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JICA

The Study on Power Supply Reliability Improvement in Jakarta

Technical Transfer Seminar

12-14th June 2013

Tokyo Electric Power Company Inc.

Nippon Koei Co., LTD

Table of Contents

- Voltage and Reactive Power Control
- Voltage Stability
- Reactive Power Compensation Planning Method
- Tokyo Blackout in 1987
- Case study of Wide Area Blackout in the United States and Canada in 2003
- Advanced Voltage and Reactive Power Control

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- Voltage and Reactive Power Control -

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Contents

- Necessity of the voltage control
- Voltage control target
- Simplified voltage calculation
- Generation and consumption of reactive power
- Comparison of voltage control equipment
- Voltage and reactive power control
- Voltage and reactive power control in a model network

Necessity of the Voltage Control

- **For safe and effective use of electrical appliances and materials**

Generally, the best performance is achieved when the equipment is operated at rated voltage. Therefore, when the voltage that is largely deviated from the rated value is applied to the equipment, its effectiveness and life expectancy can be adversely affected.

- **For secure and stable power supply**

When the voltage goes up too high, the iron core of equipment may be saturated and produce harmonics. When the voltage drops too low, transmission capability may also drop and power loss may increase to result in instability and possible large-scale failure of power supply.

Necessity of the Voltage Control

Problems caused by voltage drop:

1. Increase of active power loss (P_L)

$$P_L = P_s - P_r = \frac{P_r^2 \cdot R}{(V_r \cdot \cos\theta)^2}$$

(θ : Power factor angle at receiving end)

2. Decrease of transmission capacity (P_C) (due to the drop of thermal capacity and small-signal stability limit)

$$P_C = V_r \cdot I_{max} \cdot \cos\theta$$

$$P_C = \frac{V_s \cdot V_r \cdot \sin\delta}{X}$$

(δ : Phase angle between sending and receiving ends)

3. Generator output decrease

Output decrease of the auxiliary equipment at thermal and nuclear power stations leads to output decrease of the entire plants.

Necessity of the Voltage Control

Problems caused by voltage rise:

1. Generation of harmonics

   The equipment with iron cores may experience over-excitation by the terminal voltage rise, resulting in distortion of voltage waveforms and generation of harmonics.

2. Deteriorated insulation and shortened life of equipment

   When overvoltage is prolonged, the entire facility may experience deterioration of insulation and overall performance, causing damages and breakdowns of the equipment.

Necessity of the Voltage Control

Possible reasons for voltage fluctuation:

Demand fluctuation

Start-stop of generators and transformers

System configuration changes and load transfers

Faults in the system

Switching on / off of reactive power compensators in the system

Transformer tap changes

...etc.

Voltage Control Target in Japan

- **Electricity Utilities Industry Act**

100V → 101V ± 6V

200V → 202V ± 20V

Voltage Control Target in TEPCO

・Voltage control target

500kV network: Vref ± 0.5% (Vref: 525 – 550kV)

275kV network: Vref ± 0.7% (Vref: 270 – 300kV)

HV network: Vref ± 1% (Vref: 95 (90) – 110%)

(Reference voltage Vref is adjusted depending on the location, time, and demand level to achieve a favorable voltage profile.)

・Reactive power control target

Reactive power flow in the primary side of transformers (except 500kV transformers): 0MVar

Voltage Control Target

Points to consider when setting target values:

(1) System configuration, location and capacity of generators and reactive power compensators

(2) System characteristics, load characteristics, performance of voltage controllers

(3) Allowable voltage ranges of network equipment

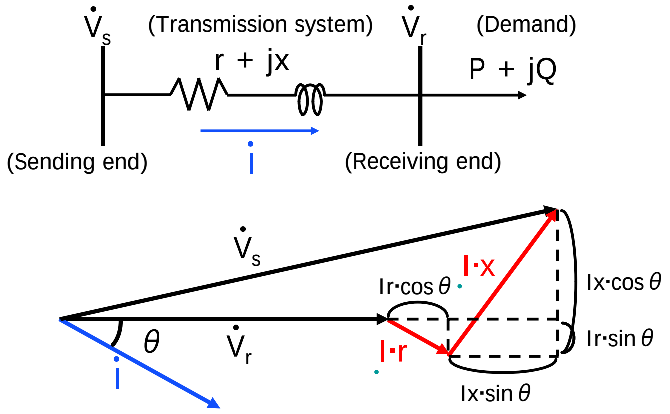
(4) Allowable voltage ranges for system security

(5) Allowable voltage ranges to maintain supply voltages to customers

(6) Appropriate reactive power distribution in the system

(7) Smaller power loss

Simplified Voltage Calculation



$$\dot{V}_s = \dot{V}_r + \dot{Z}\cdot\dot{I}$$
$$= \dot{V}_r + (Ir\cdot\cos\theta + Ix\cdot\sin\theta) + j(-Ir\cdot\sin\theta + Ix\cdot\cos\theta)$$

Simplified Voltage Calculation

$$\dot{V}_s = \dot{V}_r + \dot{Z}\cdot\dot{I}$$
$$= \dot{V}_r + (Ir\cdot\cos\theta + Ix\cdot\sin\theta) + j(-Ir\cdot\sin\theta + Ix\cdot\cos\theta)$$

$$\dot{V}_{drop} = \dot{V}_s - \dot{V}_r = \dot{Z}\cdot\dot{I}$$
$$= Ir\cdot\cos\theta + Ix\cdot\sin\theta + j(-Ir\cdot\sin\theta + Ix\cdot\cos\theta)$$

Ignore imaginary term by letting $V_s \approx 1.0$ [PU]

$$\boxed{V_{drop} \approx r\,P + x\,Q}$$

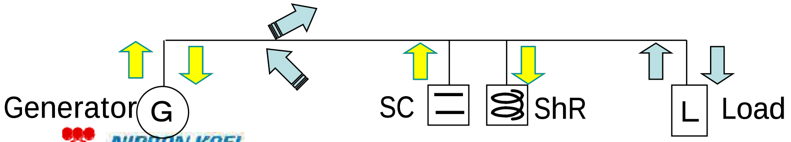
ΔQ fluctuates due to switchings of reactors / capacitors

$$\Delta V_r = x\cdot\Delta Q$$

V_s: fixed
P: constant

Generation and Consumption of Reactive Power

	Q Generation factors (Voltage rise)	**Q Consumption factors (Voltage drop)**
Non adjustable reactive power	**・Q generated by load** (due to over compensation by shunt capacitors) **・Charging capacity of transmission line**	**・Q consumed by load** **・Q loss by leakage reactance of transformers** **・Q loss in transmission lines**
Adjustable reactive power	・Generator operation (lagging) ・Shunt capacitors	・Generator operations (leading) ・Shunt reactors



Comparison of Voltage Control Equipment

	Types	Function	Advantages (A) and disadvantages (D)
Reactive power compensators	Shunt Capacitor (SC)	· Prevent system voltage drop by supplying reactive power	(A) Little need for maintenance (A) Installation possible at various locations (A,D) Effective capacity fluctuates with system voltage (D) Only switching operation possible (not continuous)
	Shunt Reactor (ShR)	· Prevent over build-up of voltage by consuming reactive power	
	Startic Var Compensator (SVC)	· High speed and continuous control of reactive and capacitive current (both to generate and absorb reactive power)	(A) High speed, sequential control of reactive power has wide application for voltage stabilization (flickers etc) (A) Little need for maintenance (A,D) Inexpensive compared to SynC but more expensive than SC and ShR
	Synchronous condensor (SynC)	· Continuous control of excitation current of synchronous equipment both by supplying and absorbing reactive power	(A) High speed, sequential control of reactive power has wide appolication for voltage stabilization (flickers etc) (D) Difficult to maintain, vibration and noise, expensive (D) Short circuit capacity of the system is enlarged
Tap changer		· Primary and secondary voltage ratio control	(A) Improvement of manufacture technology has lowered cost and better reliability （Primary equipment used for substation voltage control) (D) Only switching operation possible (not continuous)
Generator		· Control of excitation current of generator to adjust reactive power	(A) High speed and continuous control of voltage and reactive power possible (A,D) Adjustable range is limited due to stability and mechanical limitations

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Voltage and Reactive Power Control

(1) Generator excitation control (leading, lagging)

(2) Shunt capacitors and shunt reactors

(3) Transformer tap changers

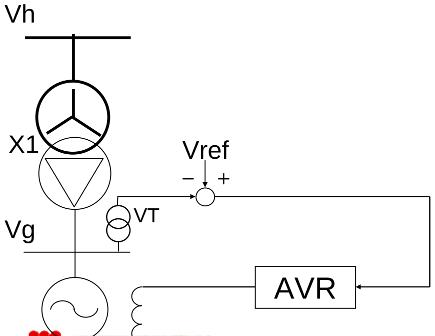
Generator Excitation Control

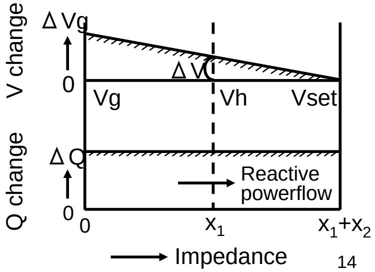
- **AQR (Automatic Q Regulator)**

  regulates reactive power flow in the system to setting values

- **AVR (Automatic Voltage Regulator)**

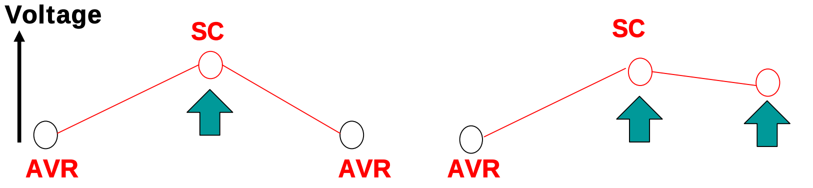
  regulates generator terminal voltage to setting values





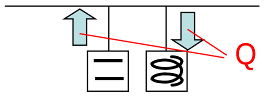
Shunt Capacitors and Shunt Reactors

Shunt capacitor supplies reactive power to the system



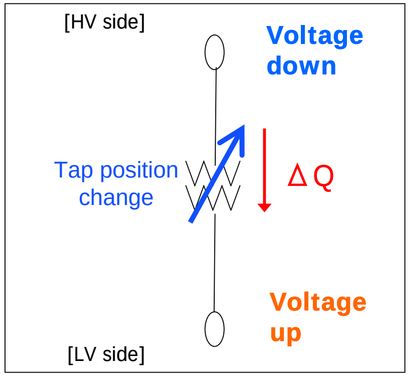
(Example 1)
When generators at both ends are controlled by AVR

(Example 2)
When only one generator at the end is controlled by AVR



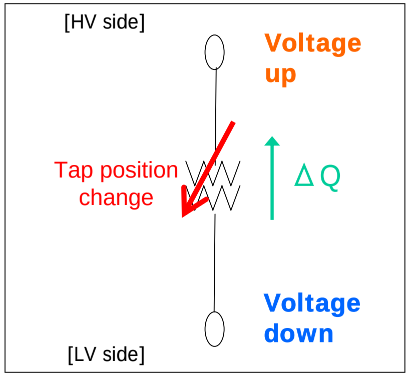
Transformer Tap Changers

When higher tap position is selected:



Transformer Tap Changers

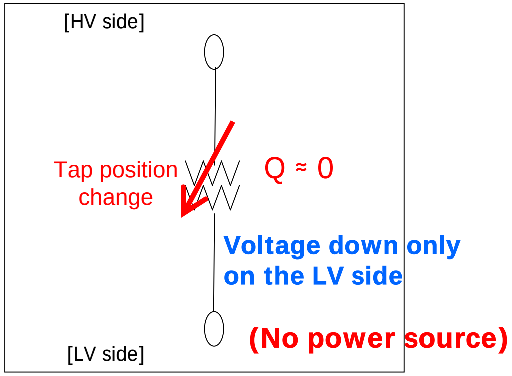
When lower tap position is selected:



Transformer Tap Changers

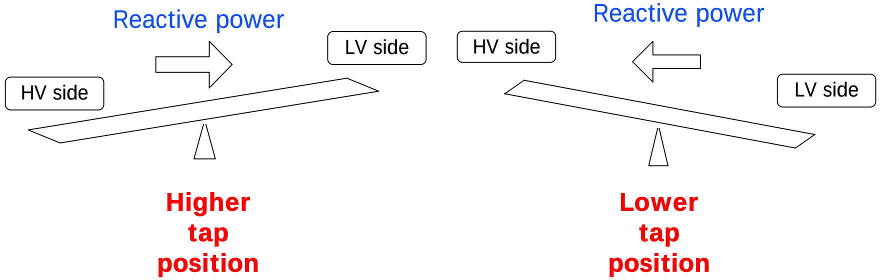
When lower tap position is selected:

(without power source on the LV side)



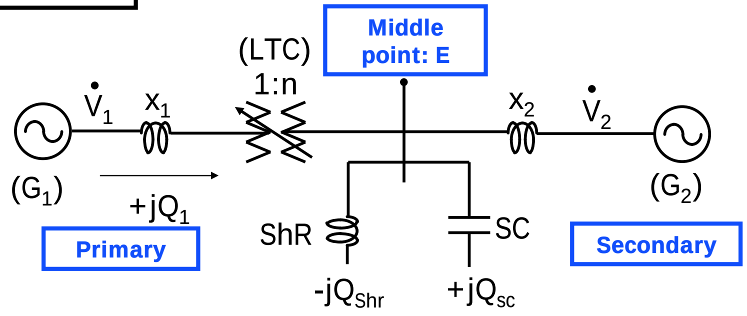
Transformer Tap Changers

Illustration of voltage control using transformer tap changers and generators with AVRs on both sides



Voltage and Reactive Power Control in a Model Network

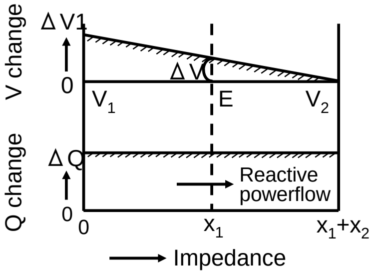
System model



Generator Excitation Control

When reactive power ΔQ is generated by the generator on the primary side and voltage at point V_1 goes up by ΔV_1 ,

$$\Delta V = x_2 \cdot \Delta Q$$
$$\Delta V_1 = (x_1 + x_2) \cdot \Delta Q$$

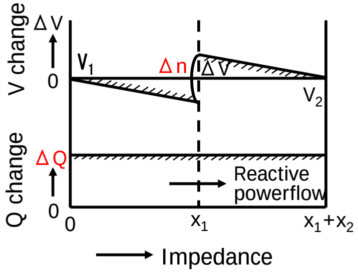


$$\frac{\Delta V}{\Delta V_1} = \frac{x_2}{x_1 + x_2} \qquad \frac{\Delta Q}{\Delta V_1} = \frac{1}{x_1 + x_2}$$

Transformer Tap Changers

When winding ratio is changed by Δn, the consequent change of system voltage and reactive power change equals the apparent addition of ΔQ flow into the system. It is because of the electromotive force corresponding to Δn inserted at the location of LTC.

$$\Delta V = x_2 \cdot \Delta Q$$
$$\Delta n = (x_1 + x_2) \cdot \Delta Q$$

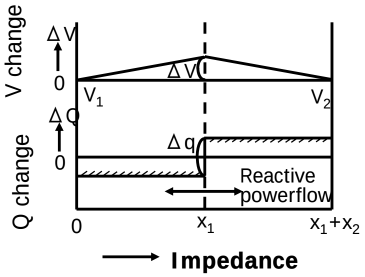


$$\frac{\Delta V}{\Delta n} = \frac{x_2}{x_1 + x_2} \qquad \frac{\Delta Q}{\Delta n} = \frac{1}{x_1 + x_2}$$

Shunt Capacitors and Shunt Reactors

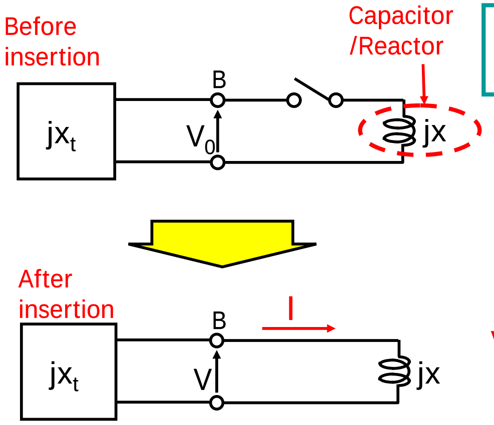
If SC is connected to the model system, voltage and reactive power changes are determined / distributed by the primary and secondary side impedance as shown in the figure.

$$\Delta V = x_1 \cdot (-\Delta Q)$$
$$\Delta V = x_2 \cdot (\Delta q - (-\Delta Q))$$



$$\frac{\Delta V}{\Delta q} = \frac{x_1 \cdot x_2}{x_1 + x_2} \qquad \frac{\Delta Q}{\Delta q} = \frac{-x_2}{x_1 + x_2}$$

Voltage Control by Shunt Capacitor / Reactor (Example)



x > 0: Reactor

x < 0: Capacitor

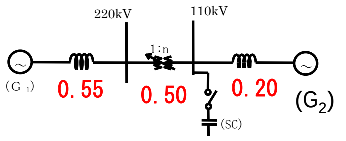
$$I = \frac{V_0}{j(x+x_t)}$$

$$V = jx \cdot I = \frac{x}{x+x_t} V_0$$

$$= \frac{1/x_t}{1/x_t+1/x} V_0$$

$$= \frac{Q_t}{Q_t+Q} V_0$$

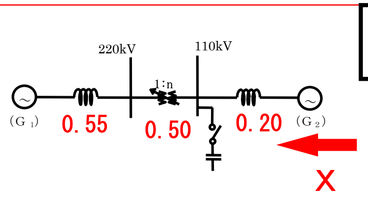
Example 1



(1) When terminal voltage of generator G_2 is raised by 1%

Base: 1000MVA
220kV
110kV

Example 1



(1) When terminal voltage of generator G_2 is raised by 1%

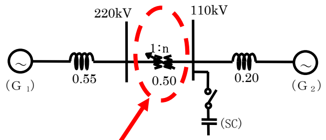
Base: 1000MVA
220kV
110kV

$$X = 0.20 + 0.50 + 0.55 = 1.25[PU]$$

$$\Delta Q = \Delta V / X$$
$$= 0.01 / 1.25 = 0.008[PU]$$
$$= 8[MVar]$$

By excitation control of the generator (lagging), terminal voltage rises and reactive power is supplied to the system.

