Electric Power Delivery Systems

Tutorial at U.C. Berkeley

September 11, 2009

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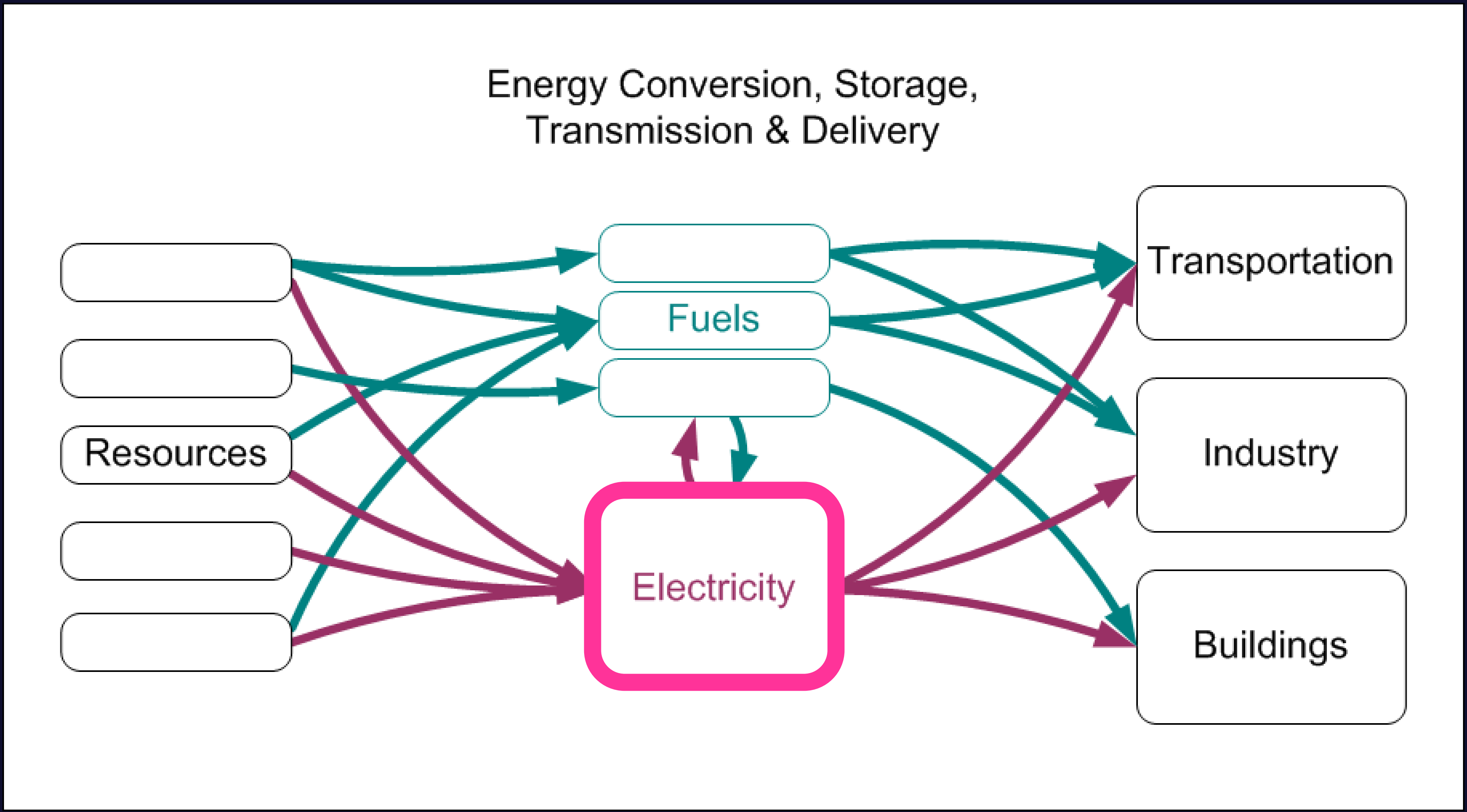
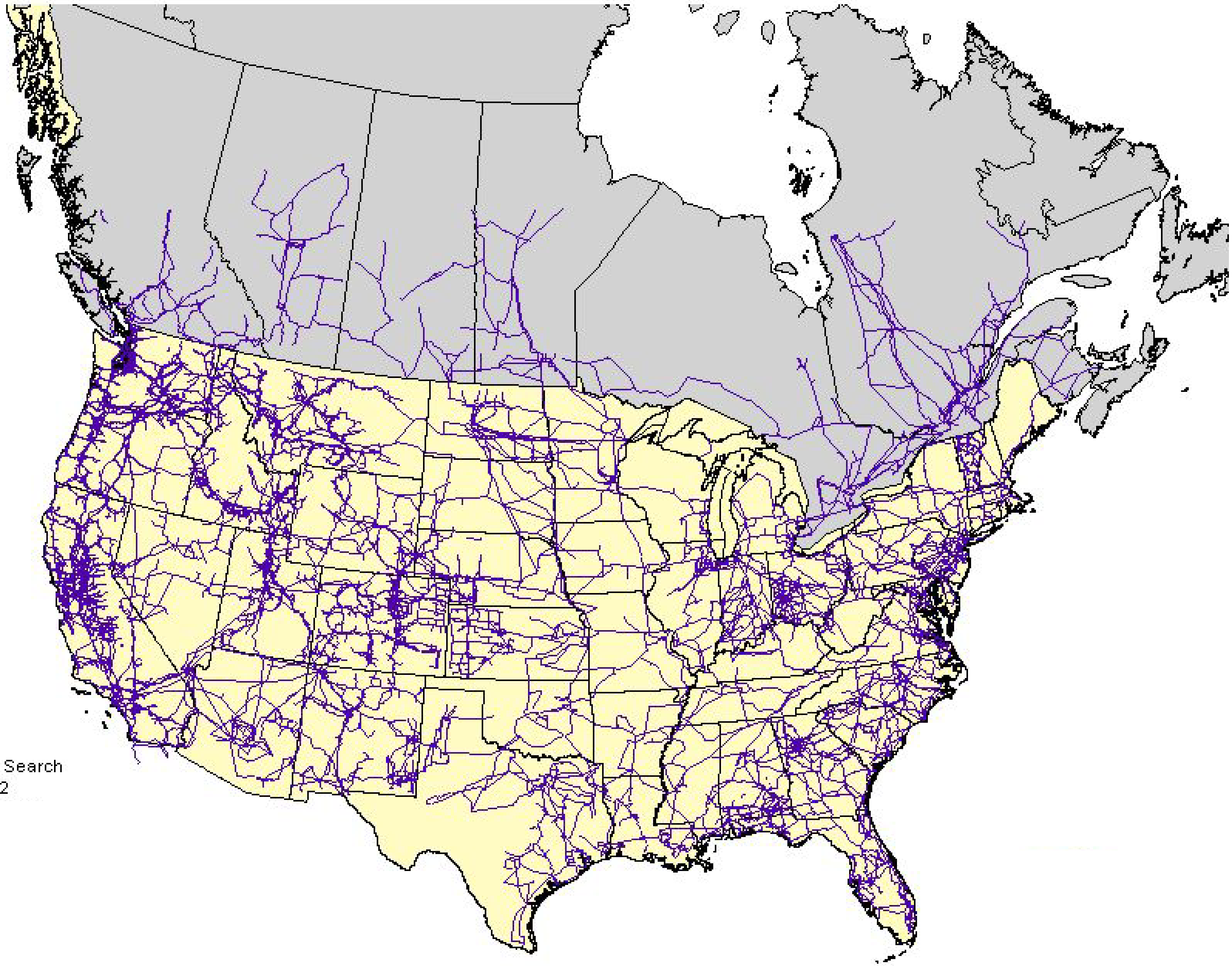
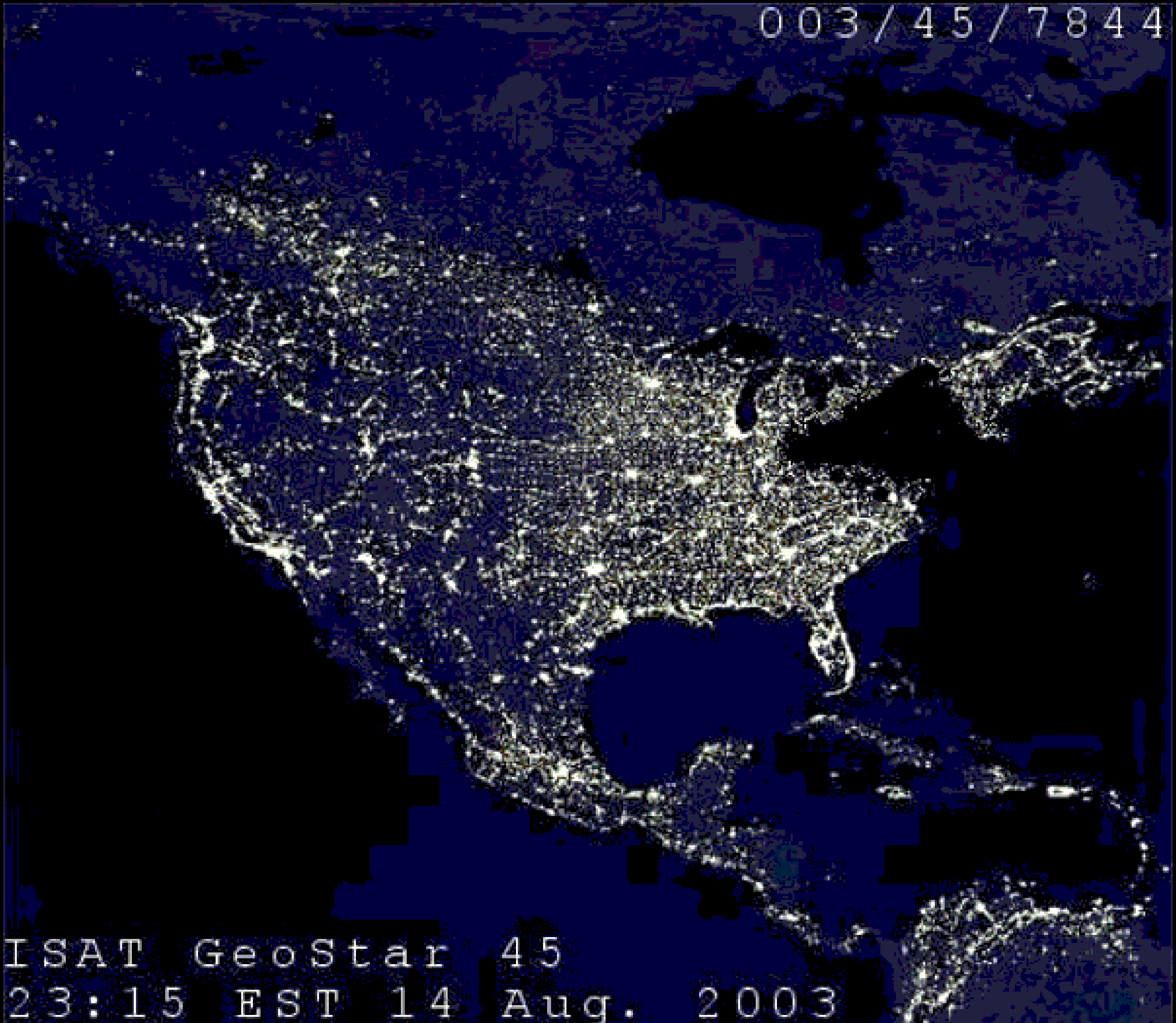
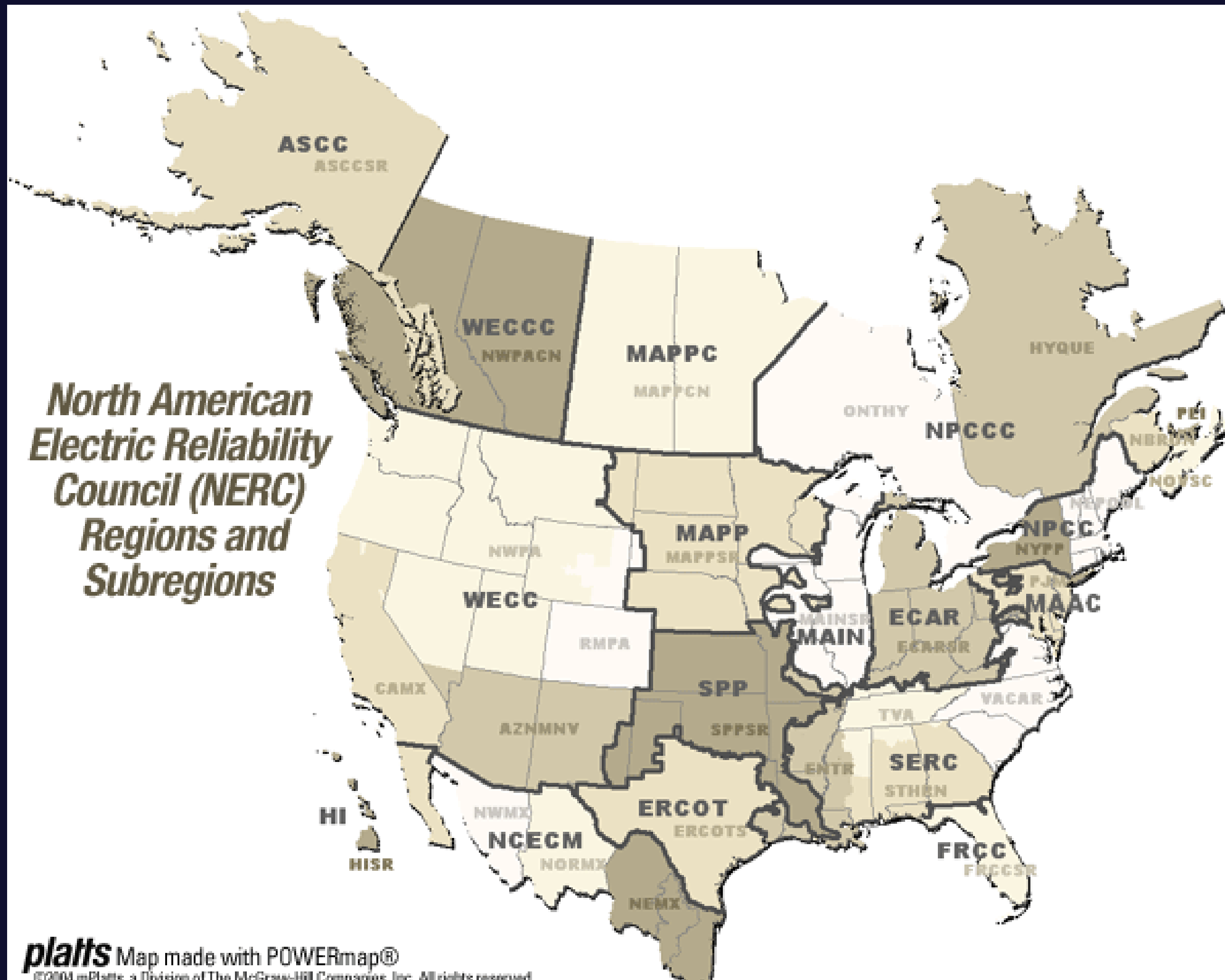

Energy Conversion, Storage,
Transmission & Delivery
Resources
Fuels
Electricity
Transportation
Industry
Buildings




003/45/7844
ISAT GeoStar 45
23:15 EST 14 Aug. 2003


North American Electric Reliability Council (NERC) Regions and Subregions
ASCC
ASCCSR
WECCC
NWPACN
MAPPC
MAPPCN
ONTHY
NPCCC
HYQUE
PEI
MAPP
MAPPSR
NWPP
WECC
RMPA
NPCC
NYPP
MAAC
ECAR
ECARSR
MAIN
MAINSR
SPP
SPPSR
CAMX
AZNMNV
VACAR
TVA
SERC
STHRN
ENTR
ERCOT
ERCOTS
HI
HISR
NWMX
NCECM
NORMX
NEMX
FRCC
FRCCSR
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Inherent complexity of electric grid:

Provide energy from diverse resources to diverse loads
through a single large, interconnected infrastructure.

Components of infrastructure are
- numerous
- diverse in type, age, behavior, control options and vulnerabilities
- under different ownership and jurisdictions
- tightly coupled: interactions propagate far, wide, and quickly.

Complex system:
no individual can sensibly and fully account for it.

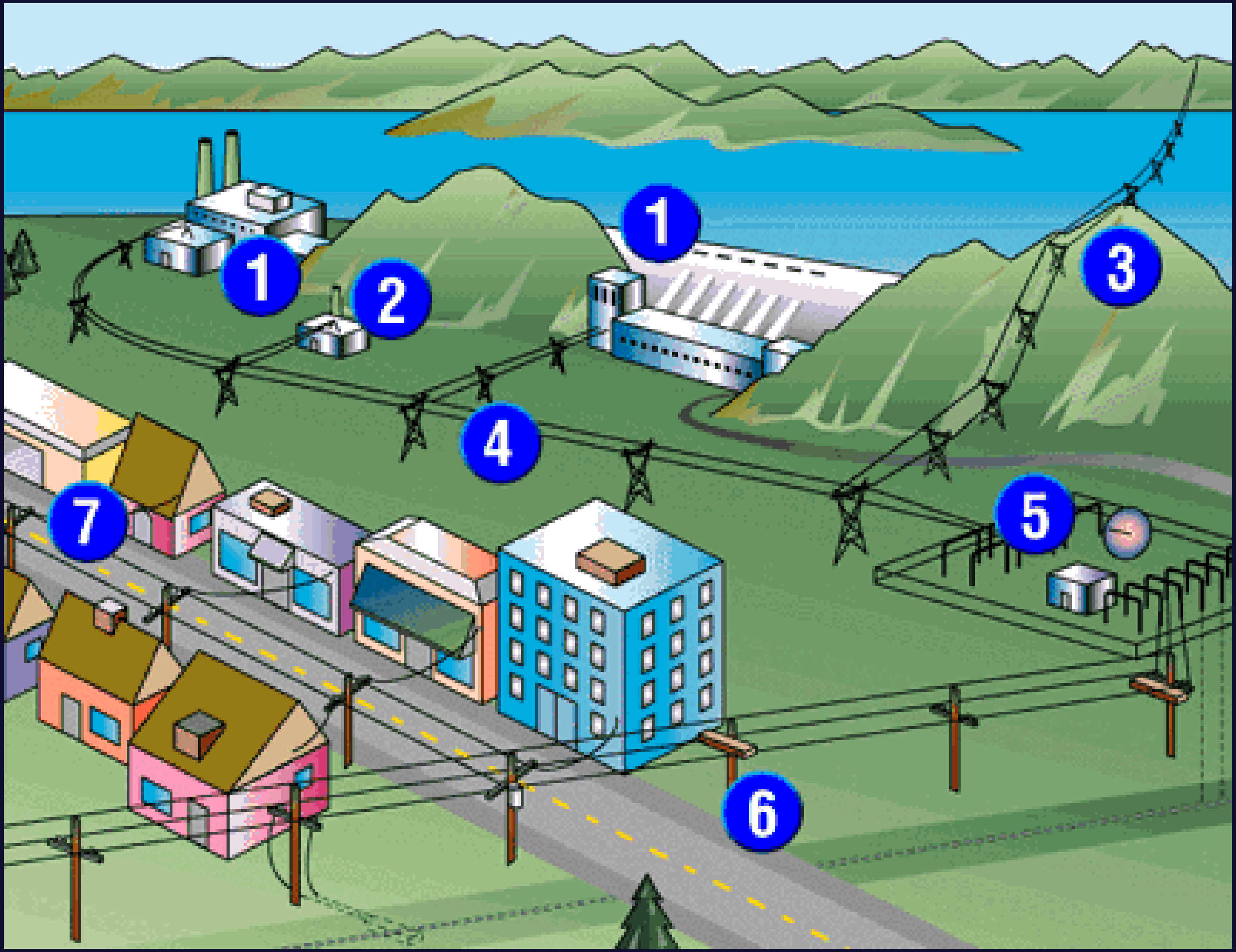
Yet the system requires control in real-time, with precise balance of inputs and outputs, based on detailed understanding of its function.

Why the grid is structured as it is

Hierarchy of transmission and distribution

Alternating current, transformers

Scale and connectivity

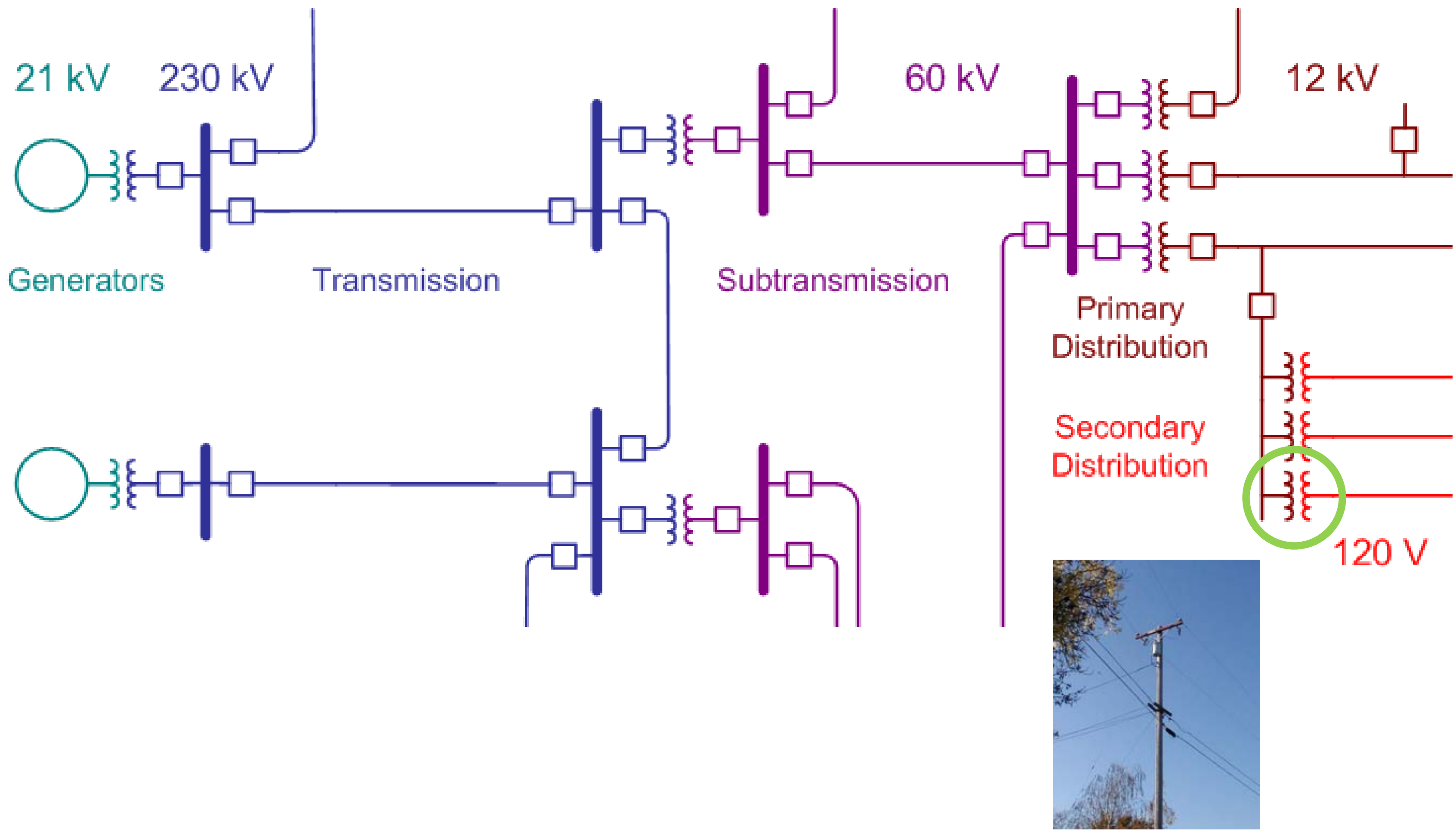


Rendition of a power system from PG&E’s website

My electric service entrance
in Sebastopol, California

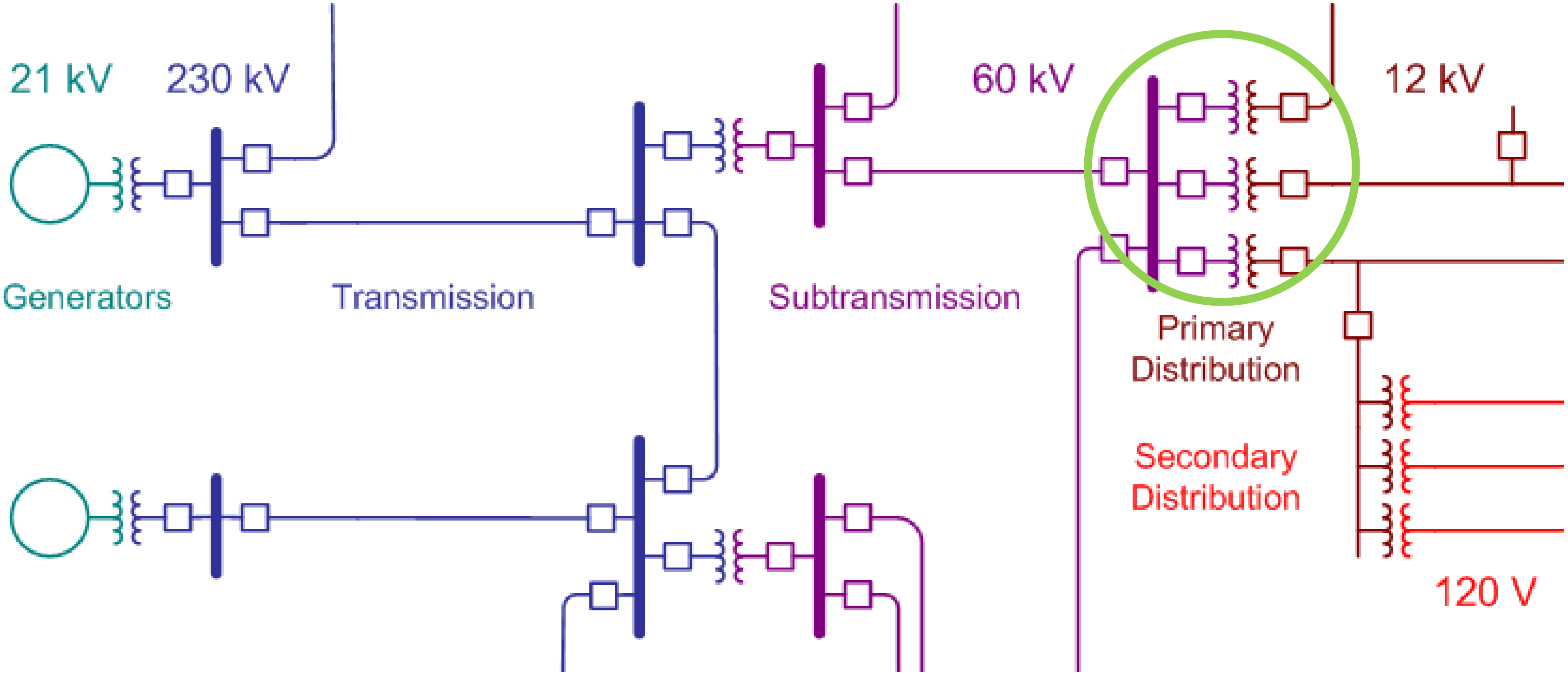
Transformer connection to local distribution circuit

Power System Structure
with typical voltage levels



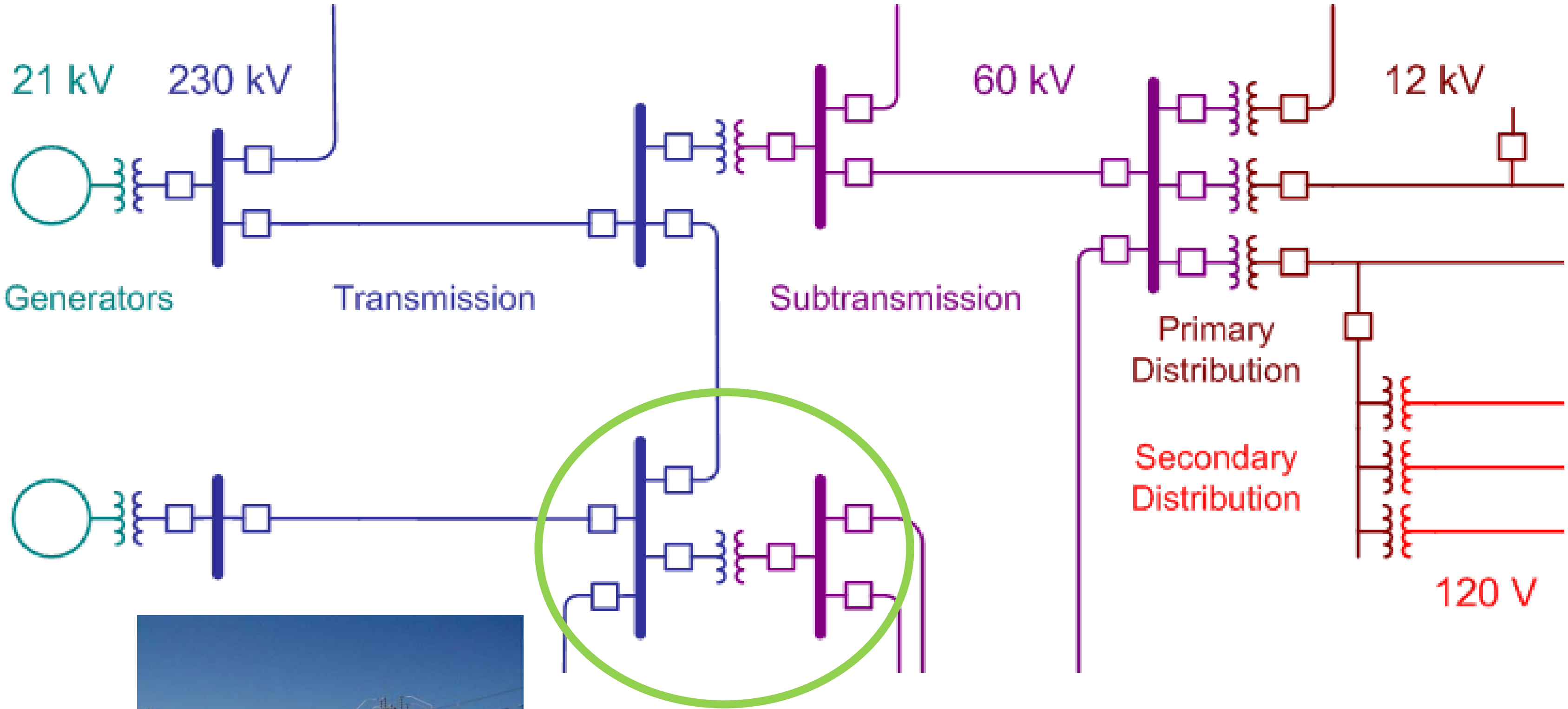

Cotati
Substation
PG&E

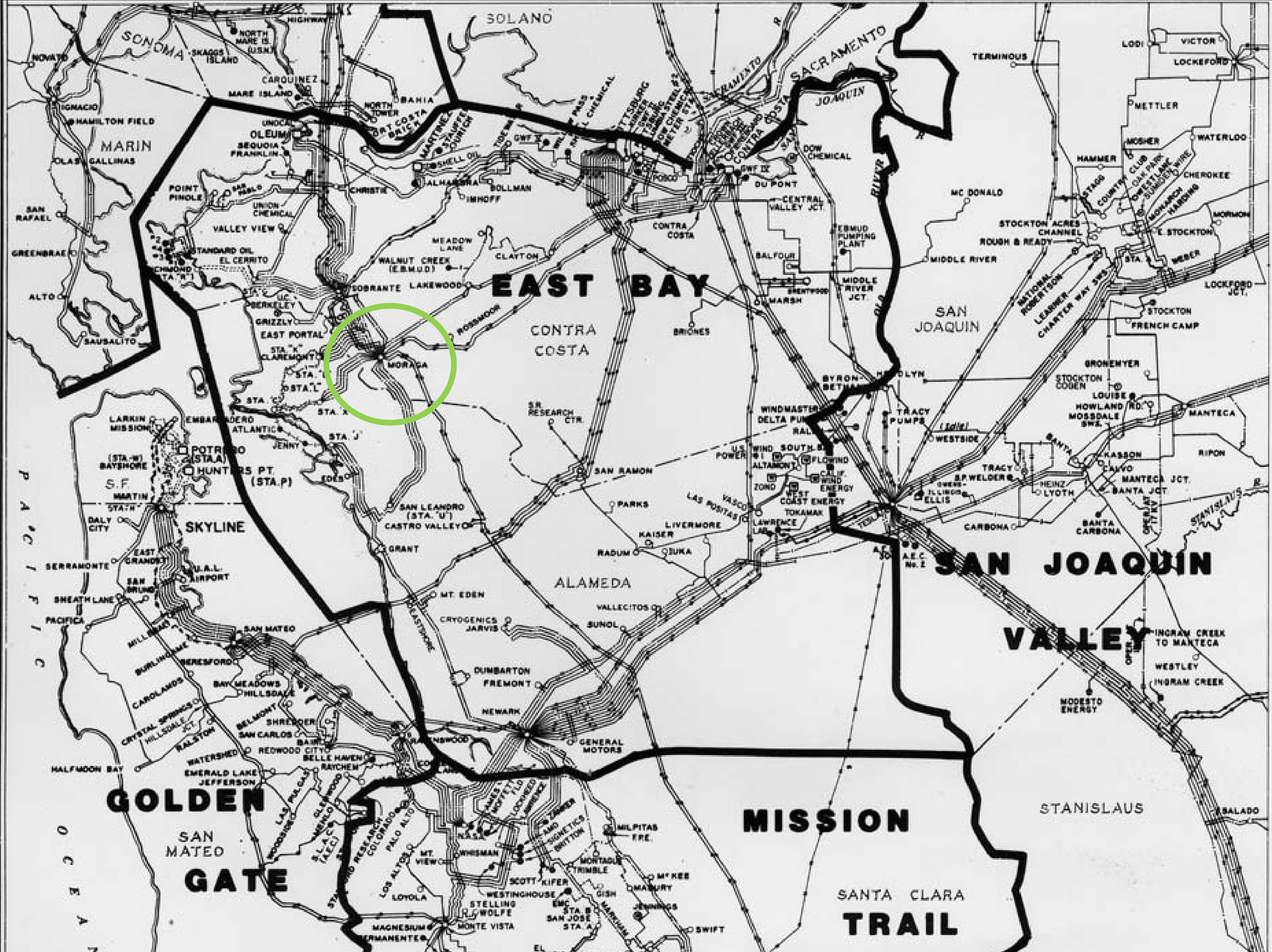
Power System Structure
with typical voltage levels



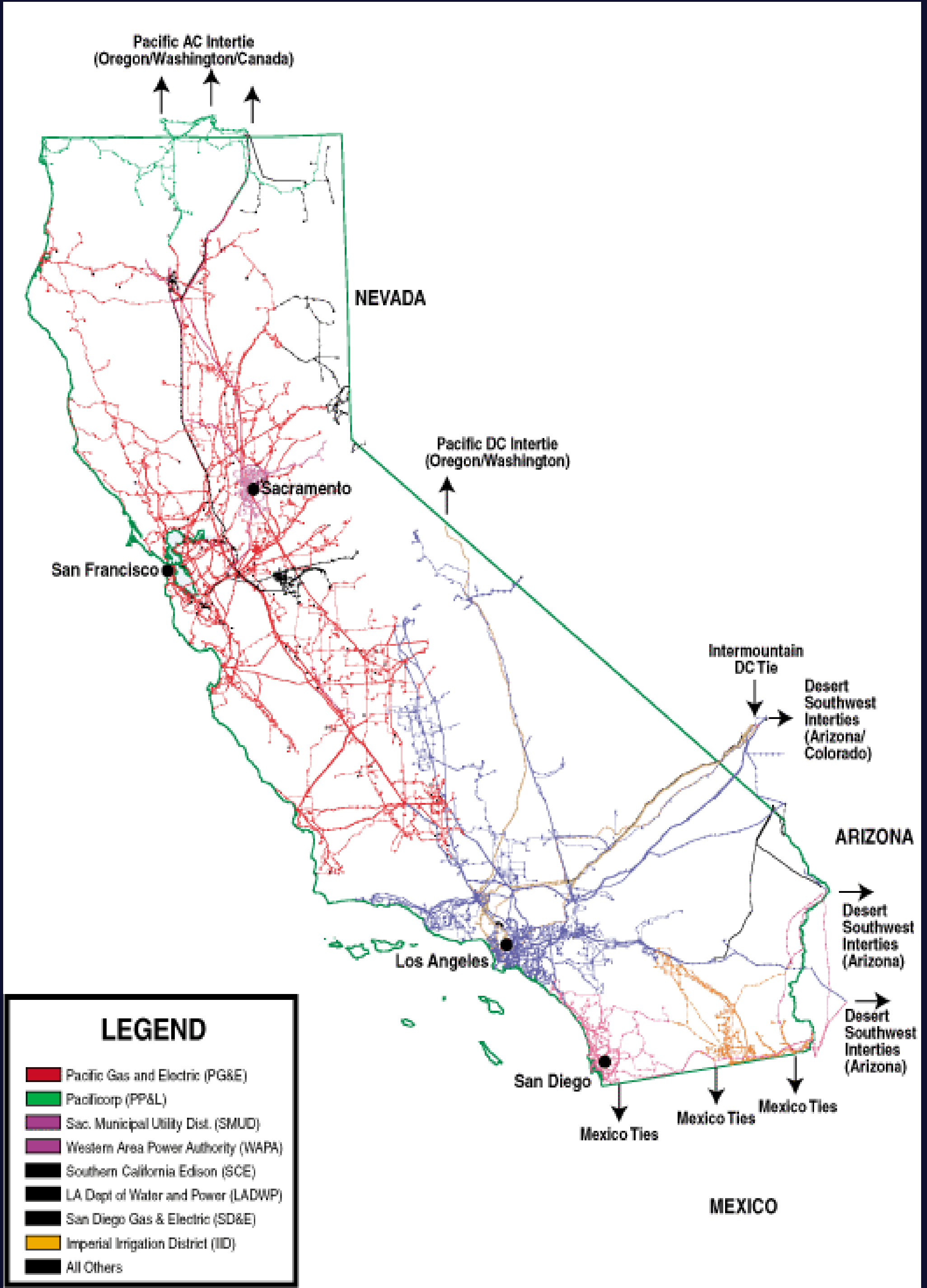
Lakeville transmission substation

Power System Structure
with typical voltage levels





EAST BAY
SAN JOAQUIN VALLEY
GOLDEN GATE
MISSION TRAIL
SKYLINE
SONOMA
SOLANO
MARIN
CONTRA COSTA
SAN JOAQUIN
ALAMEDA
SAN MATEO
SANTA CLARA
STANISLAUS
SACRAMENTO
S.F.
PACIFIC OCEAN
NOVATO
IGNACIO
HAMILTON FIELD
LAS GALLINAS
SAN RAFAEL
GREENBRAE
ALTO
SAUSALITO
SKAGGS ISLAND
NORTH MARE IS. (U.S.N.)
CARQUINEZ
MARE ISLAND
BAHIA
NORTH TOWER
UNOCAL
OLEUM
SEQUOIA
FRANKLIN
POINT PINOLE
UNION CHEMICAL
VALLEY VIEW
STANDARD OIL
EL CERRITO
CHRISTIE
SHELL OIL
ALHAMBRA
BOLLMAN
IMHOFF
MEADOW LANE
CLAYTON
WALNUT CREEK (E.B.M.U.D.)
LAKEWOOD
SOBRANTE
BERKELEY
GRIZZLY
EAST PORTAL
STA. "K"
CLAREMONT
MORAGA
ROSSMOOR
STA. "L"
STA. "C"
STA. "X"
STA. "J"
LARKIN
MISSION
EMBARCADERO
ATLANTIC
POTRERO (STA.A)
HUNTERS PT. (STA.P)
JENNY
EDES
MARTIN
DALY CITY
EAST GRAND
U.A.L. AIRPORT
SERRAMONTE
SAN BRUNO
SNEATH LANE
PACIFICA
SAN MATEO
BERESFORD
BAY MEADOWS
HILLSDALE
BELMONT
SHREDDER
SAN CARLOS
REDWOOD CITY
BELLE HAVEN
RAVENSWOOD
WATERSHED
EMERALD LAKE
JEFFERSON
HALFMOON BAY
SAN LEANDRO (STA. "U")
CASTRO VALLEY
GRANT
MT. EDEN
CRYOGENICS
JARVIS
DUMBARTON
FREMONT
NEWARK
GENERAL MOTORS
SAN RAMON
PARKS
S.R. RESEARCH CTR.
LIVERMORE
KAISER
RADUM
IUKA
VALLECITOS
SUNOL
CONTRA COSTA
BRIONES
BALFOUR
MARSH
MIDDLE RIVER JCT.
EBMUD PUMPING PLANT
CENTRAL VALLEY JCT.
DU PONT
DOW CHEMICAL
BYRON
BETHANY
BROLYN
WINDMASTER
DELTA PUMPS
TRACY PUMPS
WESTSIDE
U.S. WINDPOWER
ALTAMONT
FLOWIND
ZOND
WEST COAST ENERGY
TOKAMAK
LAWRENCE LAB
TESLA
A.E.C. No. 2
TRACY
S.P. WELDER
ELLIS
CARBONA
HEINZ
LYOTH
KASSON
MANTECA JCT.
SANTA JCT.
SANTA CARBONA
RIPON
MANTECA
HOWLAND RD.
MOSSDALE SWS.
LOUISE
STOCKTON COGEN
GRONEMYER
FRENCH CAMP
STOCKTON
LOCKFORD JCT.
WEBER
E. STOCKTON
ROUGH & READY
STOCKTON ACRES CHANNEL
MIDDLE RIVER
MC DONALD
HAMMER
MOSHER
WATERLOO
CHEROKEE
MORMON
METTLER
TERMINOUS
LODI
VICTOR
LOCKEFORD
INGRAM CREEK TO MANTECA
WESTLEY
INGRAM CREEK
MODESTO ENERGY
SALADO
MILPITAS
MONTAGUE
TRIMBLE
MC KEE
MABURY
JENNINGS
SWIFT
GISH
KIFER
SCOTT
WESTINGHOUSE
STELLING
WOLFE
MONTE VISTA
MAGNESIUM
PERMANENTE
LOYOLA
LOS ALTOS
MT. VIEW
WHISMAN
NASA
PALO ALTO
COLORADO
S.L.A.C. (A.E.C.)



