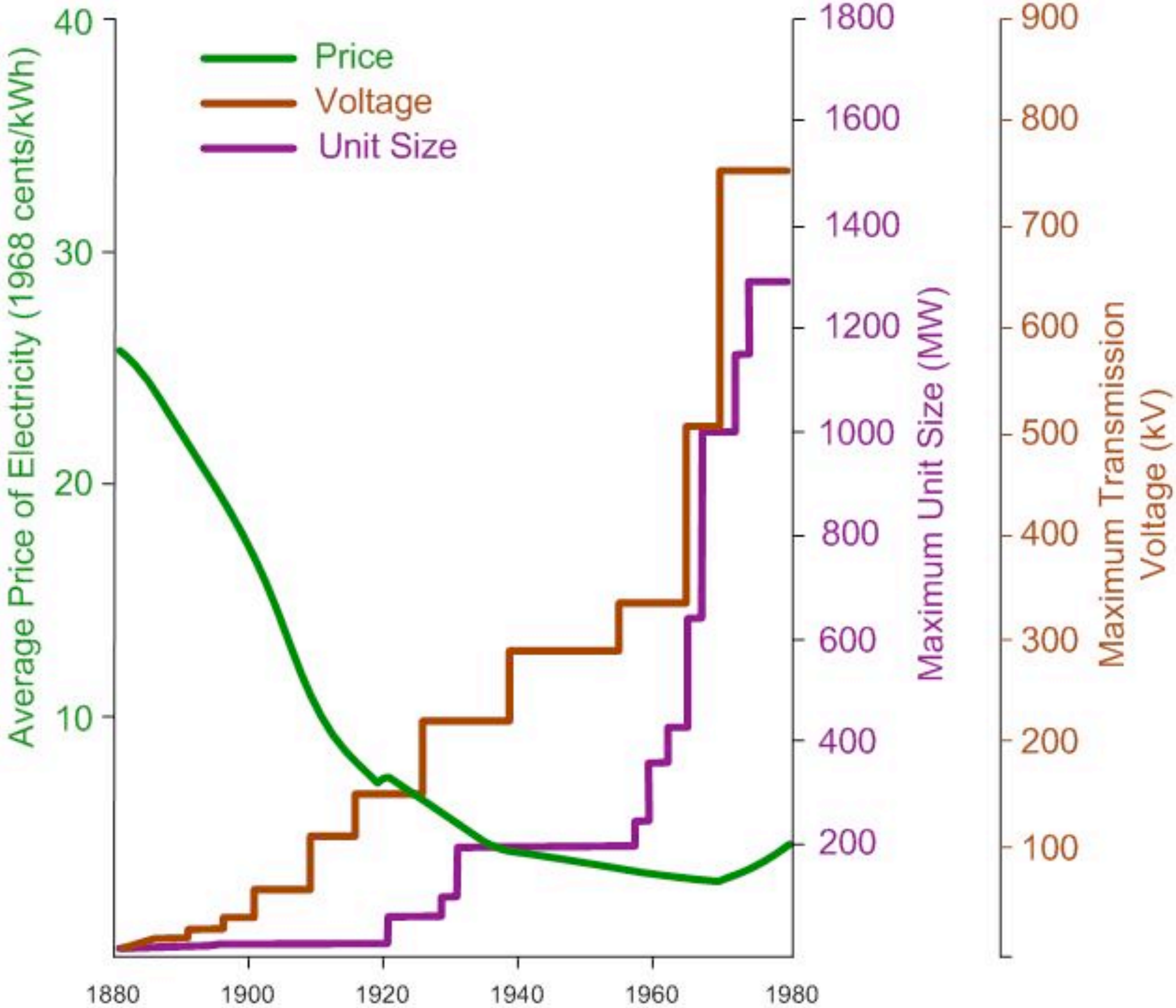
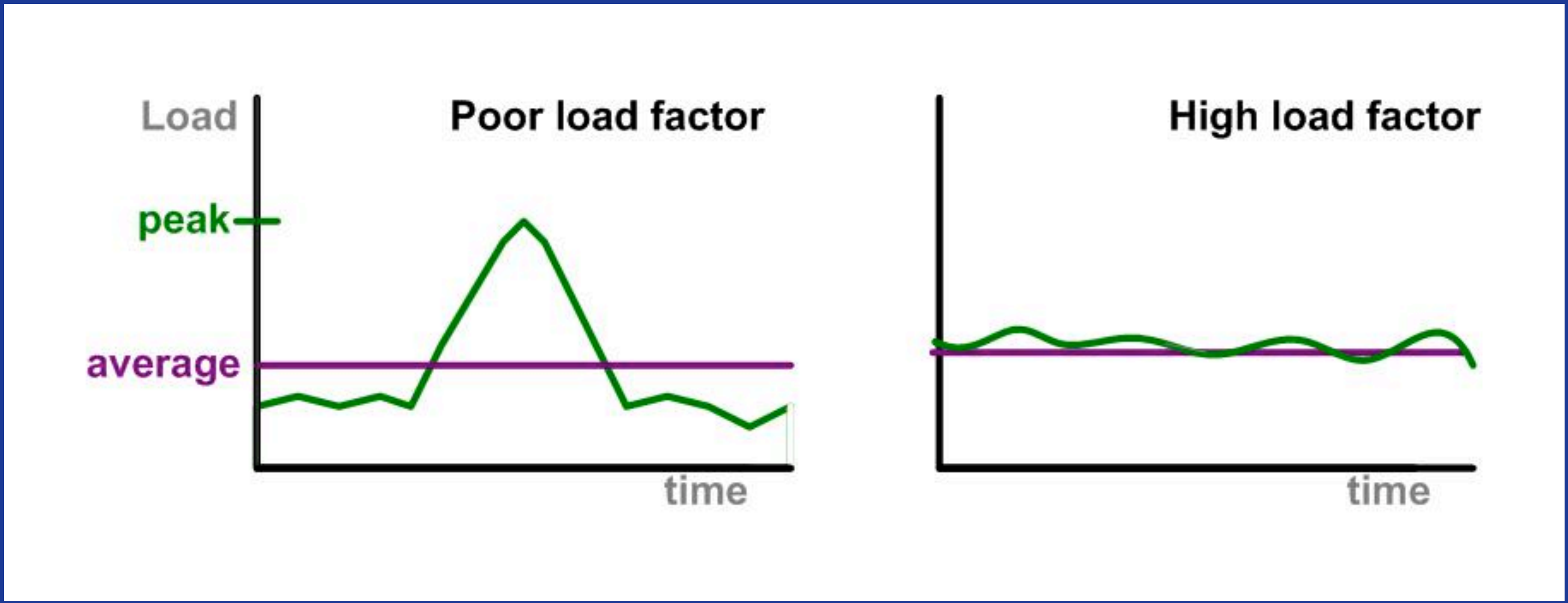
Why are grids large and interconnected?

- Economies of scale
- Load factor
- Pooled resources

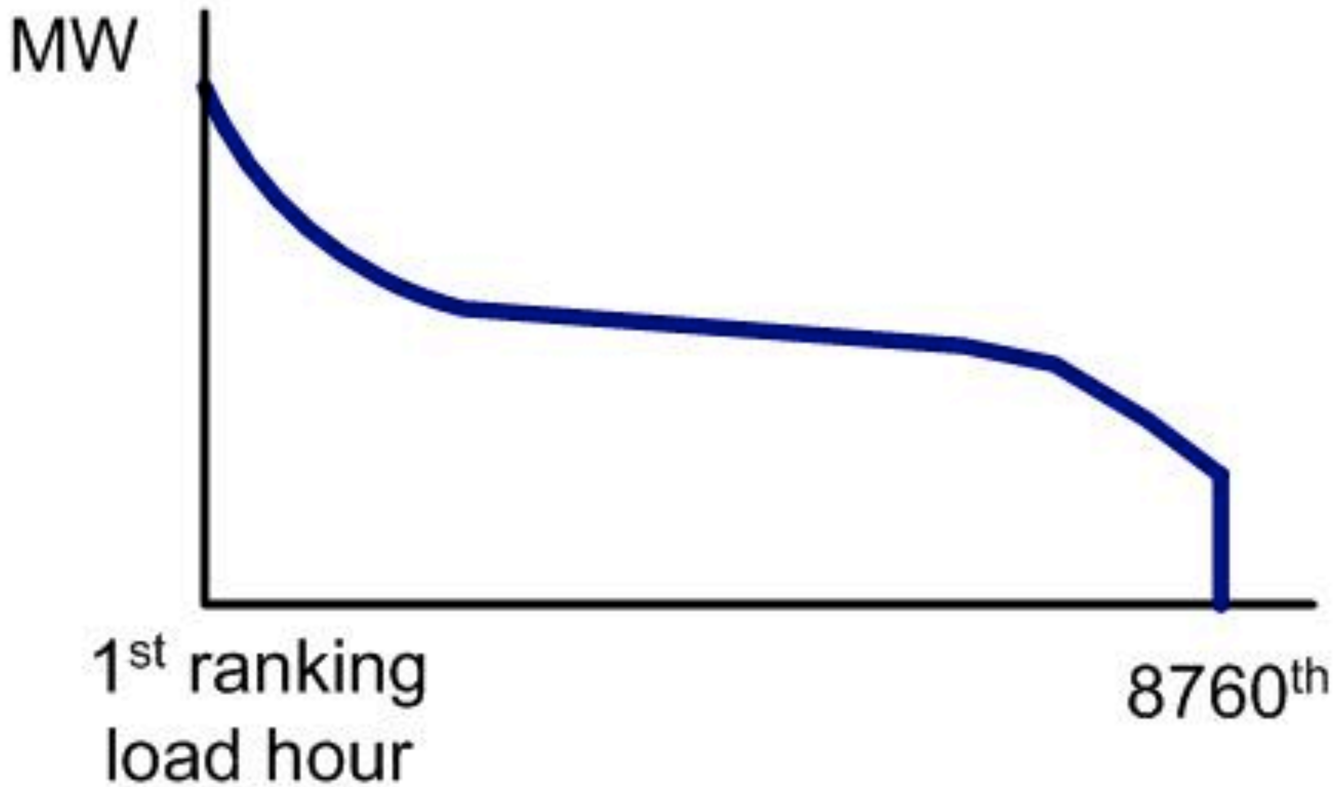


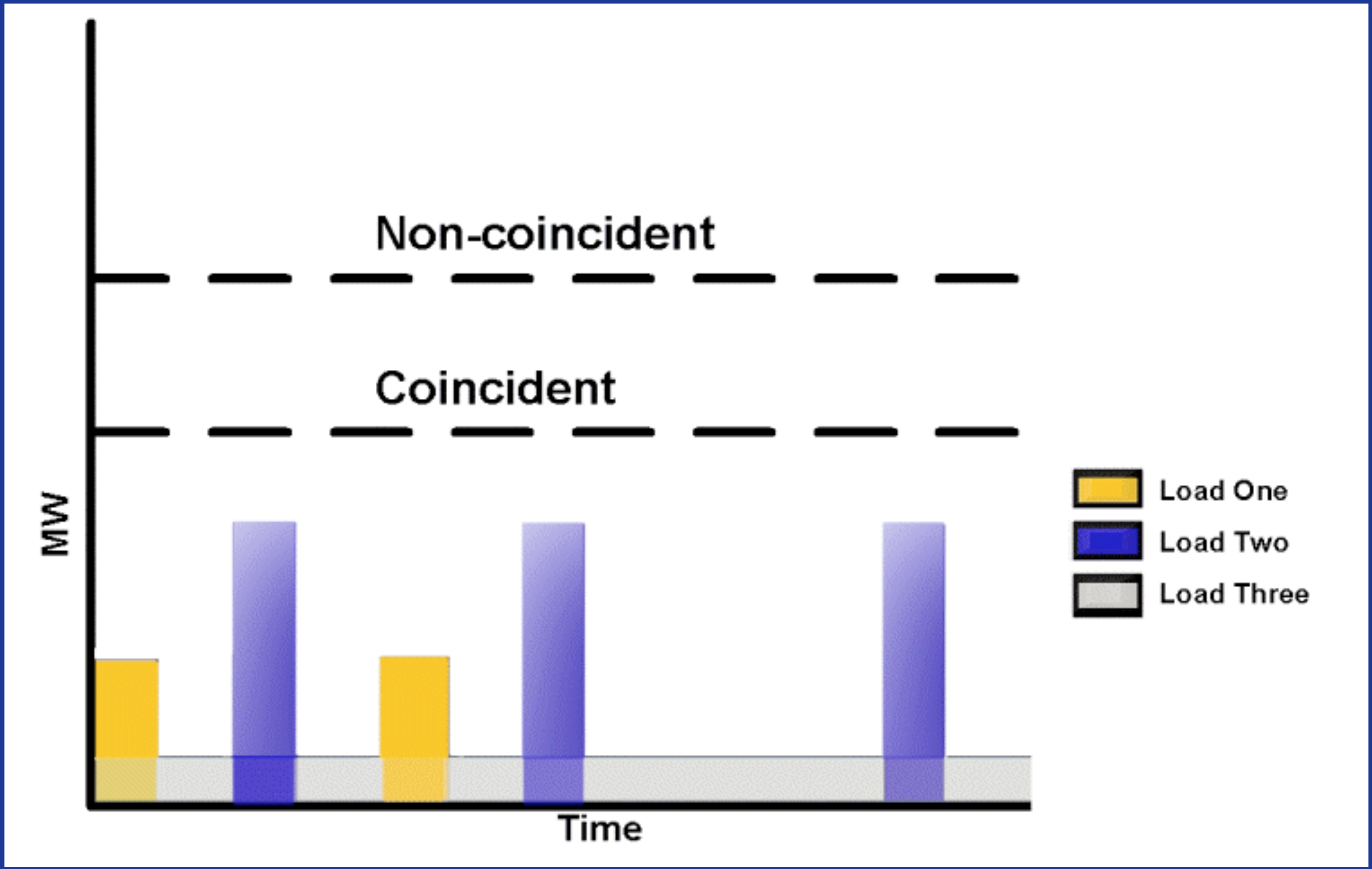
Adapted from Economic Regulatory Administration, 1981



$$\text{Load factor} = \frac{\text{average demand}}{\text{peak demand}}$$

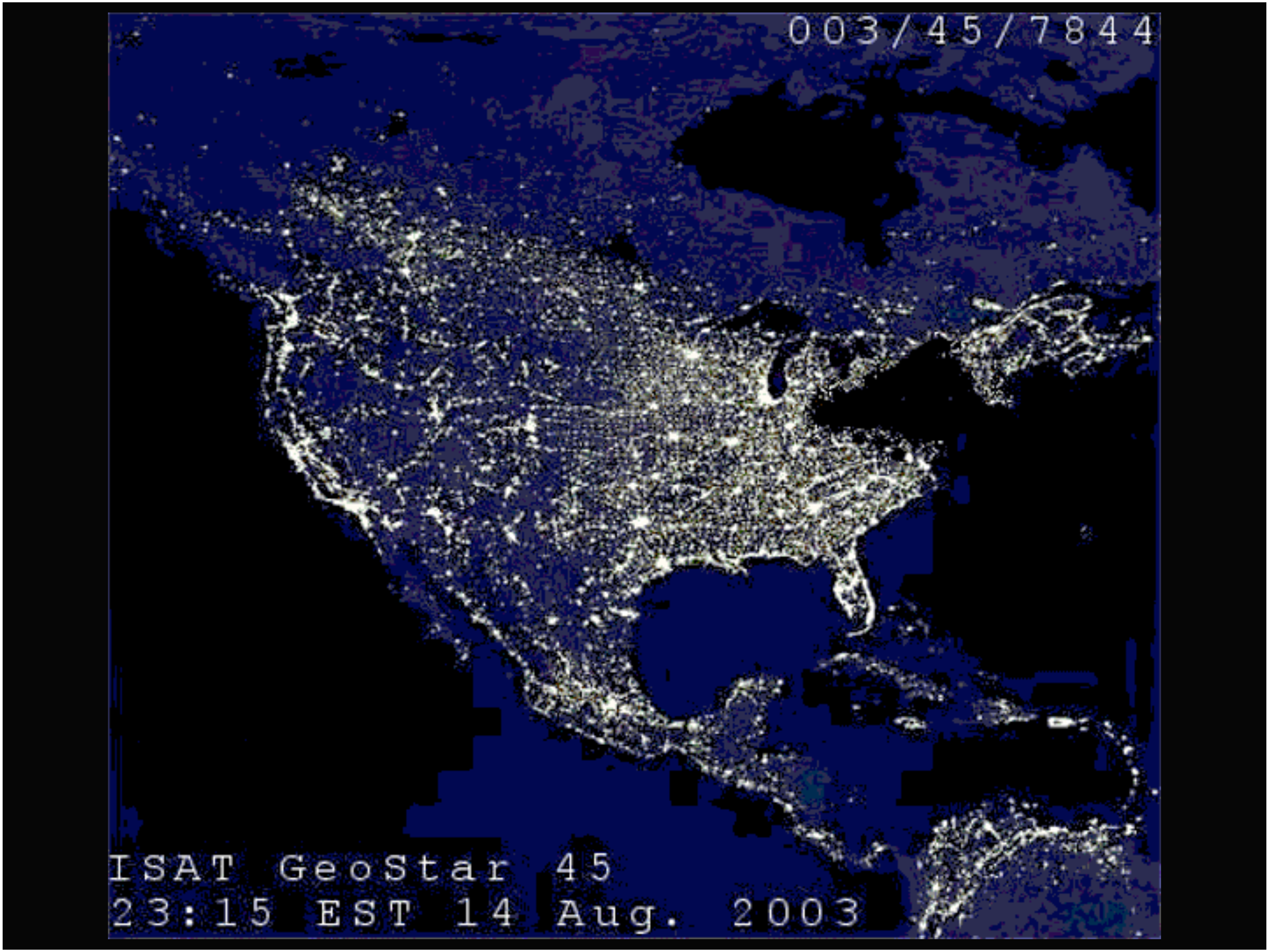
Load Duration Curve





Coincident demand = combined demand that actually occurs at a given time

Non-coincident demand = total connected demand that doesn’t usually occur all at once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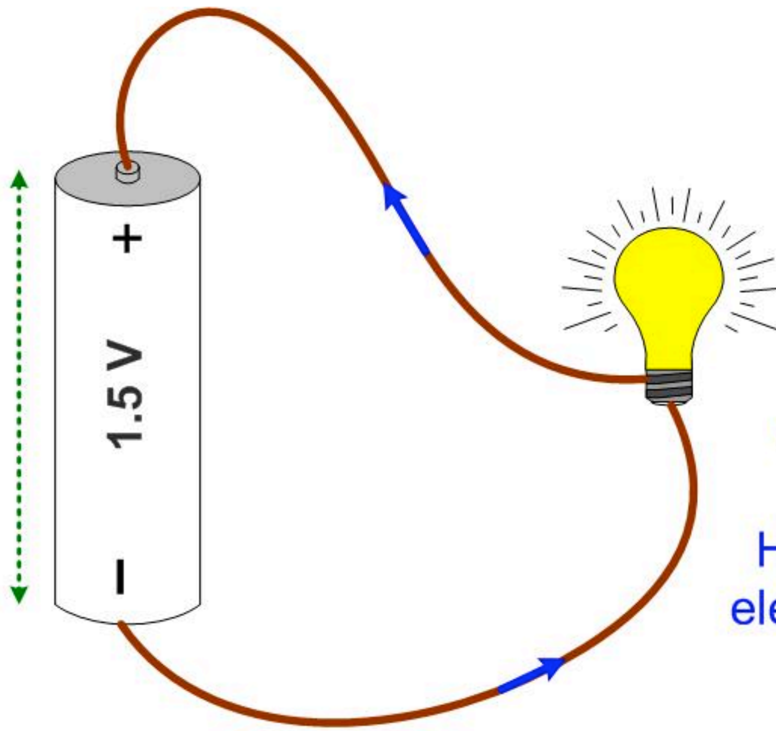
(Casual) Definition of Terms

Voltage:

How badly the electrons would rather be at the + than the - end

(Energy / Charge)



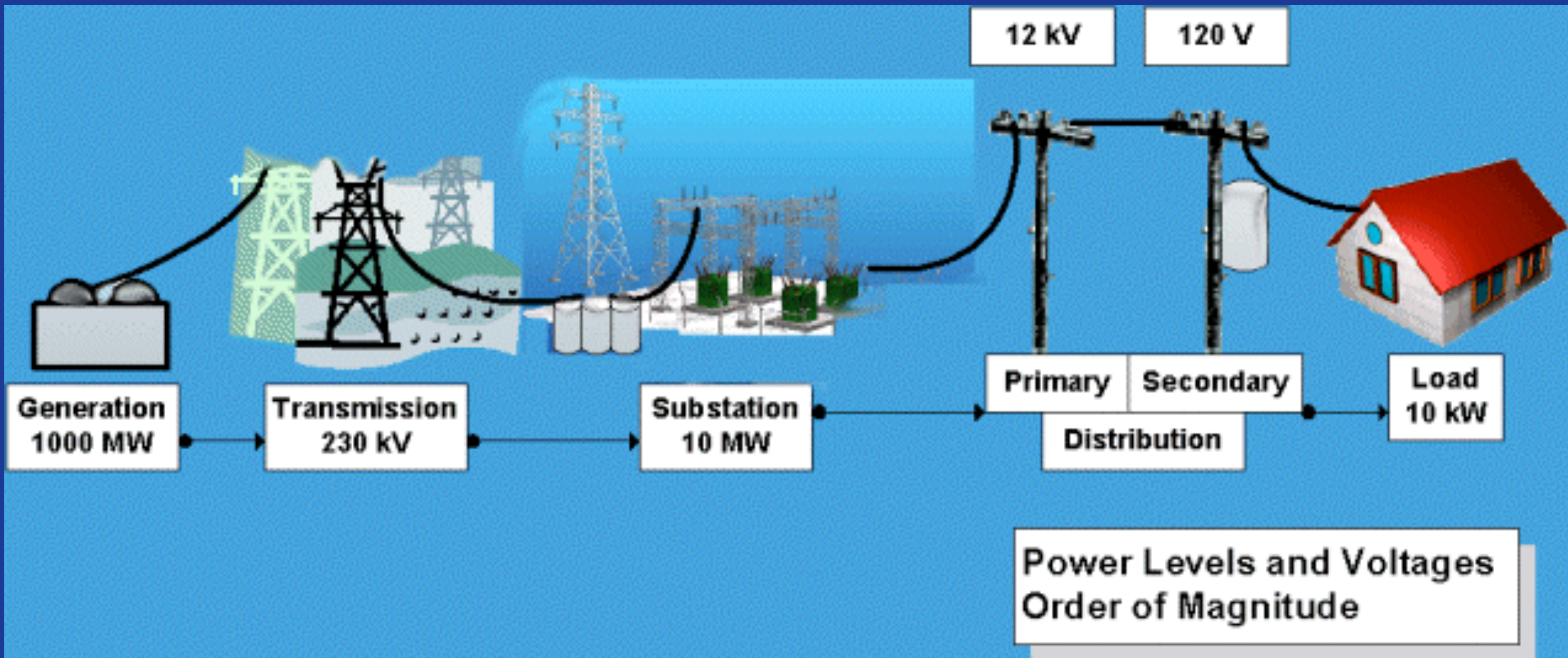
Current:

How many electrons are flowing

(Charge / Time)

Power: The rate at which the battery expends energy to move electrons, and the electrons expend energy to squeeze through the light bulb

Power = Voltage x Current (Energy / Time)


12 kV
120 V
Generation
1000 MW
Transmission
230 kV
Substation
10 MW
Primary
Secondary
Distribution
Load
10 kW
Power Levels and Voltages
Order of Magnitude

Three voltage levels:
Subtransmission (60-115kV)
Primary distribution (12-21kV)
Secondary distribution
(120/240V)

Power supplied to load $P_{LOAD} = I\,V_{LOAD}$ where $V_{LOAD} = V_{GEN} - 2V_{DROP}$

Power lost on each line $P_{LOSS} = I^2R = I\,V_{DROP}$

(V_{DROP} is usually unknown, thus I^2R is common formula)

Given P_{LOAD}, low V_{LOAD} needs large current I, increasing P_{LOSS}

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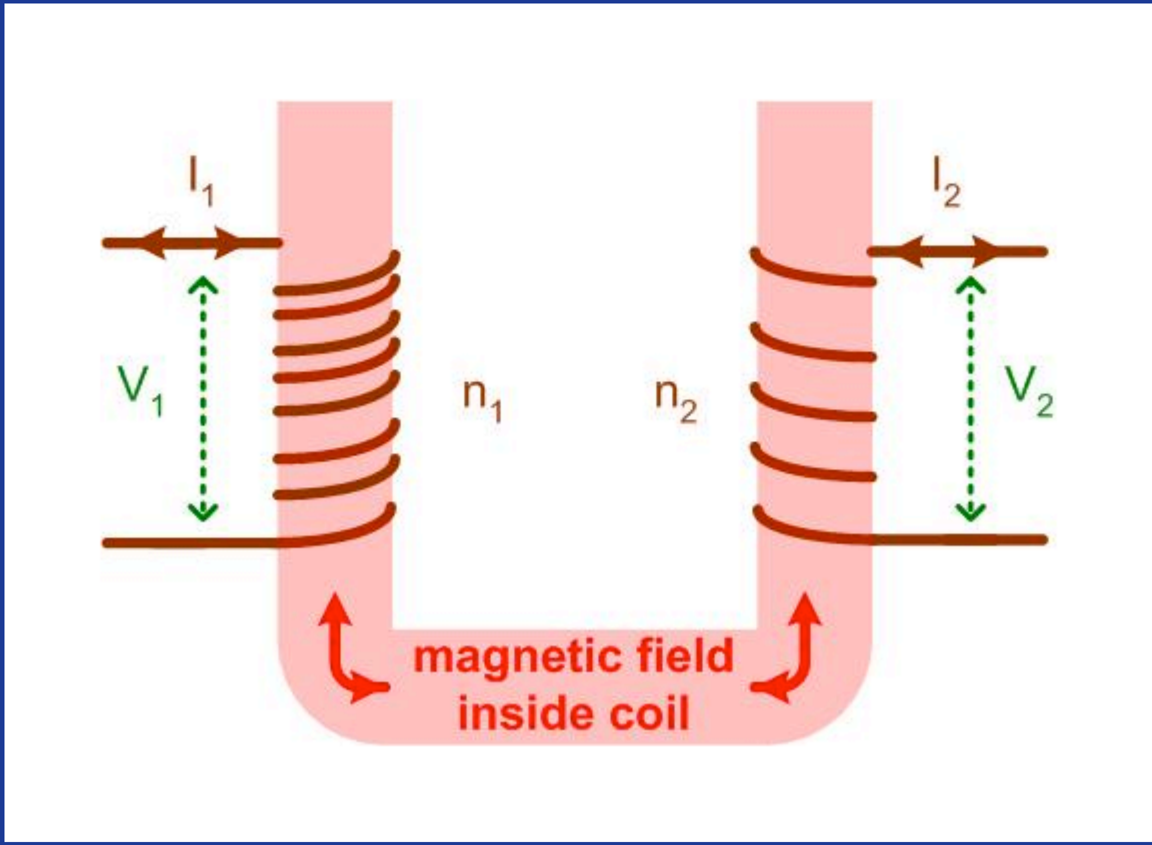
Basic Transformer

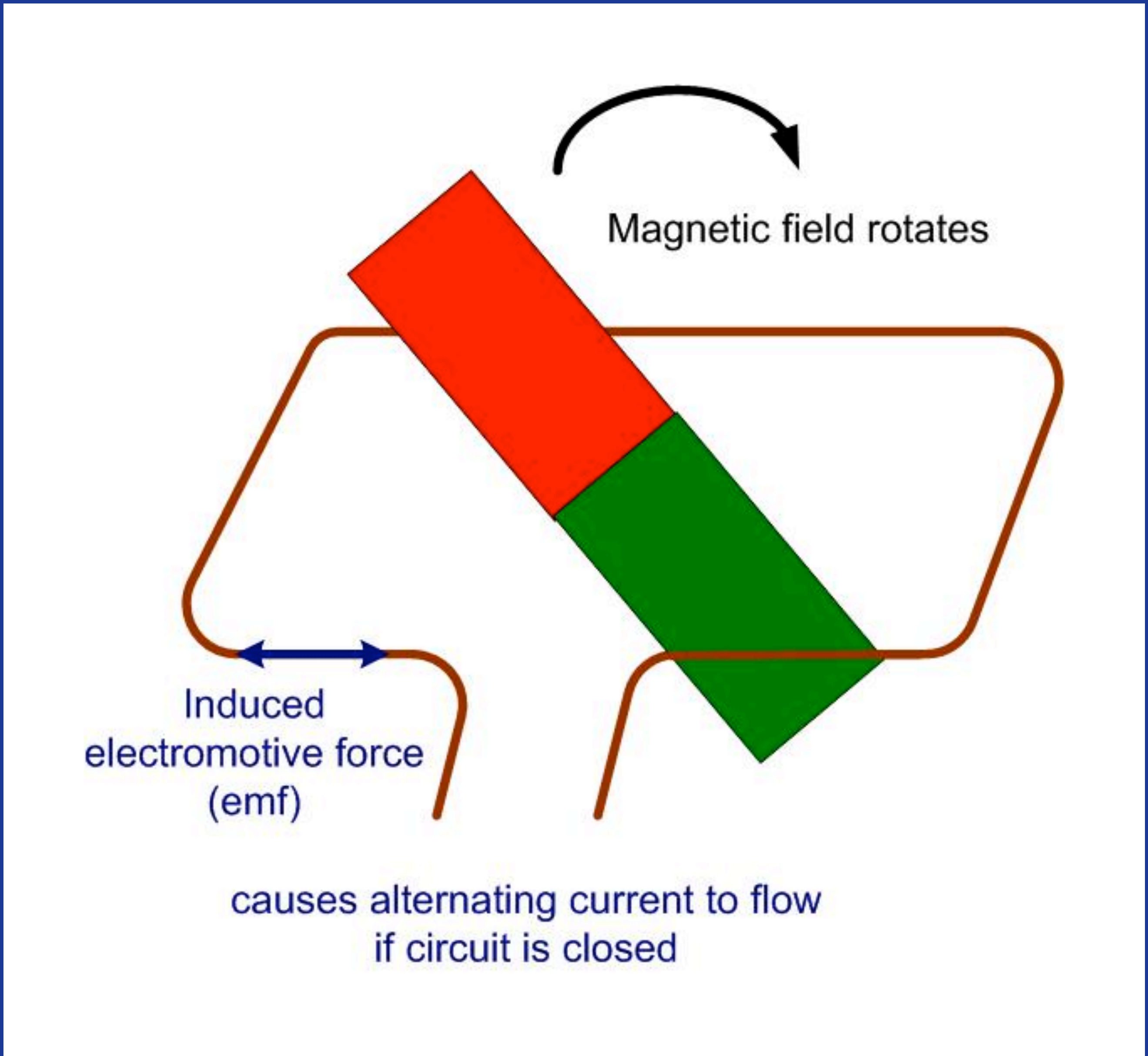


The turns ratio determines the voltage: $V_2 / V_1 = n_2 / n_1$

To satisfy energy conservation, current varies inversely with voltage:

$P_1 = P_2$ and $P = IV$, thus $I_1V_1 = I_2V_2$ (neglecting losses)

