The Voltage Ledge

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California ISO

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About Pterra Consulting

- A transmission and distribution analysis consulting firm
  - Based in Albany, NY
  - Started in 2004
- Services
  - Technical analysis, studies and assessments
  - Expert witness
  - Staff support
  - NERC Compliance
- Training
  - Courses on power system topics
- For more info, please visit us on the web:

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Objectives

- Review the nature of Voltage Collapse and some examples
- Review a Case Study of the Voltage Ledge
- Define the Voltage Ledge and identify relevant phenomena in
  - Transmission System
  - Distribution System
- Identify response strategies from a Voltage Ledge

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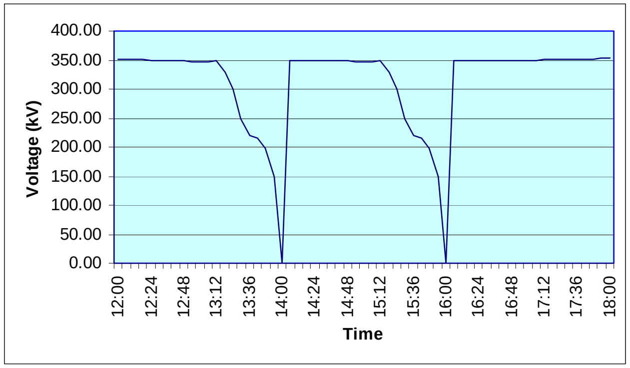
Voltage Collapse

- The sudden and precipitous collapse of voltage that occurs typically some minutes after equilibrium has been lost due to a voltage instability.
  - **Fast** collapse occurs within the transient period
  - **Slow** collapse occurs within the post-transient period or later



The Voltage Ledge

- What is it?
  - An equilibrium state, relatively stable, where voltages are below normal operating levels
  - As voltages drop towards collapse, systems may reach this mode, a “ledge” prior to or preventing freefall
  - Systems may operate “on the Ledge” for periods lasting seconds to minutes, and occasionally, hours

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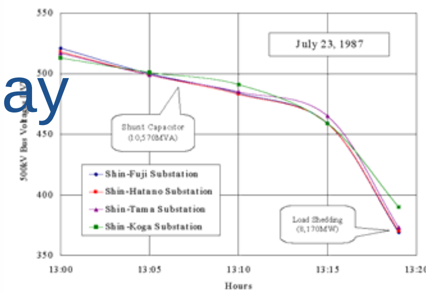
Selected System Events

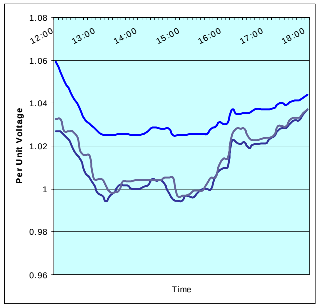
- Tokyo, Japan – July 23, 1987
  - Rapid increase in load during the day
  - Leads to dropping voltage on EHV
  - 8000+ MW of load shed



- Miami, Florida – Aug 18, 1988
  - Three phase fault
  - Slow voltage recovery
  - Loss of Load
- Southern California – Aug 5, 1997
  - Small plane hits shield wires
  - Voltage dips to 0.6 at distribution level
  - High air conditioning load

More System Events

- Atlanta, Georgia – July 30, 1999
  - Short circuit in substation
  - Slow voltage recovery
  - 5 generators trip, 1900 MW load shed



- New Jersey – July 6, 1999
  - Record heat wave
  - Voltage on EHV goes below 1.0 p.u.
  - Insulation failures in distribution networks
- Eastern Seaboard – Aug 13, 2003
  - Line contacts tree
  - Cascading outages
  - Wide spread outages

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Common Factors to these Events

- Voltages stayed at a low level for seconds to minutes prior to collapse or recovery
- Affected urban areas
- Occurred in summer, with high levels of air conditioning loads

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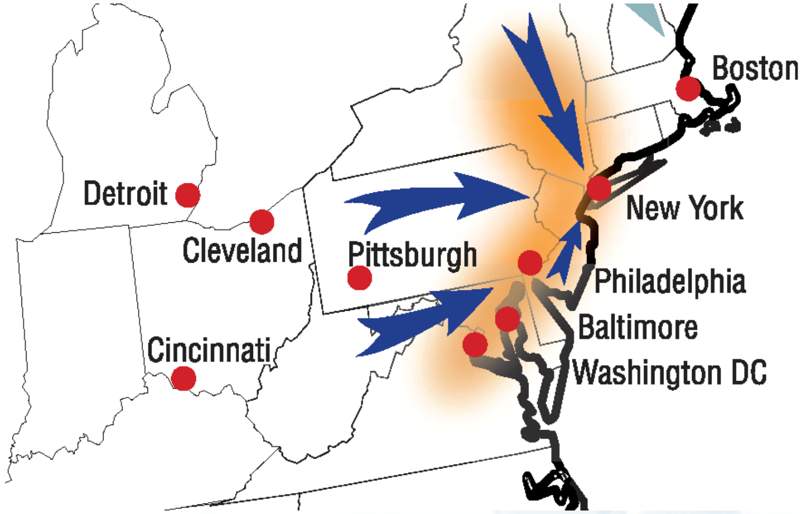
A Closer Look at 1 Event

- First 2 weeks of July 1999 in the Northeast US
- Above average temperatures
- Record system demand
  - With large air conditioning component
- Large power transfers into Eastern Seaboard