Pacific AC Intertie
(Oregon/Washington/Canada)
NEVADA
Pacific DC Intertie
(Oregon/Washington)
Sacramento
San Francisco
Intermountain
DC Tie
Desert
Southwest
Interties
(Arizona/
Colorado)
ARIZONA
Desert
Southwest
Interties
(Arizona)
Los Angeles
Desert
Southwest
Interties
(Arizona)
San Diego
Mexico Ties
Mexico Ties
Mexico Ties
MEXICO
LEGEND
Pacific Gas and Electric (PG&E)
Pacificorp (PP&L)
Sac. Municipal Utility Dist. (SMUD)
Western Area Power Authority (WAPA)
Southern California Edison (SCE)
LA Dept of Water and Power (LADWP)
San Diego Gas & Electric (SD&E)
Imperial Irrigation District (IID)
All Others

Captain Jack
Malin
Oregon
California
Round Mountain
Olinda
Table Mountain
COTP
AC INTERTIE
DC INTERTIE
Lake Tahoe
Tracy
Tesla
San Francisco
Los Banos
Path 15
Gates
Midway
Sylmar
Vincent

www.trans-elect.com

www.trans-elect.com


www.trans-elect.com

Three voltage levels:

Subtransmission (60-115kV)

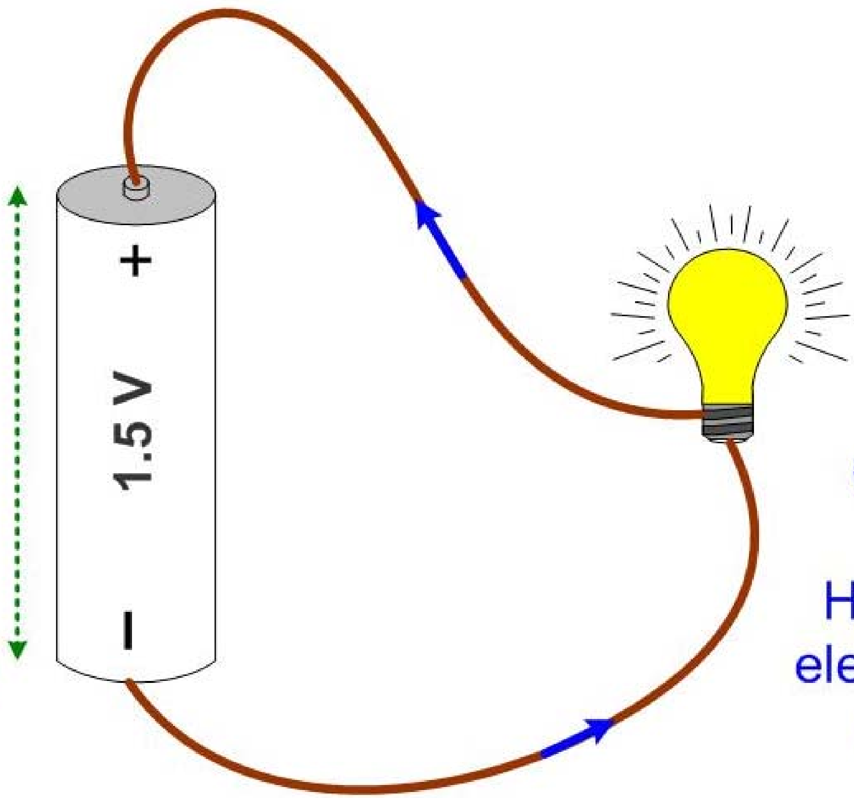
Primary distribution (12-21kV)

Secondary distribution (120/240V)

Voltage:

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

(Energy / Charge)



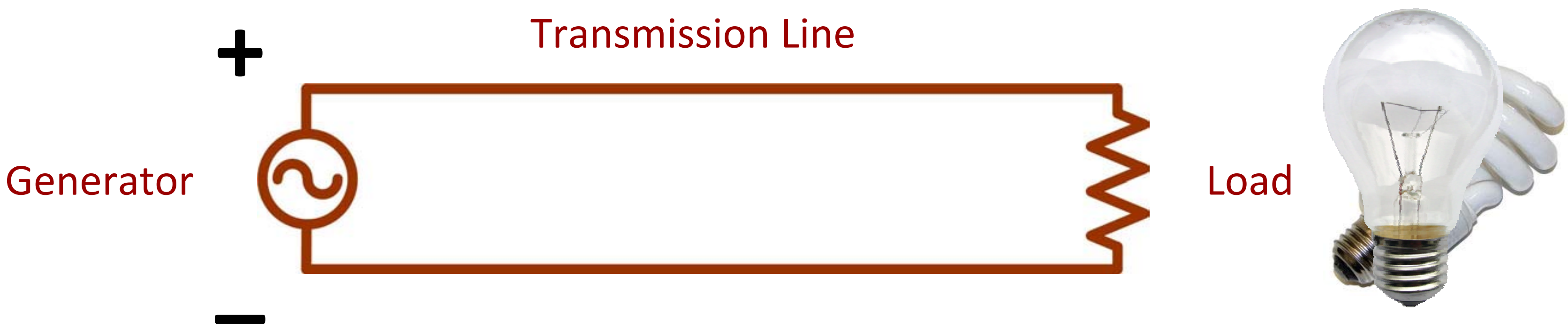
Current:

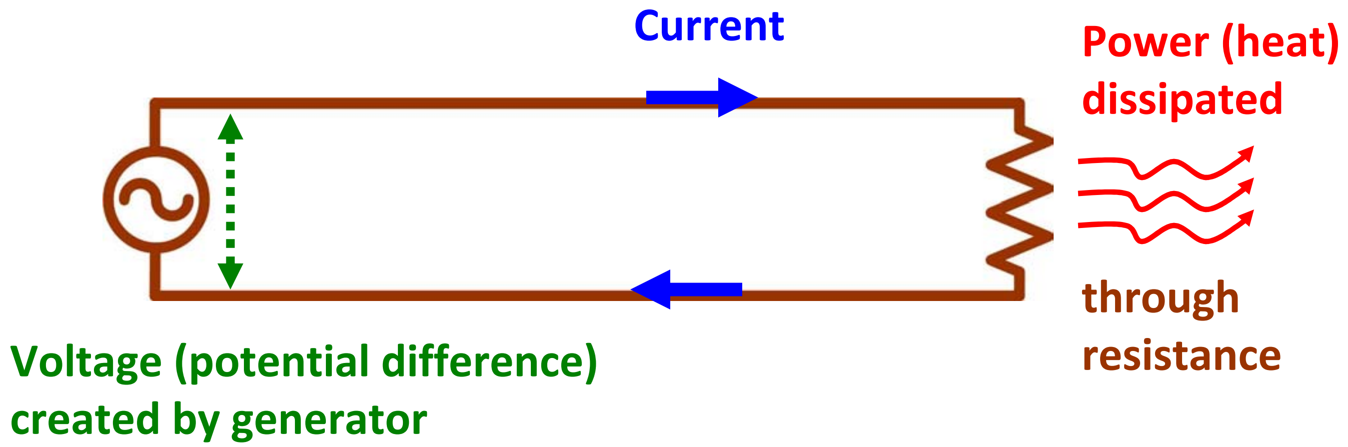
How many electrons are flowing

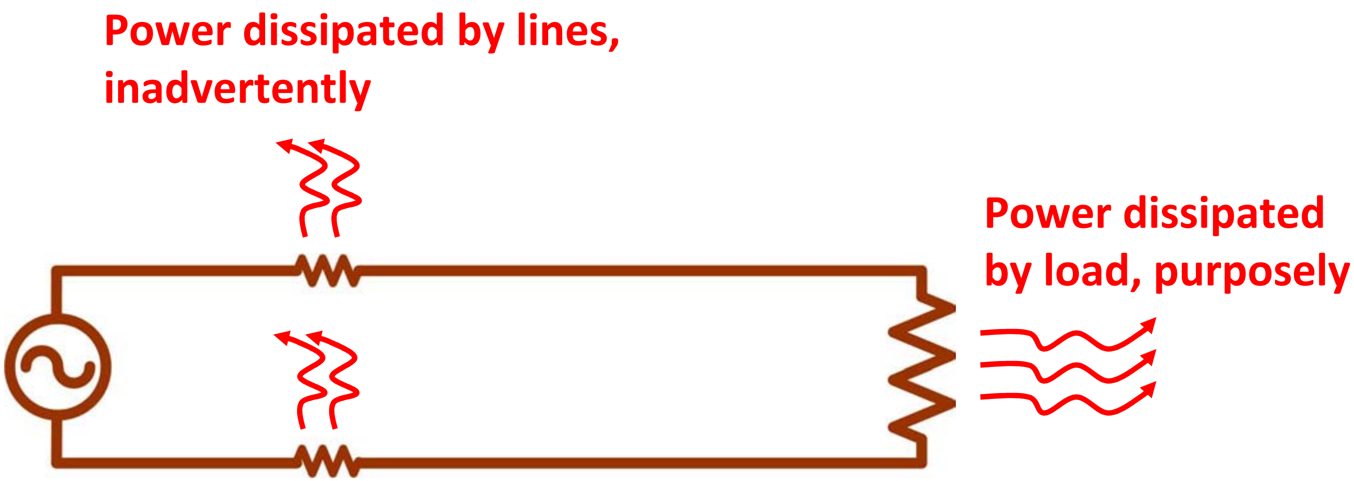
(Charge / Time)

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

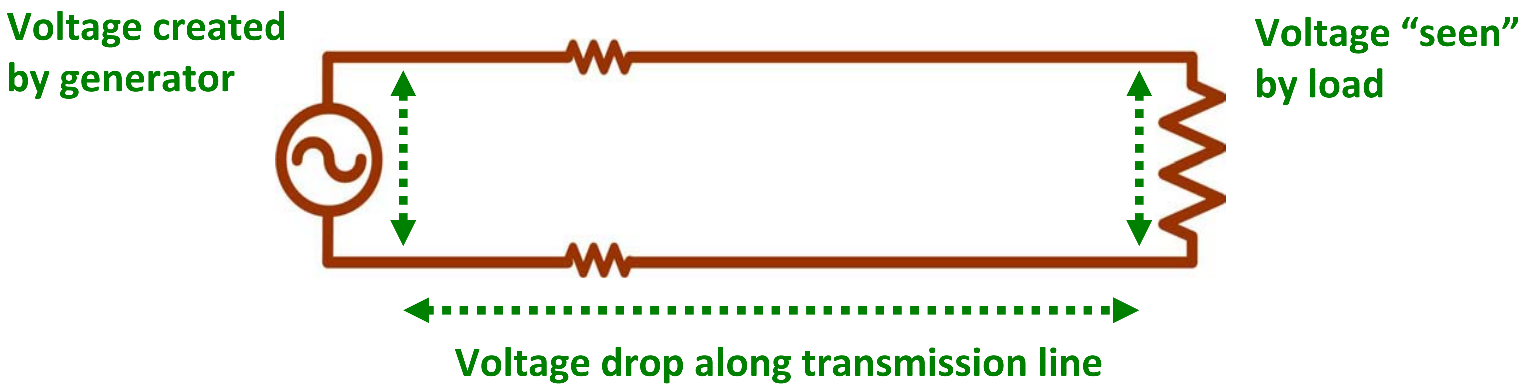
Power = Voltage x Current (Energy / Time)


Transmission Line
+
Generator
Load
−


Current
Power (heat)
dissipated
through
resistance
Voltage (potential difference)
created by generator



Resistance of conductor increases with length, decreases with cross-sectional area: material & weight constraints for minimizing R_{line}



Voltage = current x resistance

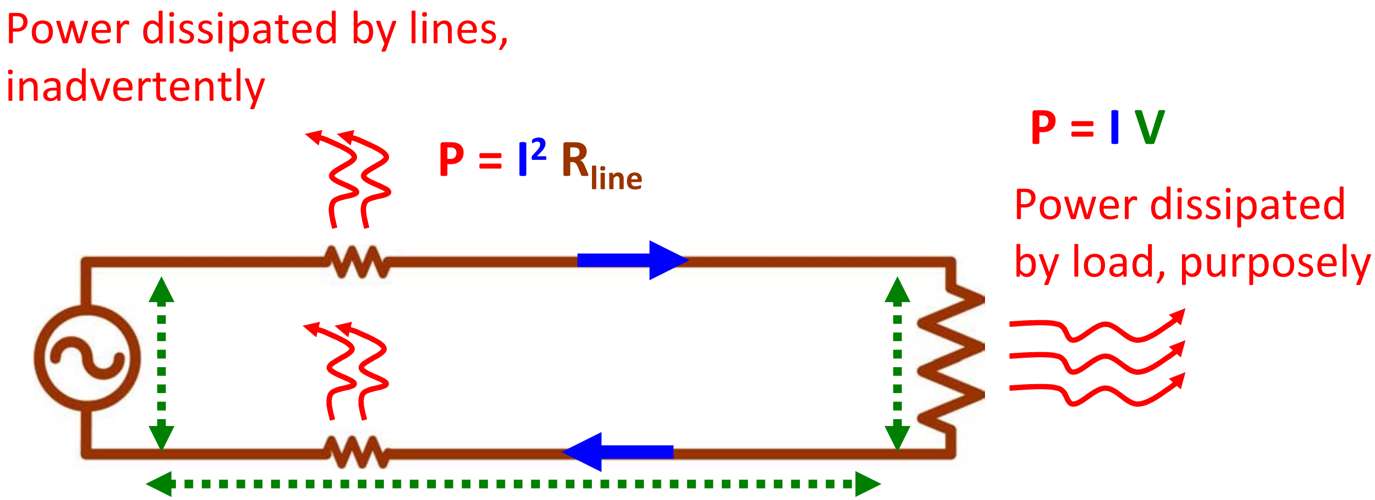
$$V = I\,R$$

$V_{drop} = I\,R_{line}$ (on both legs of circuit)

$P = I\,V$ **Power = current x voltage**

$P = I^2\,R$ **Power = current^2 x resistance**

(these are equivalent because $V = I\,R$)



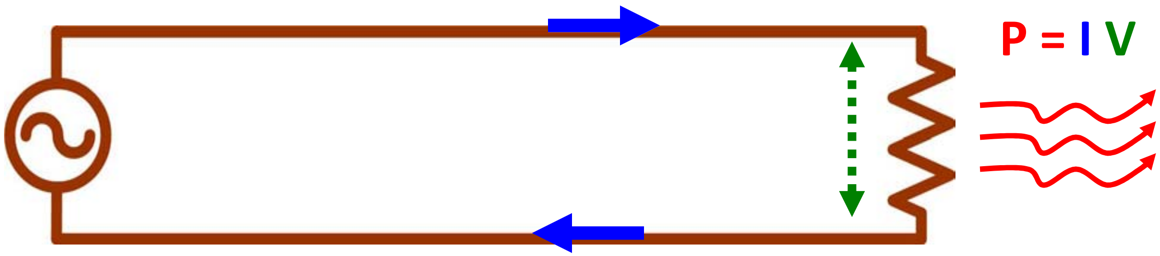
$P = I V$ **Power = current x voltage**

where V means *local* voltage drop

$P = I^2 R$ **Power = current² x resistance**

by substituting $I R_{line}$ for V_{drop} which usually isn't known

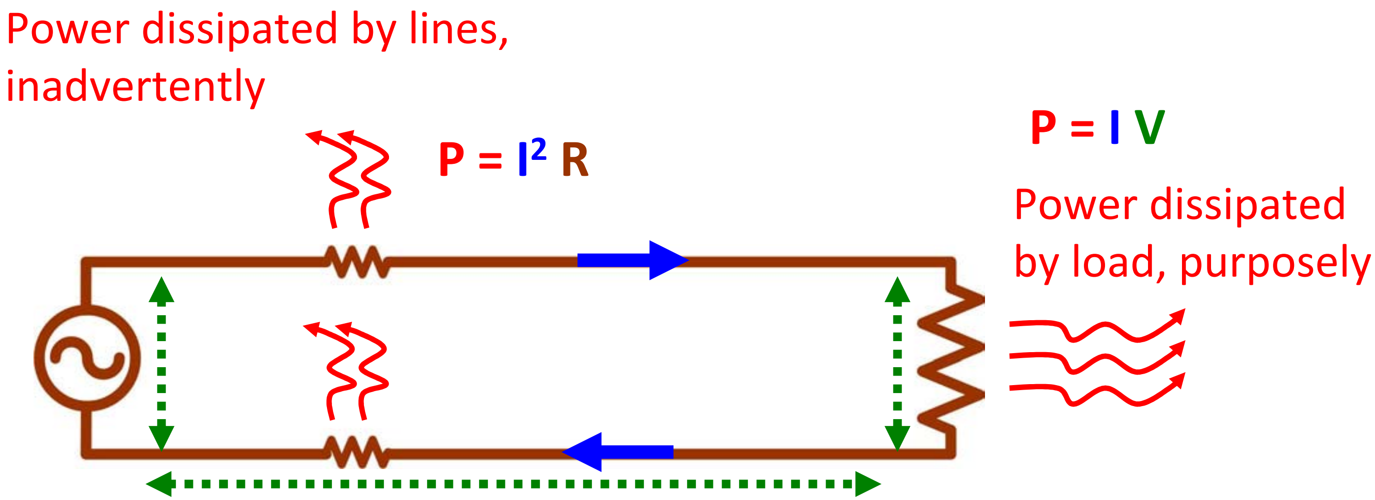
Current is the same throughout, but determined mostly by the big resistance (load)



For the load, the same amount of power could be supplied by using either combination of I V:

big current, small voltage

small current, big voltage



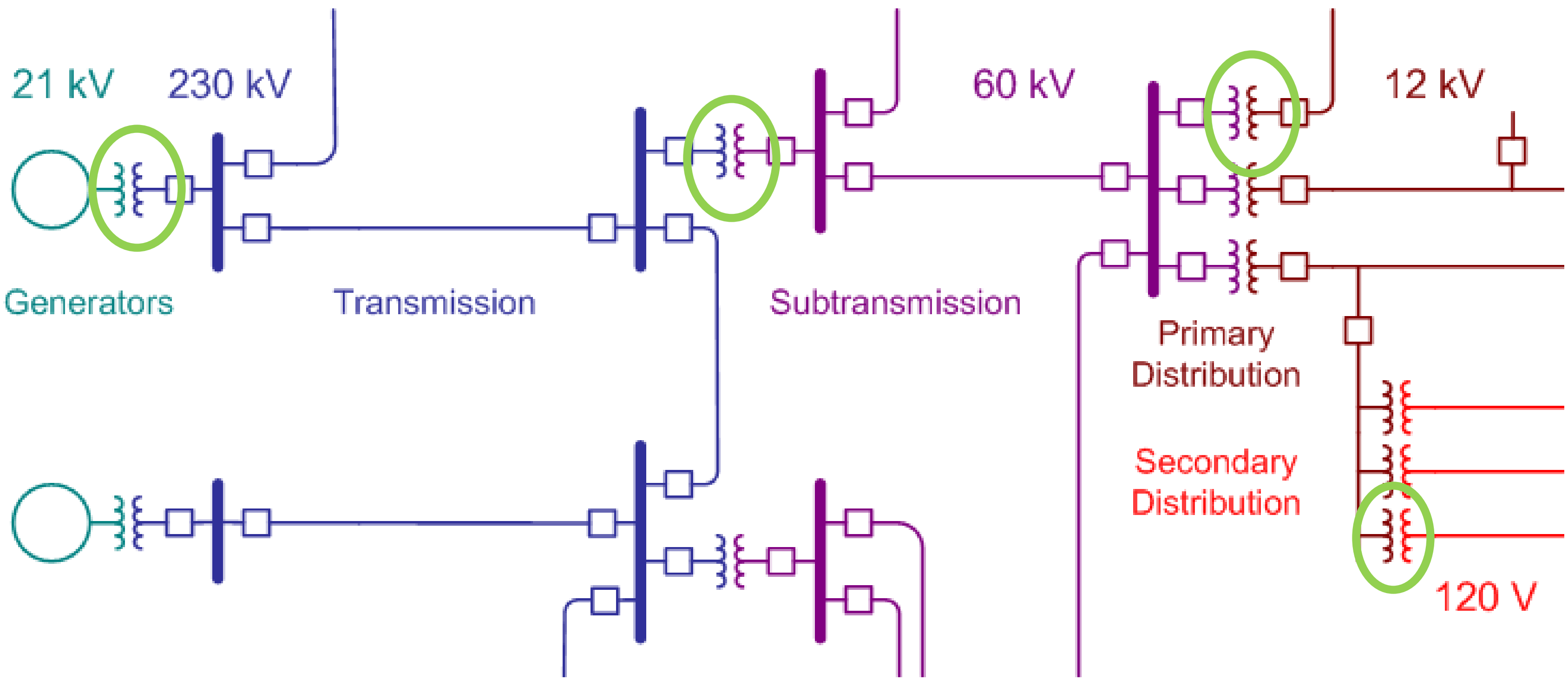
But line losses will be much greater with big current and small voltage.

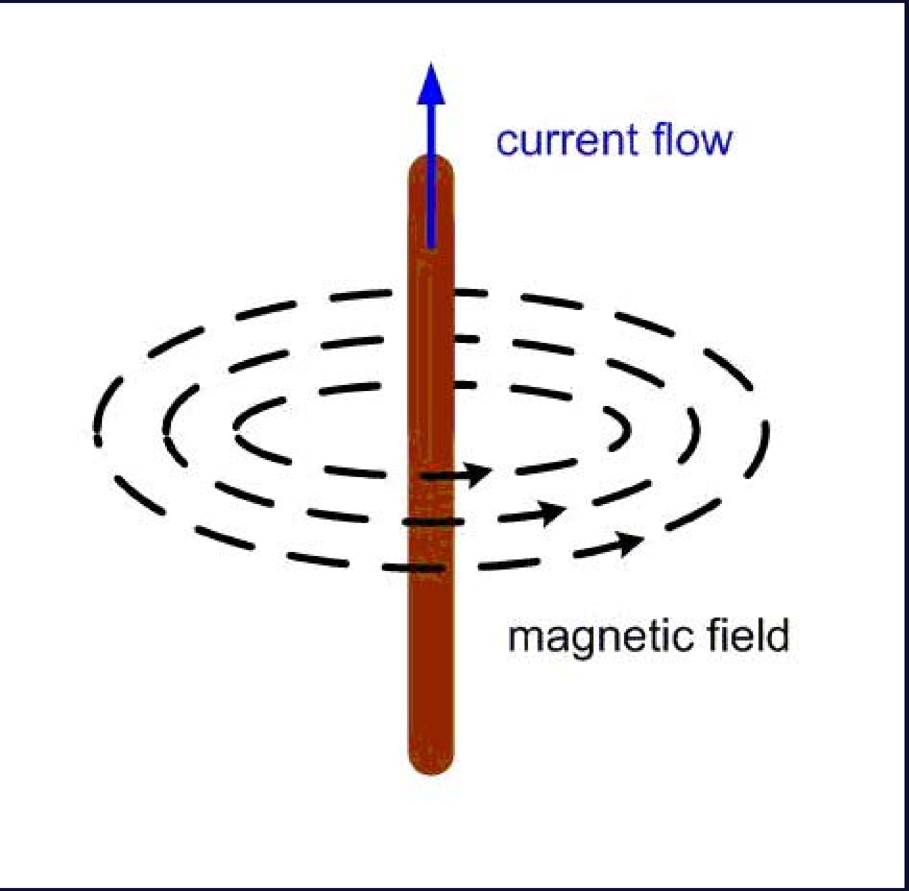
Therefore, high transmission voltage is preferred to minimize line losses.

Problem: 100,000 volts aren’t safe (or practical) for end use.

Solution: Transformers.

Power System Structure
with typical voltage levels



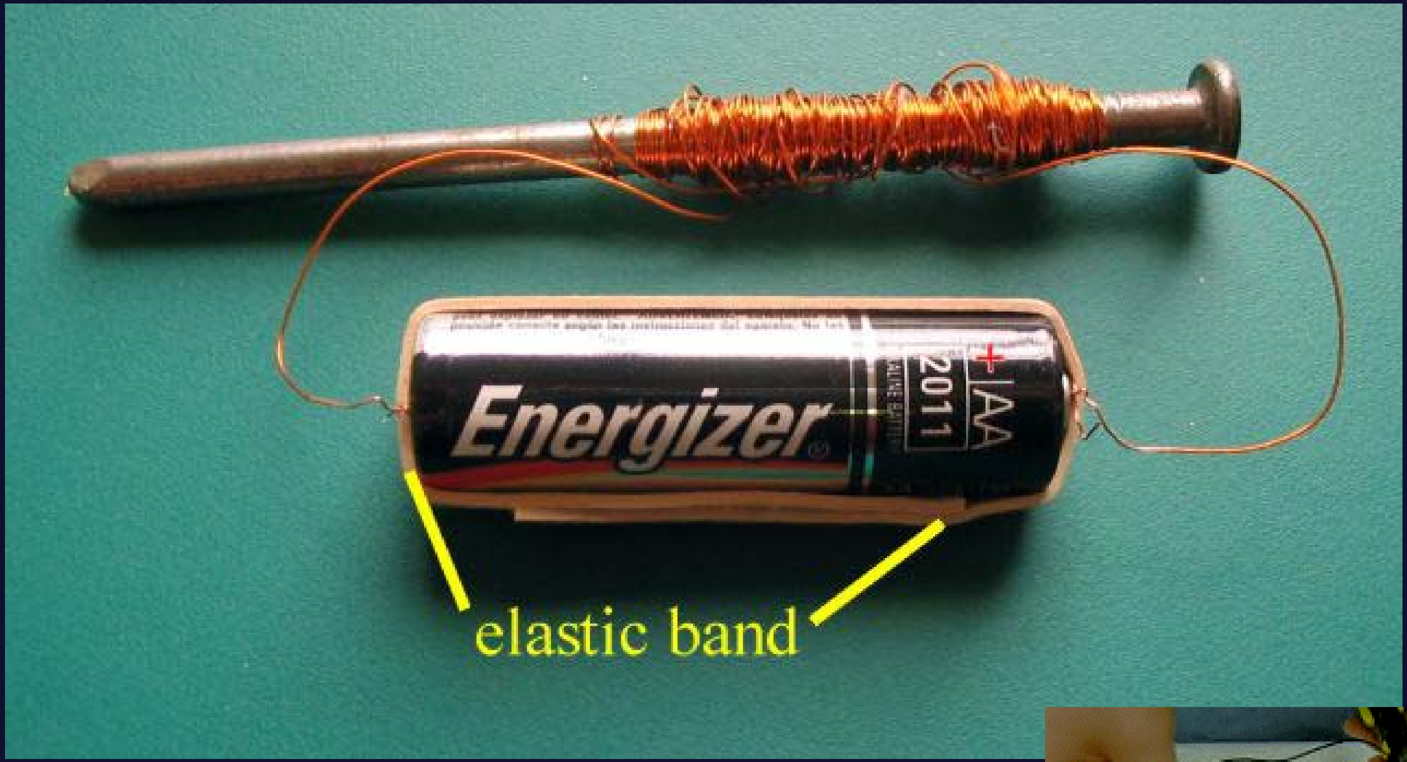


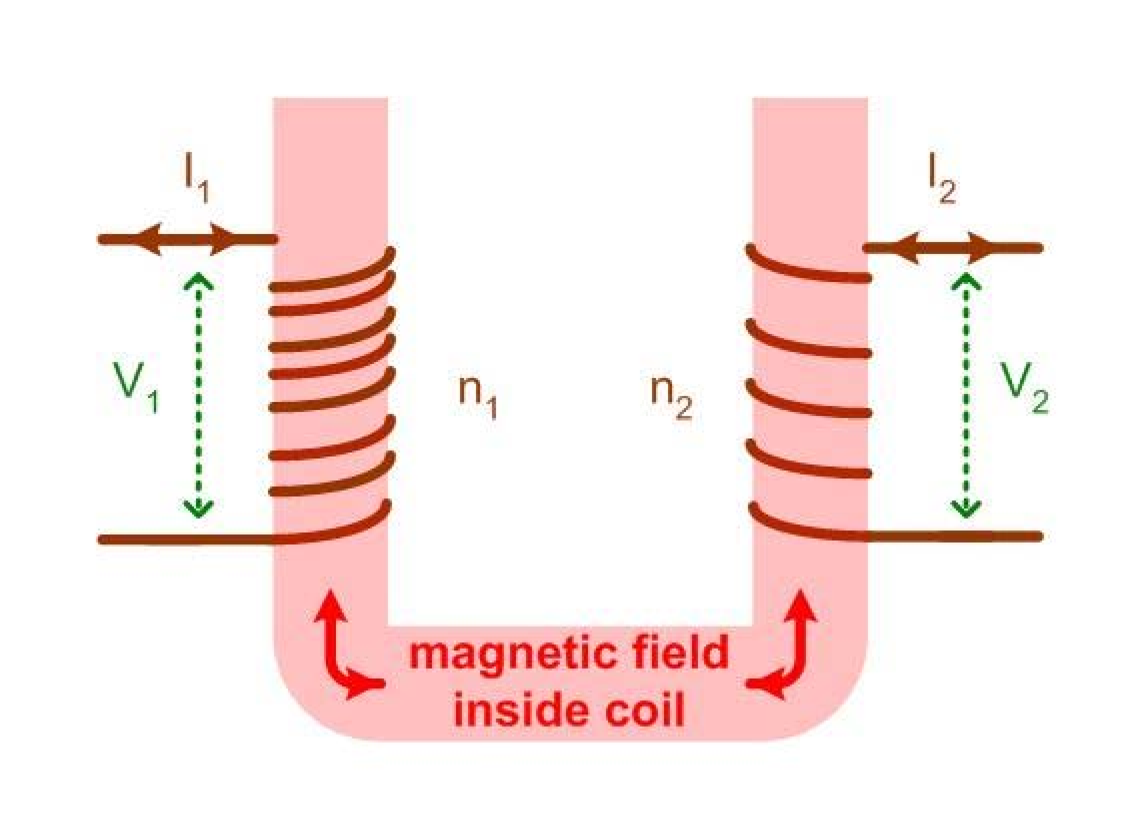
Electromagnetic induction:

the basic workings of transformers and generators

Moving electric charge (current) produces a magnetic field.

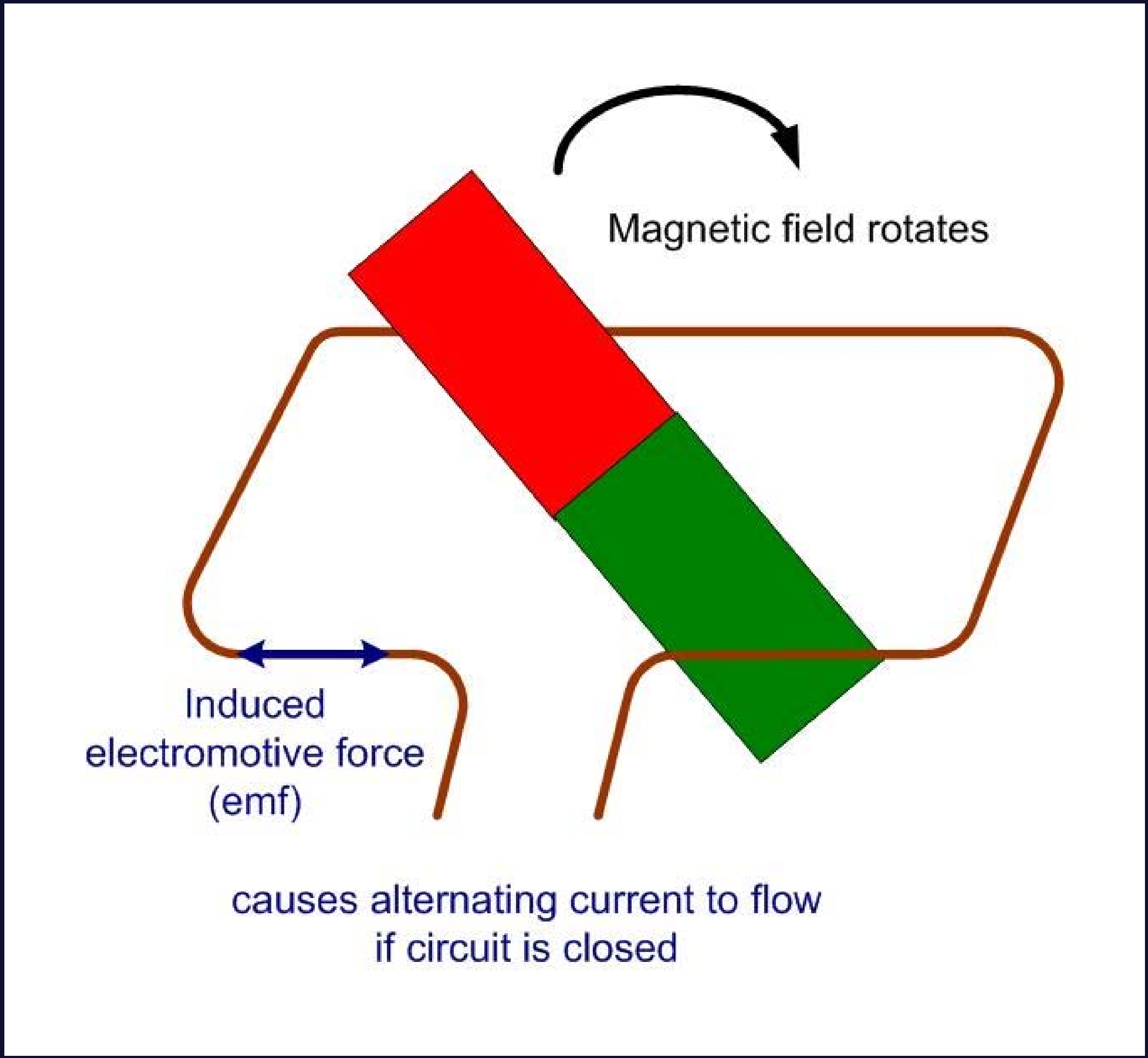
A *changing* magnetic field in turn
moves electric charges (induces current).

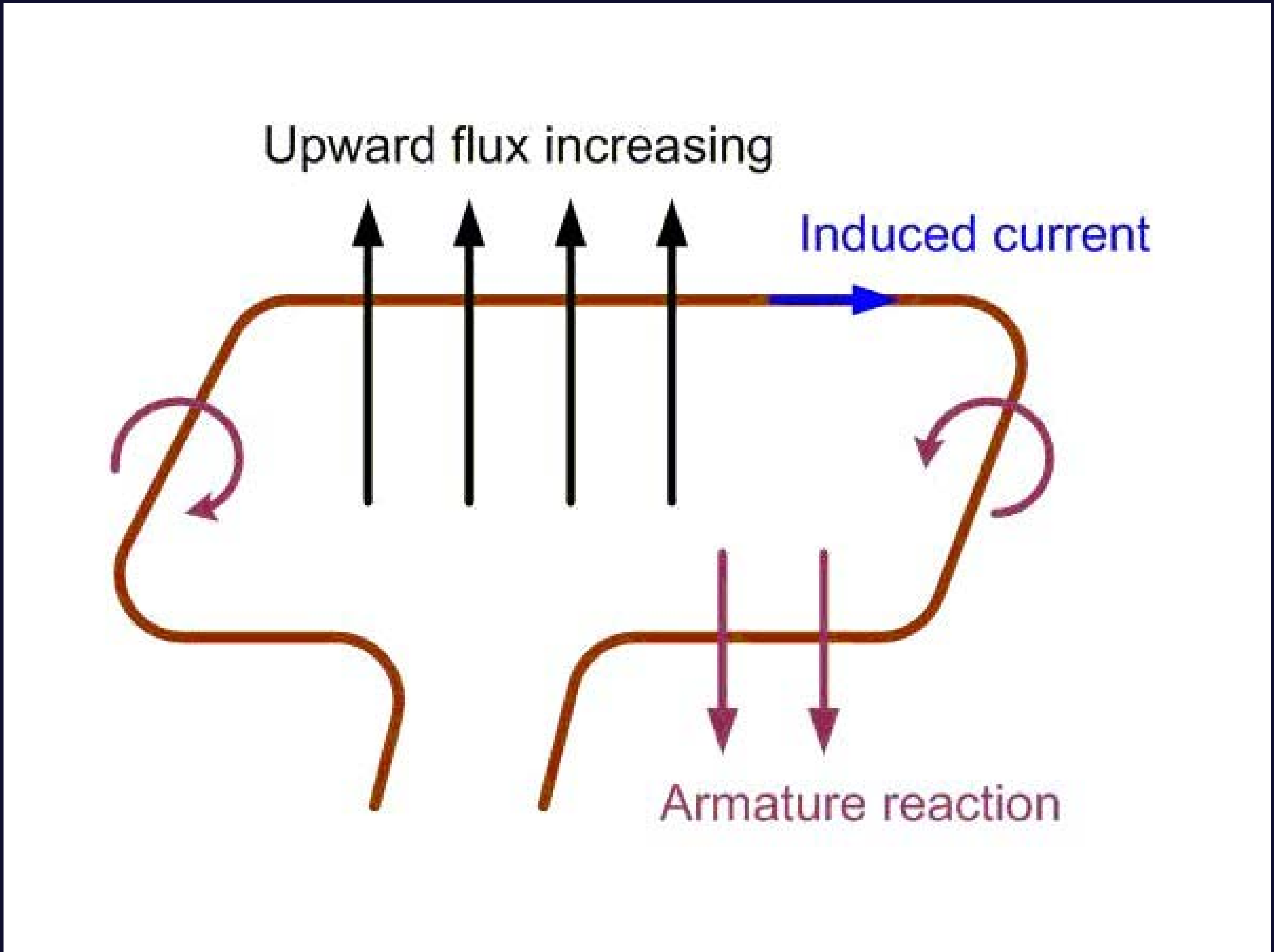

Energizer
AA
2011
elastic band



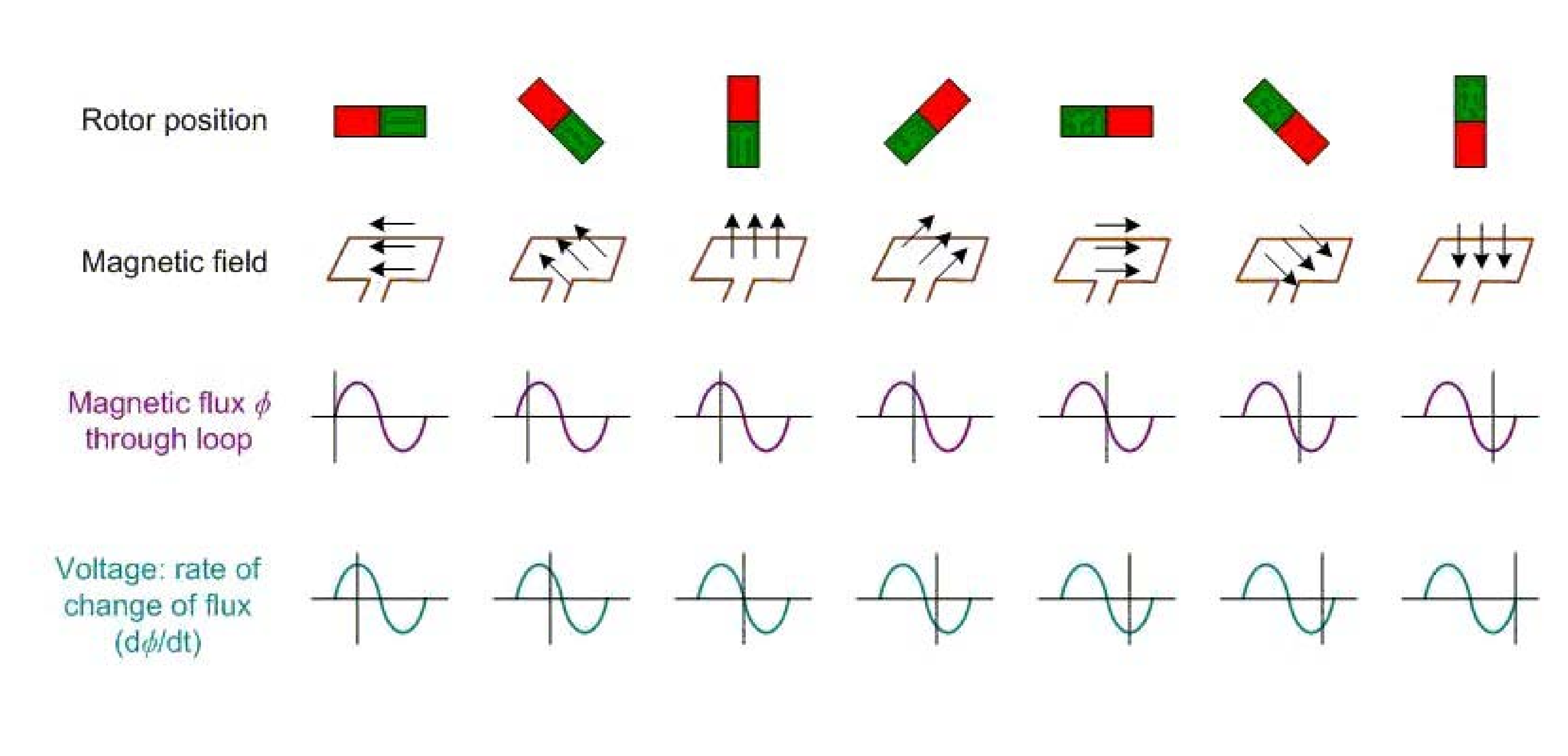
Transformer: a device to transmit electric power from one circuit to another across a magnet.

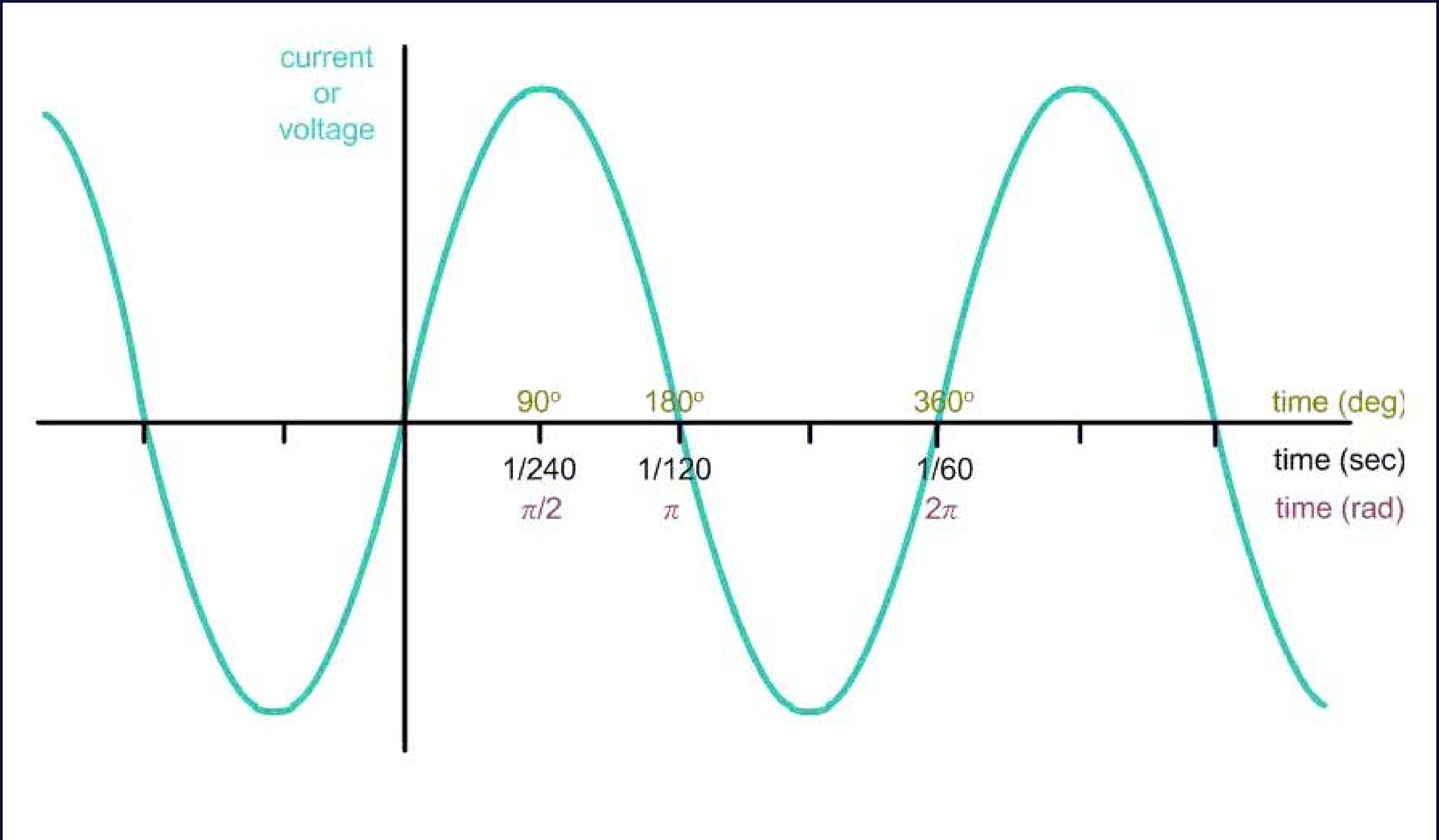
This works only with alternating current,
because a constant magnetic field doesn’t move electric charge!


Magnetic field rotates
Induced
electromotive force
(emf)
causes alternating current to flow
if circuit is closed



Magnetic field from induced current opposes the initial field


Rotor position
Magnetic field
Magnetic flux ϕ through loop
Voltage: rate of change of flux ($d\phi/dt$)

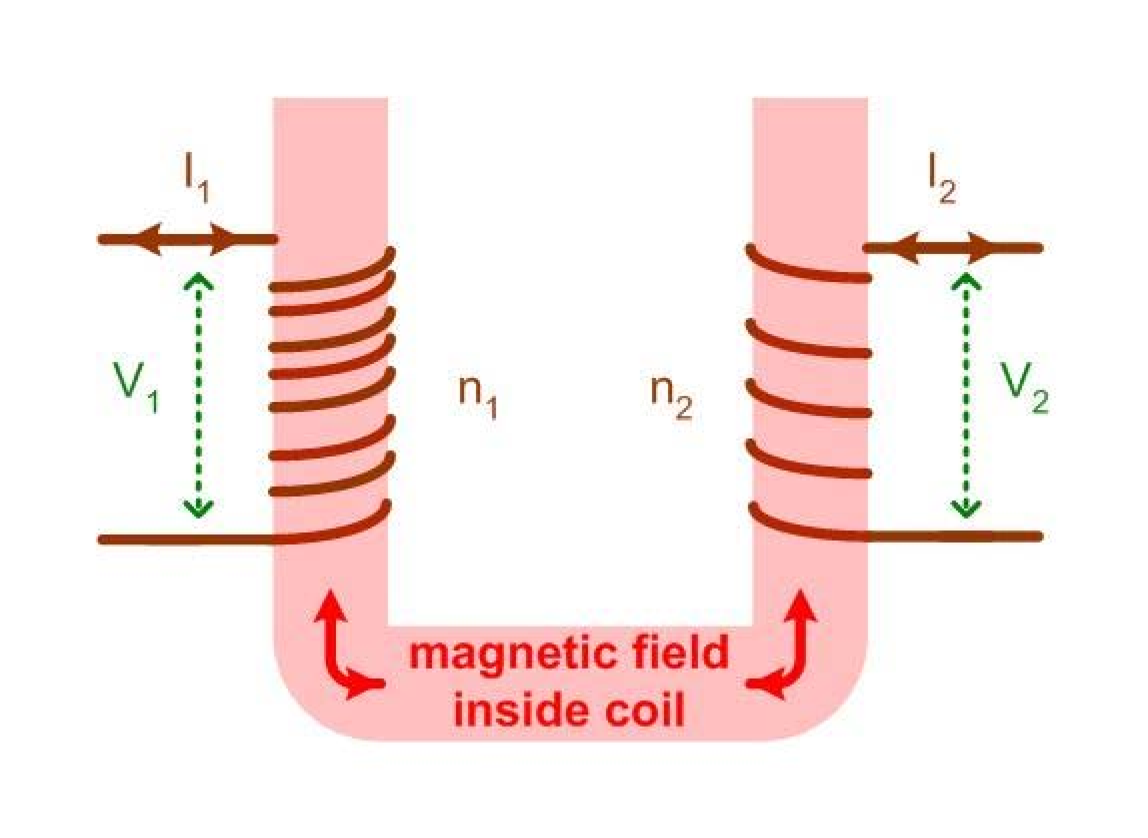


Alternating current with frequency 60 Hz

Primary side:

High voltage

Low current



Secondary side:

Low voltage

High current

The turns ratio determines the voltage on each side of the transformer

$$V_2 / V_1 = n_2 / n_1$$

To satisfy energy conservation, $P_1 = P_2$

thus $I_1 V_1 = I_2 V_2$ (neglecting losses)

Primary

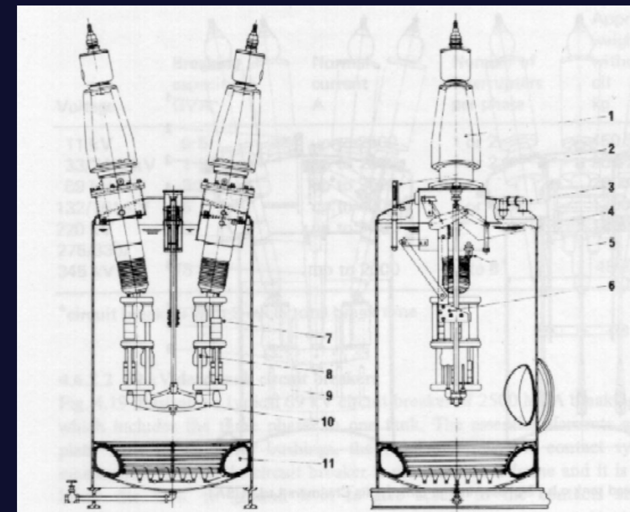
Secondary

Primary

Secondary

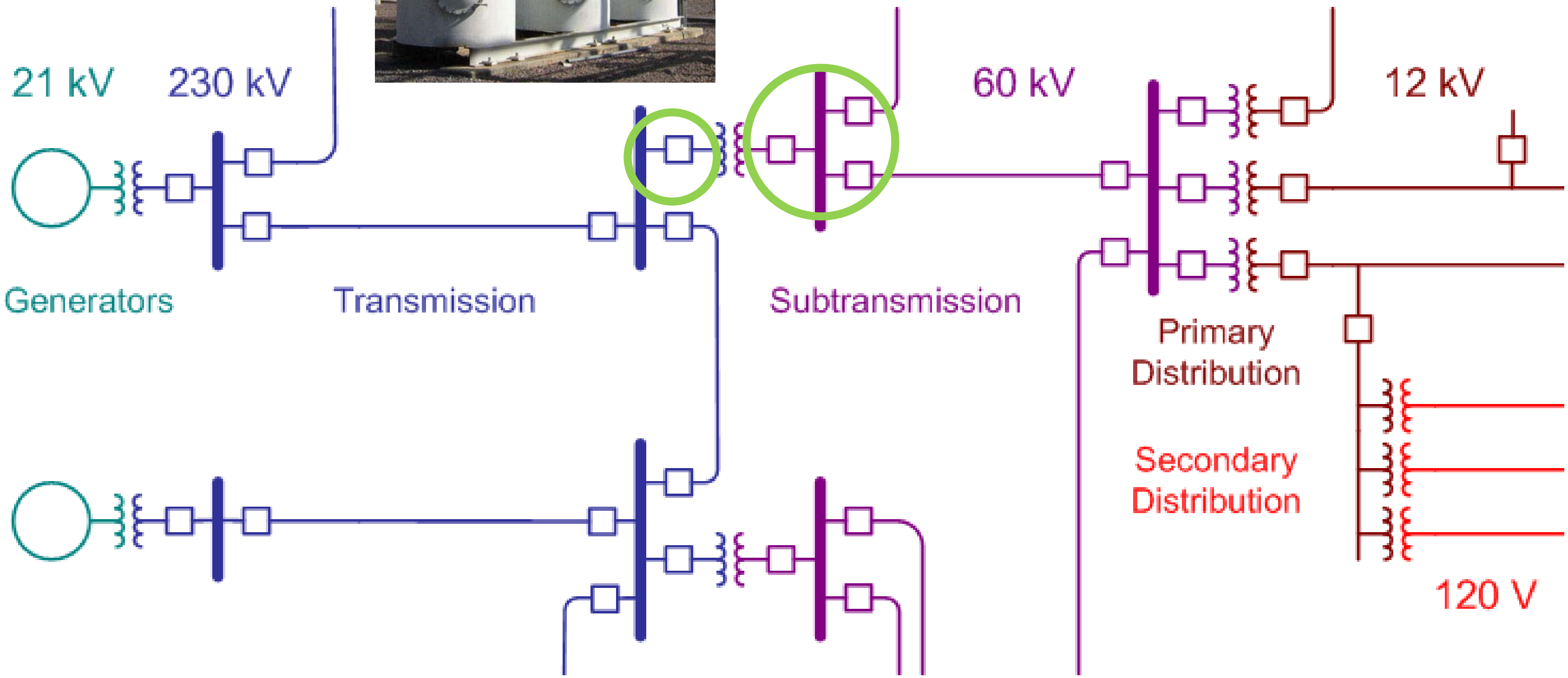

Incoming Subtransmission Lines
Electric power path through substation
34 KV in
Lightning Arresters
Air-break Switches
Outgoing Distribution Lines
Step-down Transformer
Distribution Bus
7.2 KV out
Cutout
Switches
Oil Circuit Breakers
Voltage Regulators
Metal-clad
Switchgear
Control House