Example 2

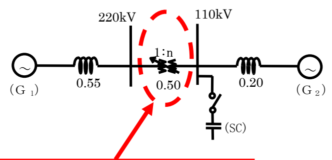


220kV±10%/110kV
(21 taps)

(2) When transformer tap is changed by 1 tap position

Base: 1000MVA
220kV
110kV

Example 2



(2) When transformer tap is changed by 1 tap position

220kV±10%/110kV
(21 taps)

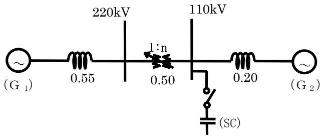
Base: 1000MVA
220kV
110kV

Δn = 20% / (21-1)taps = 1.00[%/tap]
= 0.01[PU/tap]

$\Delta Q = \Delta n / X$
= 0.01 / 1.25 = 0.008[PU]
= 8[MVar]

While voltage can be adjusted by tap changes, the absolute amount of reactive power flow in the system remains the same.

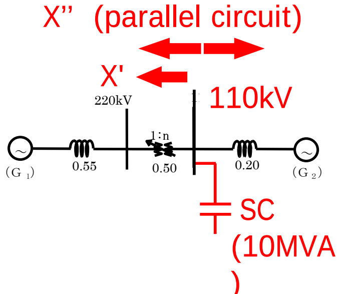
Example 3



(3) When 10MVA SC is connected to 110kV busbar

Base: 1000MVA
220kV
110kV

Example 3



(3) When 10MVA SC is connected to 110kV busbar

Base: 1000MVA
220kV
110kV

X' = 0.50 + 0.55 = 1.05[PU]

X” = (0.20×1.05)／(0.20+1.05) = 0.168[PU]

$\Delta V = X'' \times \Delta q$
= 0.168 × 0.01 = 0.00168[PU]
= 0.168[%]

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Contents

- Voltage Stability
- Static Load Model
- PV Curve
- QV Curve

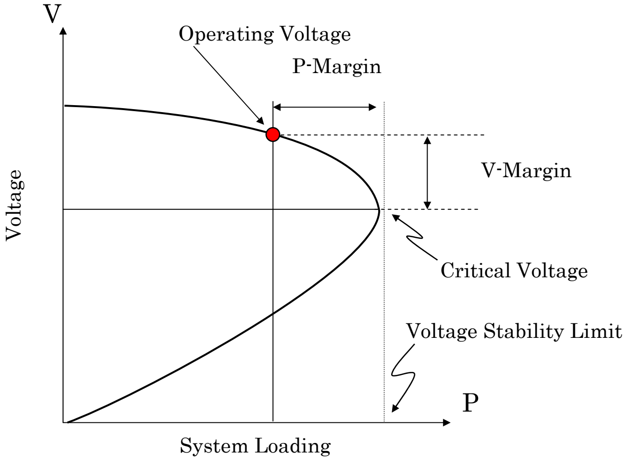
Basic Terms (1) Voltage Stability

Voltages in power system depend on the network condition such as network configurations, operating conditions of generators, load conditions, and reactive compensation devices.

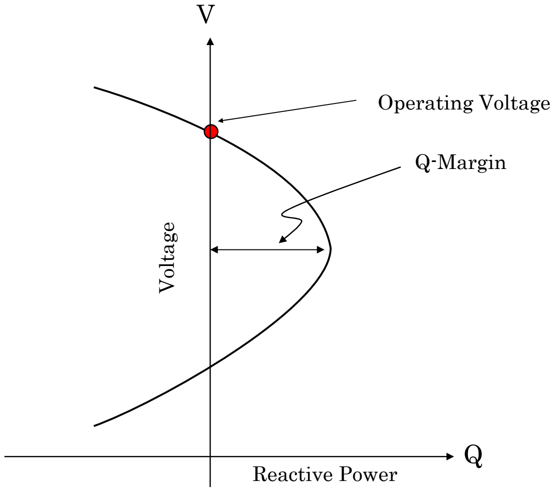
Voltage stability is the ability of a power system
to maintain acceptable voltages at all buses in the system under normal condition and after being subjected to a disturbance.

Load characteristics also affect voltage stability.

Basic Terms (2) P-V Curve



Basic Terms (3) Q-V Curve



Static Load Models (1)

$$P = P_0 (V / V_0)^m \qquad (1)$$

$$Q = Q_0 (V / V_0)^n \qquad (2)$$

P : Active power load
Q : Reactive power load
V : Bus voltage
V_0 : Bus voltage in the initial operating condition
P_0 : Active power load in the initial operating condition
Q_0 : Reactive power load in the initial operating condition

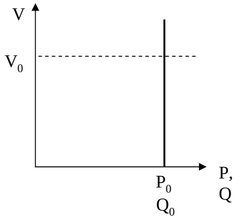
Static Load Models (2)

(a) constant power

m,n = 0

$$P = P_0 (V / V_0)^0$$

$$Q = Q_0 (V / V_0)^0$$

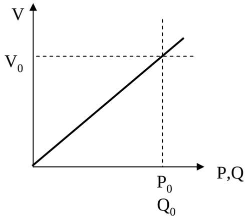


(b) constant current

m,n = 1

$$P = P_0 (V / V_0)^1$$

$$Q = Q_0 (V / V_0)^1$$

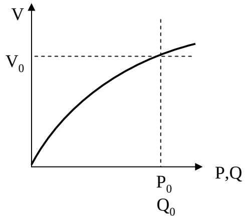


(c) constant impedance

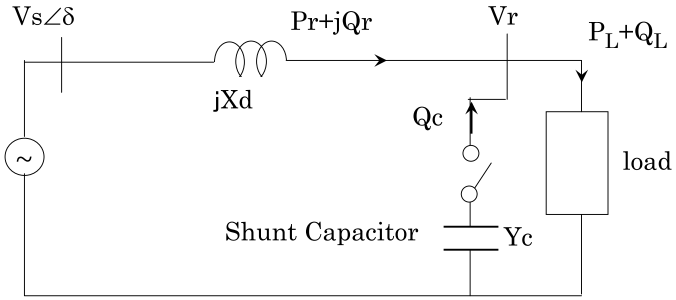
m,n = 2

$$P = P_0 (V / V_0)^2$$

$$Q = Q_0 (V / V_0)^2$$



Preparation for P-V Curve (1)



Vr : receiving end voltage (angle reference)
Vs : sending end voltage
δ : sending end phase angle
Xd : system reactance

Preparation for P-V Curve (2)

Reactive Power from shunt capacitor at receiving end is given by

$$Q_C = Y_C V_r^{\,2} \qquad (1)$$

Voltage at sending end is given by

$$\dot{V}_s = V_s e^{j\delta} = V_s(\cos\delta + j\sin\delta) \qquad (2)$$

The relation between sending and receiving voltage is

$$\dot{V}_s = V_r + jX_d\dot{I} \qquad (3)$$

The relation between active and reactive power at receiving end is

$$P_r + jQ_r = V_r\bar{\dot{I}} \qquad (4)$$

Preparation for P-V Curve (3)

Eliminating $\dot{V}_s$ from (2) and (3),

$$V_s(\cos\delta + j\sin\delta) = V_r + jX_d\dot{I}$$

$$\dot{I} = \frac{V_s(\cos\delta + j\sin\delta) - V_r}{jX_d} = \frac{V_s(j\cos\delta - \sin\delta) - jV_r}{-X_d}$$

$$= \frac{V_s\sin\delta - j(V_s\cos\delta - V_r)}{X_d}$$

$$\bar{\dot{I}} = \frac{V_s\sin\delta + j(V_s\cos\delta - V_r)}{X_d} \qquad (5)$$

Preparation for P-V Curve (4)

Substituting this $\bar{\dot{I}}$ to (4),

$$P_r + jQ_r = V_r\bar{\dot{I}} = \frac{V_sV_r\sin\delta + j(V_sV_r\cos\delta - V_r^{\,2})}{X_d}$$

$$P_r = P_L = \frac{V_sV_r}{Xd}\sin\delta \qquad (6)$$

$$Q_L = Q_r + Q_c = \frac{V_sV_r\cos\delta - V_r^{\,2}}{Xd} + Y_cV_r^{\,2} \qquad (7)$$

Preparation for P-V Curve (5)

From Equation(6) and (7),

$$\sin\delta = \frac{XdP_L}{V_sV_r}\ , \qquad \cos\delta = \frac{Xd}{V_sV_r}\left(Q_L + \frac{V_r^{\,2}}{Xd} - Y_cV_r^{\,2}\right)$$

Since $\sin^2\delta + \cos^2\delta = 1$,

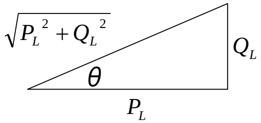
$$P_L^{\,2} + \left(Q_L + \frac{V_r^{\,2}}{Xd} - Y_CV_r^{\,2}\right)^2 = \frac{V_s^{\,2}V_r^{\,2}}{Xd^{\,2}} \qquad (8)$$

(8) is the base equation to draw P-V curves.

Preparation for P-V Curve (6)

f : power factor of the load

$$\frac{P_L}{\sqrt{P_L^{2}+Q_L^{2}}} = \cos\theta = f$$



$$P_L^{2} = f^{2}(P_L^{2}+Q_L^{2}) \quad , \quad Q_L^{2} = \frac{P_L^{2}}{f^{2}} - P_L^{2} = \frac{1-f^{2}}{f^{2}}P_L^{2}$$

$$Q_L = \frac{\sqrt{1-f^{2}}}{f}P_L \qquad (9)$$

Preparation for P-V Curve (7)

Substituting (9) to (8) and eliminating Q_L,

$$P_L^{2} + \left(\frac{\sqrt{1-f^{2}}}{f}P_L + \left(\frac{1}{X_d} - Y_C\right)V_r^{2}\right)^{2} = \frac{V_s^{2}V_r^{2}}{X_d^{2}} \qquad (10)$$

$$P_L^{2} + \frac{1-f^{2}}{f^{2}}P_L^{2} + \frac{2\sqrt{1-f^{2}}}{f}P_L\left(\frac{1}{X_d} - Y_c\right)V_r^{2} + \left(\frac{1}{X_d} - Y_c\right)^{2}V_r^{4} = \frac{V_s^{2}V_r^{2}}{X_d^{2}}$$

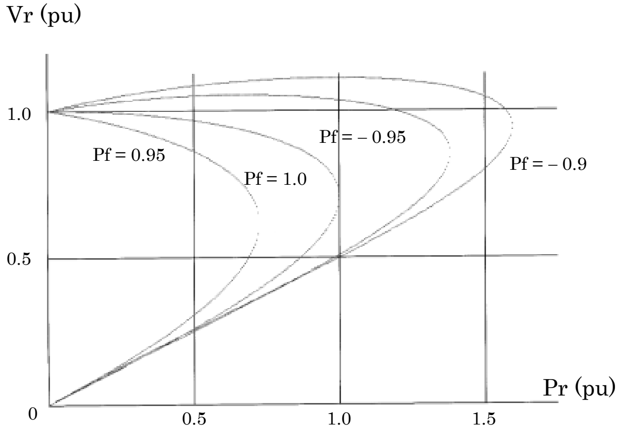
$$\left(\frac{1}{X_d} - Y_c\right)^{2}V_r^{4} + \left\{\frac{2\sqrt{1-f^{2}}}{f}\left(\frac{1}{X_d} - Y_c\right)P_L - \frac{V_s^{2}}{X_d^{2}}\right\}V_r^{2} + \frac{P_L^{2}}{f^{2}} = 0 \qquad (11)$$

Preparation for P-V Curve (8)

defining V_r^{2} as v,

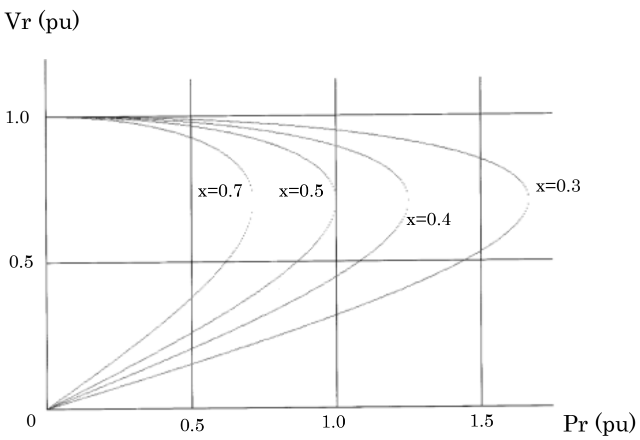
$$\left(\frac{1}{X_d} - Y_c\right)^{2}v^{2} + \left\{\frac{2\sqrt{1-f^{2}}}{f}\left(\frac{1}{X_d} - Y_c\right)P_L - \frac{V_s^{2}}{X_d^{2}}\right\}v + \frac{P_L^{2}}{f^{2}} = 0 \qquad (12)$$

P-V Curves (1)



The relationship between Vr and Pr for different power factors of the load

P-V Curves (2)



The relationship between Vr and Pr for different reactance Xd

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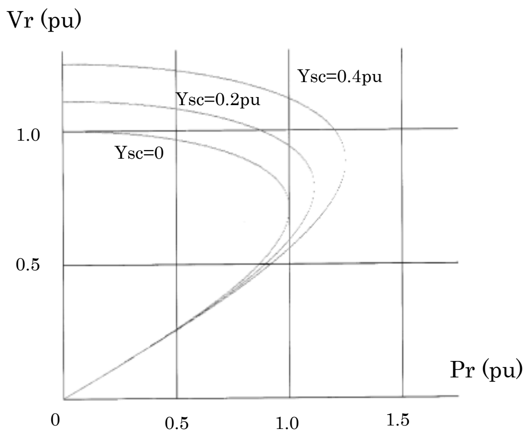
P-V Curves (3)



The relationship between Vr and Pr for different admittance Yc

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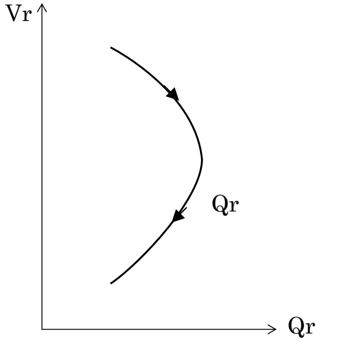
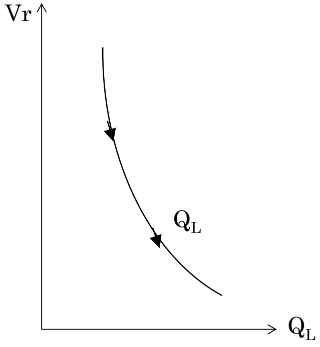
Q-V Curves (1)

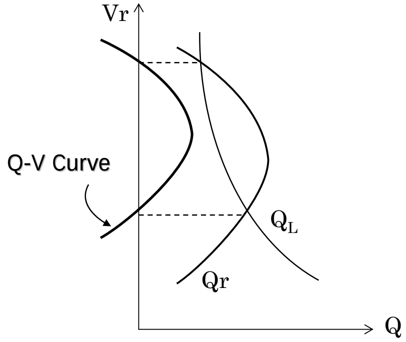


Reactive power
provided from power system



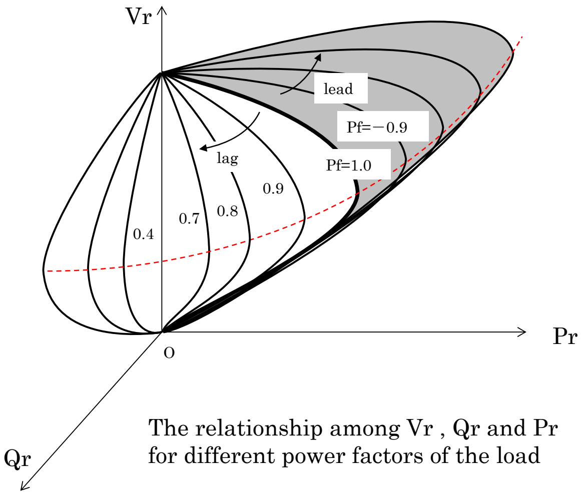
Reactive power
required by load

Q-V Curves (2)



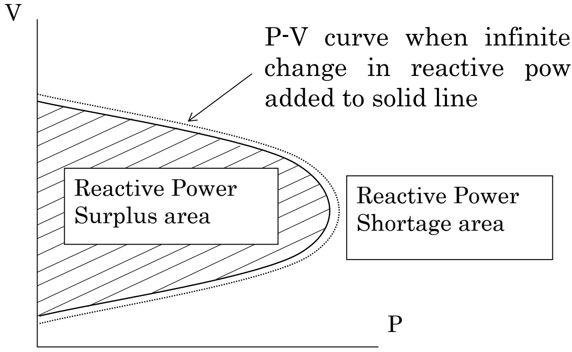
Difference between Qr and Q_L

P-Q-V Curve



The relationship among Vr , Qr and Pr
for different power factors of the load

Static Voltage Stability (1)