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July 1999 Event

- Observations
  - In New England
    - Many generating units were out on maintenance or for re-fueling
    - This was in preparation for the typical peak load in late July, early August
  - New York City
    - Heat related failures in connections, cables and transformers
  - In Long Island
    - Incipient voltage collapse in the South Fork area
    - Some overloaded wires burned down
    - Requested voluntary customer reduction and responded to 5% voltage reduction

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July 1999 Event

- Observations
  - Atlantic Coast Section of PJM
    - Experienced steep voltage declines in 500 kV system on two occasions
    - First time 500 kV voltage went below 1.0 per unit
  - In New Jersey
    - Terminator and cable failures in 3 transformers causes shutdown of City Dock substation
    - At Red Bank substation, 2 transformers fail leading to disconnection of 100,000 customers
    - Over a thousand failed poletop transformers
  - In the Delmarva Peninsula
    - Capacity deficiency in local generation
    - System operator reports impending voltage collapse

Questions about the July 1999 Event

- There was no voltage collapse - why?
- Transmission voltages were depressed for 2-2½ hours – how?
- Impacted distribution system more than the transmission system – reasons?
- Which operator or other actions allowed the system to recover to normal operations?

Transmission System Phenomena

- While demand is rising …
  - Increased usage of transmission system
    - Transmission lines change from supplying VARs to absorbing VARs
  - Generators delivering VARs approach reactive limits
    - Transient and steady-state capability
  - Static VAR devices reach limit

Transmission Line Reactive Characteristic

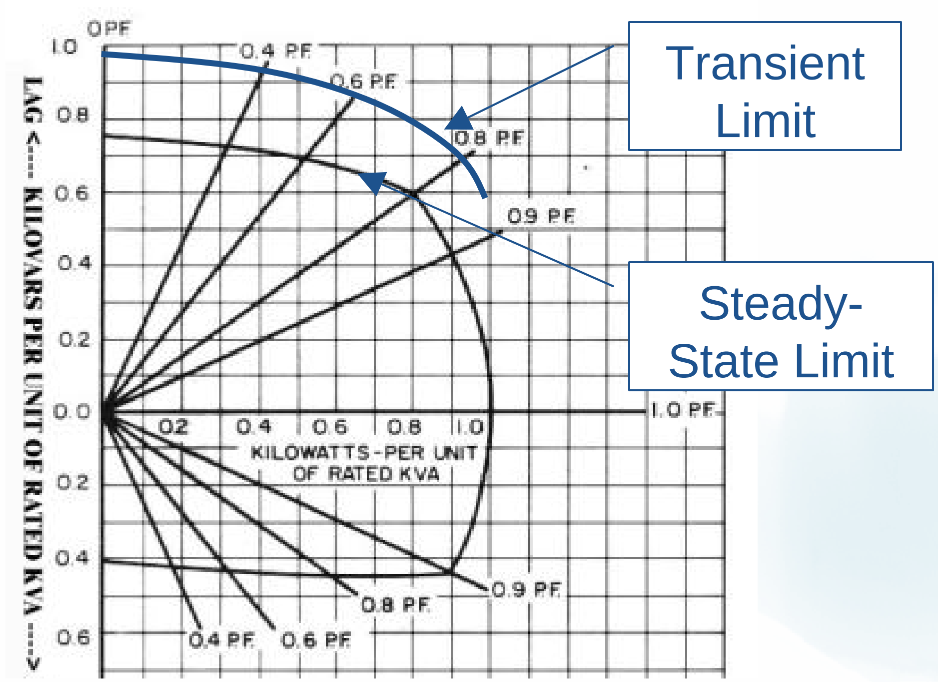
- Sample Transmission Usage

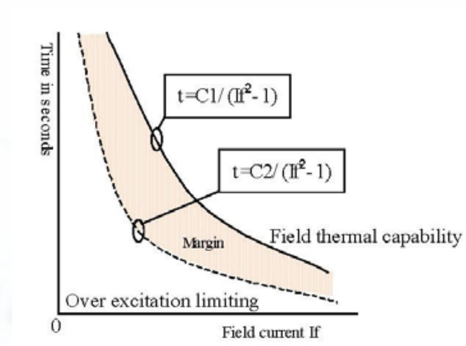
	MW	MVAR
Light Load	200	80
Natural Load	450	0
Rate A	900	-300
High Load	1200	-600

- Reactive Losses increase

Generator Reactive Response

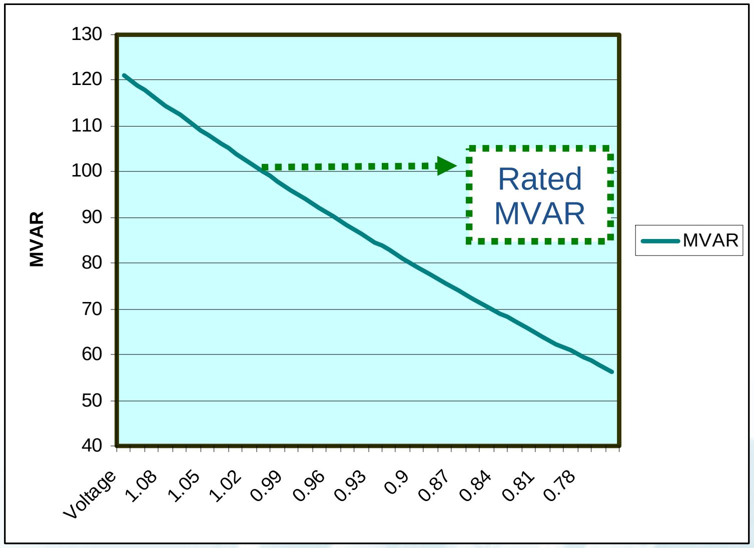
- Generator reactive capability
  - Steady-state – reactive capability decreases as MW output increases
  - Transient – available for durations of seconds to minutes