Image: OSHA



Oil circuit breakers

SF_6 circuit breaker

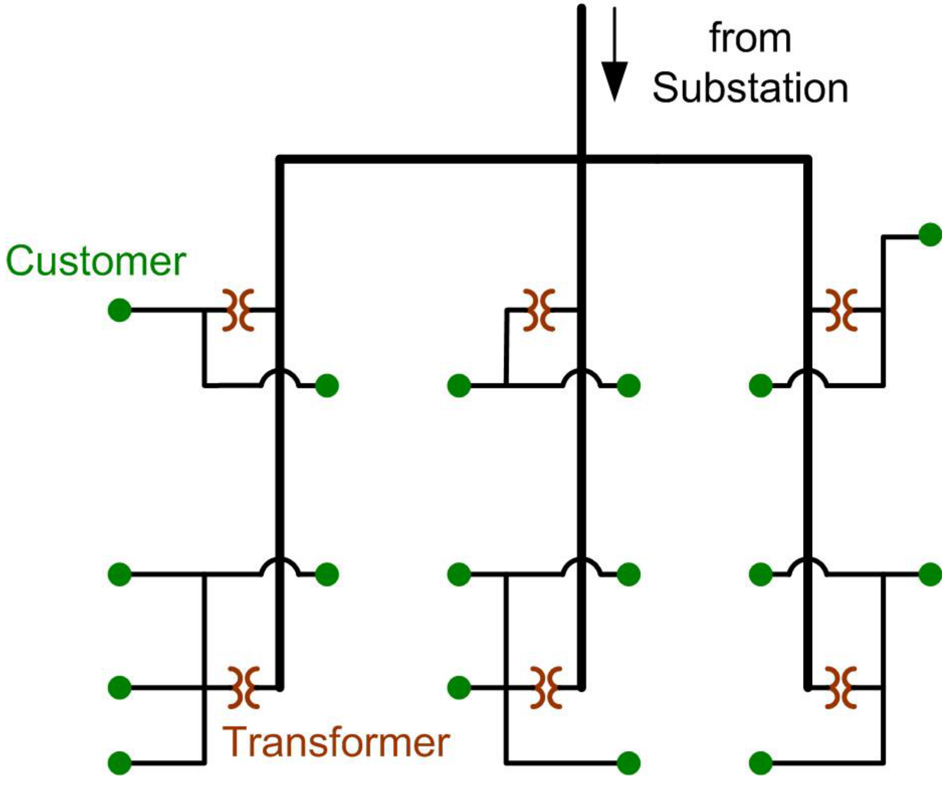

21 kV
230 kV
60 kV
12 kV
Generators
Transmission
Subtransmission
Primary
Distribution
Secondary
Distribution
120 V

Distribution Systems

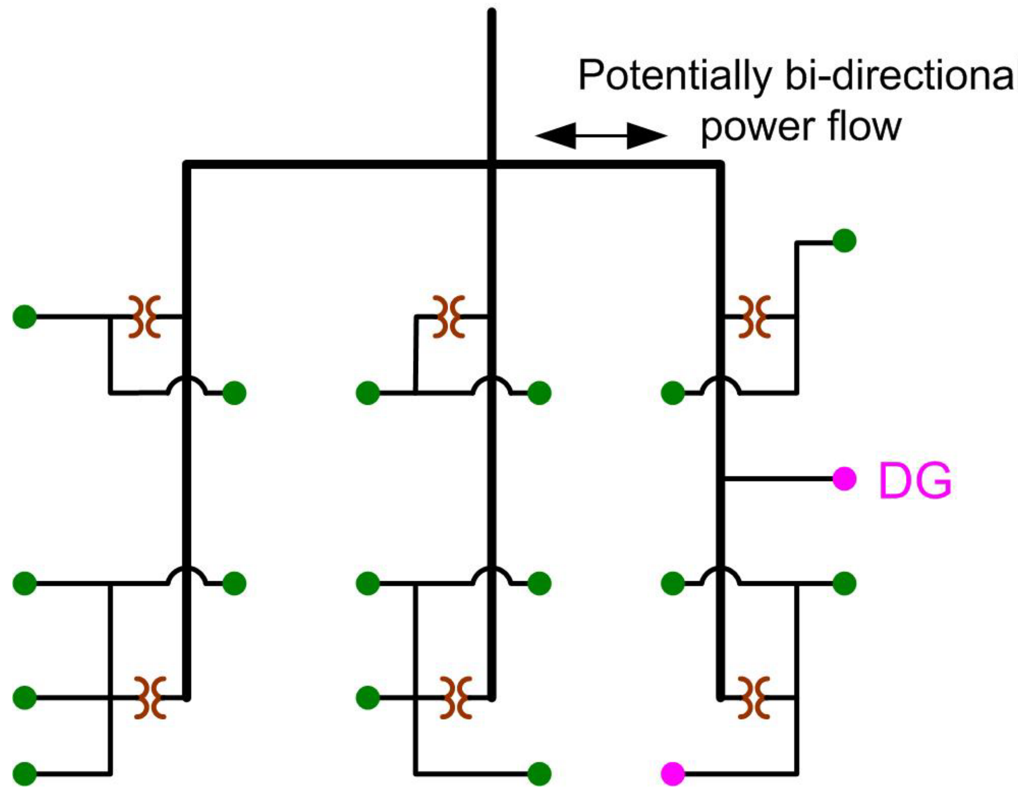
Components: conductors
transformers
switchgear
protection
voltage regulation
loads

Topology: Radial, Loop and Network Designs

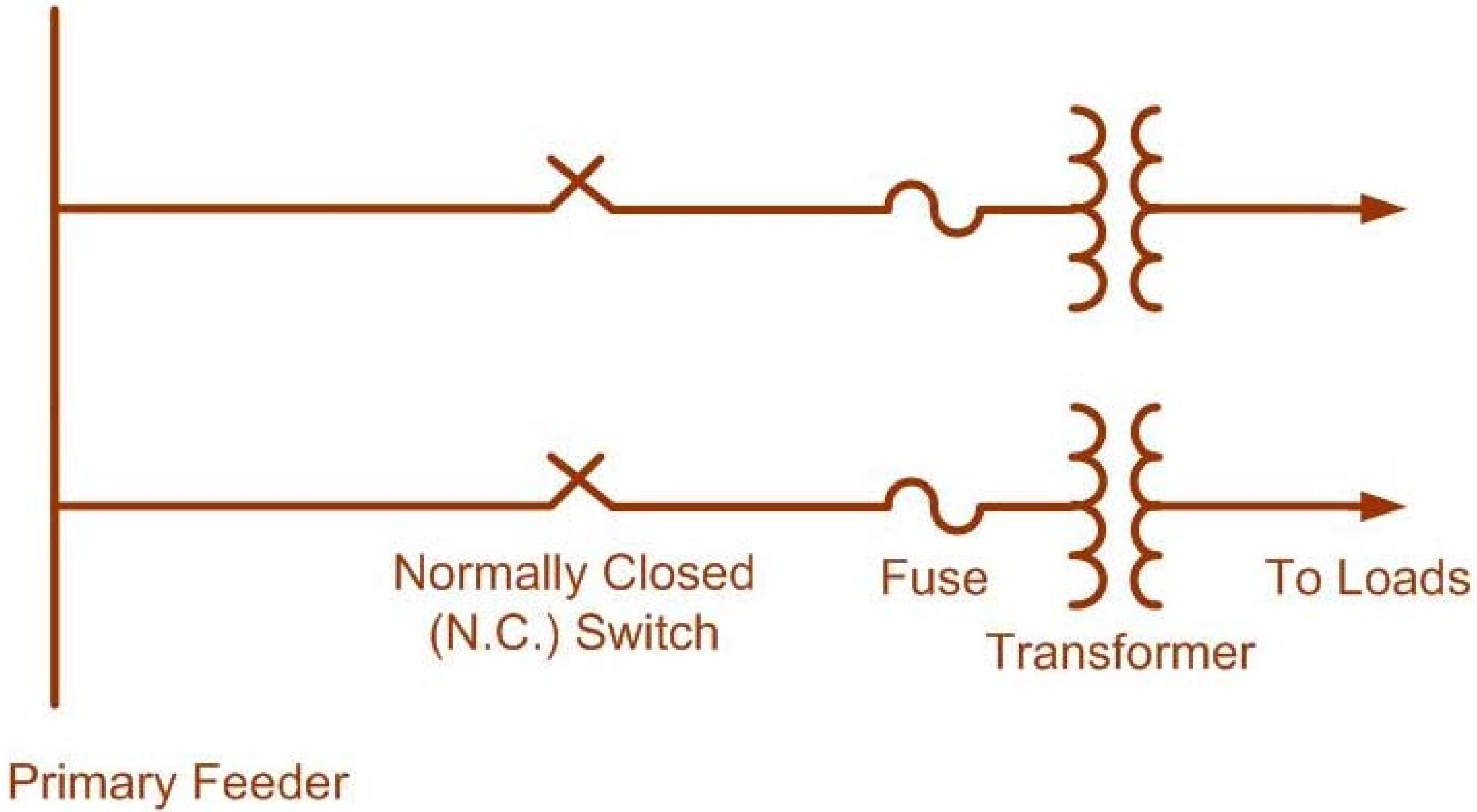
Typical Distribution System Layout
with radial topology & power flow

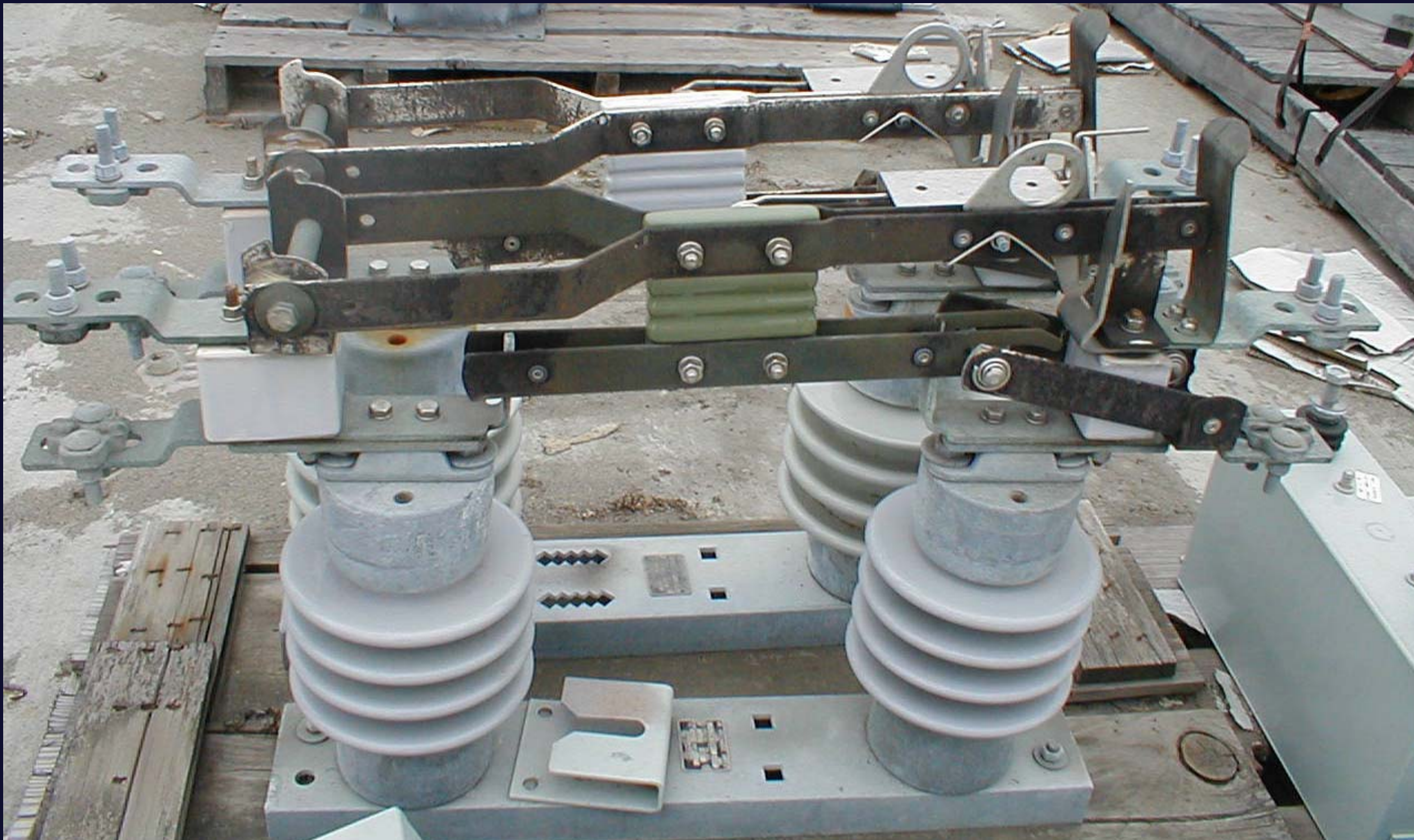


Radial Distribution System with Distributed Generation



Basic Radial System



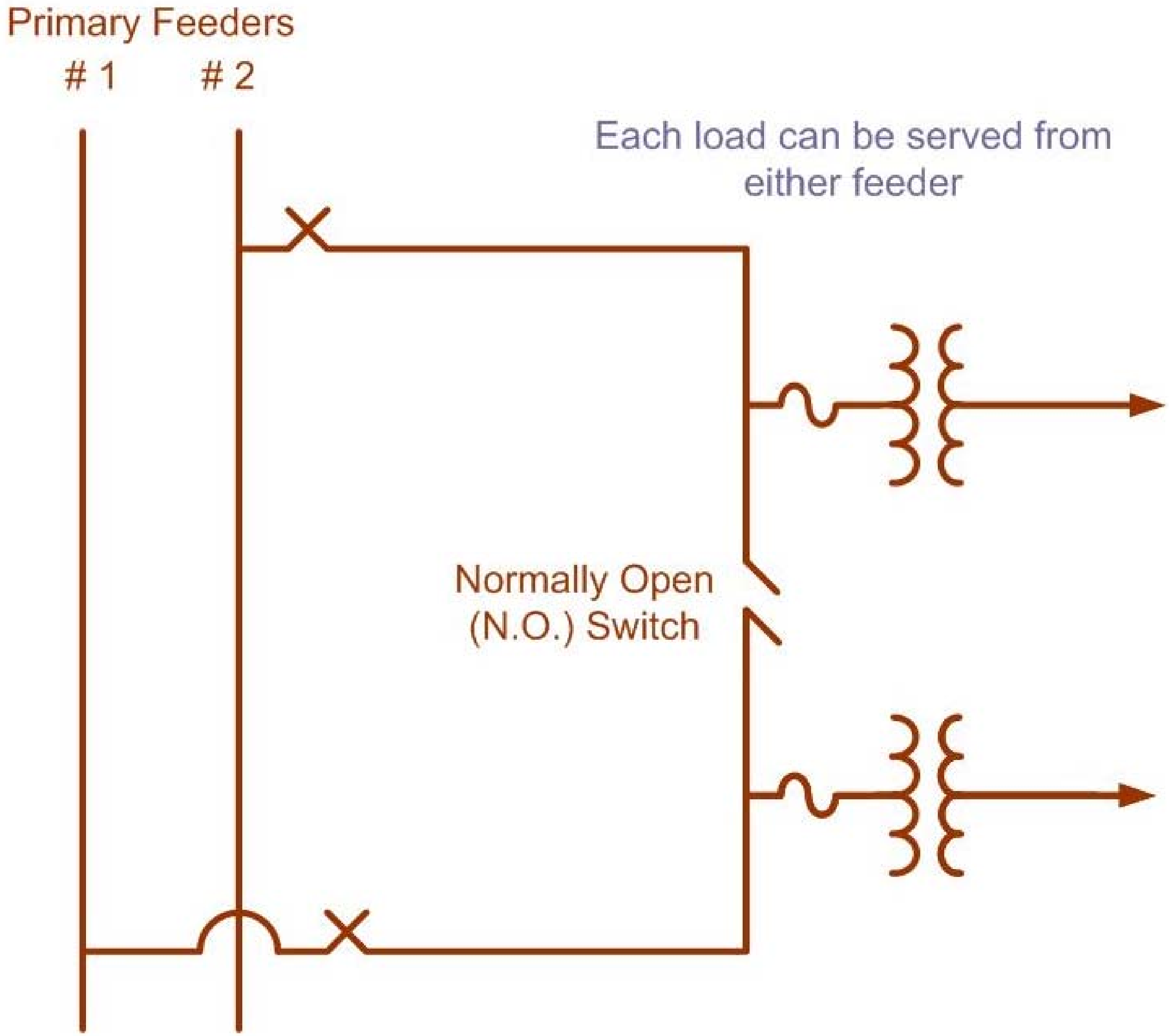


Air Switch

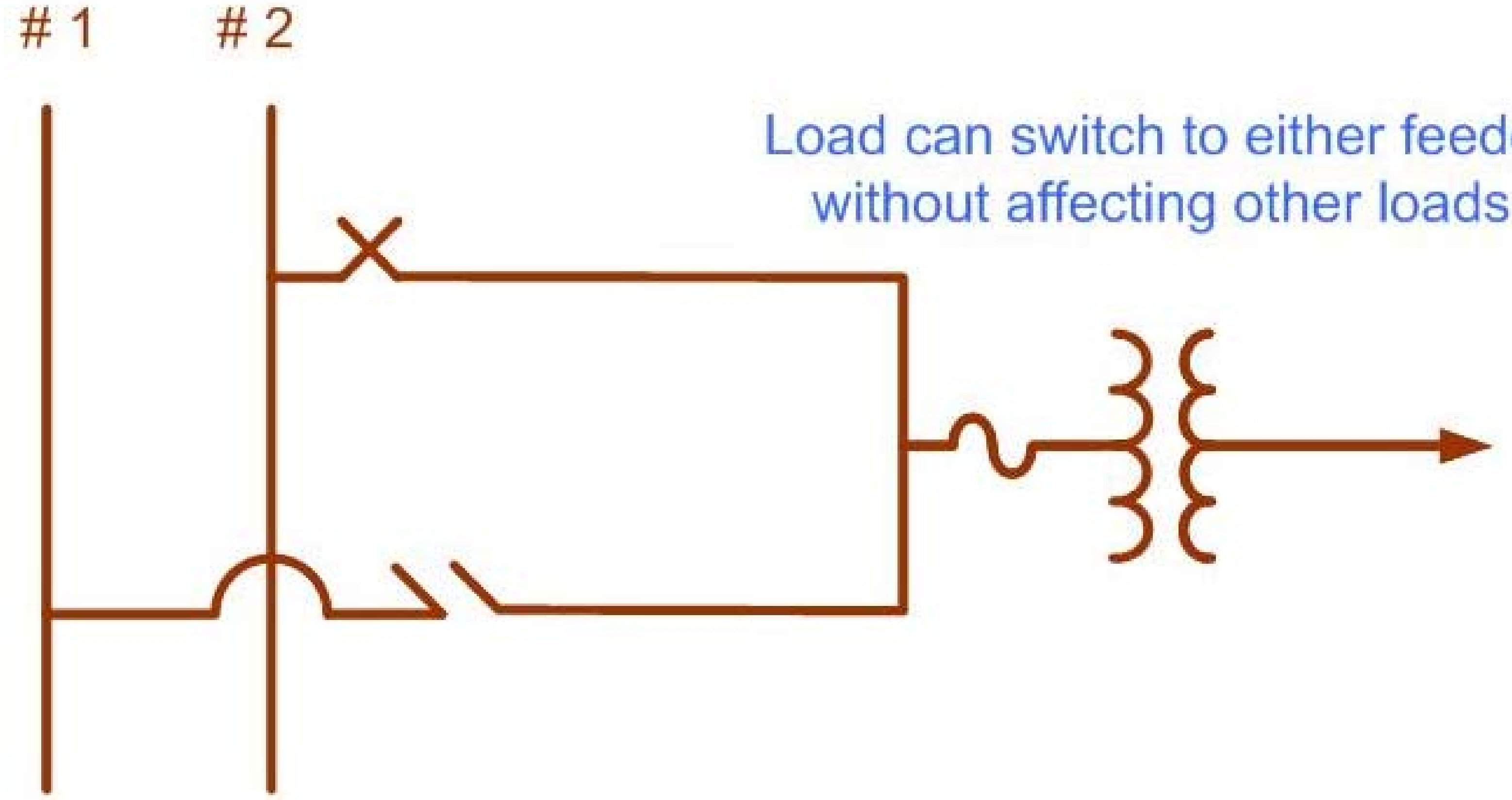
S&C Type XS Fuse Cutouts

Outdoor Distribution
(4.16 kV through 25 kV)

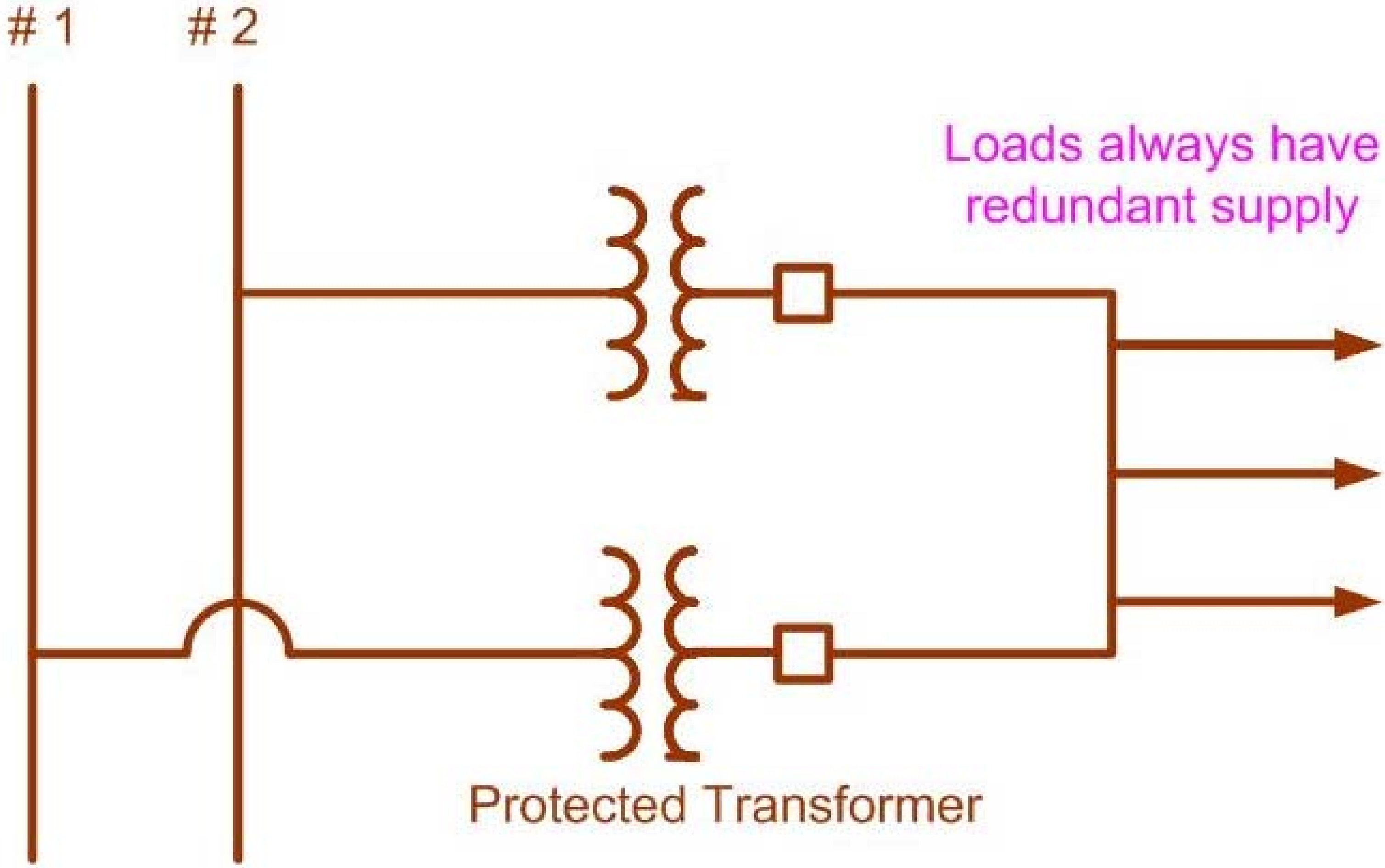
Loop System

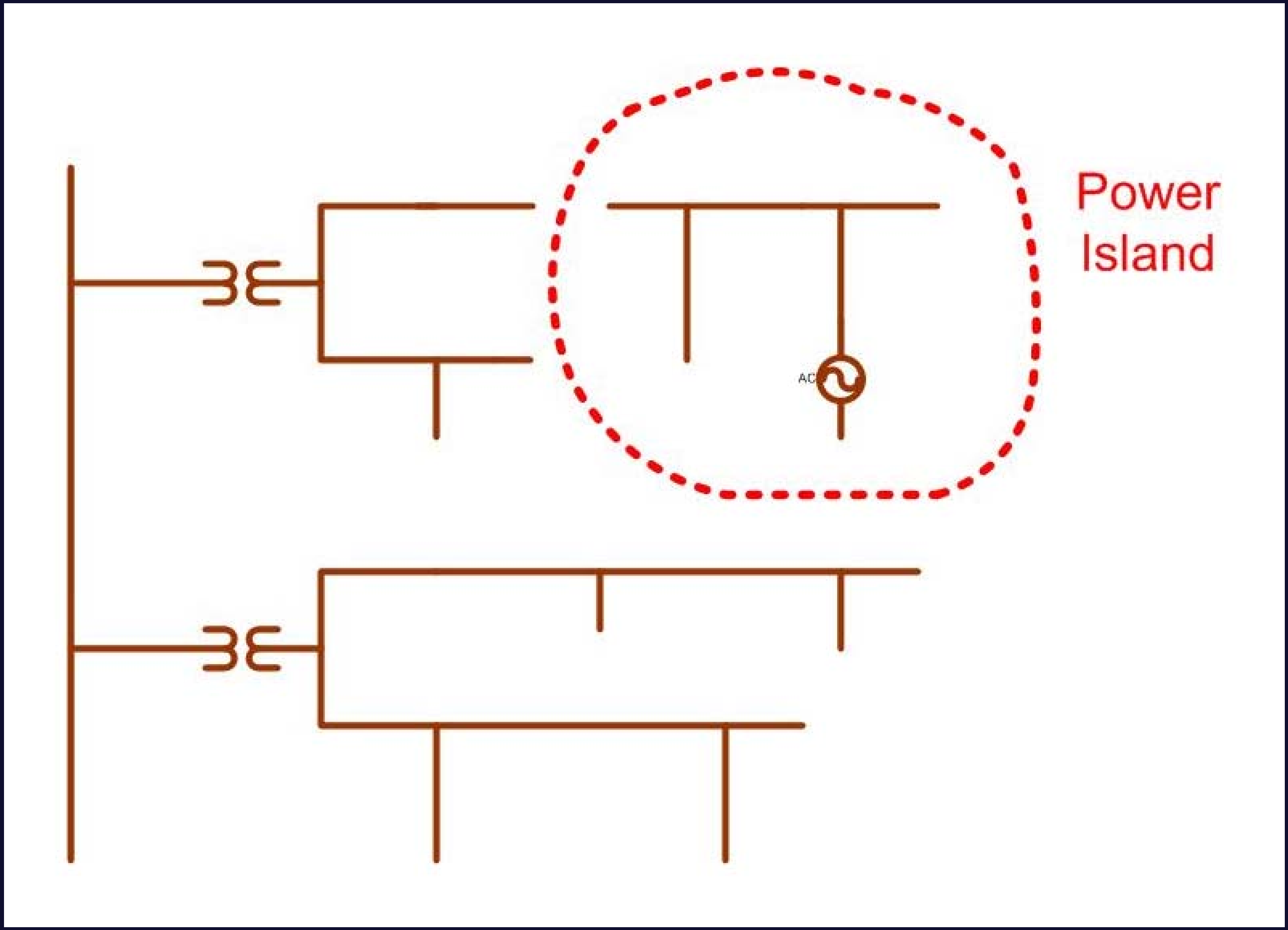

Primary Feeders
1
2
Each load can be served from either feeder
Normally Open (N.O.) Switch

Primary Selective System



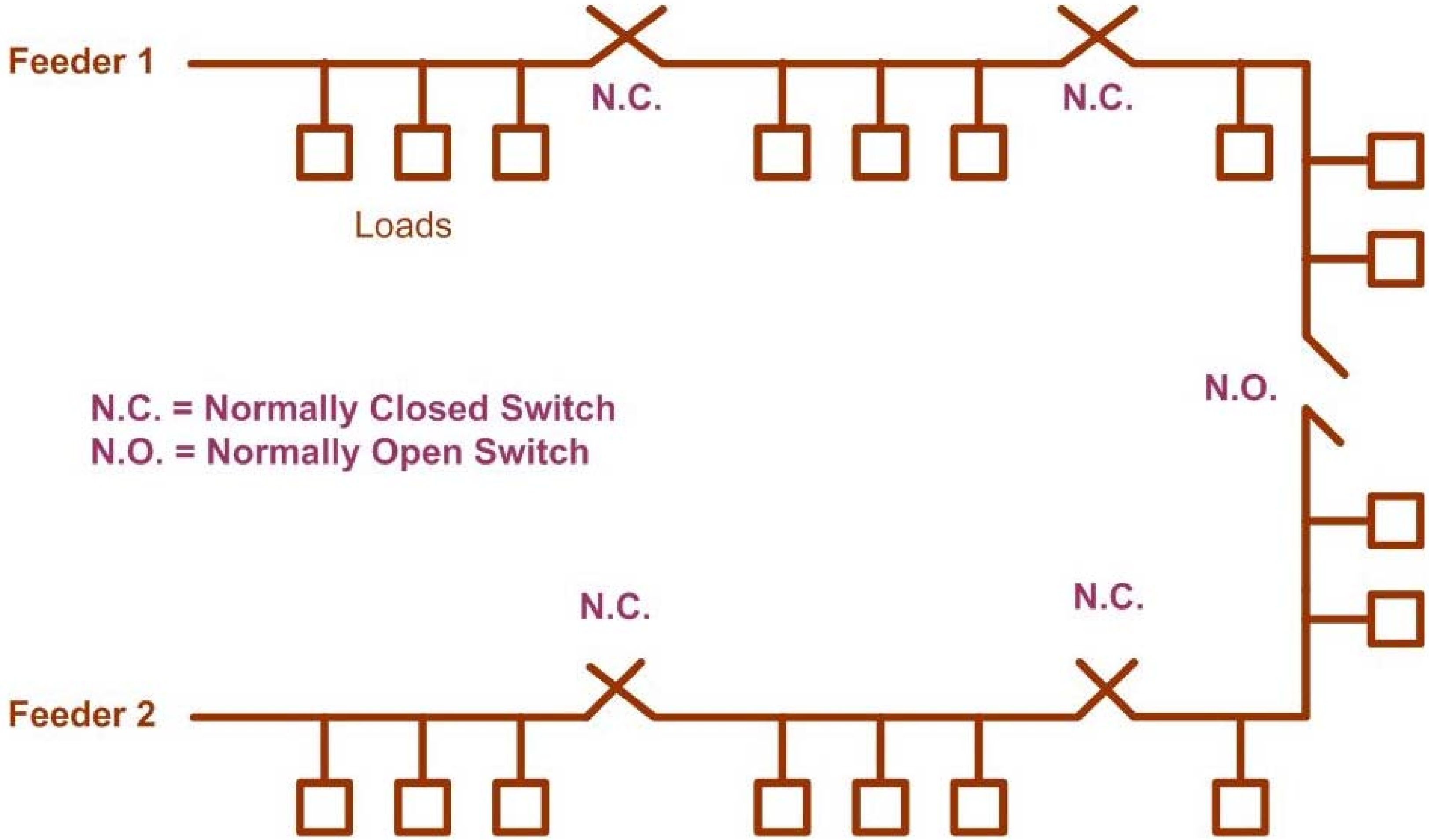
Spot Network



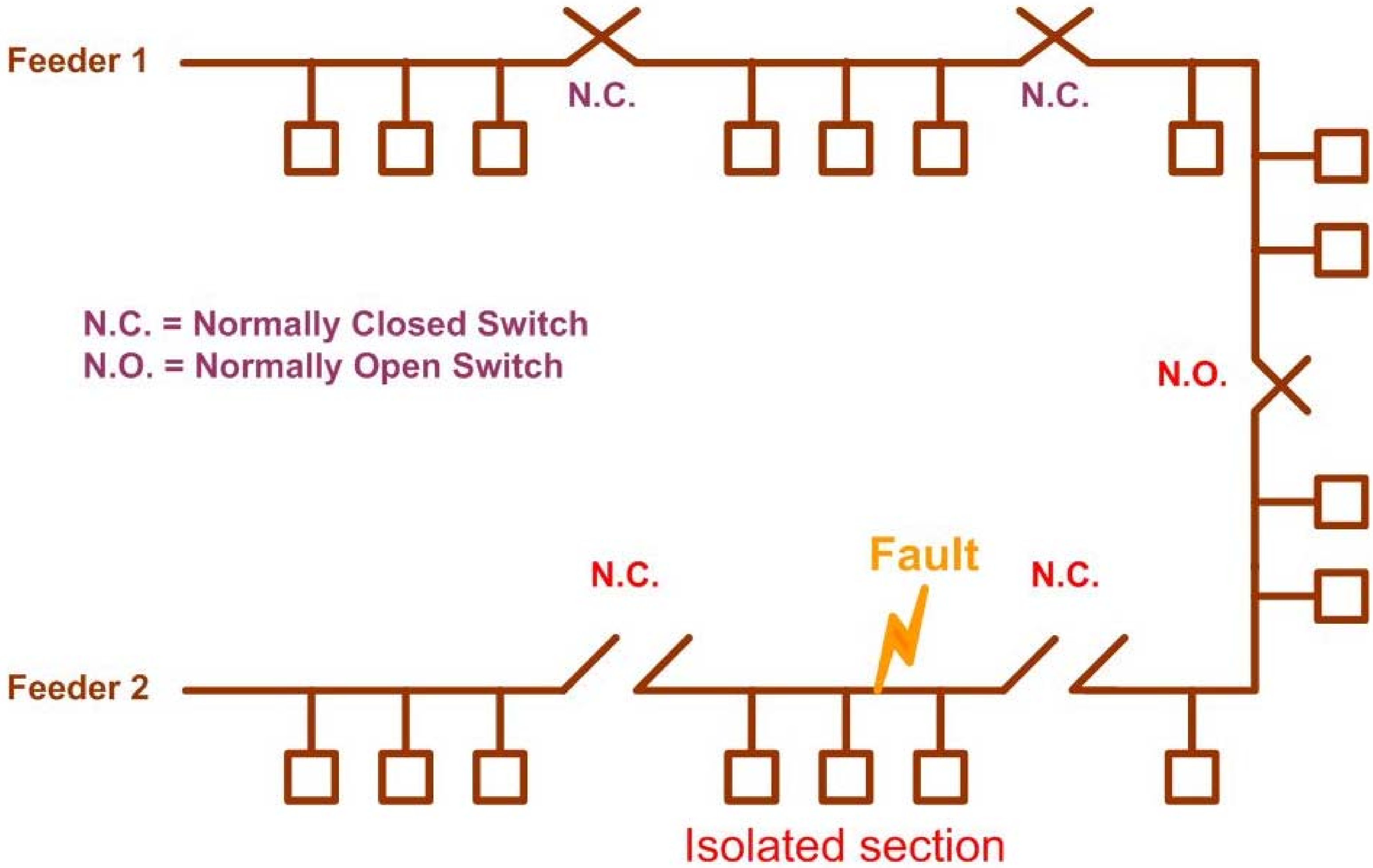


Power
Island
AC

Sectionalizing a Loop System: Before



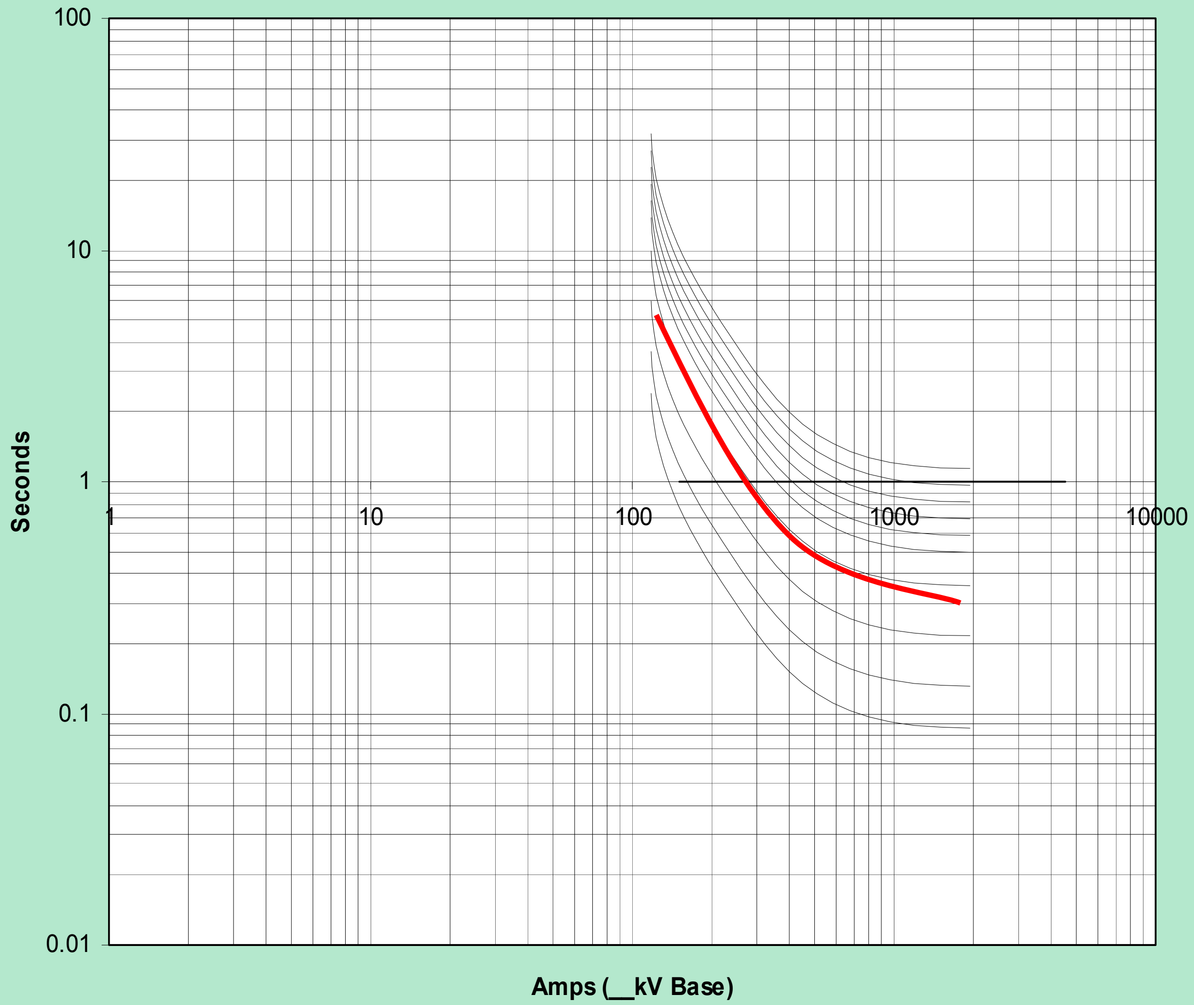
Sectionalizing a Loop System: After




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

Recloser

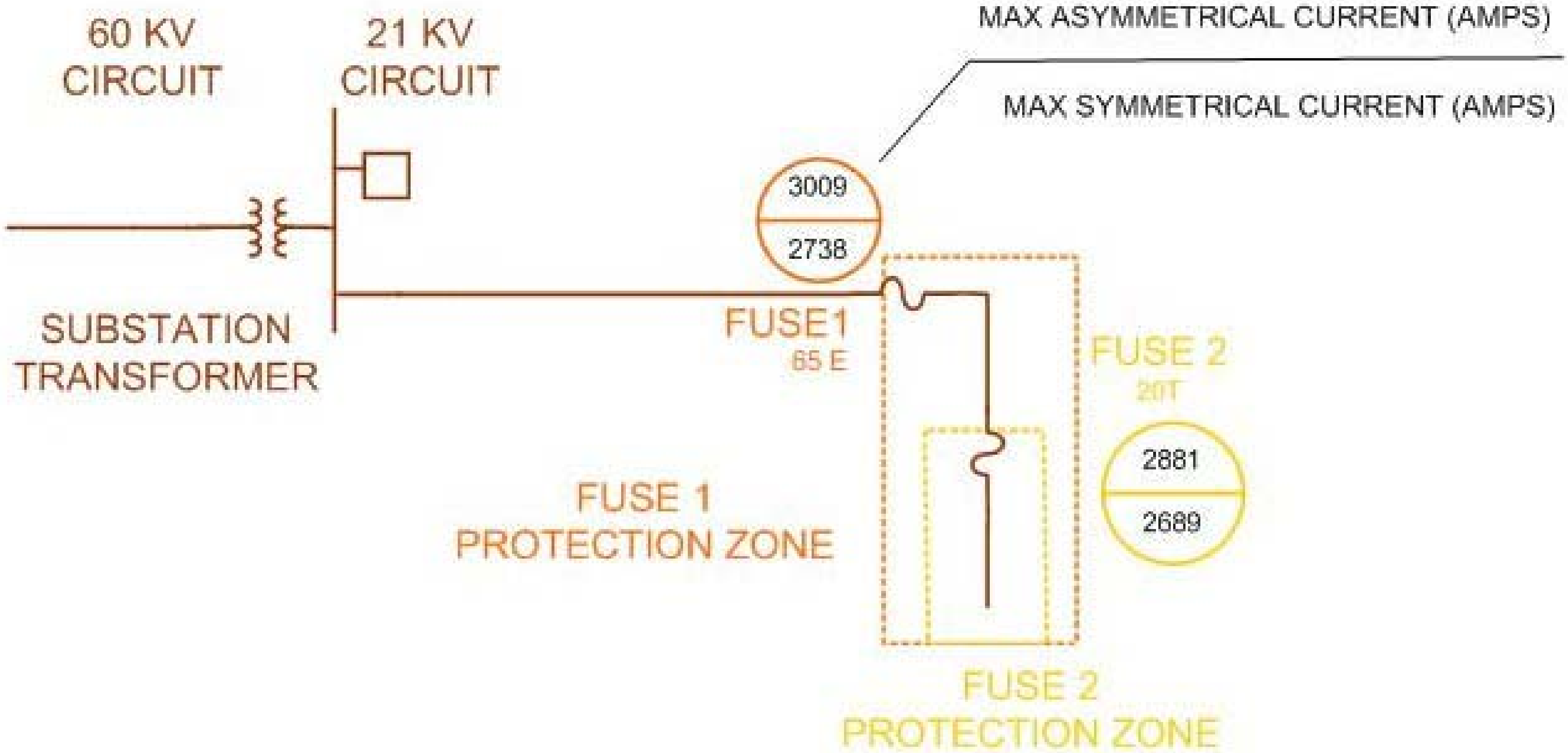
Curve Coordination Sheet



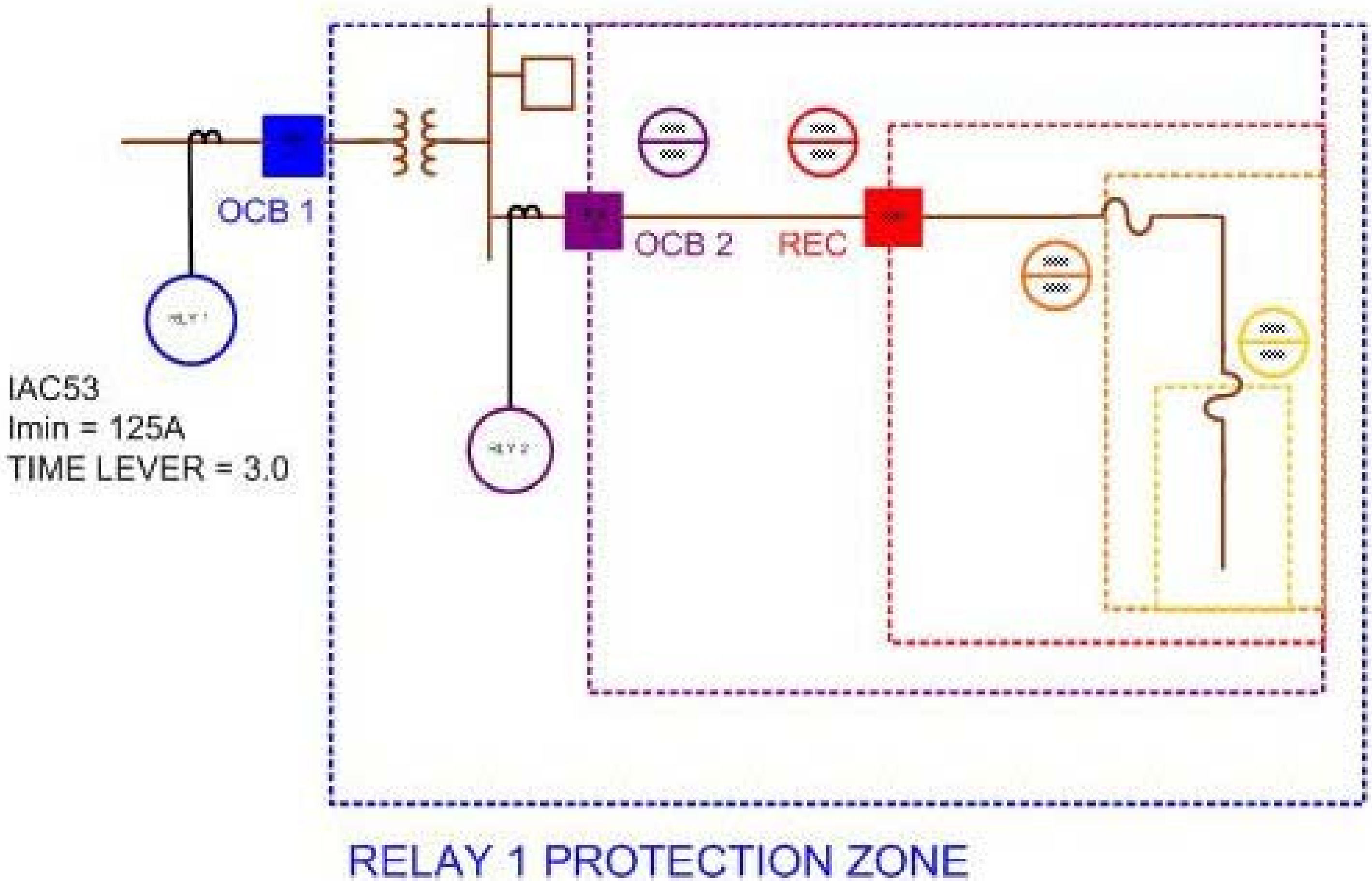

INFORMATION
TAG

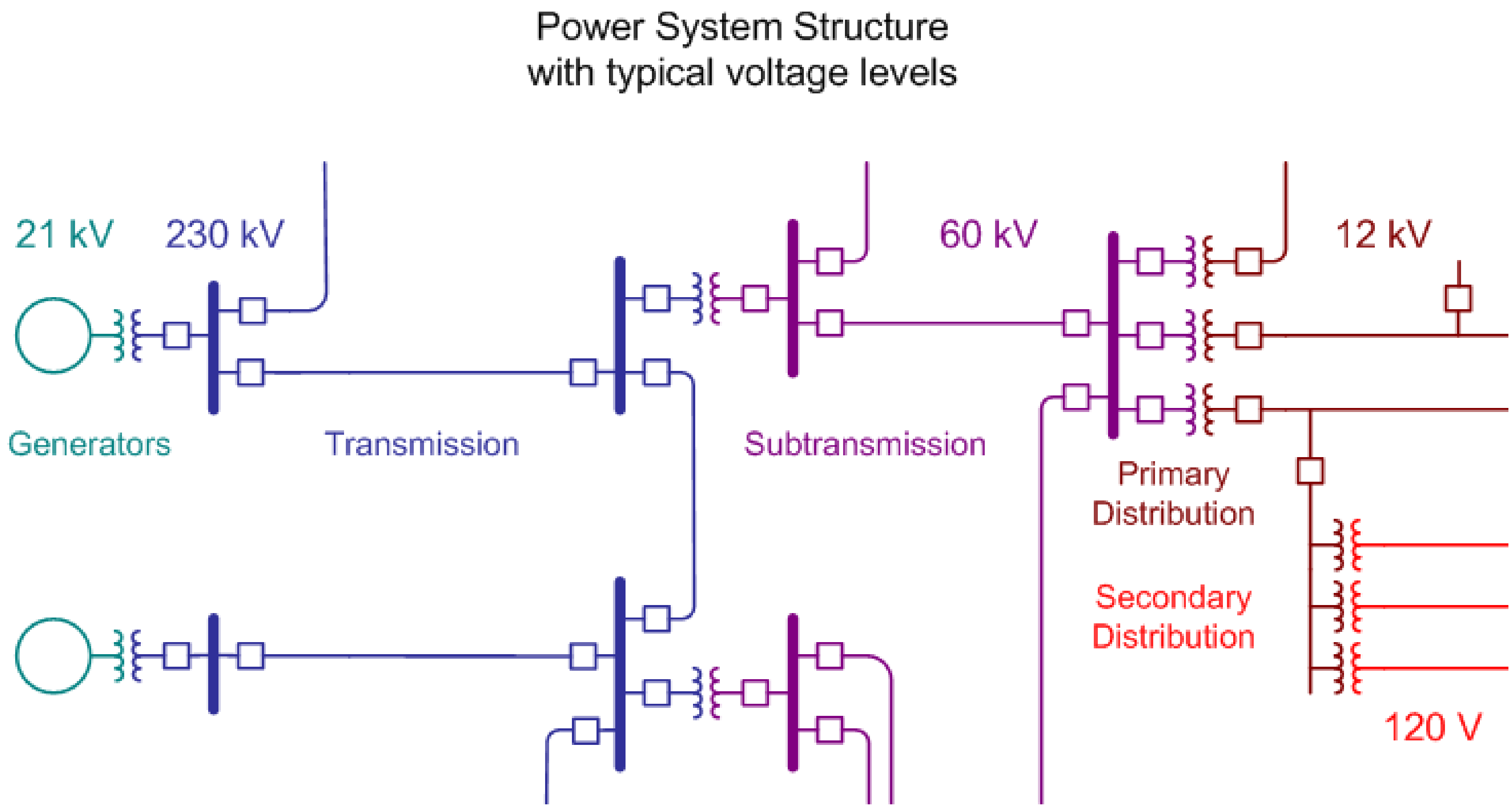
?