The most basic generator



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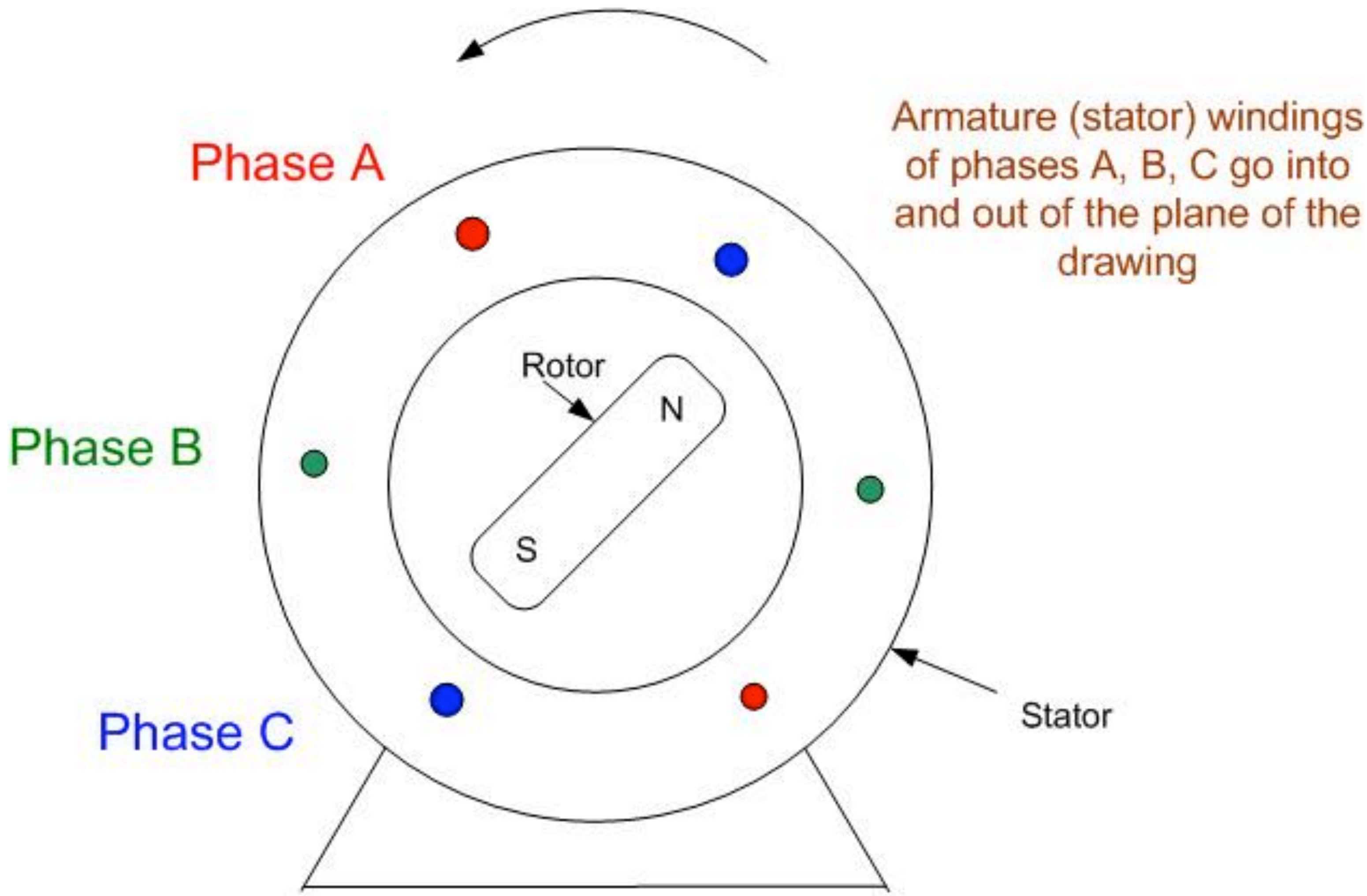
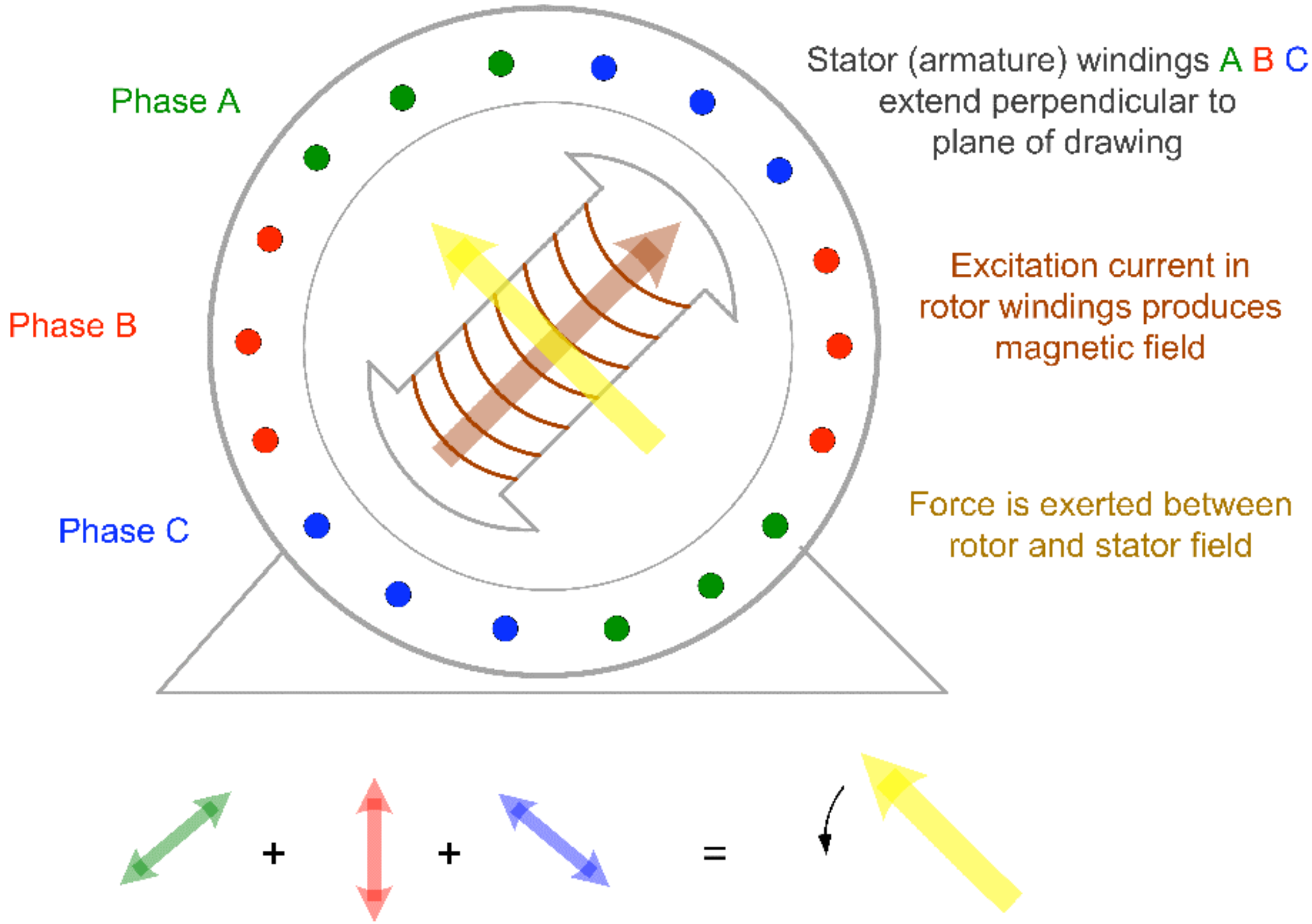


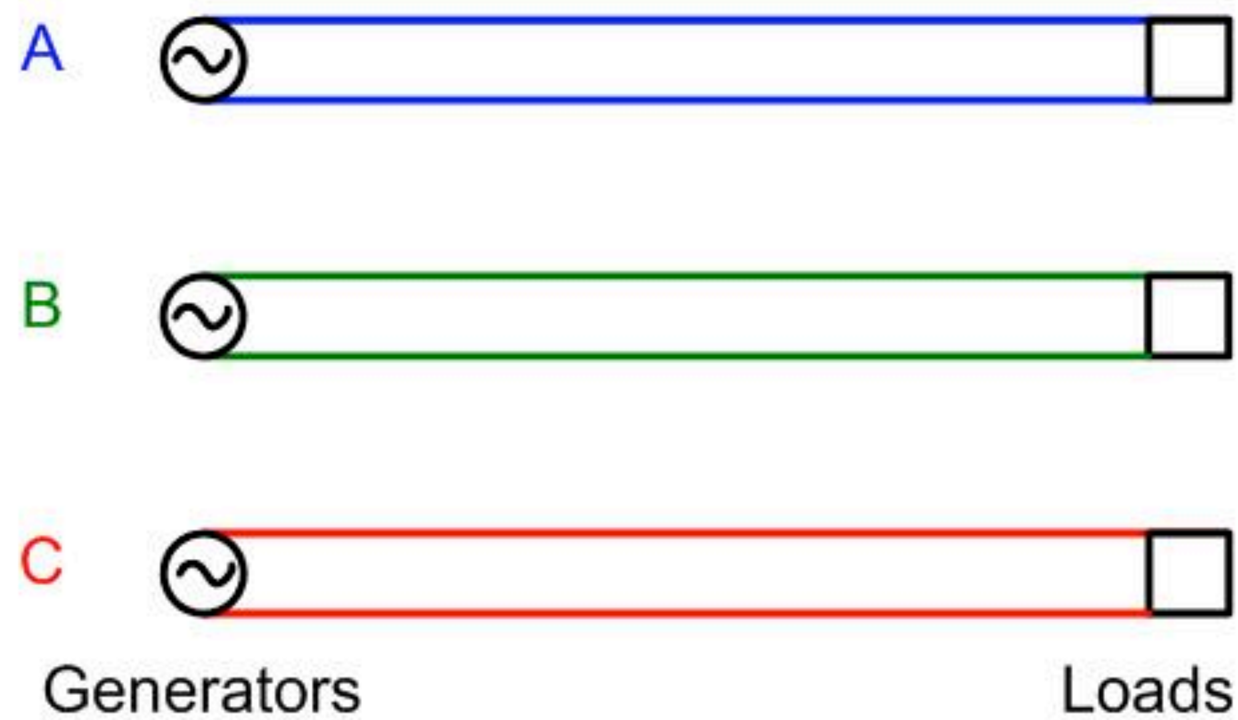
Basic Generator

Three-phase, synchronous generator

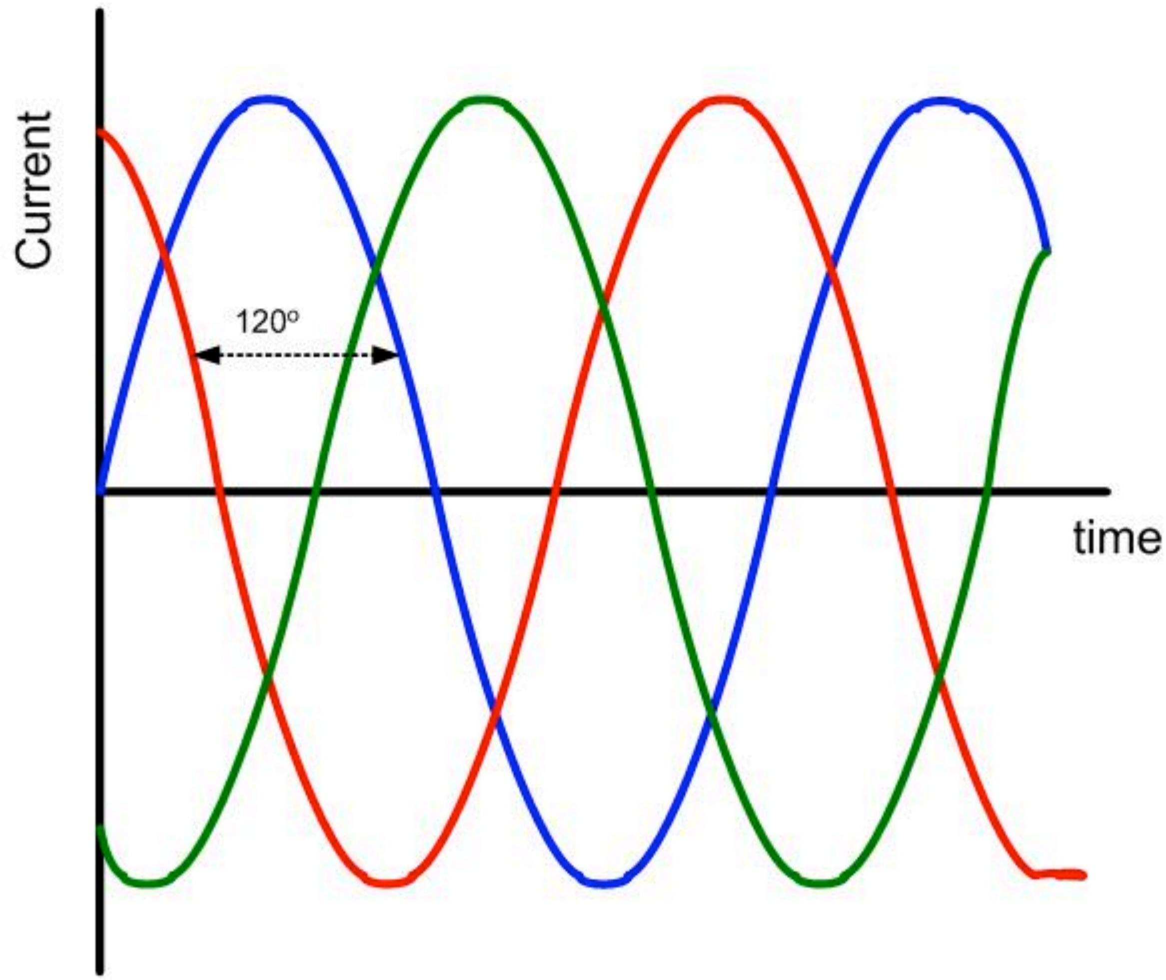


Alternating magnetic fields from stator windings sum up to produce a rotating field (stator field) of constant strength

How one would imagine three circuits, requiring six conductors

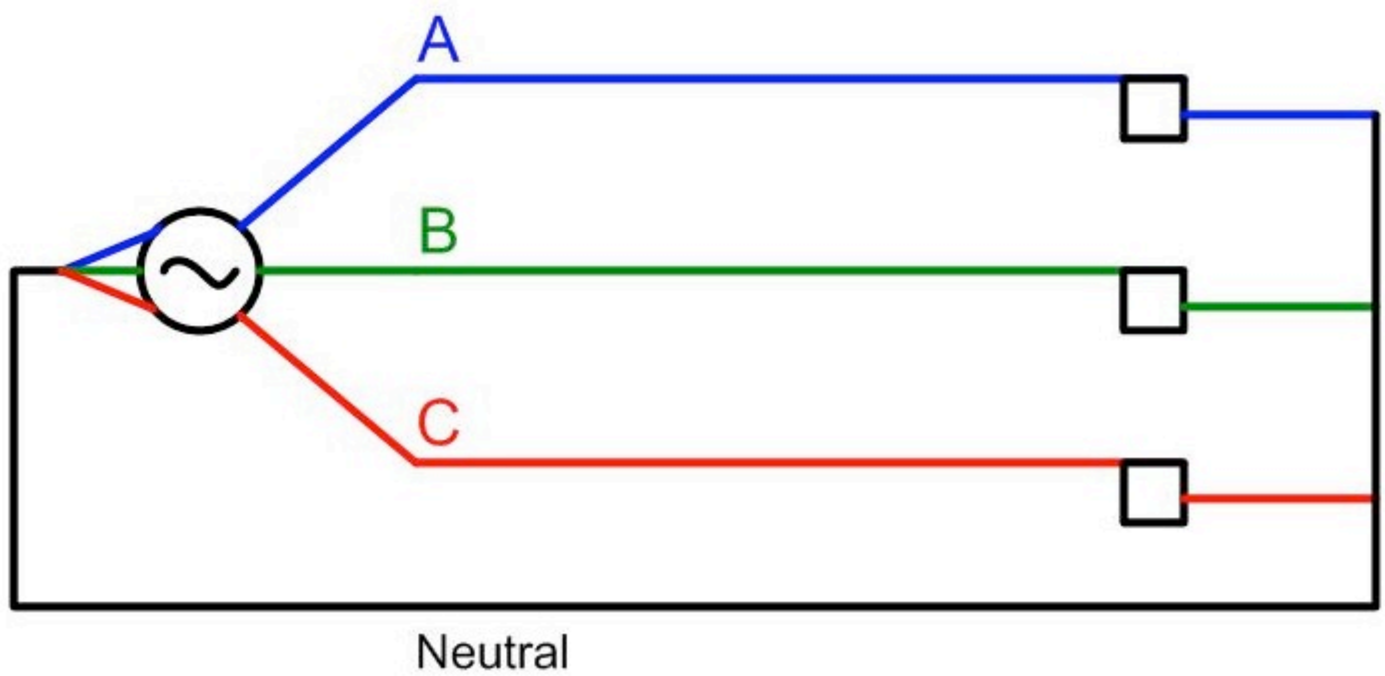


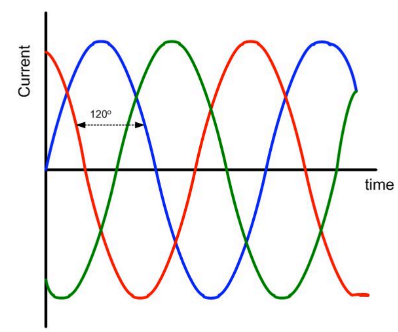
Staggered Three-Phase Current



I(t) + I(t) + I(t) = 0 always

Three circuits with shared return flow





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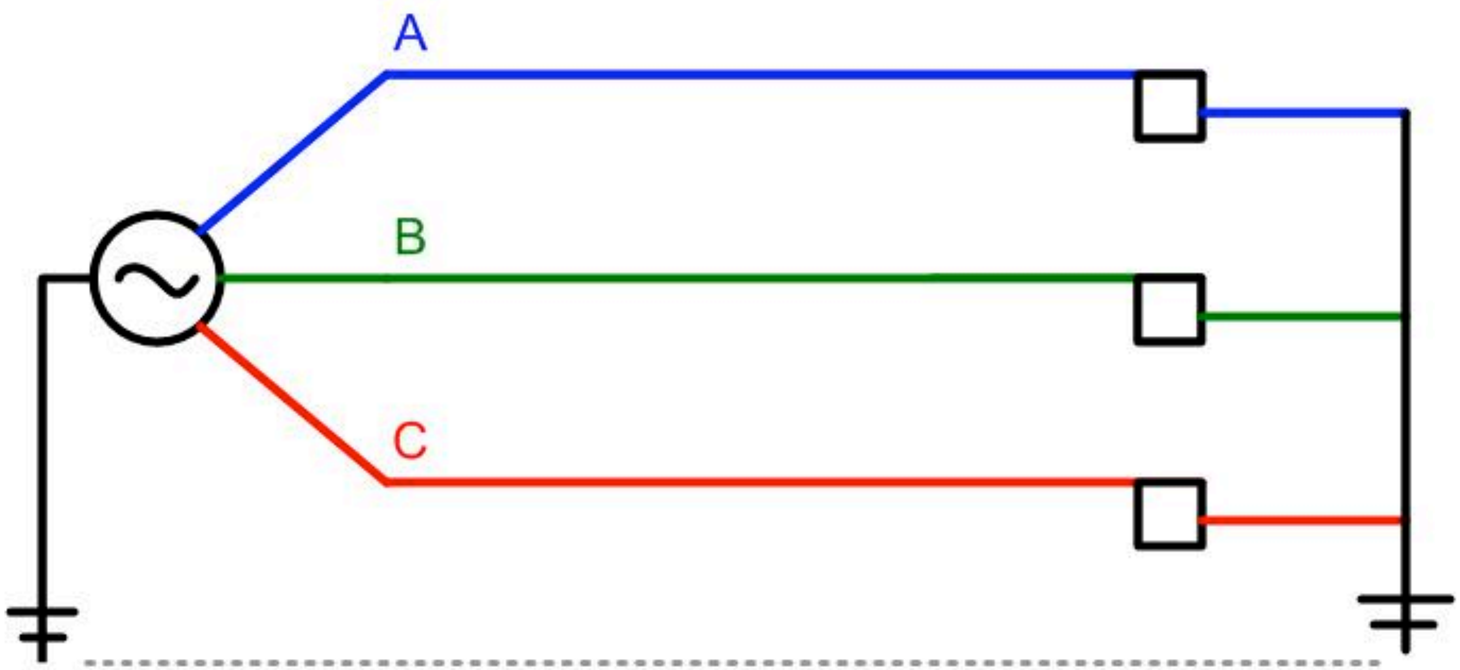
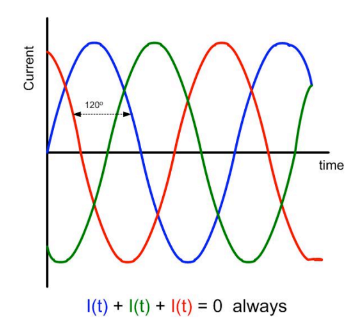


Since the sum of currents in Phases A, B, C is zero *(if loads are balanced)* the neutral conductor carries no current and can be eliminated.



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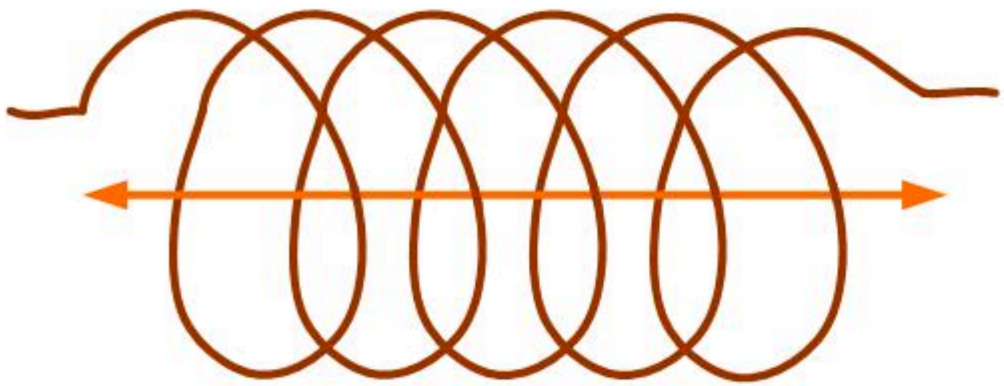
Reactive Power

The “bad cholesterol”
of power lines

Inductor



Magnetic field created by current in coil

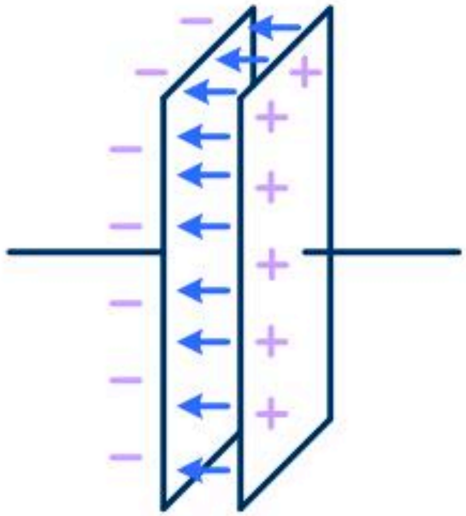
stores energy in magnetic field

preferentially transmits current of lower frequency or d.c.