Static VAR Devices

- Reactive power from static var devices *operating at limit* change as the square of voltage
  - Capacitor banks
  - SVCs



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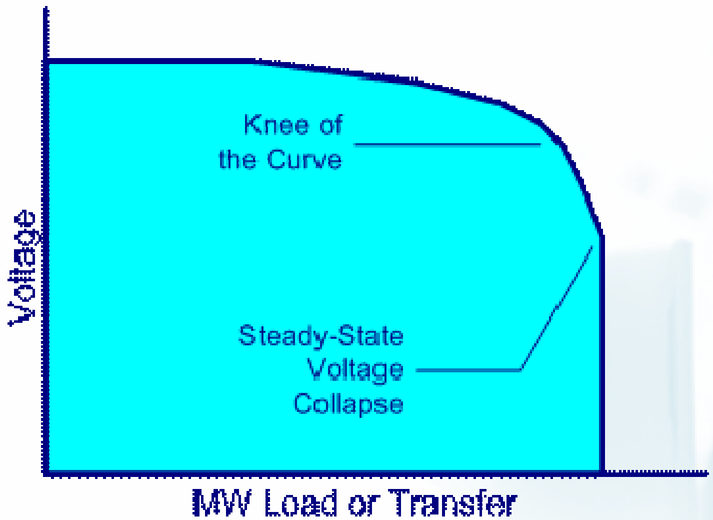
P-V Curves

- P-V curves are a method to identify dropping voltage as a function of load or transfer --- from the transmission POV



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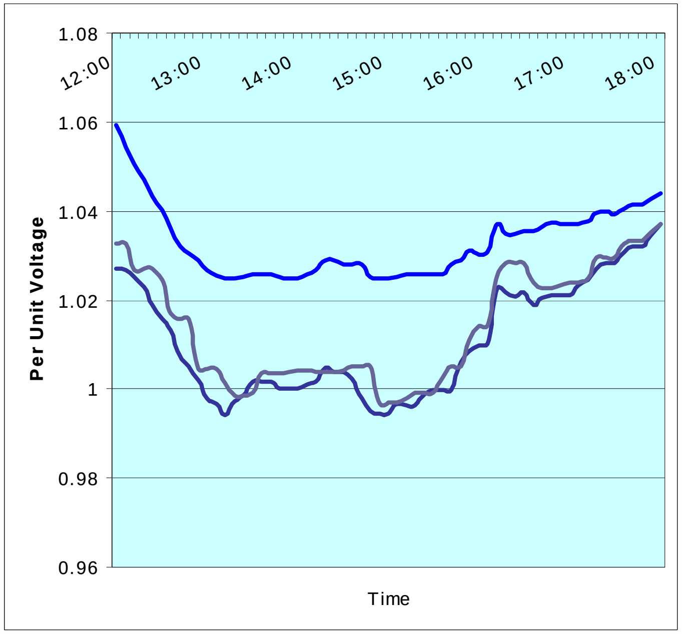
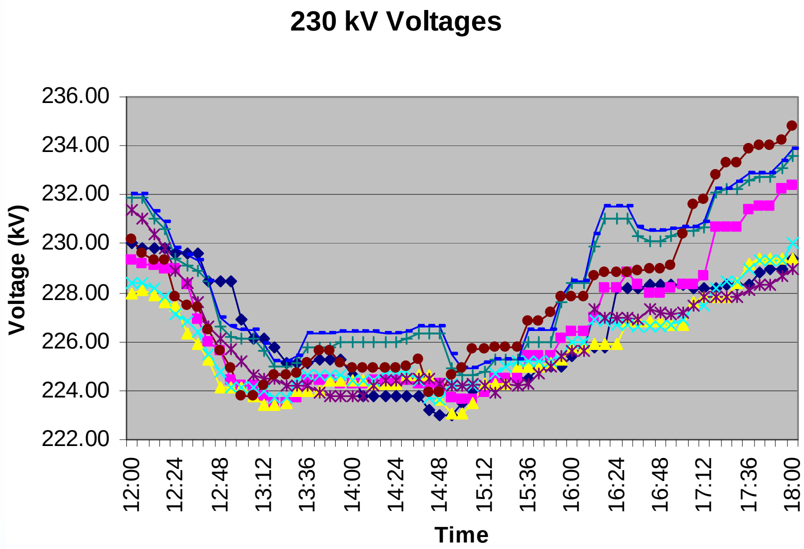
July 1999 Event