Sample Circuit for Coordination Study of Various Overcurrent Protective Devices



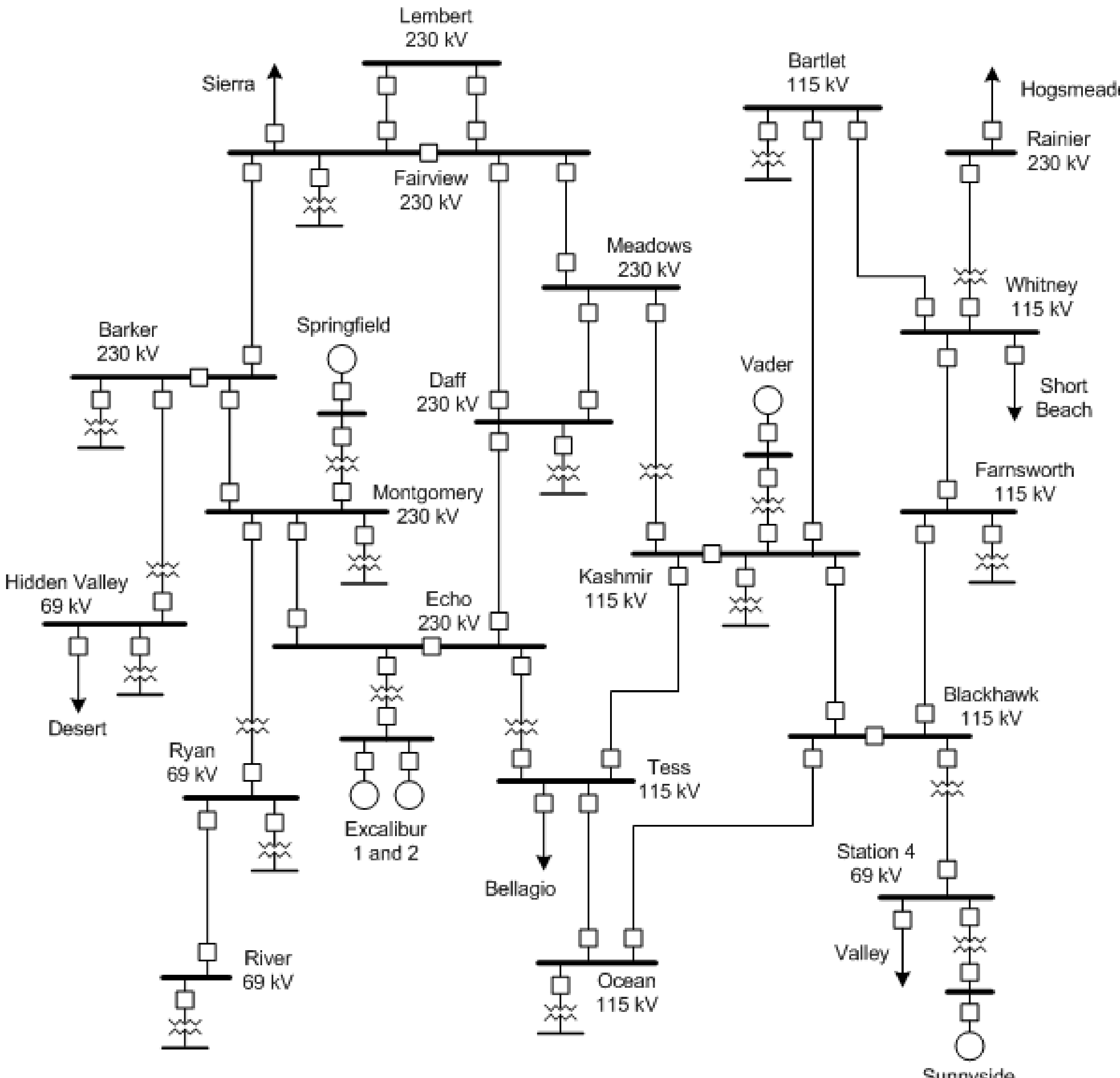
Five Devices Coordinated



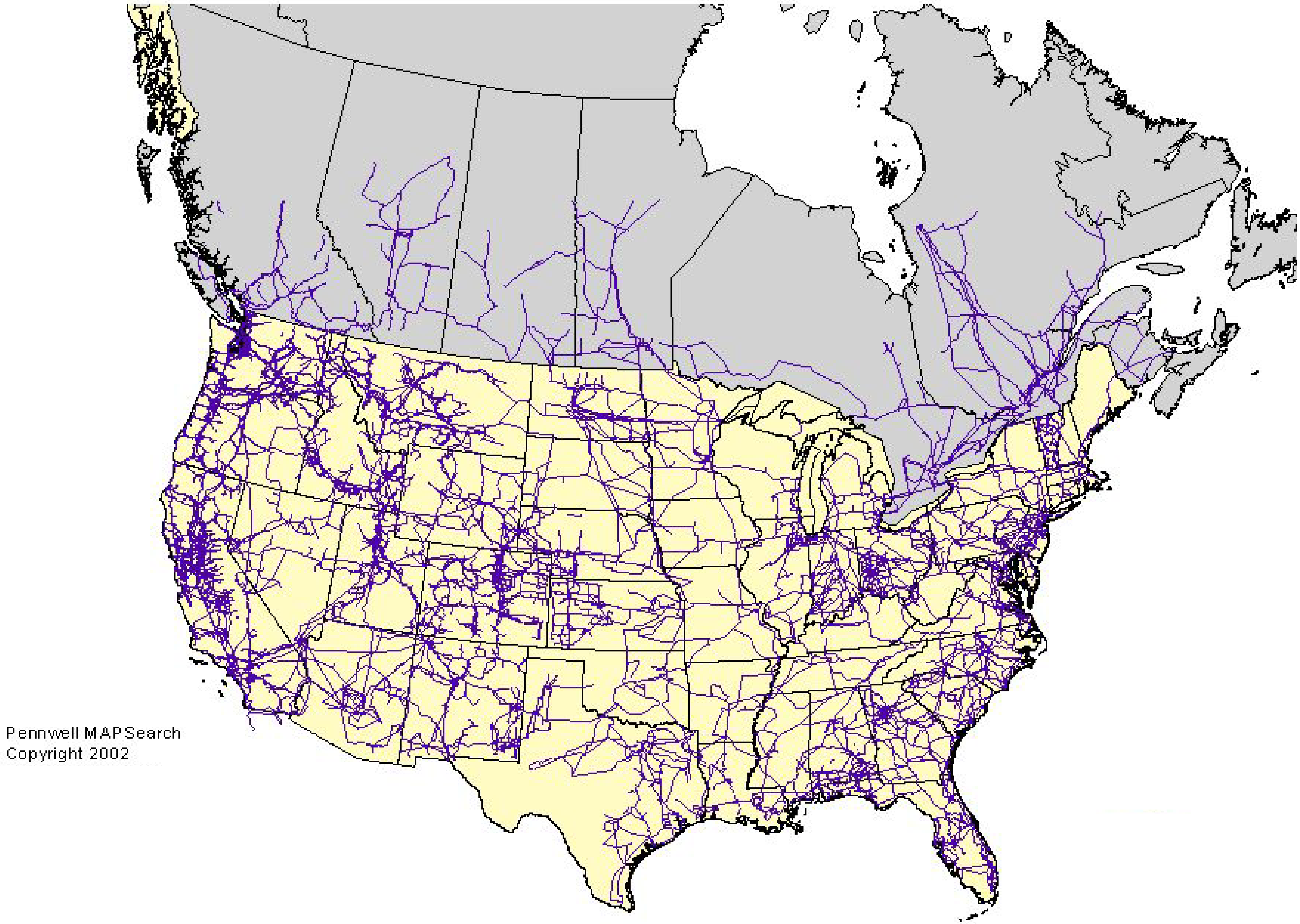


Network structure at transmission level

Radial structure at distribution level



Lembert
230 kV
Sierra
Bartlet
115 kV
Hogsmeade
Rainier
230 kV
Fairview
230 kV
Meadows
230 kV
Whitney
115 kV
Barker
230 kV
Springfield
Vader
Short
Beach
Daff
230 kV
Farnsworth
115 kV
Montgomery
230 kV
Kashmir
115 kV
Hidden Valley
69 kV
Echo
230 kV
Blackhawk
115 kV
Desert
Ryan
69 kV
Tess
115 kV
Excalibur
1 and 2
Station 4
69 kV
Bellagio
Valley
River
69 kV
Ocean
115 kV
Sunnyside

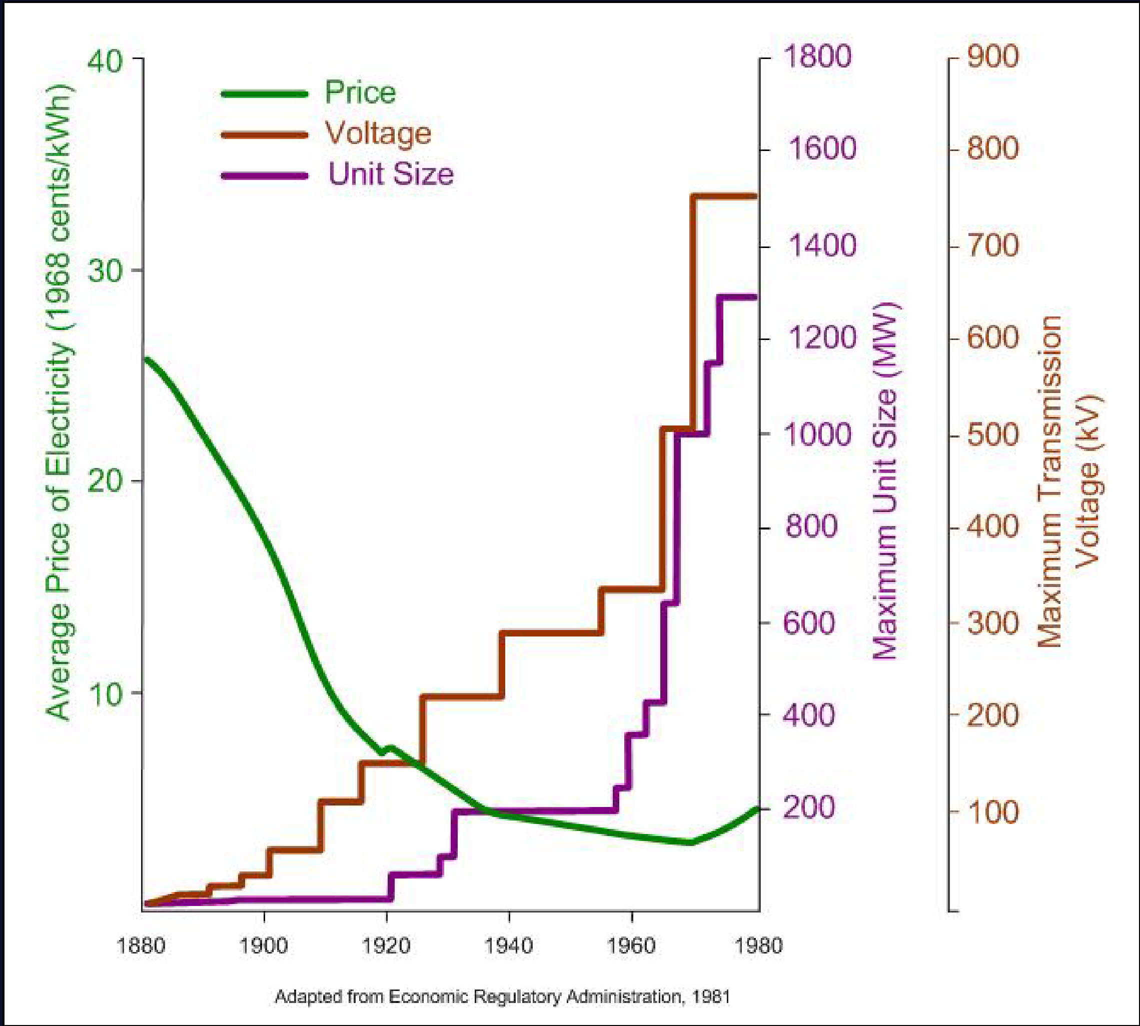

Pennwell MAPSearch
Copyright 2002

UCTE
Interconnected network of UCTE
01.07.2005
Scale 1 : 2 500 000
Legend
Plants and stations:
Hydro Power Plant
Wind Farm
Thermal Power Plant
Substation
Substations + power plants
Converter station
Under construction
Lines:
750 kV transmission line
500 kV transmission line
380-400 kV transmission line
300-330 kV transmission line
220 kV transmission line
132-150 kV transmission line
DC-line
Power systems of UCTE
Other power systems
The map shows:
NORGE
SVERIGE
EESTI
LATVIA
LIETUVA
ROSSIJA
BELORUSSIJA
ROSSIJA
DANMARK
GREAT BRITAIN
REPUBLIC OF IRELAND
NEDERLAND
DEUTSCHLAND
POLSKA
UKRAINA
SLOVENSKO
MOLDOVA
ROMANIA
ÖSTERREICH
MAGYARORSZAG
FRANCE
HRVATSKA
BOSNA I HERCEGOVINA
SAN MARINO
MONACO
SRBIJA I CRNA GORA
BULGARIA
ESPAÑA
ANDORRA
ITALIA
MAKEDONIJA
SHQIPERIA
HELLAS
TÜRKIYE
PORTUGAL
ALGERIE
MALTA

Historical changes in the electric power industry

Geographic expansion and greater regional interconnectivity to take advantage of:

- Economies of scale
- Load diversity
- Shared reserves



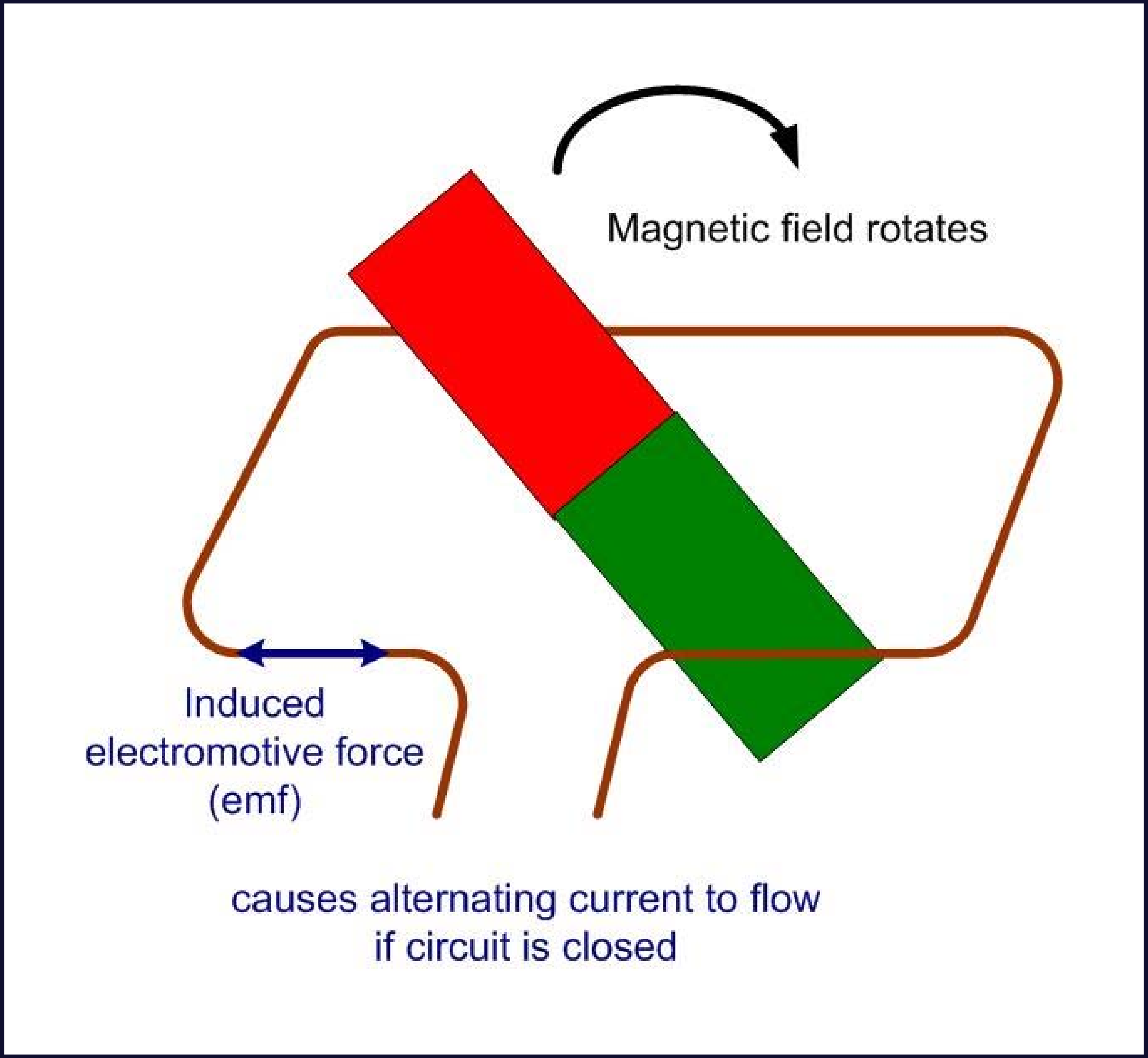
Generators & three-phase transmission

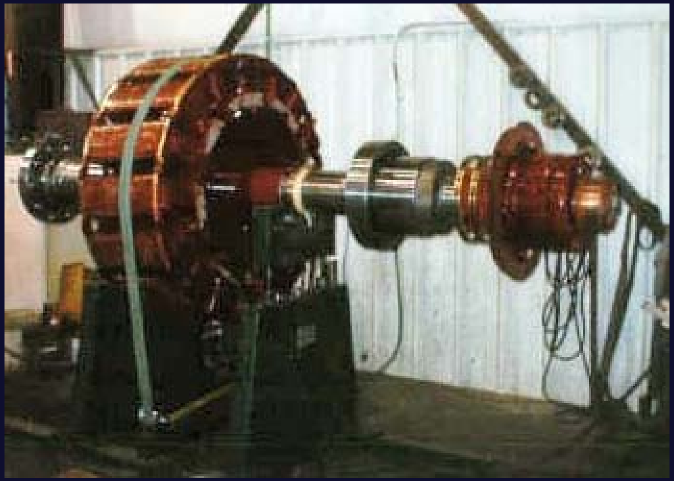
Synchronous three-phase generators

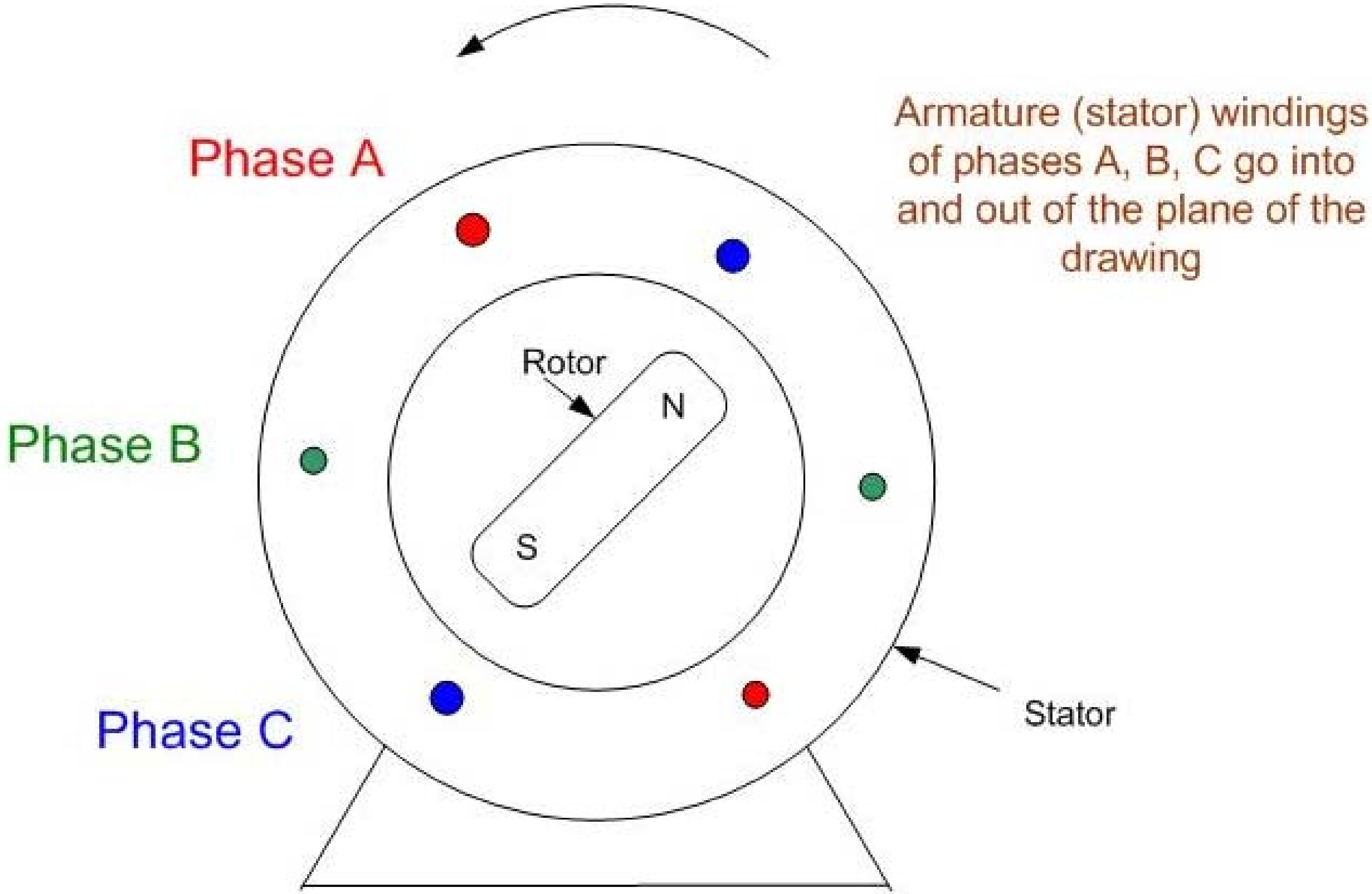
Why three-phase?

Induction generators and inverters


Diablo Canyon Unit 1, Courtesy of Jim Zimmerlin


Magnetic field rotates
Induced
electromotive force
(emf)
causes alternating current to flow
if circuit is closed

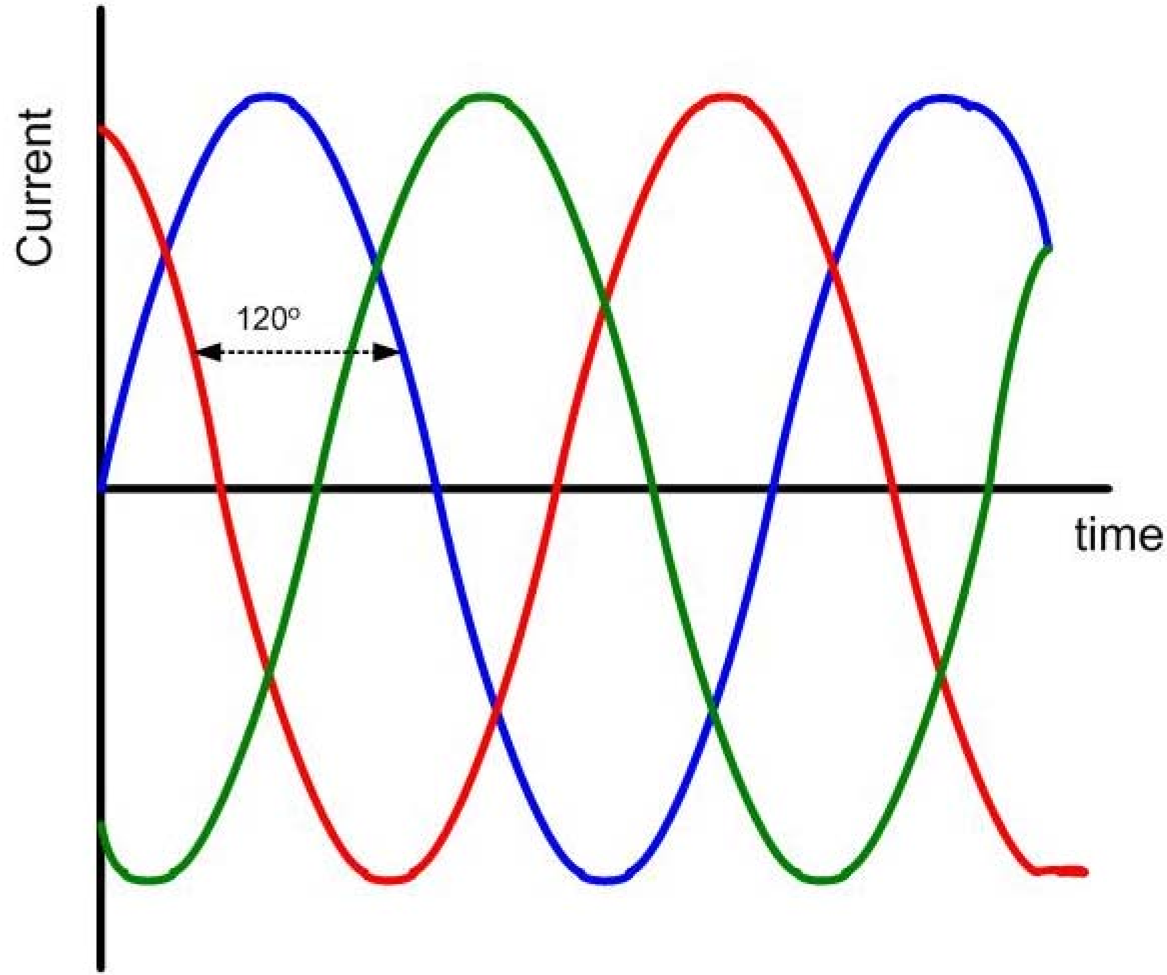


Basic Generator

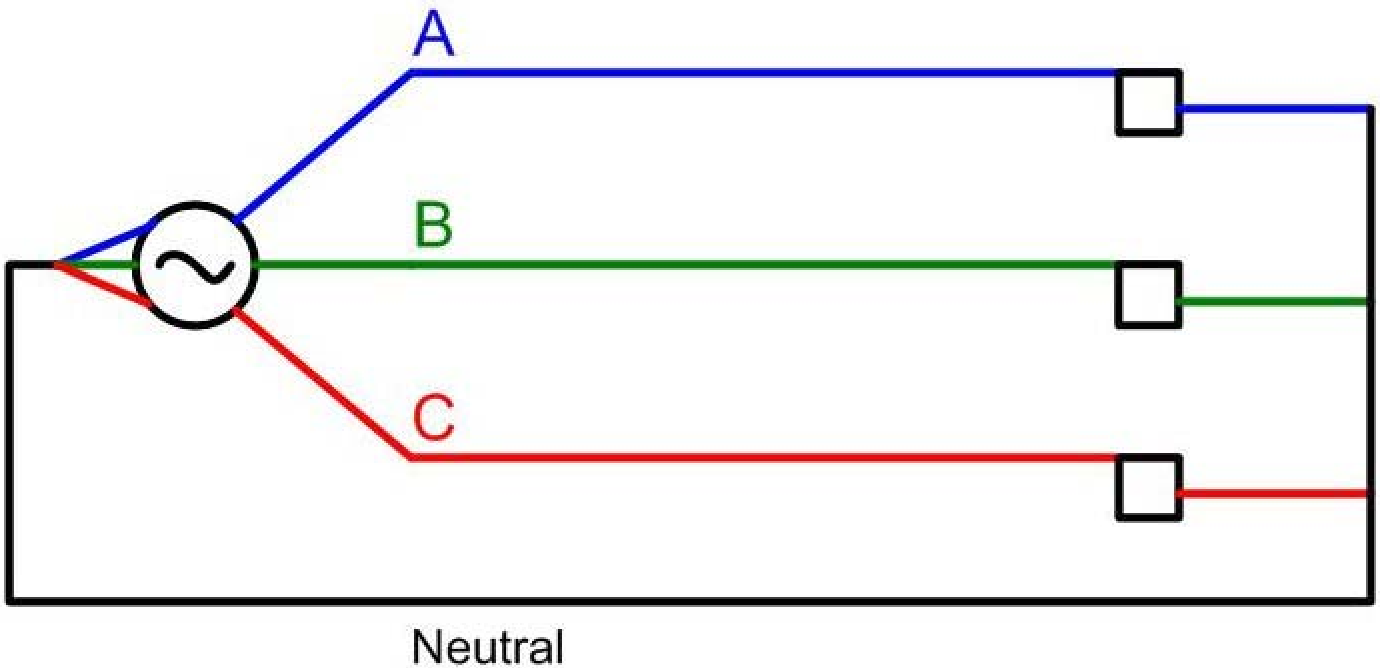
How one would imagine three circuits, requiring six conductors

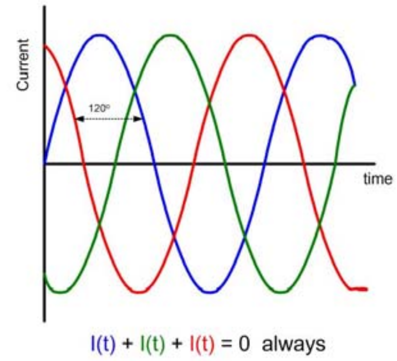
Staggered Three-Phase Current

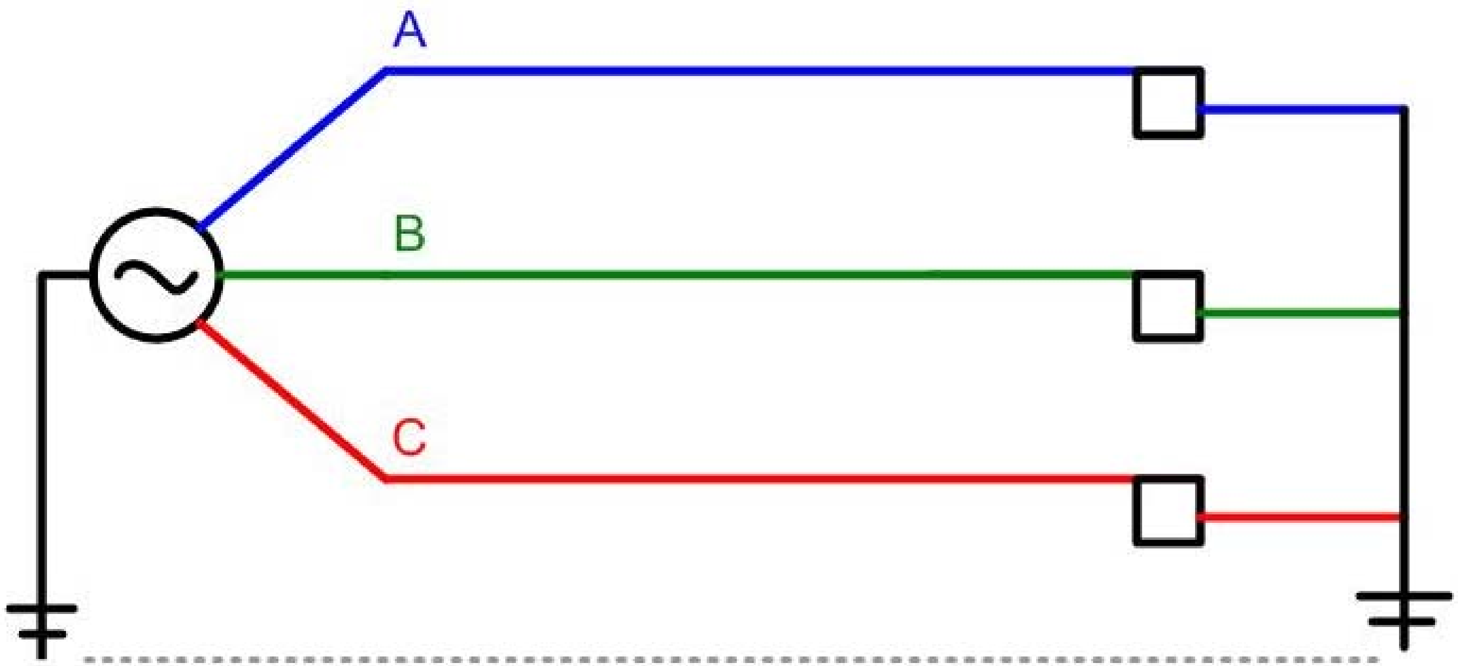


I(t) + I(t) + I(t) = 0 always

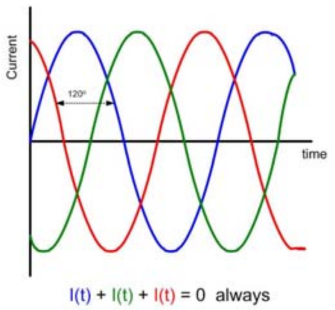
Three circuits with shared return flow



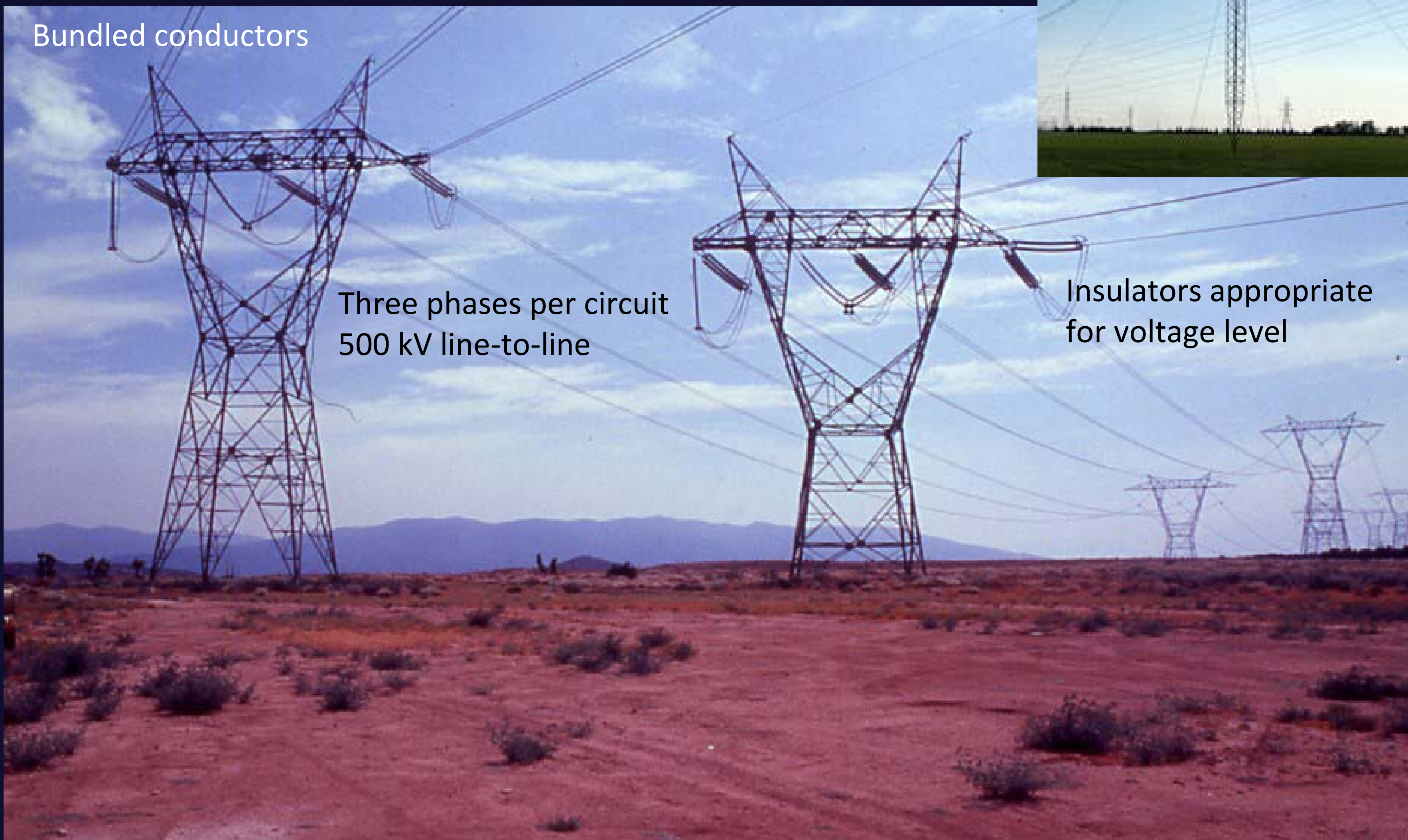




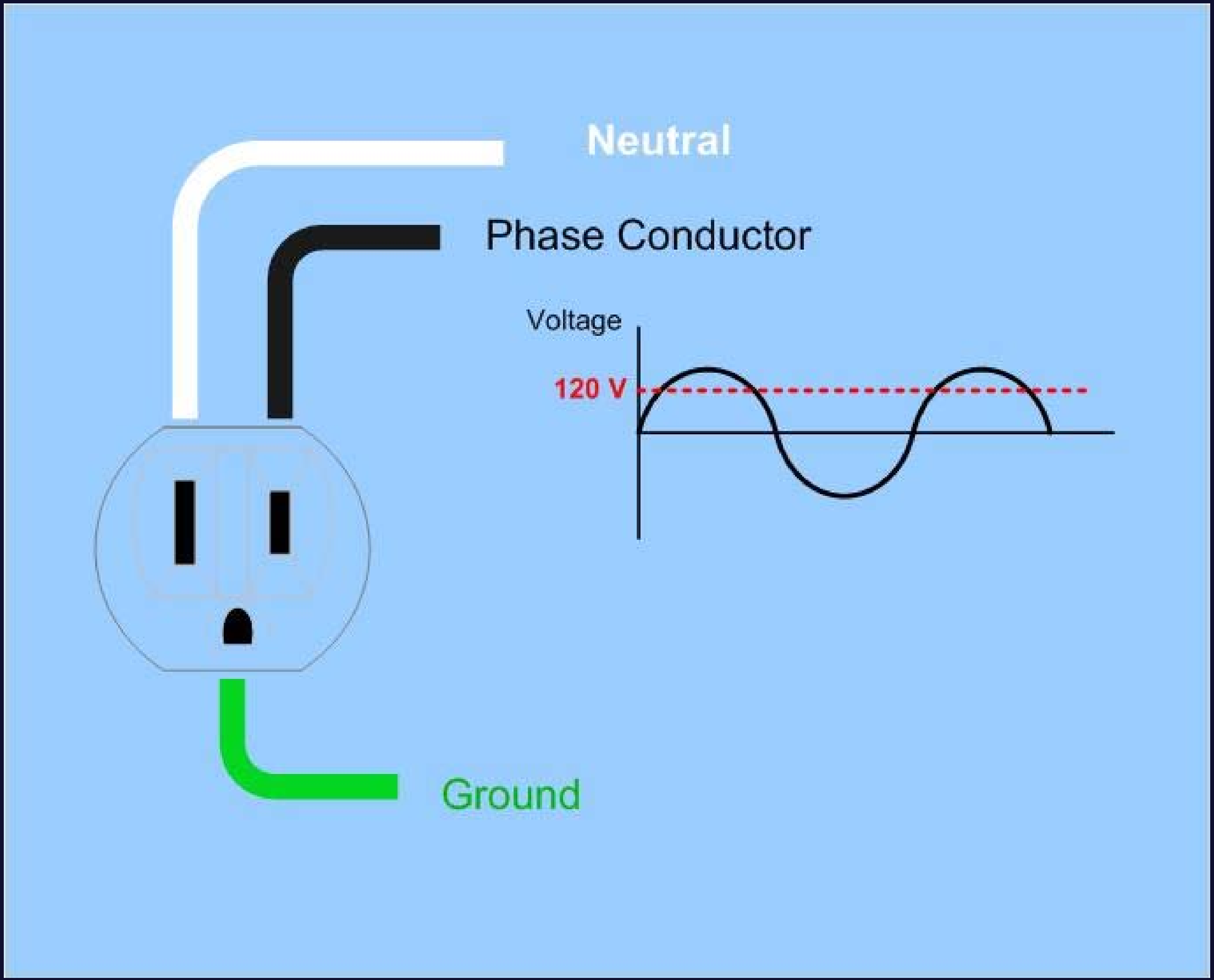
Since the sum of currents in Phases A, B, C is zero *(if loads are balanced)* the neutral conductor carries no current and can be eliminated.



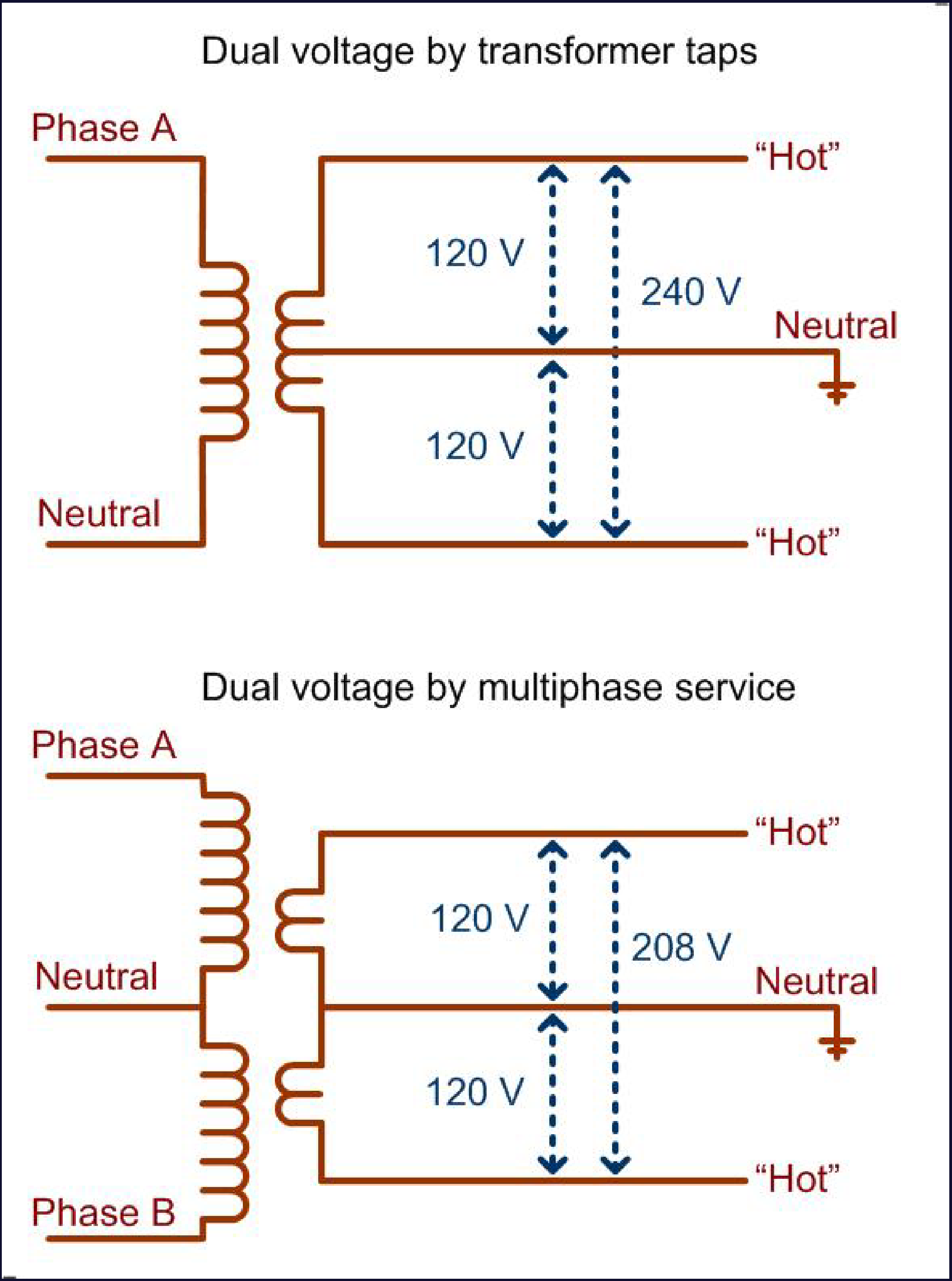
High-voltage d.c. line
± 500 kV



The familiar 120V a.c. outlet

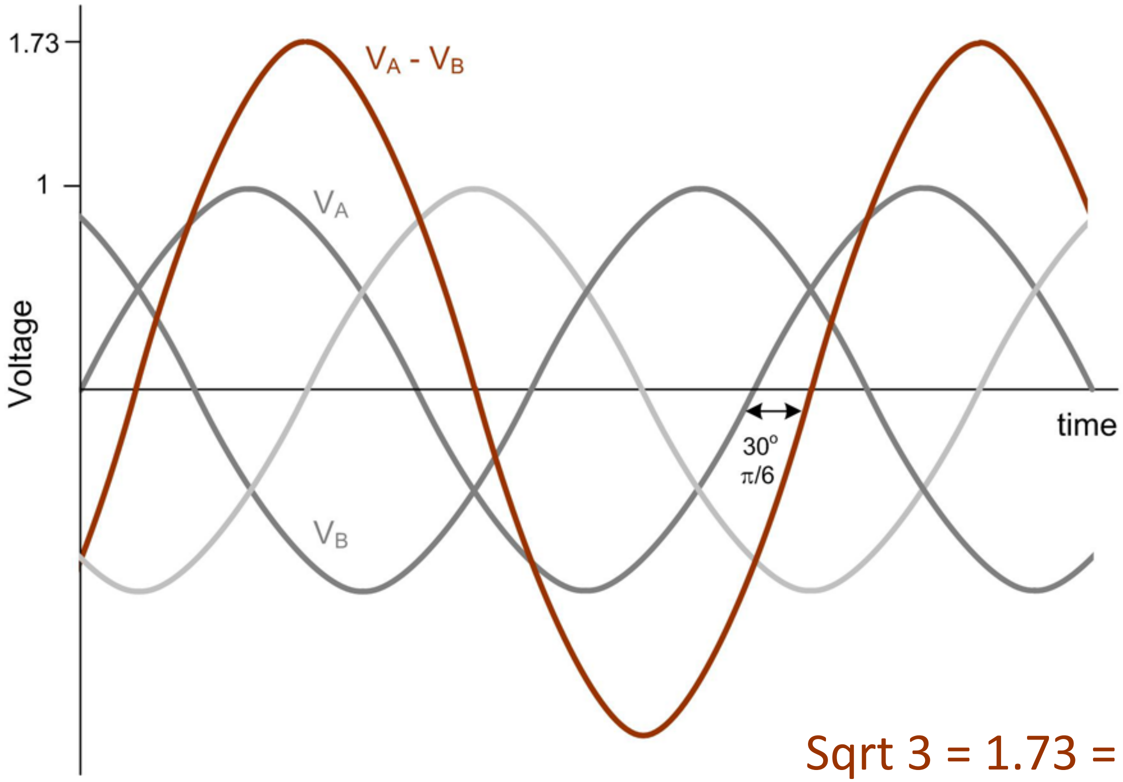


Three-phase primary distribution circuit and single-phase lateral



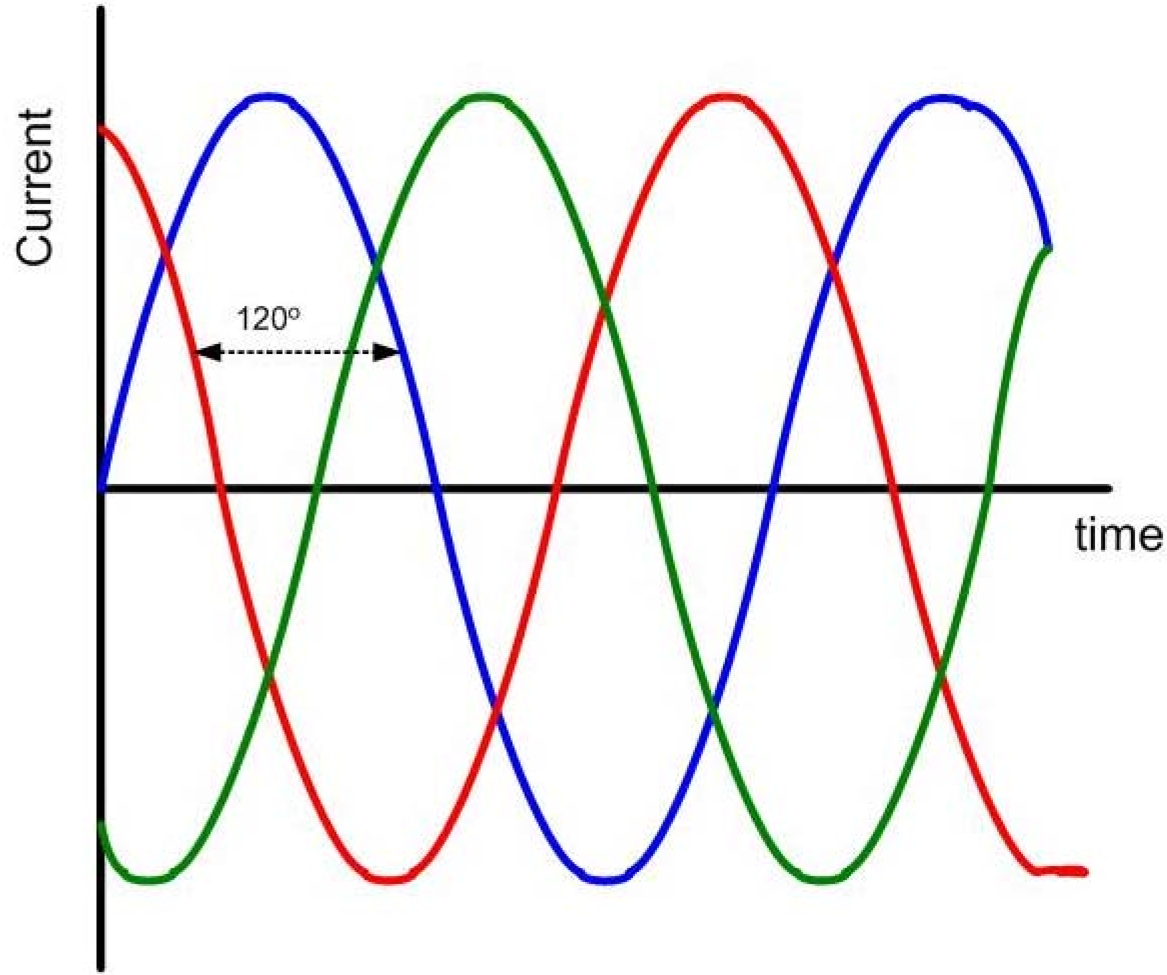
Single-phase 120/240 service is obtained by tapping the same transformer in different places.