P-V curve when infinitesimal change in reactive power is added to solid line

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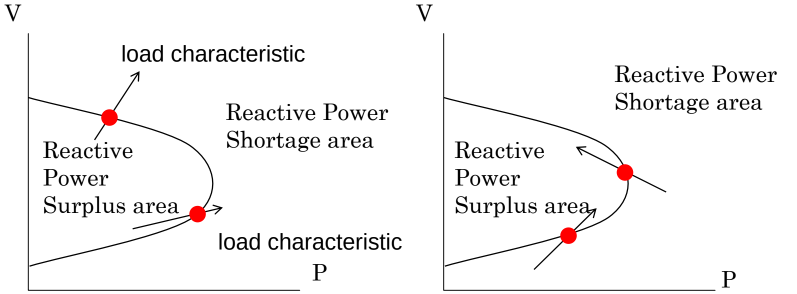
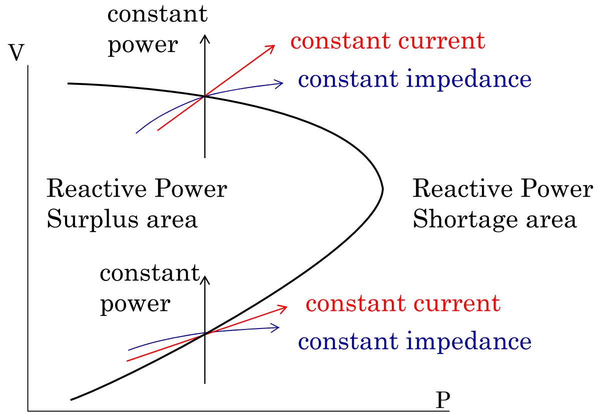
Static Voltage Stability (2)



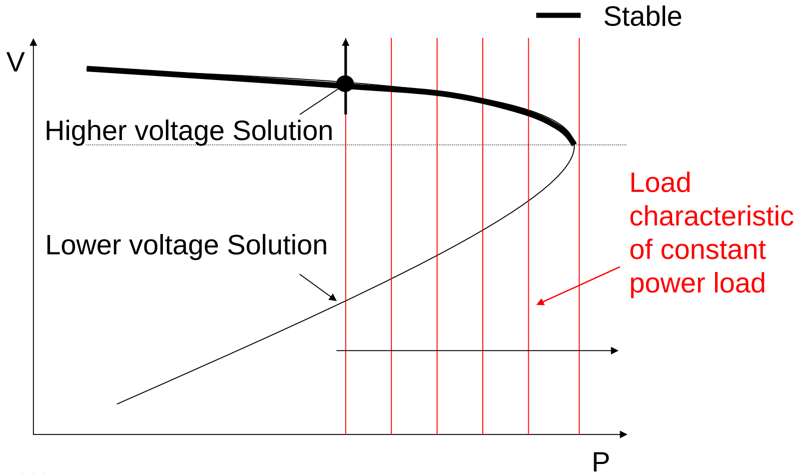
Stable operating point

Unstable operating point

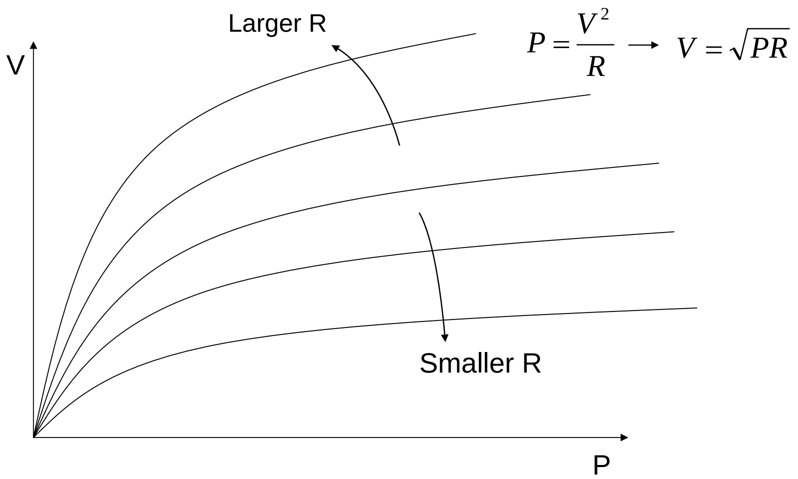
Static Voltage Stability (3)



Operating Point and P-V Curve (1)

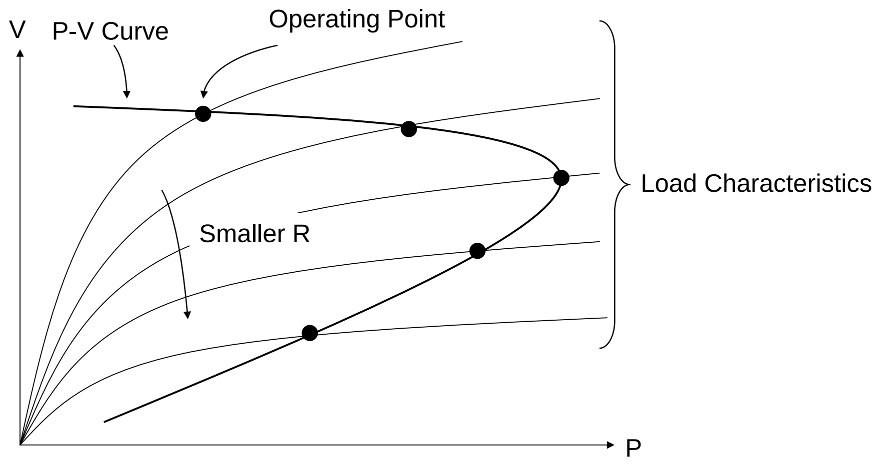


Operating Point and P-V Curve (2)



$$P = \frac{V^2}{R} \longrightarrow V = \sqrt{PR}$$

Operating Point and P-V Curve (3)



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- Reactive power compensation planning method
Technical Transfer Seminar

12th June. 2013
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Installation of Shunt Capacitors/Reactors for 500 kV, 275 kV, 154 kV Substations

- **Basically, Shunt Capacitors/Reactors are installed at tertiary sides of transformers.**
- **A. When a tertiary side doesn't have enough capacity, other locations are examined.**
- **B. Shunt reactors for 275 kV cable charge compensation are directly connected to cables in power source substations and connected to bus bars in other substations.**

Installation of Shunt Capacitors/Reactors for 66 kV Substations

- **A. Basically Shunt capacitors are installed in out-door type substations.**
- **B. Basically, shunt capacitors are installed at the secondary sides of 66 kV substations. 1 unit for 1 bank.**
- **C. For existing substations, dead spaces should be utilized. When the substations are rehabilitated or changed in facilities, layouts should be considered to assure the spaces for installation of shunt capacitors.**

Standard Capacity of Shunt Capacitors/Reactors in TEPCO

	Voltage	Capacity (MVA)
Shunt Capacitors	154 kV	-
	66 kV	20, 20, 40, 60, 80, 120
	22 kV	20, 30
	6.6	6.0 (4.0)
Shunt Reactors	500	
	275	150, 200
	66	30, 40, 80
	22	20, 30

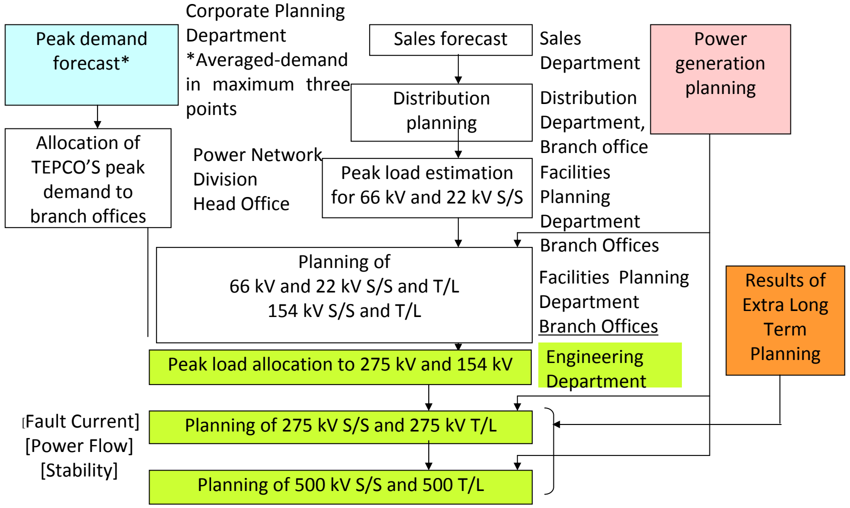
Power Network Planning of TEPCO

- **There are three types of power network plan in TEPCO.**
- **Extra Long Term Planning (for 20-30 years later)**
- **Middle-Long Term Planning (for next 10 years)**
- **Reactive Power Planning (for next year)**

Middle-Long Term Planning and Reactive Power Planning are made every year.

Extra Long Term Planning has been no longer carried out now, because power demand growth of TEPCO has been very low recently. However, it was needed for put up with rapid growth of power demand to see a correct direction of bulk power network configuration.

Middle-Long Term Network Planning (For next 10 years)



Peak demand forecast*

Corporate Planning Department

*Averaged-demand in maximum three points

Allocation of TEPCO'S peak demand to branch offices

Sales forecast

Sales Department

Distribution planning

Distribution Department, Branch office

Power generation planning

Power Network Division Head Office

Peak load estimation for 66 kV and 22 kV S/S

Facilities Planning Department

Branch Offices

Planning of 66 kV and 22 kV S/S and T/L 154 kV S/S and T/L

Facilities Planning Department

Branch Offices

Results of Extra Long Term Planning

Peak load allocation to 275 kV and 154 kV

Engineering Department

[Fault Current]

[Power Flow]

[Stability]

Planning of 275 kV S/S and 275 kV T/L

Planning of 500 kV S/S and 500 T/L

Reactive Power Planning of TEPCO

- **For Peak Power Demand**
  - **Plan of shunt capacitors for reactive power compensation for increased reactive power load / losses**
- **For Off Peak Power Demand**
  - **Plan of shunt reactors to restrain system voltage by surplus reactive power in the targeted range**
- **Every year, the plan is made for the next year.**

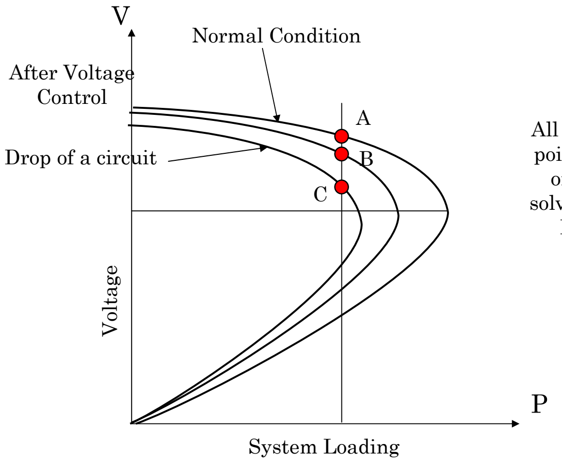
Demand Forecast Used for Planning of TEPCO

- **H3: Averaged Three Days Peak Demand**
- **H1: Peak Demand in Level of Once a 5 years**
- **H0: Demand corresponding to Power Supply Ability**

Reactive Power Plan for Peak Power Demand

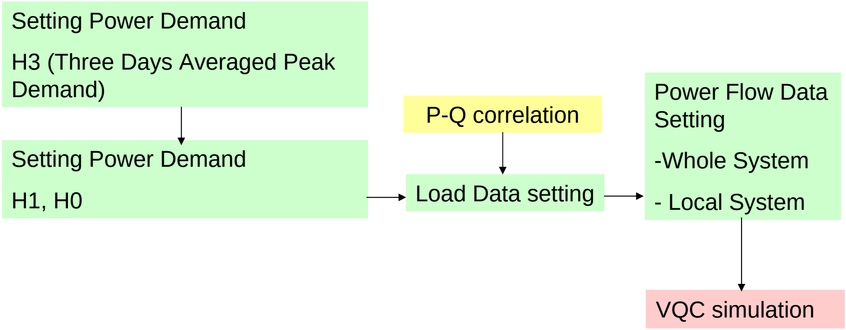
- 500 kV, 275 kV
  - **H1: Maintain Voltage Stability in N-1**
  - **H0: Maintain Voltage Stability in Normal Condition**
- 154 kV, 66 kV
  - **H3: Maintain Voltage in N-1**
  - **H1: Maintain Voltage Stability in case of single-circuit stopped**
  - **H1: Maintain Voltage in Normal Condition(154 kV: 140 kV, 66 kV: 60 kV)**

P-V Curve



All the operation points should be on the upper solvable points of P-V curves

Procedure of Reactive Power Compensation Planning for Peak Demand



Setting Power Demand

H3 (Three Days Averaged Peak Demand)

Setting Power Demand

H1, H0

P-Q correlation

Load Data setting

Power Flow Data Setting

-Whole System

- Local System

VQC simulation

TEPCO's practice in Voltage Analysis

- **Voltage Stability Analysis is conducted by using VQC Simulation Program every year**
- **Precise Q load Estimation based on P - Q relationship data acquired at each 66kV node**
- **Installation Planning of Shunt Capacitors / Reactors etc.**
- **Study to determine the coordinated setting of Voltage Control Equipment (VQC, PSVR etc.)**
- **Evaluation of marginal demand under critical contingencies (Calculate PV curves for critical N-1 & N-2 contingencies)**

Studies for Ensuring Voltage Stability

- **Quasi-Steady State Analysis**
  - Steep rise in demand after lunch break; 600MW/min
  - The whole TEPCO transmission system above 66kV
  - Response and Switching by VQC, SVC, PSVR and Tap Changers
  - No dynamics of loads and generators
- **Quasi-steady state analysis check;**
  - Transfer capability limits during contingencies; and
  - Reactive power reserve at generators is maintained by switching on shunt capacitors during demand increase

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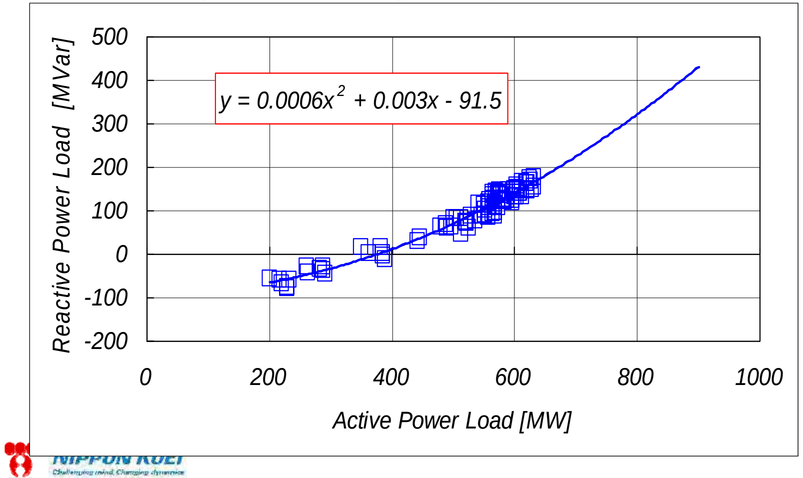
Prediction of Reactive Power Load (An example)

Regression analysis between active and reactive power load data acquired in summer peak days

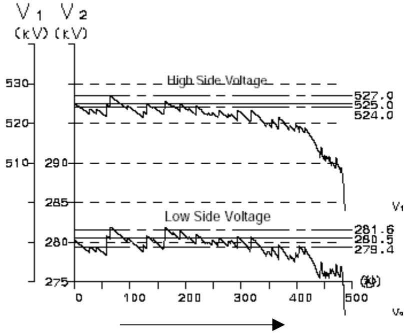


VQC Simulation Program Developed by TEPCO

- **Power Flow & Voltage Calculation in Time-domain**
- **Operation of voltage control equipment is modeled in detail (On/Off of Shunt Capacitors/Reactors, Tap-Changing & PSVR control etc.)**
- **Variable simulation conditions**
  - Rate of demand increase
  - Contingency (N-1 & N-2, Faulted Facilities)
  - Load Characteristics (Basically Constant P & Q)