500 kV voltages





Voltages were depressed for 2-2.5 hours

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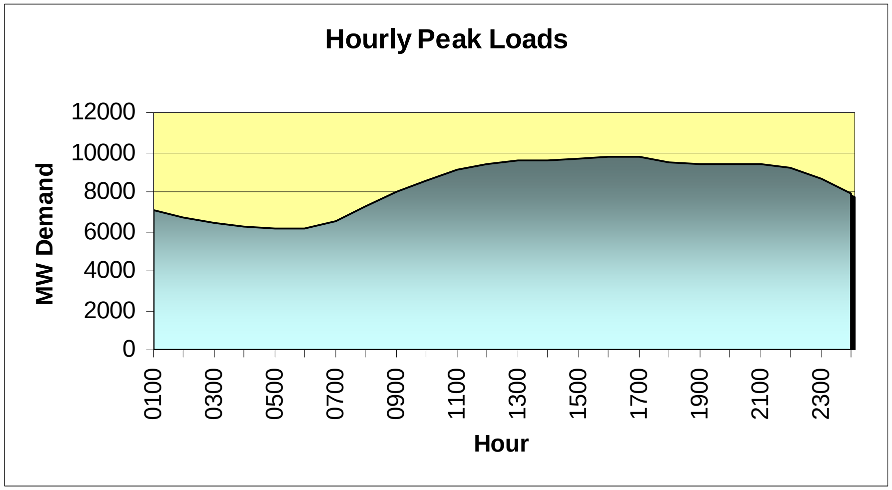
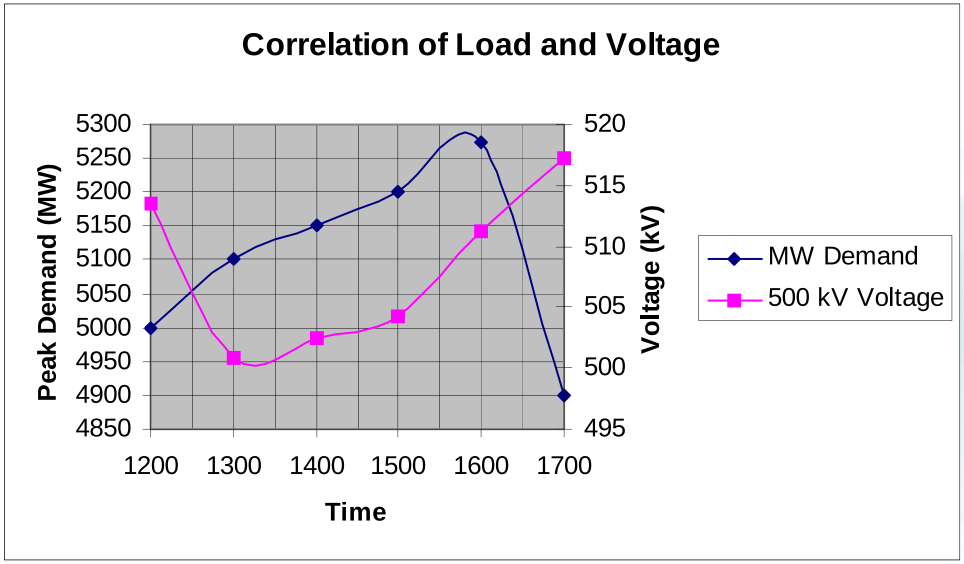
July 1999 Event

Normal daily load rise





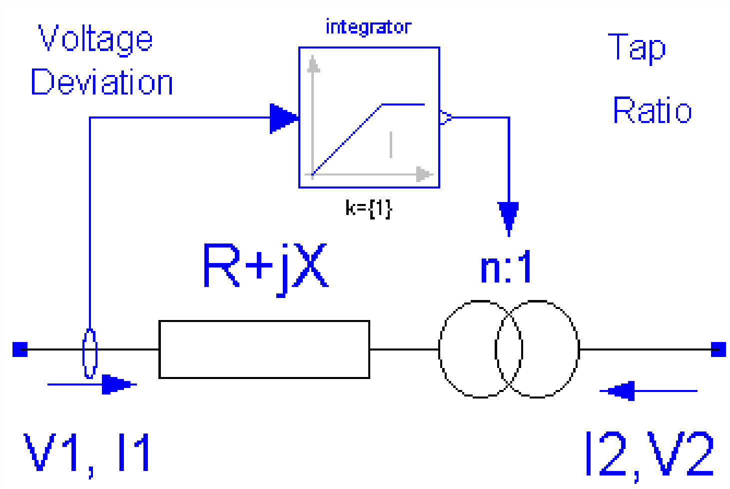
Voltages recover
while load
was still rising

Distribution System Phenomena

- As voltage drops on the transmission side …
  - Tap-changing transformers boost voltage on the secondary side
  - Capacitors switch in to maintain feeder voltages
  - Loads are initially oblivious …

Distribution Transformers

- Are set to maintain a certain voltage on the customer (low voltage) side
- Taps adjust automatically to maintain setpoint voltage