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

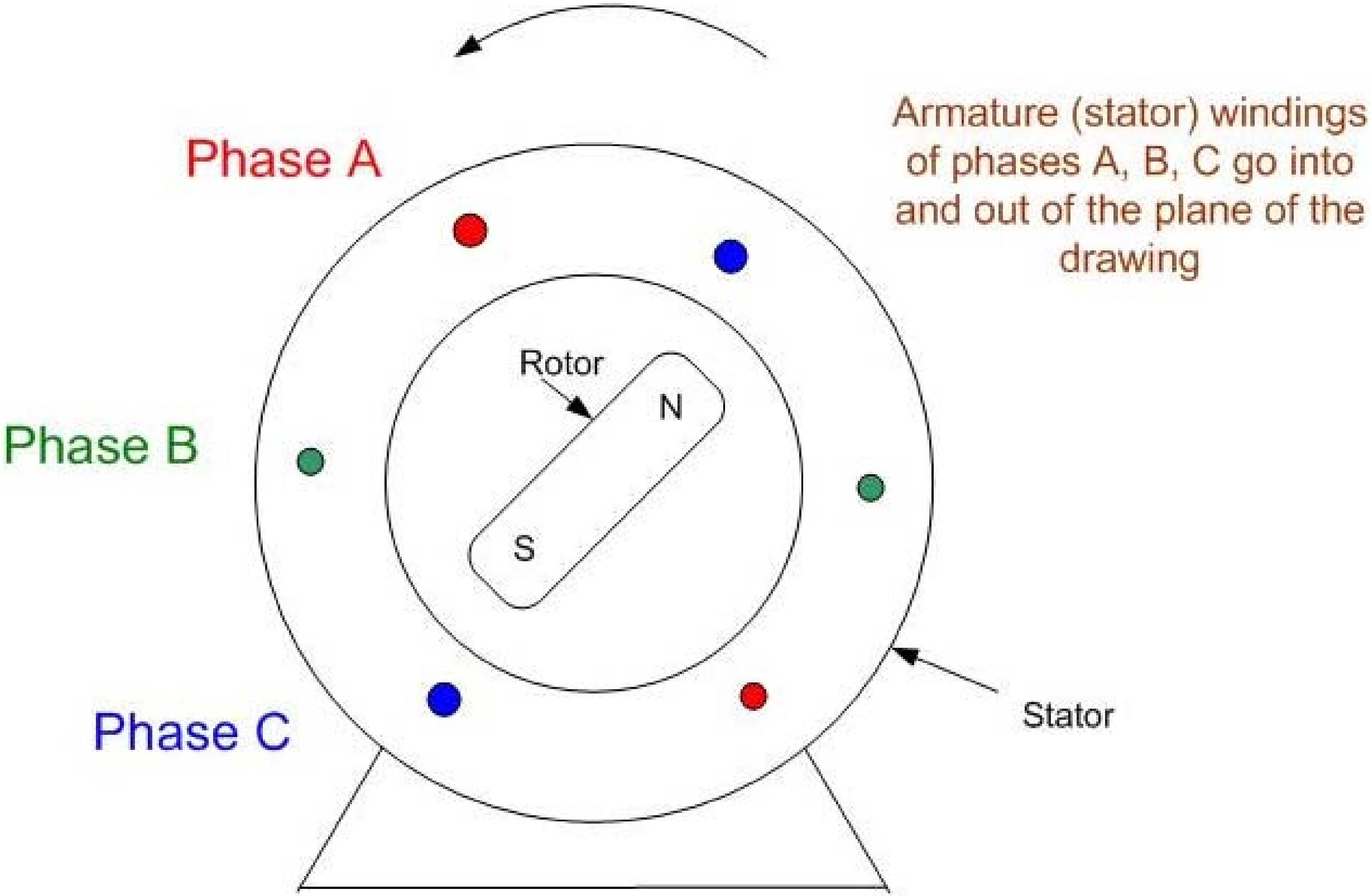


Sqrt 3 = 1.73 = 208/120

Staggered Three-Phase Current

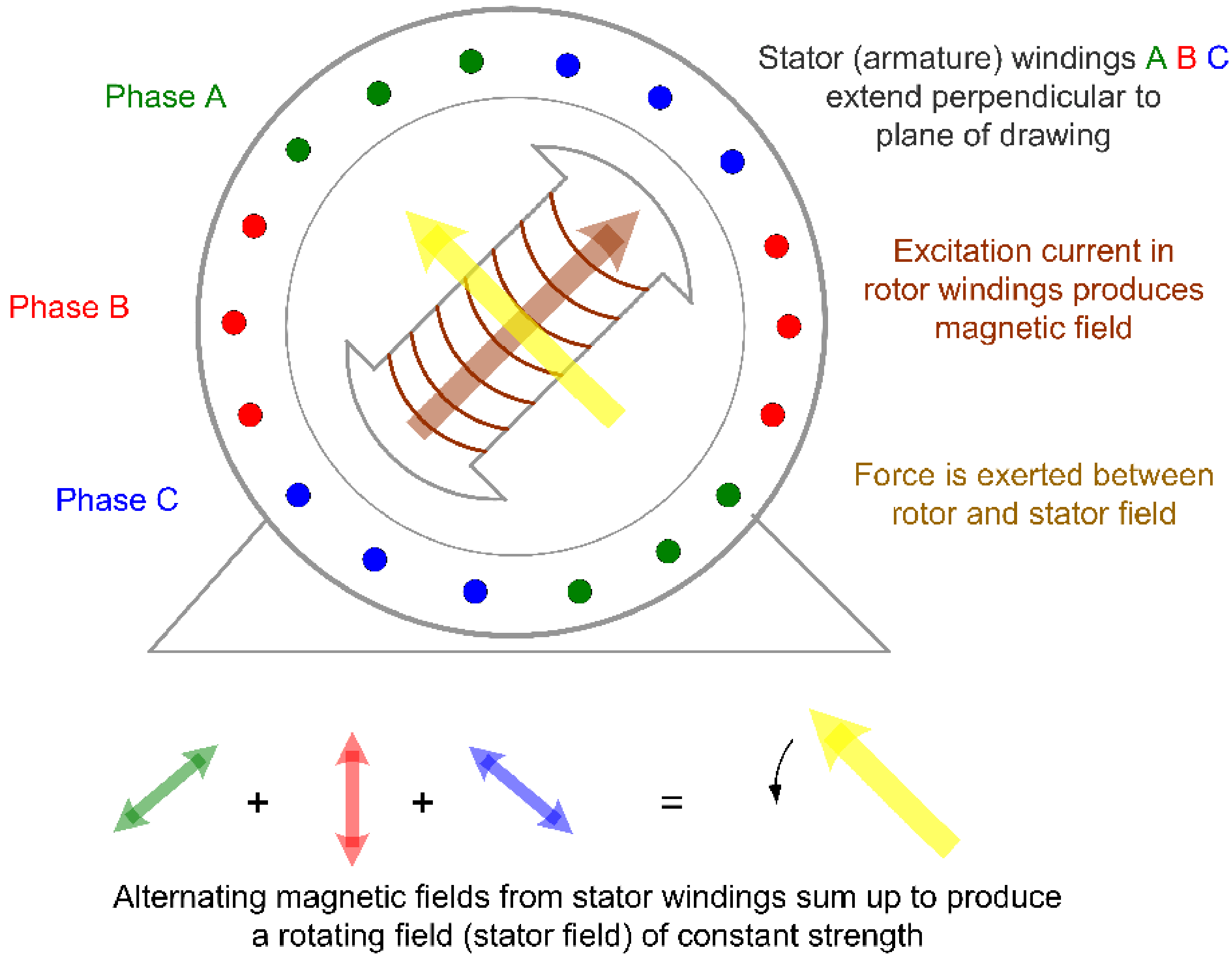


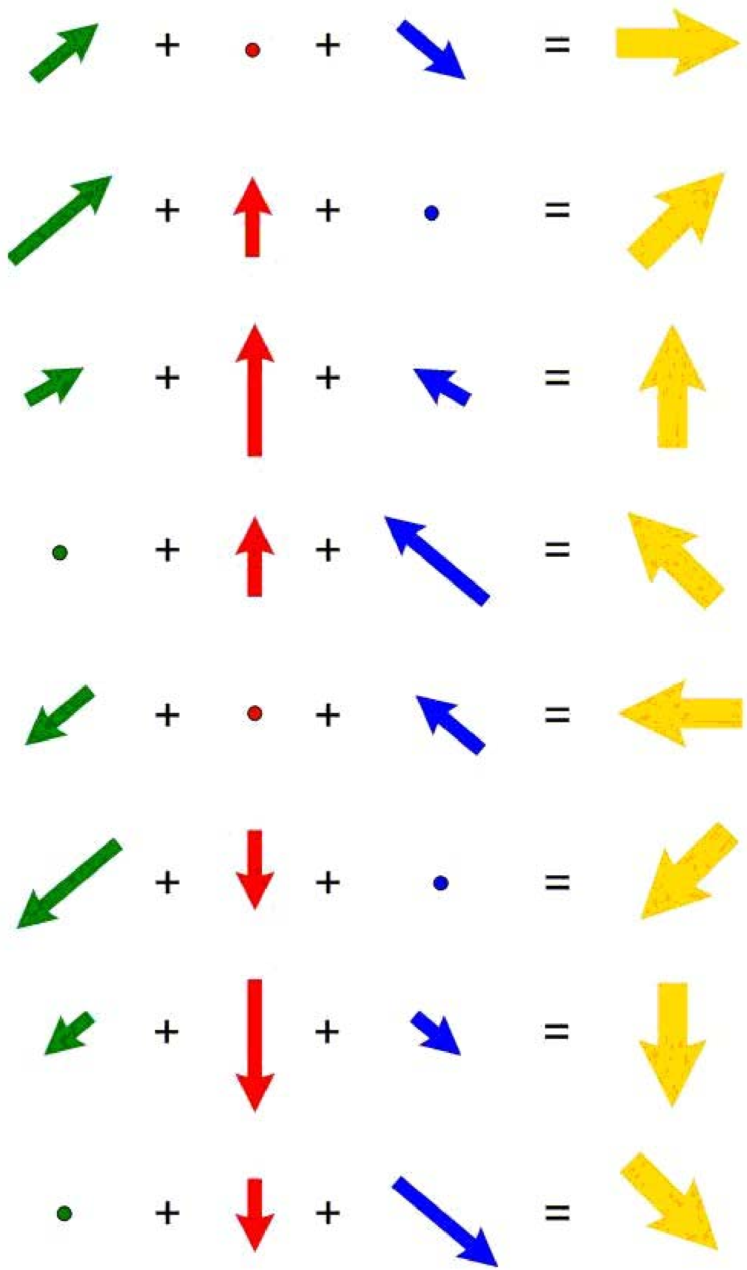
$I(t) + I(t) + I(t) = 0$ always



Basic Generator

Three-phase, synchronous generator





The magnetic fields from currents in each phase are fixed in space but their magnitude varies in time.

Their geometric combination appears as the rotating stator field of constant magnitude.

Types of generating equipment:

Synchronous generator

- standard for large-scale utility applications
- affords maximum control, stability
- requires external “excitation” source

Induction generator

- an electric induction motor run backwards

Inverter

- produces a.c. from d.c. (PV, fuel cells)

Reactive Power

The “bad cholesterol” of power lines

Types of Loads

Purely resistive loads

- Incandescent lamps
- Heaters: range, toaster, iron, space heater…

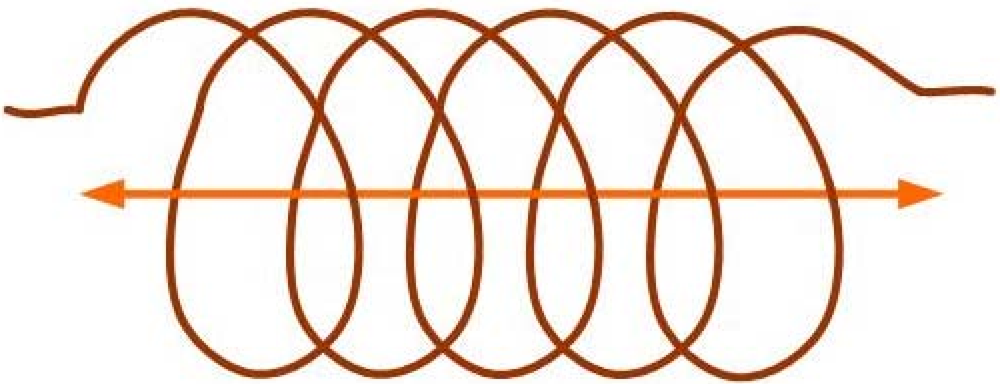
Motors (inductive loads)

- 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

Inductor



Magnetic field created
by current in coil

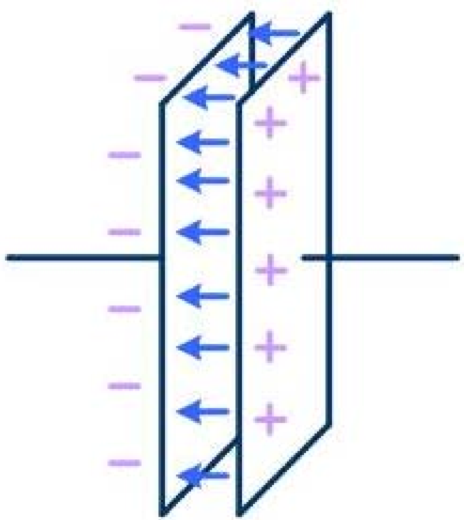
stores energy in magnetic field

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

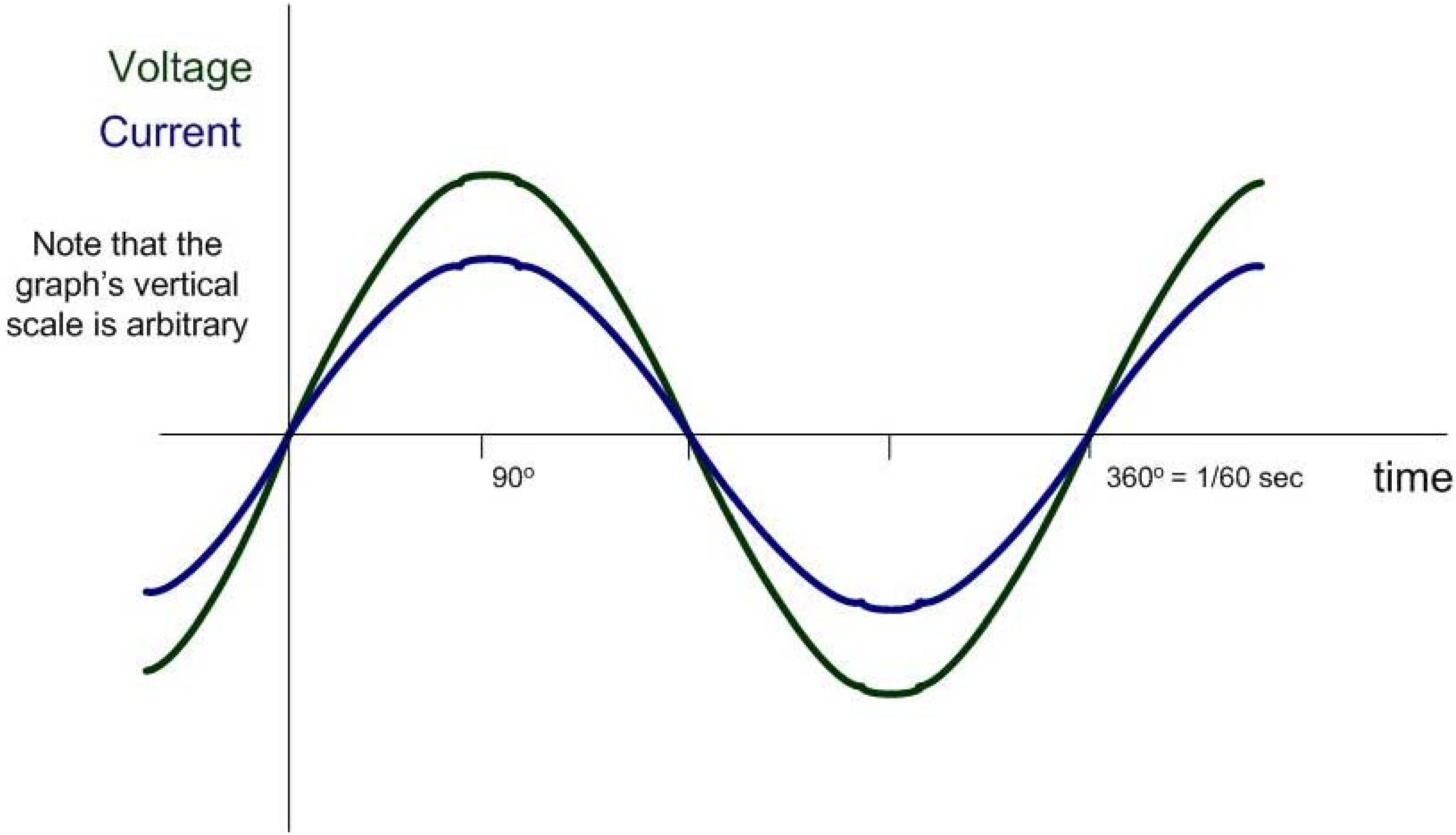
stores energy in electric field

preferentially transmits alternating current
of higher frequency

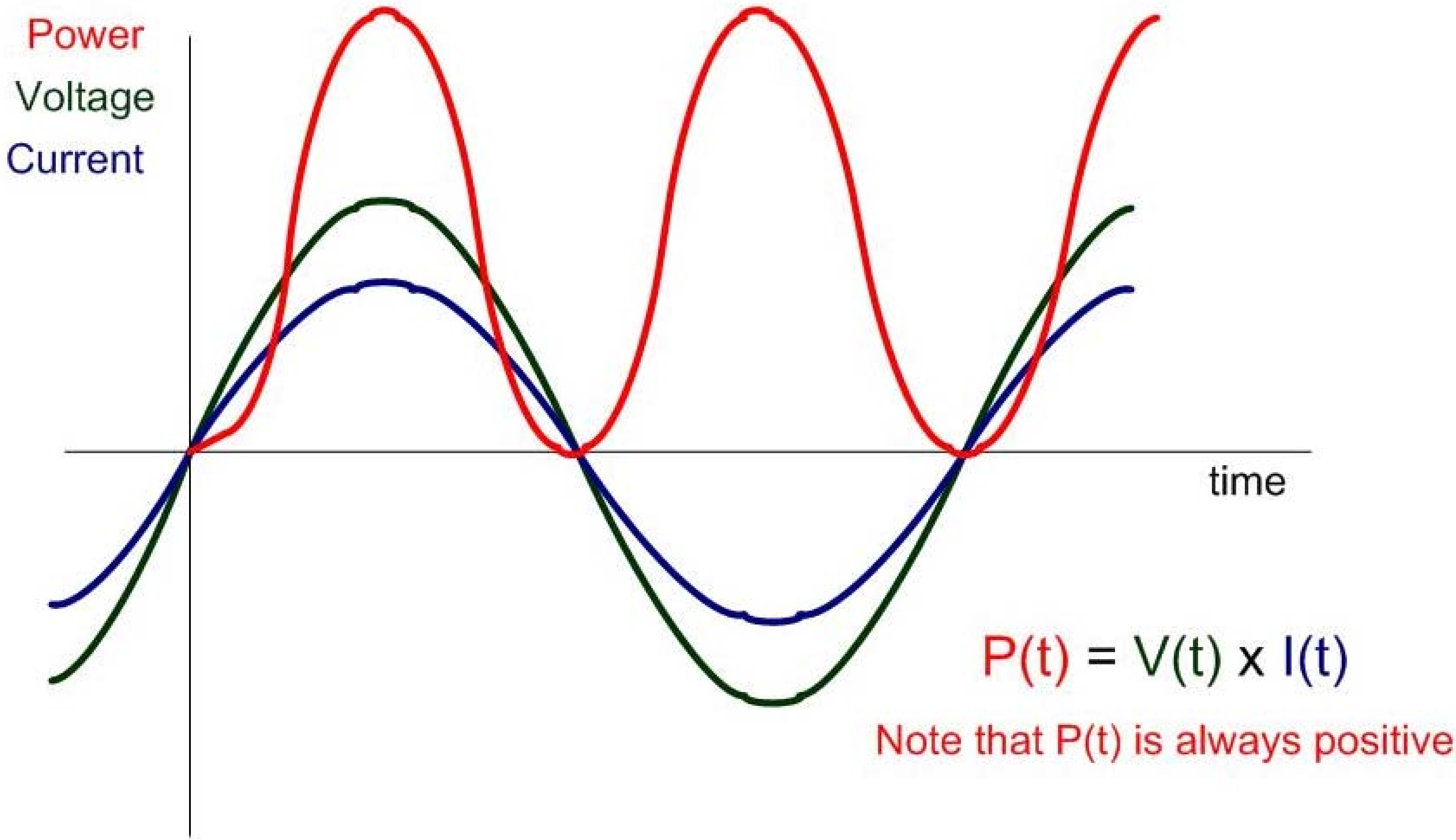
resists changes in voltage

causes alternating current to lead voltage

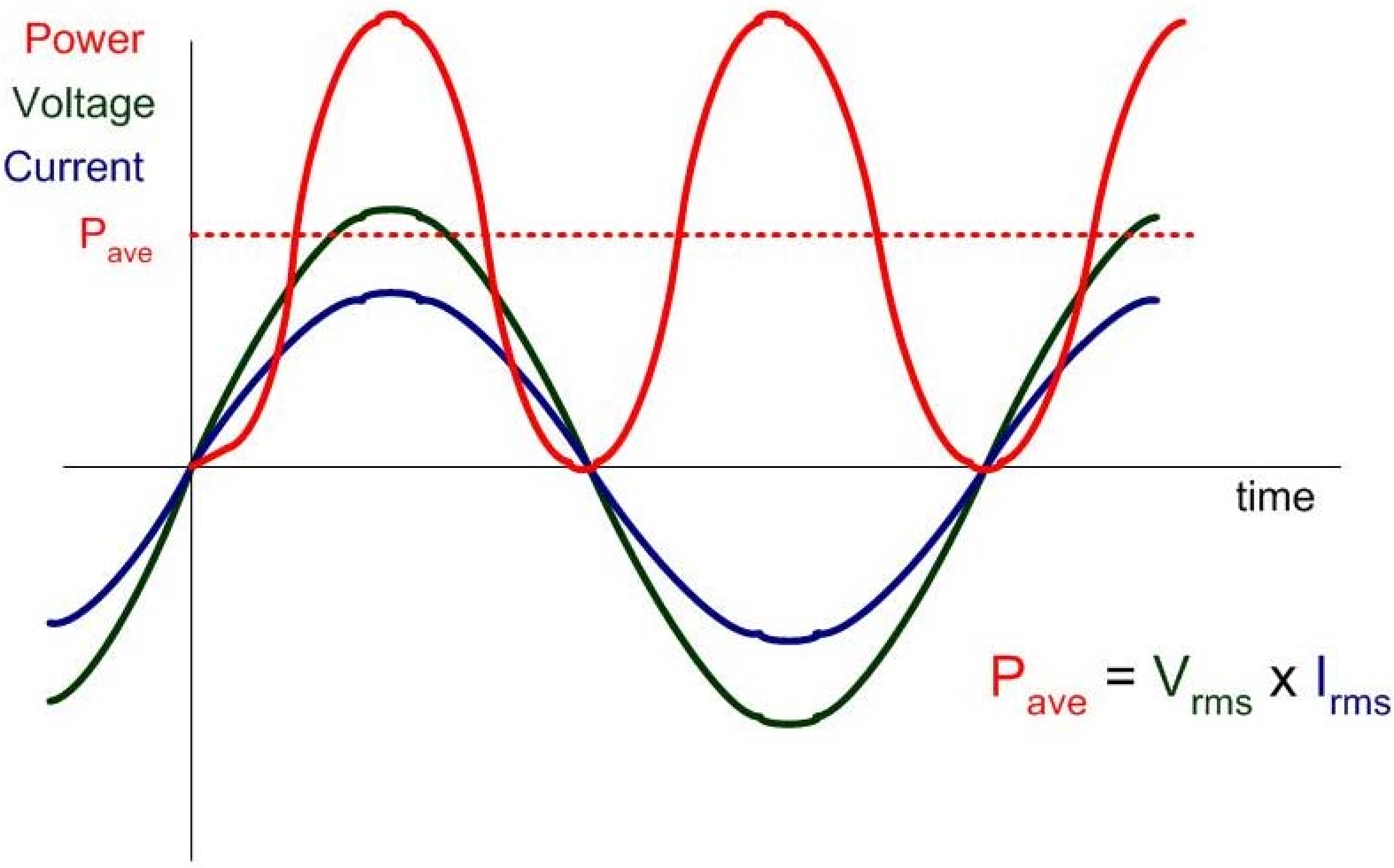
A.C. voltage and current for a resistor



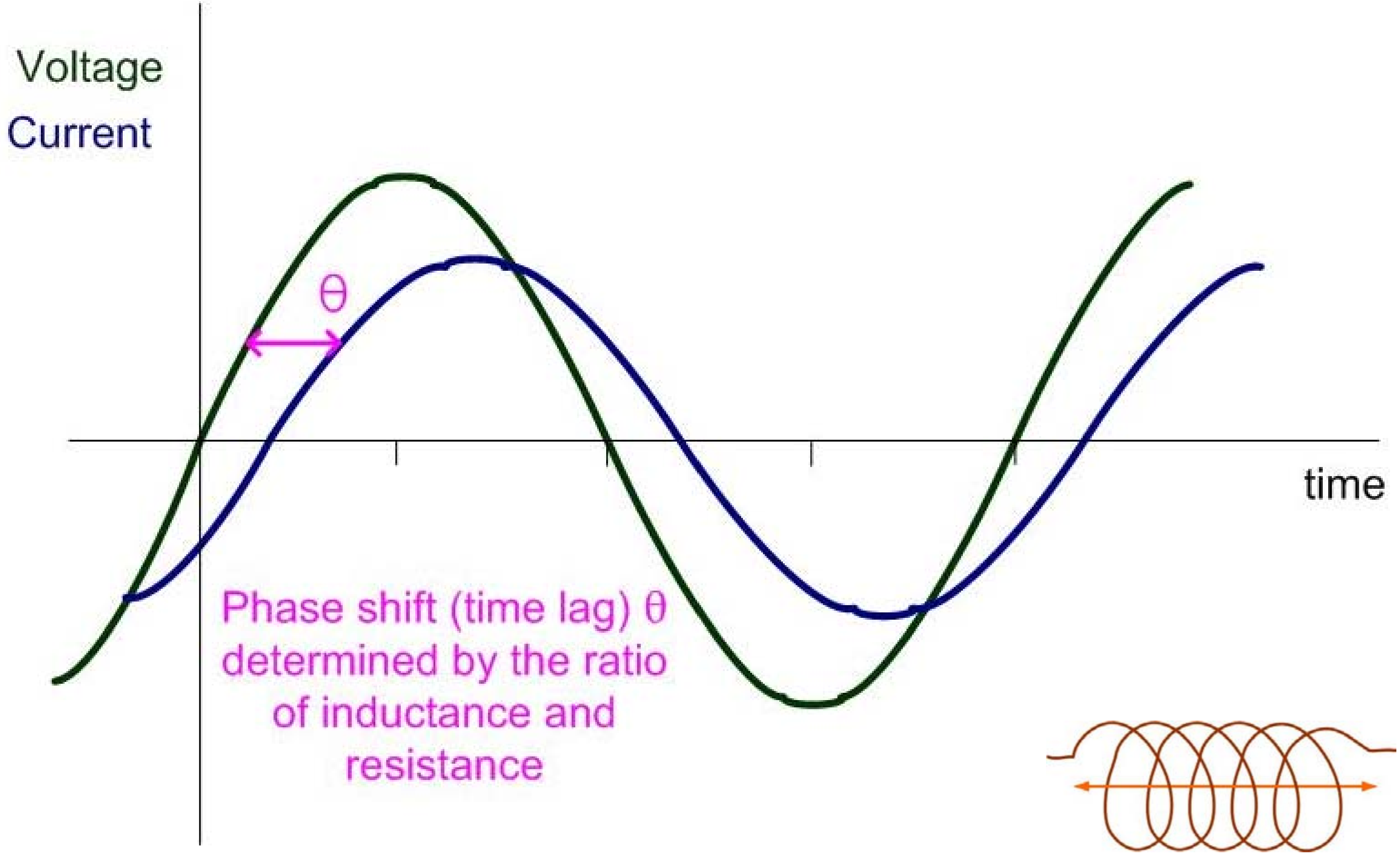
Instantaneous power for a resistor



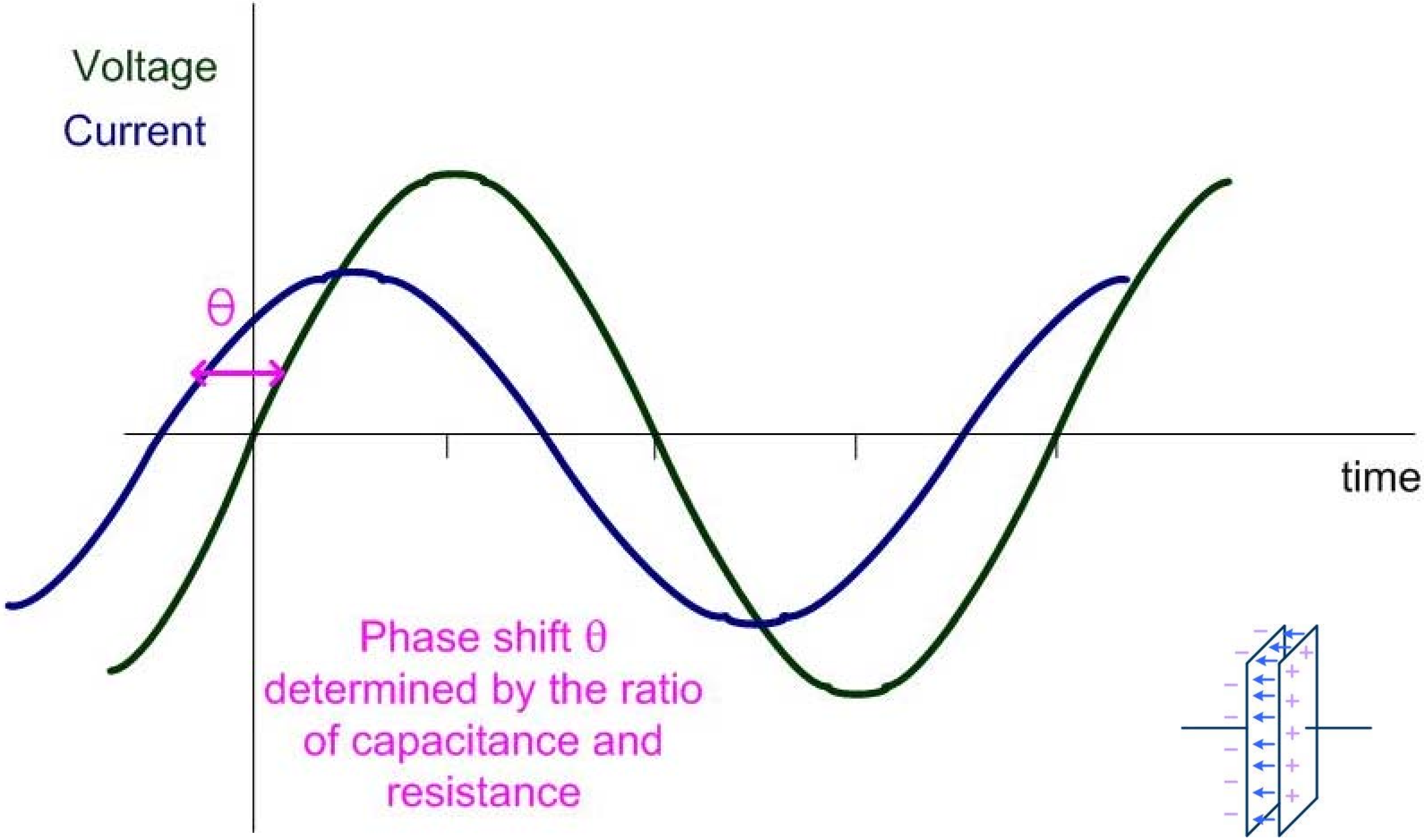
Instantaneous and average power for a resistor



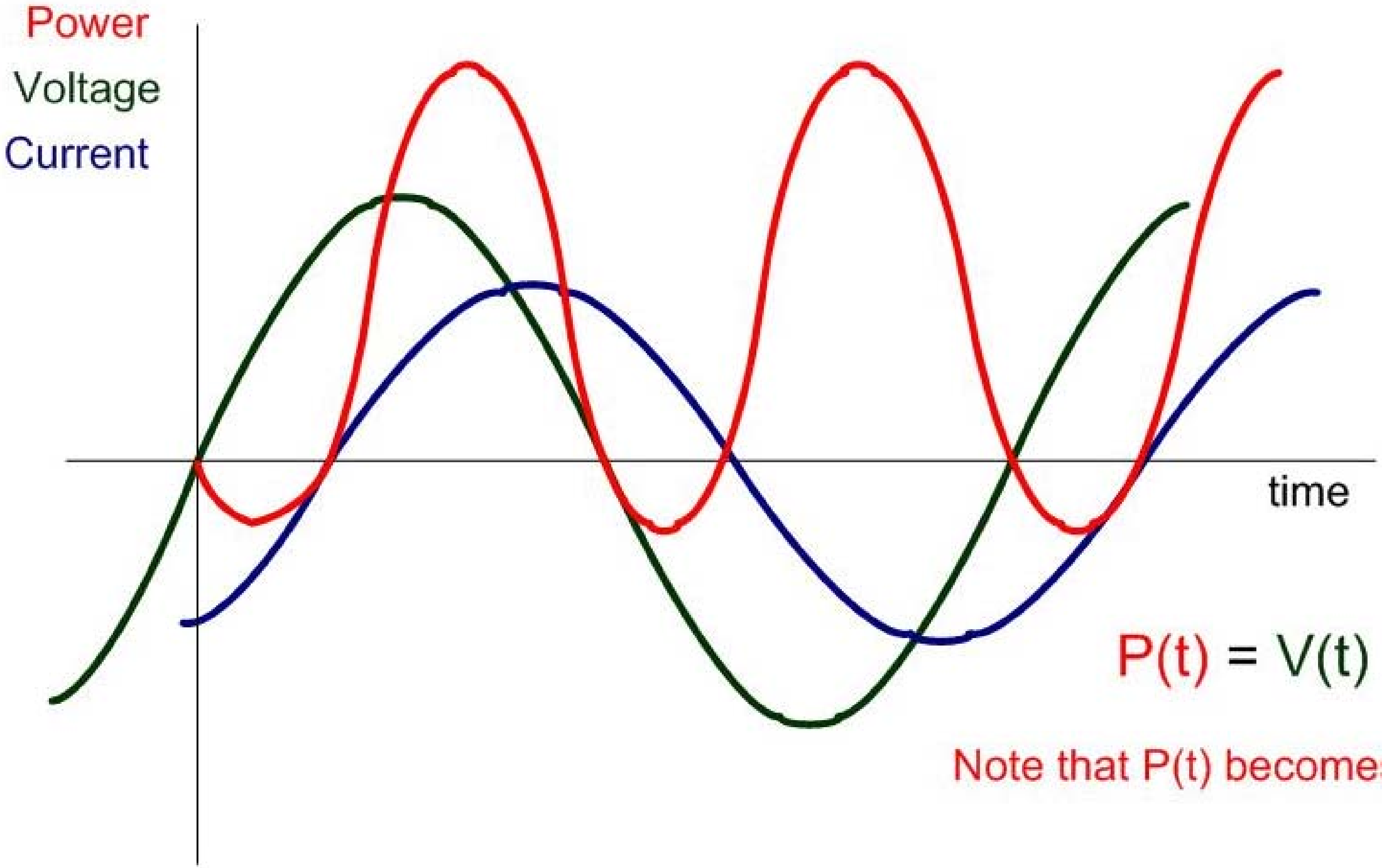
A.C. voltage and current for an inductor: Current lags behind voltage



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



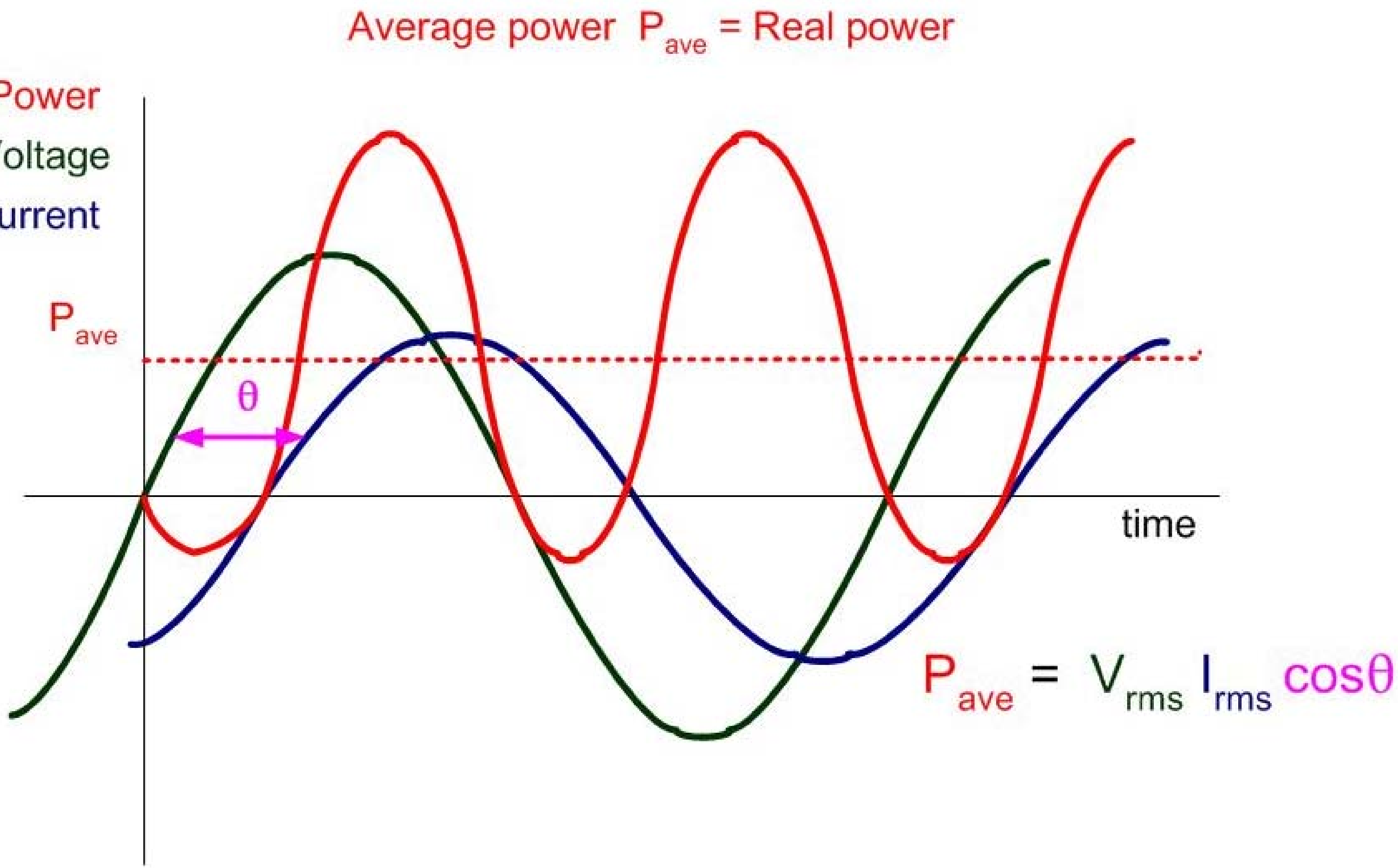
Instantaneous power for an inductor



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

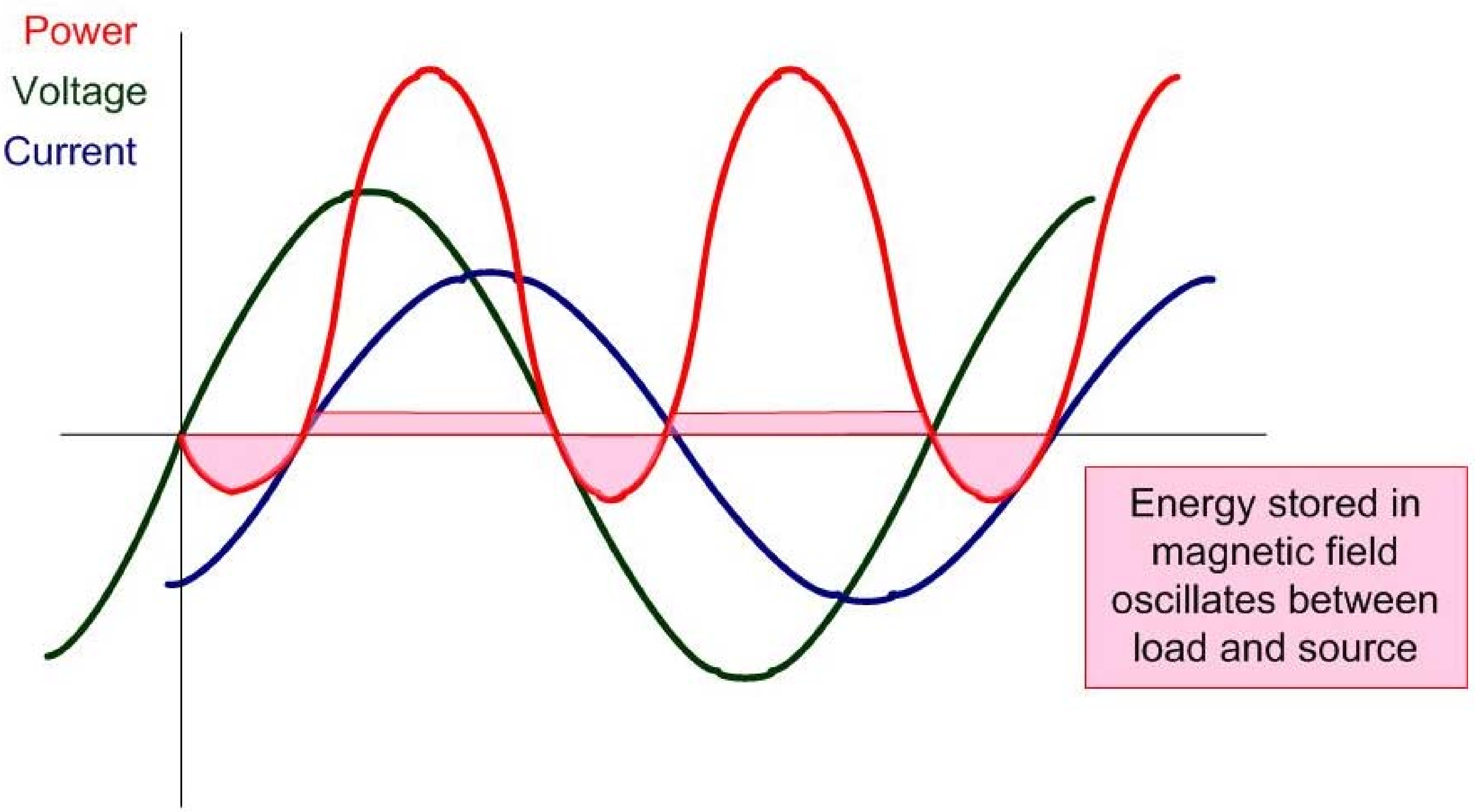
Note that P(t) becomes negative

Instantaneous and average power for an inductor

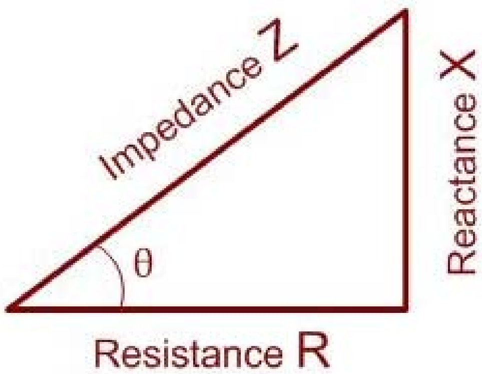


Instantaneous and reactive power for an inductor

Negative portion of P(t) determines reactive power



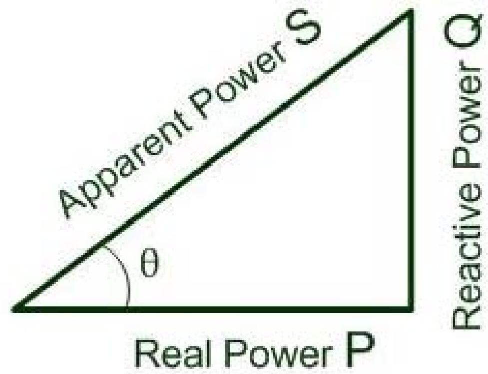
Complex Power



$$Z = R + jX$$

$$R = Z\cos\theta$$

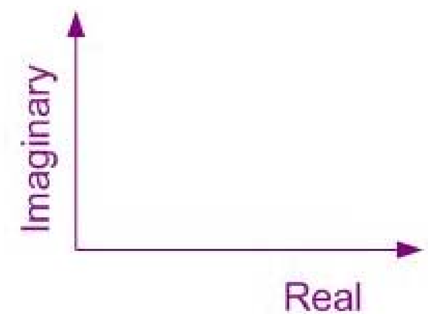
θ is the time lag between current & voltage, determined by the load



$$S = P + jQ$$

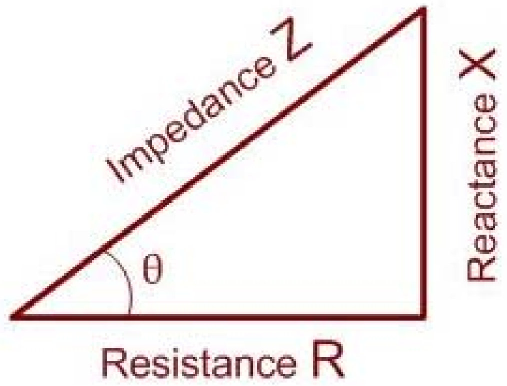
$$P = S\cos\theta$$

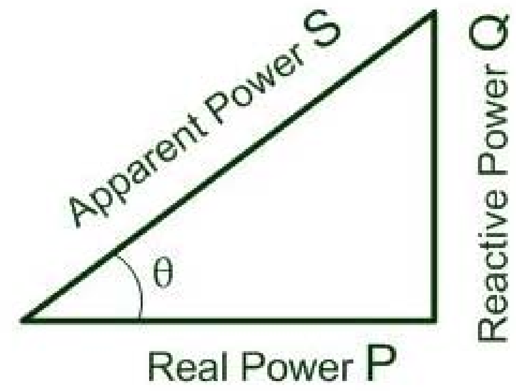
$\cos\theta$ is the Power Factor (p.f.)



j indicates the imaginary direction

$$j^2 = -1$$





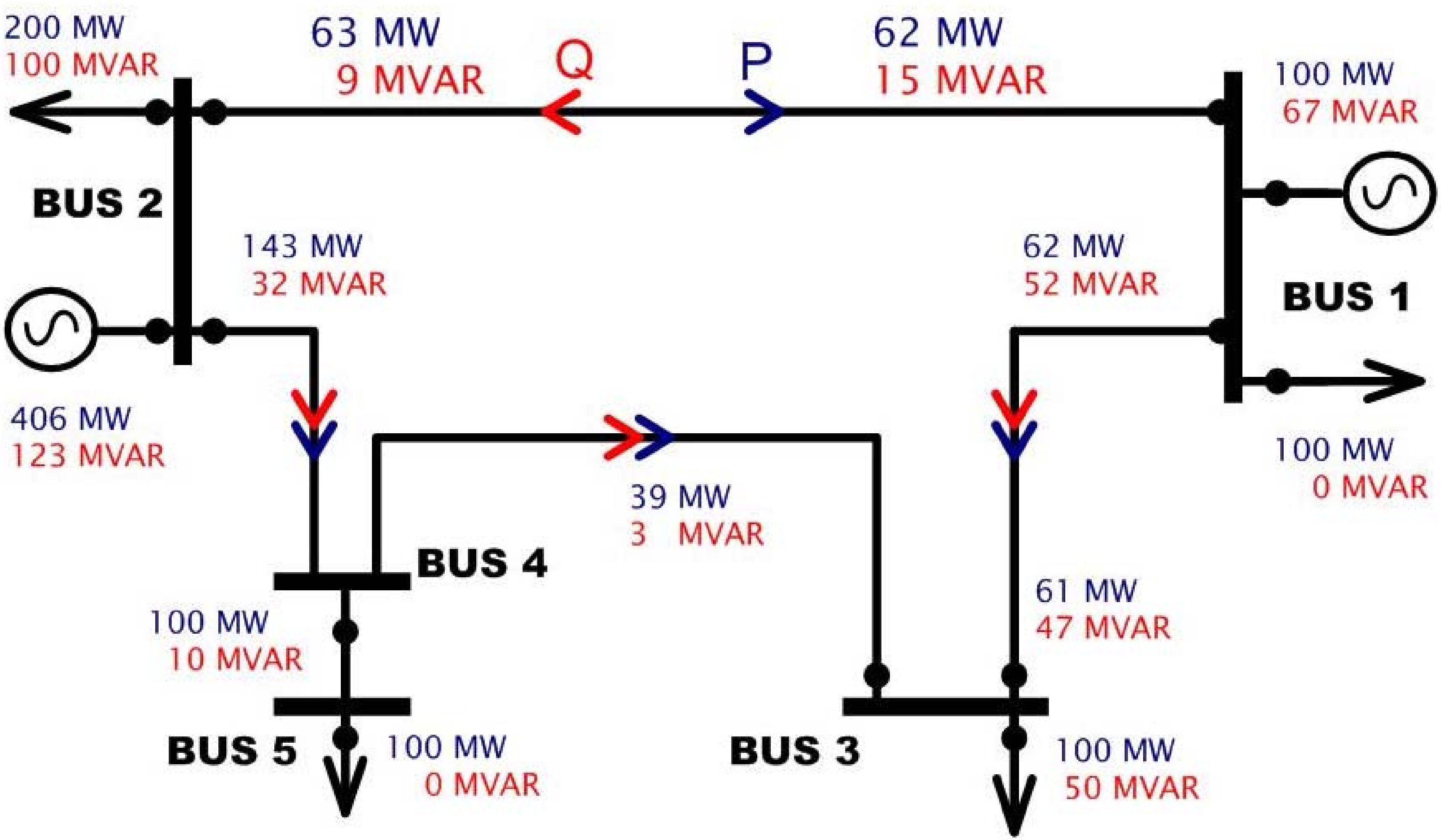
R, X, Z, θ are determined by physical properties of load

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



Real power P measured in megawatts (MW)

Reactive power Q measured in megavolt-amperes reactive (MVAR)

Power generated = Power demanded

"THE LAW OF ENERGY CONSERVATION IS STRICTLY ENFORCED."