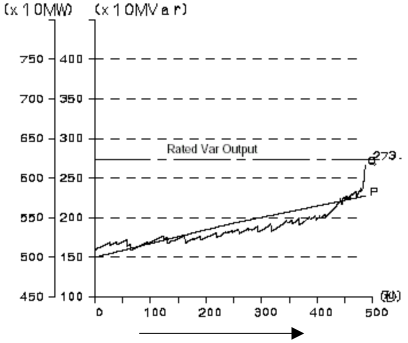
VQC Simulation Studies

500kV and 275kV Busbar Voltages



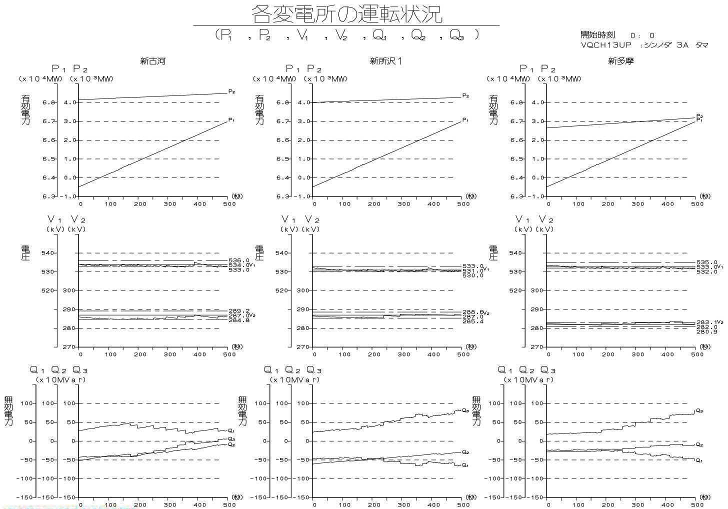
Demand Increasing

Increase in Active and Reactive Load Demand

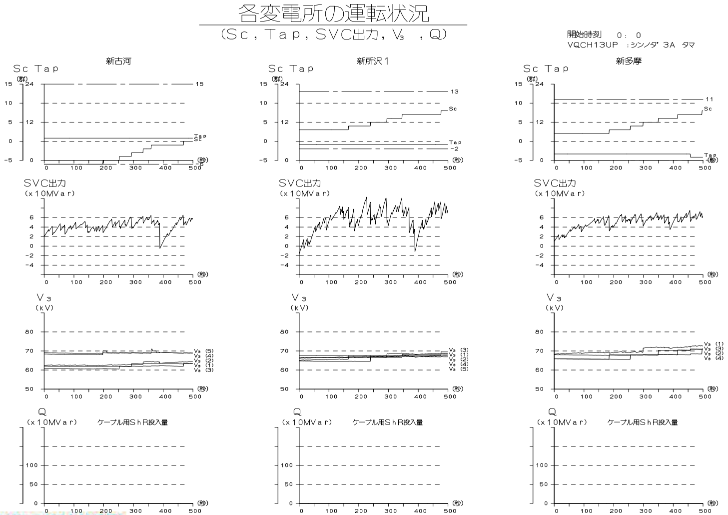


Demand Increasing

Output of VQC simulation (1)



Output of VQC simulation (2)



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- Information Exchange about Power System Data
Technical Transfer Seminar

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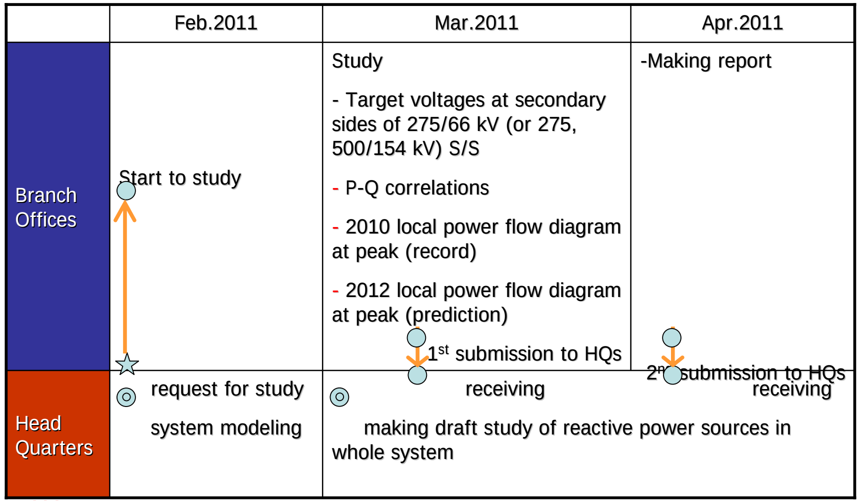
TEPCO's organization regarding power system plan and operation

- **Branch Offices (10)**
  - Depts.
  - Service Center
    - Control & Maintenance Office
  - Load-dispatching Station
  - Construction Center
- **Engineering Dept.**
- **Transmission Dept.**
  - Transmission & Substations Construction Center
- Distribution Dept.
- **Power System Operation Dept.**
  - Central Load Dispatching Office
    - System Load Dispatching Office
  - Load-dispatching Operation & Maintenance Training Center
- Electronic Telecommunications Dept
- Power System Office (3)
  - Remote Control & Maintenance Office
  - Transmission Office

Flow of Reactive Power Planning
- Example of 2011



Feb.2011 | Mar.2011 | Apr.2011

Branch Offices

Start to study

Study

- Target voltages at secondary sides of 275/66 kV (or 275, 500/154 kV) S/S

- P-Q correlations

- 2010 local power flow diagram at peak (record)

- 2012 local power flow diagram at peak (prediction)

-Making report

1st submission to HQs

2nd submission to HQs

Head Quarters

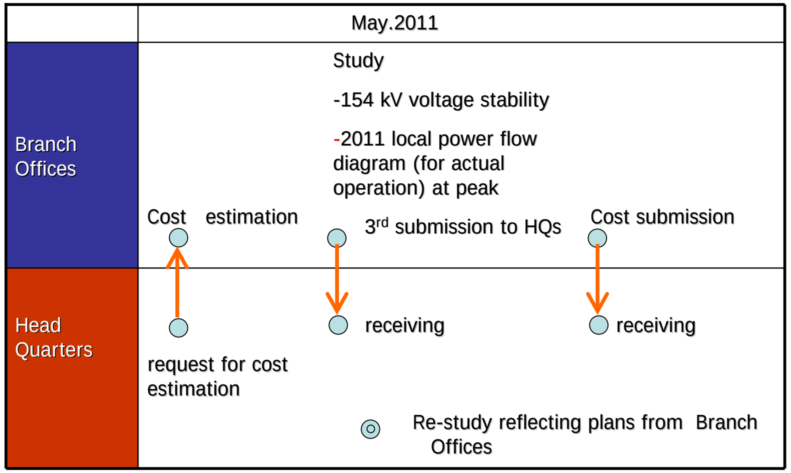
request for study

system modeling

receiving

receiving

making draft study of reactive power sources in whole system



May.2011

Branch Offices

Study

-154 kV voltage stability

-2011 local power flow diagram (for actual operation) at peak

Cost estimation

3rd submission to HQs

Cost submission

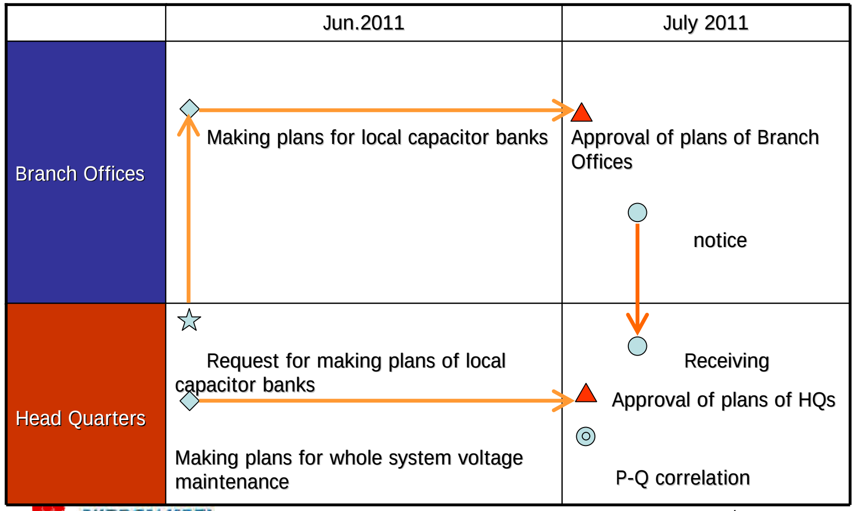
Head Quarters

receiving

receiving

request for cost estimation

Re-study reflecting plans from Branch Offices



Jun.2011 | July 2011

Branch Offices

Making plans for local capacitor banks

Approval of plans of Branch Offices

notice

Head Quarters

Request for making plans of local capacitor banks

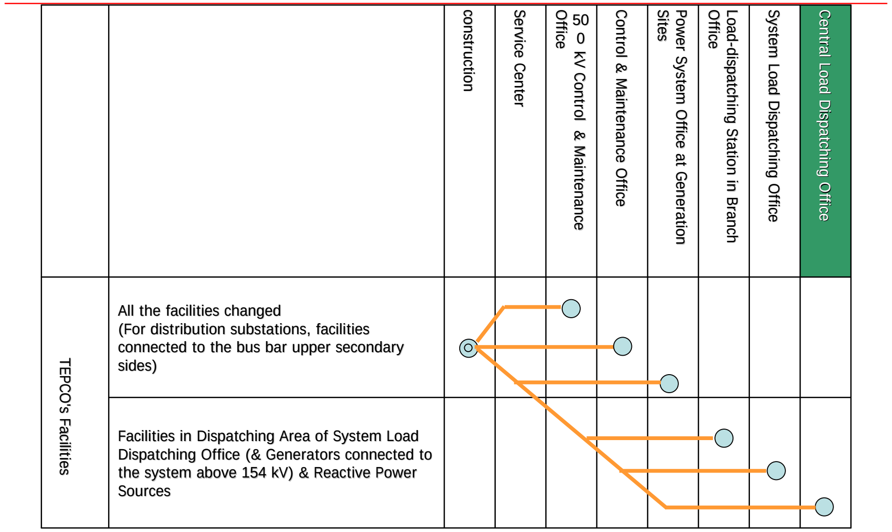
Receiving

Approval of plans of HQs

Making plans for whole system voltage maintenance

P-Q correlation measurement

Information Exchange Flow of Facilities Change
- TEPCO's Facilities

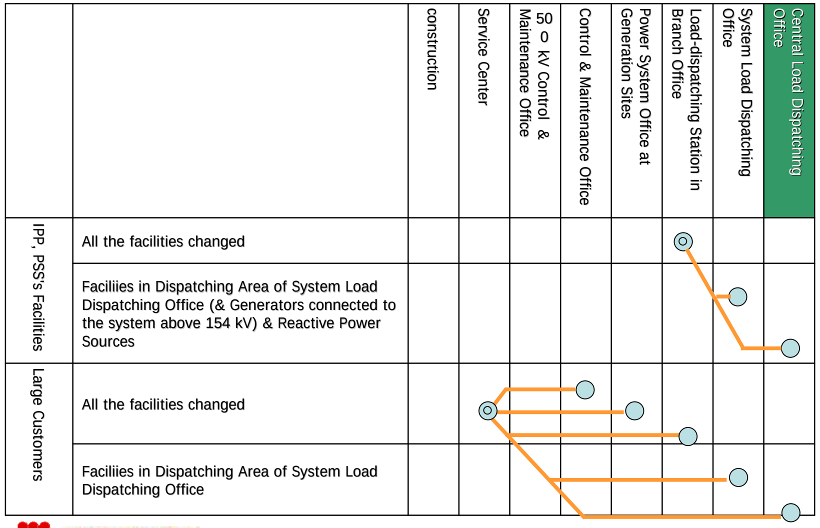


All the facilities changed (For distribution substations, facilities connected to the bus bar upper secondary sides)

Facilities in Dispatching Area of System Load Dispatching Office (& Generators connected to the system above 154 kV) & Reactive Power Sources

◎ Submitter ○ Accepter

Information Exchange Flow of Facilities Change
- IPP/ Large Customers



		construction	Service Center	500 kV Control & Maintenance Office	Control & Maintenance Office	Power System Office at Generation Sites	Load-dispatching Station in Branch Office	System Load Dispatching Office	Central Load Dispatching Office
IPP, PSS's Facilities	All the facilities changed						◎		
	Faciliies in Dispatching Area of System Load Dispatching Office (& Generators connected to the system above 154 kV) & Reactive Power Sources							○	○
Large Customers	All the facilities changed		◎		○	○	○		
	Faciliies in Dispatching Area of System Load Dispatching Office							○	○

Examples of Data Format

Office to be notified	Date of Issue	Issue No.

Notification Changes of Power System Facilities

Name of Facilities		**Expected Completion Data**	
Location			
Outline of Construction (Explanation, Figure)			

Generators (1)

Name			**Xd**	**%**
Unit No.			**Xd'**	**%**
Manufacturer			**Xd"**	**%**
Type			**Xq**	**%**
Admitted Power Output		**MW**	**Xq'**	**%**
Nominal Capacity		**MVA**	**Xq"**	**%**
Nominal Power Output		**MW**	**X2**	**%**
Nominal Current		**A**	**X0**	**%**
House Use	**Nominal Operation**	**MW**	**Xl**	**%**
	Minimum load operation	**MW**	**Ra**	**%**
Nominal Power Factor		**%**	**Td'**	**second**
Nominal Voltage		**kV**	**Td"**	**second**
Short Circuit Ratio			**Tdo'**	**second**
GD2			**Tdo"**	**second**
Unit Inertia Constant M		**MWs/MVA**	**Tq'**	**second**
No. of Damper Windings			**Tq"**	**second**
Rotation Speed		**rpm**	**Tqo'**	**second**
Turbine Bypass Capacity for Nuclear Power Plant		**%**	**Tqo"**	**second**
Cooling Methodology			**Ta**	**second**
Date of Manufacture				
Data Source				

- Machine Base
- Identifying data condition as (1) measurement (2) plan (3) estimation (4) saturation (5) not saturation

Generators (2)

	Plant Name		**Type**	
	Unit No.		**Excitation Capacity**	
	Manufacture		**Date of Manufacture**	
	Type of Operation	**AVR**	**APFR**	**AQR**
Operation Mode	**Normal Operation**	**Gen. PSPP. Reactive Power.**	**Gen. PSPP. Reactive Power.**	**Gen. PSPP. Reactive Power.**
Applicable Operation Mode		**Gen. PSPP. Reactive Power.**	**Gen. PSPP. Reactive Power.**	**Gen. PSPP. Reactive Power.**
Allowable Setting Range		**% - % of Nominal Voltage**	**P.F. (Q=bP)** **Lead % - Lag %**	**Q=a+bP** **a: PU b: Q/P**
Minimum Setting Value		**%**	**%**	**a: MVar b: Q/P**
Dead Band		**%**	**%**	
Setting Value	**Generation**	**%**	**%**	**a: MVar b:**
	Pumped Storage	**%**	**%**	**a: MVar b: Q/P**
	Reactive Power	**%**	**%**	**a: MVar b: Q/P**
	Test Energizing	**at Output %-**	**%**	**a: MVar b:**
Change of Operation Mode		**Remote Capable. Only at site.**	**Remote Capable. Only at site.**	**Remote Capable. Only at site.**
Change in Setting Value	**Control Function**	**Remote Capable. Only at site.**	**Remote Capable. Only at site.**	**Remote Capable. Only at site.**
	Condition	**Capable during operation or not**	**Capable during operation or not**	**Capable during operation or not**

Generators (3)

			Maximum	Minimum
Allowable Control Range of Reactive Power	Generation	Nominal	MVar	MVar
		Minimum	MVar	MVar
	Pumped Storage		MVar	MVar
	Reactive Power Output		MVar	MVar
	Test Energizing		MVar	MVar

Overhead Transmission Line (1)

Name of Lines			Voltage/No. of Circuits		
Interval					
Tower Type					
	a	m	m	m	m
	b	m	m	m	m
	C	m	m	m	m
	D	m	m	m	m
	E	m	m	m	m
	F	m	m	m	m
	G	m	m	m	m
	h	m	m	m	m
	i	m	m	m	m
	j	m	m	m	m
	k	m	m	m	m
	l	m	m	m	m
	m	m	m	m	m
	n	m	m	m	m
	o	m	m	m	m
	p	m	m	m	m
	q	m	m	m	m
	r	m	m	m	m
	s	m	m	m	m
	t	m	m	m	m

Overhead Transmission Line (2)

Length		km	km	km	km
Land Conditions		Mountain Plain	Mountain Plain	Mountain Plain	Mountain Plain
Conductor		Mountain Plain	Mountain Plain	Mountain Plain	Mountain Plain
Number of Bundles		Mountain Plain	Mountain Plain	Mountain Plain	Mountain Plain
Distance of Bundles					
Co-mounted T/L	Name				
	Voltage/No. of Circuits				
	Conductor				
	Number of Bundles				
	Distance of Bundles				
Earth Wire	Conductor				
	Number of Wires				

Underground Cables

	Name of Lines			Voltage/No. of Circuits		
	Interval			Type of Estimation	Calculation Measurement	
			Black	Red	White	Averaged
Impedance	Positive Sequence	Resistance	ohm	ohm	ohm	ohm
		Reactance	ohm	ohm	ohm	ohm
		Capacitance	micro F	micro F	micro F	micro F
	Zero Sequence	Resistance	ohm	ohm	ohm	ohm
		Reactance	ohm	ohm	ohm	ohm

Allowable Capacity	Condition				
	Continuous				
	0.5 hours				
	1 hour				
	2 hours				
	4 hours				
	8 hours				

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- Tokyo Blackout in 1987 -

Technical Transfer Seminar
13th June. 2013
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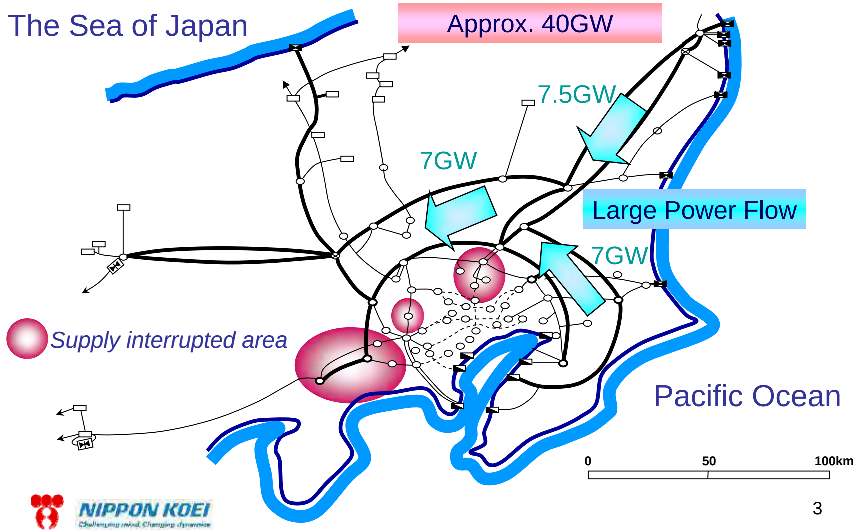
CONTENTS