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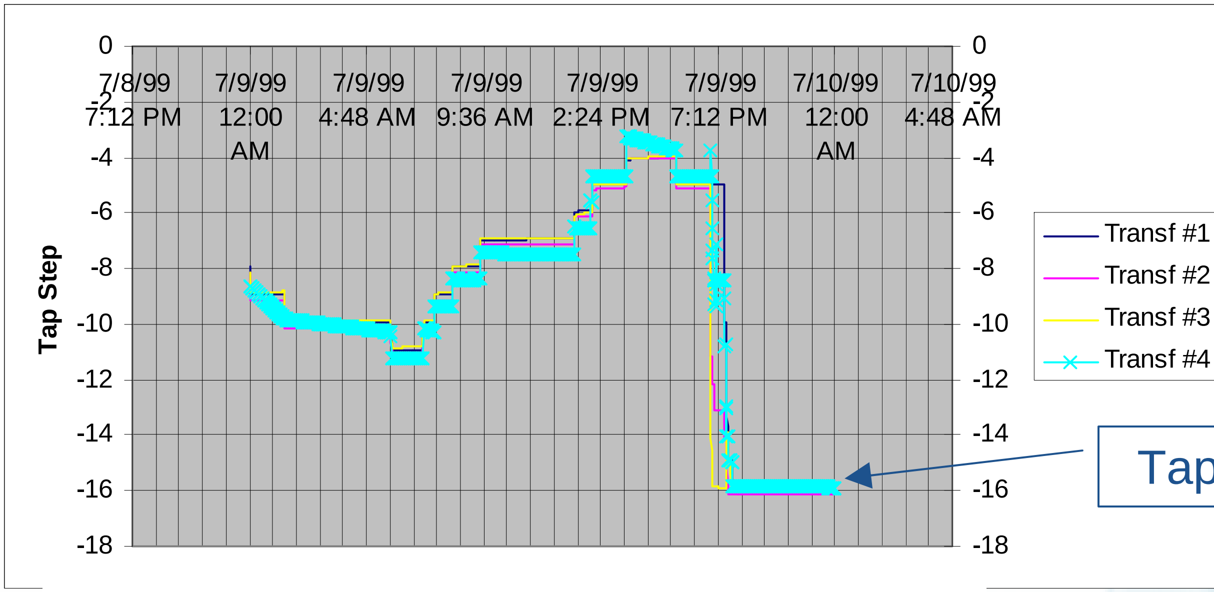
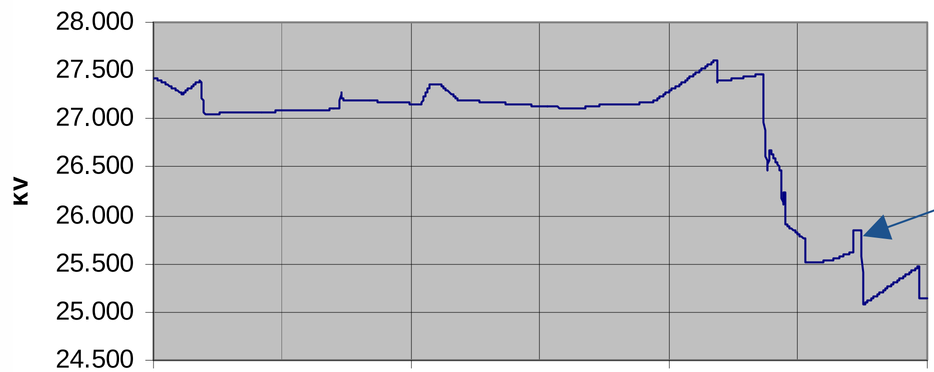
Distribution Transformers