resists changes in current

causes alternating current to lag voltage

Capacitor



Electric field across gap
between conducting plates

stores electric charge

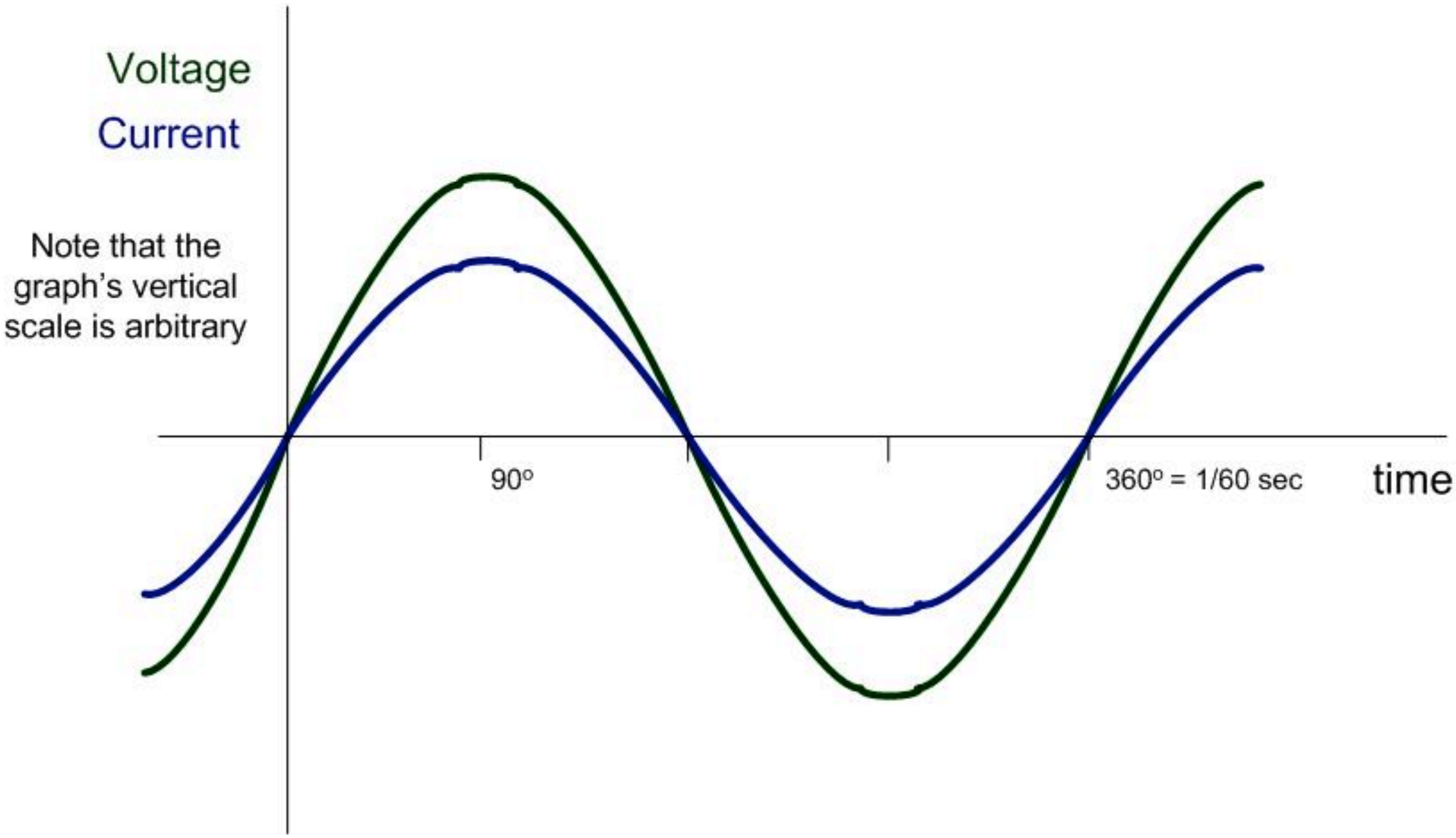
stores energy in electric field

preferentially transmits alternating current
of higher frequency

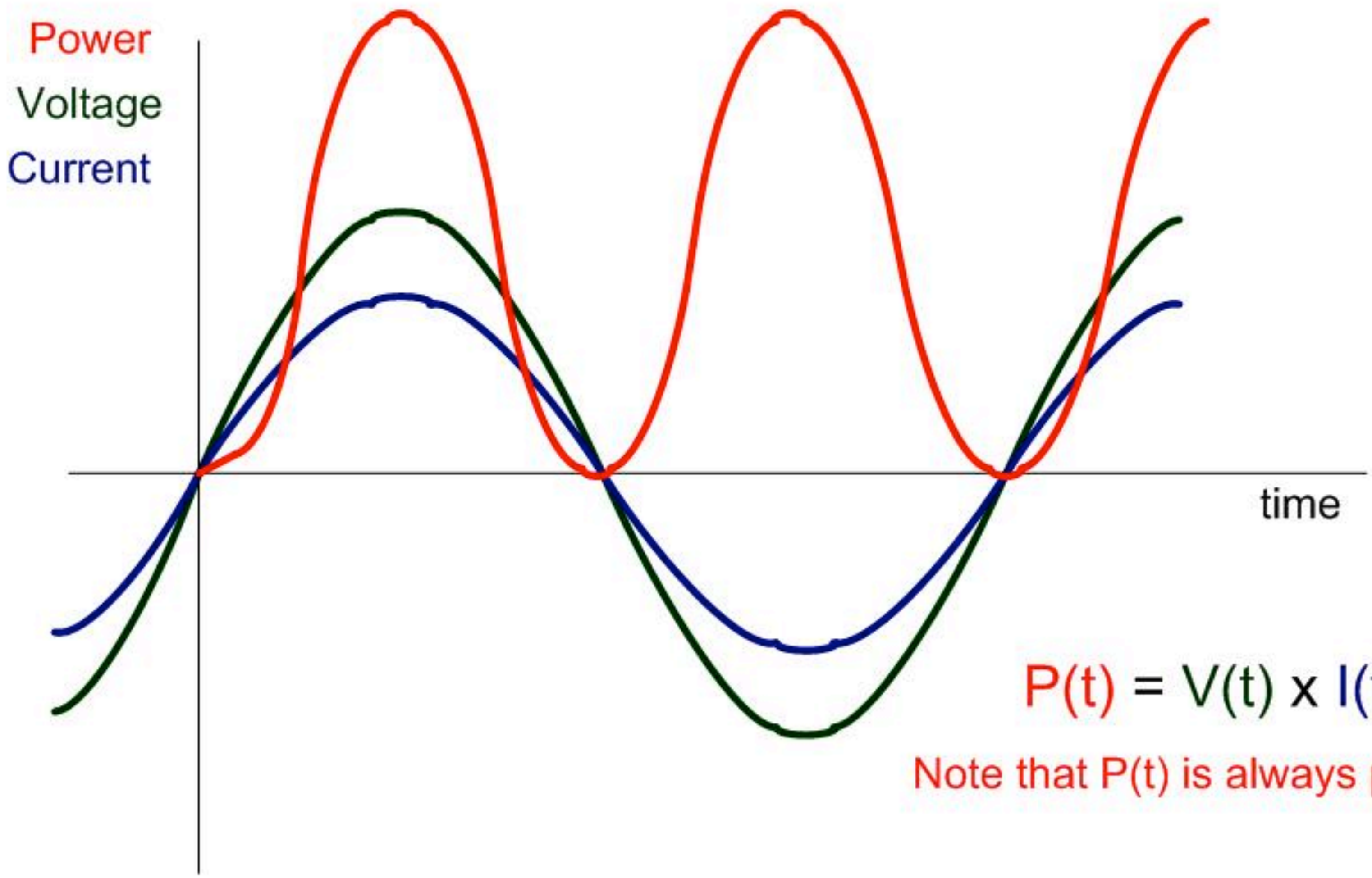
resists changes in voltage

causes alternating current to lead voltage

A.C. voltage and current for a resistor



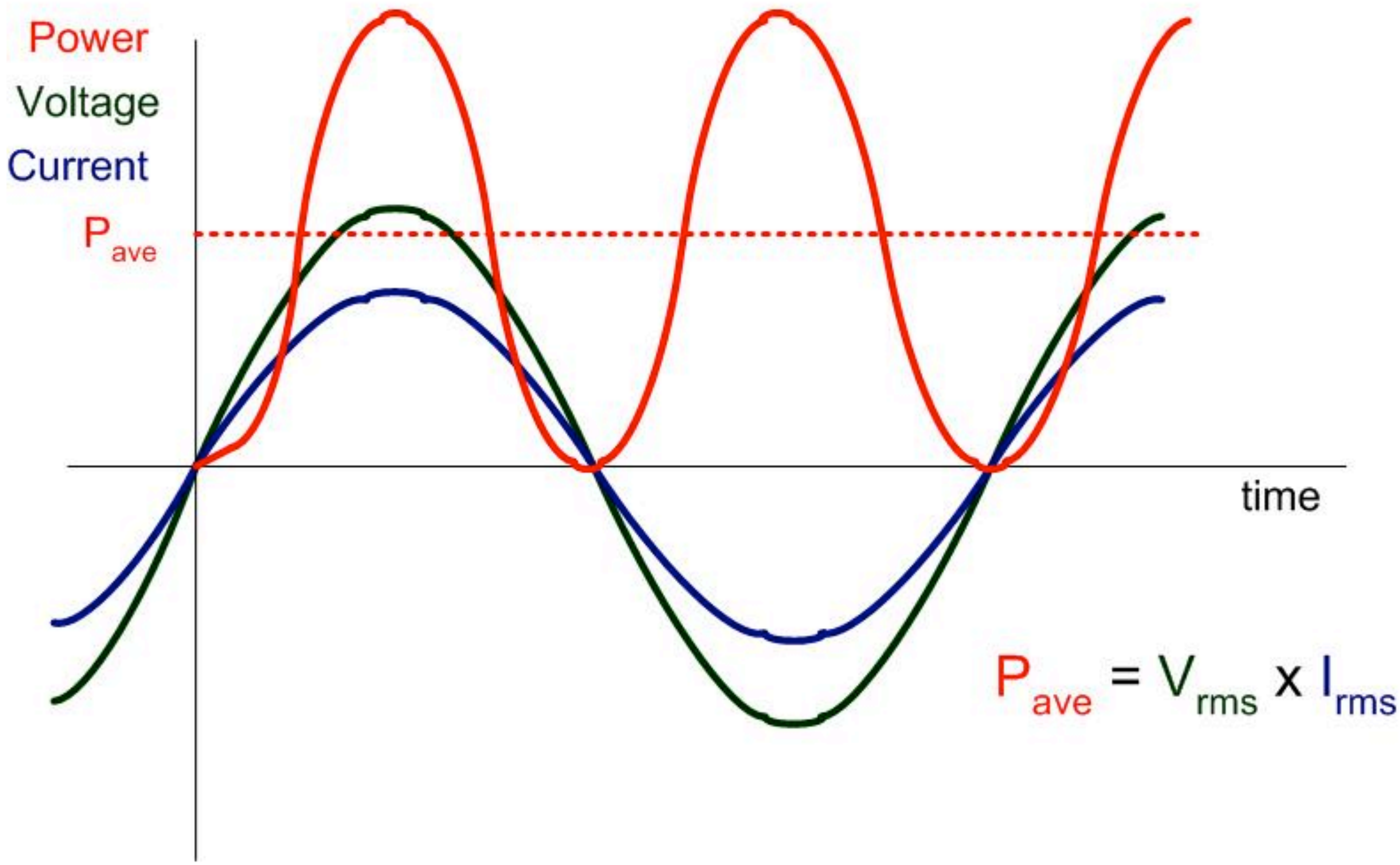
Instantaneous power for a resistor



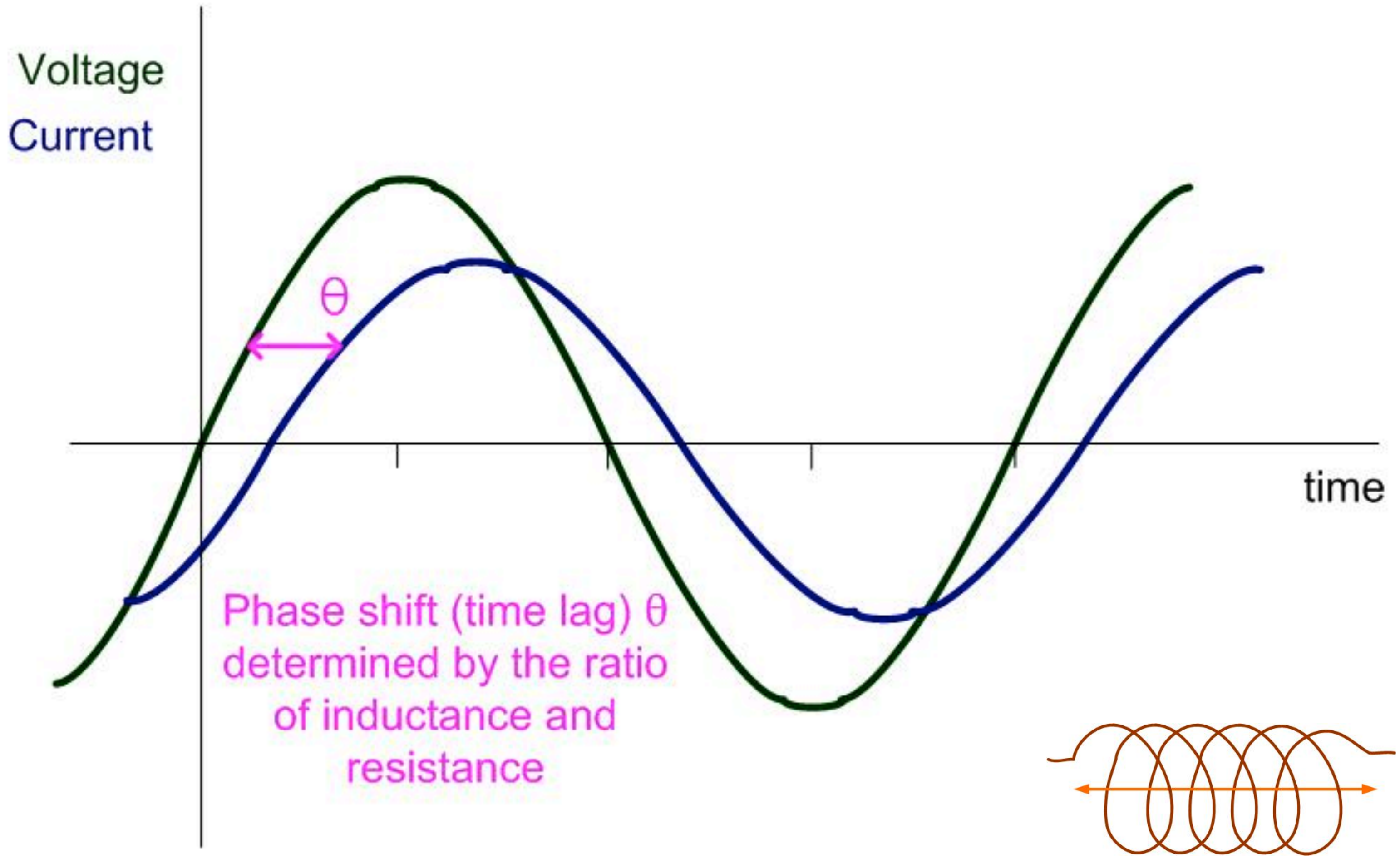
$P(t) = V(t) \times I(t)$

Note that P(t) is always positive

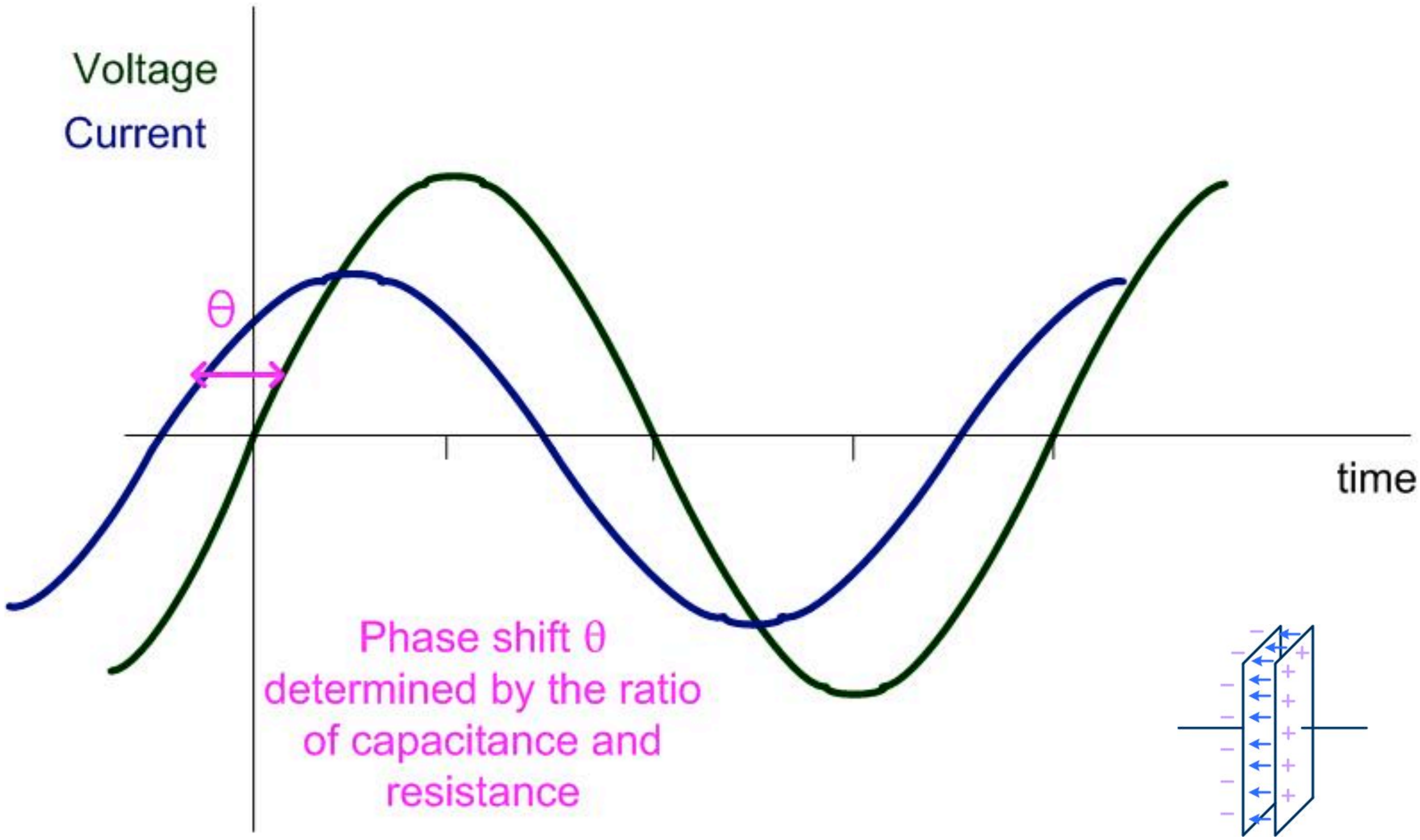
Instantaneous and average power for a resistor



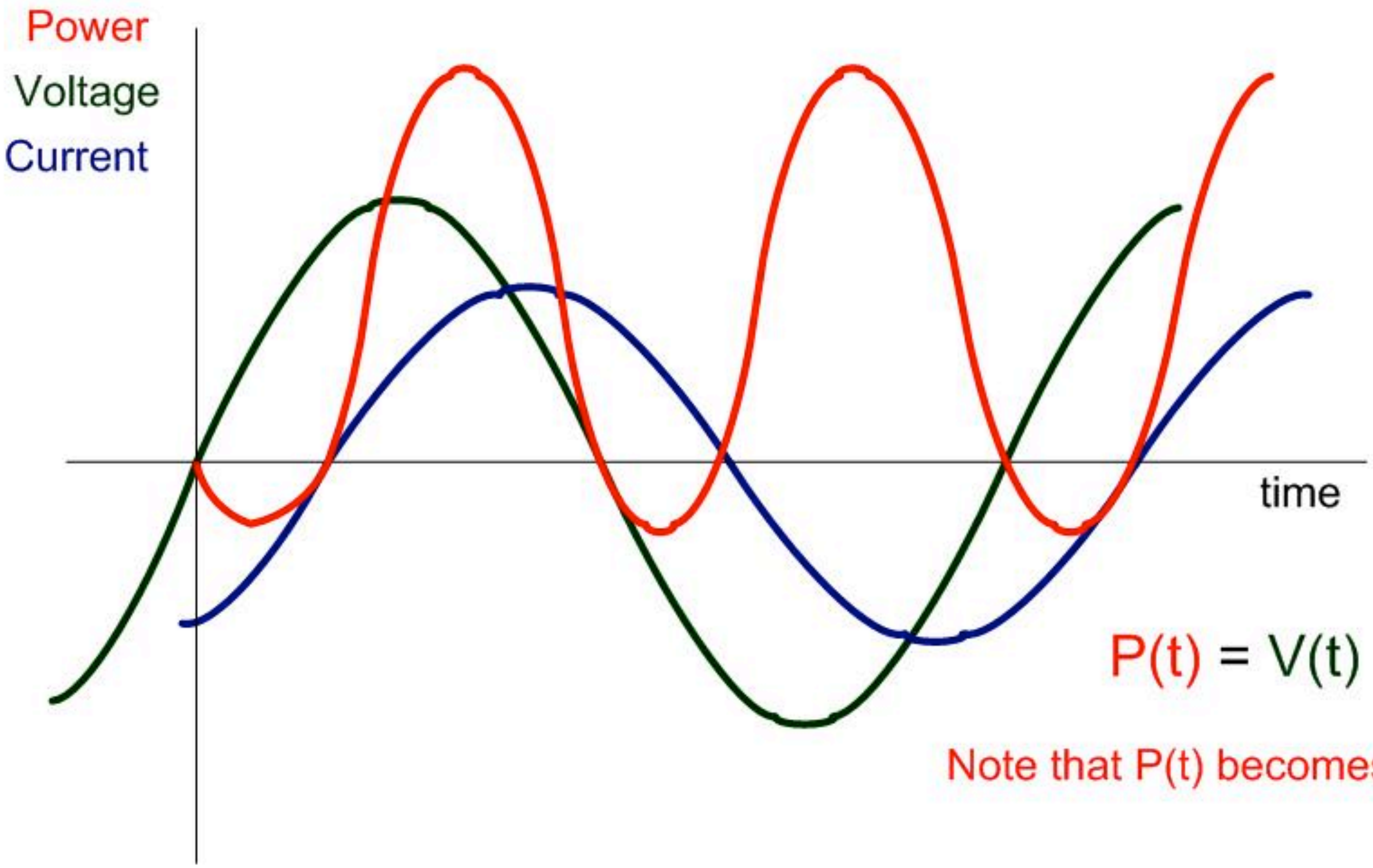
A.C. voltage and current for an inductor: Current lags behind voltage



A.C. voltage and current for a capacitor: Current leads voltage



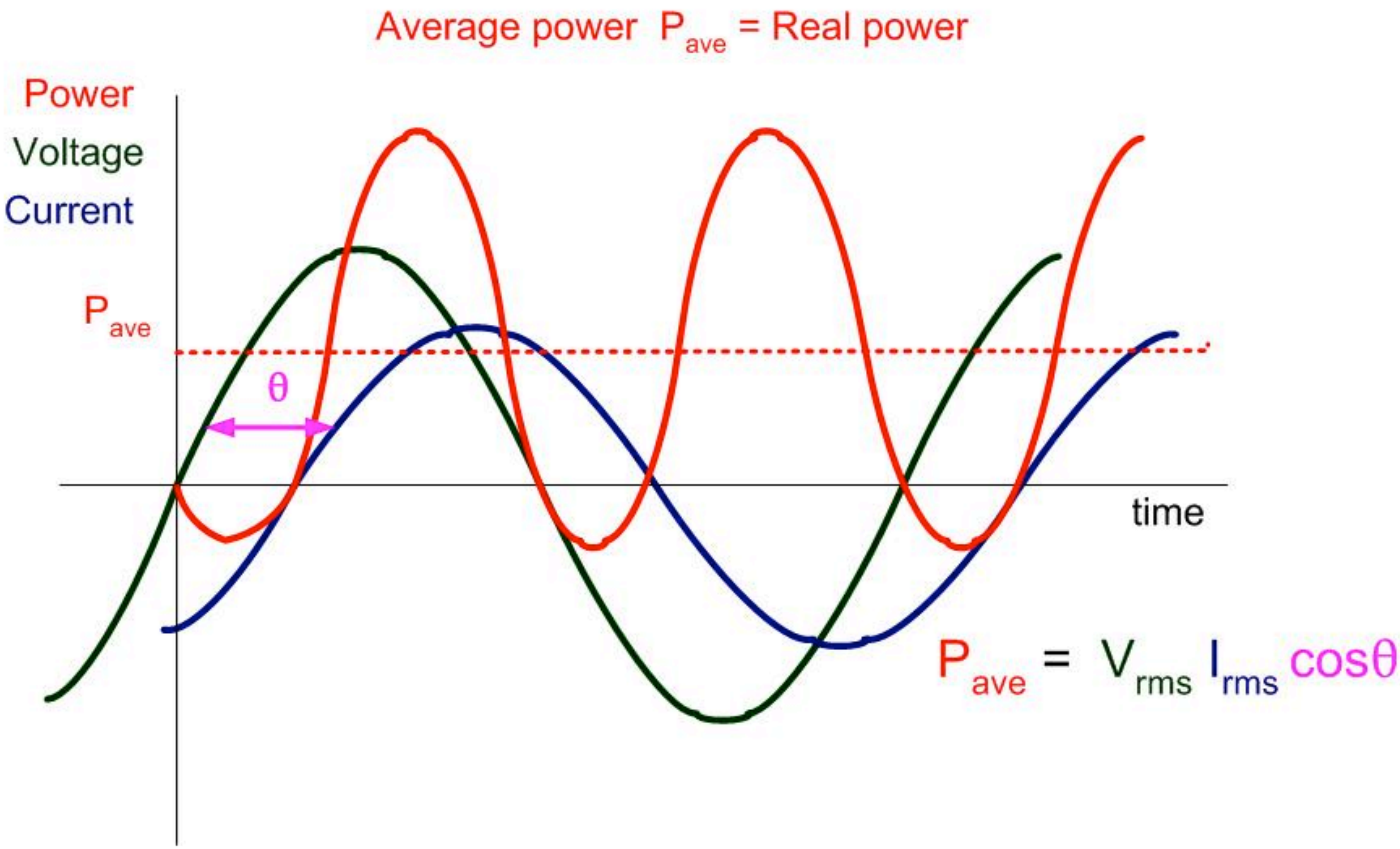
Instantaneous power for an inductor



$P(t) = V(t) \times I(t)$

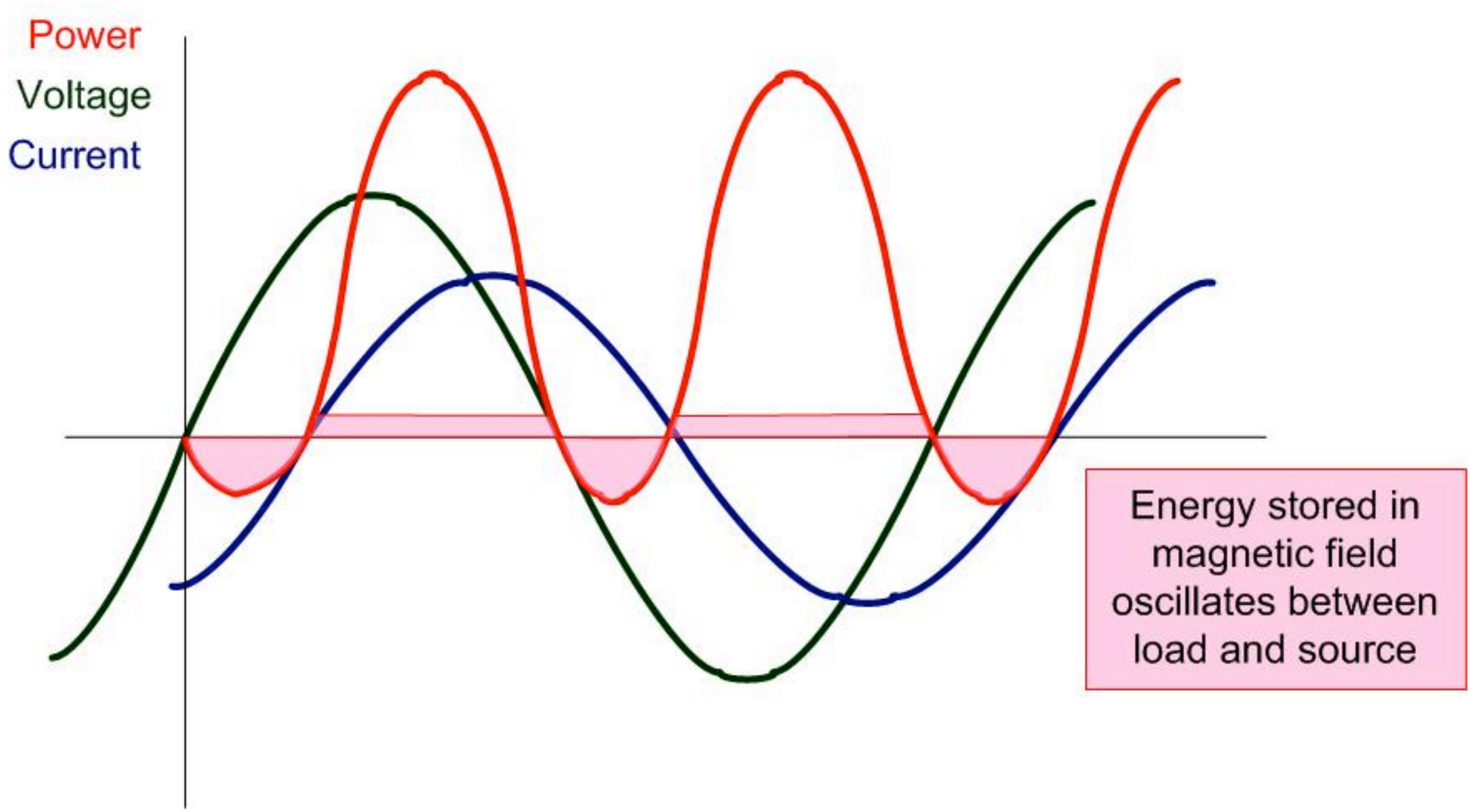
Note that P(t) becomes negative

Instantaneous and average power for an inductor

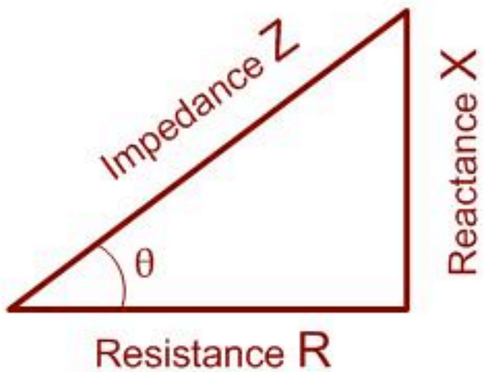


Instantaneous and reactive power for an inductor

Negative portion of P(t) determines reactive power



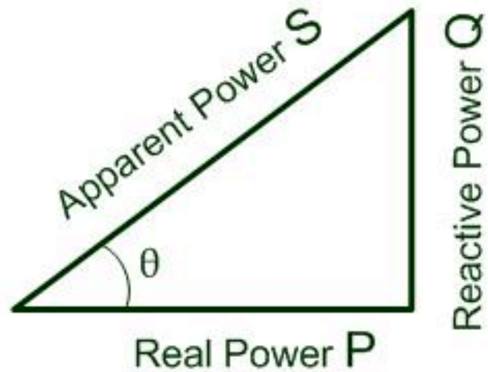
Complex Power



$$Z = R + jX$$

$$R = Z\cos\theta$$

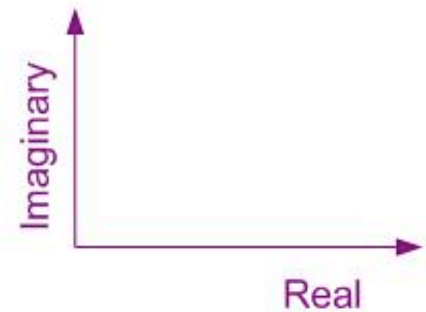
θ is the time lag between current & voltage, determined by the load



$$S = P + jQ$$

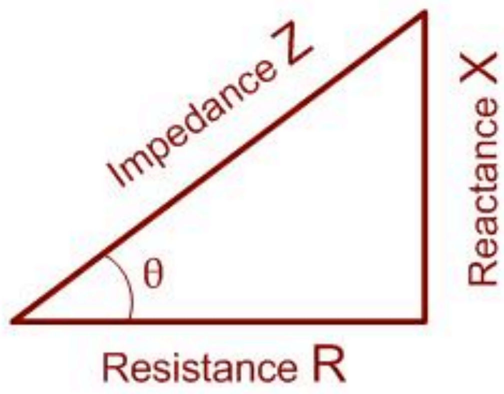
$$P = S\cos\theta$$

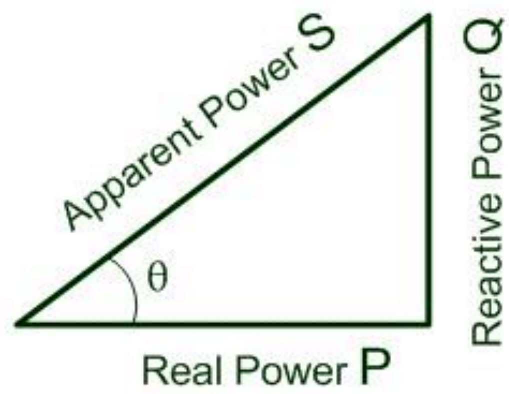
$\cos\theta$ is the Power Factor (p.f.)



j indicates the imaginary direction

$$j^2 = -1$$





R, X, Z, θ are determined by physical properties of load

S = I V determines magnitude of power

Given a voltage V applied,
V = I Z determines current

θ determines ratio of P and Q

Power Source can maintain V only if it provides correct P and Q

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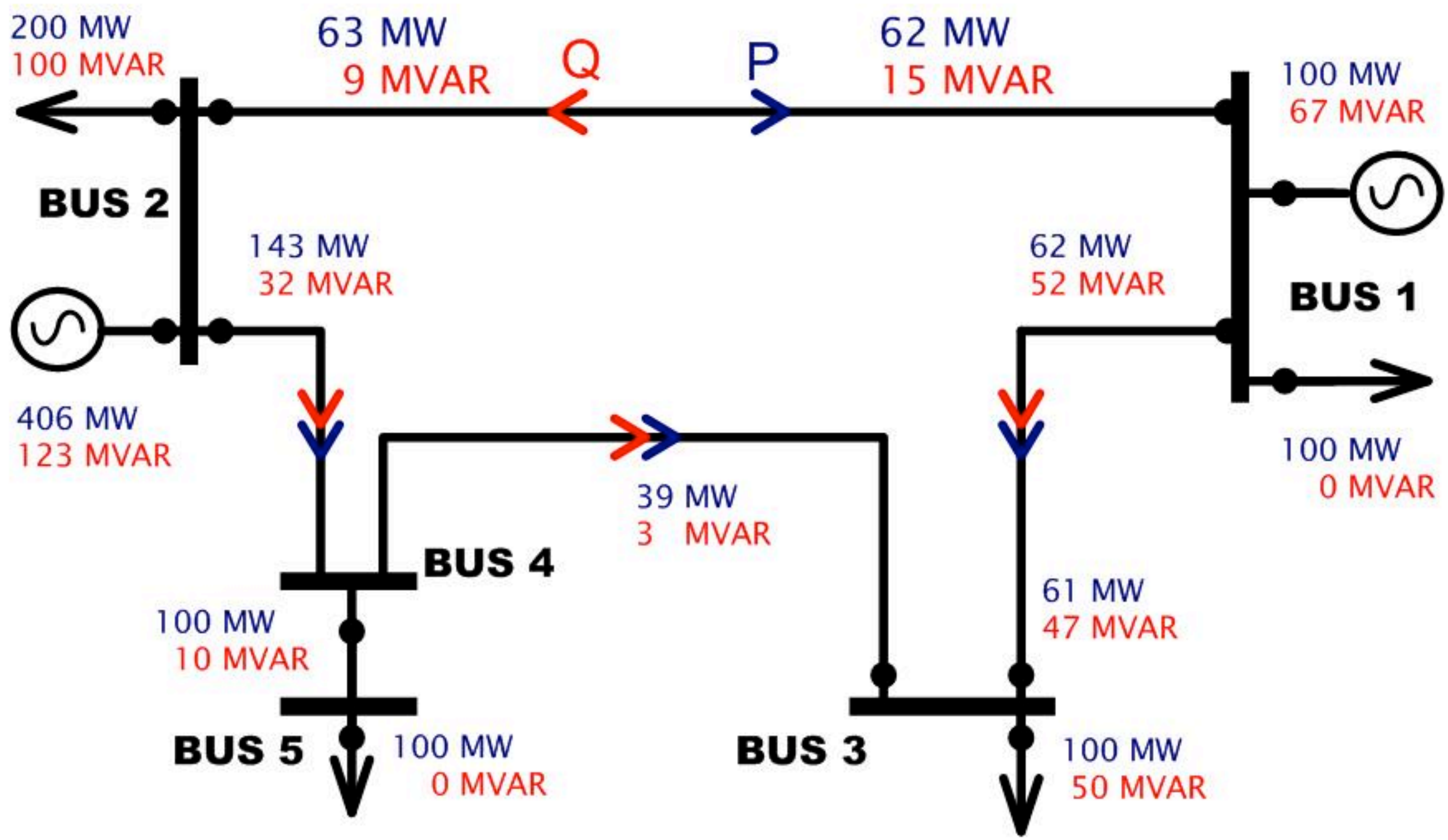
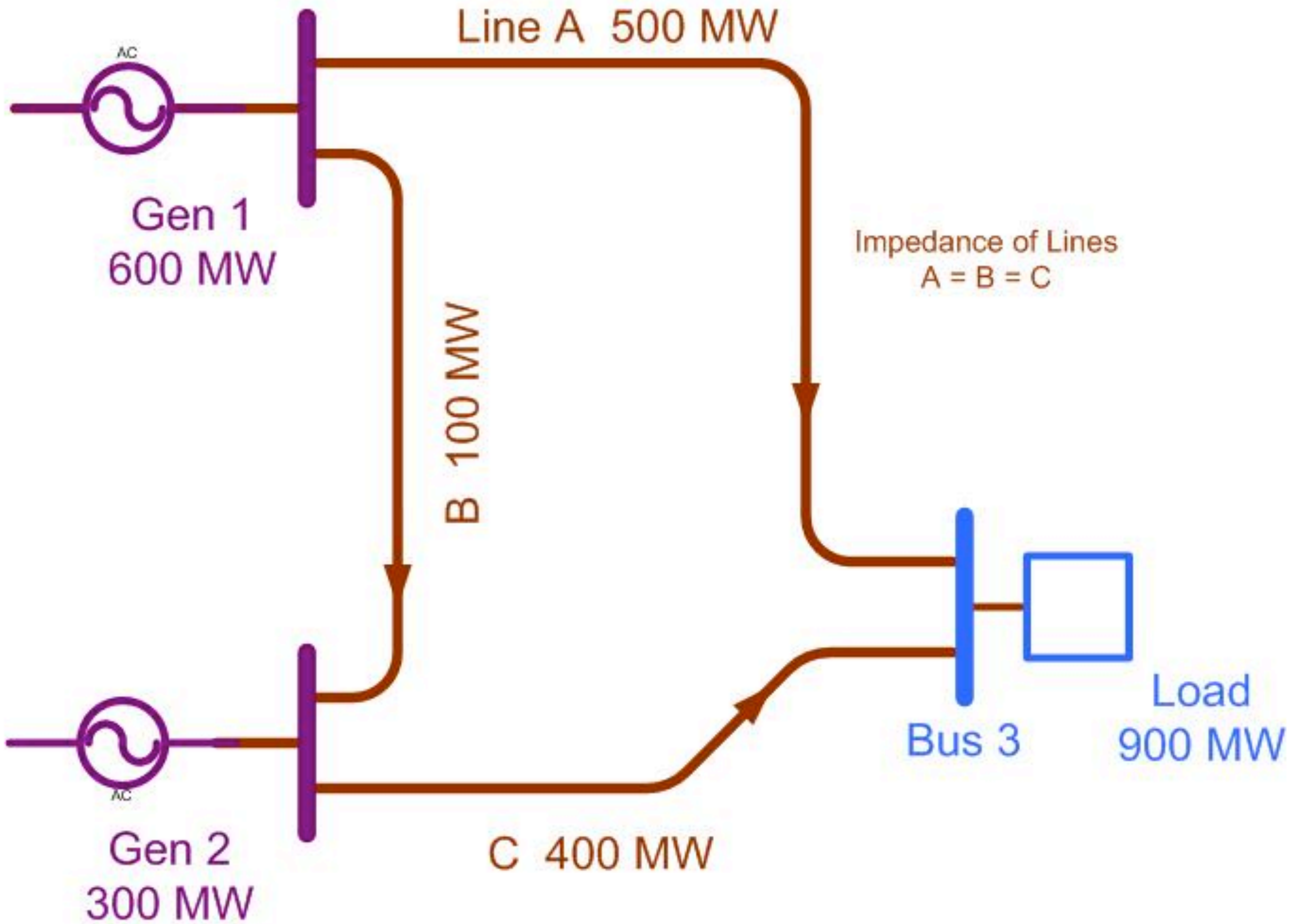


Power flow analysis for a 5-bus system



Power Flow Example

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Why transmit power at high voltages?

Why use alternating current?

Why use three phases?

What is reactive power?

How to predict power flow?

How to balance supply and demand?

How to assess performance?

Power generated = Power demanded

"The Law of Energy Conservation is strictly enforced."

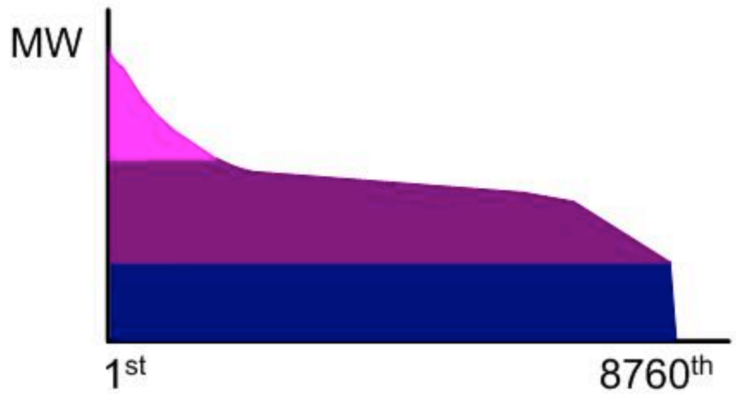
Real power imbalance:
Loss of frequency control

Reactive power imbalance:
Loss of voltage control

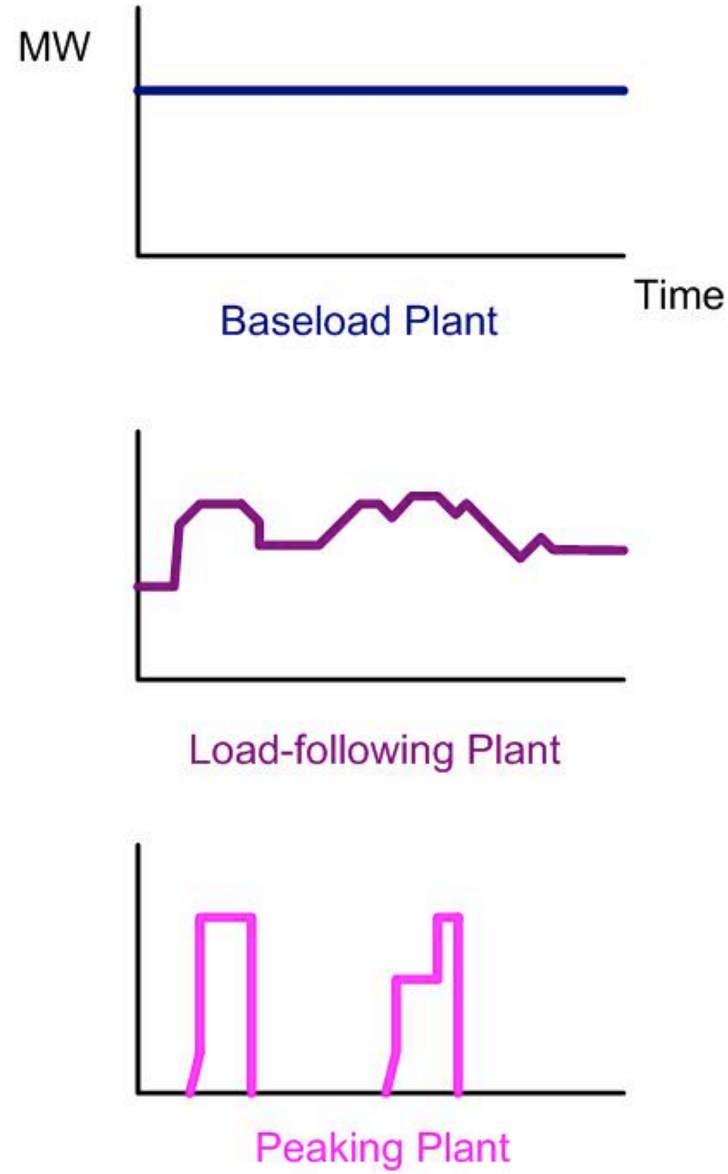
How to balance supply & demand?