- **Importance of Appropriate Voltage Control**
  - **TEPCO's Experience of Voltage Collapse in 1987**
- **Countermeasures that TEPCO has taken since 1987**
  - **Resource of Reactive Power**
  - **Improved Voltage Operation and Control Measures**

Importance of Appropriate Voltage Control

Transmission Network of TEPCO in 1987



TEPCO Experience of Voltage Collapse

- In July 1987, TEPCO experienced extensive outages caused by voltage instability
- Not contingencies but rapid demand increase led to the situation of no power flow solution, e.g. Voltage Collapse
- 8GW loads were lost due to protective relay operations for transmission lines and transformers under extreme low voltage (approx. 20％ of the total demand)
- The interrupted loads were restored within 4 hours

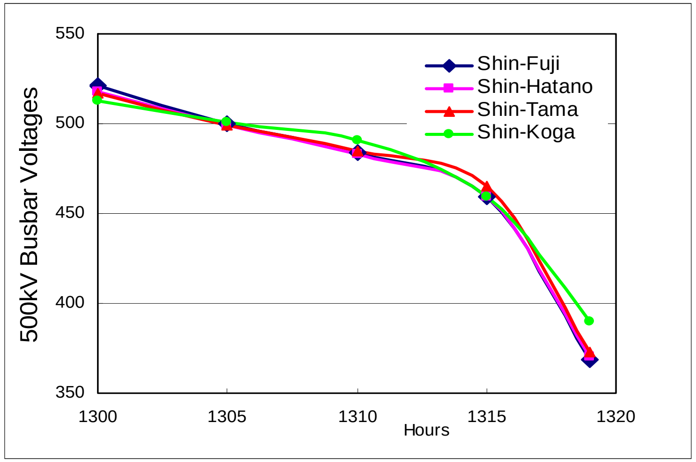
Chief Events in July 23, 1987

- 12:40PM
  - The total demand has reached 36.5GW, steep increasing after lunch break
- 13:00
  - Shunt Capacitors were put in service and reactive power supply from generators were increased to meet the increasing Var consumption
- 13:00-13:10
  - The load increased at 400MW／min., which was much steeper than forecast
  - All available capacitors were put into the system
  - Voltages at 500kV substations gradually fell down

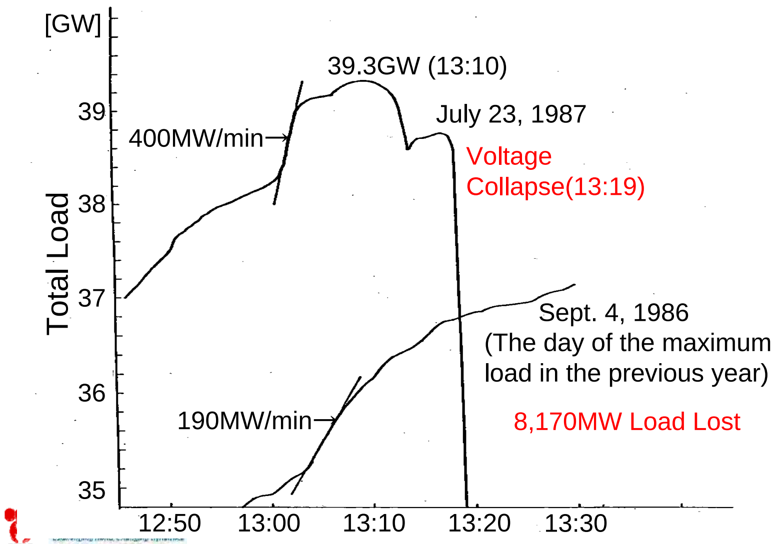
Chief Events in July 23, 1987 (cont.)

- 13:10
  - The load has reached 39.3GW, the highest level
- 13:15
  - Voltages at the 500kV substations close to Tokyo metropolitan area decreased to around 460kV
- 13:19
  - Voltages at the 500kV substations fell down rapidly (about 370kV at the western area, 390kV at the central area)
  - Protective relays operated due to the voltage fall, consequently three substations were shut down
  - Power outage of 8,168MW

Busbar voltages at 500kV substations in the event of Voltage Collapse



Load Curve (12:50 - 13:20)



Main Causes of Voltage Collapse

- Heavy loading in 500kV bulk transmission network;
  2 times or more SIL (Surge Impedance Loading)
- Rapid power demand increase; 0.4 GW/min

- Insufficient practical knowledge on voltage instability phenomena
- Insufficient reactive power (Var) supply capability in terms of quantity and speed

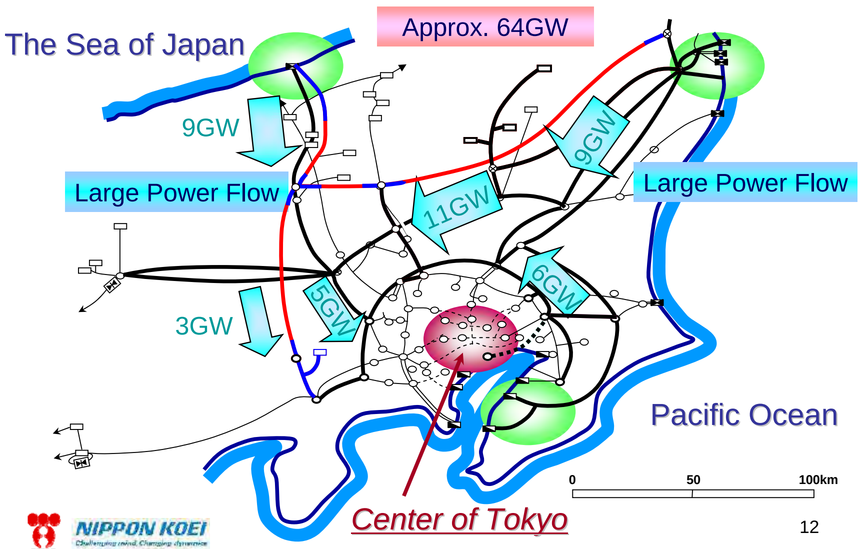
---

Countermeasures that TEPCO has taken since 1987

TEPCO's extensive system engineering experience since 1987

- TEPCO has enhanced power transfer capability by
  - installing numerous amount of Switched Shunt Capacitors up to 18GVAr to EHV S/Ss,
  - applying Automatic Controller (VQC) that switches on the Shunt Capacitors within a few seconds,
  - applying High speed high side voltage controller (PSVR) to about 80 generators connected to the EHV network
- TEPCO believes that automatic switching of shunt capacitors is regarded as a sort of dynamic reactive power resources
- In addition, Bulk Power System enhancement has been implemented, particularly acceleration of the existing plans on new transmission and substation constructions

Present Transmission Network in TEPCO



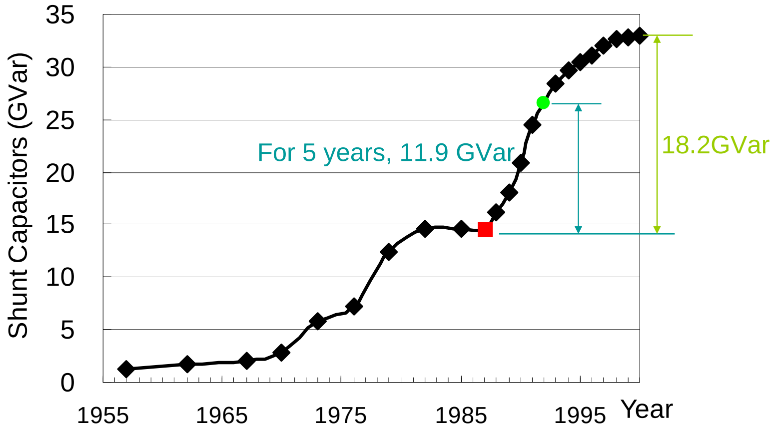
Reinforcement in Q resource

To secure sufficient Q supply, TEPCO has installed numerous amount of Q resources other than generators:

(1987 – present)

● **Shunt Capacitors**	**: 18,200MVA**
● **SVCs**	**: 600MVA**
● **Synchronous Condensers**	**: 1,368MVA**

Shunt Capacitors installed in TEPCO power system



Installation of LVR (or VR) to tertiary circuit of transformer

- In order to maintain the high-side voltage at higher level, shunt capacitors connected to tertiary side are switched on.

↓

- In order to maintain the low-side voltage within allowable range, lower tap positions are selected.

↓

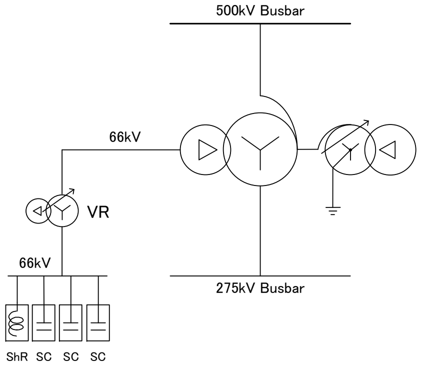
- The voltage at tertiary side exceeds the upper limit.

↓

- Installation of LVR or VR is required to lower the voltage at tertiary side.

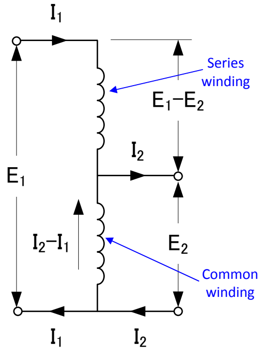
Auto transformers are applied for 500/275kV transformers.

- ➢ The primary and secondary winding shares same common single winding.
- ➢ On load tap changer is connected at the neutral end of high voltage winding.



Connection Diagram of Auto Transformer

- In an auto transformer the primary and secondary winding shares same common single winding.
- Single phase auto transformers is smaller in size & lighter in weight and also cheaper than common dual-winding type transformer.
- Because of electrical conductivity of the primary and secondary windings, the lower voltage circuit is liable to be impressed upon by higher voltage. To avoid breakdown in the lower voltage circuit, it becomes necessary to design the low voltage circuit to withstand higher voltage.
- The leakage flux between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.



$$E_1 \cdot I_1 = E_2 \cdot I_2 = S$$

$$S_s = \frac{S(E_1 - E_2)}{E_1}$$

$$\gamma = \frac{S_S}{S} = \frac{E_1 - E_2}{E_1}$$

Improved Voltage Operation and Control Measures

- **Monitoring**
  - **Reinforcement in Monitoring of Voltage and Reactive Power Flow on Dynamic Map Board**
  - **Development of On-Line Voltage Security Monitoring System**
- **Operational measures**
  - **Improvement in Voltage Control Procedures so as to operate system voltage as higher as possible**
  - **Review of Voltage Control Operation Manual**
  - **Updating of VQC Setting to meet system condition**
- **Protection and Control System**
  - **Improvement of the existing VQC controllers**
  - **Development of Under Voltage Load Shedding scheme**

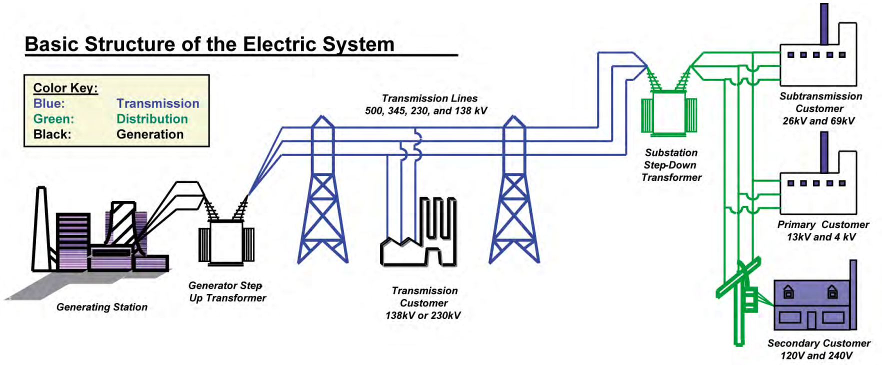
Improved Voltage Operation and Control Measures (Cont')

- **Lecture and Training**
  - **To give lecture for shift operates working at dispatching centers, 500kV substations and power stations**
  - **New dispatcher training to acquire skills through drills**
- **Improvement in Off-line Digital Simulation**
  - **Development of a new simulation tool that can model VQC control action**
  - **Establishment of a new load forecasting methodology, particularly reactive power load**
  - **Establishment of new evaluation methodologies to assess voltage stability limit**
  - **Accumulation of useful know-how to determine appropriate settings for Voltage Controllers**

JICA
The Study on Power Supply Reliability Improvement in Jakarta
- Case study of wide area blackout in the United States and Canada in 2003
Technical Transfer Seminar

13th June. 2013
Tokyo Electric Power Company Inc.
Nippon Koei Co., LTD

Power System Overview



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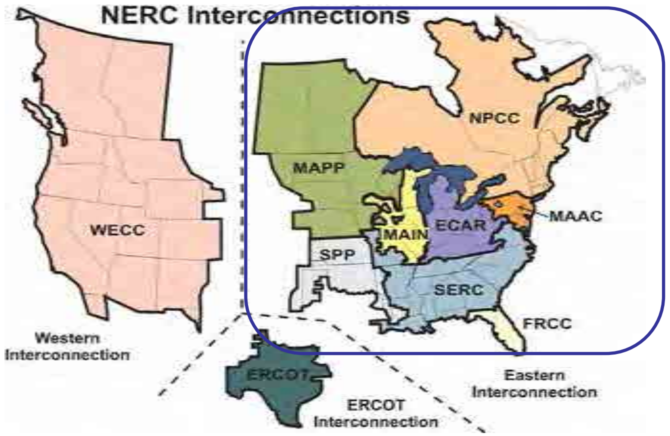
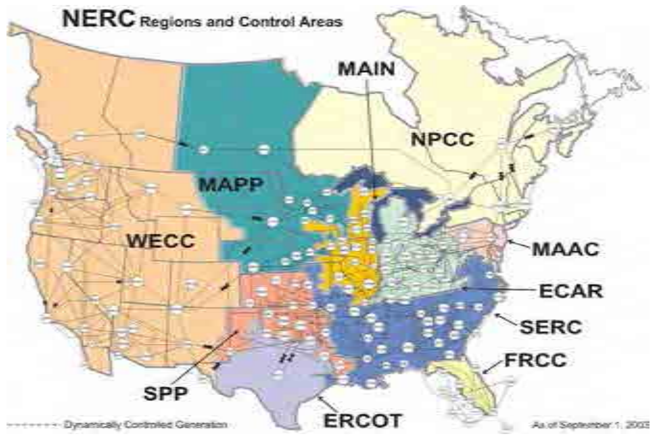
3 Interconnections / 10 NERC Regions

NERC's members are ten regional reliability councils.



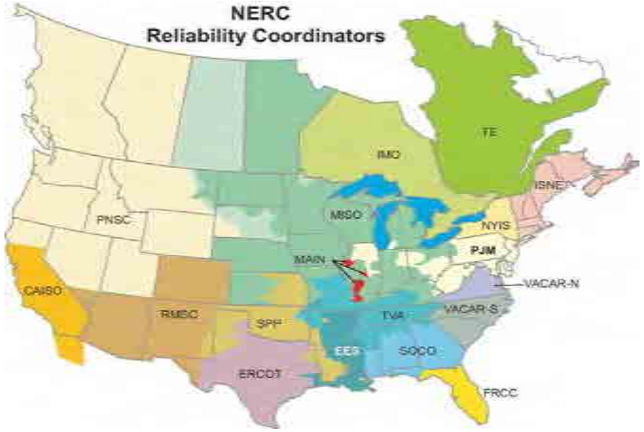
NERC Control Areas



Control Area

- A control area is a geographic area within which a single entity, Independent System Operator (ISO), or Regional Transmission Organization (RTO) balances generation and loads in real time to maintain reliable operation.
- The primary functions of ISOs and RTOs are to manage in real time and on a day-ahead basis the reliability of the bulk power system and the operation of wholesale electricity markets within their footprint.
- ISOs and RTOs do not own transmission assets; they operate or direct the operation of assets owned by their members.
- ISOs and RTOs may be control areas themselves, or they may encompass more than one control area.

NERC Reliability Coordinators



Reliability coordinators provide reliability oversight over a wide region

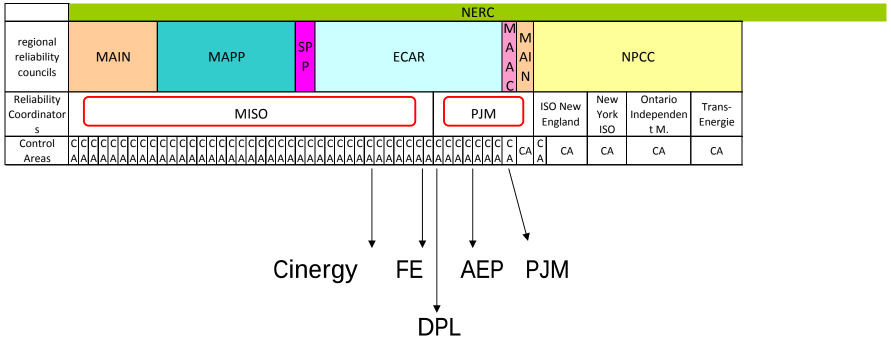
- They prepare reliability assessments, provide a wide-area view of reliability, and coordinate emergency operations in real time for one or more control areas. They may operate, but do not participate in, wholesale or retail market functions. There are currently 18 reliability coordinators in North America. Figure shows the locations and boundaries of their respective areas.