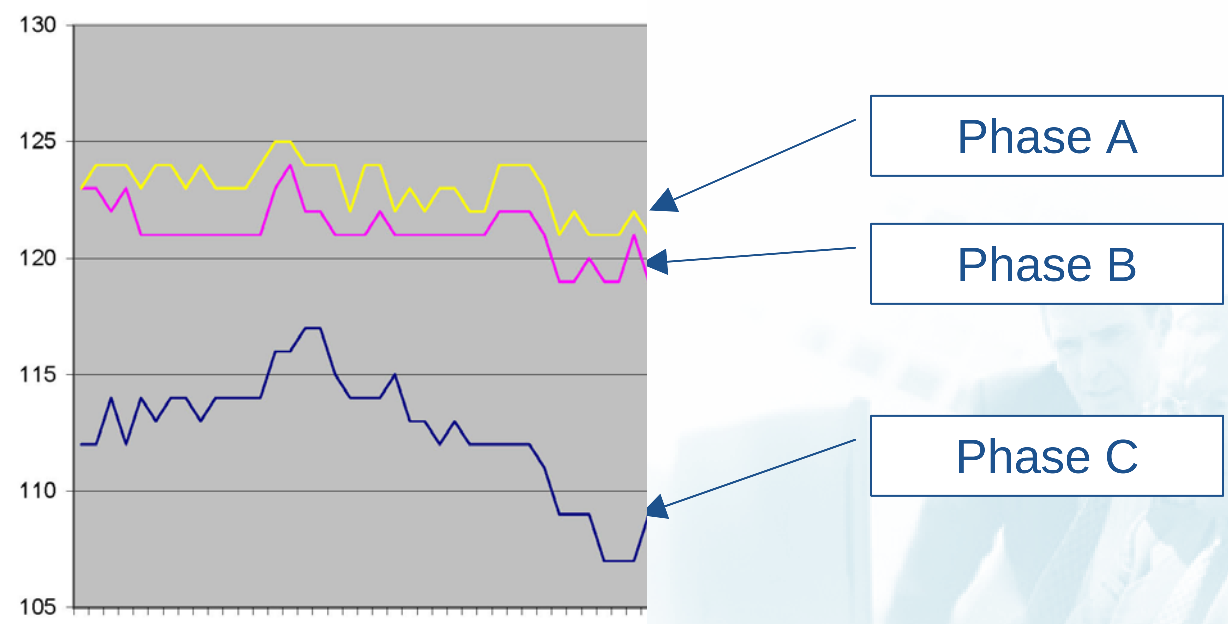
Taps at Limit



Dropping Voltage

Voltage Drop in The Secondary

- Imbalance in the 3 phases results in larger drop in weaker phase



Distribution Loads

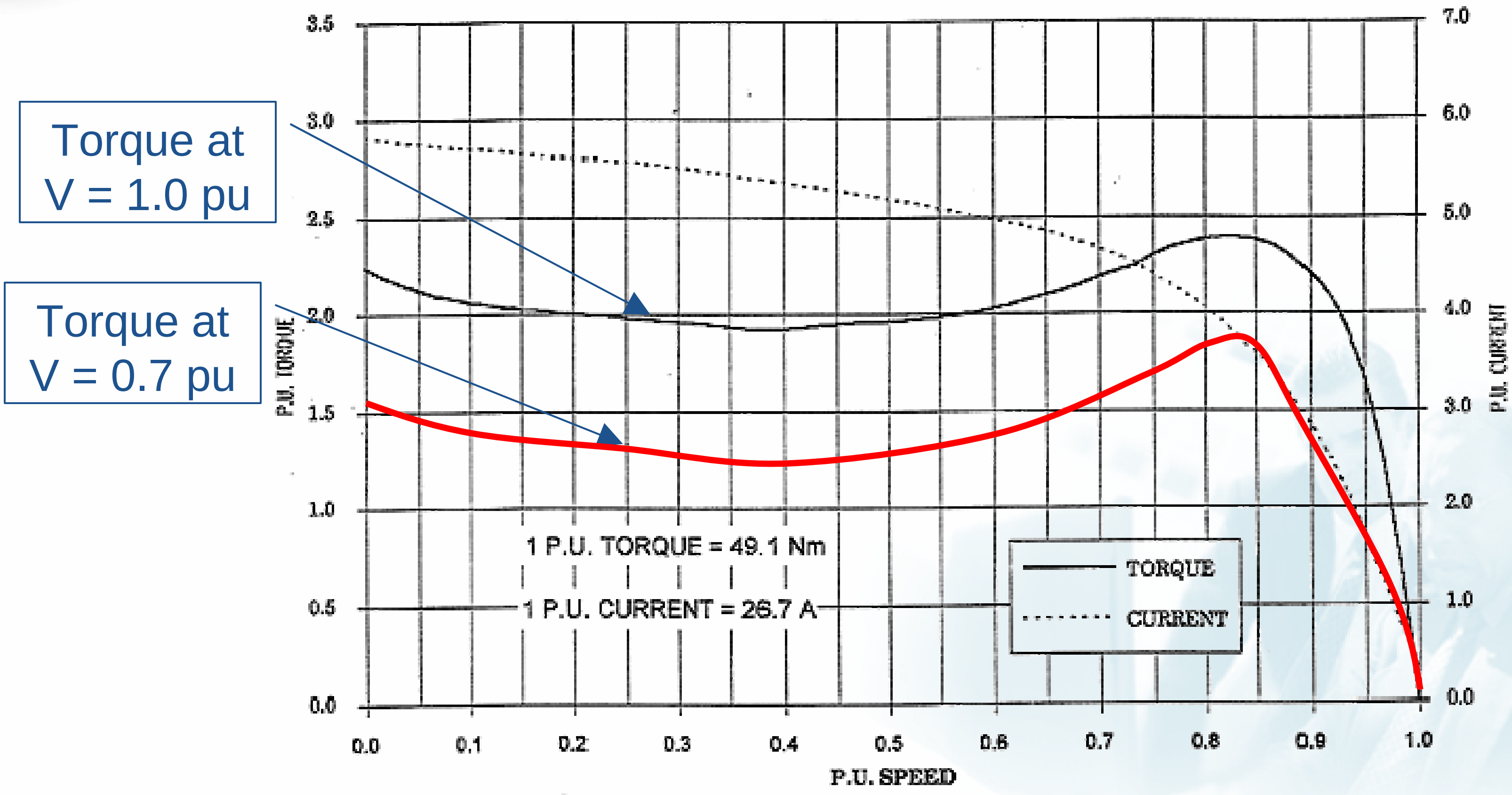
- When voltage drops at distribution loads …
  - Motor loads may stall
  - Motor loads may tripout
  - Other types of load reduce demand
  - Some loads self-restore

Air Conditioning Load - Characteristics

- Low inertia motors
  - Slows down quickly --- Prone to stalling
    - Residential air conditioning motors stall if voltage drops below 60% nominal for 5 cycles
  - Speeds up quickly --- sudden load injections
- Protection
  - Thermal overload
  - Undervoltage - tripout