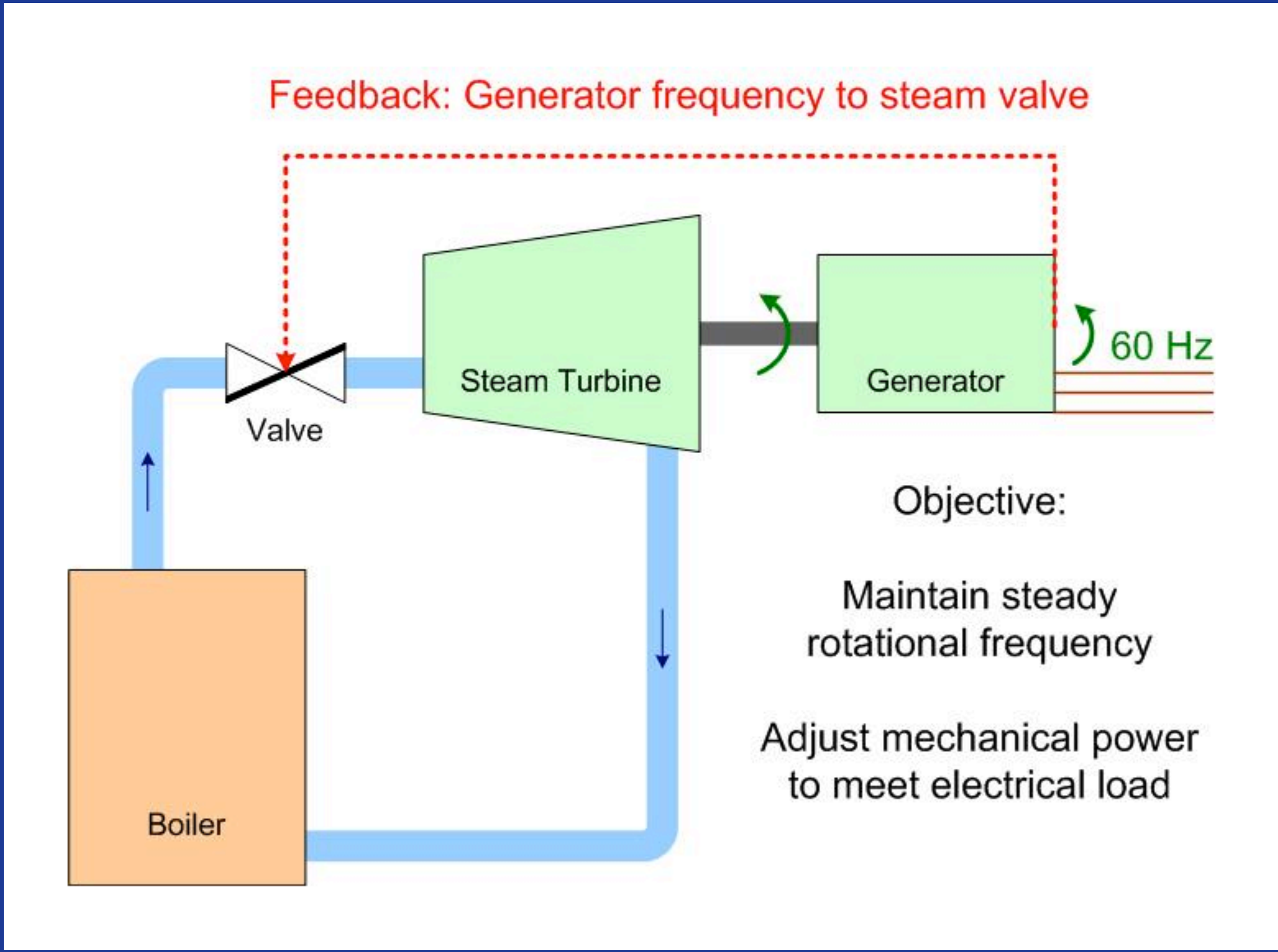
Successive approximations on different time scales:

1. Scheduling
2. Generator control
3. Stability



Traditional Dispatch:
Filling the load duration
curve from the bottom up

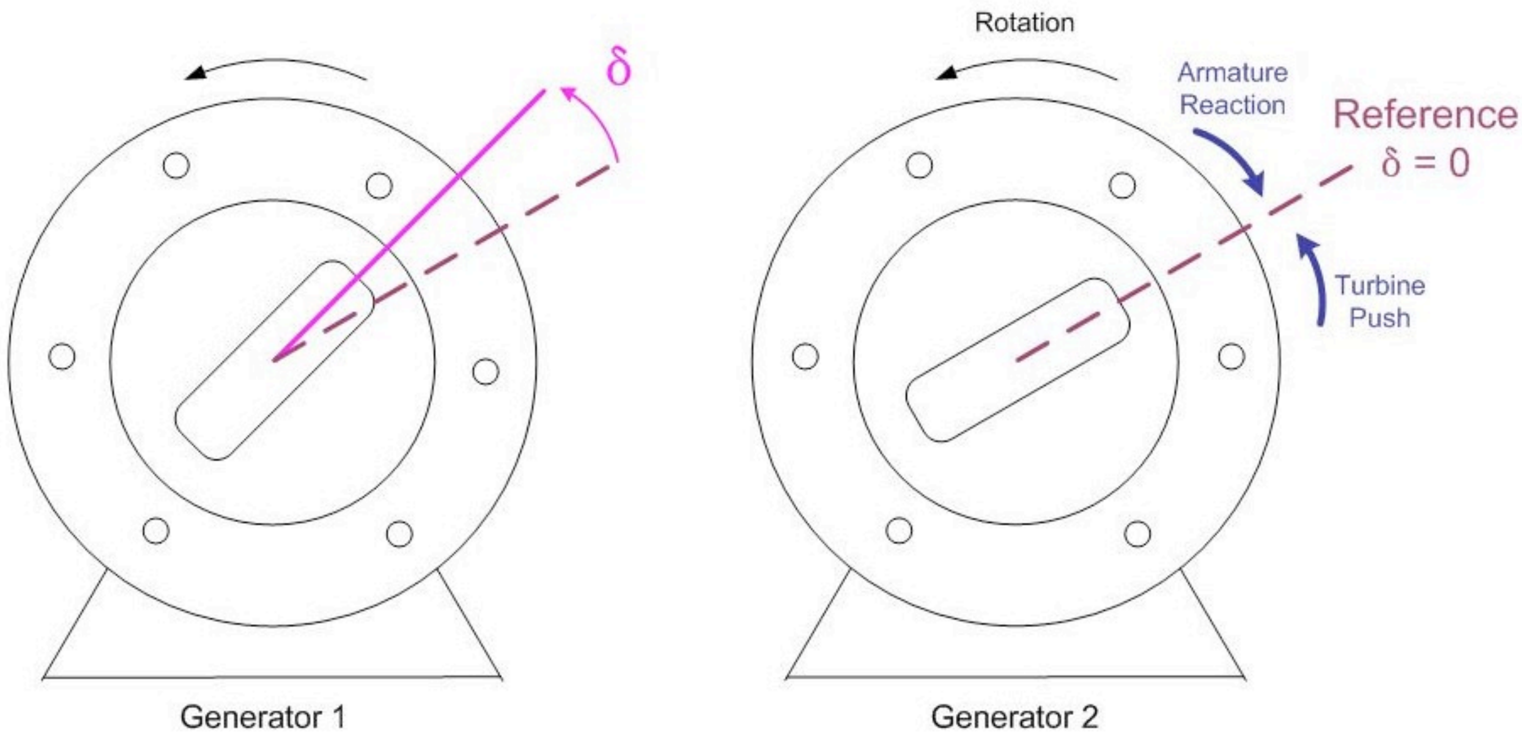




Generator control: operating “on the governor”

Generator Voltage Angle

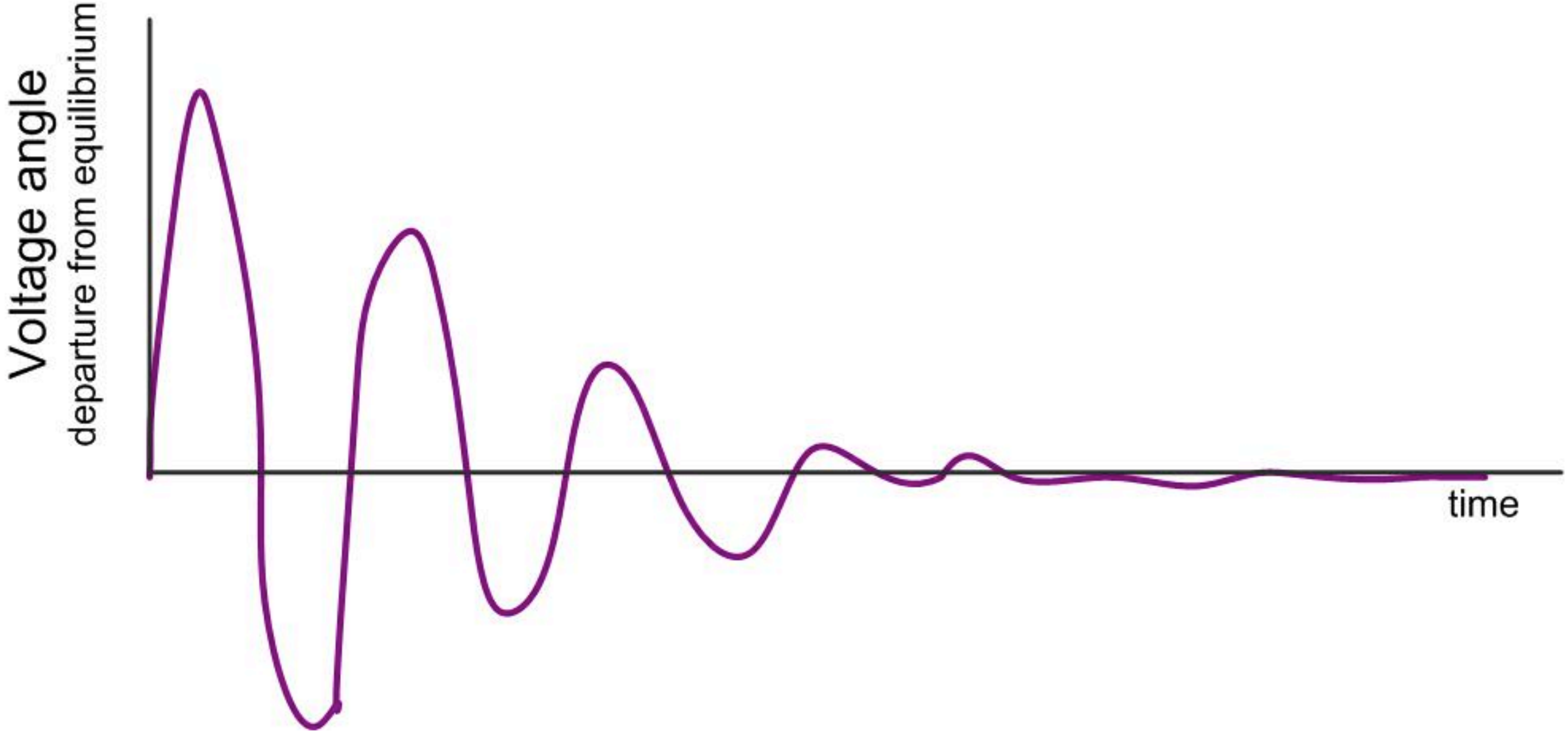
Generators are spinning at the same frequency, but Gen 1 leads Gen 2 by a voltage angle δ



The voltage angle δ is related to the amount of real power injected into the system by each generator

Generator stability:

Absorbing a sudden change in load



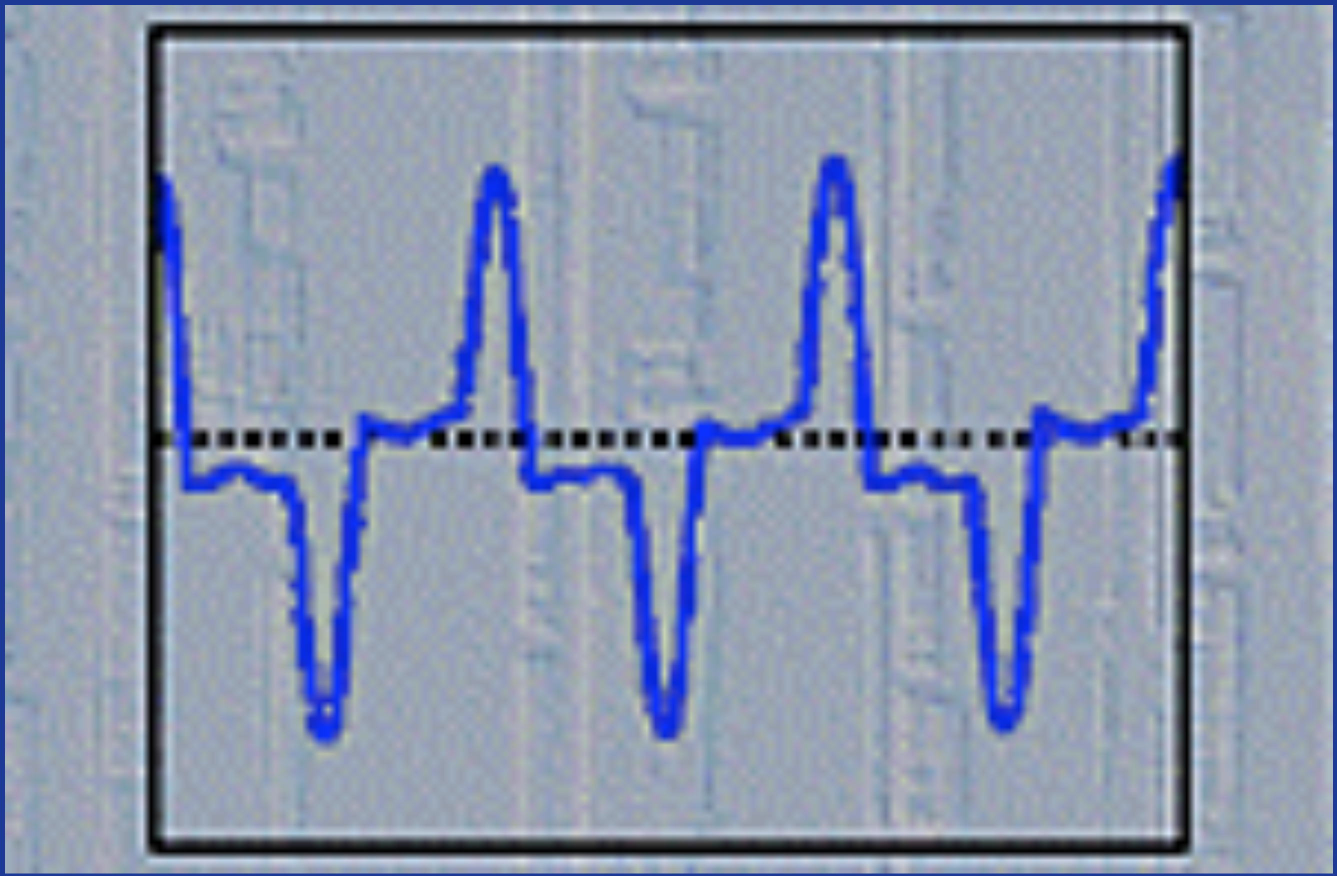
Questions about power systems

How to visualize the grid?
Why are grids large and interconnected?
Why transmit power at high voltages?
Why use alternating current?
Why use three phases?
What is reactive power?
How to predict power flow?
How to balance supply and demand?
How to assess performance?

Power System Performance Measures

Power quality:	voltage a.c. frequency waveform
Reliability:	outage frequency & duration probabilistic measures
Security:	contingency analysis

The a.c. sine wave and power quality: voltage magnitude, frequency, and waveform



www.niagaramohawk.com

Measures of reliability:

Outage frequency

Outage duration

Loss-of-load probability (LOLP)

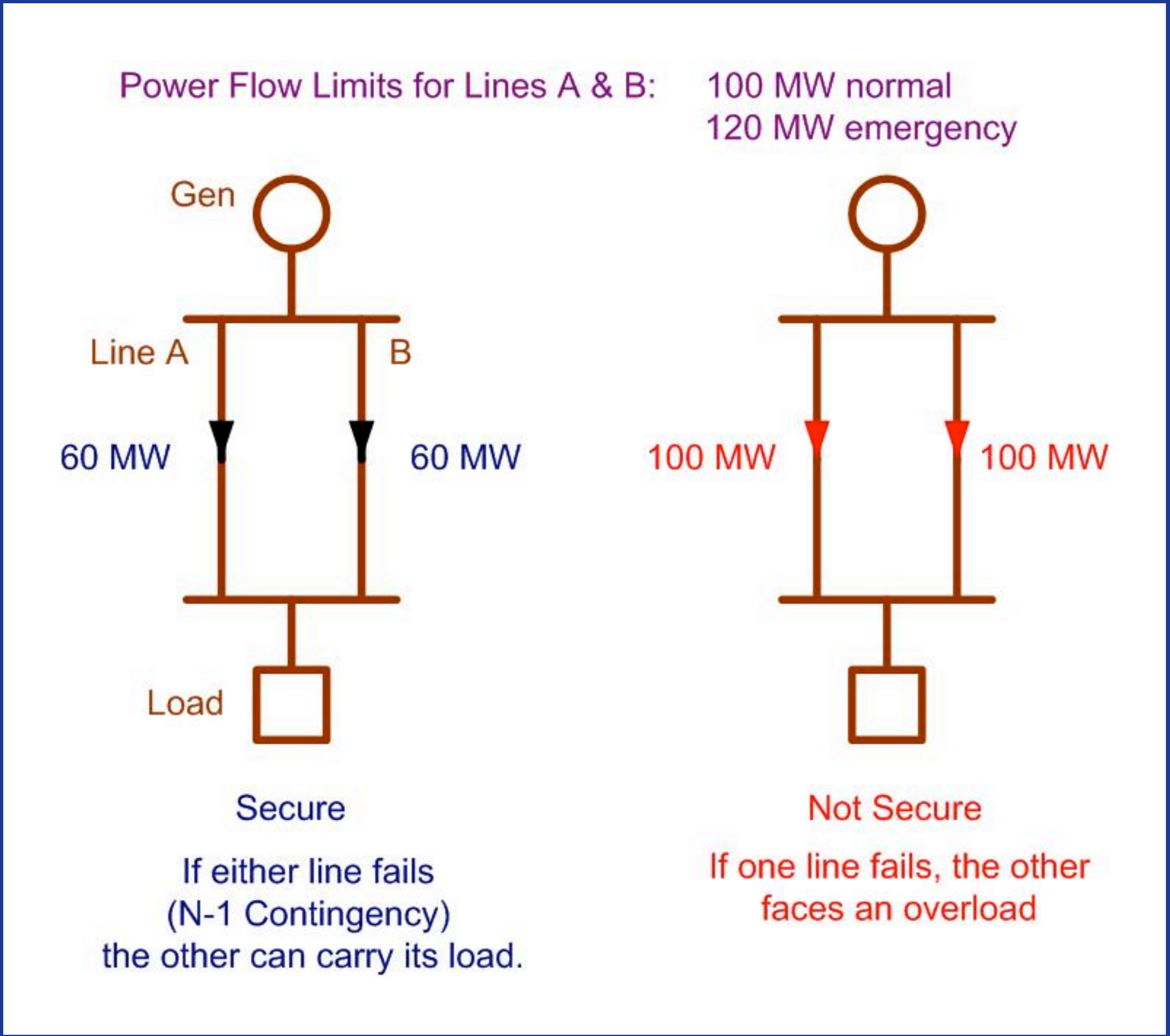
Loss-of-load expectation (LOLE)

Expected unserved energy (EUE)

Security:
The width of the operating envelope

Contingency Analysis and the N-1 Criterion

A “contingency”



Security
and the

N-1 Criterion

What is reliability worth?

Key concepts:

Obligation to serve

One-day-in-ten-years criterion

“Gold-plating”

Value of Service (VOS)

Human Factors

Distribution Engineers and Operators:

Different responsibilities,

different cultures


HIGH

Different Responsibilities

Sample engineering tasks:

Planning, equipment selection & sizing, innovation.

Engineers' responsibility:

Make system perform optimally under design conditions.

Sample operation tasks:

Switching, maintenance, service restoration.

Operators' responsibility:

Make system perform safely and minimize harm under any conceivable condition; avert calamity.

Different Cultures: Cognitive representations of distribution systems

Engineering representation:	Operator representation:
Abstract	Physical
Analytical	Holistic
Formal	Empirical
Deterministic	Fuzzy

Both are functional adaptations to work context; both are “correct”.

Desirable system properties...

for Engineers:

Efficiency
Speed
Information
Precision
Control

for Operators:

Safety
Robustness
Transparency
Veracity
Stability

Example: Efficiency vs. Robustness

How best to prevent an overload?

Approach I

Shift loads to utilize equipment capacity evenly.

Approach II

Have ample spare capacity to accommodate load peaks.

Example: Information vs. Transparency

Which is more useful?

Option 1

Real-time data from 100 sensor points

Option 2

Data from 5 key points with changes highlighted

Example: Precision vs. Veracity

Measurement A   100 ± 10%

Absolutely reliable source; if it failed, you'd know.

Measurement B   100 ± 1%

Very small chance the measurement has nothing to do with reality and you'd have no idea.

Q: Which is better information?

A: Depends on what you want to use it for.

(If the information is wrong, will it kill anyone?)

Example: Control vs. Stability

Scenario (i)

Operators are able to measure and influence a parameter so as to keep it within a narrow range.

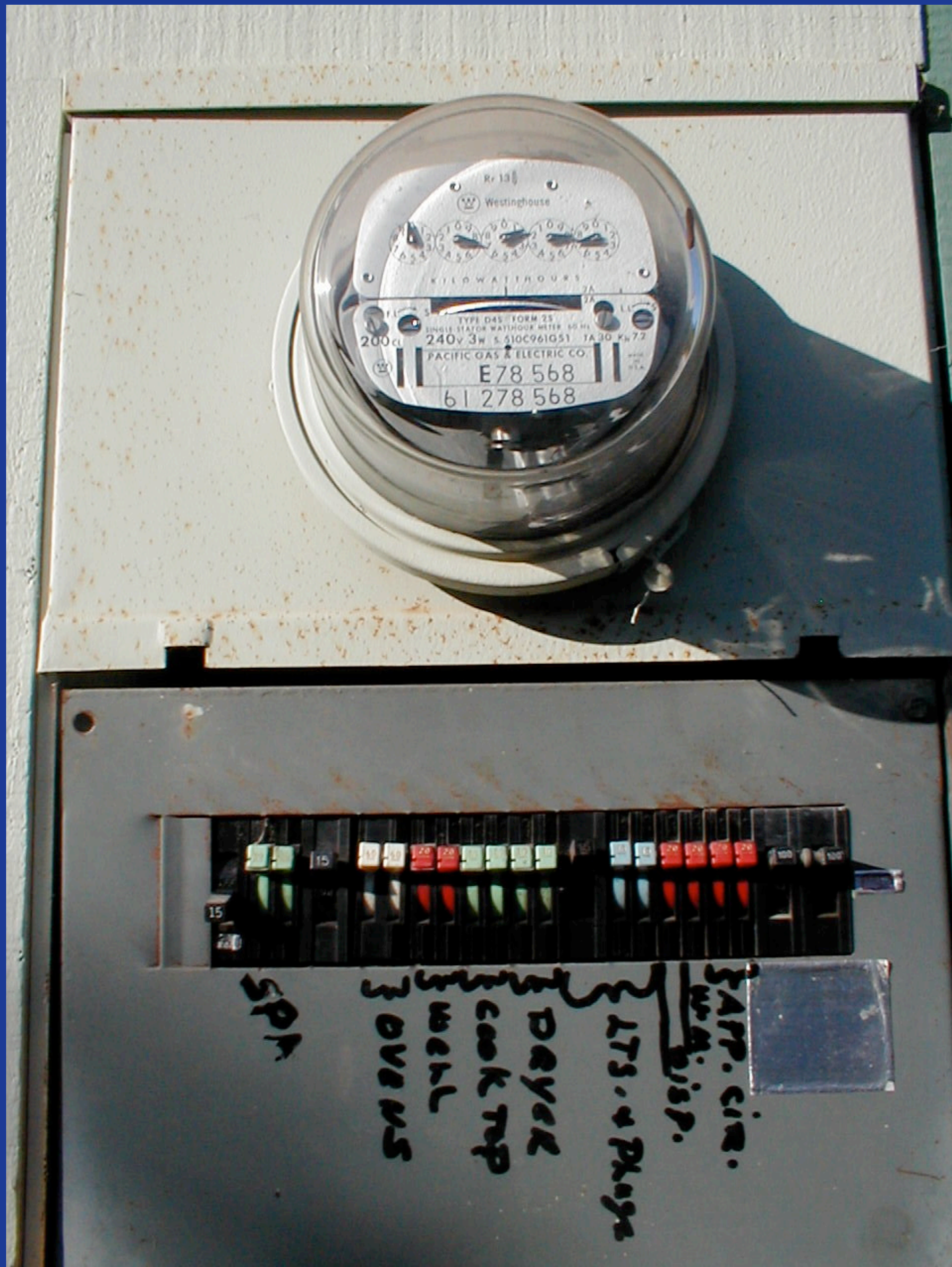
Scenario (ii)

The parameter tends to stay within a safe range by itself. Nobody expects operators to intervene constantly.

Which is preferable?

Distribution Systems

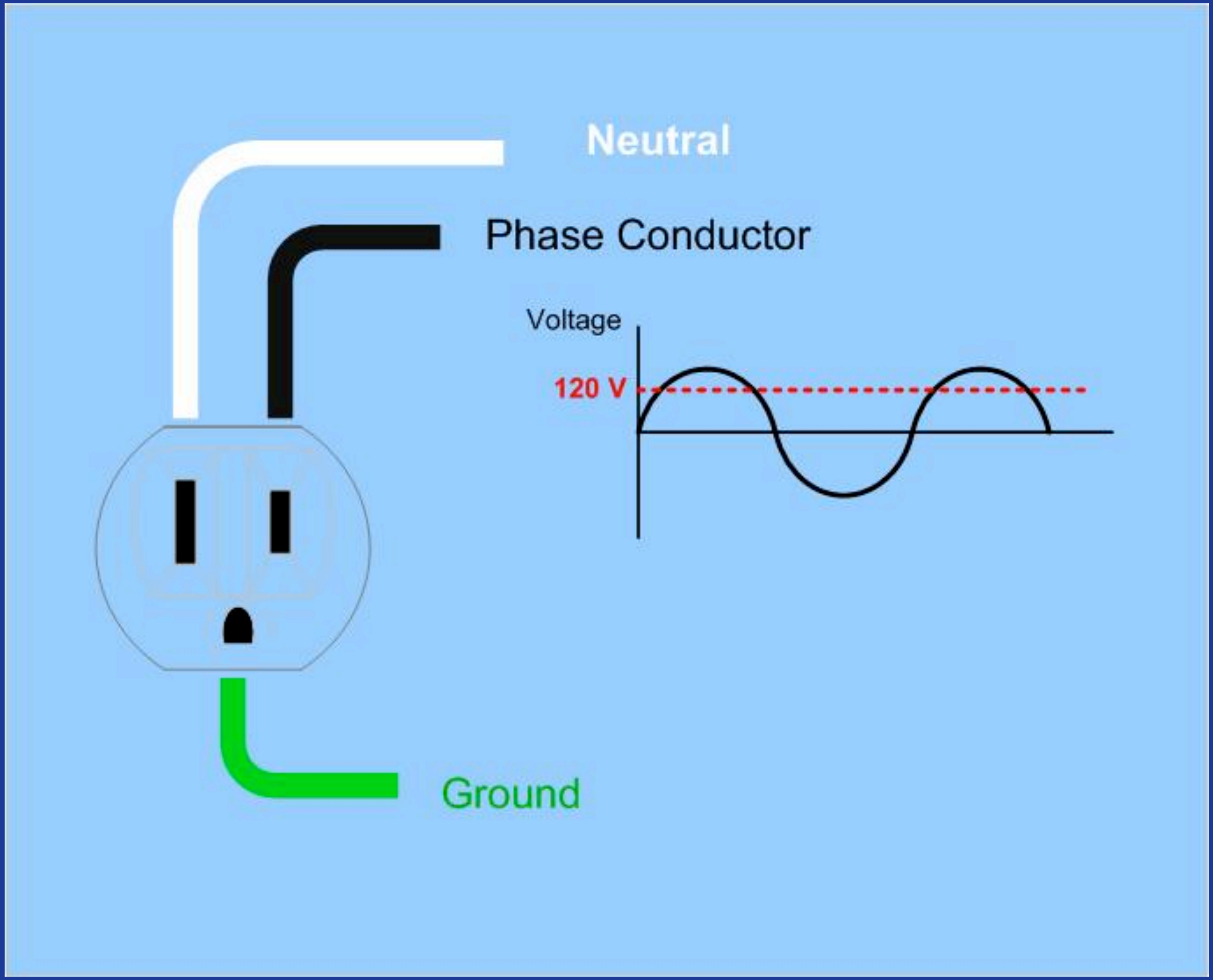
My PG&E service entrance

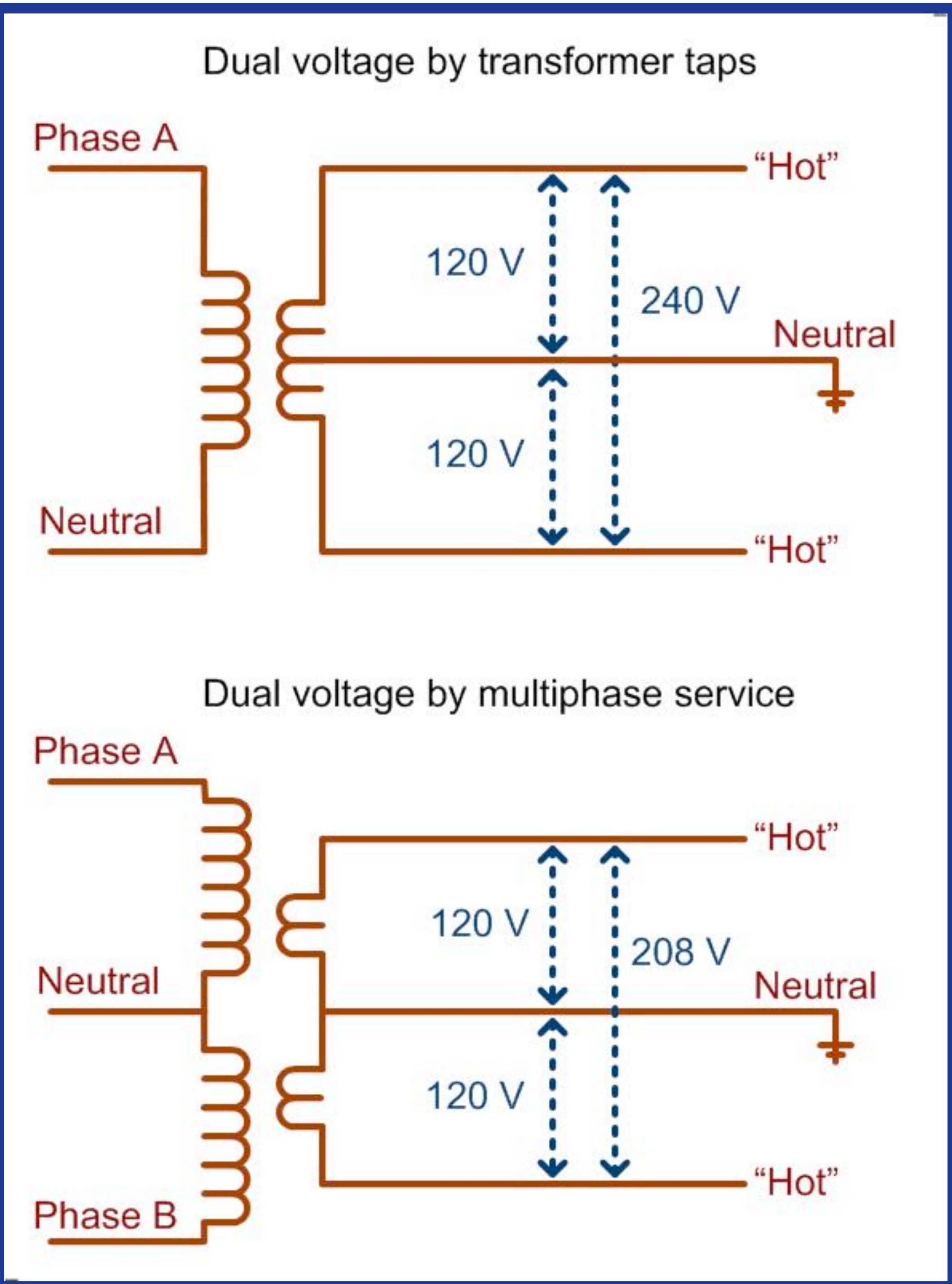


My meter & circuit breaker panel

(Note general funkiness.)

The familiar 120V a.c. outlet

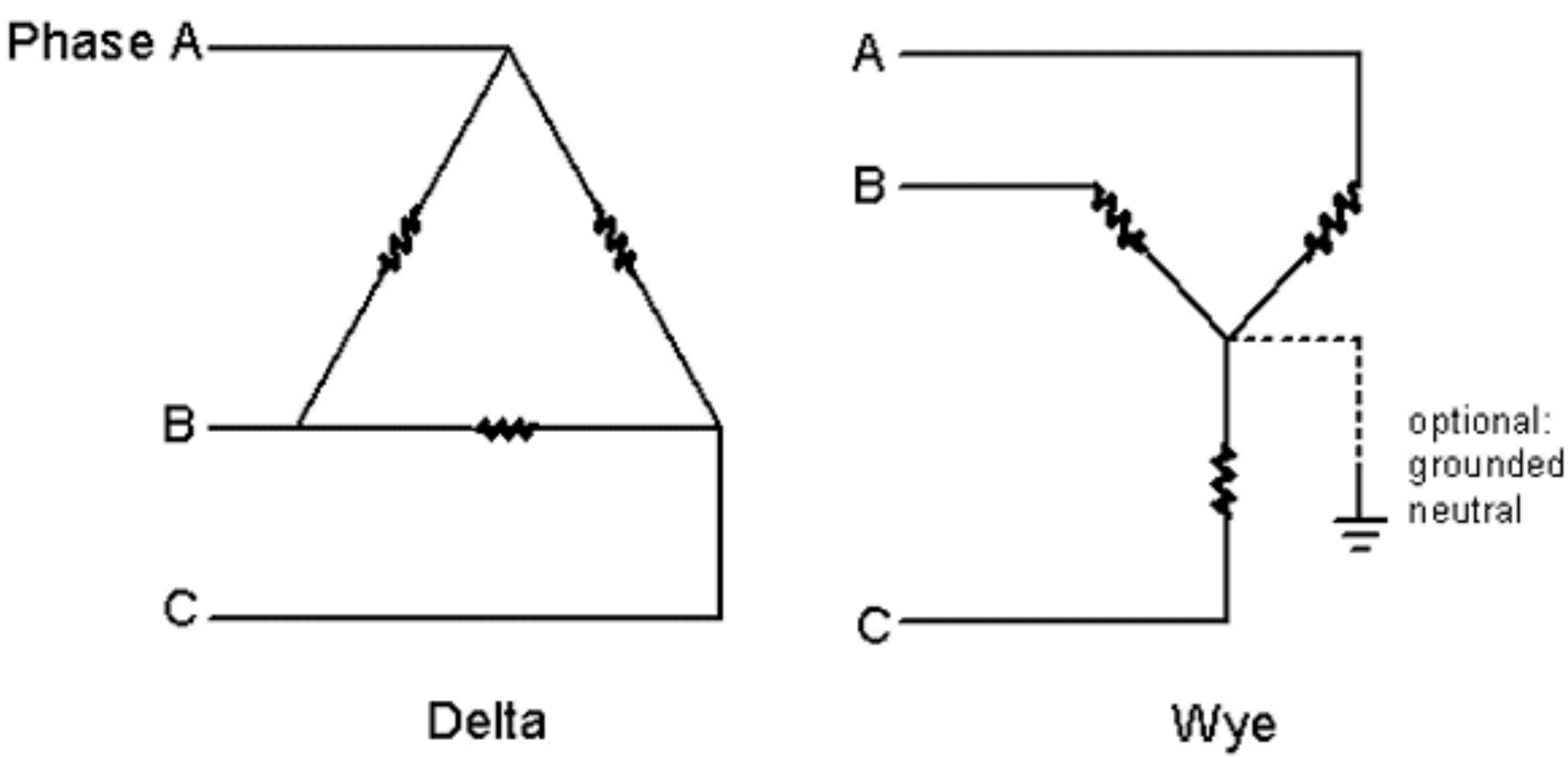




Single-phase 120/240 service is obtained by tapping the same transformer in different places.