Key Parties in the Pre-Cascade Phase of the August 14 Blackout

- Five RTOs/ISOs are within the area directly affected by the August 14 blackout. They are:
  - Midwest Independent System Operator (MISO)
  - PJM Interconnection (PJM)
  - New York Independent System Operator
  - (NYISO)
  - New England Independent System Operator
  - (ISO-NE)
  - Ontario Independent Market Operator (IMO)

Institutional Complexities and Reliability in the Midwest

Reliability Coordinator (RC)	Control Areas in RC Areas	Regional Reliability Councils Affected and Number of Control Areas	Control Areas of Interest in RC Area
MISO	37	ECAR(12), MAIN(9), MAPP(14), SPP(2)	FE, Cinergy, Michigan Electric Coordinated System
PJM	9	MAAC(1), ECAR(7), MAIN(1)	PJM, AEP, Dayton Power & Light
ISO New England	2	NPCC(2)	ISONE, Maritimes
New York ISO	1	NPCC(1)	NYISO
Ontario Independent Market Operator	1	NPCC(1)	IMO
Trans-Energie	1	NPCC(1)	Hydro Quebec

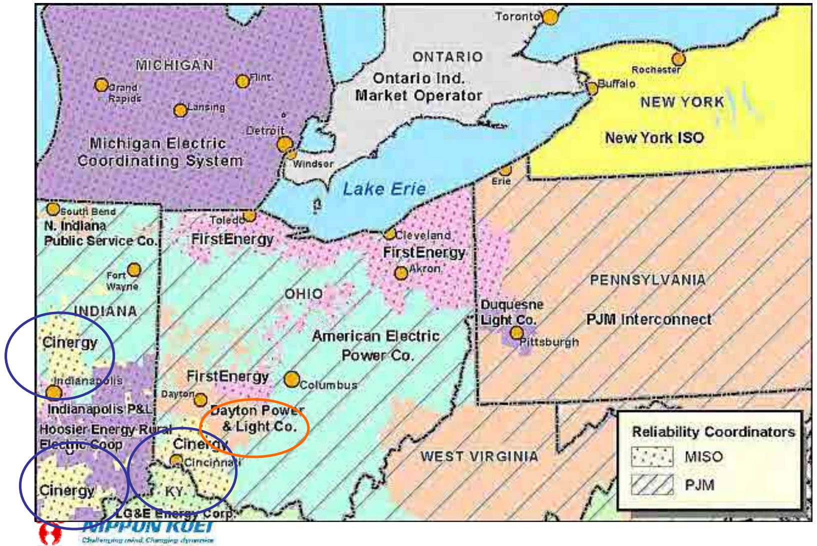


- **FirstEnergy (FE) consists of seven electric utility operating companies. Four of these companies, Ohio Edison, Toledo Edison, The Illuminating Company, and Penn Power, operate in the NERC ECAR region, with MISO serving as their reliability coordinator. These four companies now operate as one integrated control area managed by FE.4**
- **AEP is both a transmission operator and a control area operator.**

- **The Midwest Independent System Operator (MISO) is the reliability coordinator for a region of more than 1 million square miles (2.6 million square kilometers), stretching from Manitoba, Canada in the north to Kentucky in the south, from Montana in the west to western Pennsylvania in the east. Reliability coordination is provided by two offices, one in Minnesota, and the other at the MISO headquarters in Indiana. Overall, MISO provides reliability coordination for 37 control areas, most of which are members of MISO.**

- PJM is one of the original ISOs formed after FERC orders 888 and 889, but was established as a regional power pool in 1935. PJM recently expanded its footprint to include control areas and transmission operators within MAIN and ECAR (PJMWest).
- It performs its duties as a reliability coordinator in different ways, depending on the control areas involved. For PJM-East, it is both the control area and reliability coordinator for ten utilities, whose transmission systems span the Mid-Atlantic region of New Jersey, most of Pennsylvania, Delaware, Maryland, West Virginia, Ohio, Virginia, and the District of Columbia. The PJM-West facility has the reliability coordinator desk for five control areas (AEP, Commonwealth Edison, Duquesne Light, Dayton Power and Light, and Ohio Valley Electric Cooperative) and three generation-only control areas (Duke Energy's Washington County (Ohio) facility, Duke's Lawrence County/Hanging Rock (Ohio) facility, and Allegheny Energy's Buchanan (West Virginia) facility.

Footprints of Reliability Coordinators in Midwest



12:08 Cinergy 345-, 230-,and 138-kV Lines Out of Service

- Transmission lines on the Cinergy 345-, 230-,and 138-kV systems experienced a series of outages starting at 12:08 EDT and remained out of service during the entire blackout.
  - The loss of these lines was not electrically related to subsequent events in northern Ohio that led to the blackout.

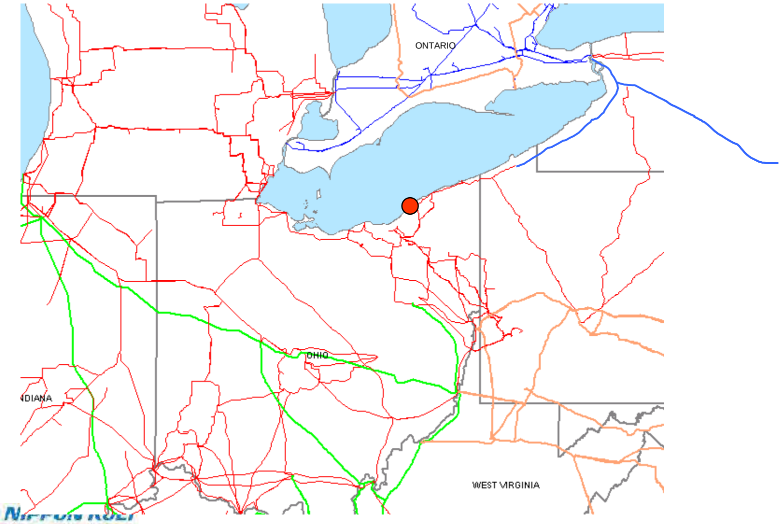
MISO State Estimator and Reliability Analysis

- MISO state estimator and contingency analysis ineffective from 12:37 to 16:04
  - State estimator not solving due to missing information on lines out in Cinergy then DPL
  - Human error in not resetting SE automatic trigger
- Using Flowgate Monitoring tool to monitor conditions on previously identified critical flowgates

13:31 Eastlake Unit 5 597 MW Tripped

- Eastlake Unit 5 is a 597 MW (net) generating unit located west of Cleveland on Lake Erie. It is a major source of reactive power support for the Cleveland area. It tripped at 13:31 EDT.
- The cause of the trip was that as the Eastlake 5 operator sought to increase the unit's reactive power output, the unit's protection system detected that VAr output exceeded the unit's VAr capability and tripped the unit off-line.
- The loss of the Eastlake 5 unit did not put the grid into an unreliable state—i.e., it was still able to withstand safely another contingency. However, the loss of the unit required FE to import additional power to make up for the loss of the unit's output (612 MW), made voltage management in northern Ohio more challenging, and gave FE operators less flexibility in operating their system (see details on pages 45-46 and 49-50).

East Lake 5 Trip: 1:31:34 PM



14:02 DPL 345-kV Line Tripped

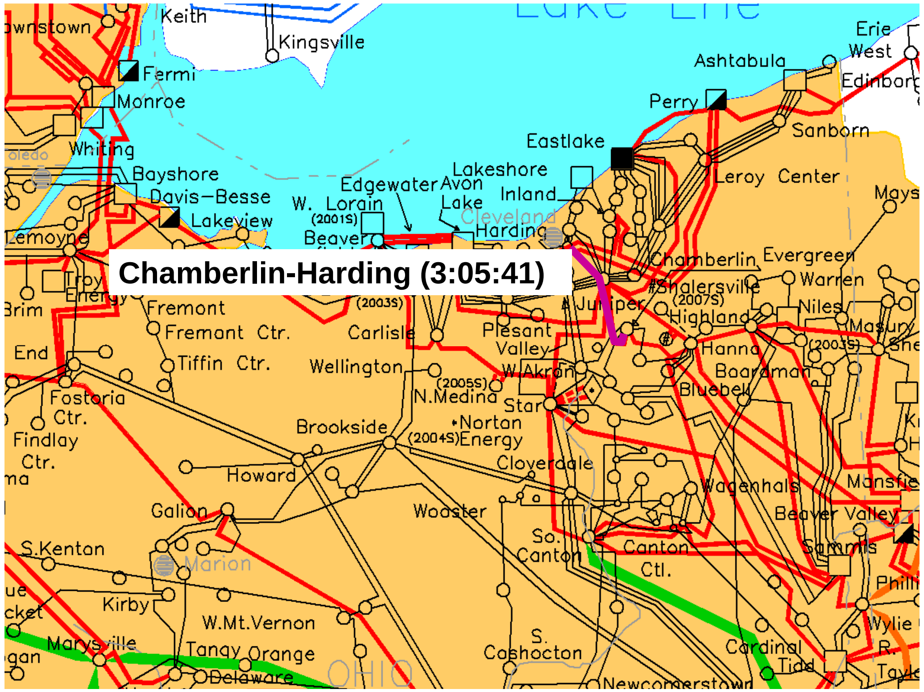
- The Stuart-Atlanta 345-kV line, operated by DPL, and monitored by the PJM reliability coordinator, tripped at 14:02 EDT
- This was the result of a tree contact, and the line remained out of service the entire afternoon.
- System modeling by the investigation team has shown that this outage did not cause the subsequent events in northern Ohio that led to the blackout.
- However, since the line was not in MISO's footprint, MISO operators did not monitor the status of this line and did not know it had gone out of service. This led to a data mismatch that prevented MISO's state estimator (a key monitoring tool) from producing usable results later in the day at a time when system conditions in FE's control area were deteriorating

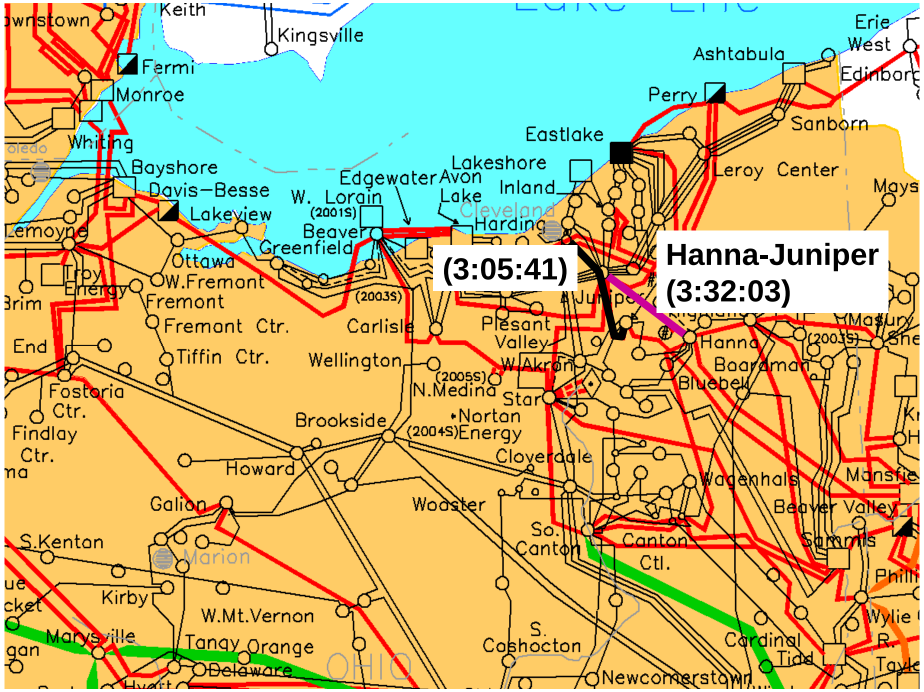
FirstEnergy Computer Failures

- 14:14 Alarm logger fails and operators are not aware
  - No further alarms to FE operators
- 14:20 Several remote consoles fail
- 14:41 EMS server hosting alarm processor and other functions fails to backup
- 14:54 Backup server fails
  - EMS continues to function but with very degraded performance (59 second refresh)
  - FE system data passed normally to others: MISO and AEP
  - AGC function degraded and strip charts flat-lined
- 15:08 IT warm reboot of EMS appears to work but alarm process not tested and still in failed condition
- No contingency analysis of events during the day including loss of East Lake 5 and subsequent line trips

Phone Calls to FirstEnergy

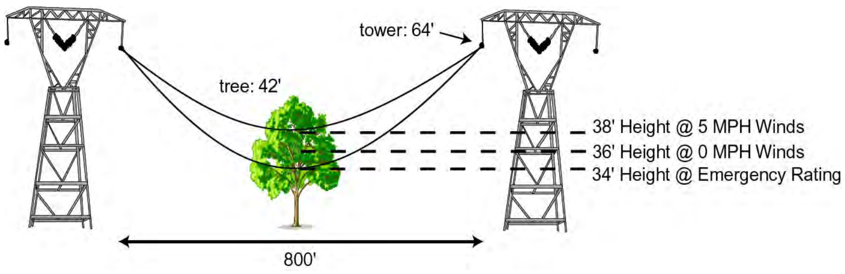
- **FE received calls from MISO, AEP, and PJM indicating problems on the FE system but did not recognize evolving emergency**
  - **14:32 AEP calls regarding trip and reclose of Star-S. Canton**
  - **15:19 AEP calls again confirming Star-S. Canton trip and reclose**
  - **15:35 Calls received about “spikes” seen on system**
  - **15:36 MISO calls FE regarding contingency overload on Star-Juniper for loss of Hanna-Juniper**
  - **15:45 FE tree trimming crew calls in regarding Hanna-Juniper flashover to a tree**
  - **PJM called MISO at 15:48 and FE at 15:56 regarding overloads on FE system**

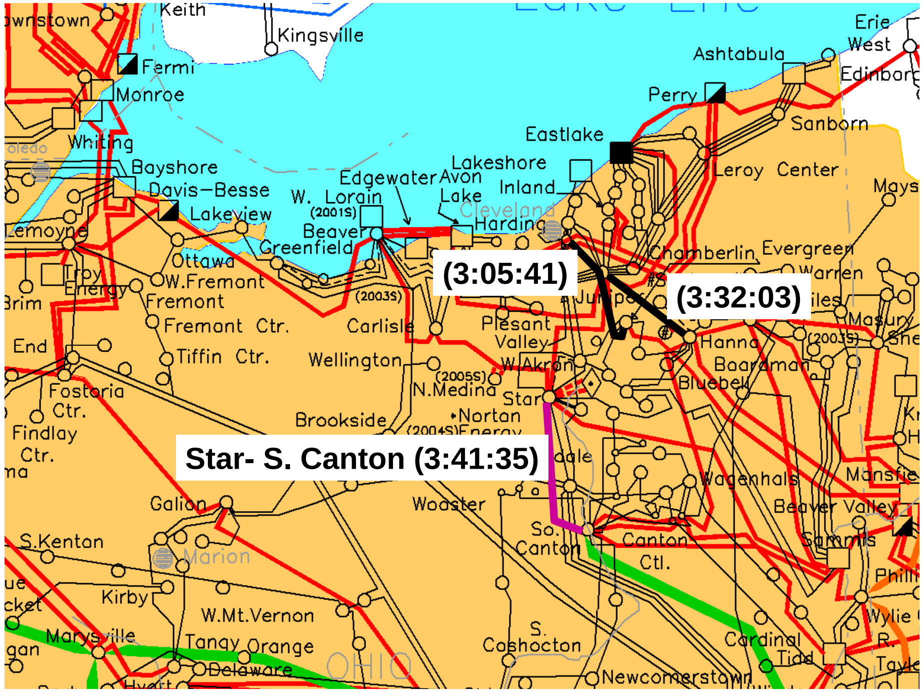




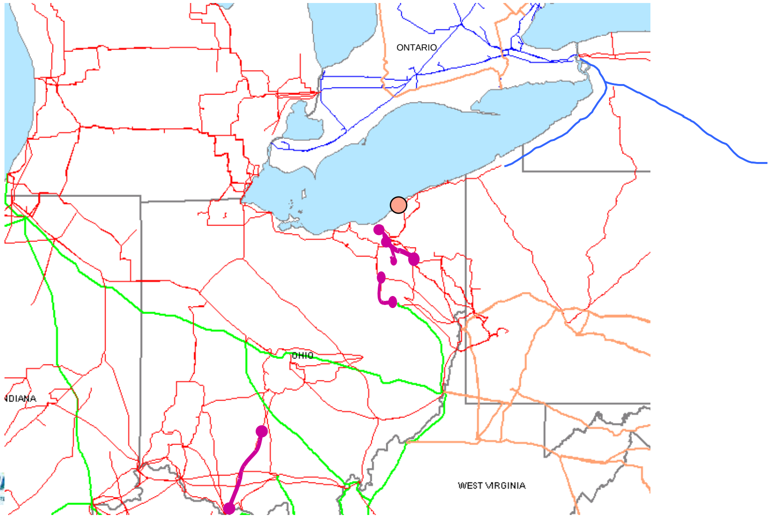
Hanna Juniper Confirmed as Tree Contact at Less than Emergency Ratings of Line