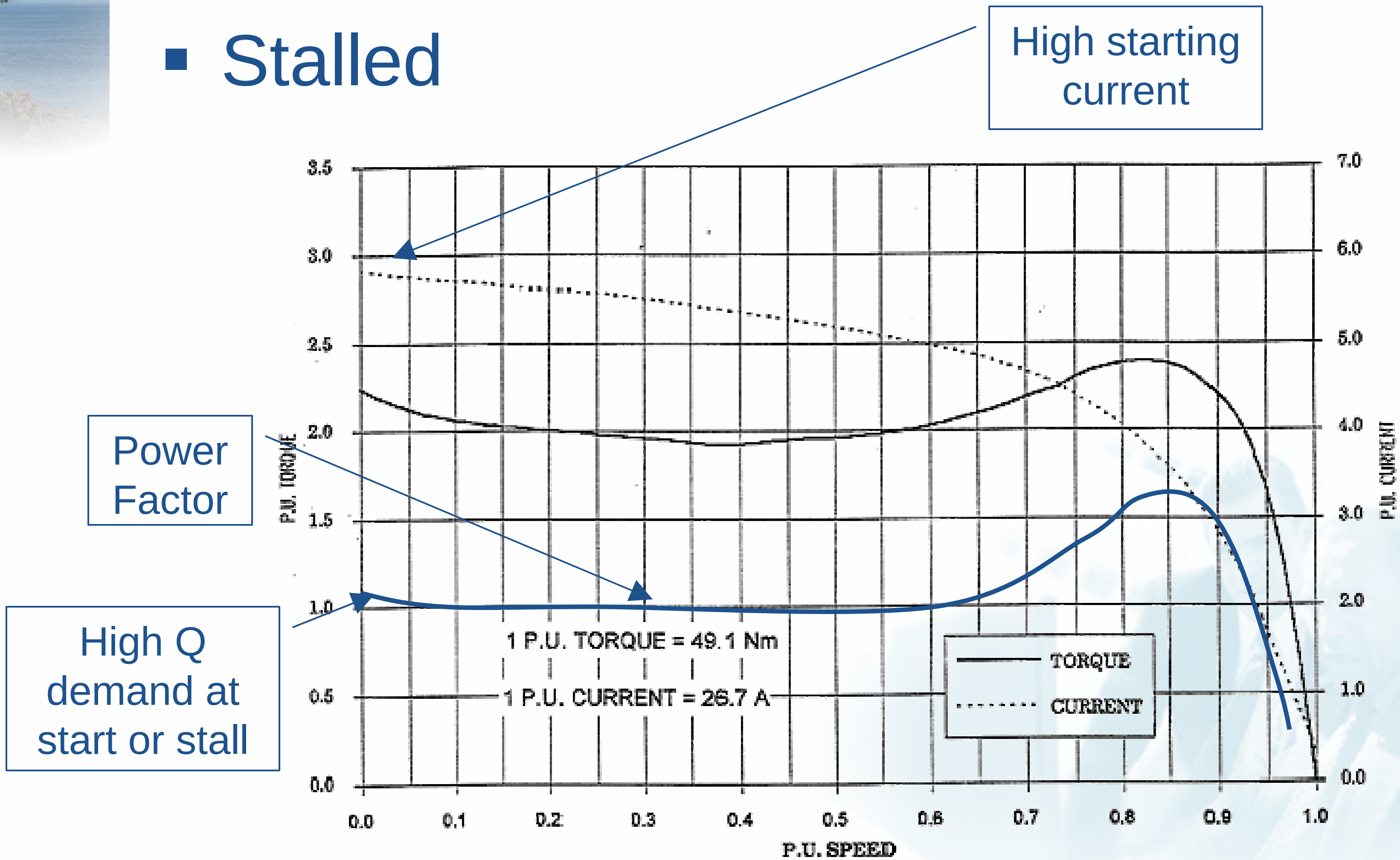
Motors

- Stalling



Motors

- Stalled



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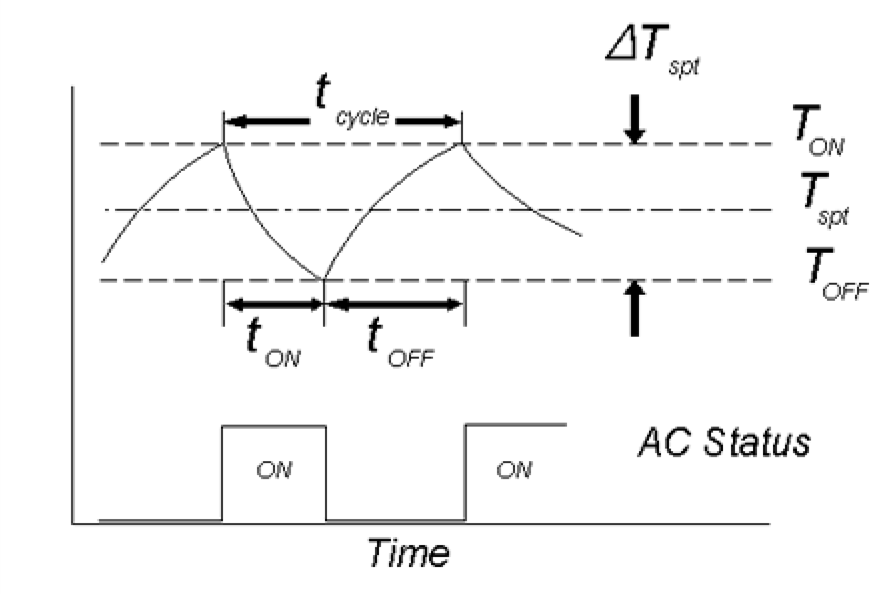
Self-restoring load

- Adjust cycle time at low voltage
- Restores to previous demand even at low voltage conditions