120/208 service is obtained with a phase-to-ground and a phase-to-phase connection.

Two configurations for connecting single phase loads to a three phase system



Types of Loads

- Purely resistive loads
  - Incandescent lamps
  - Heaters: range, toaster, iron, space heater…
- Motors (inductive loads)
  - Pumps: air conditioner, refrigerator, well
  - Power tools
  - Household appliances: washer/dryer, mixer…
- Electronics with transformers (inductive loads)
  - Power supply for computer
  - Battery chargers, adaptor plugs
  - Microwave oven
  - Fluorescent ballast

Distribution system design & components

- Distribution transformers
- Primary & secondary distribution lines
- Radial, loop & network systems
- Protection
- Voltage regulation

My neighbor's transformer

Upper lines: Primary distribution (12 kV)

Going out & underground: Secondary distribution (120/240V)
Lower lines: cable, phone

Single-
Phase
Transformer

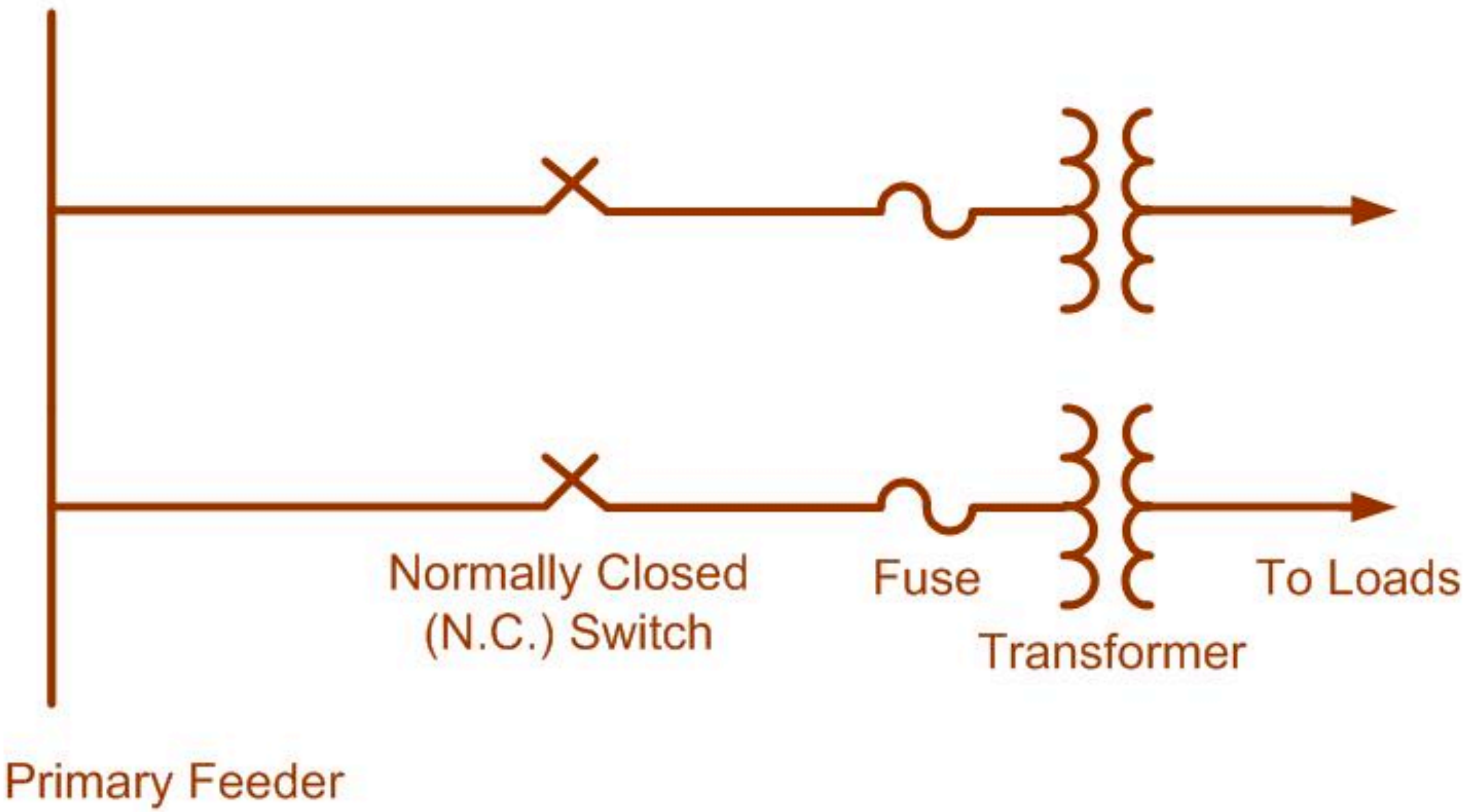
Three-phase primary distribution circuit and single-phase lateral

Three-phase distribution circuit from substation, going underground

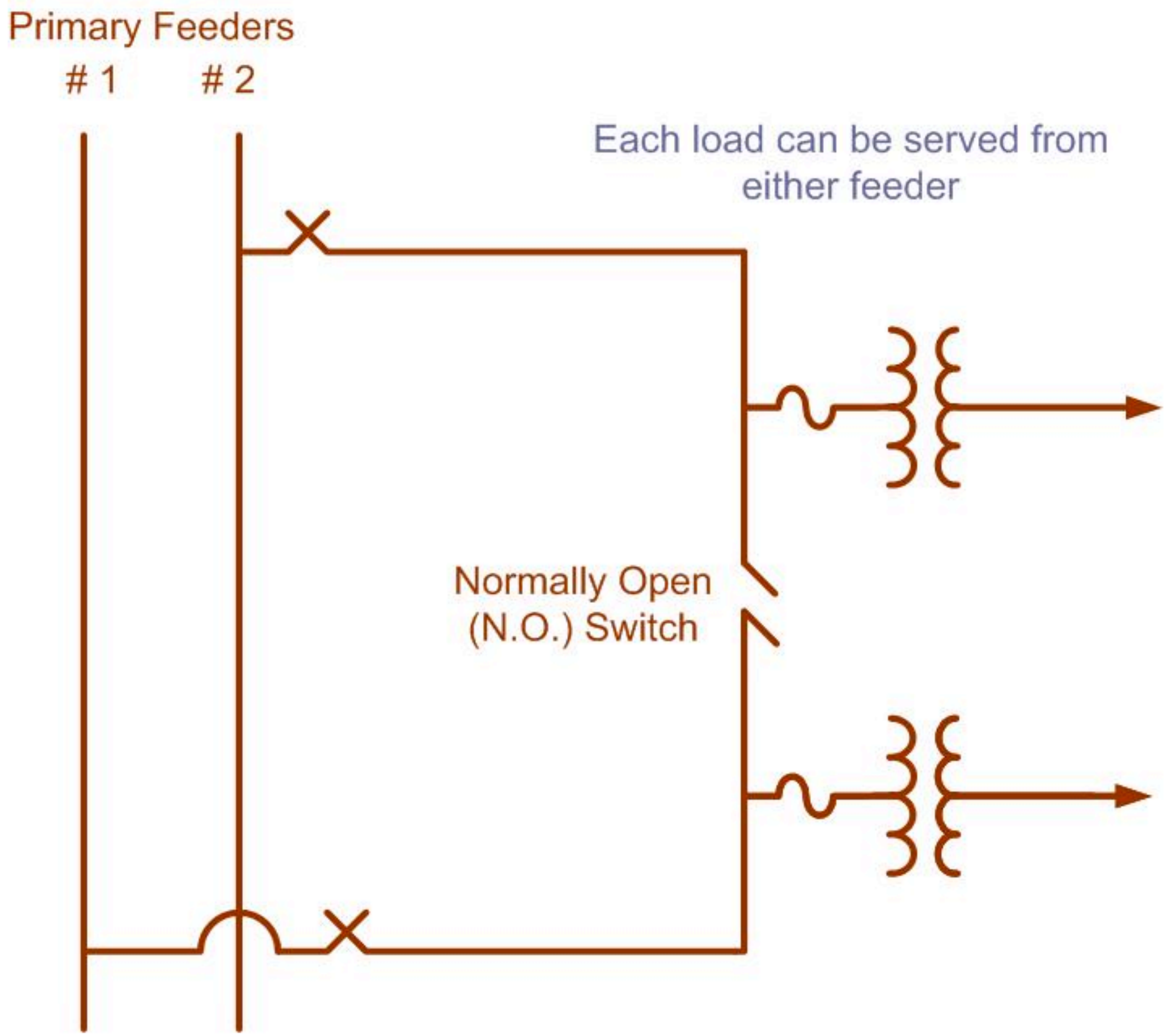
Distribution System Topology:

Radial, Loop and Network Designs

Basic Radial System

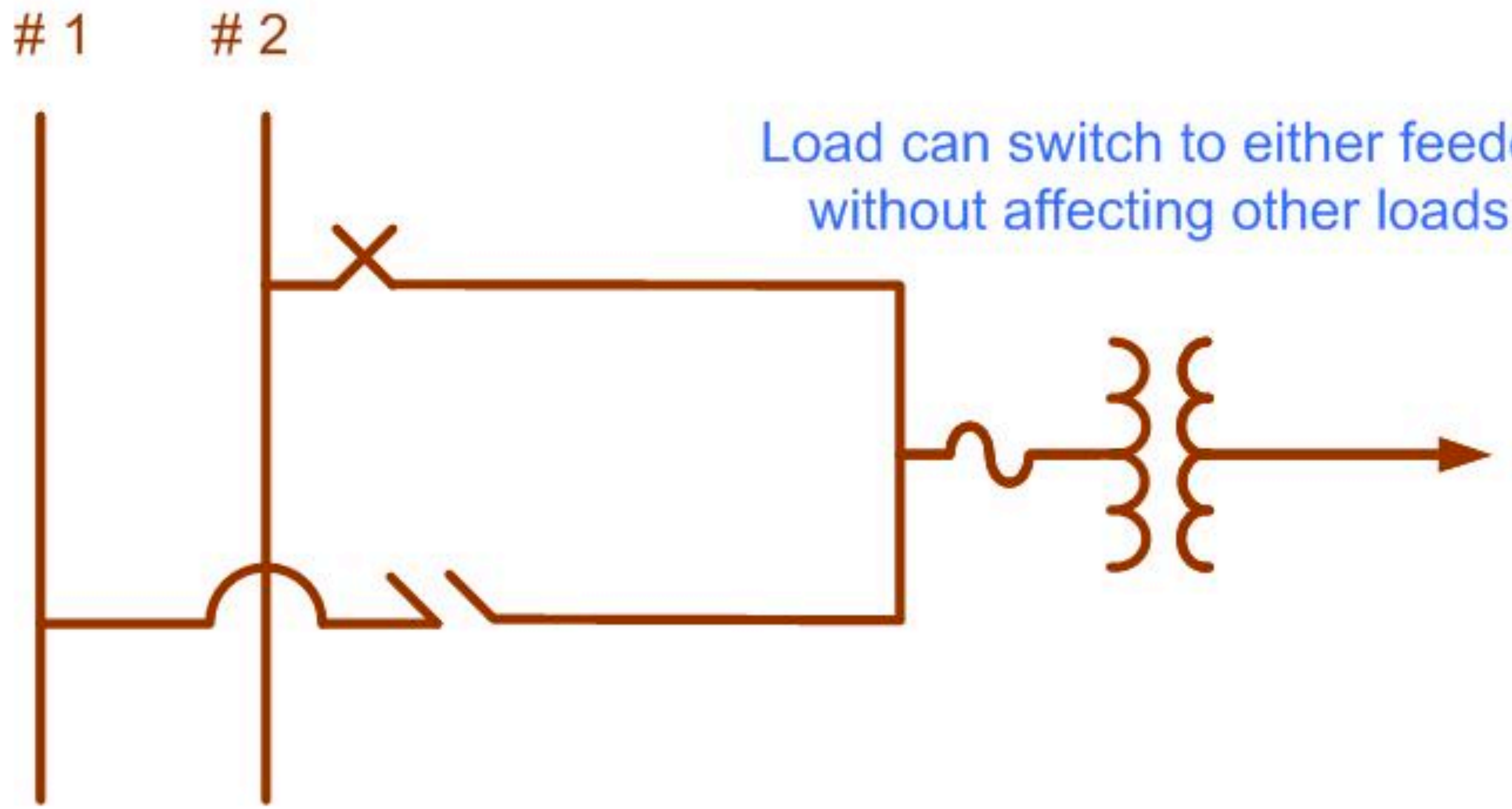


Loop System



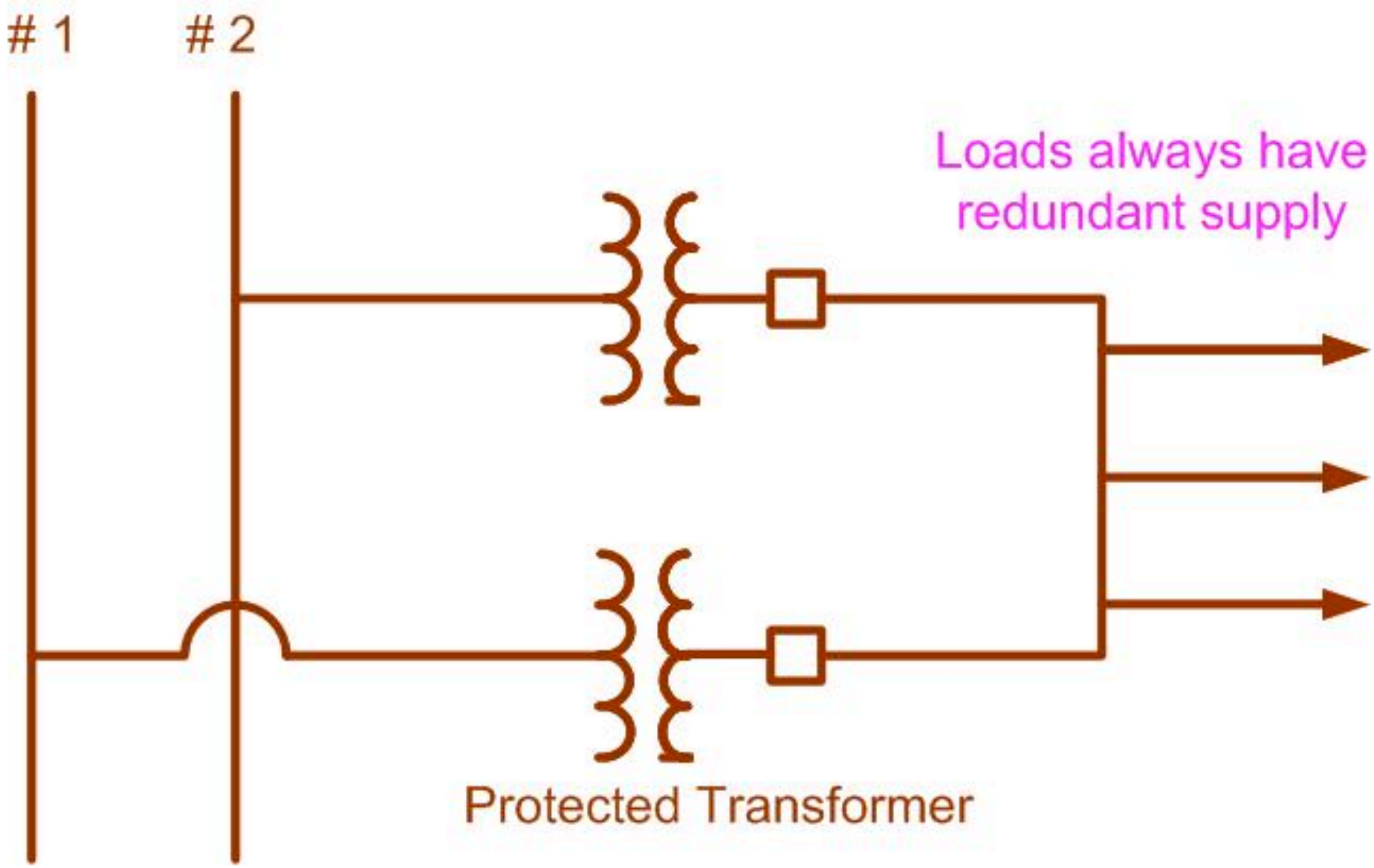
Primary Feeders
1
2
Each load can be served from either feeder
Normally Open (N.O.) Switch

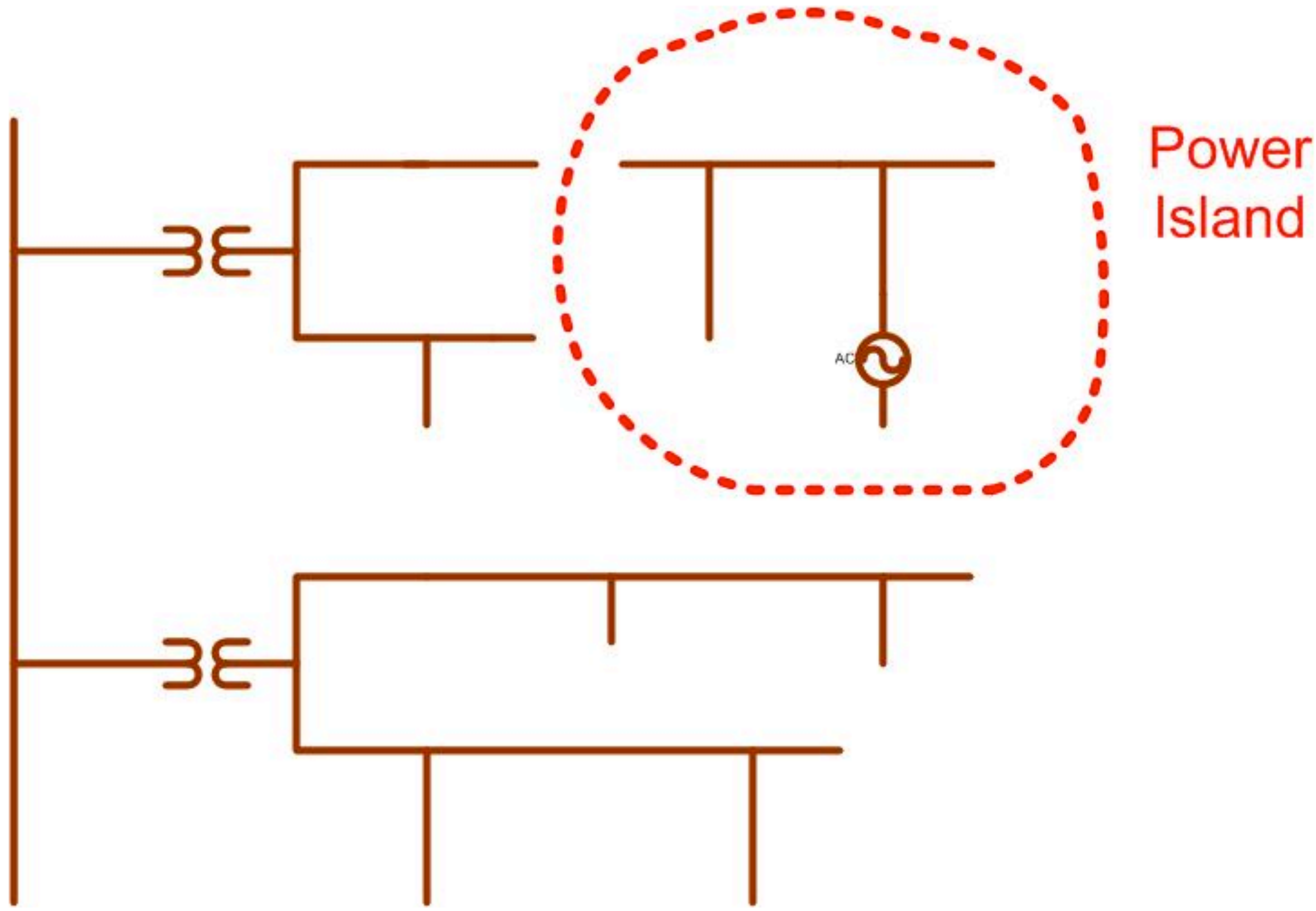
Primary Selective System



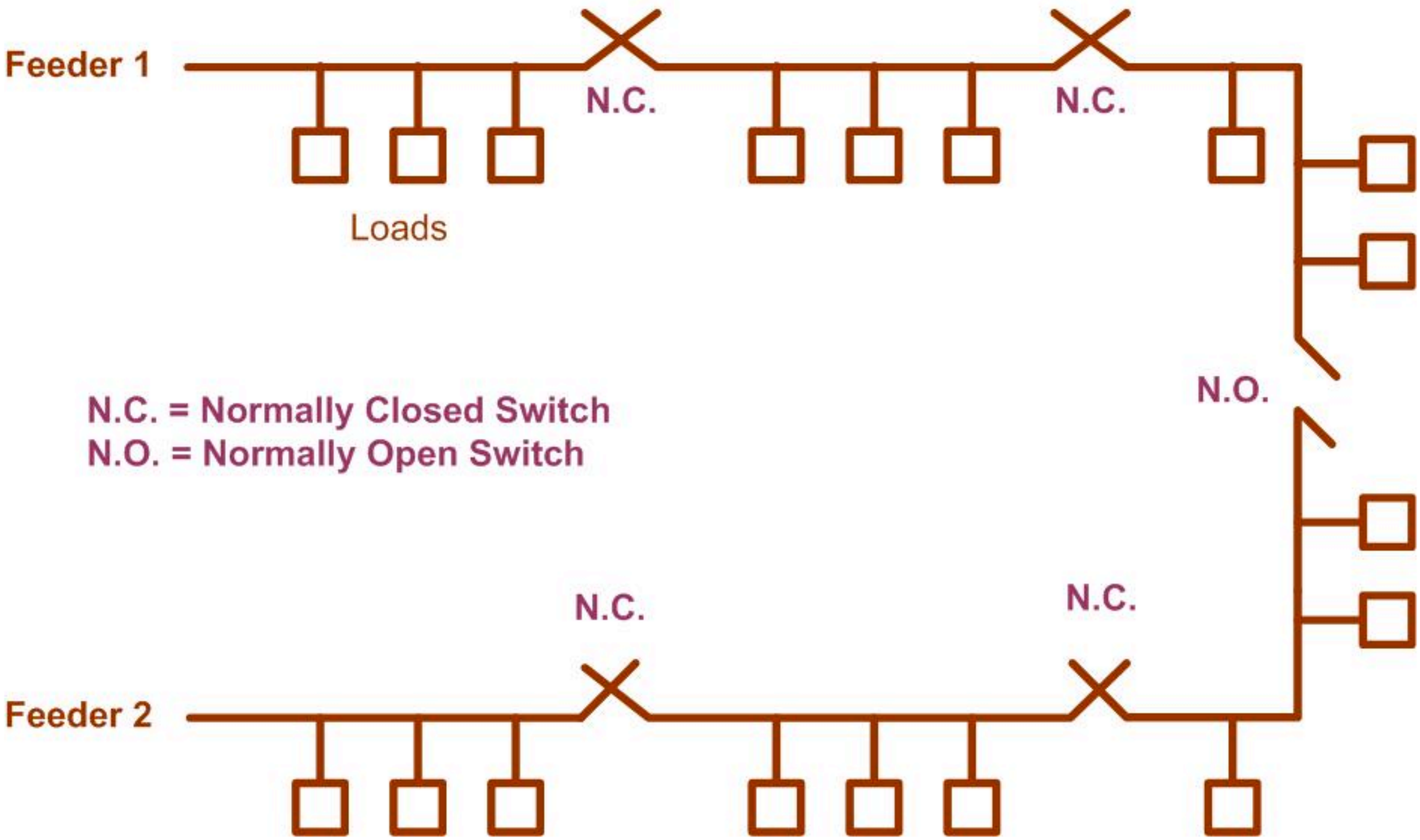
Load can switch to either feeder without affecting other loads