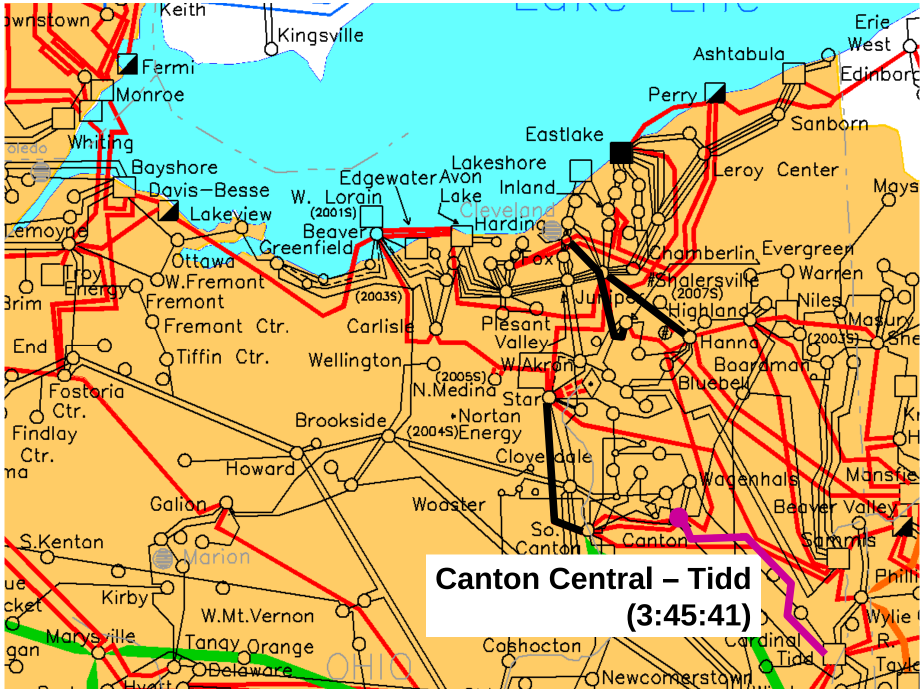
Effects of Ambient Conditions on Ratings

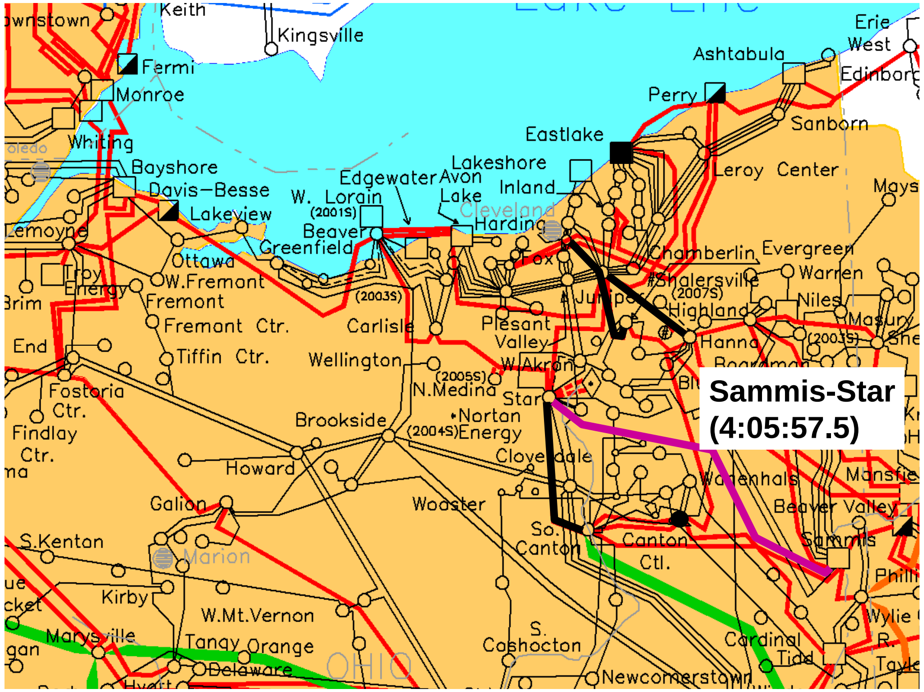




Situation after Initial Trips 3:05:41 – 3:41:35

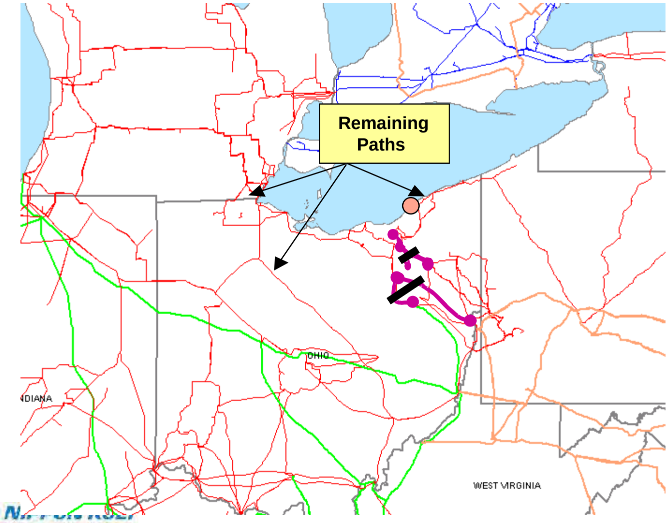






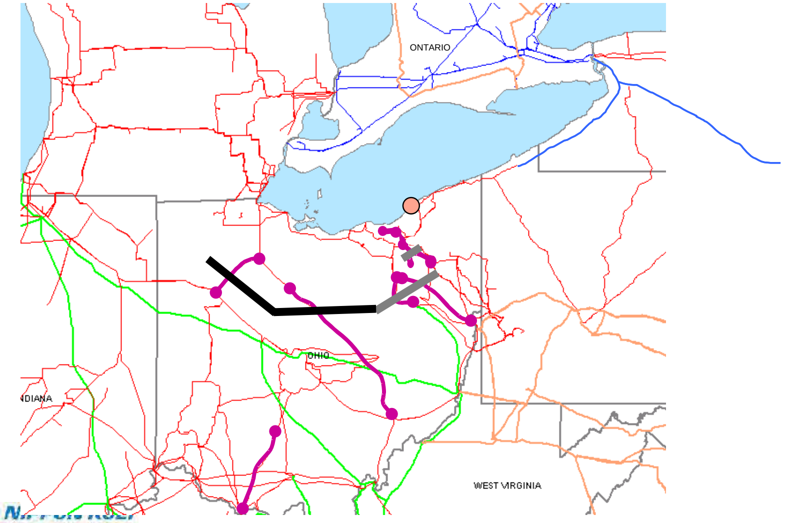
Sammis-Star (4:05:57.5)

Major Path to Cleveland Blocked after Loss of Sammis-Star 4:05:57.5 PM

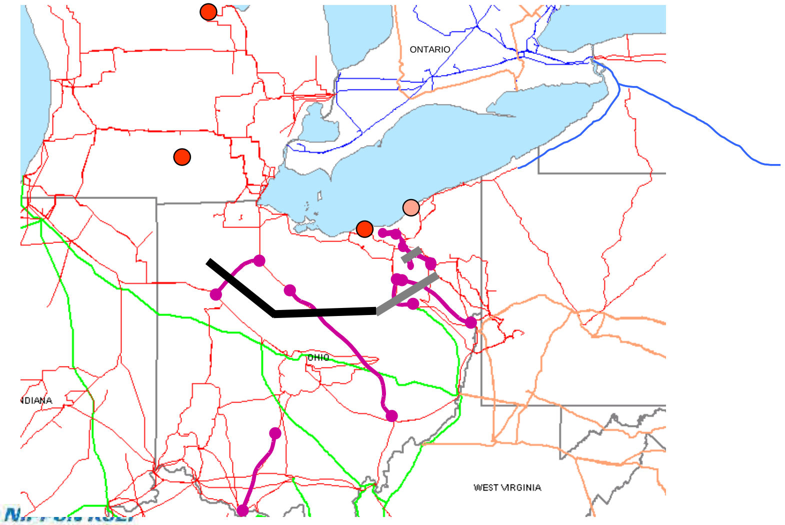


Remaining Paths

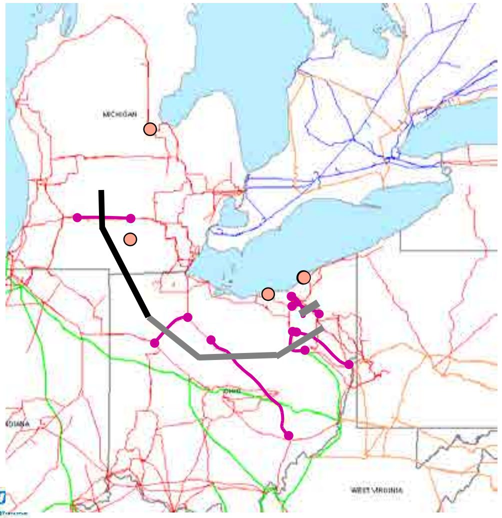
345 kV Lines Trip Across Ohio to West



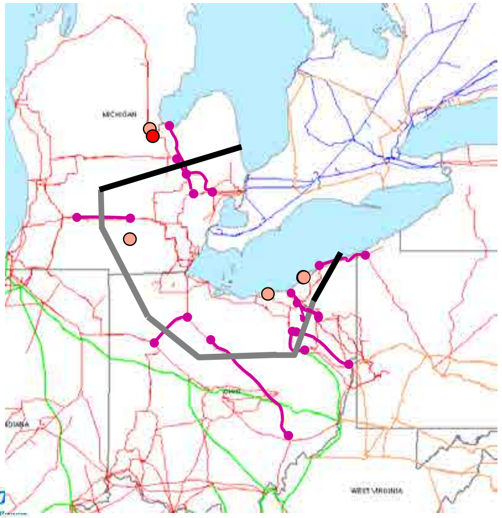
Generation Trips 4:09:08 – 4:10:27 PM



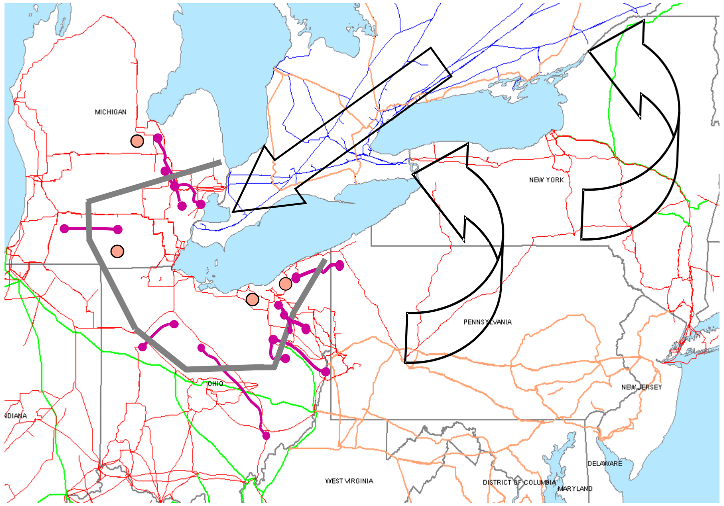
345 kV Transmission Cascade Moves North into Michigan 4:10:36 – 4:10:37 PM



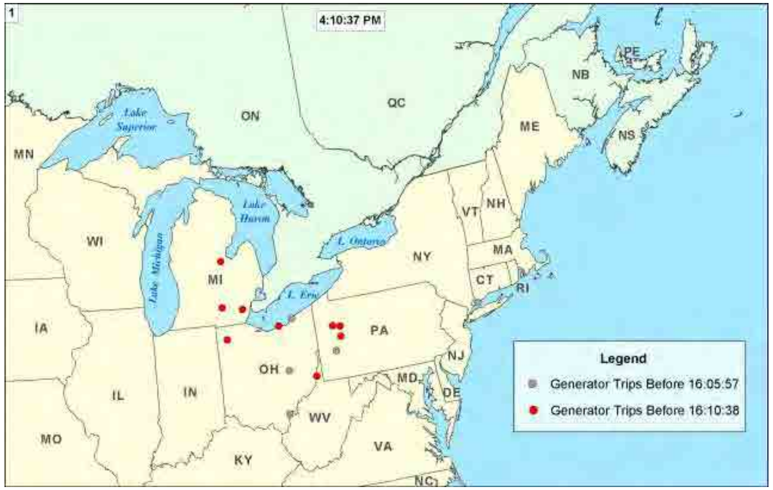
Northern Ohio and Eastern Michigan Served Only from Ontario after 4:10:37.5 – 4:10:38.6 PM