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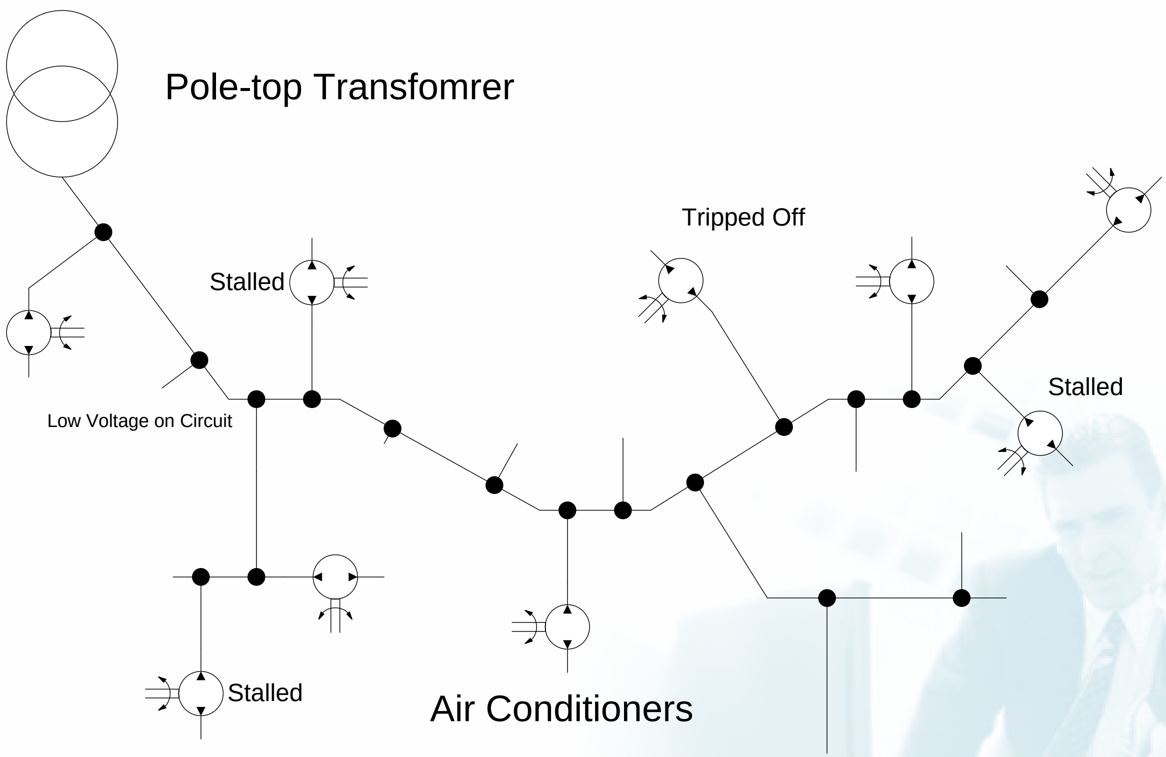
Typical Feeder on the Voltage Ledge



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Voltage Ledge

- An equilibrium state where:
  - Dynamic effects that would drive down voltage are balanced by effects that recover voltage
- Effects that **drive down** voltage:
  - Loads that have low voltage tolerance that allow them to recover to their normal demand level at lower terminal voltages, such as variable speed motors, or thermostat-controlled loads
  - Motor loads that **stall**, causing an increase in reactive demand

Voltage Ledge

- Effects that **recover** voltage:
  - The natural response of loads to decrease power demand as terminal voltages decrease
  - The **dropout** of contactors due to low voltage, most notably in motors, such as air conditioners and pumps

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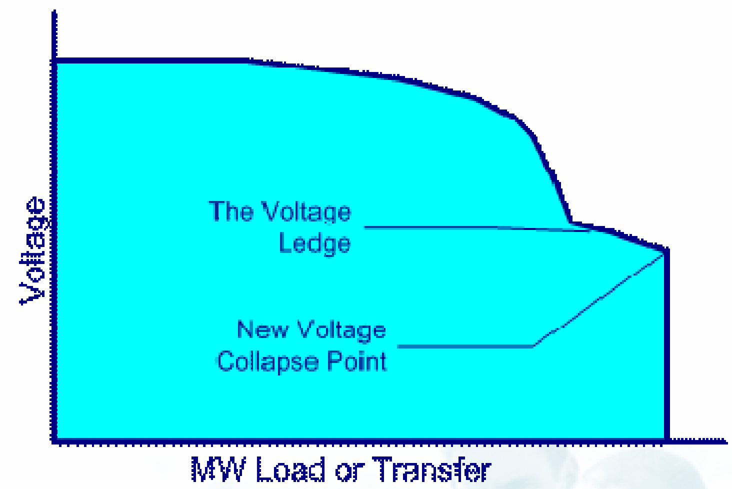
Voltage Ledge

- Can be visualized on the P-V curve as a flattening or Ledge near the voltage collapse point
- Any effort to increase load, is matched by voltage-dependent effects that reduce load



Ledge is narrower than shown in picture

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Voltage Ledge

- Other aspects of the Voltage Ledge
  - When operators attempt to add reactive power to the region operating on the Voltage Ledge, the VARs may be absorbed **without noticeable change** in condition
  - Most of the significant phenomena occurs in the **distribution** system
    - The transmission system appears normal, and within voltage criteria!

Consequences

- Operating on the Ledge for prolonged periods lead to …
  - Additional heating on the secondary circuits
  - Insulation failures on cables and pole-top transformers
  - Small generators on the feeders may not start up at low voltage
  - … Outages

July 1999 Event

- Assessment
  - Caused by Heat Storm resulting in
    - Record energy demand
      - Large cooling component
    - High imports into the Eastern Seaboard
  - Lack of reactive support in the load areas
  - Failures in the distribution system due to high currents (low voltages), high temperatures and humidity

July 1999 Event

- Assessment
  - When EHV voltage dropped to 1.0 p.u., operating guidelines did not indicate need for further emergency procedures
  - Voltage collapse was averted by:
    - Major contingency NOT occurring
    - Operator response to localize supply – reducing transfers

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Responding to the Ledge

- On the day of …
  - Reduce power transfers
  - Call on local generation reserves
  - Wait until demand reduces due to lower ambient temperatures
- A year or so ahead …
  - Provide for local VAR support
  - Add static VAR devices
  - Study low voltage load shedding

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Thank you for your time

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