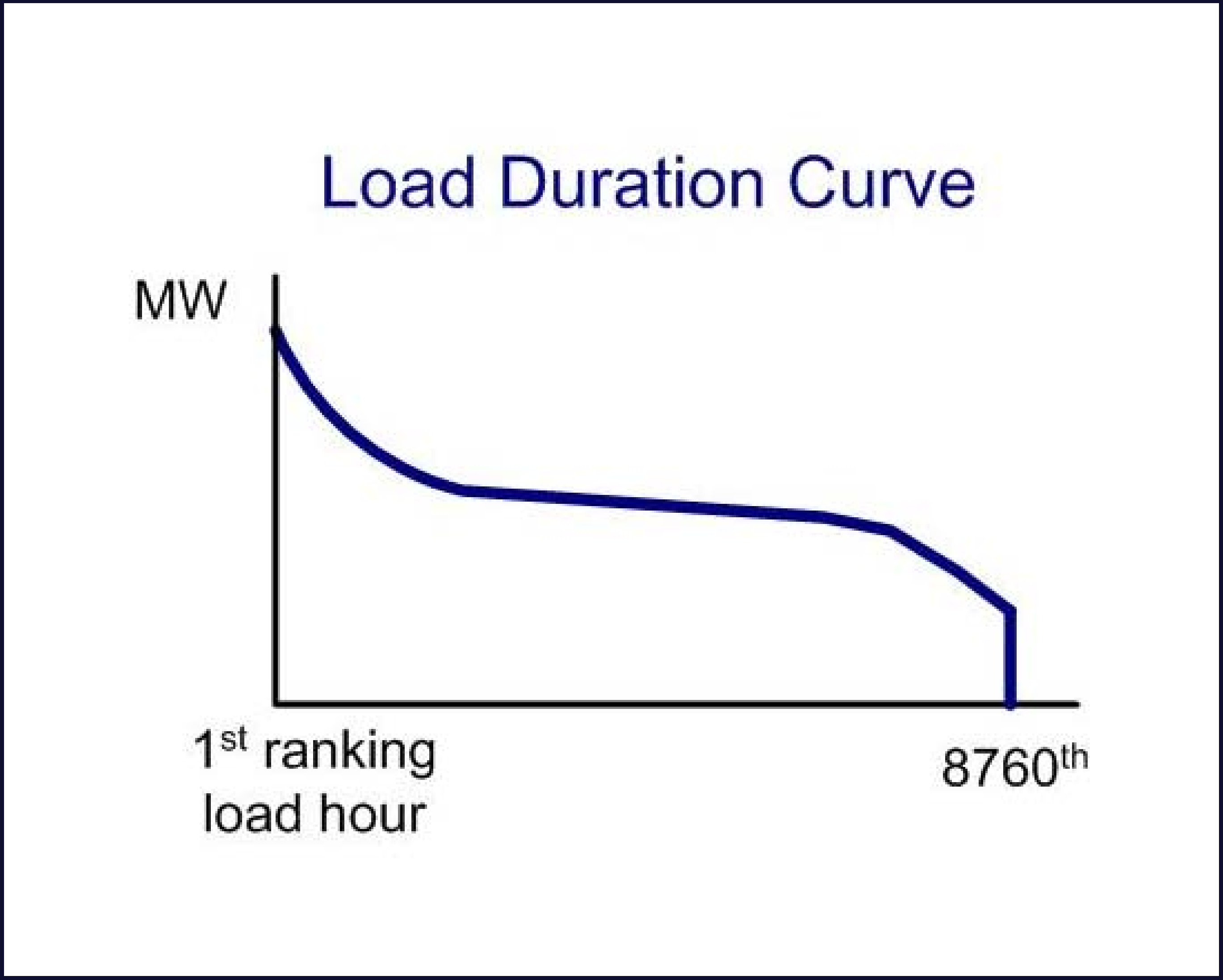
Real power imbalance:
Loss of frequency control

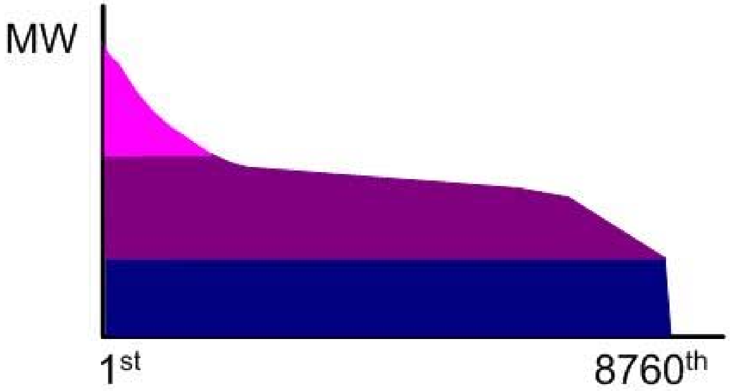
Reactive power imbalance:
Loss of voltage control

How to balance supply & demand?

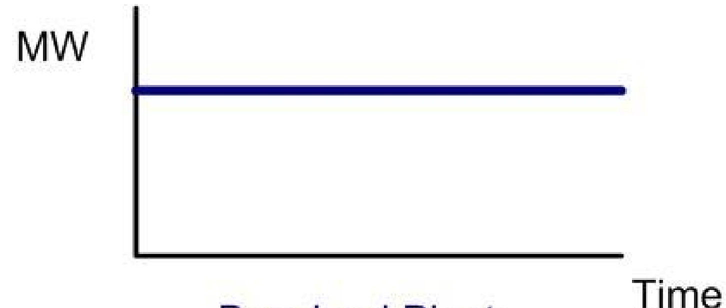
Successive approximations on different time scales:

1. Scheduling (day ahead, hour ahead)
2. Generator control
3. Inherent stability

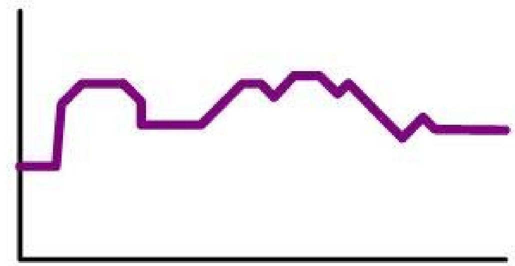

Load Duration Curve
MW
1st ranking
load hour
8760th



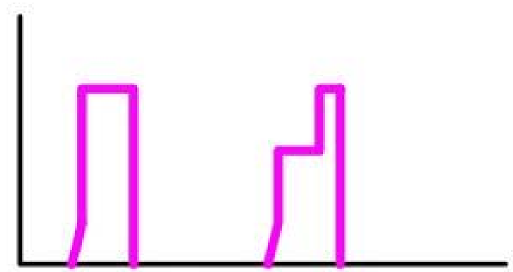
Traditional Dispatch:
Filling the load duration
curve from the bottom up



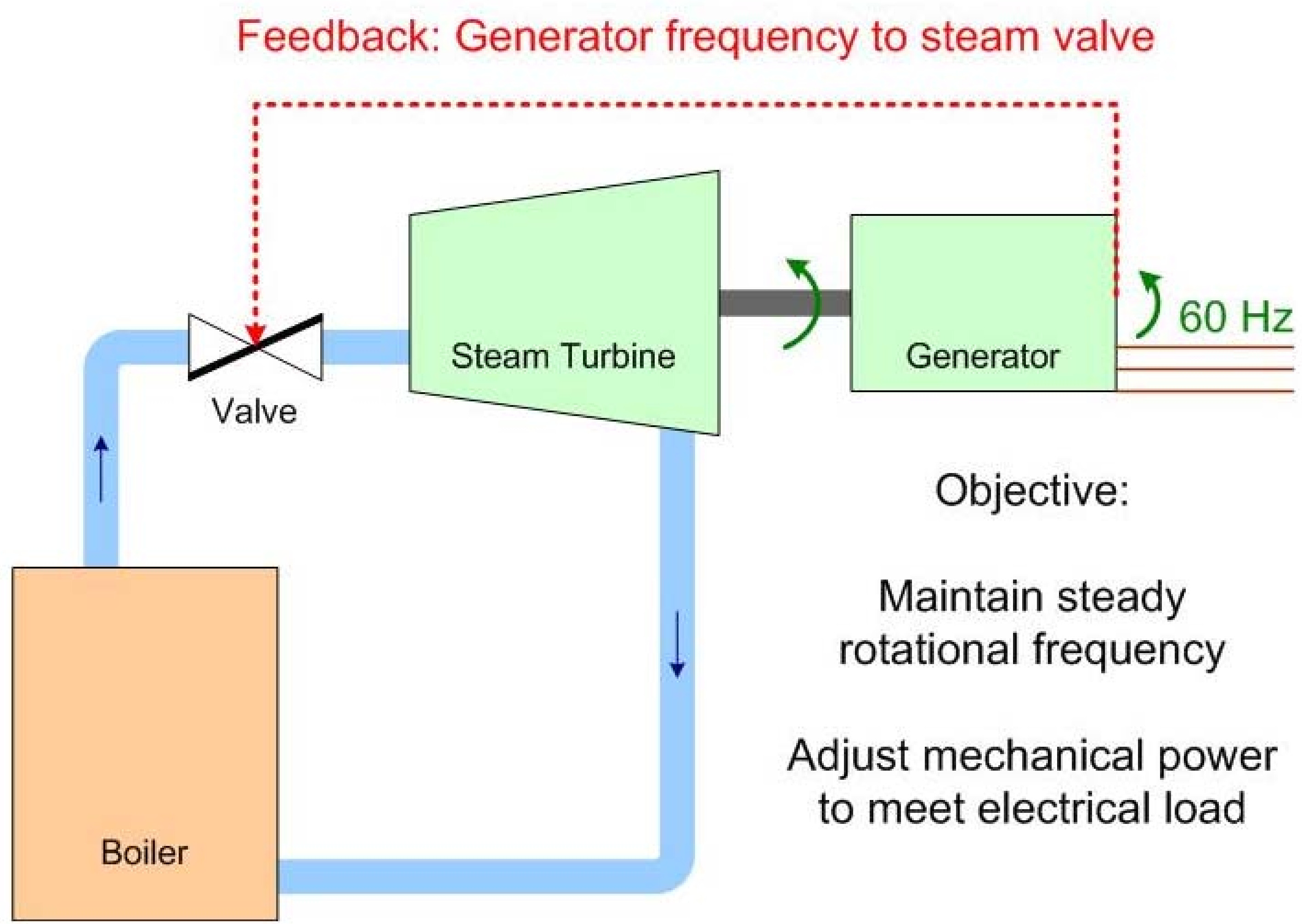
Baseload Plant



Load-following Plant

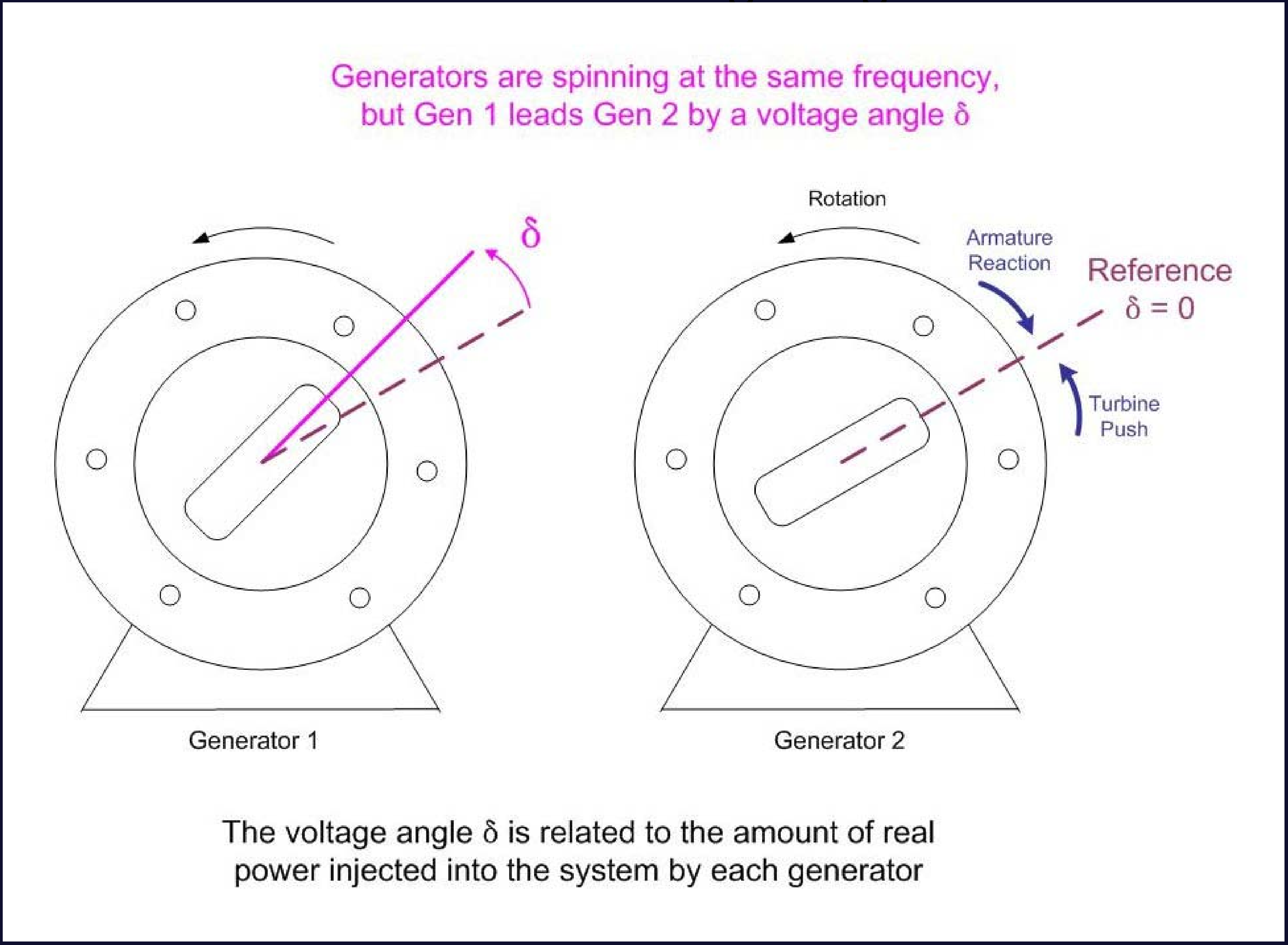


Peaking Plant



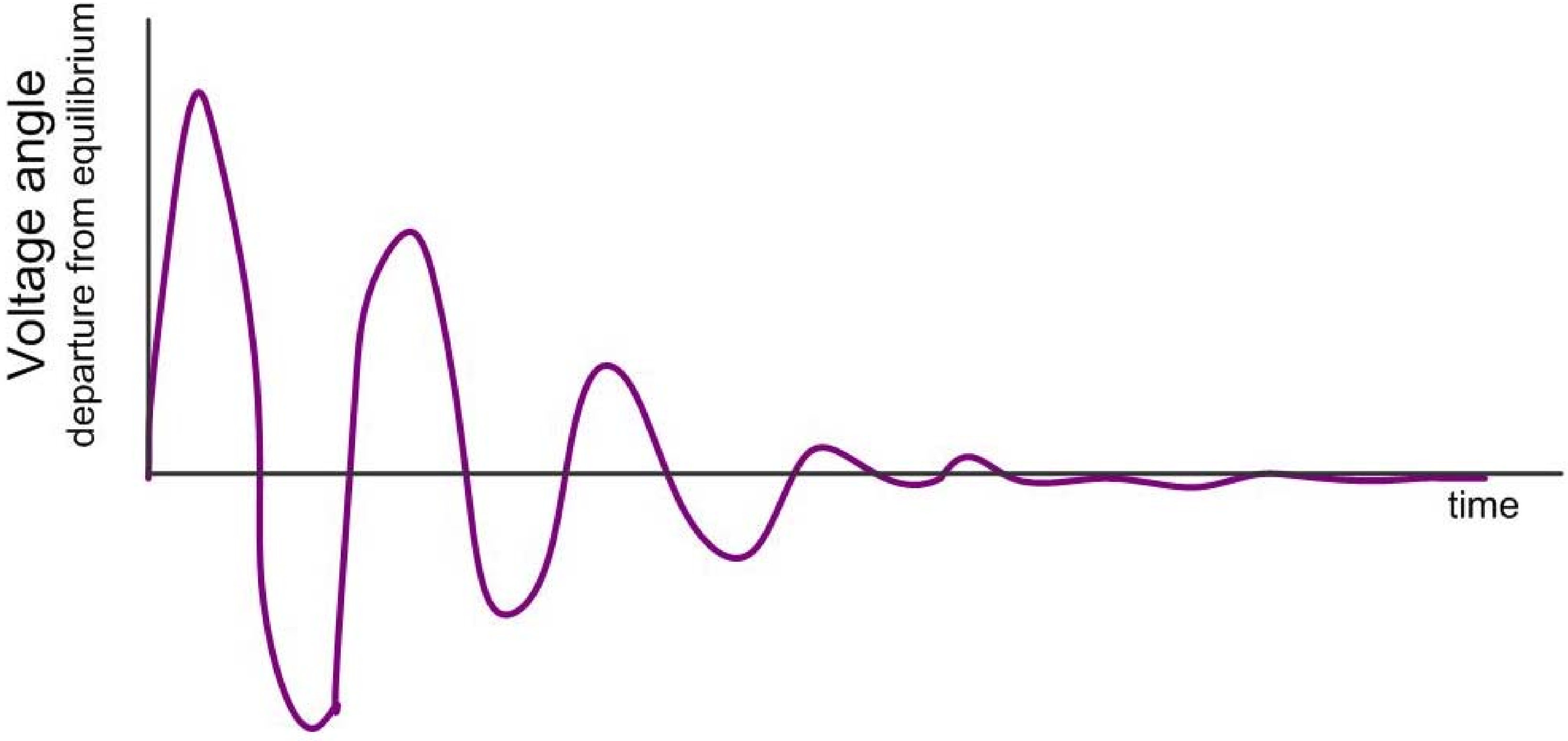
Generator control: operating “on the governor”

Generator Voltage Angle



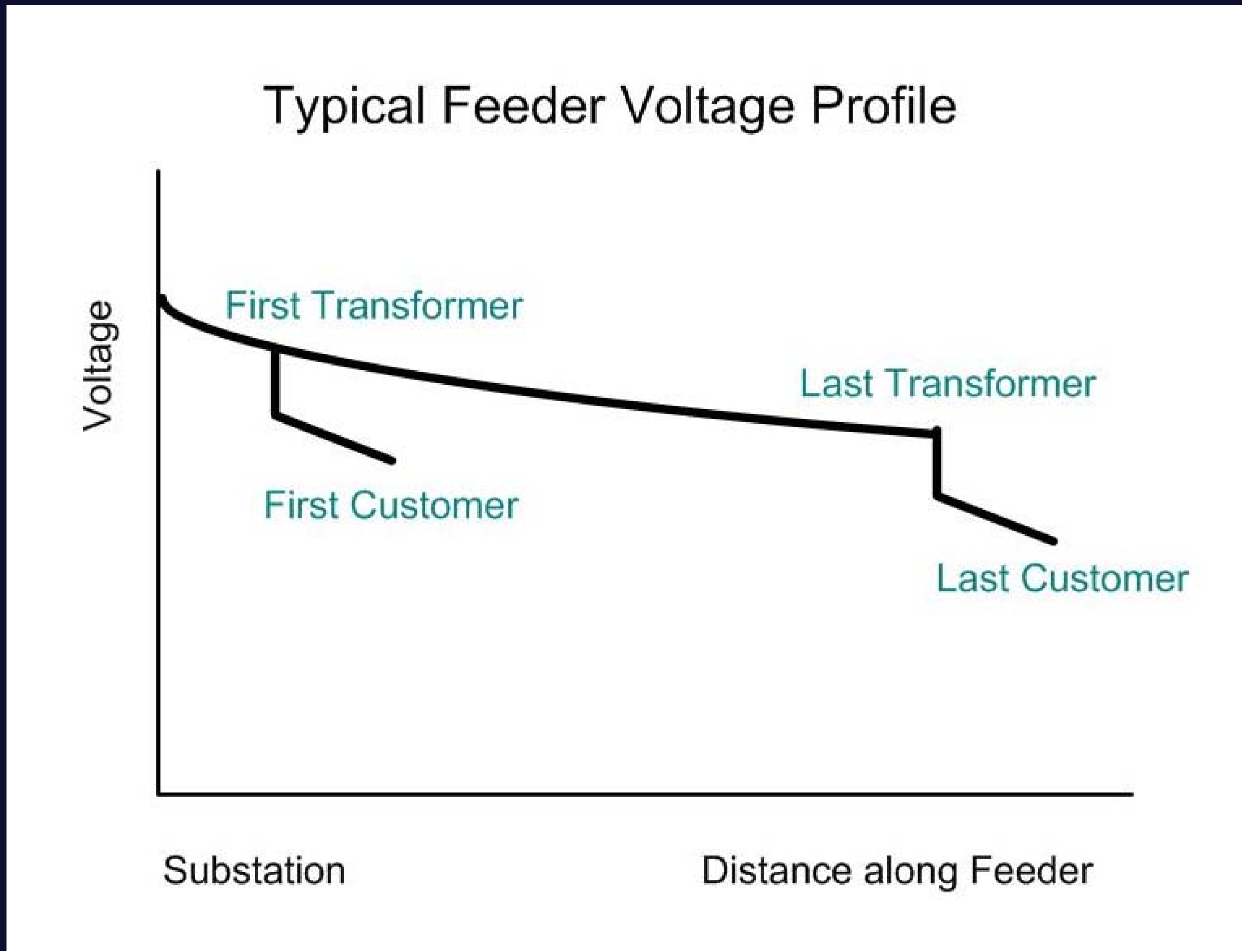
Generator stability:

Absorbing a sudden change in load



Power System Performance Measures

Power quality:	voltage a.c. frequency waveform
Reliability:	outage frequency & duration probabilistic measures
Security:	width of operating envelope

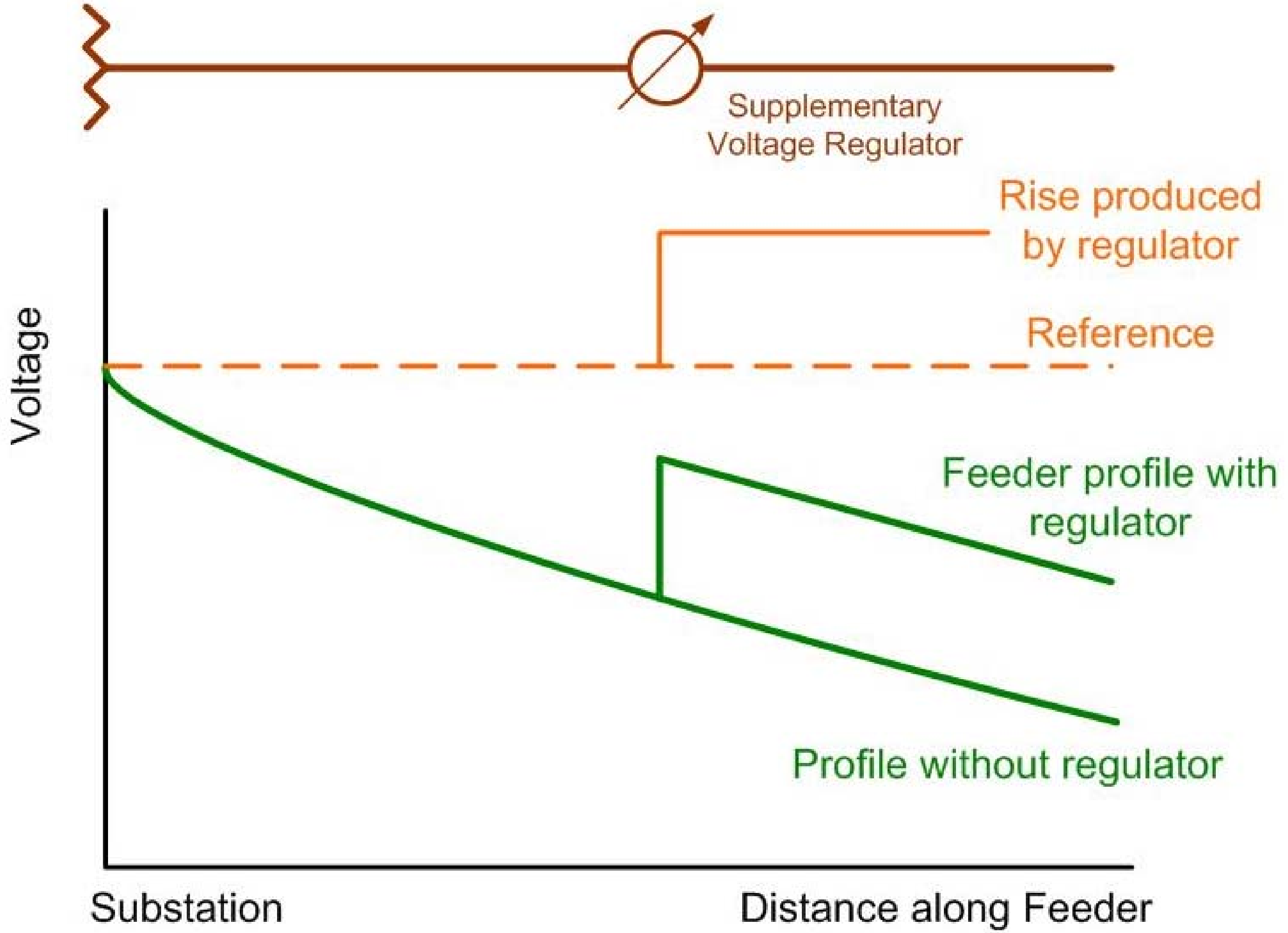


V_{DROP} is a function of current (load), line resistance, and settings on voltage control equipment
(transformers, voltage regulators, capacitors)

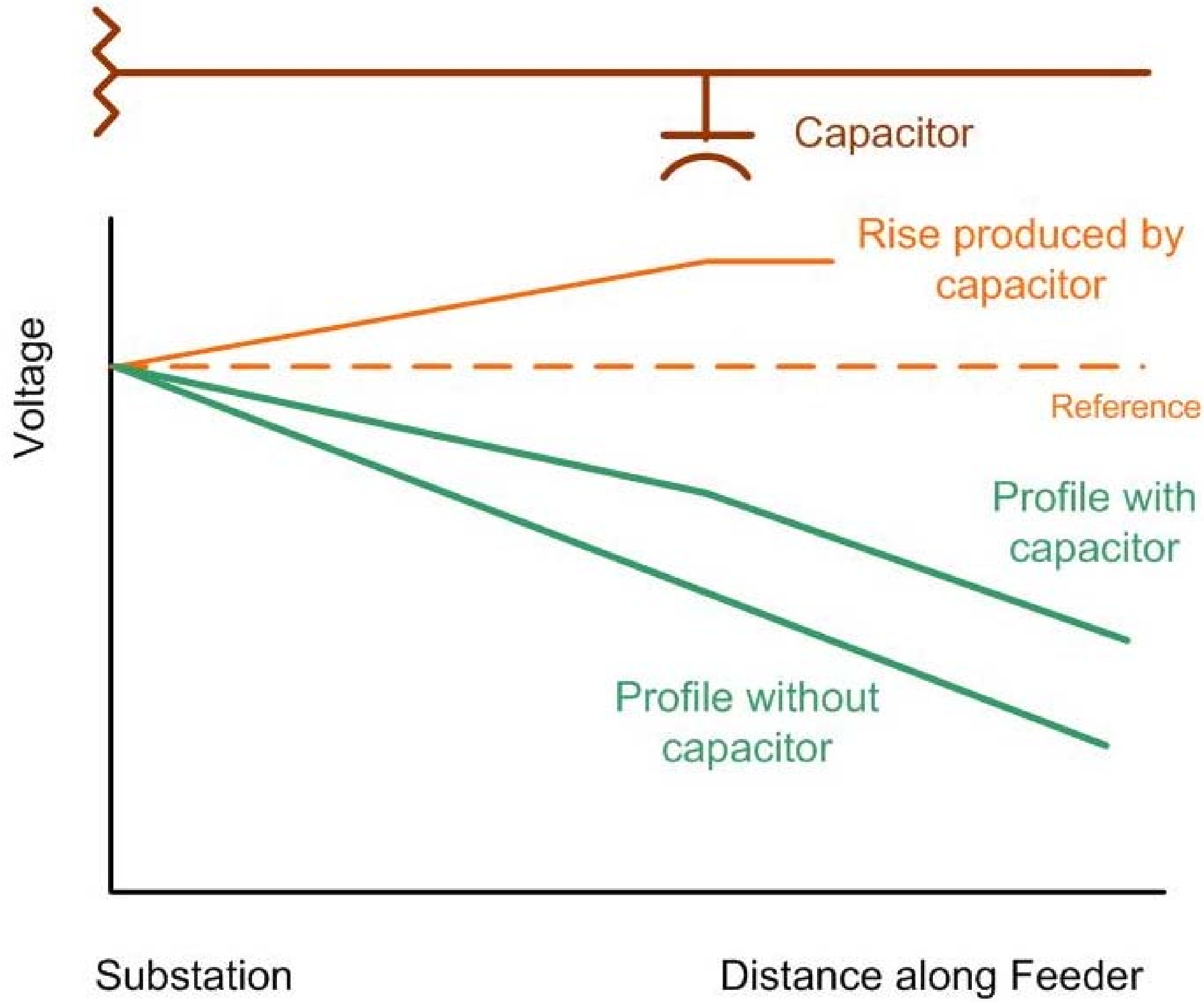
Voltage regulator

(on right)

Feeder Voltage Profile with Voltage Regulator



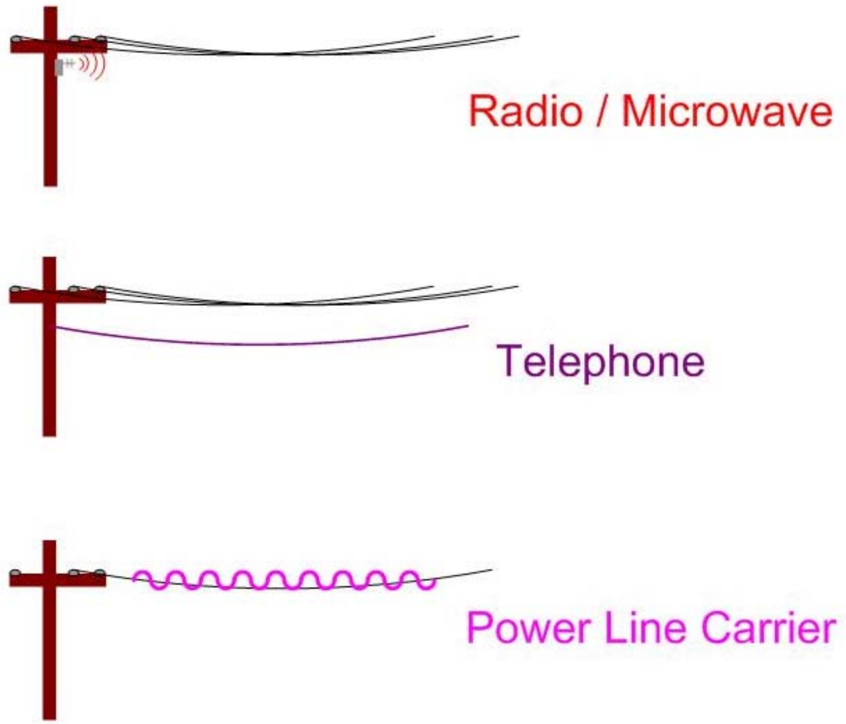
Feeder Voltage Profile with Shunt Capacitor



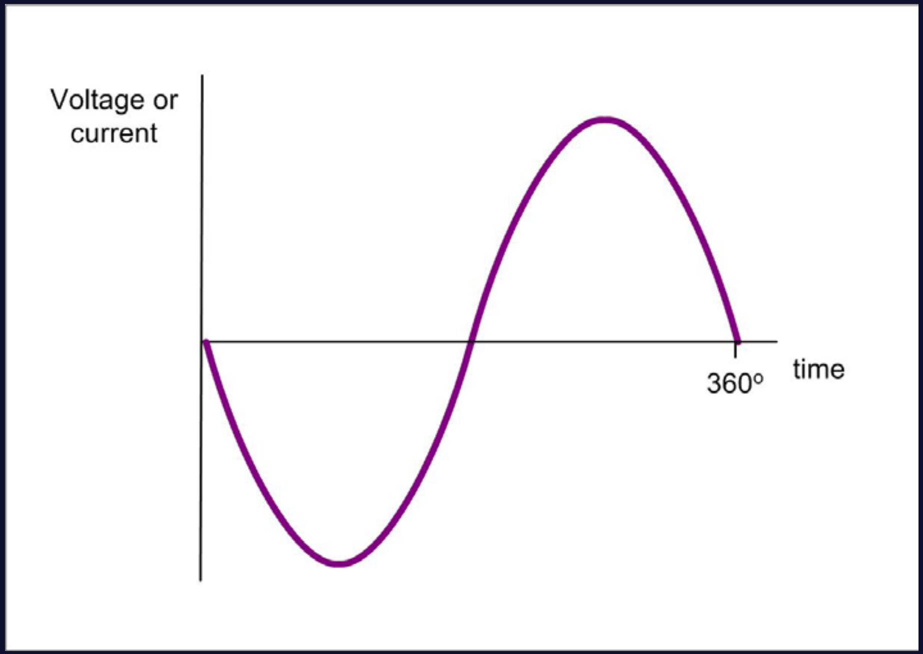
Capacitors

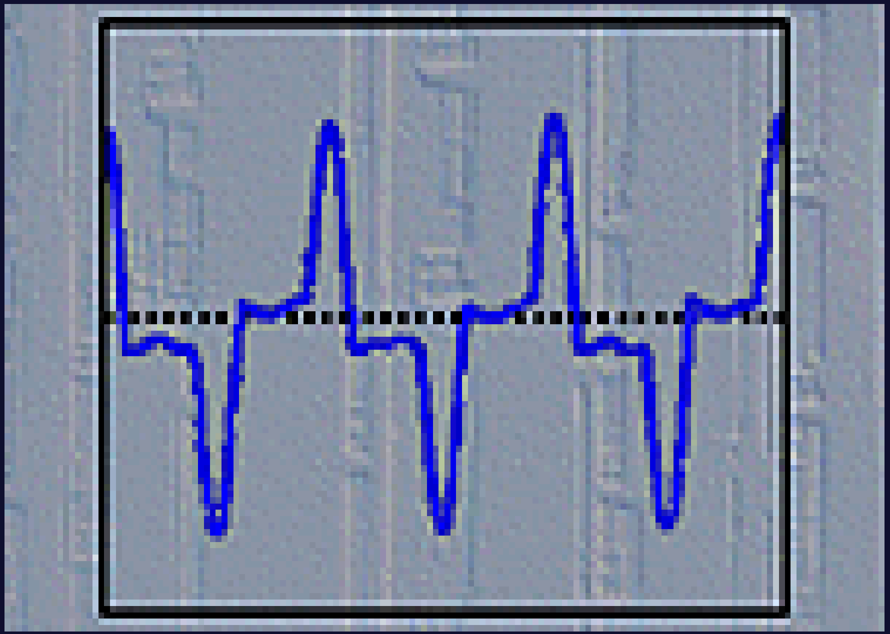
Capacitor and switch

Telecommunications in Power Systems



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





Measures of reliability:

Outage frequency

Outage duration

Loss-of-load probability (LOLP)

Loss-of-load expectation (LOLE)

Expected unserved energy (EUE)

What is reliability worth?