Spot Network

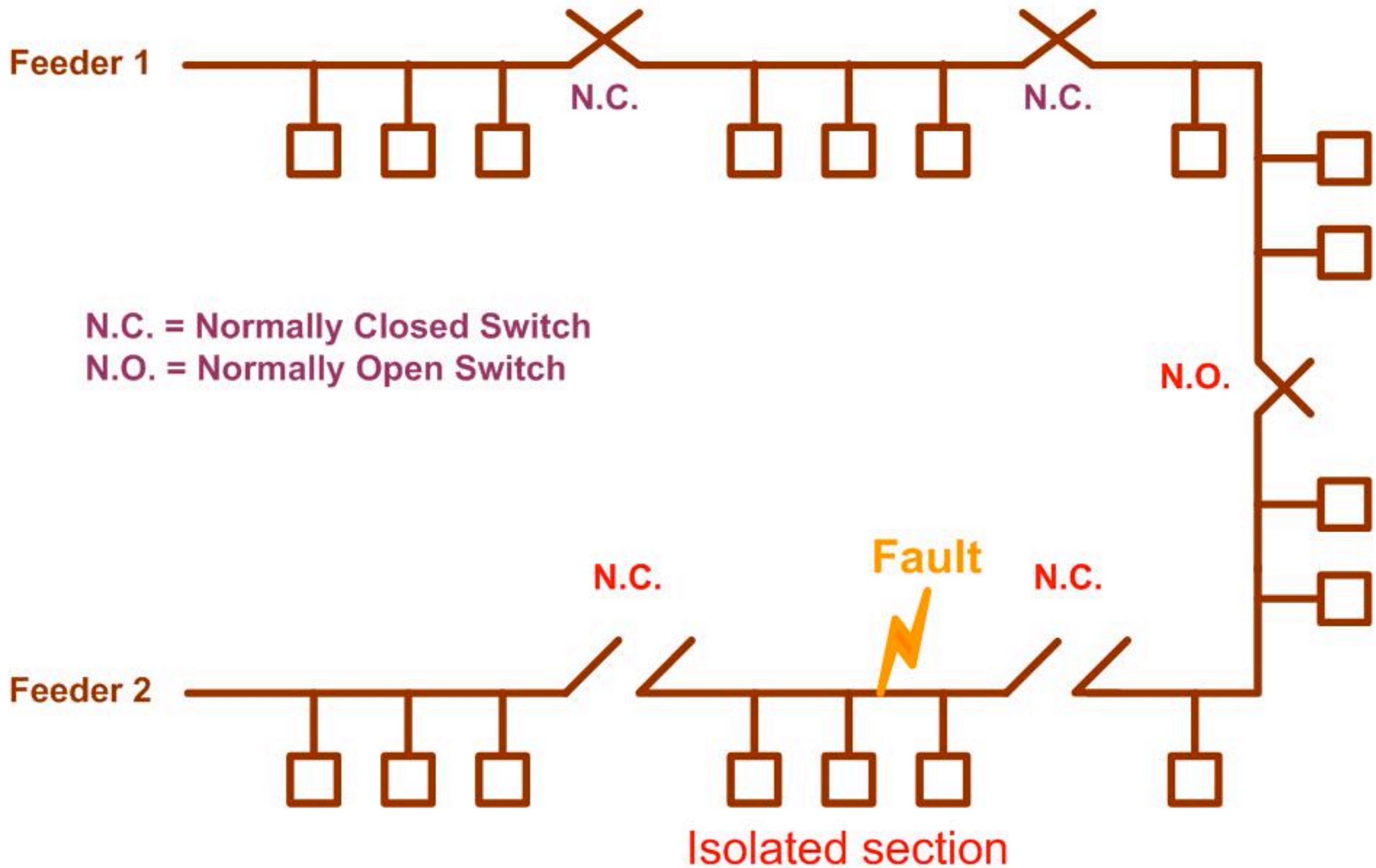


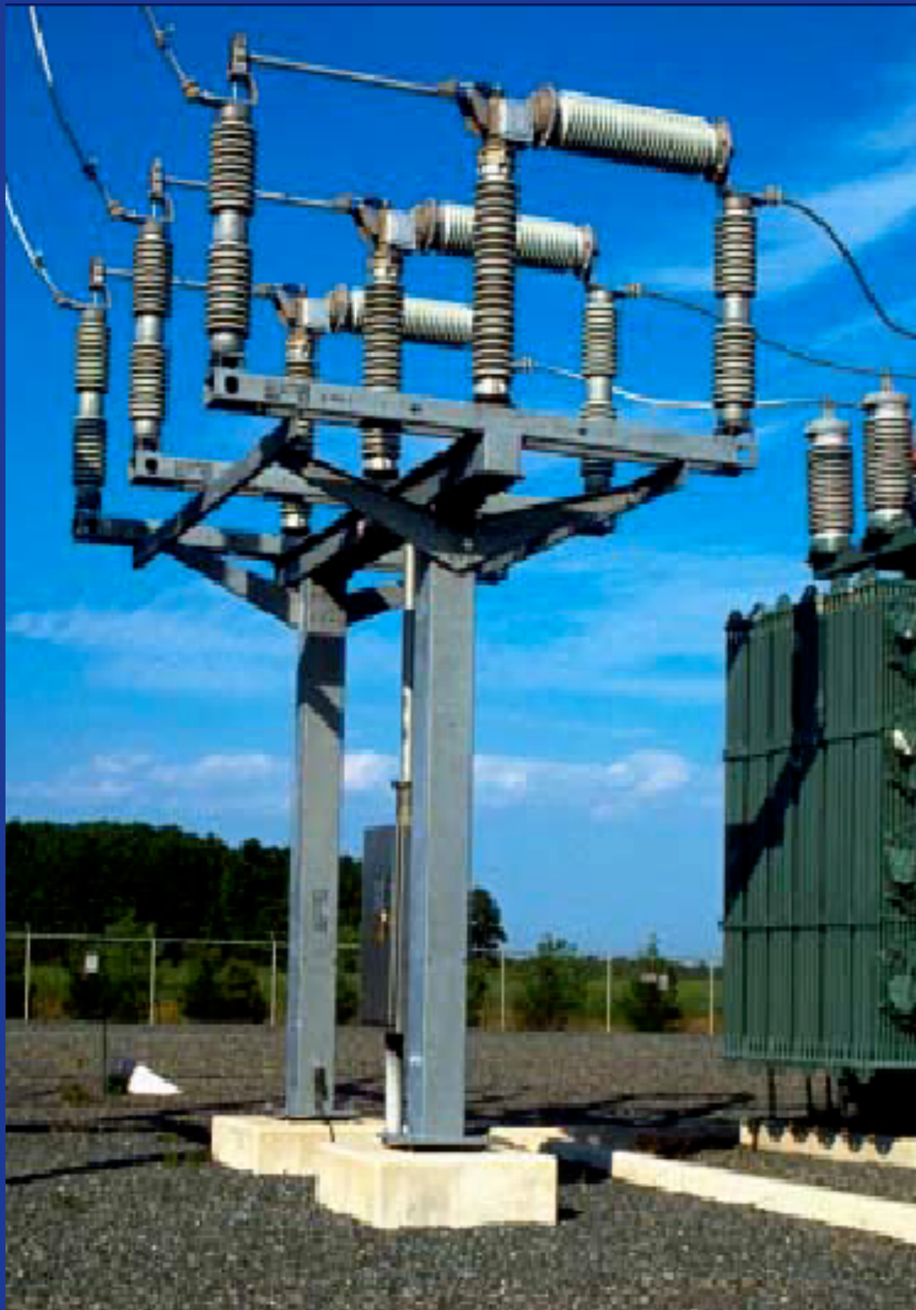

Power
Island
AC

Sectionalizing a Loop System: Before



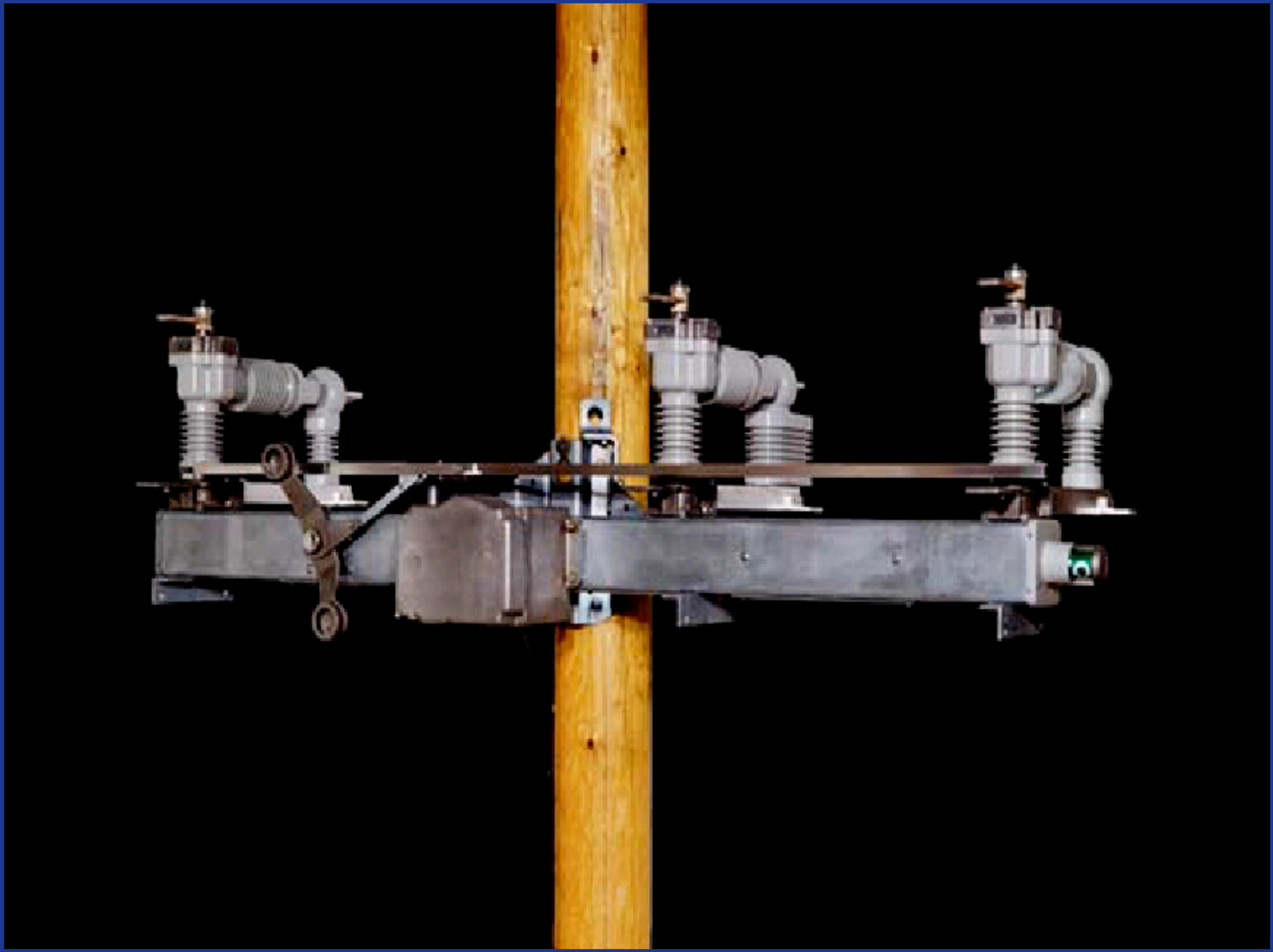
Sectionalizing a Loop System: After





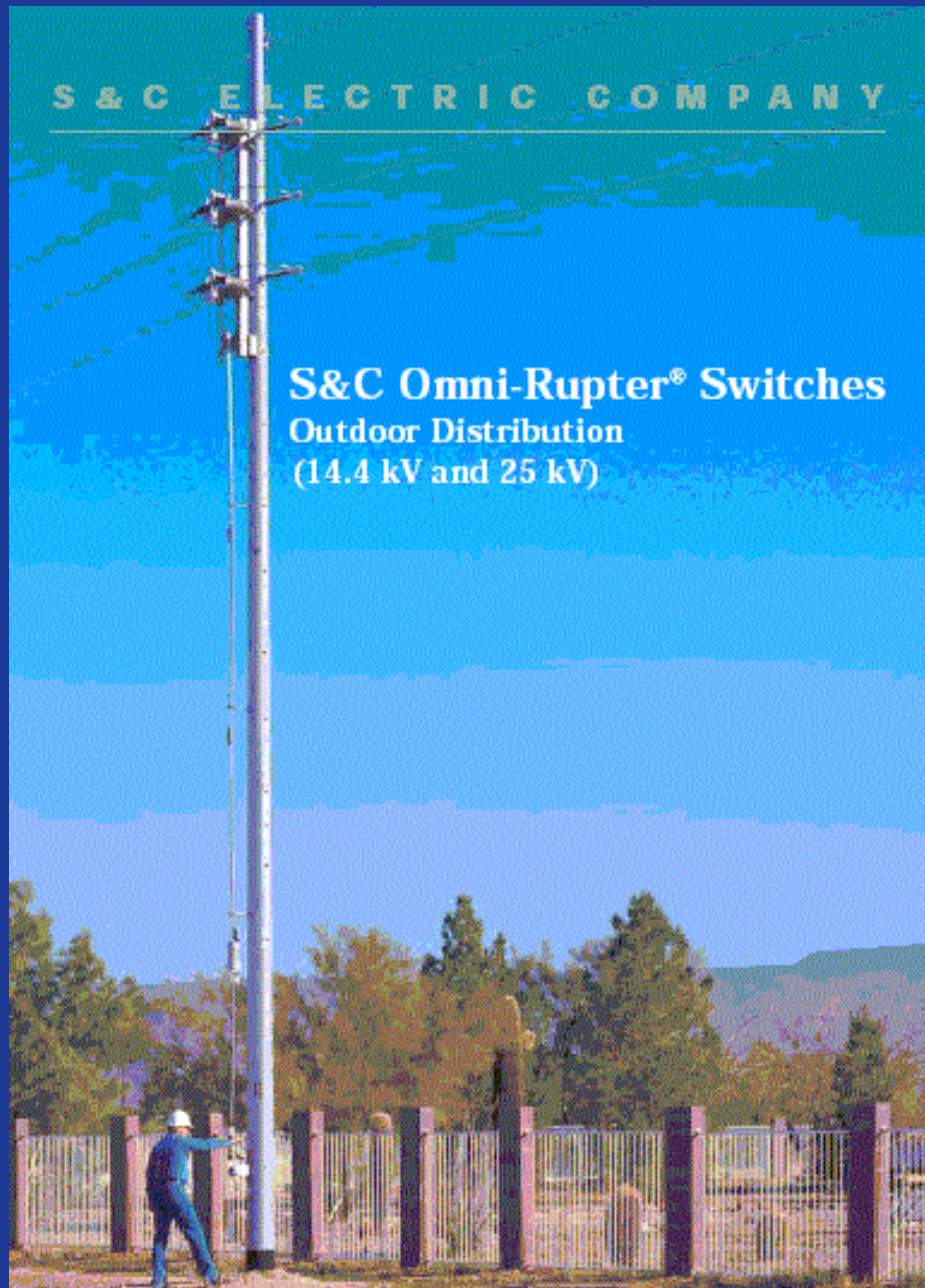
115kV Switch
(S&C)

Air Switch



ScadaMate Switch (S&C)

Overhead
Switch


S&C ELECTRIC COMPANY
S&C Omni-Rupter® Switches
Outdoor Distribution
(14.4 kV and 25 kV)


WARNING
Hazardous Voltage
CAUTION
CASE GROUNDED
8 6 4
PG&E
12KV

Recloser

Underground
Switch

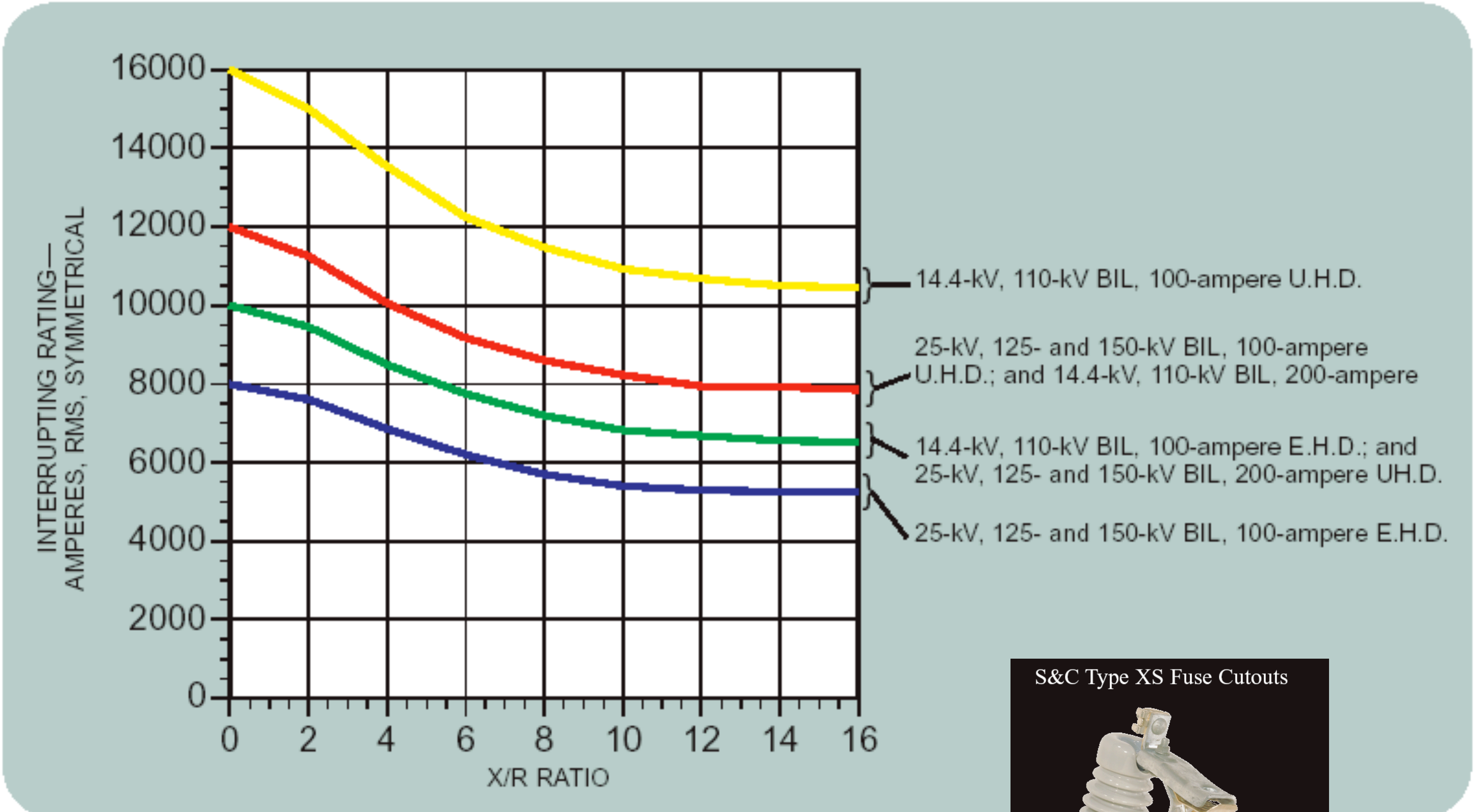
Substation circuit breaker (S&C)

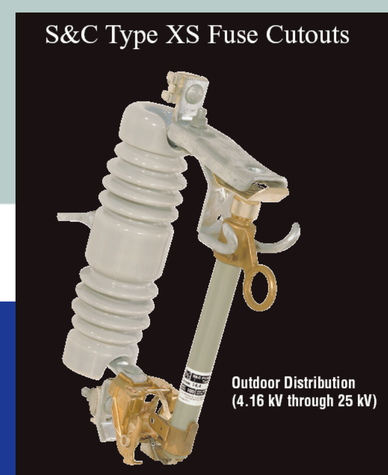

INFORMATION
TAG

S&C Type XS Fuse Cutouts

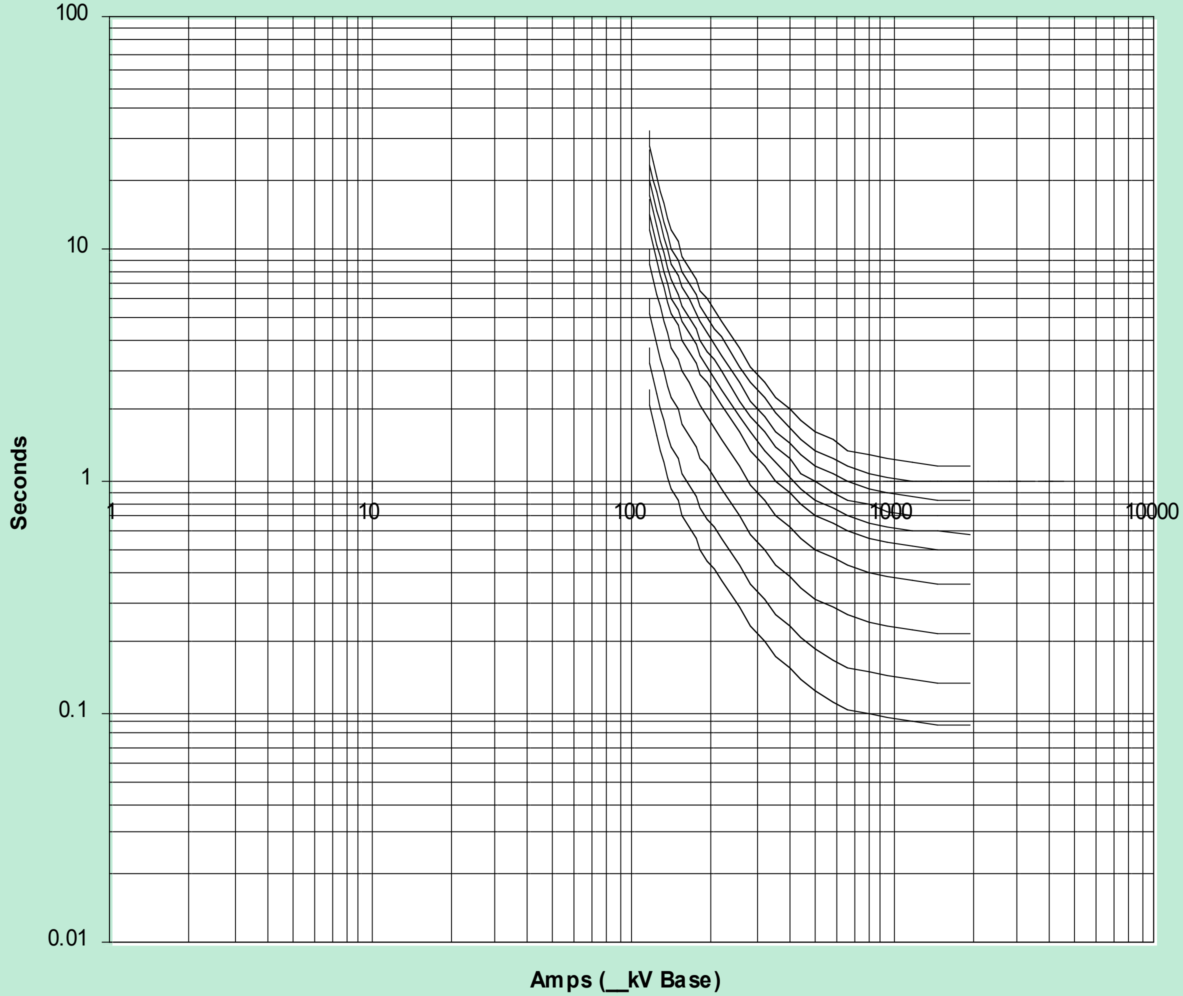
Outdoor Distribution
(4.16 kV through 25 kV)

Symmetrical Interrupting Ratings at Various X/R Ratios

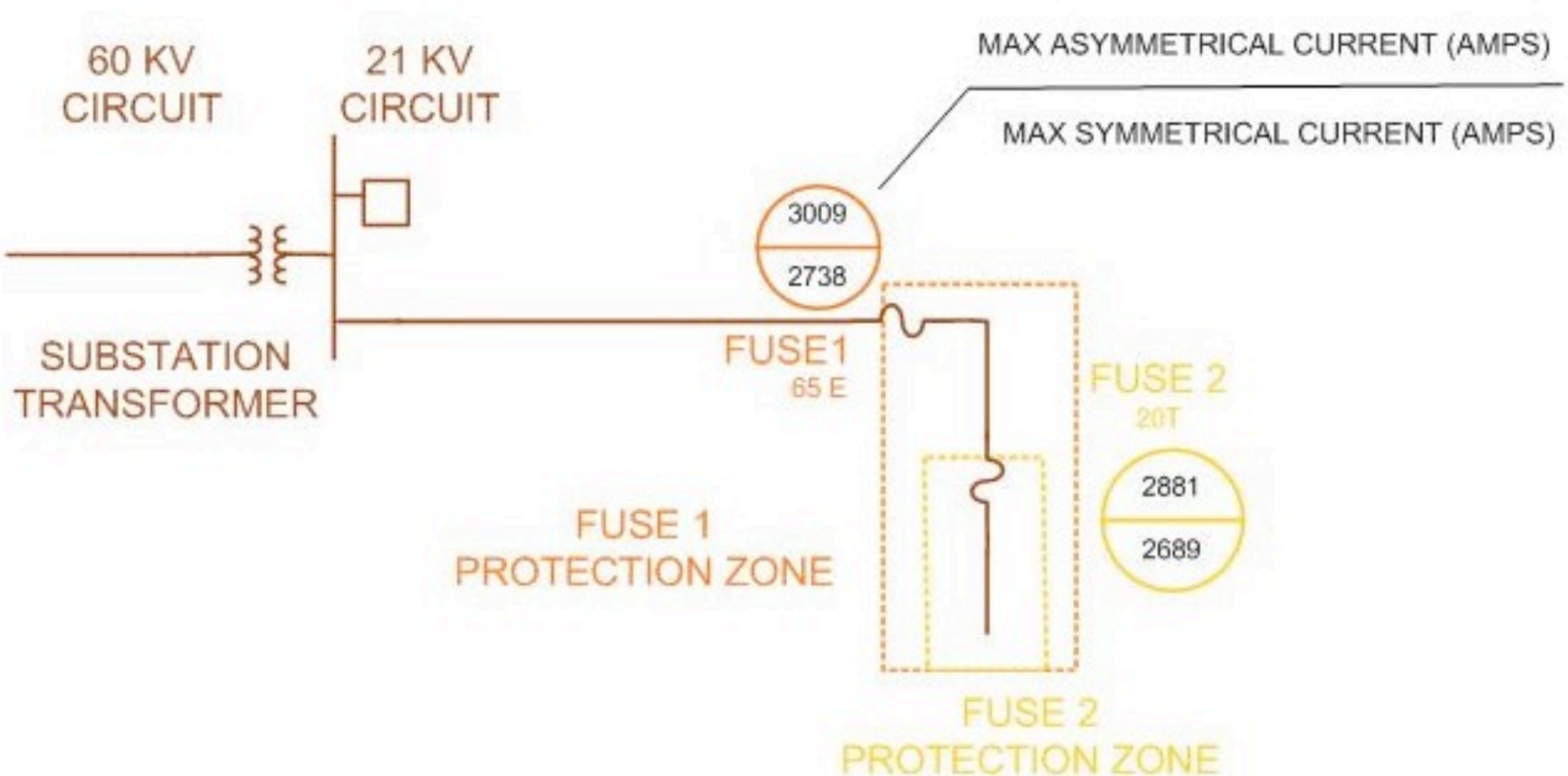


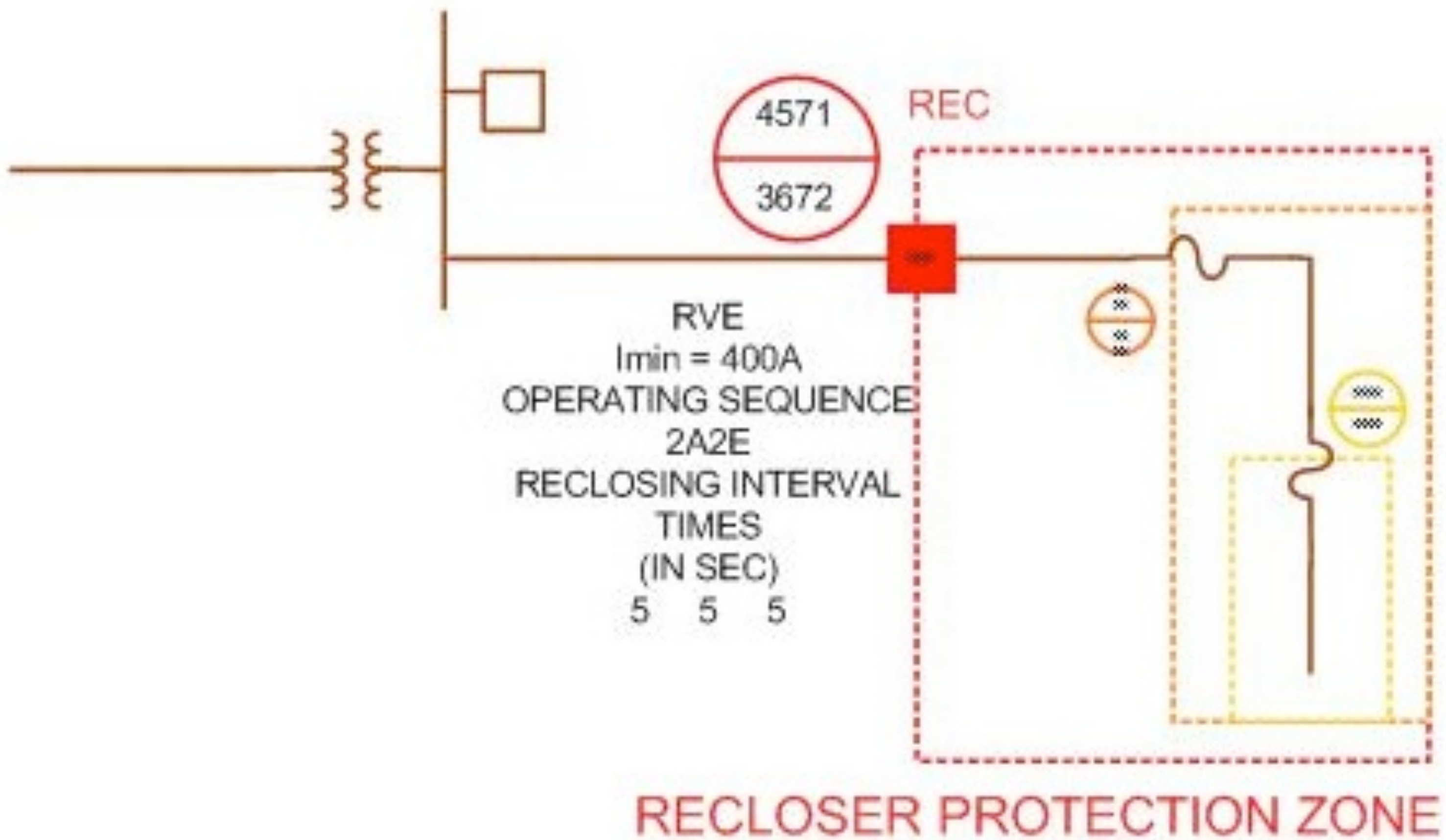


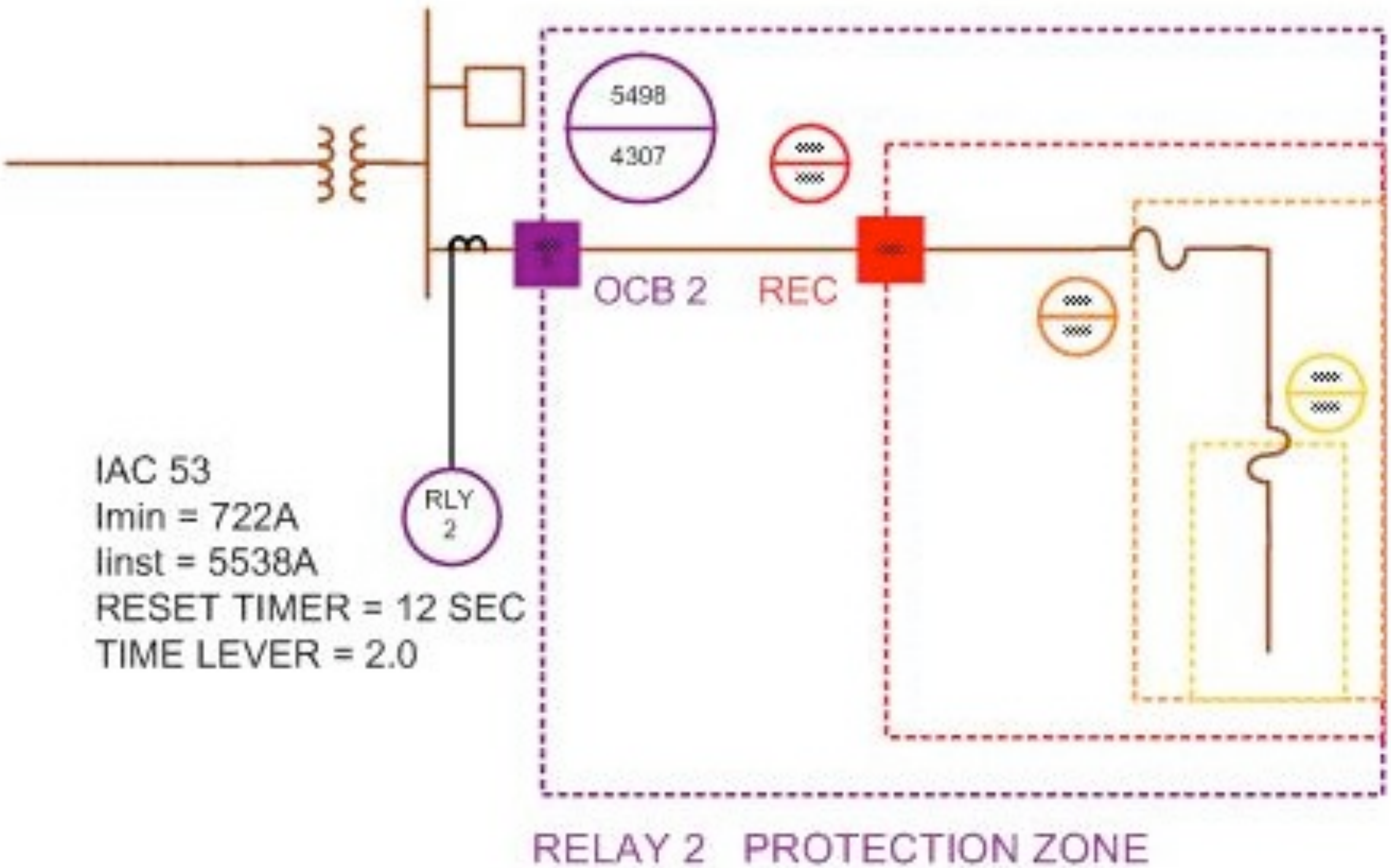
Curve Coordination Sheet



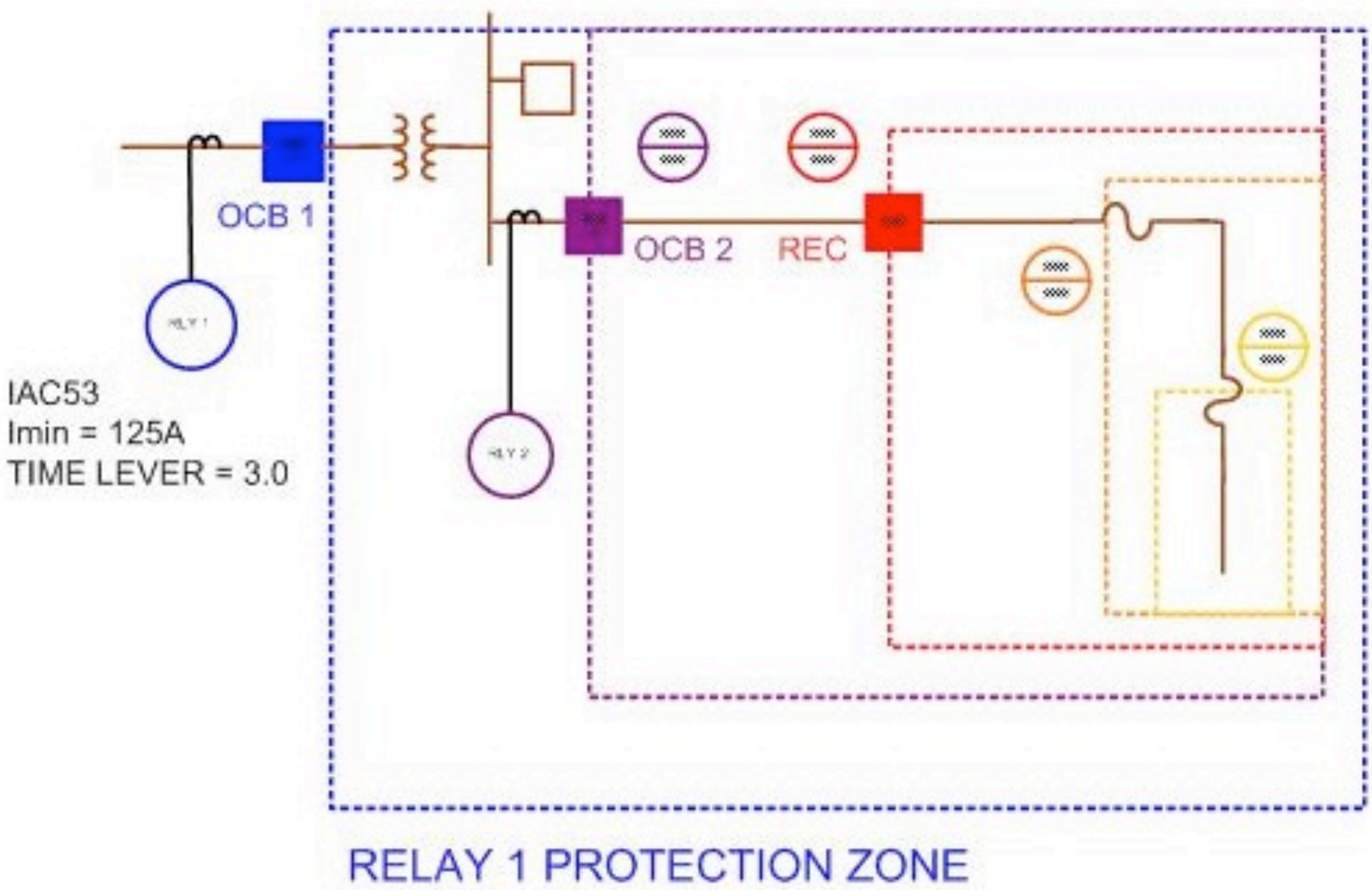
Sample Circuit for Coordination Study of Various Overcurrent Protective Devices