Historical standards:

- Obligation to serve
- One-day-in-ten-years criterion

Economic approaches:

- Value of Service
- Interruptible tarriffs

Bottom line: widespread outages (still) unacceptable;
Demand for power at system level is *very* inelastic

Security:
The width of the operating envelope

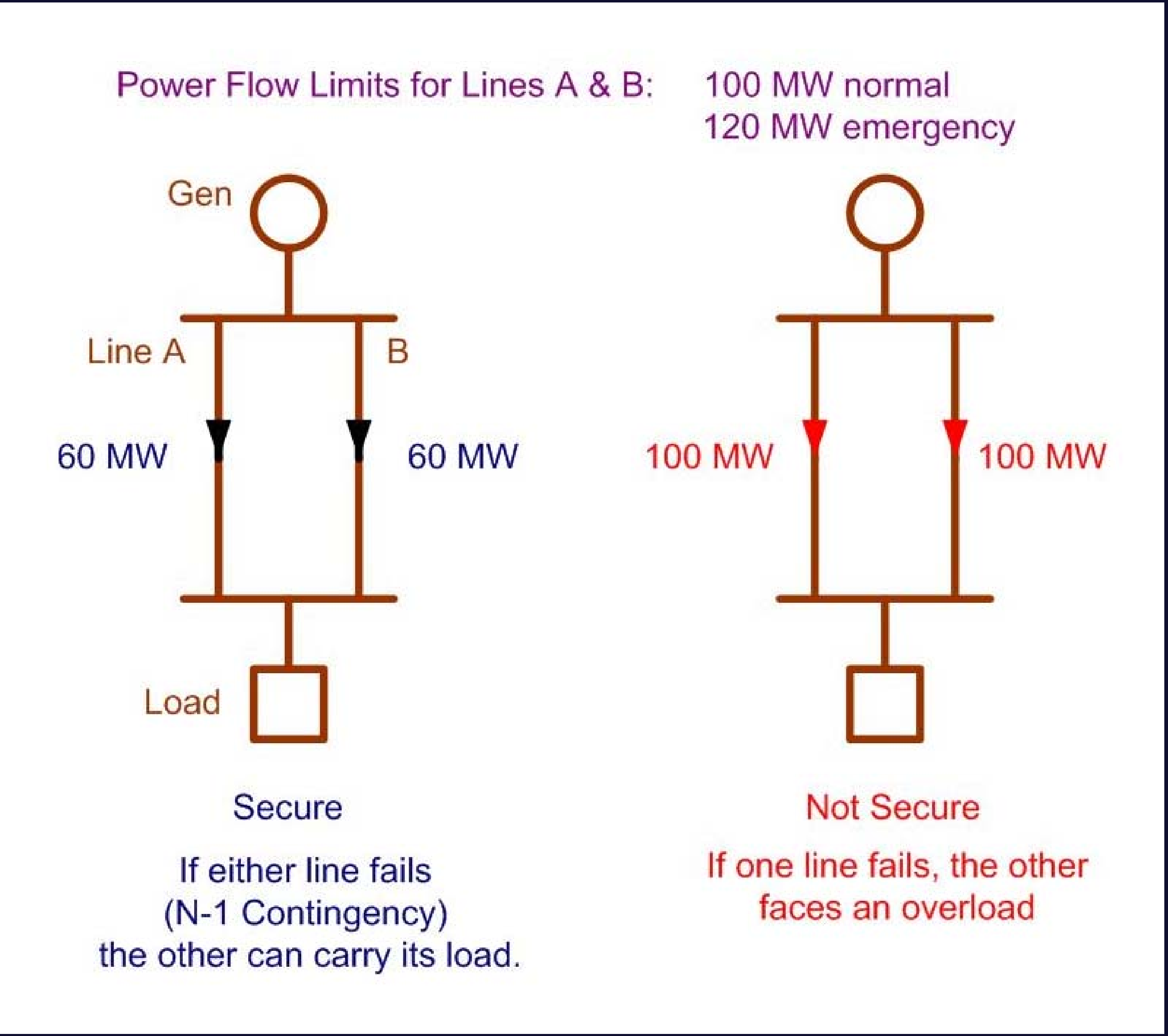
Contingency Analysis

N-1 Criterion

A “contingency”

Security and the

N-1 Criterion

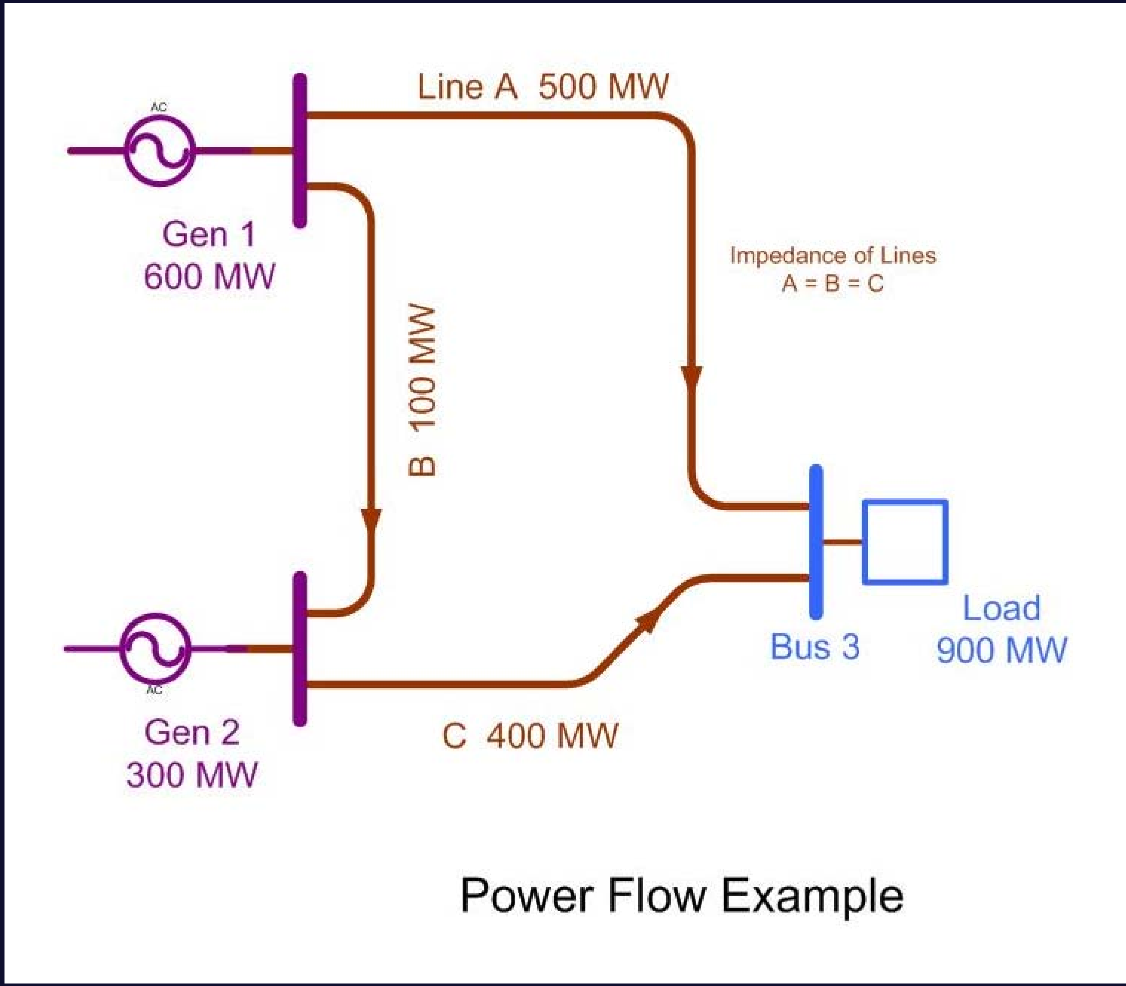


Power Flow Analysis

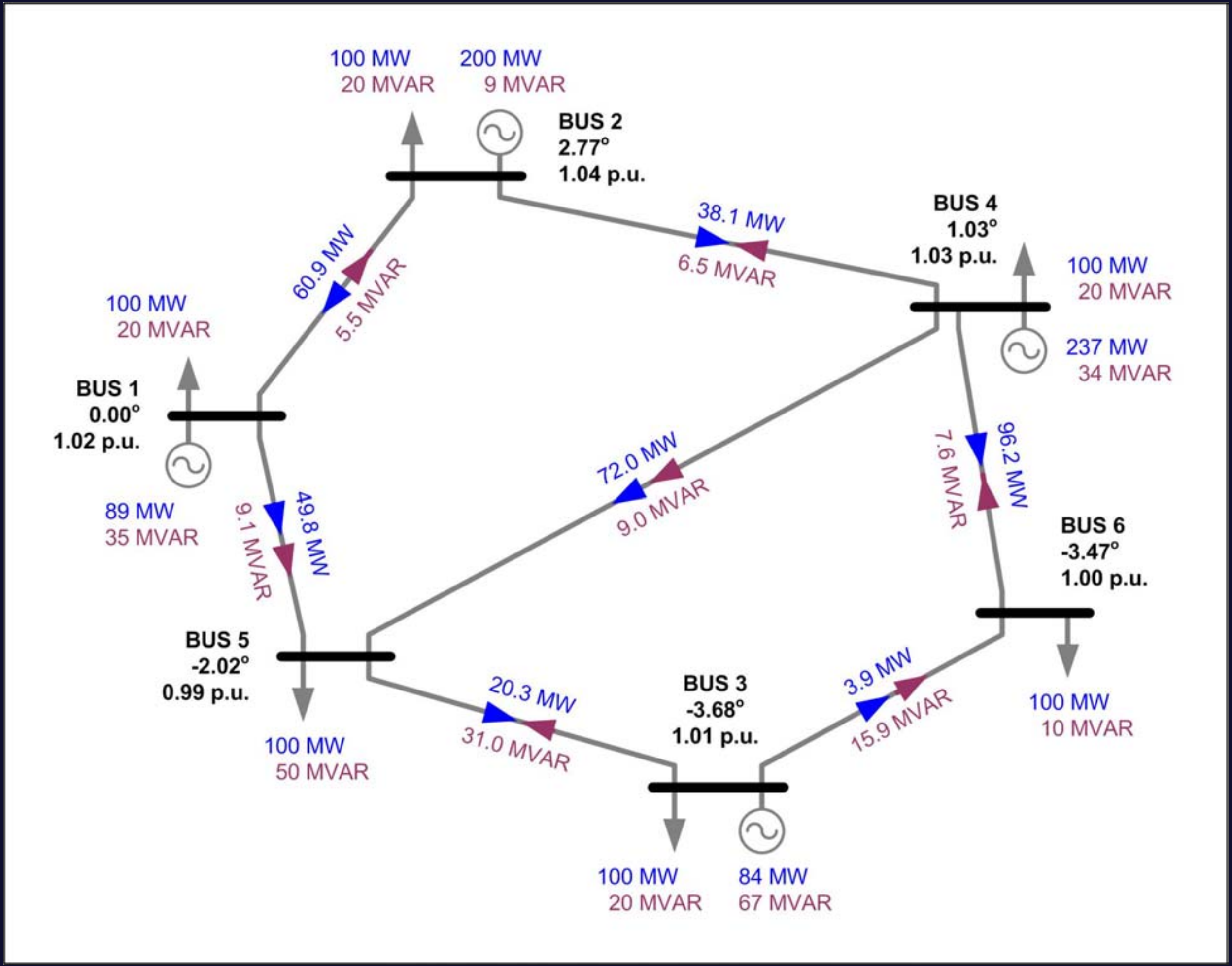
Numerical simulation of grid

Required due to mathematical complexity of system

Way cool

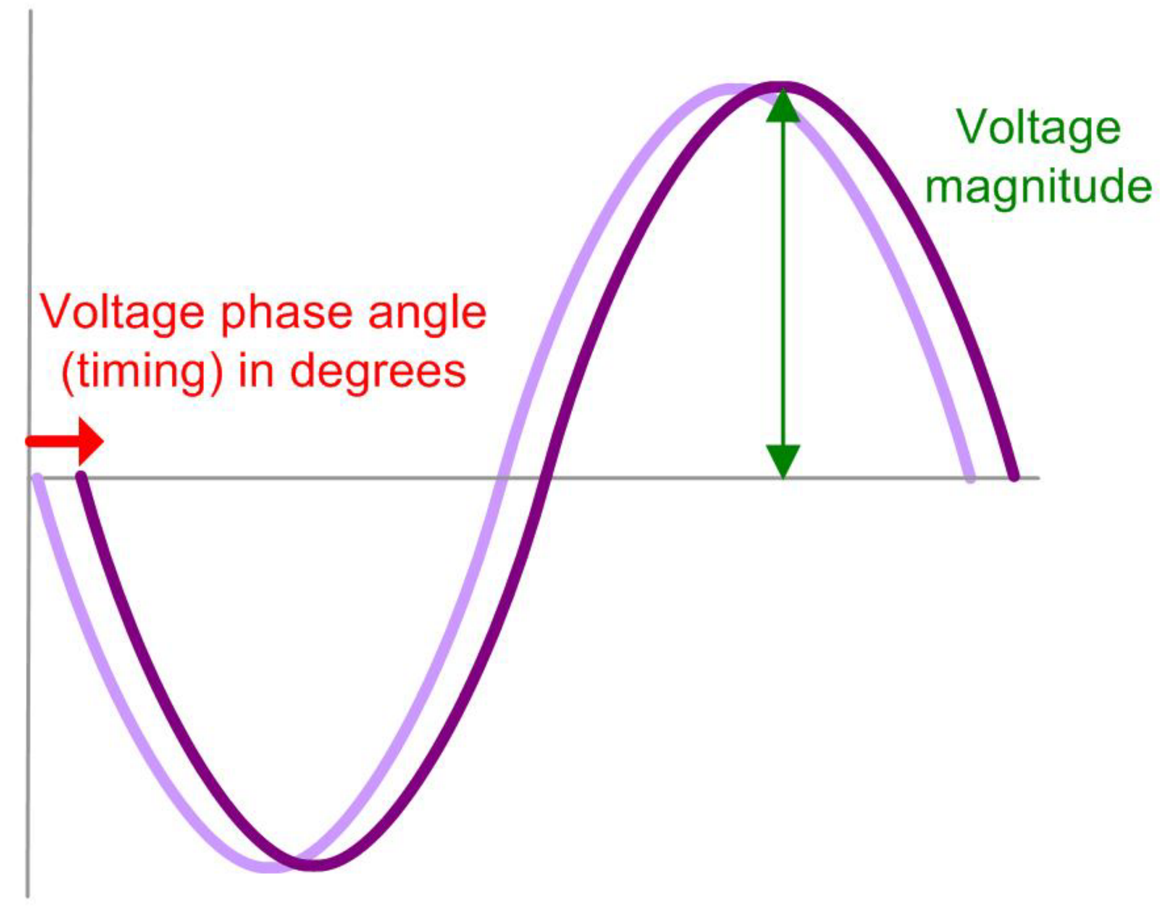


Not obvious:
how a change at one generator or load will affect line flows

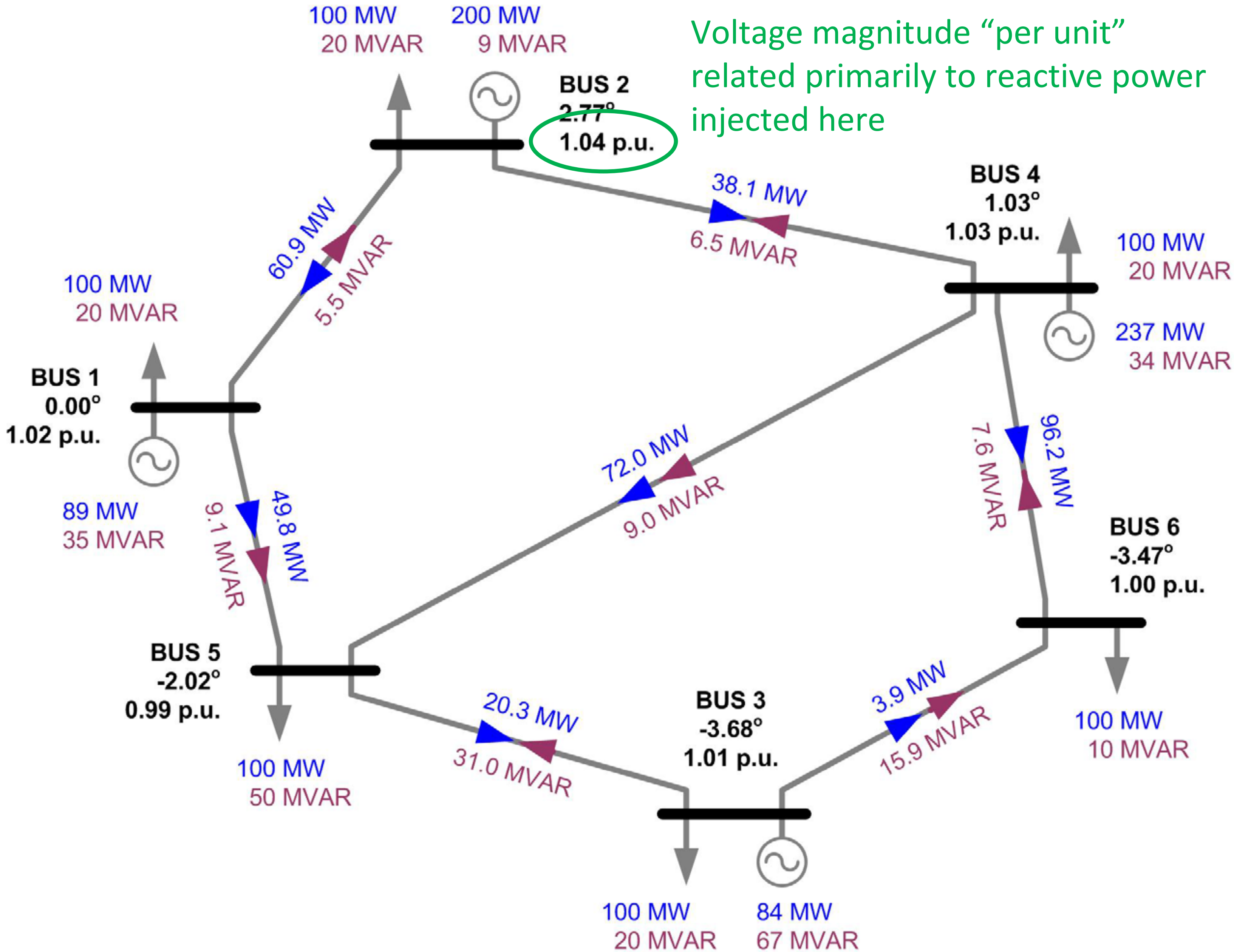


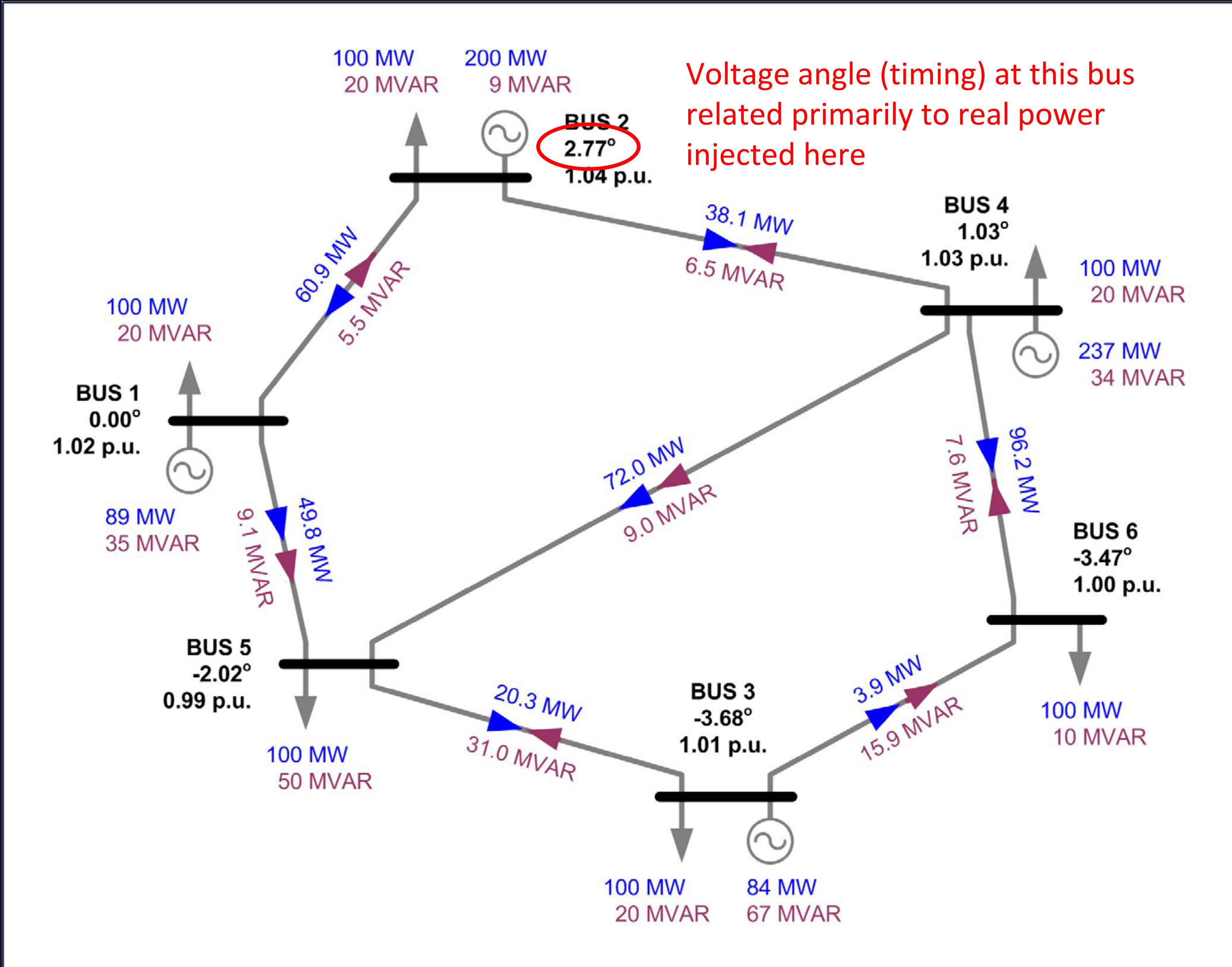
Power flow problem:

Given MW and MVAR injected (or consumed) at each bus,
find voltage angle and magnitude at each bus,
which will determine line flows


Voltage magnitude
Voltage phase angle (timing) in degrees

Voltage magnitude “per unit” related primarily to reactive power injected here





Voltage angle (timing) at this bus related primarily to real power injected here
100 MW
20 MVAR
200 MW
9 MVAR
BUS 2
2.77°
1.04 p.u.
38.1 MW
6.5 MVAR
BUS 4
1.03°
1.03 p.u.
100 MW
20 MVAR
237 MW
34 MVAR
60.9 MW
5.5 MVAR
100 MW
20 MVAR
BUS 1
0.00°
1.02 p.u.
89 MW
35 MVAR
49.8 MW
9.1 MVAR
72.0 MW
9.0 MVAR
7.6 MVAR
96.2 MW
BUS 6
-3.47°
1.00 p.u.
BUS 5
-2.02°
0.99 p.u.
100 MW
50 MVAR
20.3 MW
31.0 MVAR
BUS 3
-3.68°
1.01 p.u.
3.9 MW
15.9 MVAR
100 MW
10 MVAR
100 MW
20 MVAR
84 MW
67 MVAR

Power flow equations:

$$P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k)]$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\theta_i - \theta_k) - b_{ik}\cos(\theta_i - \theta_k)]$$

You can’t solve these explicitly for voltage magnitudes & angles given P_i and Q_i

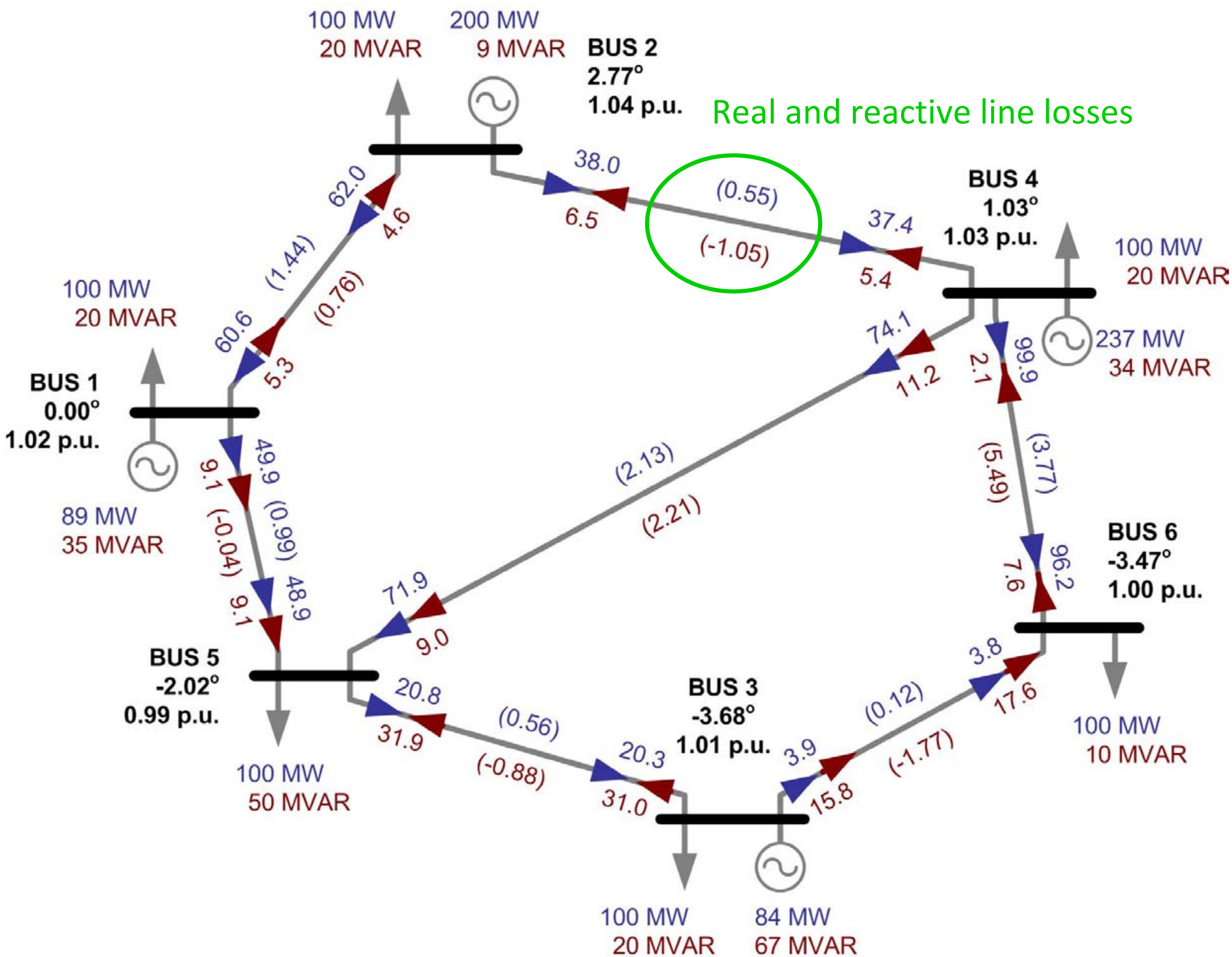
Real power
Voltage magnitudes
Voltage angles

$$P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k)]$$

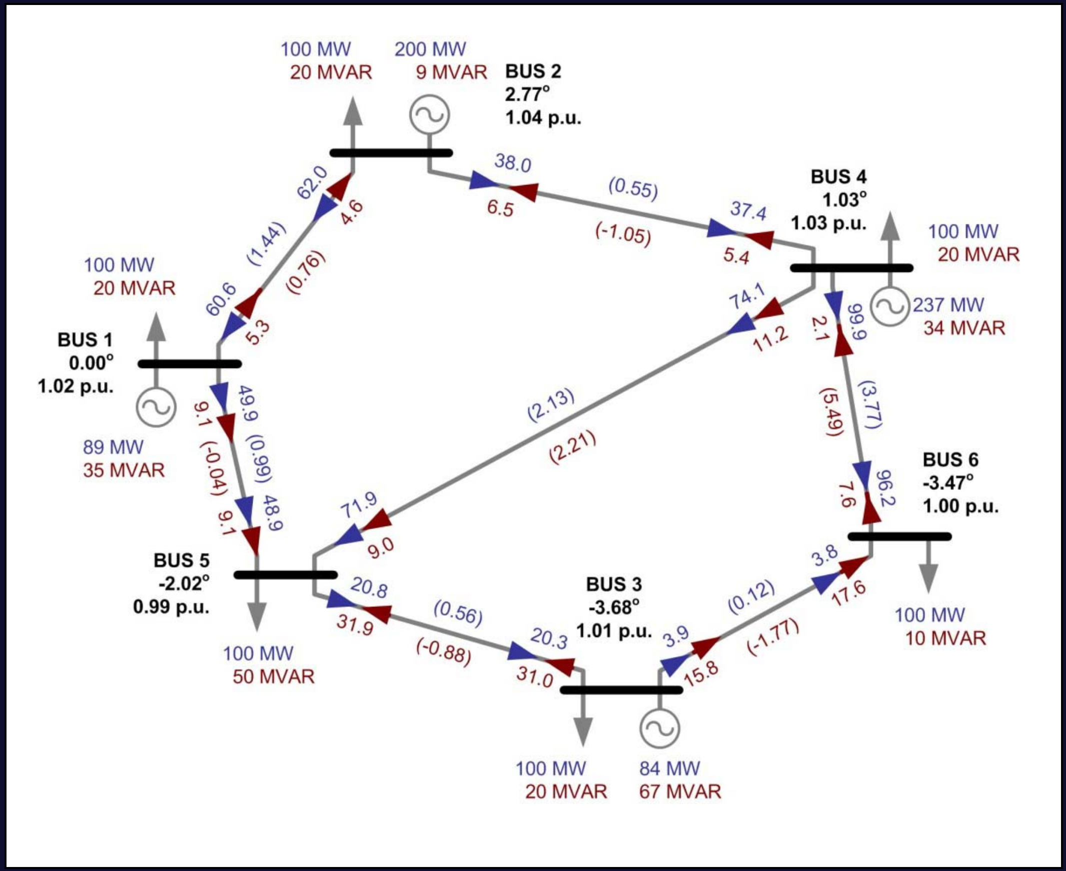
$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\theta_i - \theta_k) - b_{ik}\cos(\theta_i - \theta_k)]$$

Reactive power
Conductance
Susceptance

i label for the bus in question
k label for all the other buses



Real and reactive line losses
BUS 1
0.00°
1.02 p.u.
BUS 2
2.77°
1.04 p.u.
BUS 3
-3.68°
1.01 p.u.
BUS 4
1.03°
1.03 p.u.
BUS 5
-2.02°
0.99 p.u.
BUS 6
-3.47°
1.00 p.u.
100 MW
20 MVAR
200 MW
9 MVAR
100 MW
20 MVAR
89 MW
35 MVAR
100 MW
20 MVAR
237 MW
34 MVAR
100 MW
50 MVAR
100 MW
20 MVAR
84 MW
67 MVAR
100 MW
10 MVAR
38.0
6.5
(0.55)
(-1.05)
37.4
5.4
62.0
4.6
(1.44)
(0.76)
60.6
5.3
49.9
9.1
(0.99)
(-0.04)
48.9
9.1
74.1
11.2
(2.13)
(2.21)
71.9
9.0
99.9
2.1
(3.77)
(5.49)
96.2
7.6
20.8
31.9
(0.56)
(-0.88)
20.3
31.0
3.9
15.8
(0.12)
(-1.77)
3.8
17.6



Stability means that variations of voltage magnitude and angle at each bus are dampened by appropriate changes in real and reactive power which tend to counteract the variations (negative feedback).

Loss of voltage and angle stability = *&%$#@!!

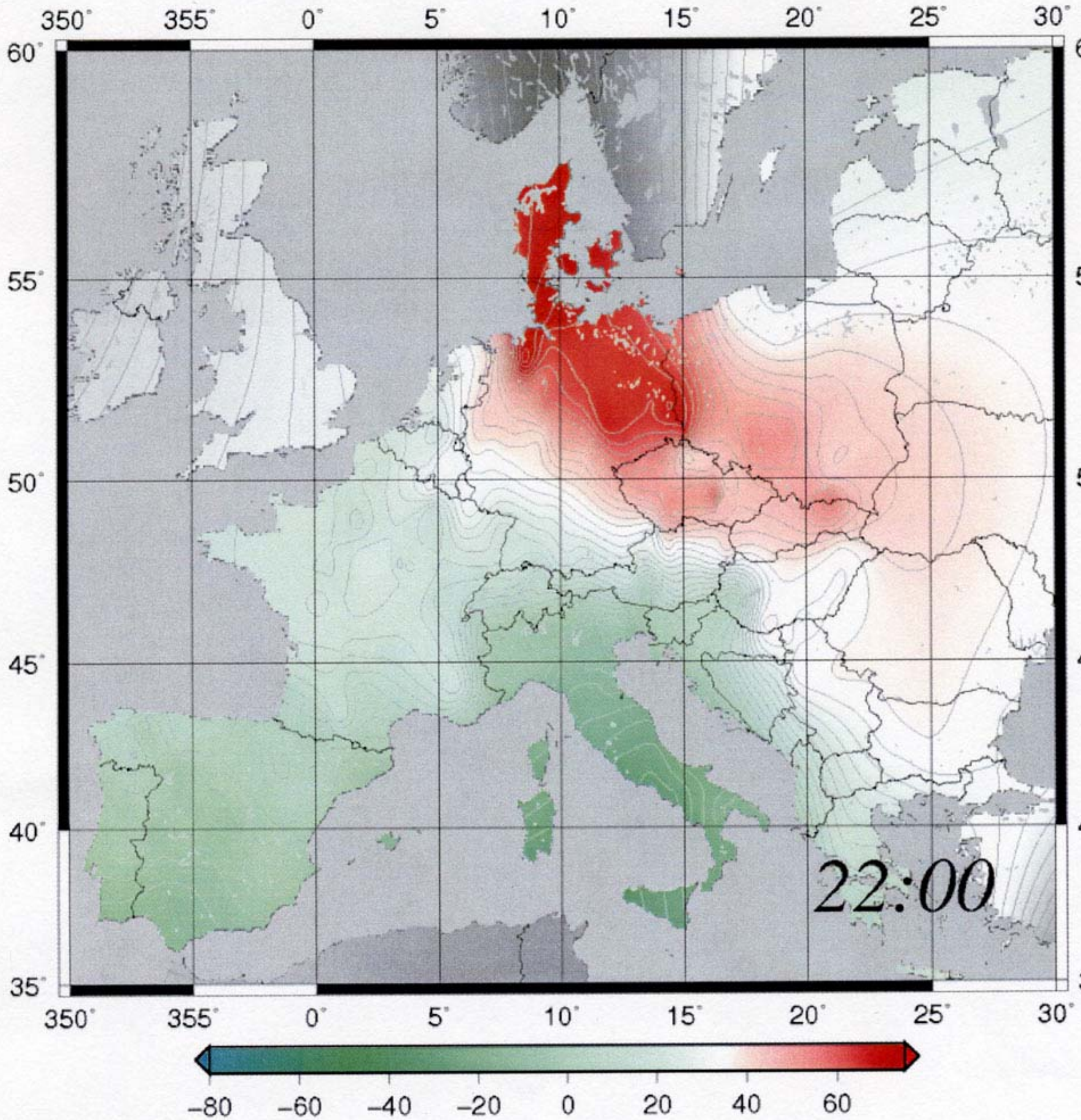
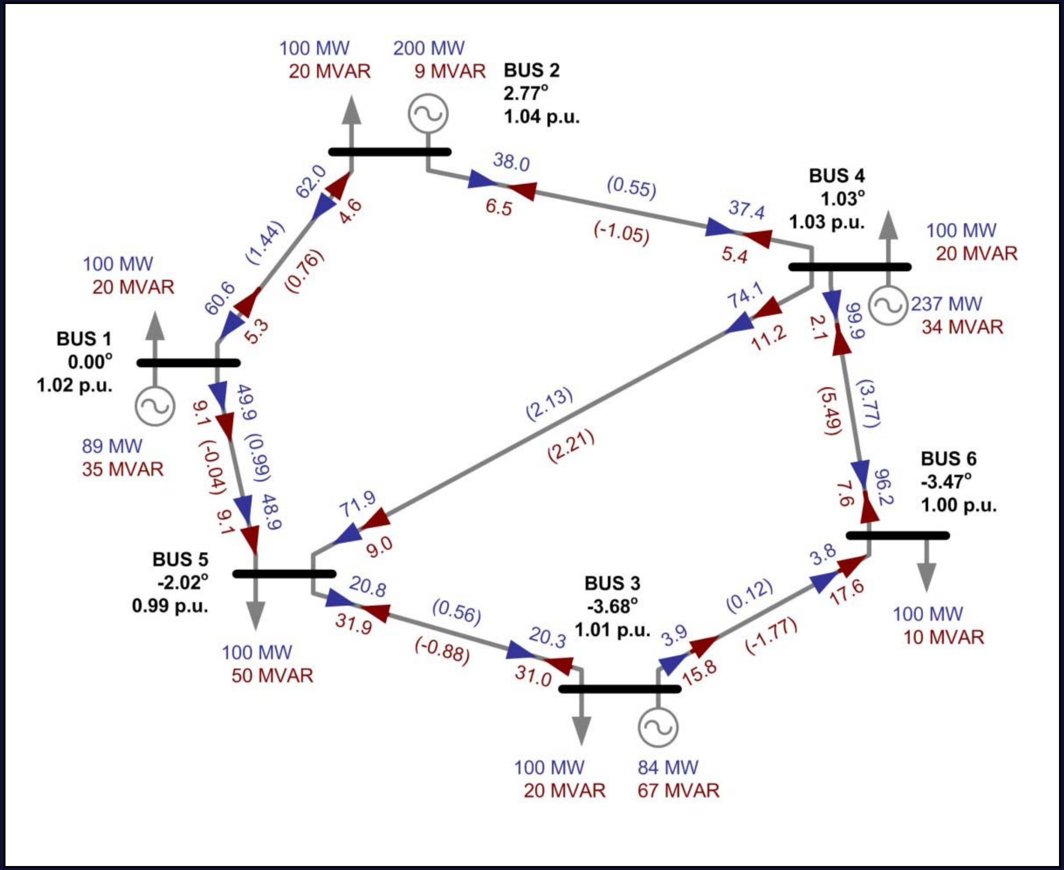


Fig. D1a: **Voltage phase angle differences in the UCTE system at 22:00 /ELES/**

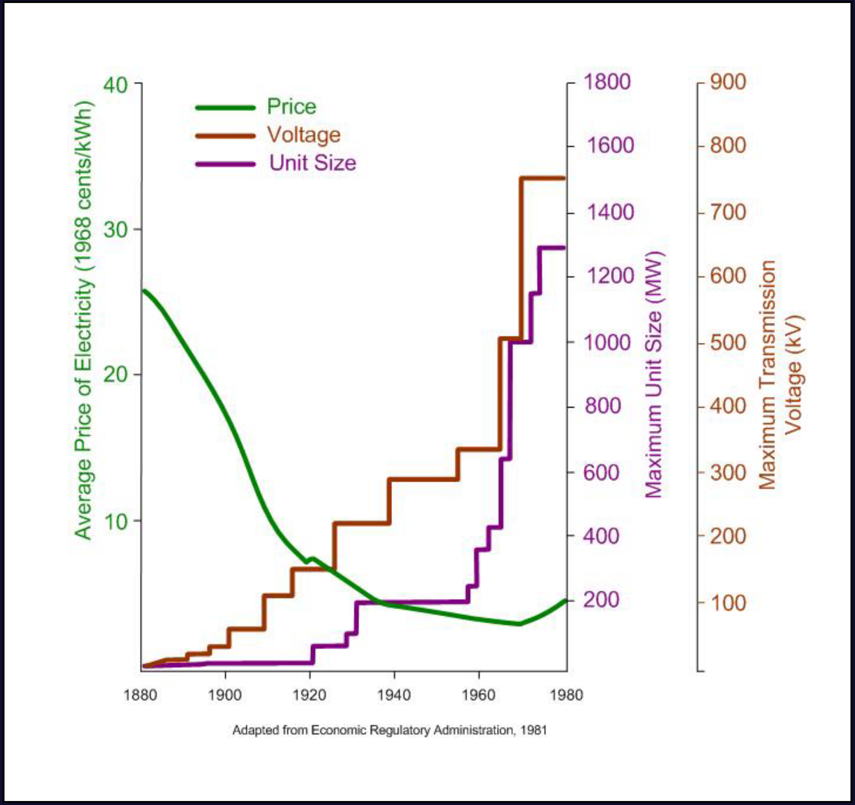


General Problem:

Line flows are subject to laws of physics, not politics or economics.

Historical changes in the electric power industry

Geographic expansion and greater regional interconnectivity:
"Bigger is better"



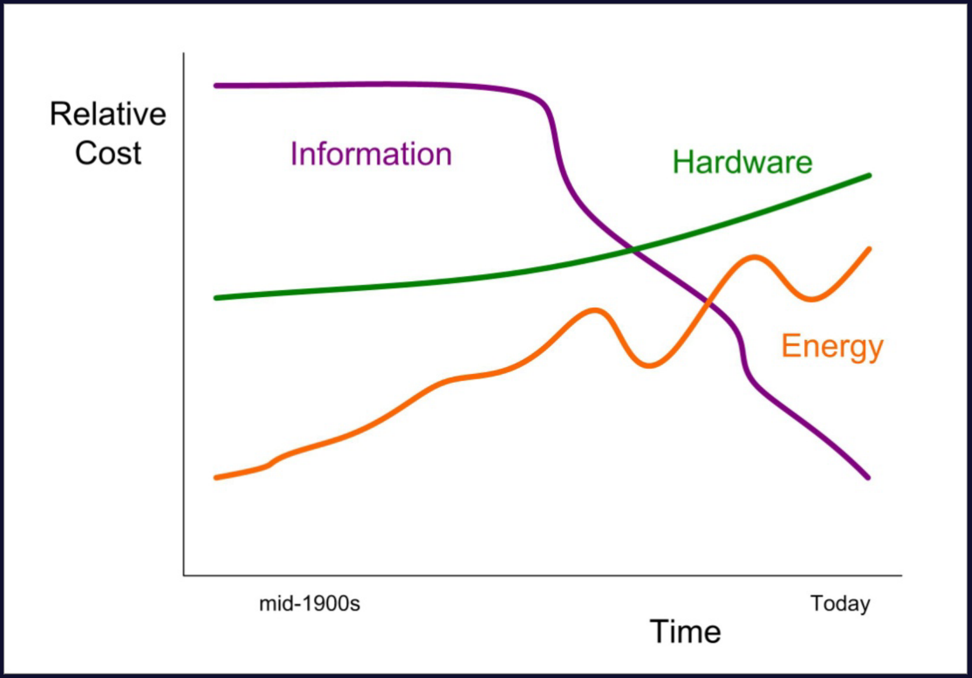
More recent historical changes

- Restructured market:

  Redefined economic objectives

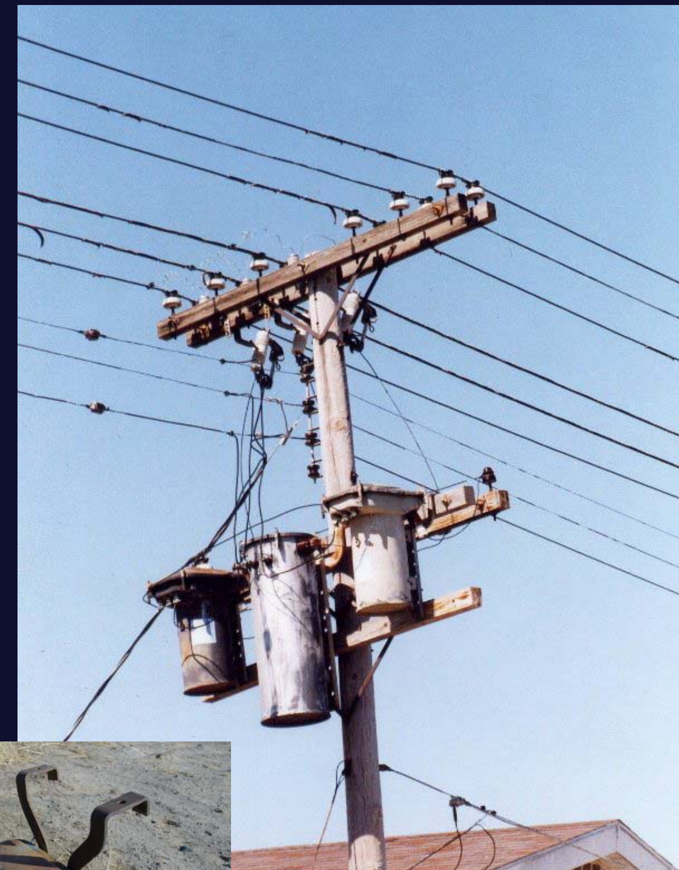
  Increased transaction volume

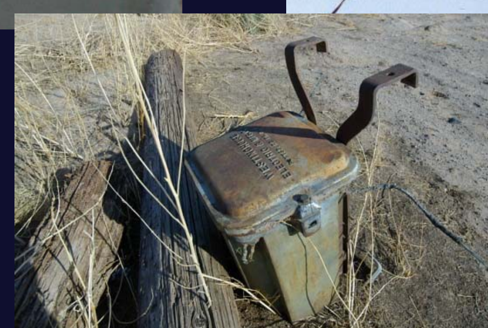
  Need for inter-organizational negotiation
- Demand no longer purely independent variable
- Size vs. smarts: Incentive for more refined control



Opportunities for refined control:

- Monitor the operating state at many nodes
  throughout T&D system
- Control real and reactive output of many small
  generators based on real-time grid conditions
  and availability of intermittent resources
- Control demand based on grid conditions
  (demand response)
- Flexible AC Transmission Systems (FACTS):
  Change effective transmission link impedance
  in real-time, using solid state devices





Some seasoned components of our $\$10^{12}$ infrastructure


upload in www.top81.cn
Grovers


upload in www.top81.cn
Hercul
U.P. CYCL
Marcus Forrell

Challenges for control operators in the "New World":

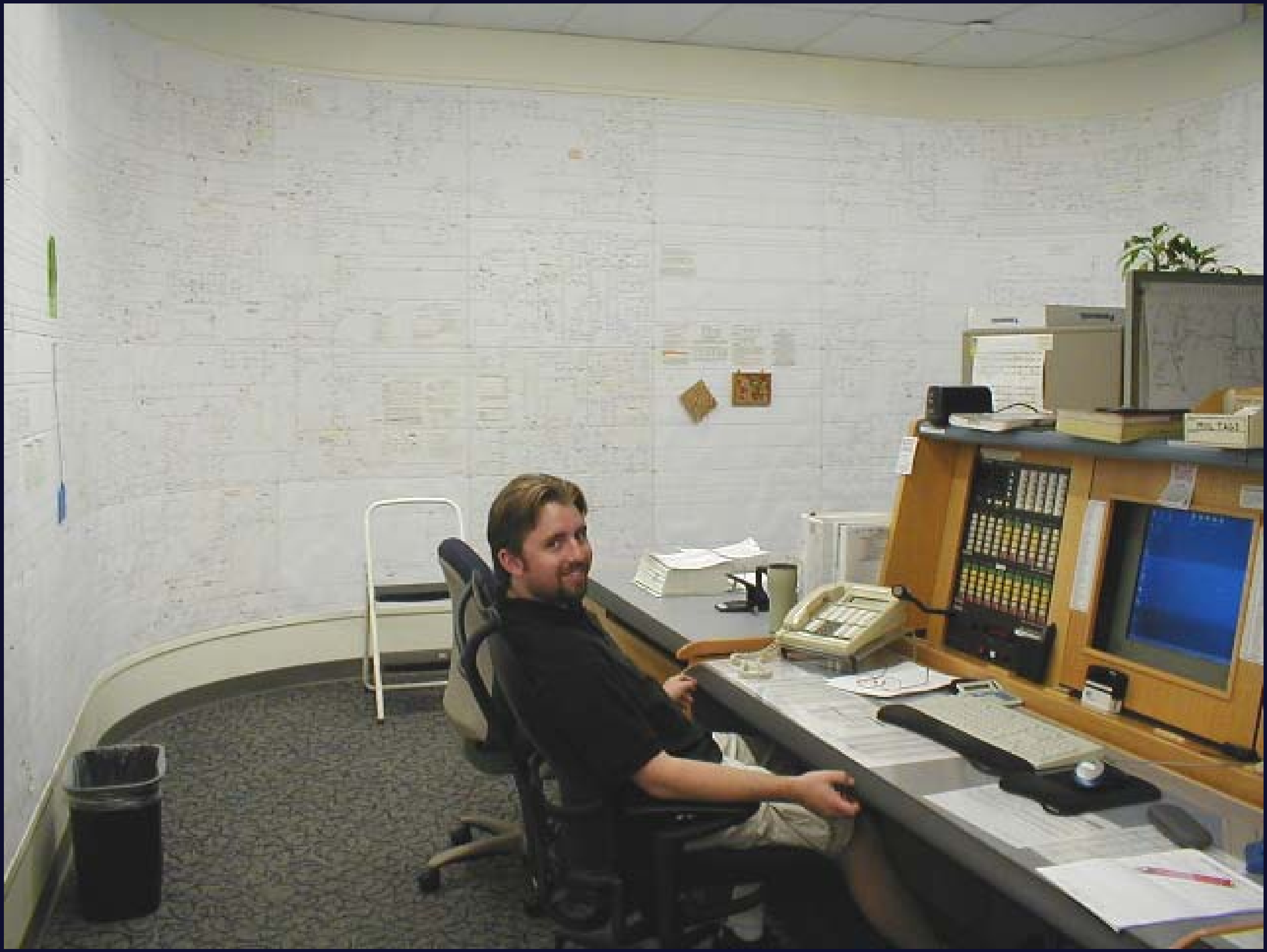
- Lower reserve margins, T&D capacity
- Competing pressures and objectives
- Information and transaction volume
- Cooperation, trust
- High stakes

Human Factors

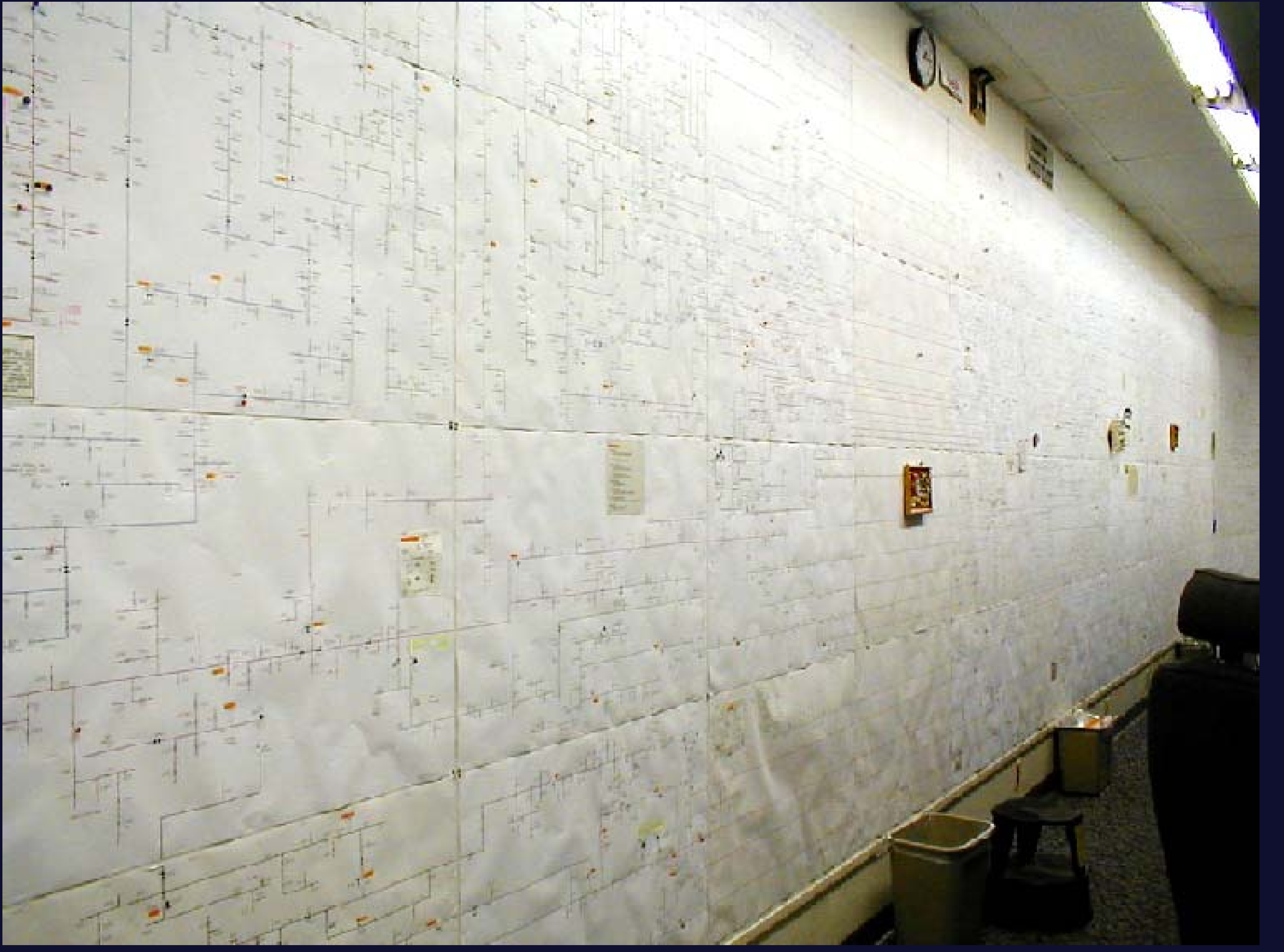
Engineers and Operators

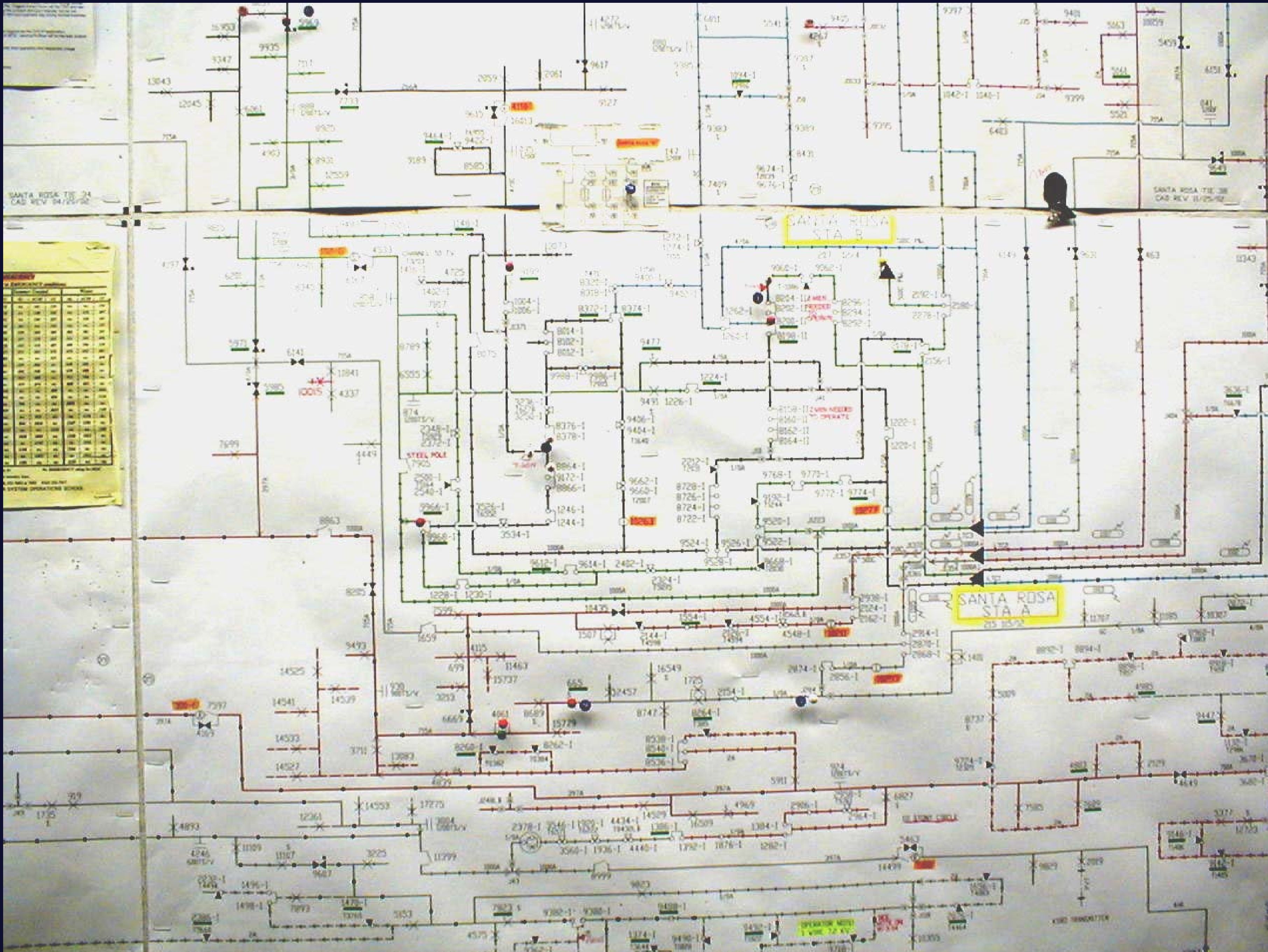
Different responsibilities, different cultures