4571
3672
REC
RVE
Imin = 400A
OPERATING SEQUENCE
2A2E
RECLOSING INTERVAL
TIMES
(IN SEC)
5 5 5
RECLOSER PROTECTION ZONE

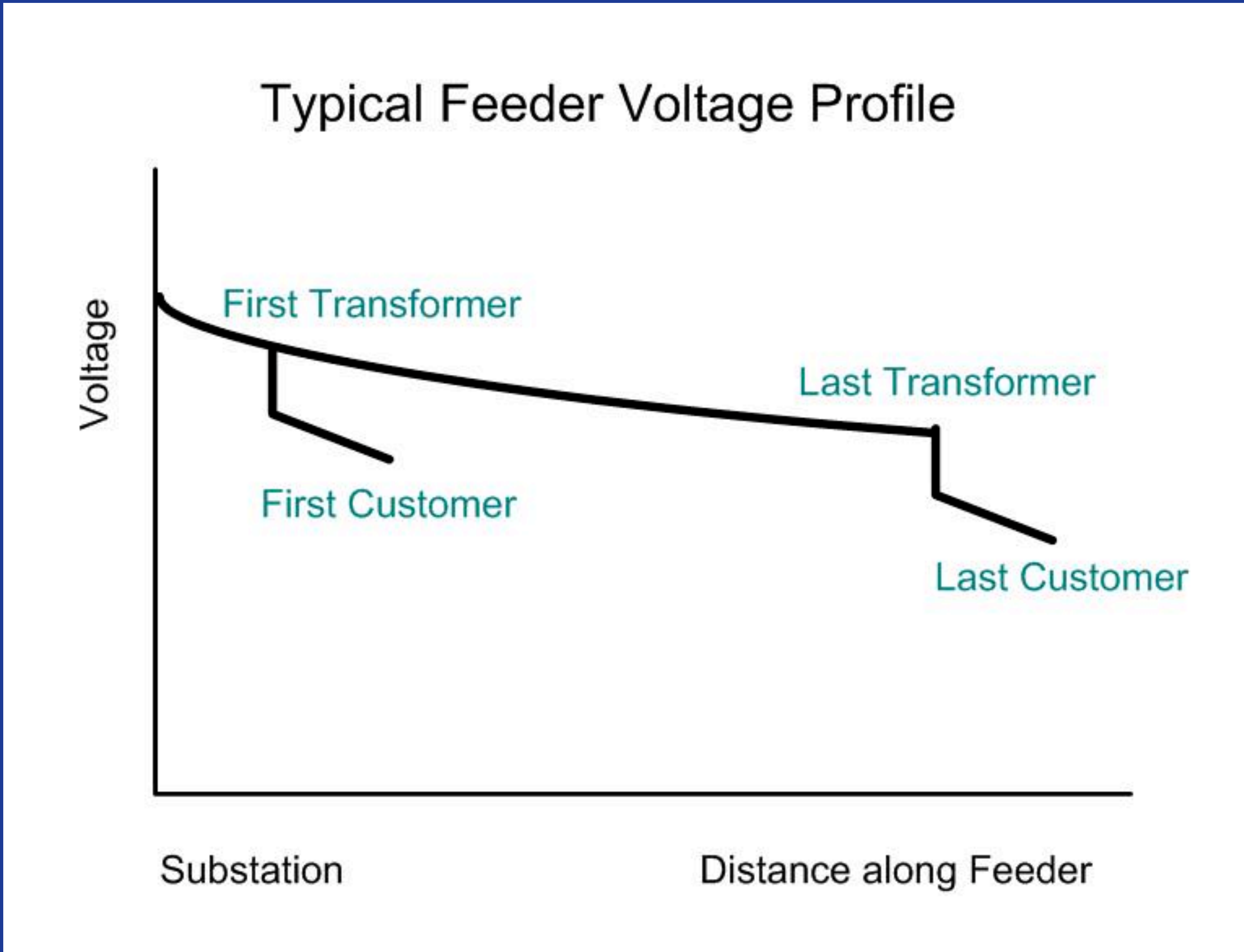

5498
4307
OCB 2
REC
IAC 53
Imin = 722A
Iinst = 5538A
RESET TIMER = 12 SEC
TIME LEVER = 2.0
RLY 2
RELAY 2 PROTECTION ZONE

Five Devices Coordinated

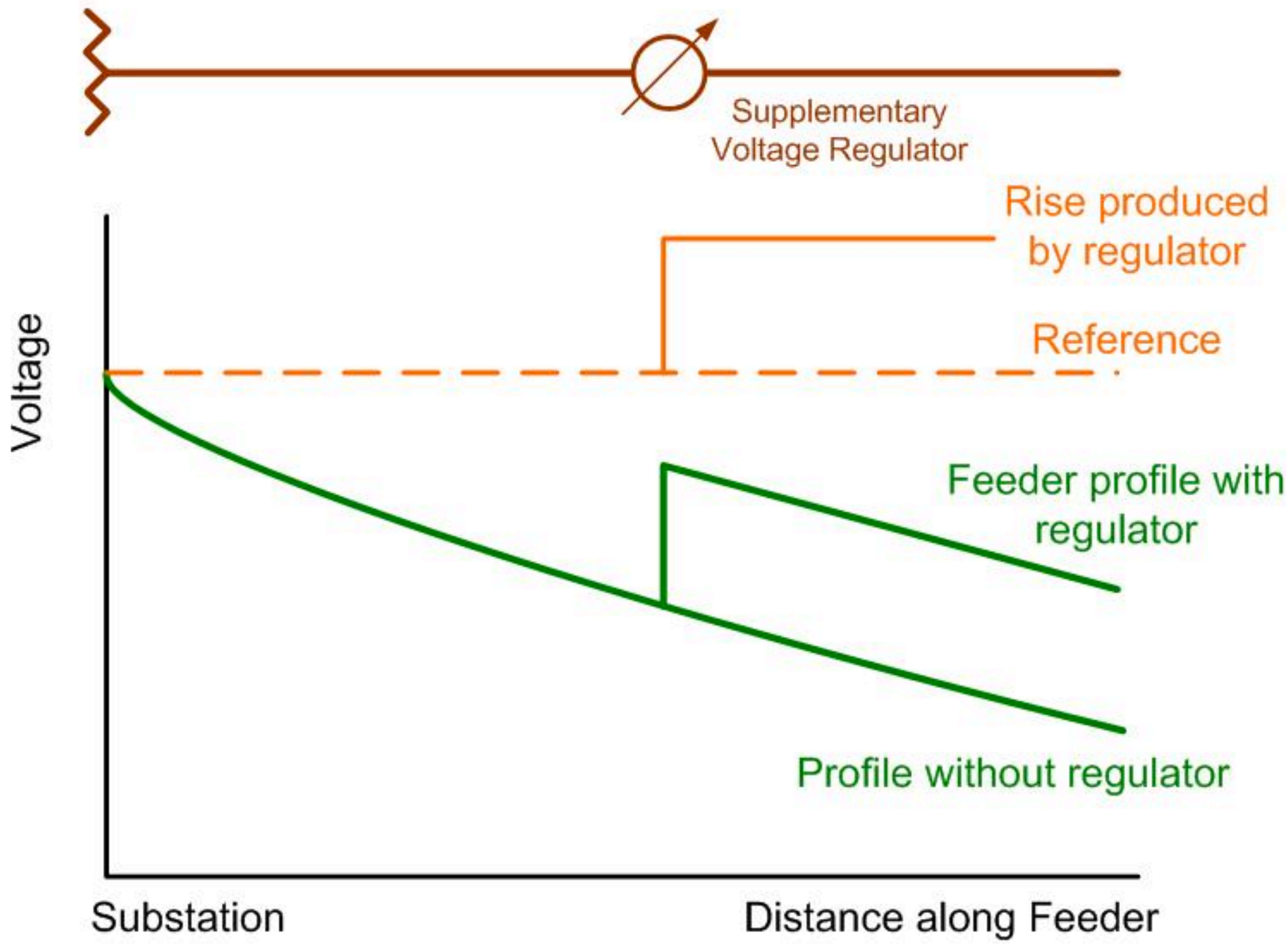


Voltage drop along a distribution feeder

V_{DROP} is a function of current (load), line resistance, and voltage control equipment settings (transformers, capacitors)

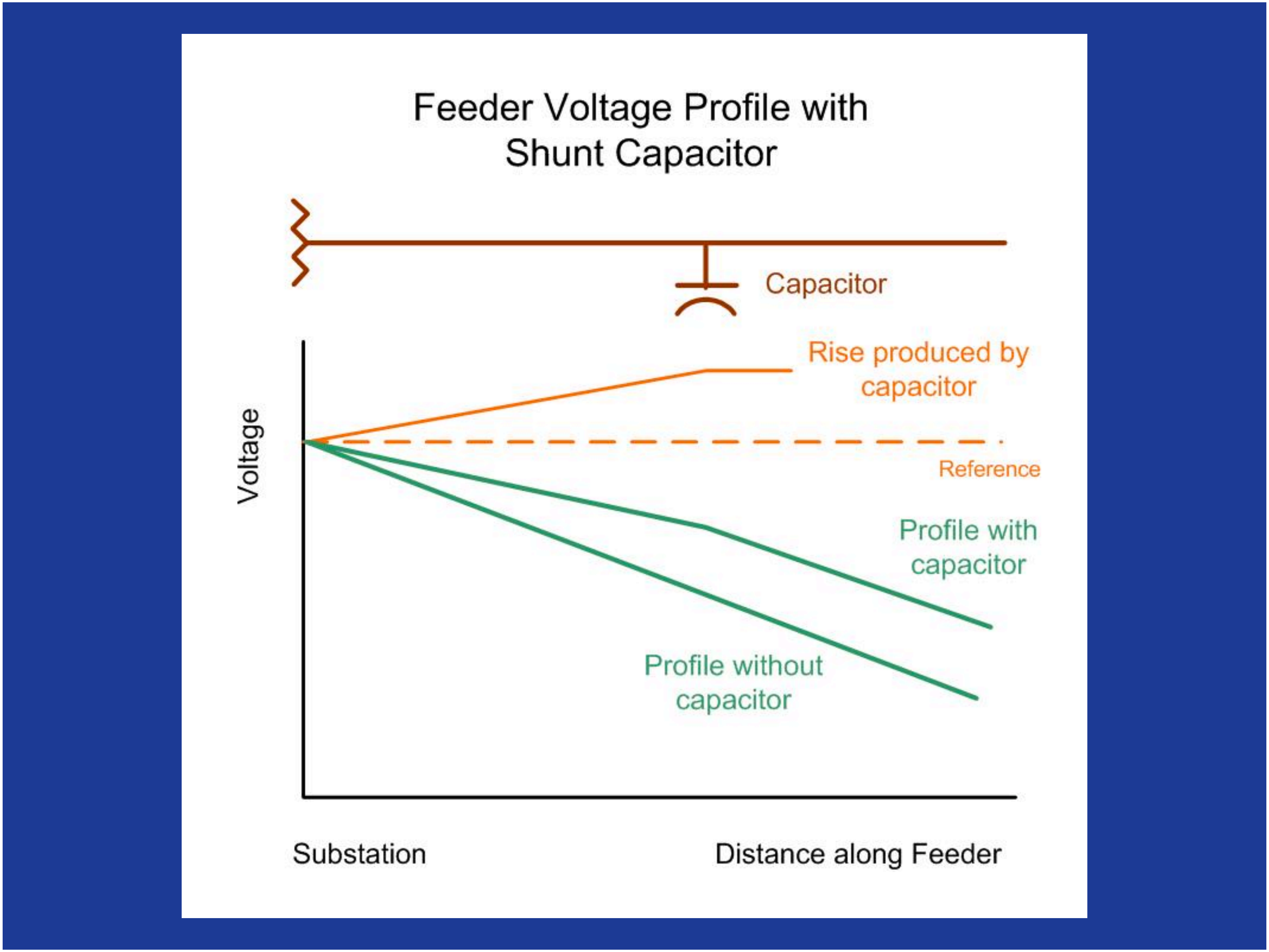

Typical Feeder Voltage Profile
Voltage
First Transformer
Last Transformer
First Customer
Last Customer
Substation
Distance along Feeder

Feeder Voltage Profile with Voltage Regulator



Voltage

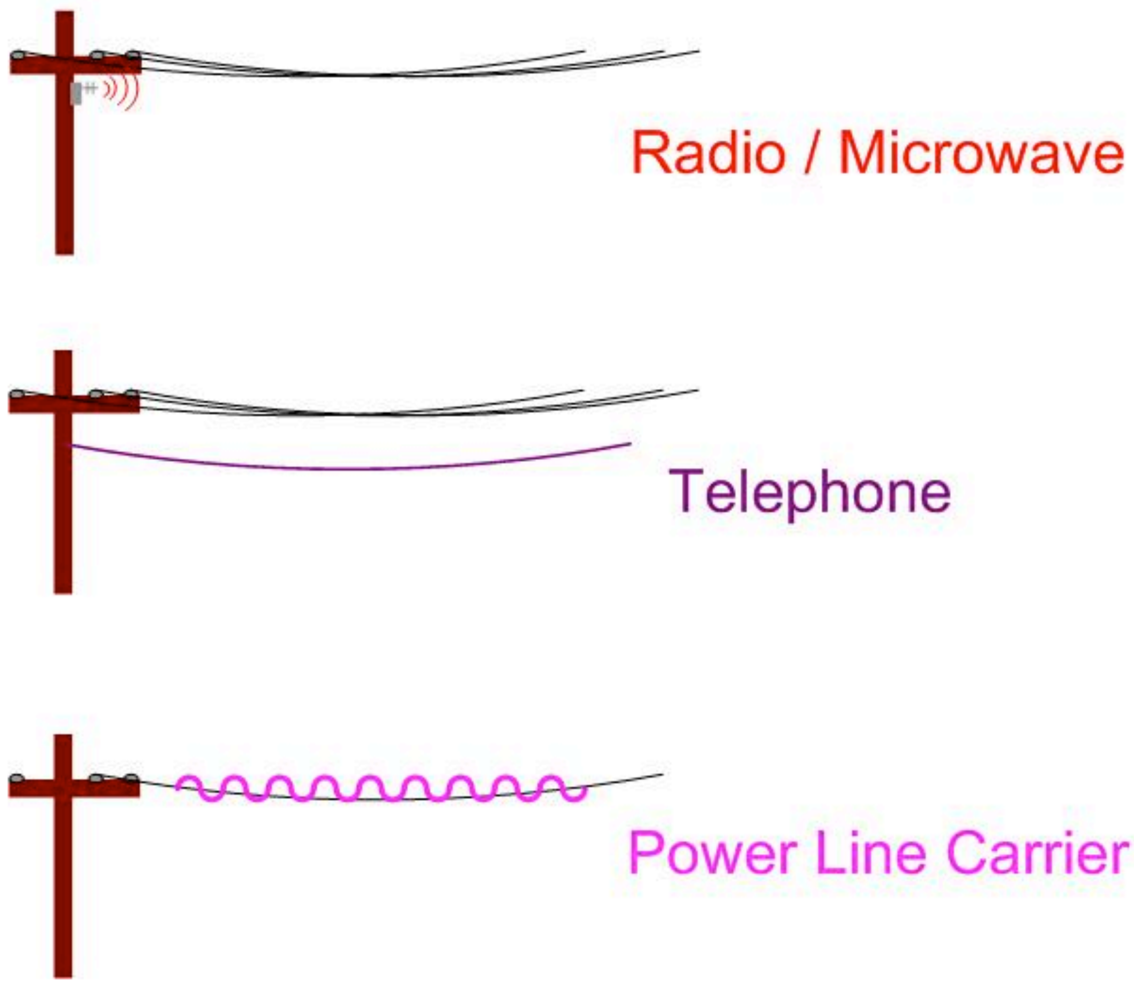
Regulator

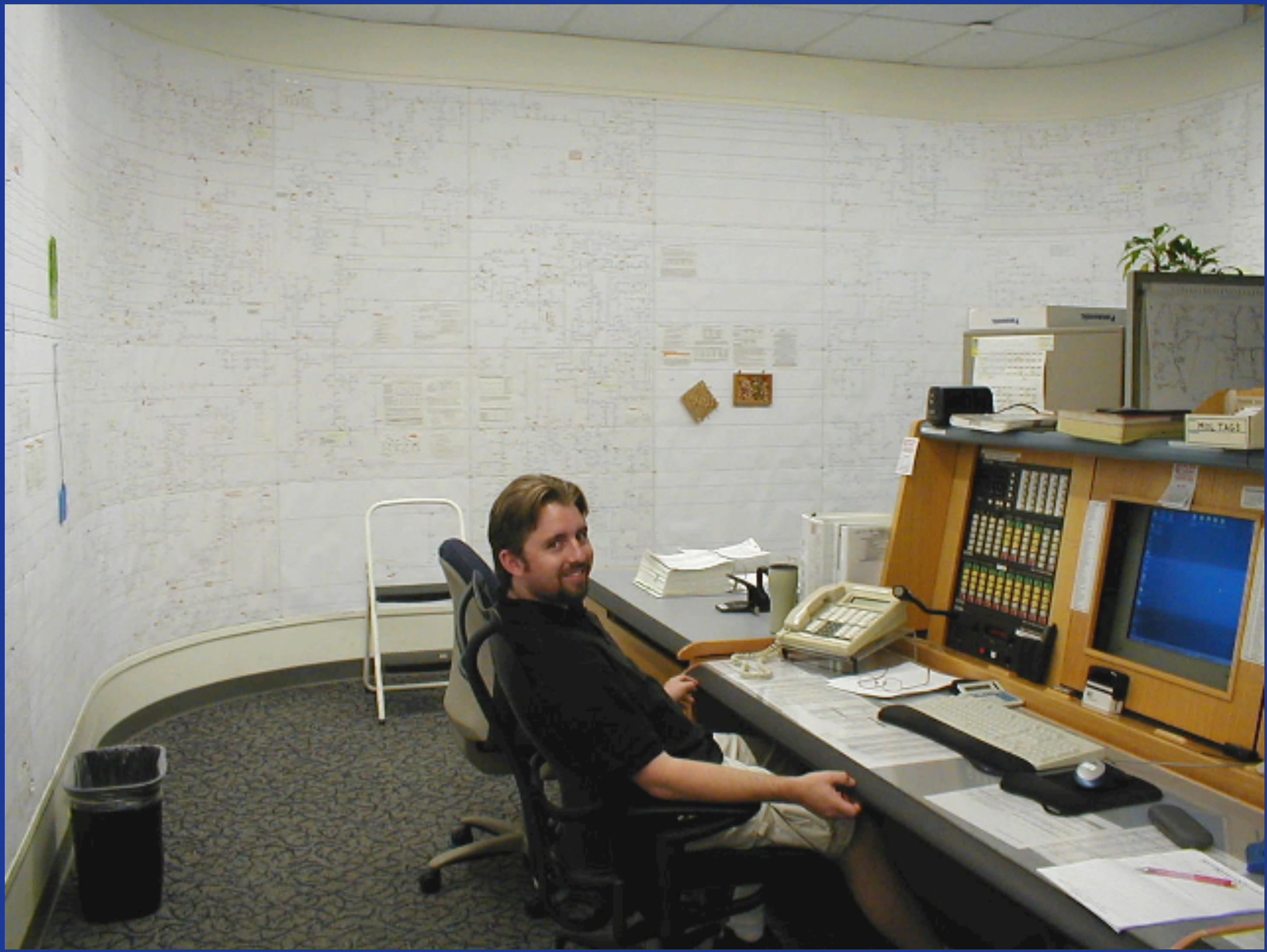

Feeder Voltage Profile with
Shunt Capacitor
Capacitor
Rise produced by
capacitor
Reference
Voltage
Profile with
capacitor
Profile without
capacitor
Substation
Distance along Feeder

Capacitors

Capacitor
and switch

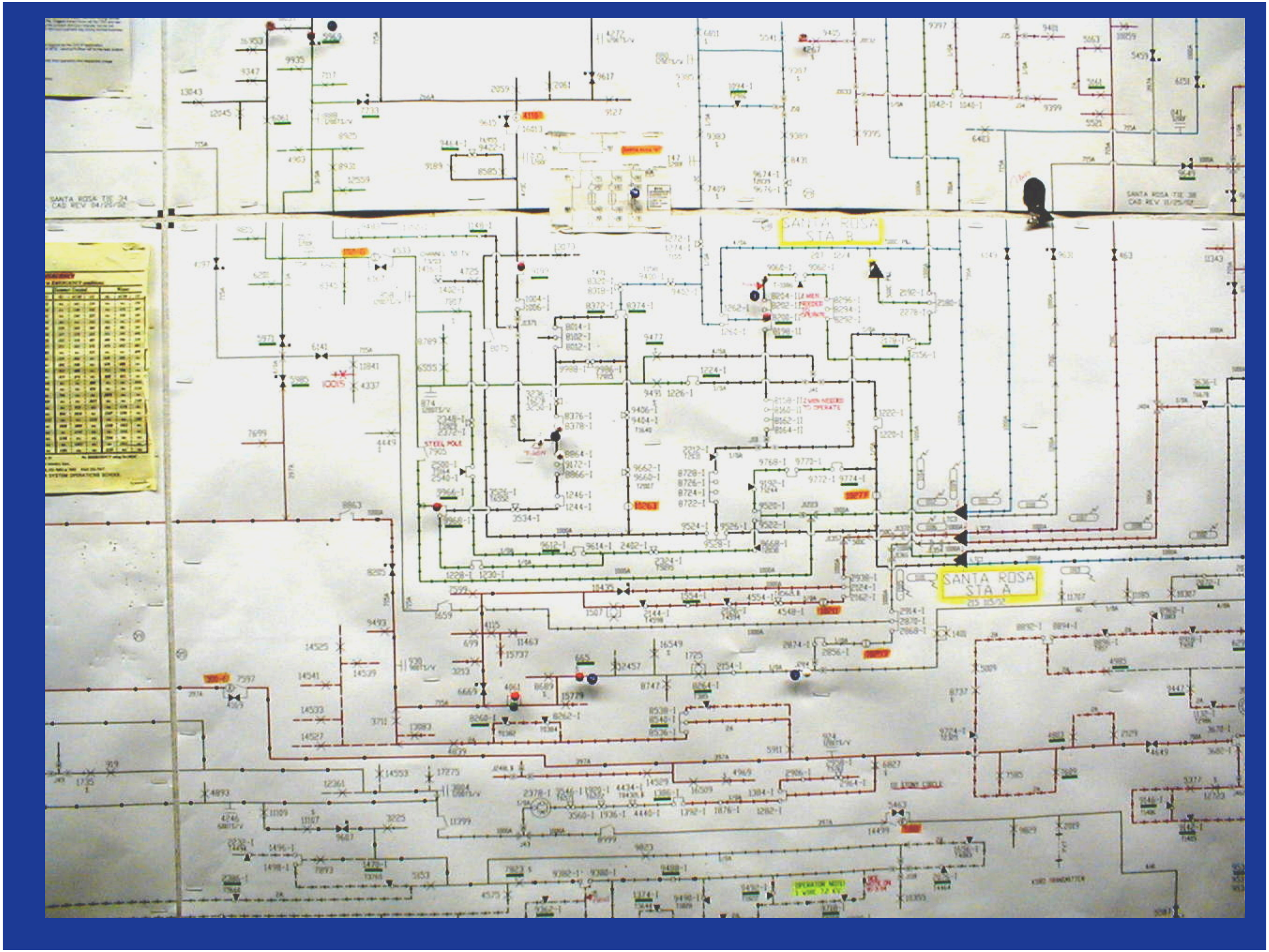
Telecommunications in Power Systems



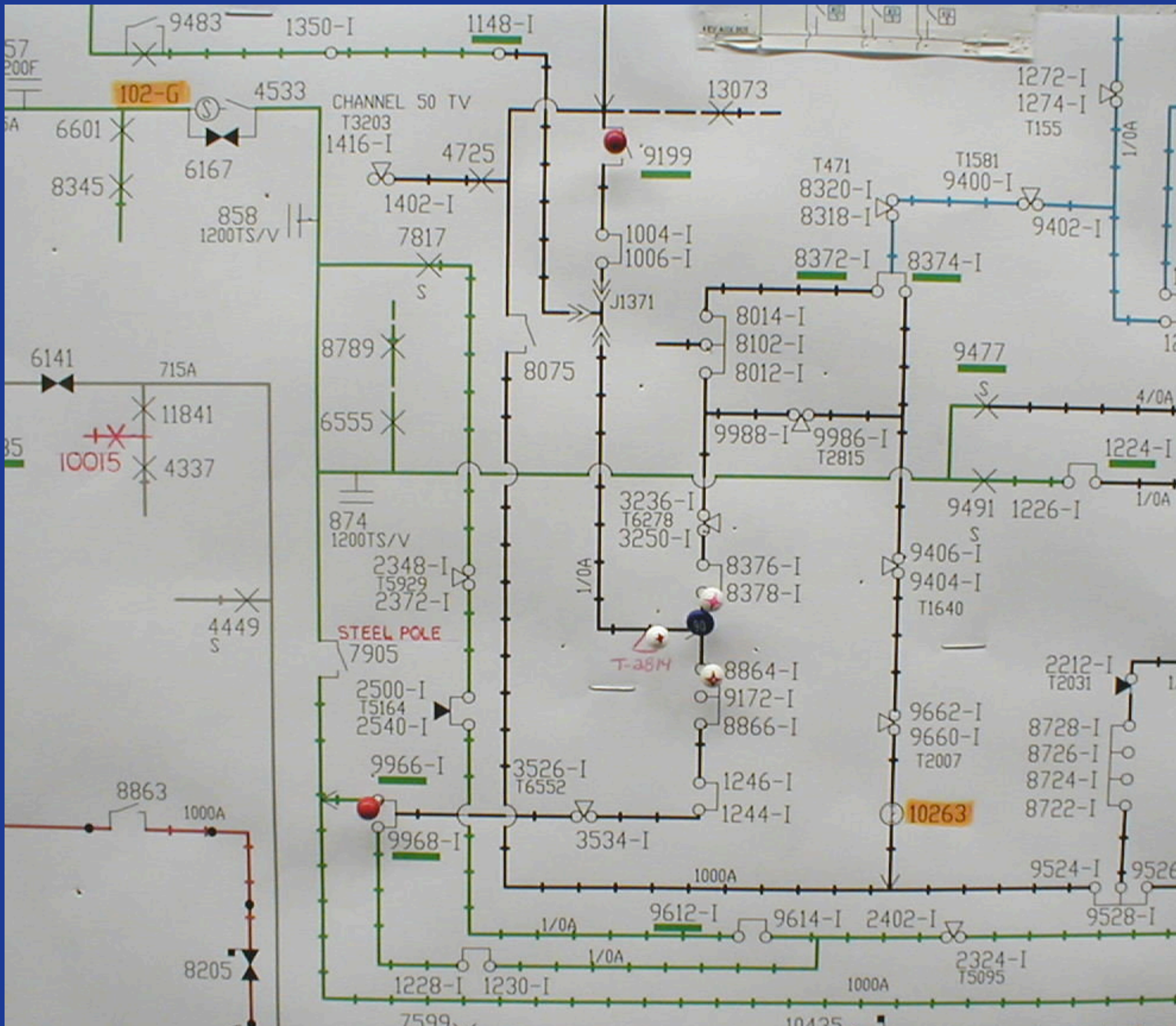


Distribution Operator (DO) Desk

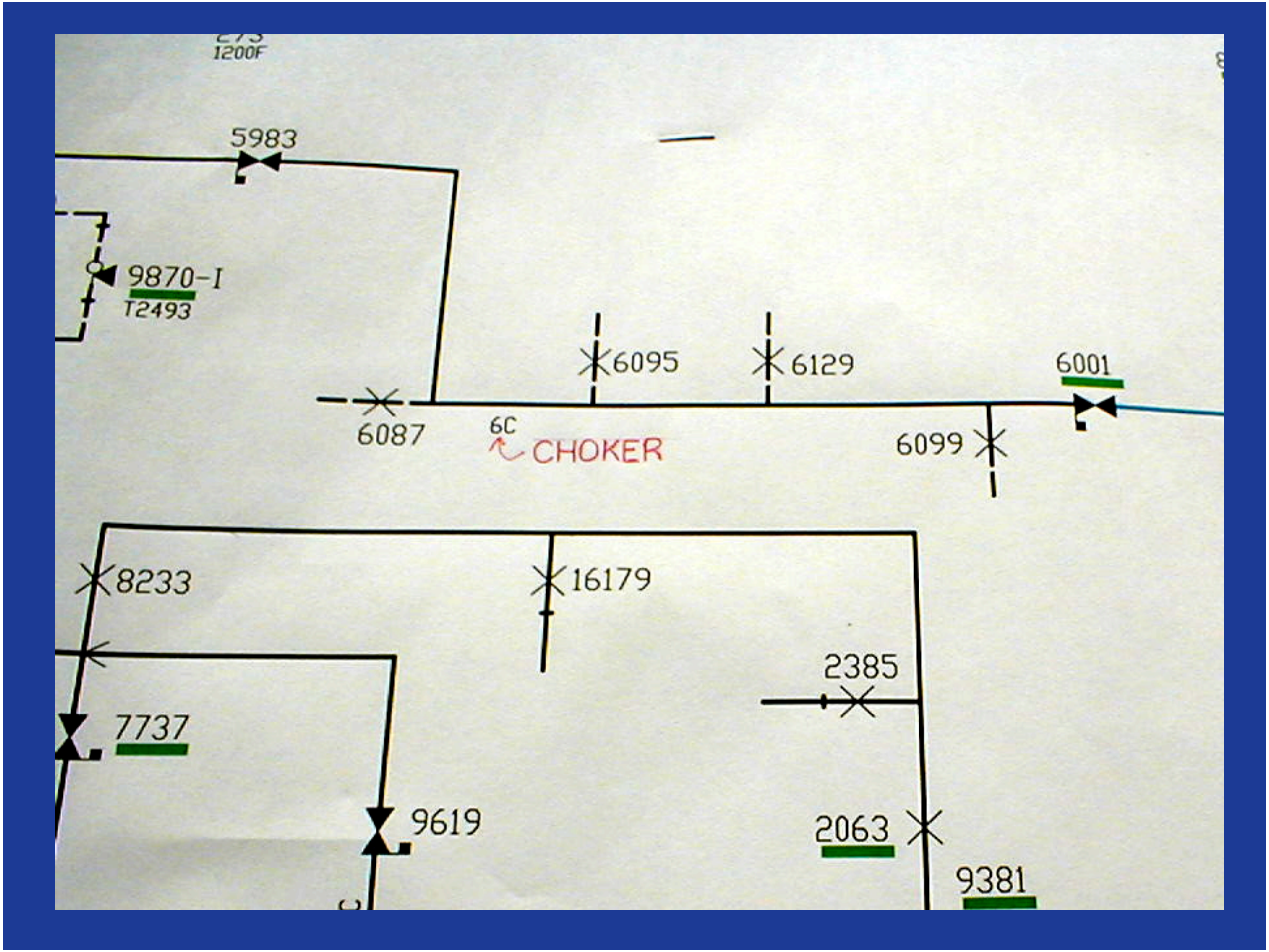
Wall Map at the DO Office

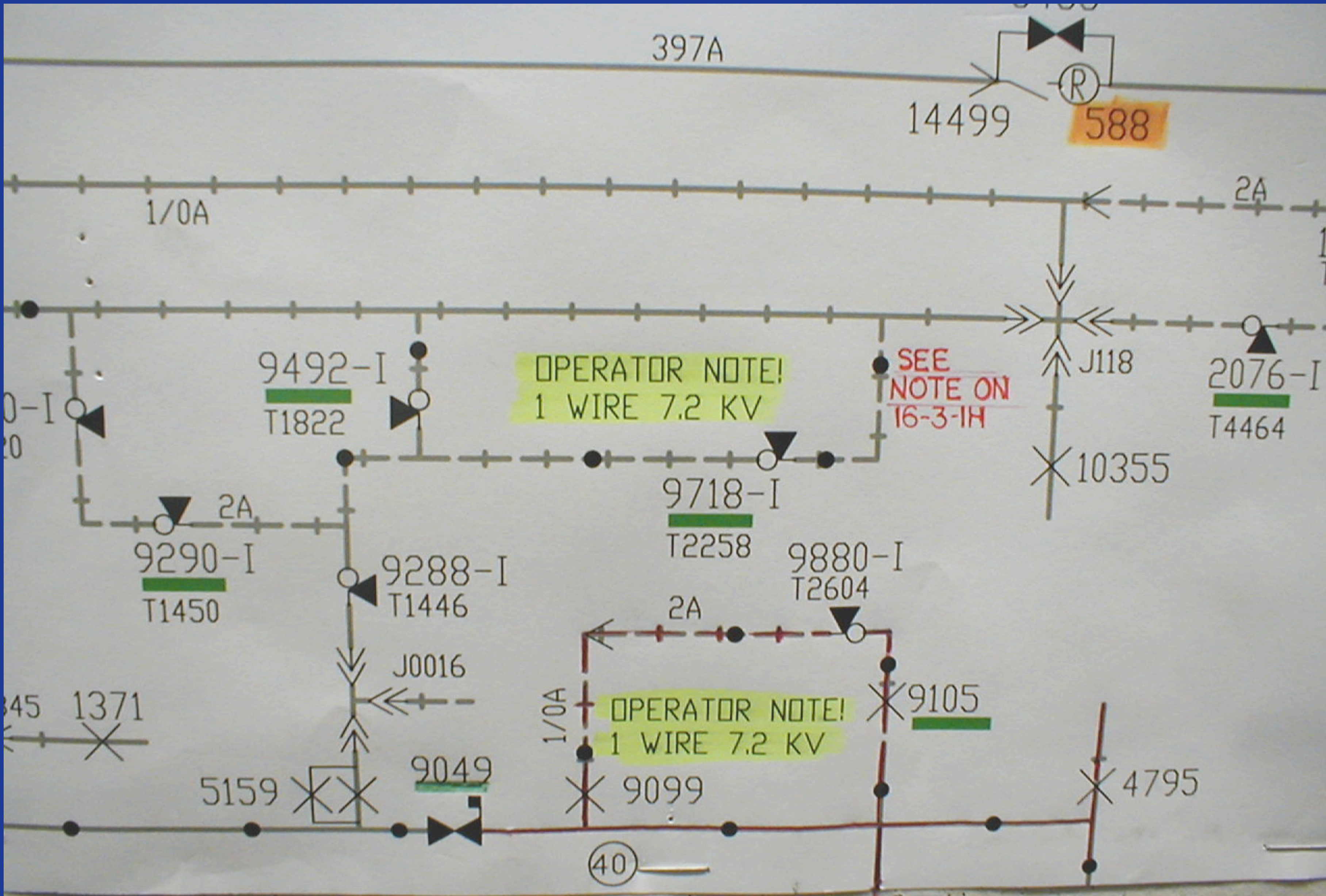


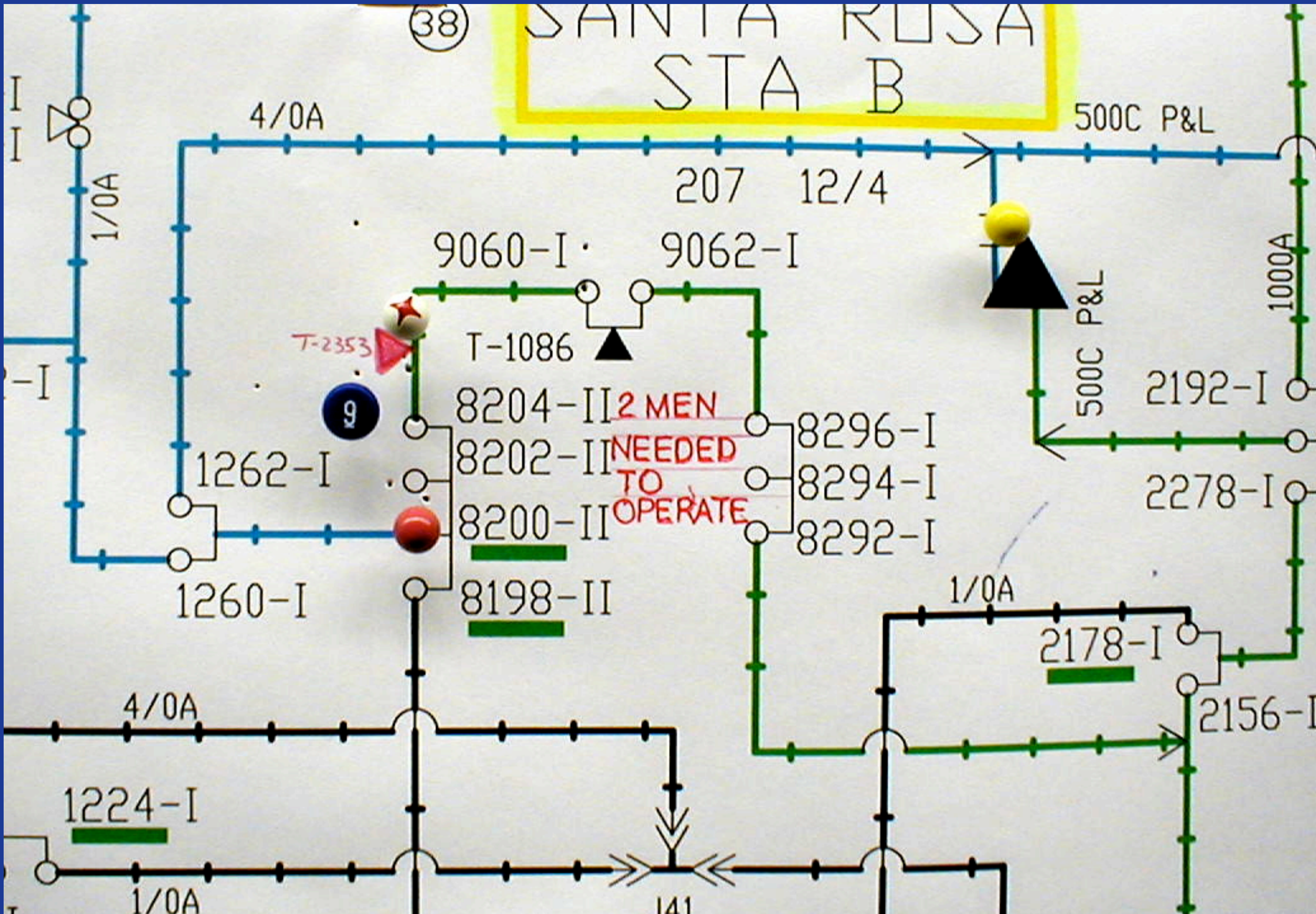
SANTA ROSA
STA B
SANTA ROSA
STA A



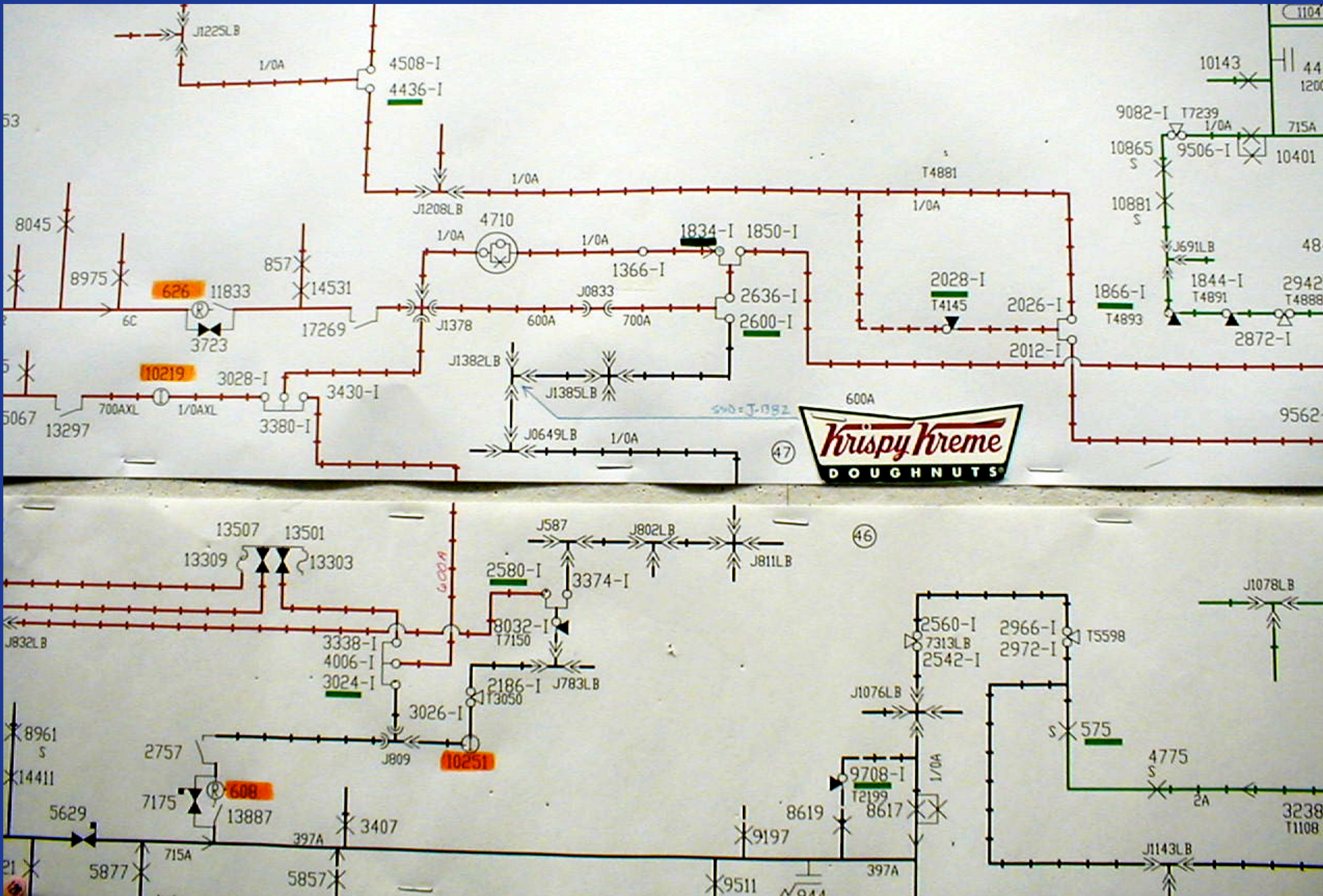
9483
1350-I
1148-I
102-G
4533
CHANNEL 50 TV
T3203
1416-I
4725
13073
9199
1272-I
1274-I
T155
1/0A
6601
6167
8345
858
1200TS/V
1402-I
7817
1004-I
1006-I
J1371
T471
8320-I
8318-I
T1581
9400-I
9402-I
8372-I
8374-I
8014-I
8102-I
8012-I
8789
6555
8075
9477
6141
715A
11841
10015
4337
9988-I
9986-I
T2815
4/0A
1224-I
3236-I
T6278
3250-I
874
1200TS/V
9491
1226-I
1/0A
2348-I
T5929
2372-I
8376-I
8378-I
9406-I
9404-I
T1640
4449
STEEL POLE
7905
T-2814
8864-I
9172-I
8866-I
2500-I
T5164
2540-I
2212-I
T2031
9662-I
9660-I
T2007
8728-I
8726-I
8724-I
8722-I
9966-I
3526-I
T6552
1246-I
1244-I
8863
1000A
10263
3534-I
9968-I
9524-I
9526
9528-I
9612-I
9614-I
2402-I
8205
2324-I
T5095
1228-I
1230-I
7599
10435

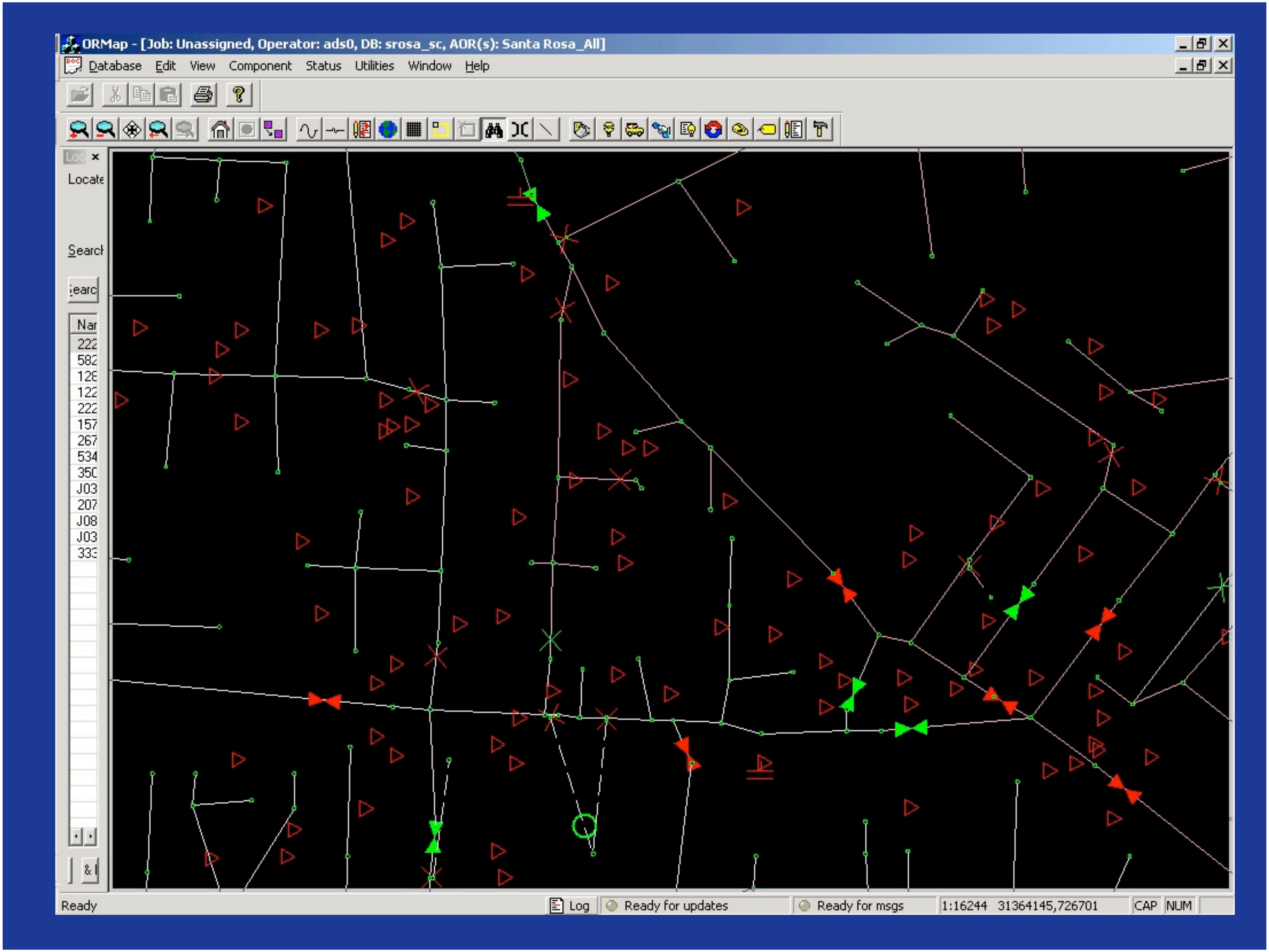

1200F
5983
9870-I
T2493
6095
6129
6001
6087
6C
CHOKER
6099
8233
16179
2385
7737
9619
2063
9381

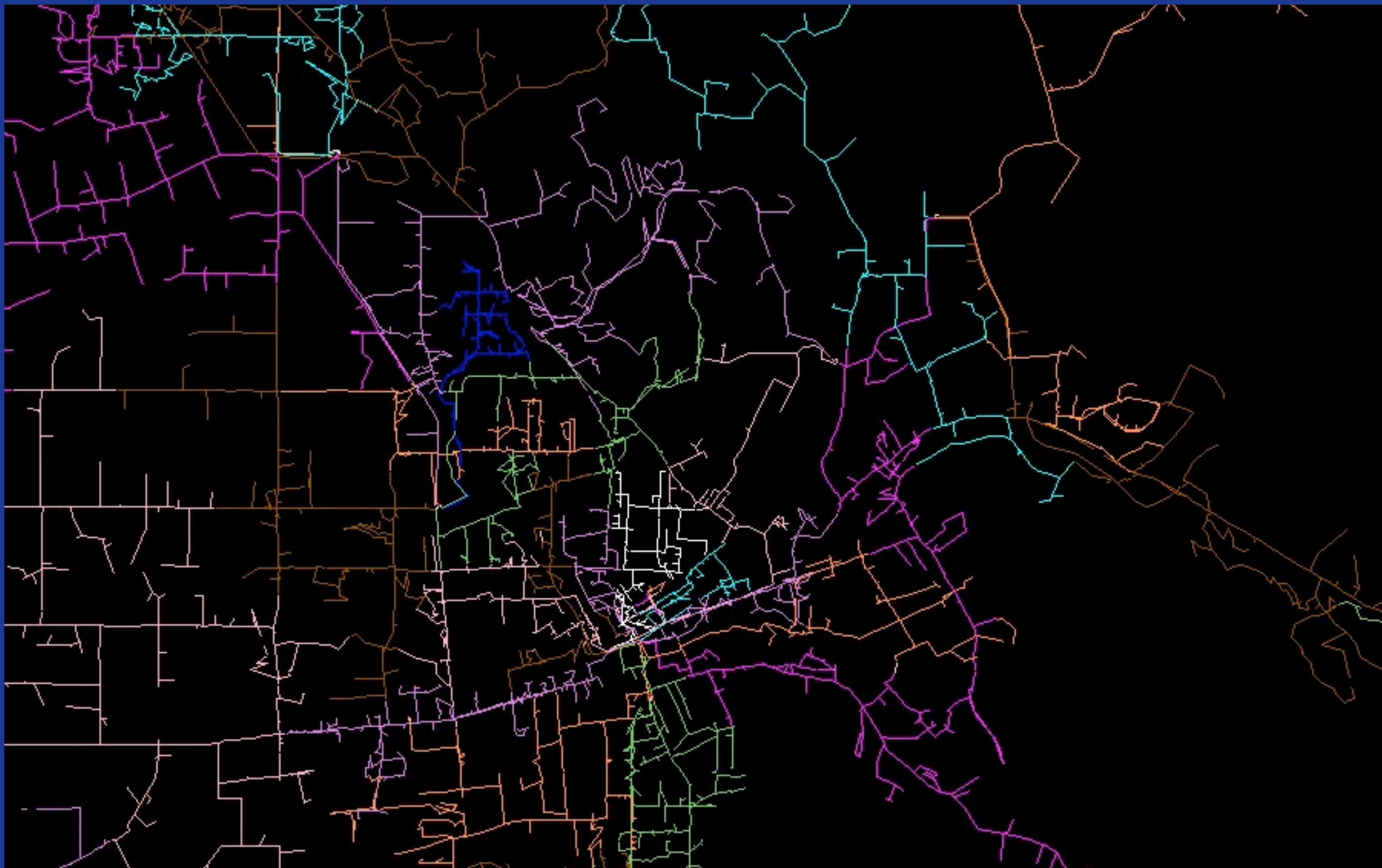

397A
14499
588
1/0A
2A
9492-I
T1822
OPERATOR NOTE!
1 WIRE 7.2 KV
SEE
NOTE ON
16-3-1H
J118
2076-I
T4464
10355
9290-I
T1450
2A
9718-I
T2258
9288-I
T1446
9880-I
T2604
2A
J0016
1371
1/0A
OPERATOR NOTE!
1 WIRE 7.2 KV
9105
5159
9049
9099
4795
40

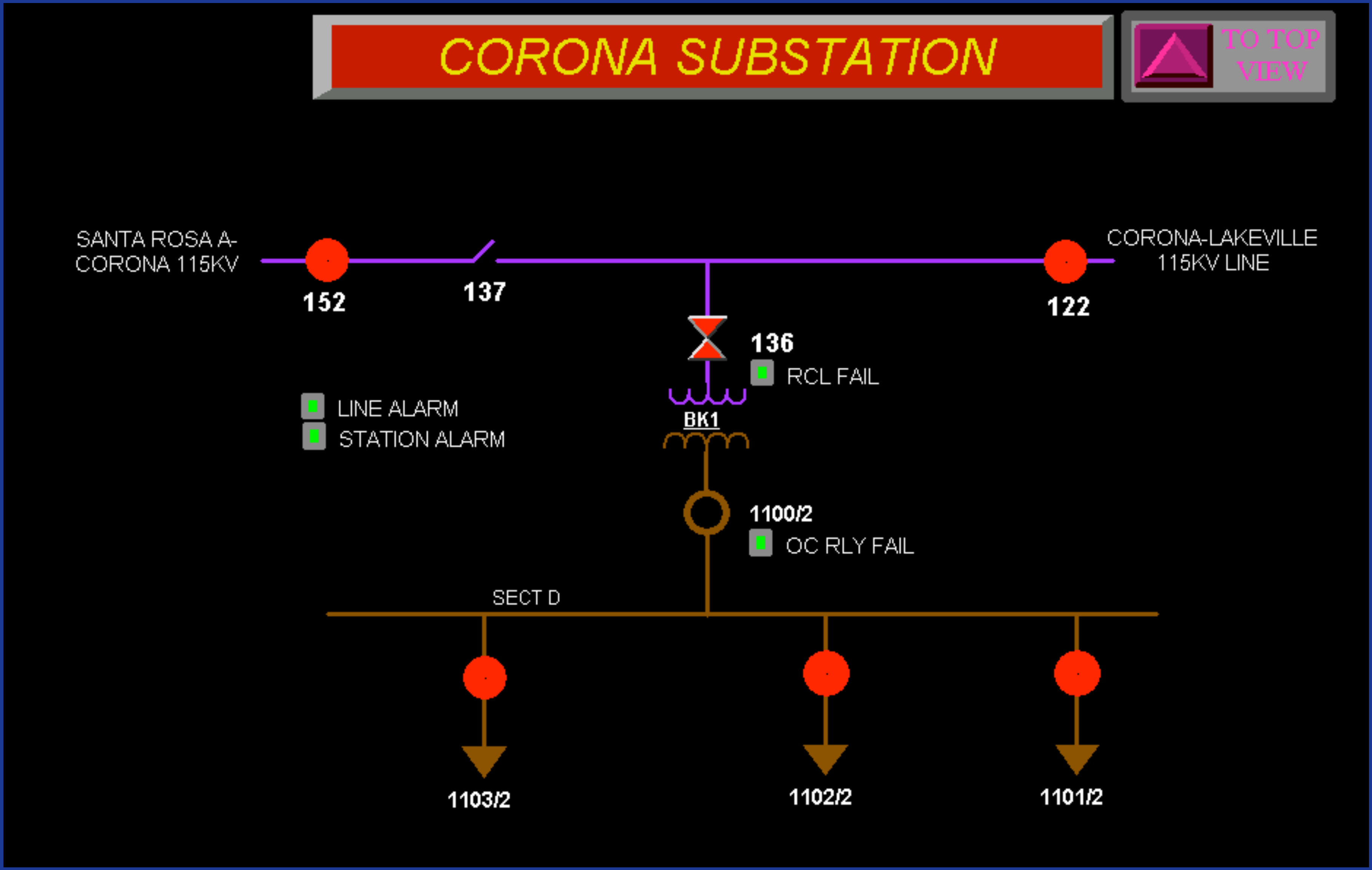


38
SANTA ROSA
STA B
4/0A
1/0A
500C P&L
207
12/4
9060-I
9062-I
T-1086
T-2353
1000A
P&L
500C
2192-I
8204-II
8202-II
8200-II
8198-II
2 MEN
NEEDED
TO
OPERATE
8296-I
8294-I
8292-I
1262-I
1260-I
2278-I
1/0A
2178-I
2156-I
4/0A
1224-I
1/0A
J41

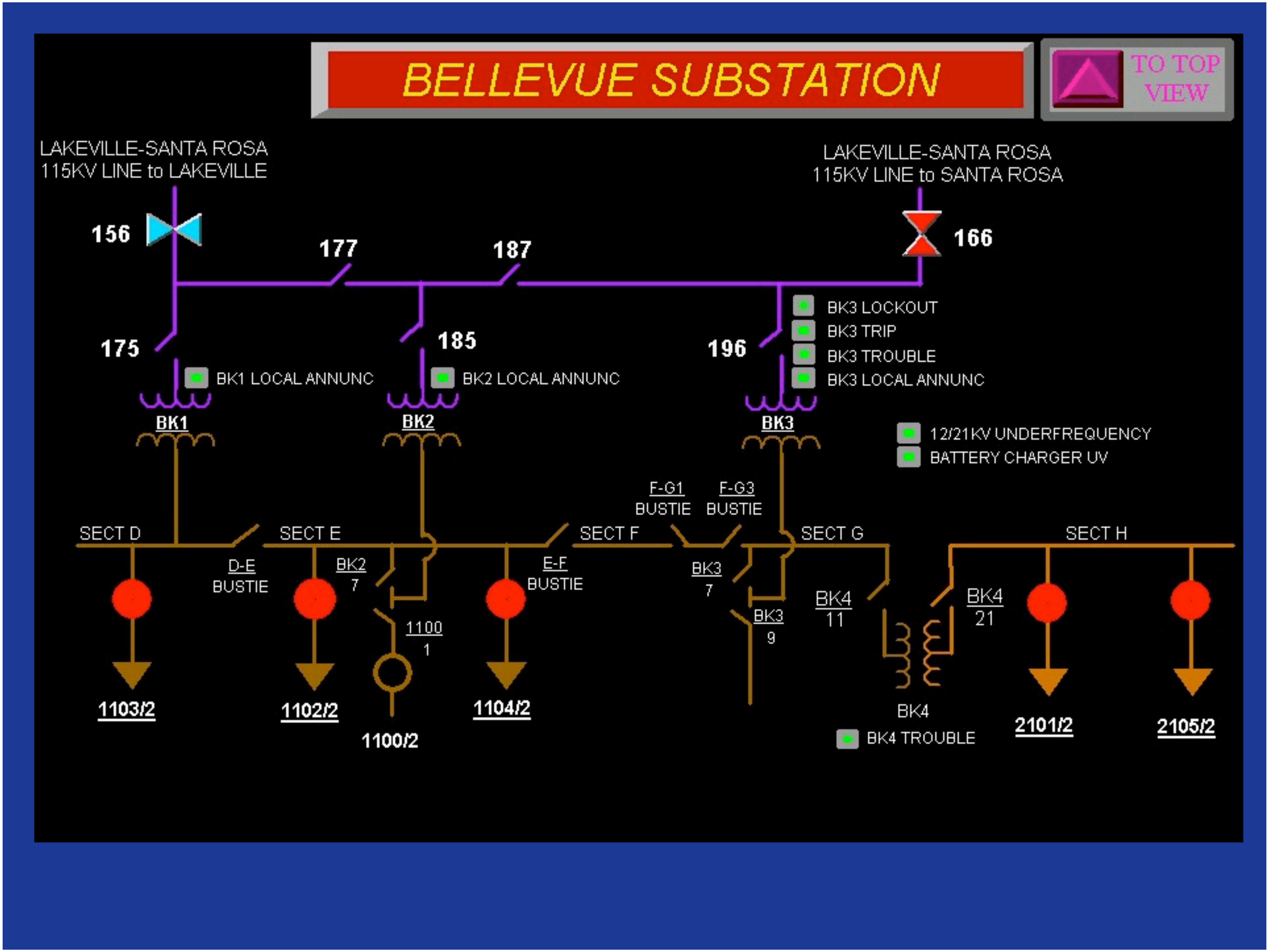

J1225LB
1/0A
4508-I
4436-I
8045
8975
857
14531
626
11833
3723
17269
J1208LB
4710
1/0A
J1378
600A
J0833
700A
1366-I
1834-I
1850-I
2636-I
2600-I
T4881
2028-I
T4145
2026-I
2012-I
1866-I
T4893
10143
9082-I
T7239
9506-I
10401
715A
10865
10881
J691LB
1844-I
T4891
2942-
T4888
2872-I
10219
3028-I
3430-I
3380-I
13297
700AXL
1/0AXL
J1382LB
J1385LB
J0649LB
600A
9562-
47
Krispy Kreme
DOUGHNUTS
46
13507
13501
13309
13303
J832LB
2580-I
3374-I
J587
J802LB
J811LB
3338-I
4006-I
3024-I
8032-I
T7150
2186-I
T3050
J783LB
3026-I
J809
10251
J1078LB
2560-I
7313LB
2542-I
2966-I
2972-I
T5598
J1076LB
575
4775
2A
3238-
T1108
9708-I
T2199
8617
8619
9197
9511
944
397A
J1143LB
8961
14411
2757
7175
608
13887
5629
715A
5877
5857
3407

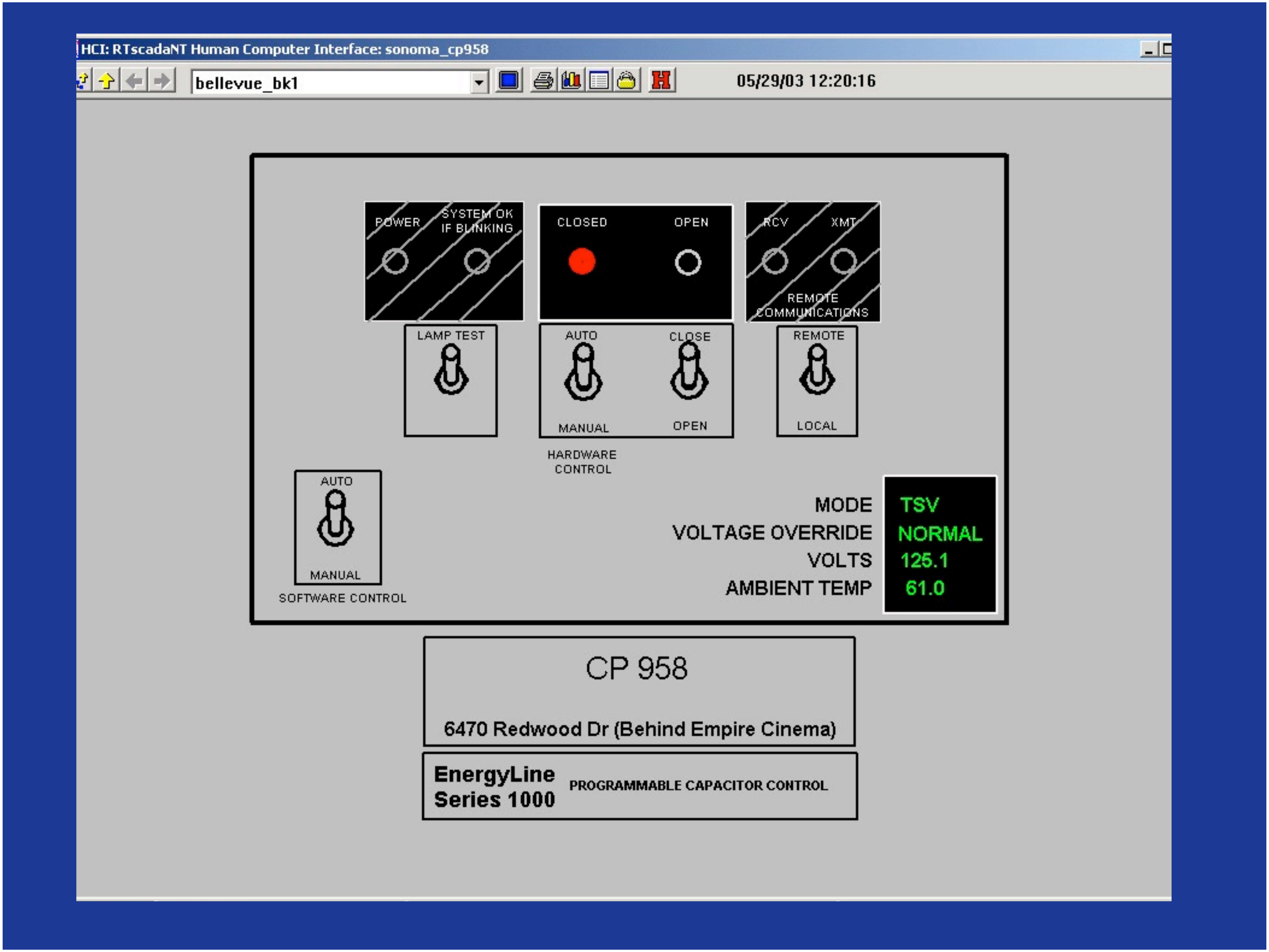

ORMap - [Job: Unassigned, Operator: ads0, DB: srosa_sc, AOR(s): Santa Rosa_All]
Database Edit View Component Status Utilities Window Help
Locate
Search
Ready
Log
Ready for updates
Ready for msgs
1:16244 31364145,726701
CAP
NUM

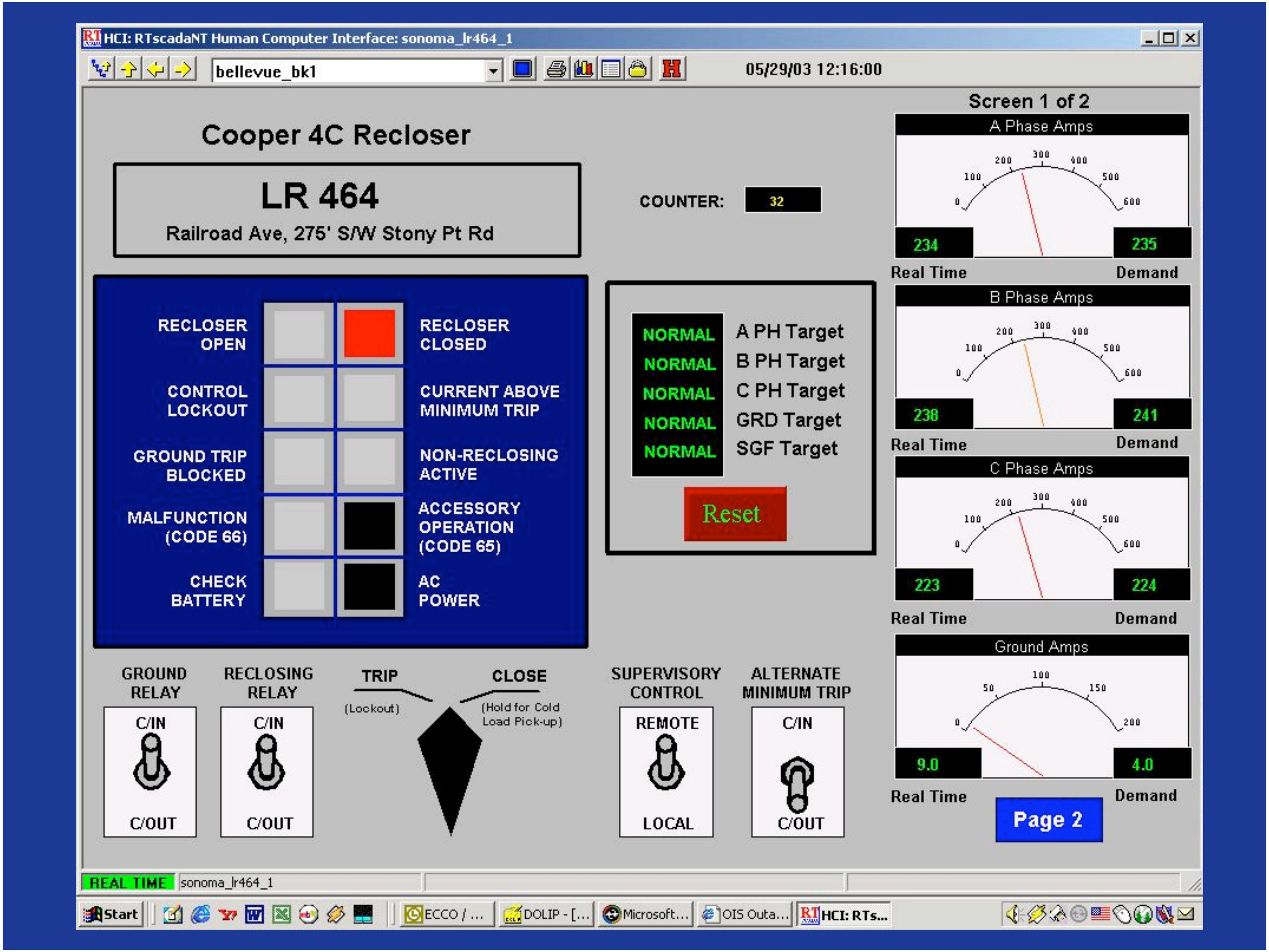




SCADA Screen


BELLEVUE SUBSTATION
TO TOP VIEW
LAKEVILLE-SANTA ROSA
115KV LINE to LAKEVILLE
LAKEVILLE-SANTA ROSA
115KV LINE to SANTA ROSA
156
177
187
166
175
185
196
BK3 LOCKOUT
BK3 TRIP
BK3 TROUBLE
BK3 LOCAL ANNUNC
BK1 LOCAL ANNUNC
BK2 LOCAL ANNUNC
BK1
BK2
BK3
12/21KV UNDERFREQUENCY
BATTERY CHARGER UV
F-G1
BUSTIE
F-G3
BUSTIE
SECT D
SECT E
SECT F
SECT G
SECT H
D-E
BUSTIE
BK2
7
E-F
BUSTIE
BK3
7
BK3
9
BK4
11
BK4
21
1100
1
1103/2
1102/2
1100/2
1104/2
BK4
BK4 TROUBLE
2101/2
2105/2


HCI: RTscadaNT Human Computer Interface: sonoma_cp958
bellevue_bk1
05/29/03 12:20:16
POWER
SYSTEM OK IF BLINKING
CLOSED
OPEN
RCV
XMT
REMOTE COMMUNICATIONS
LAMP TEST
AUTO
CLOSE
MANUAL
OPEN
REMOTE
LOCAL
HARDWARE CONTROL
AUTO
MANUAL
SOFTWARE CONTROL
MODE
VOLTAGE OVERRIDE
VOLTS
AMBIENT TEMP
TSV
NORMAL
125.1
61.0
CP 958
6470 Redwood Dr (Behind Empire Cinema)
EnergyLine Series 1000
PROGRAMMABLE CAPACITOR CONTROL


HCI: RTscadaNT Human Computer Interface: sonoma_lr464_1
bellevue_bk1
05/29/03 12:16:00
Screen 1 of 2
Cooper 4C Recloser
LR 464
Railroad Ave, 275' S/W Stony Pt Rd
COUNTER: 32
RECLOSER OPEN
RECLOSER CLOSED
CONTROL LOCKOUT
CURRENT ABOVE MINIMUM TRIP
GROUND TRIP BLOCKED
NON-RECLOSING ACTIVE
MALFUNCTION (CODE 66)
ACCESSORY OPERATION (CODE 65)
CHECK BATTERY
AC POWER
NORMAL A PH Target
NORMAL B PH Target
NORMAL C PH Target
NORMAL GRD Target
NORMAL SGF Target
Reset
A Phase Amps
234 Real Time
235 Demand
B Phase Amps
238 Real Time
241 Demand
C Phase Amps
223 Real Time
224 Demand
Ground Amps
9.0 Real Time
4.0 Demand
GROUND RELAY C/IN C/OUT
RECLOSING RELAY C/IN C/OUT
TRIP (Lockout)
CLOSE (Hold for Cold Load Pick-up)
SUPERVISORY CONTROL REMOTE LOCAL
ALTERNATE MINIMUM TRIP C/IN C/OUT
Page 2
REAL TIME sonoma_lr464_1
Start

The End