HIGH

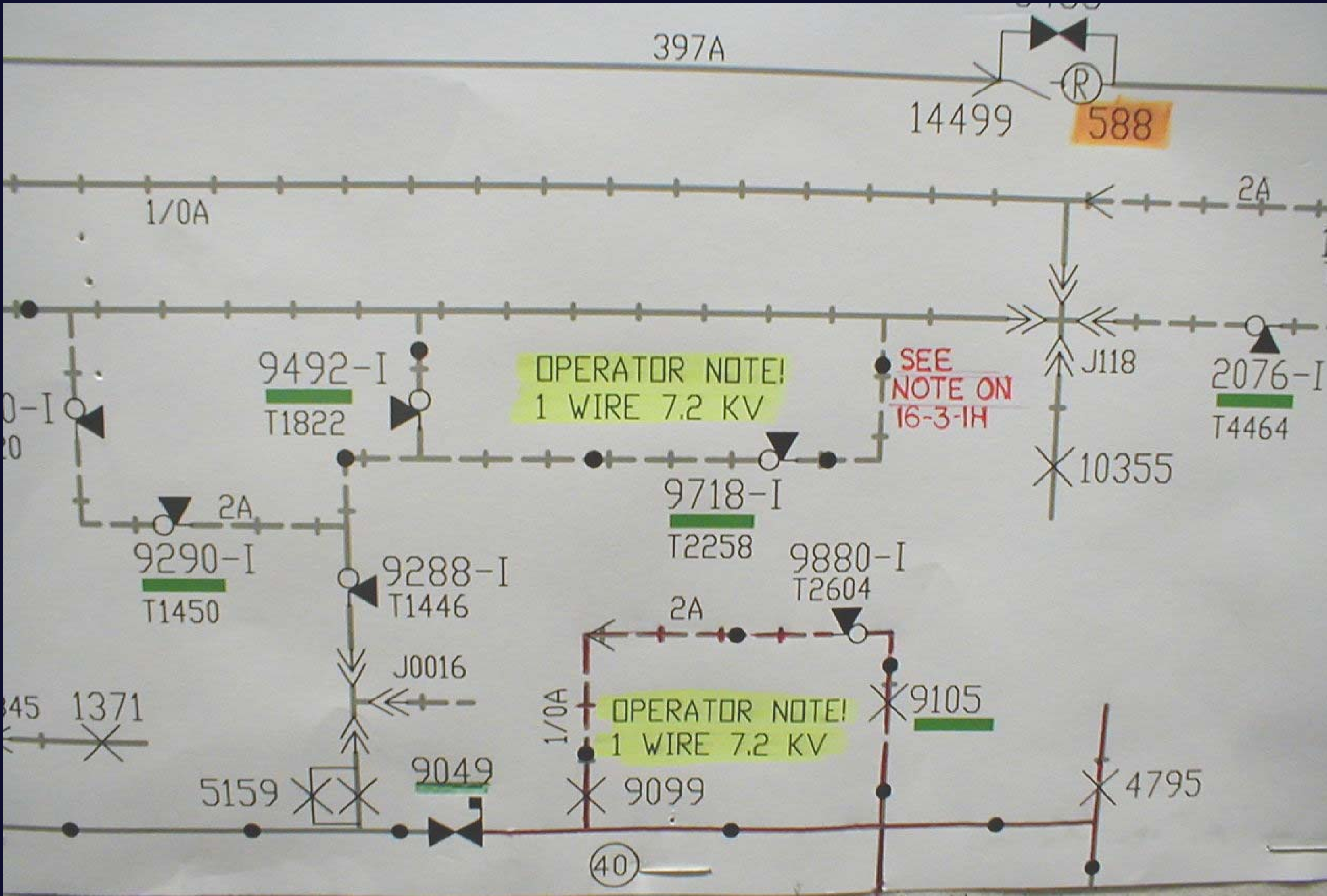


Regional Distribution Operator Desk & Wall Map

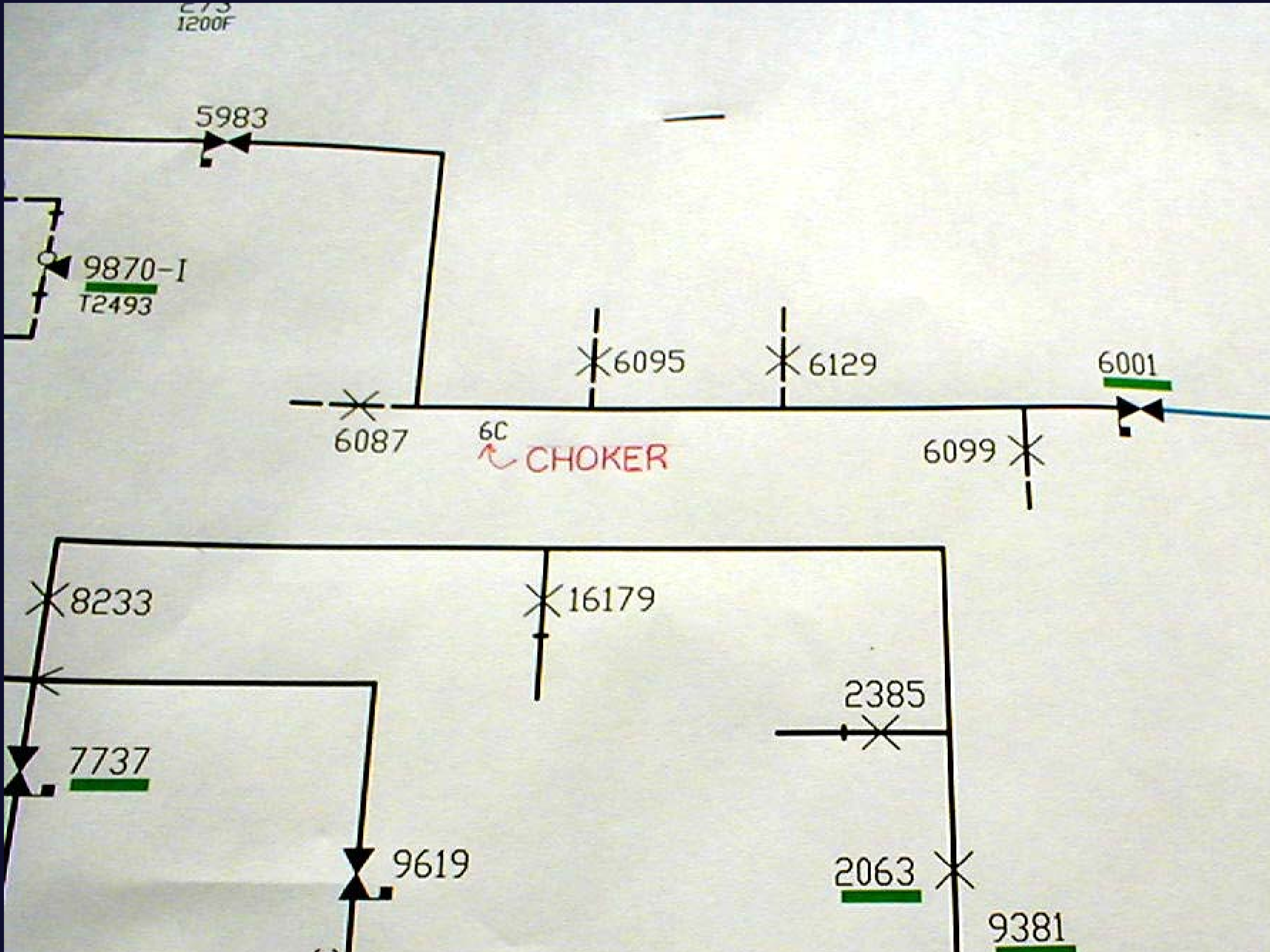


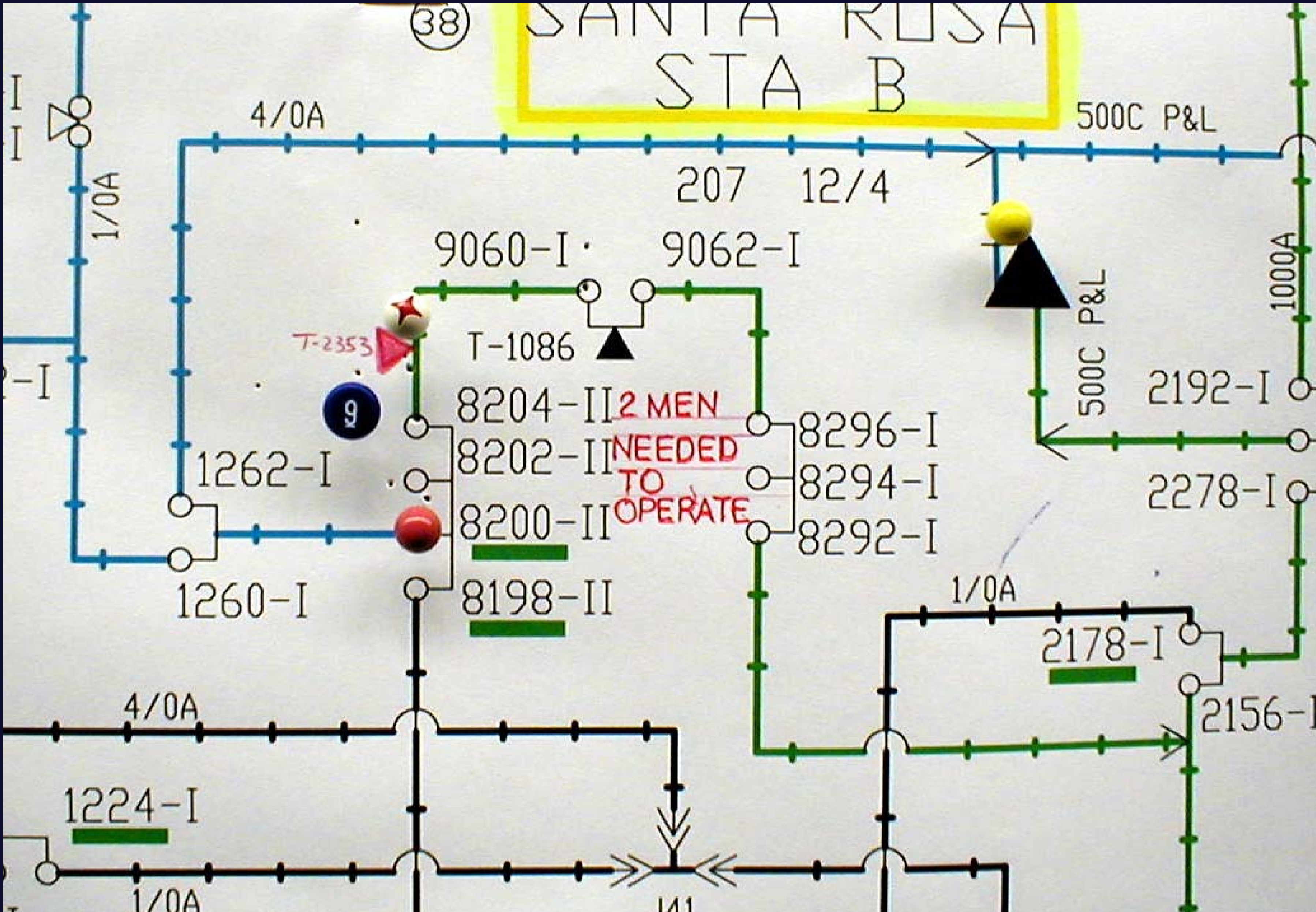


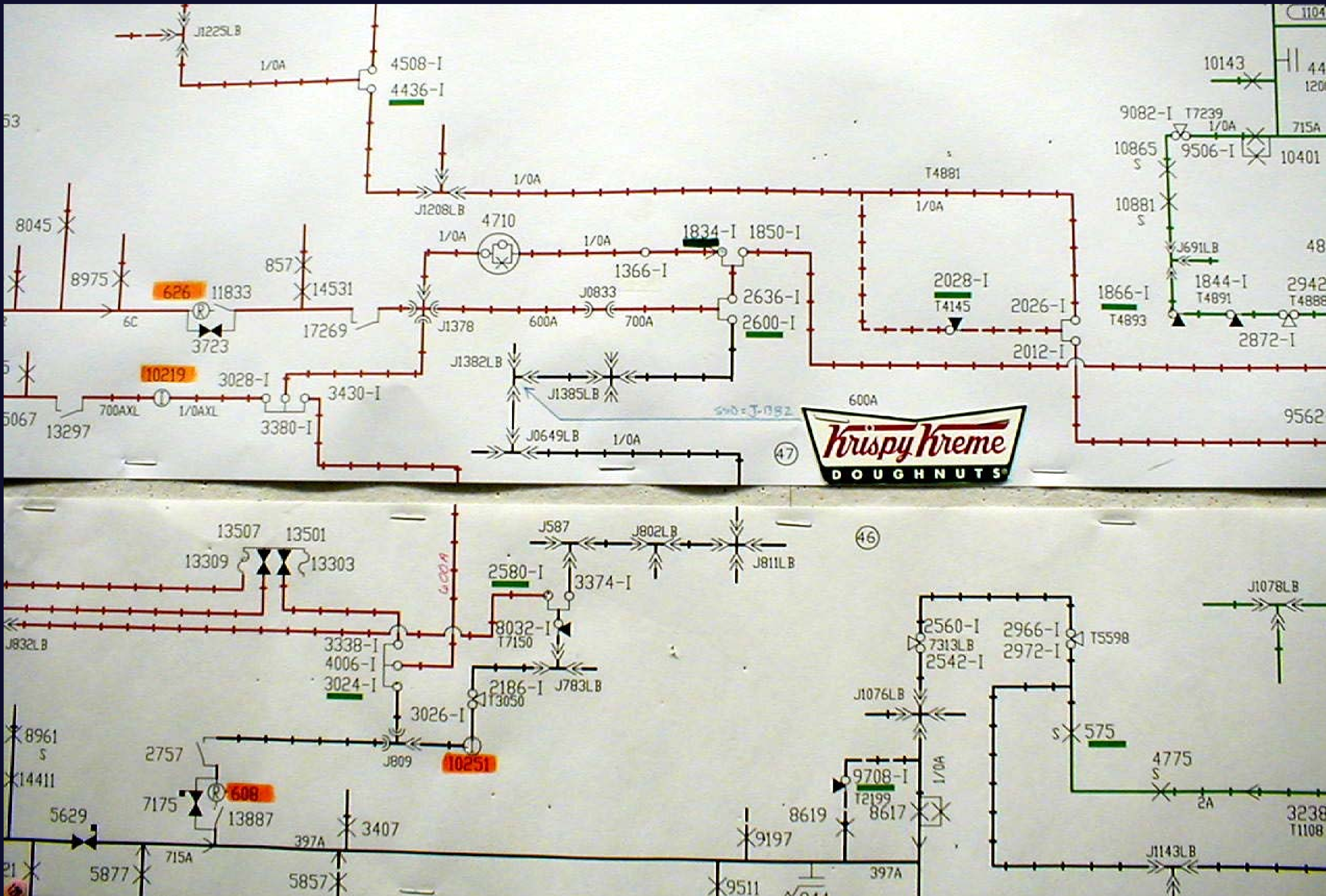
SANTA ROSA STA B
SANTA ROSA STA A
SANTA ROSA TIE 24
SANTA ROSA TIE 38
STEEL POLE
2 MEN NEEDED TO OPERATE



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


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


38
SANTA ROSA
STA B
4/0A
500C P&L
1/0A
207
12/4
9060-I
9062-I
1000A
T-2353
T-1086
P&L
500C
2192-I
2 MEN
NEEDED
TO
OPERATE
8204-II
8202-II
8200-II
8198-II
8296-I
8294-I
8292-I
9
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
1/0A
J1208LB
T4881
1/0A
8045
8975
857
14531
626
11833
6C
3723
17269
J1378
600A
J0833
700A
4710
1/0A
1366-I
1834-I
1850-I
2636-I
2600-I
2028-I
T4145
2026-I
2012-I
10219
3028-I
3430-I
700AXL
1/0AXL
13297
3380-I
J1382LB
J1385LB
J0649LB
1/0A
600A
47
Krispy Kreme
DOUGHNUTS
10143
9082-I
T7239
1/0A
715A
10865
9506-I
10401
10881
J691LB
1866-I
T4893
1844-I
T4891
2942-
T4888
2872-I
9562-
13507
13501
13309
13303
J832LB
J587
J802LB
J811LB
46
2580-I
3374-I
8032-I
T7150
3338-I
4006-I
3024-I
2186-I
T3050
J783LB
3026-I
J809
10251
8961
14411
2757
7175
608
13887
5629
715A
5877
397A
3407
5857
2560-I
7313LB
2542-I
2966-I
2972-I
T5598
J1078LB
J1076LB
575
4775
2A
3238-
T1108
9708-I
T2199
8619
8617
1/0A
9197
9511
944
397A
J1143LB

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:

- Abstract
- Analytical
- Formal
- Deterministic

Operator representation:

- Physical
- Holistic
- Empirical
- Fuzzy

Both are “correct” functional adaptations to work context.

Desirable system properties...

for Engineers:	for Operators:
Efficiency	Safety
Speed	Robustness
Information	Transparency
Precision	Veracity
Control	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 ideal range.

Scenario (ii)

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

Which is preferable?

Slides I thought I might use during Q&A

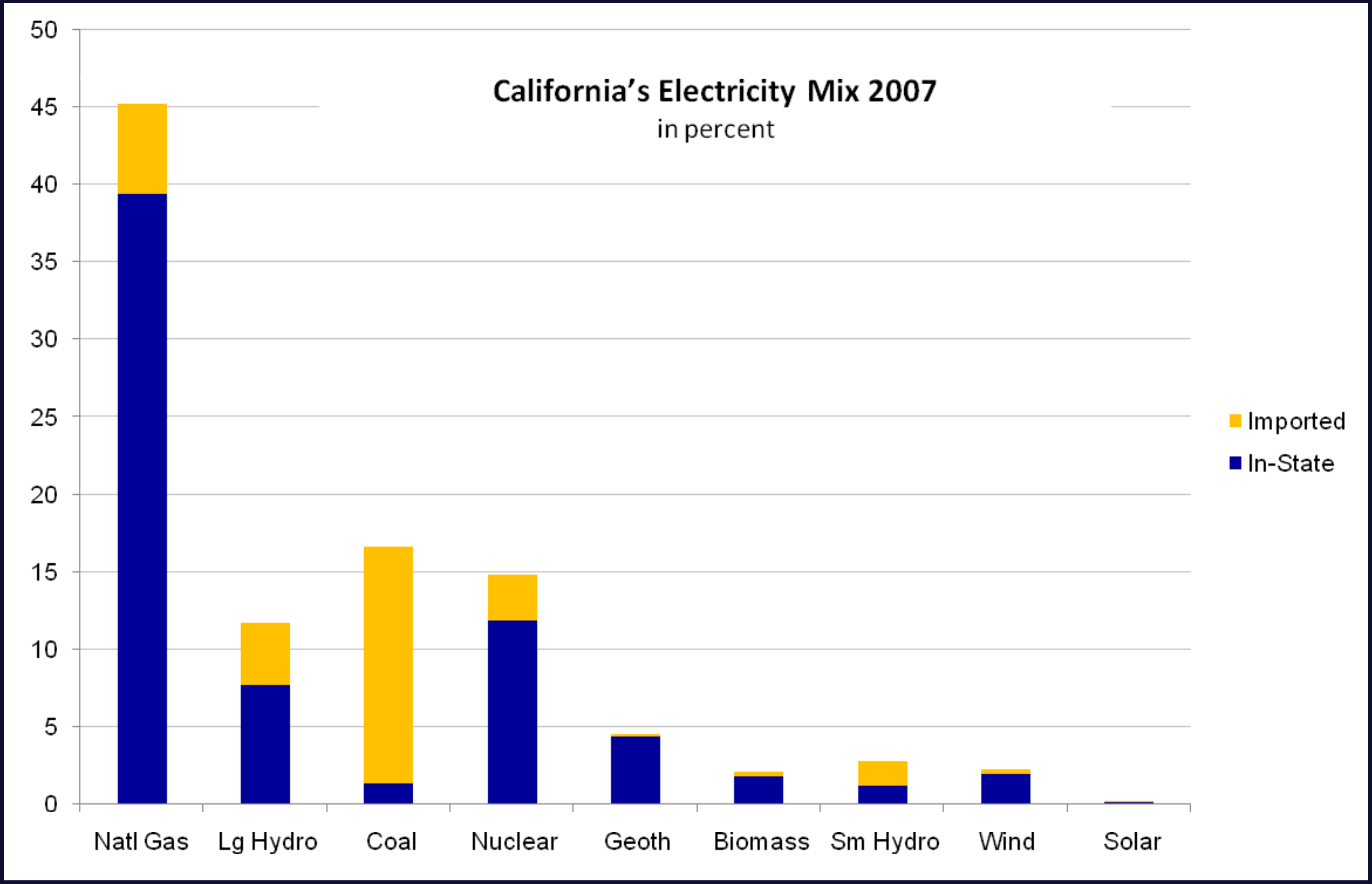
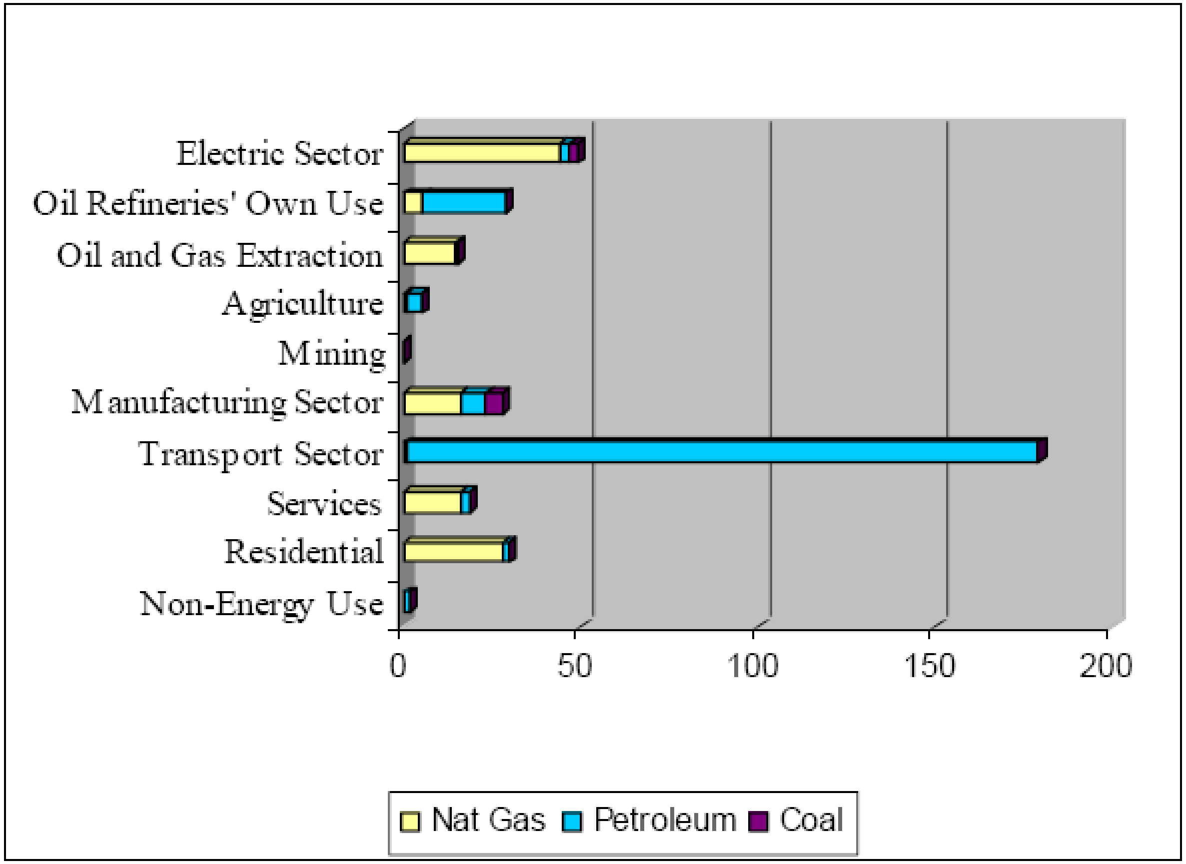
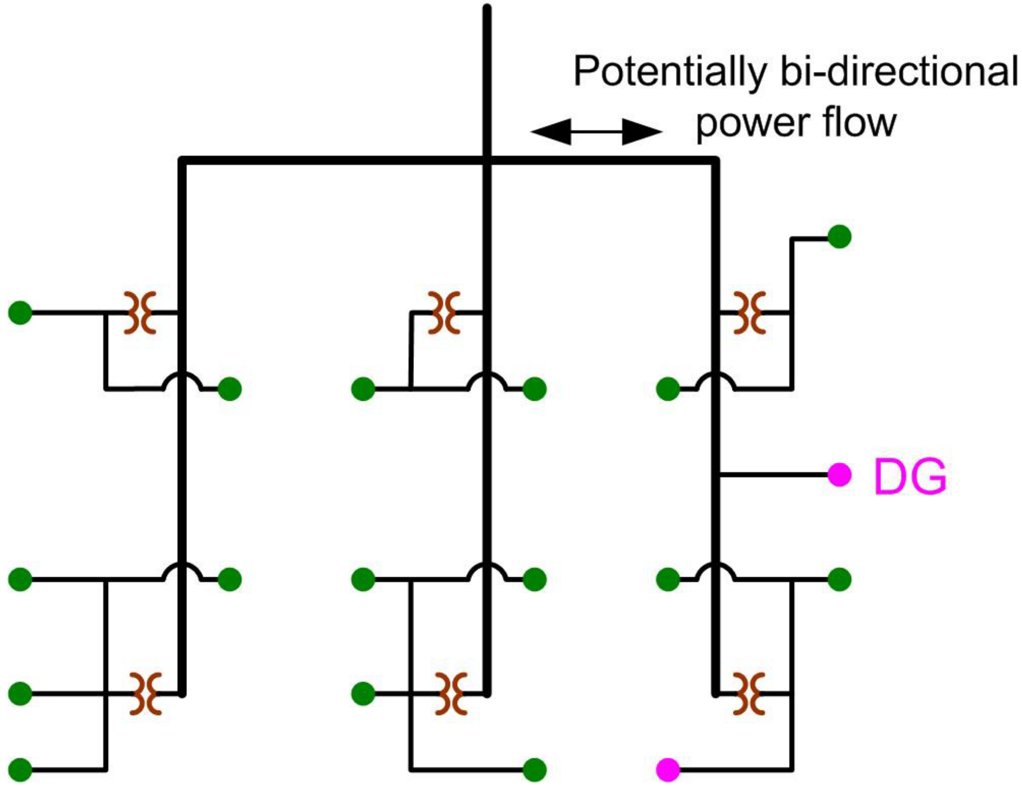

California’s Electricity Mix 2007
in percent
50
45
40
35
30
25
20
15
10
5
0
Natl Gas
Lg Hydro
Coal
Nuclear
Geoth
Biomass
Sm Hydro
Wind
Solar
Imported
In-State

Figure 5. CO_2 Emissions fuel combustion in California by fuel and sector in 2000, Mt CO_2



Distributed and intermittent resources

Radial Distribution System with Distributed Generation



System benefits of distributed generation

- Reduced line losses
- Local voltage/VAR control
- Avoided or deferred T&D capacity upgrades

- Islanding options

Integration of distributed and intermittent resources: a coordination challenge

Protection coordination:
bi-directional power flow in radial distribution systems

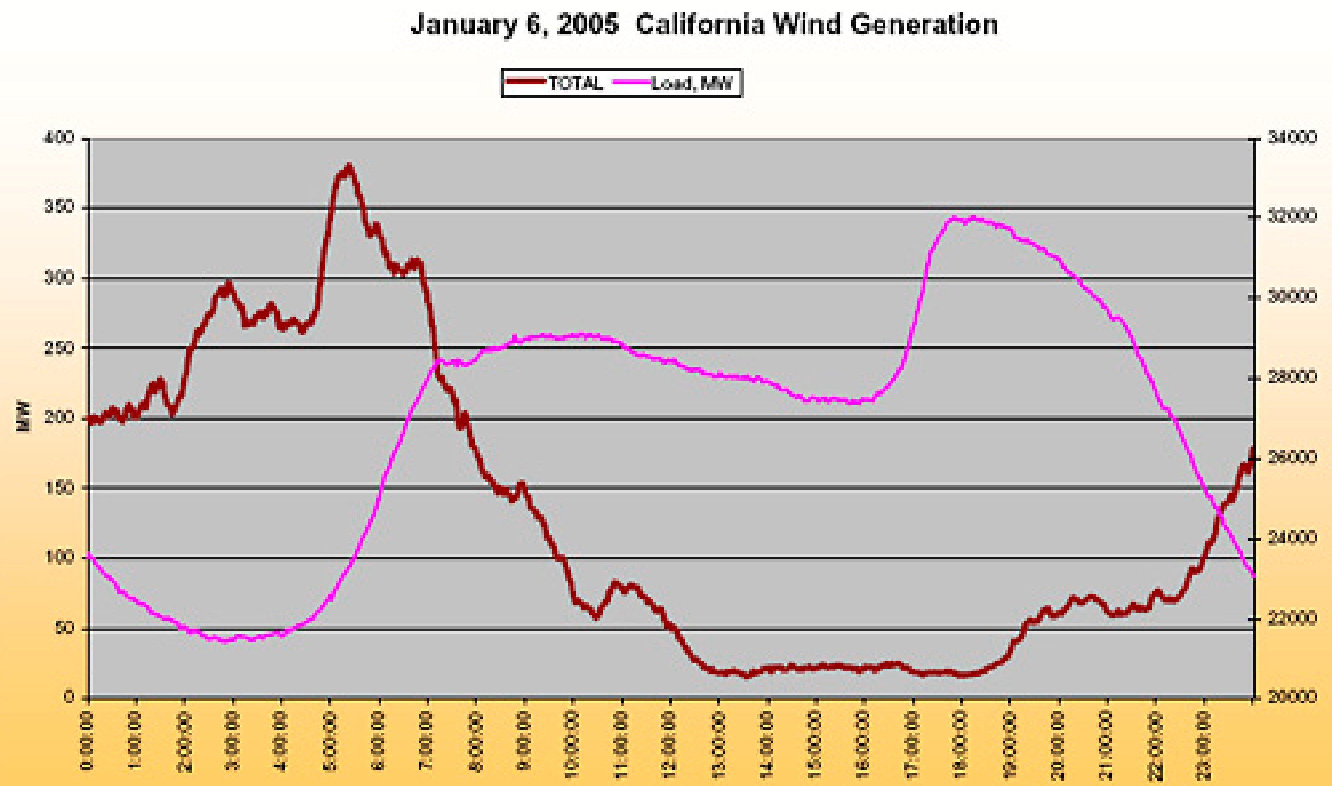
Temporal coordination:
seasonal, hourly and instantaneous dispatch
possible inclusion of energy storage (electrical, thermal)

Geographic coordination:
transmission resources, rights of way, system stability

CALIFORNIA ISO

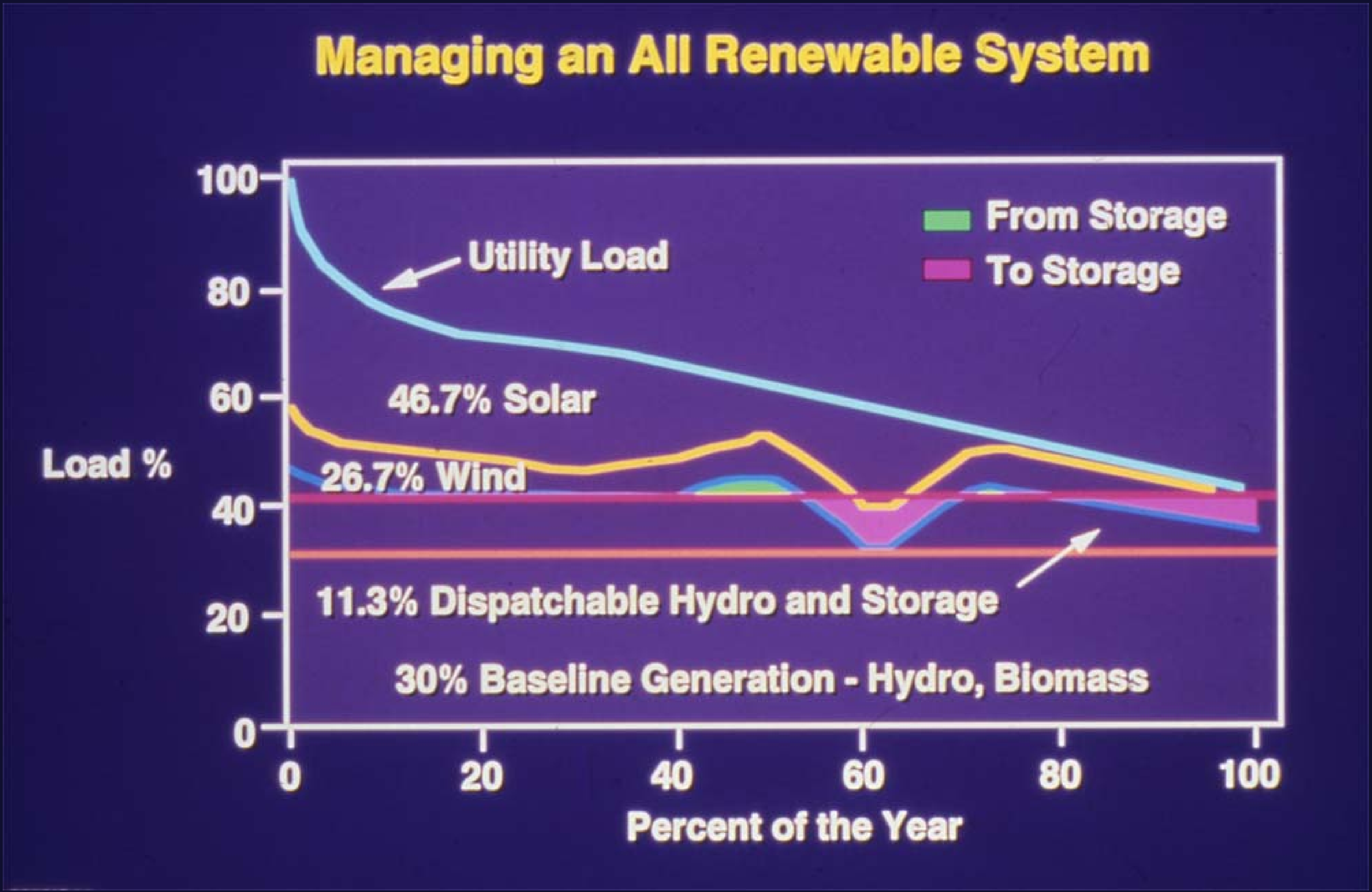
California Independent
System Operator

Wind Generation And System Load Have Different Daily Patterns



Created By: Yuri Makarov

LST UPDT: 3/22/2005

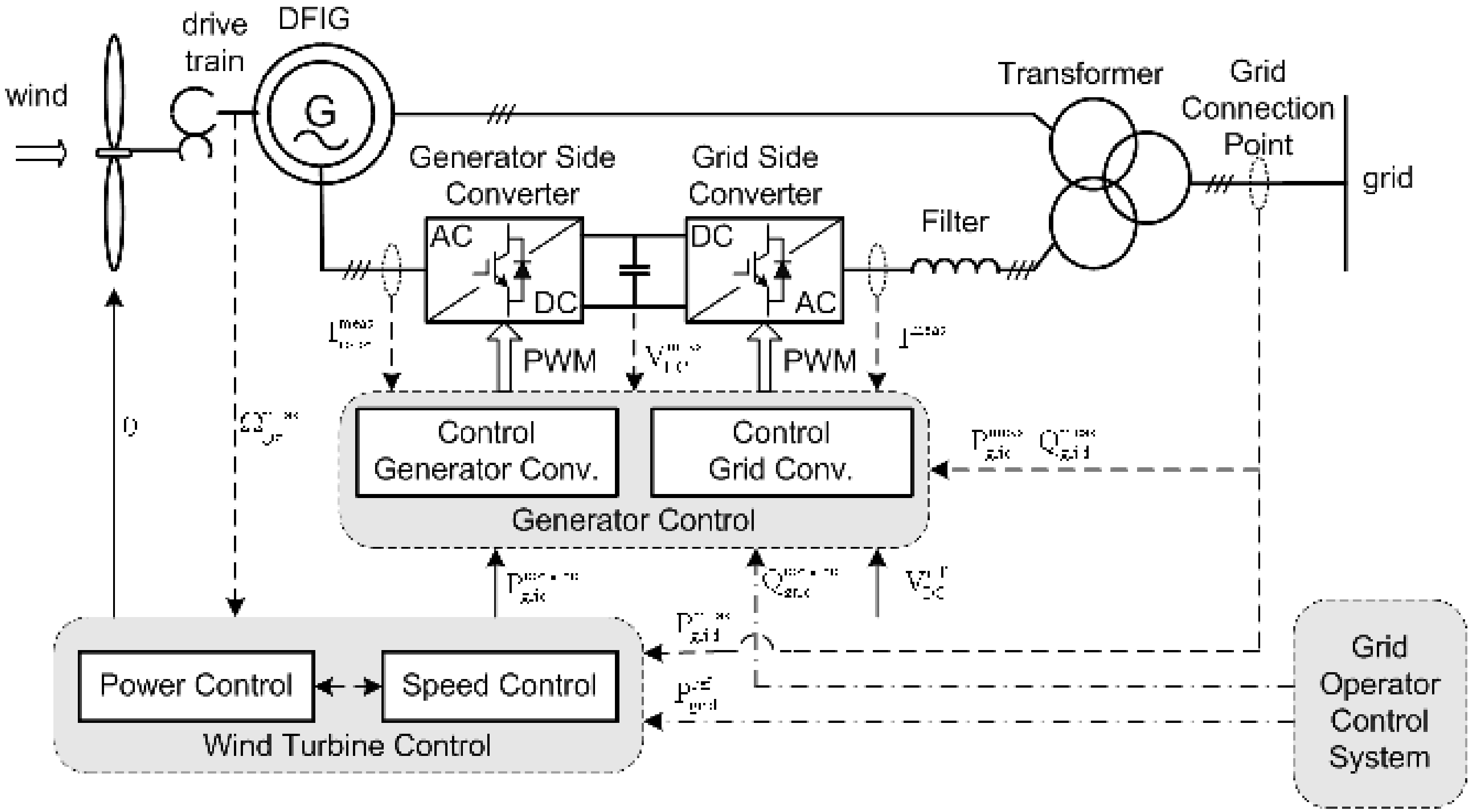


Pacific Gas & Electric, 1989

Kramer Junction, CA circa 1990


Vestas 1.8 MW 260’ height, 135’ radius

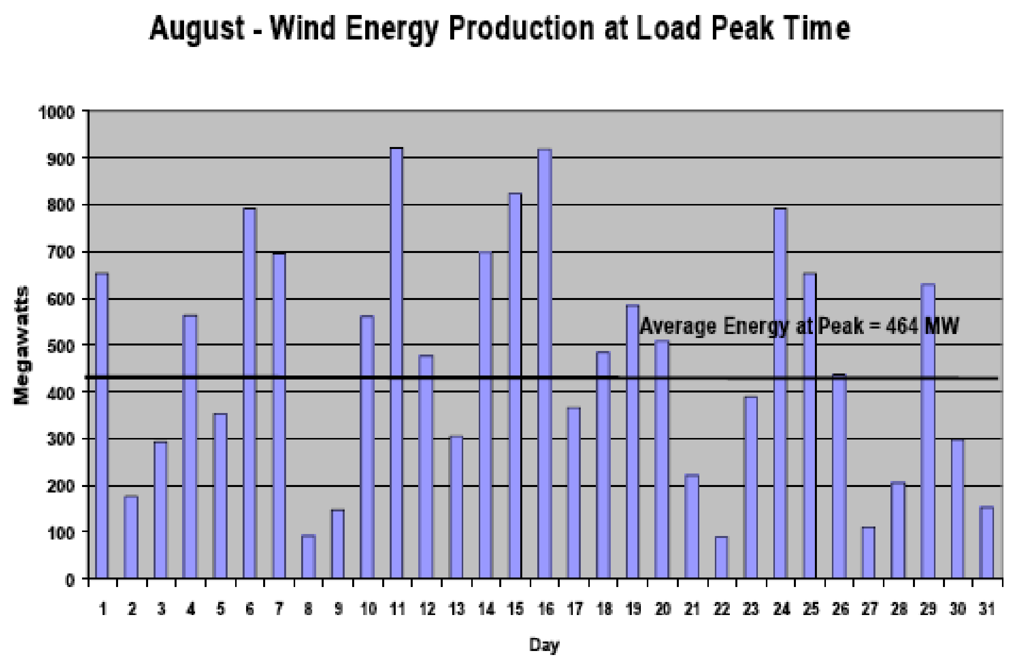
Doubly-fed induction generator



Advanced wind generator control system

Institute of Energy Technology, Aalborg University, Denmark

Appendix B – Continued



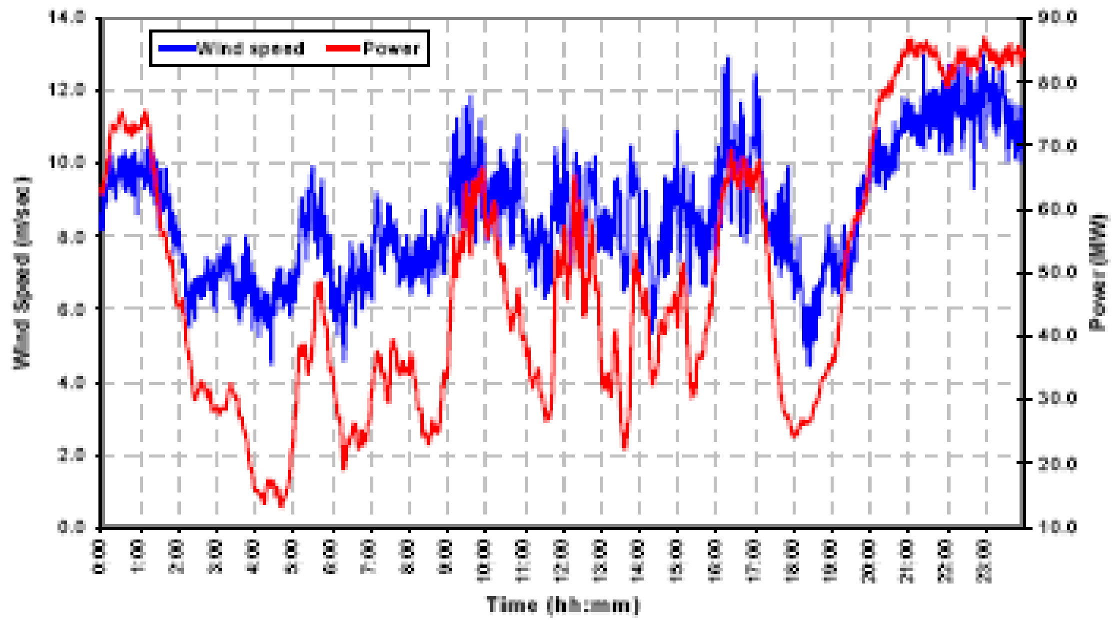


Figure 5. 1-minute average power and wind speed

SW Minnesota wind data, National Renewable Resource Laboratory:

Wind Power Plant Behaviors: Analyses of Long-Term Wind Power Data (2004)

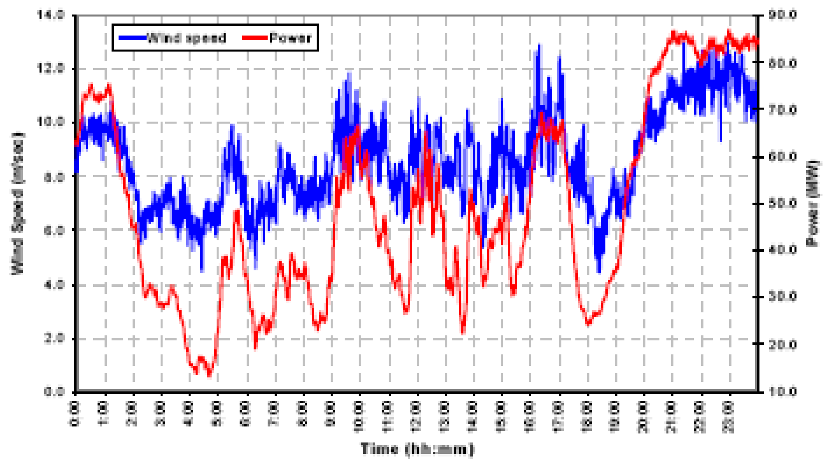


Figure 5. 1-minute average power and wind speed

Short-term variability of power output, NREL study case:

Installed capacity ≈ 100 MW, typical output ≈ 50 MW

1-second variations maximally 320 kW, but typically closer to 100 kW

→ variations around 1-2% of output (not too dramatic)

Short-term variability smoothed by aggregation over large wind farm