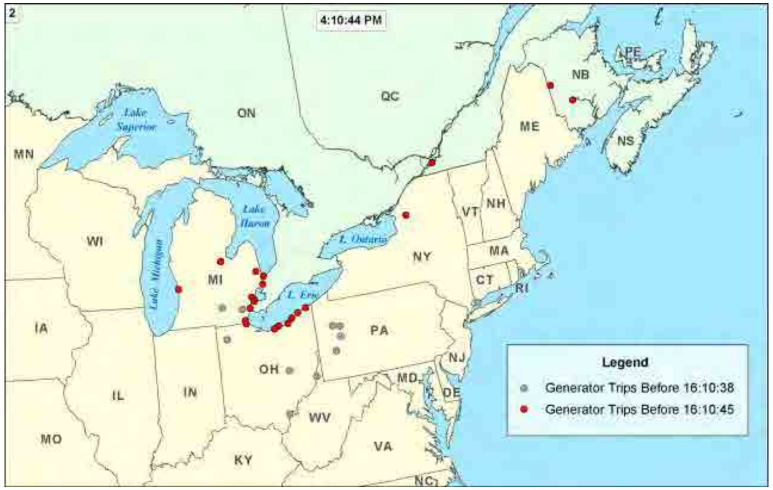
Power Transfers Shift at 4:10:38.6 PM



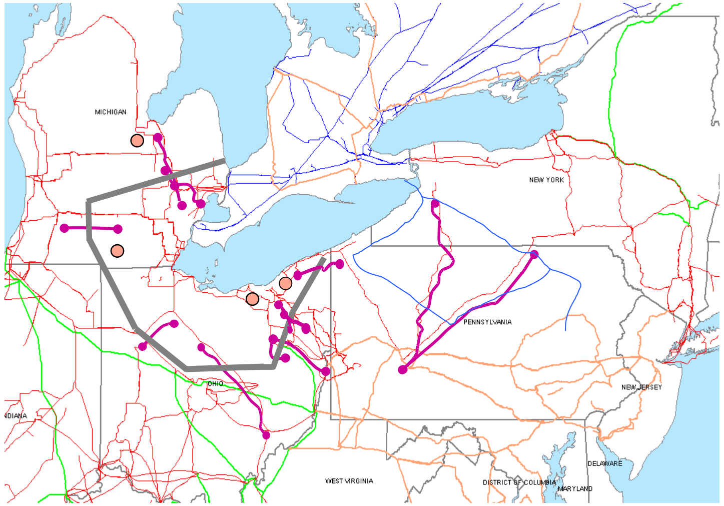
Generator Trips to 16:10:38



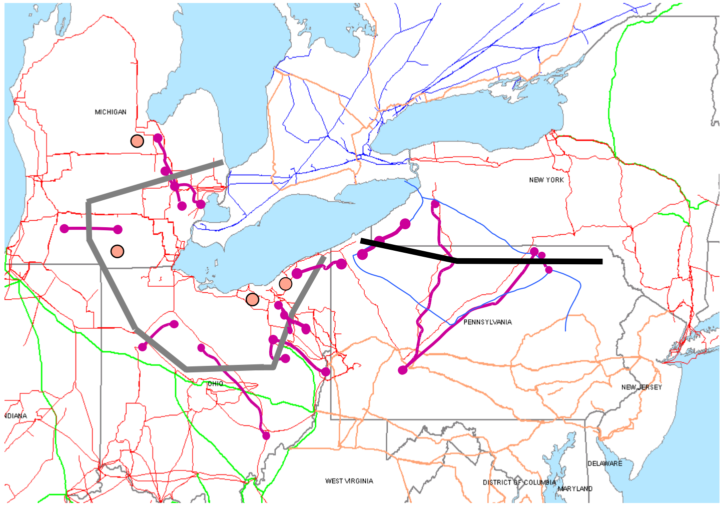
Generator Trips – Next 7 Seconds



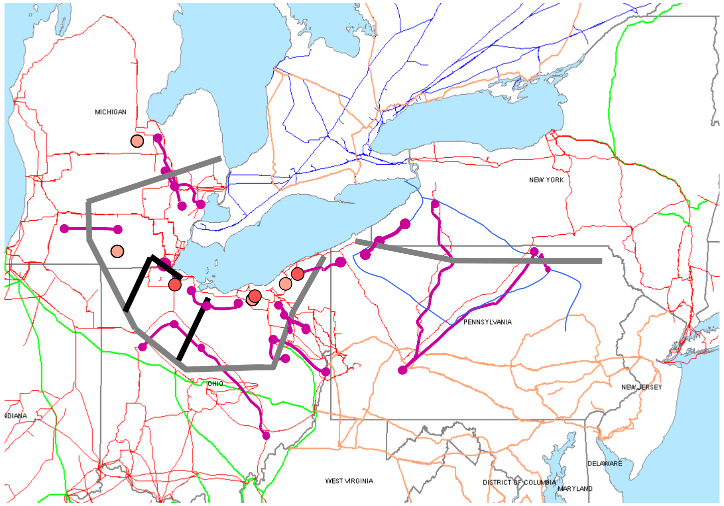
Overloads on PJM – NY Ties 4:10:39 PM



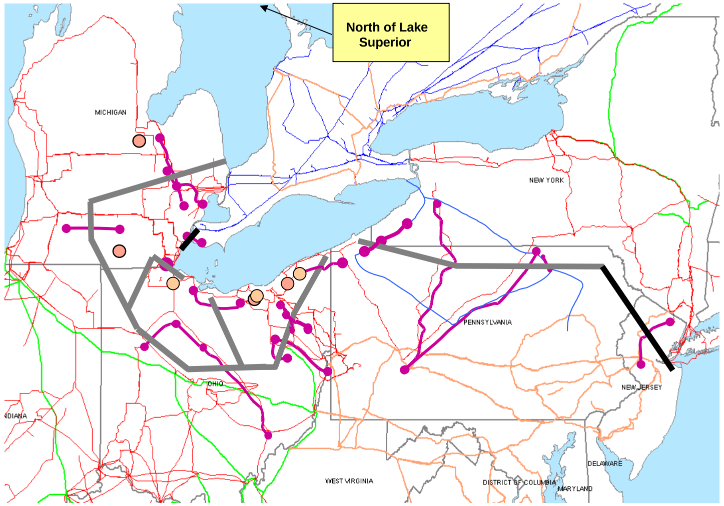
PJM – NY Separating 4:10:44 PM



Cleveland – Toledo Island 4:10:39 - 4:10:46 PM
Cleveland Blacks Out

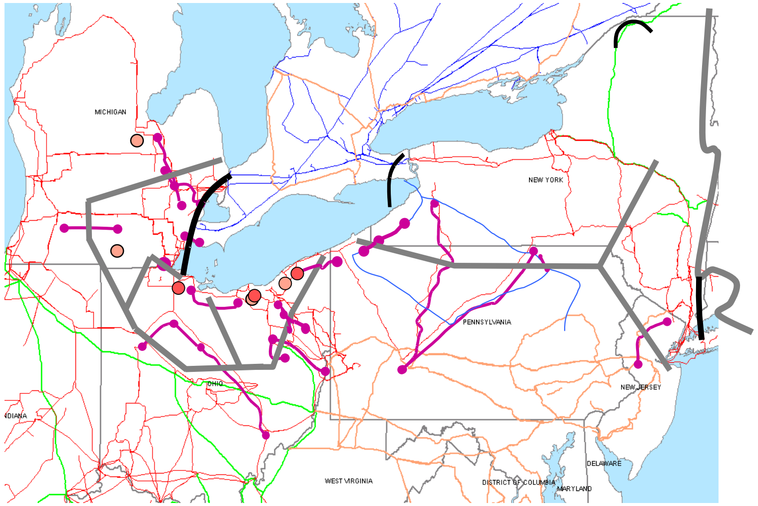


Northeast Completes Separation from Eastern Interconnection 4:10:43 – 4:10:45 PM

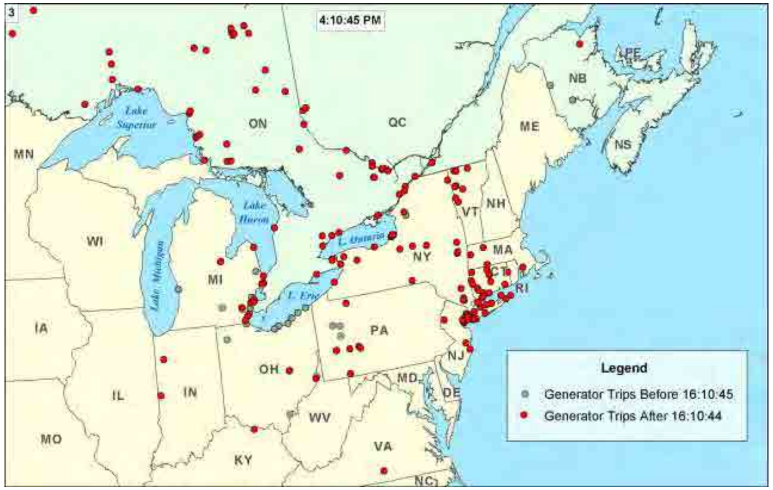


North of Lake Superior

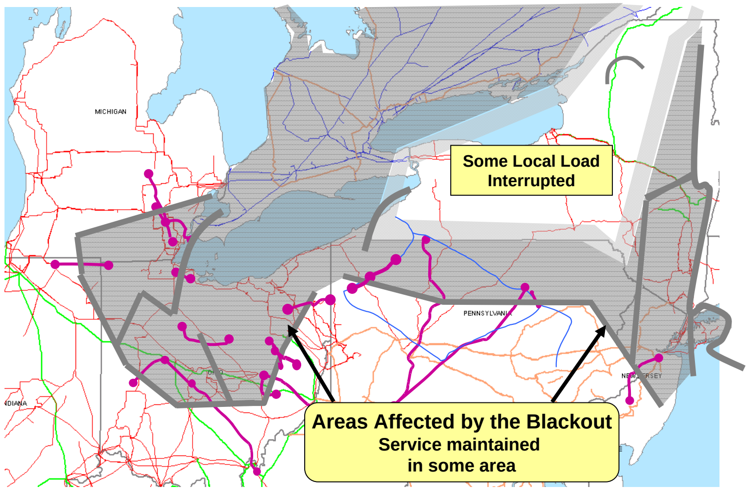
Island Breaks Up: 4:10:46 – 4:13 PM



Generator Trips – After 16:10:44



End of the Cascade



Some Local Load Interrupted

Areas Affected by the Blackout
Service maintained in some area

Overview of Recommendations

- **1. Correct the Direct Causes of the August 14, 2003 Blackout.**
- **2. Strengthen the NERC Compliance Enforcement Program.**
- **3. Initiate Control Area and Reliability Coordinator Reliability Readiness Audits.**
- **4. Evaluate Vegetation Management Procedures and Results.**
- **5. Establish a Program to Track Implementation of Recommendations.**

- **6. Improve Operator and Reliability Coordinator Training**
- **7. Evaluate Reactive Power and Voltage Control Practices.**
- **8. Improve System Protection to Slow or Limit the Spread of Future Cascading Outages.**
- **9. Clarify Reliability Coordinator and Control Area Functions, Responsibilities, Capabilities**
- **and Authorities.**
- **10. Establish Guidelines for Real-Time Operating Tools.**
- **11. Evaluate Lessons Learned During System Restoration.**
- **12. Install Additional Time-Synchronized Recording Devices as Needed.**
- **13. Reevaluate System Design, Planning and Operating Criteria.**
- **14. Improve System Modeling Data and Data Exchange Practices.**

JICA
The Study on Power Supply Reliability Improvement in Jakarta

- Advanced voltage and reactive power control -

Technical Transfer Seminar

13th June. 2013

Tokyo Electric Power Company Inc.

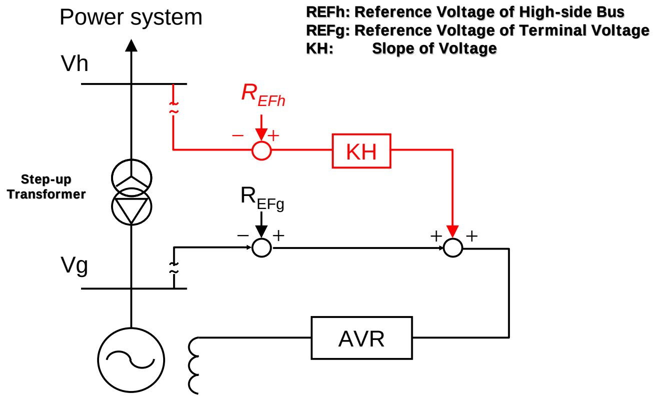
Nippon Koei Co., LTD

Contents

- Advanced high side voltage regulator
- Advanced substation voltage control
- Coordinated voltage control in transmission networks
- Voltage and reactive power control scheme (local and centralized)
- Trend of PMU Technology

Power System Voltage Regulator (PSVR)

- Applied to all generators connected to 500 & 275kV system
- Regulate high-side busbar voltage VH at predetermined reference voltage

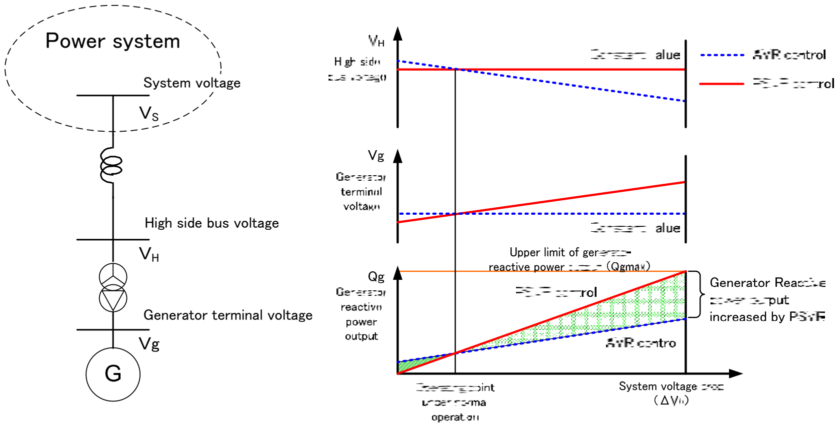


REFh: Reference Voltage of High-side Bus
REFg: Reference Voltage of Terminal Voltage
KH: Slope of Voltage

PSVR Control Structure

Power System Voltage Regulator (PSVR)

Control Characteristics of PSVR and AVR



Voltage Control Patterns of PSVR

Application purpose of Each Control Pattern

Control Patterns	System Voltage	
	Day	Night
Pattern A	High	Normal
Pattern B	Slightly high	Slightly high
Pattern C	Normal	Normal
Pattern D	Normal	Under operation of many pumped-storage hydro generators
Pattern Holiday	Low	Low

Control Patterns According to Peak Demand

	Peak Demand			
	Above ◎◎GW	Below ◎◎GW	Below △△GW	Holiday
Control Patterns	Pattern A	Pattern C	Pattern Holiday	Pattern Holiday

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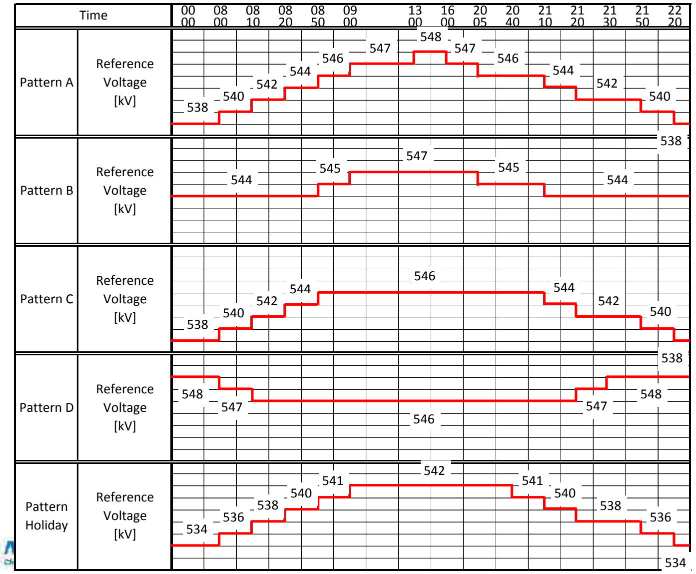
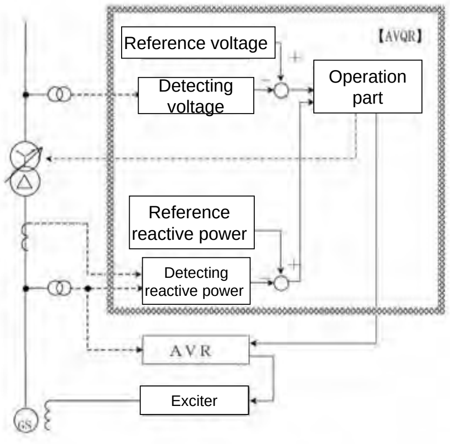
Voltage Control Patterns of PSVR

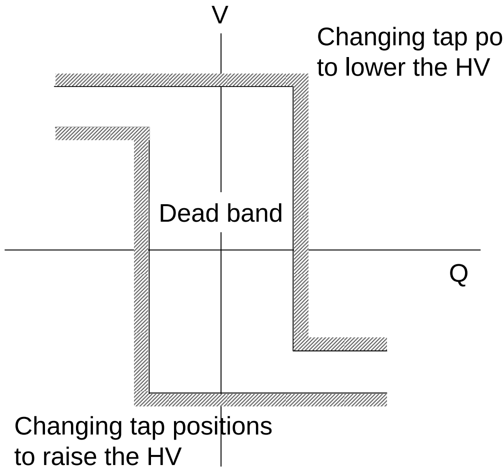


Automatic Voltage and Reactive Power Regulator (AVQR)



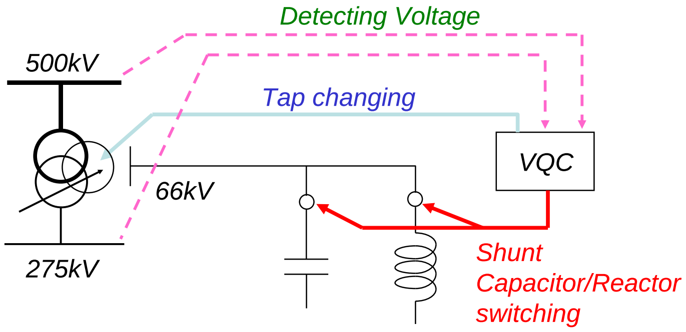
AVQR Control Structure

Automatic Voltage and Reactive Power Regulator (AVQR)



AVQR Control Structure

Voltage and Reactive Power Controller (VQC)



Detecting Voltage

500kV

Tap changing

VQC

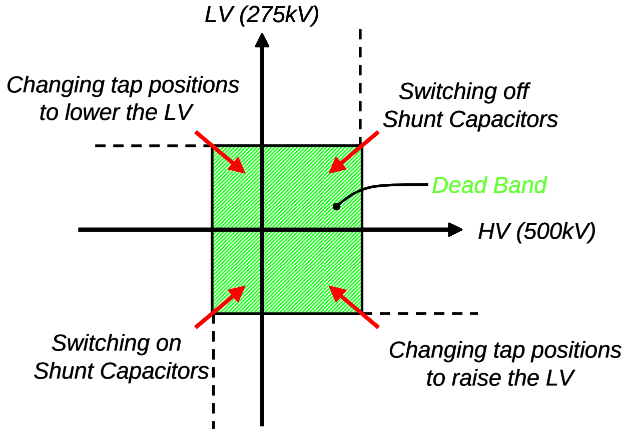
66kV

275kV

Shunt
Capacitor/Reactor
switching

VQC Control Structure

VQC Control Structure (V1-V2 Mode)



LV (275kV)

Changing tap positions
to lower the LV

Switching off
Shunt Capacitors

Dead Band

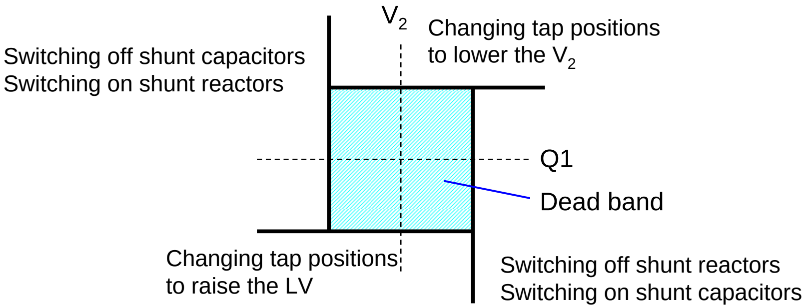
HV (500kV)

Switching on
Shunt Capacitors

Changing tap positions
to raise the LV

V1-V2 Mode

VQC Control Structure (V2-Q1 Mode)



Switching off shunt capacitors
Switching on shunt reactors

V_2

Changing tap positions
to lower the V_2

Q1

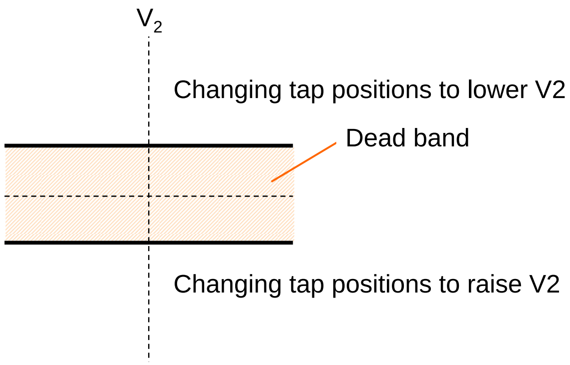
Dead band

Changing tap positions
to raise the LV

Switching off shunt reactors
Switching on shunt capacitors

V2-Q1 Mode

VQC Control Structure (V2 Mode)



V_2

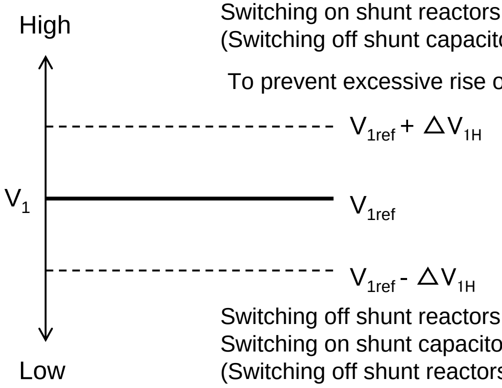
Changing tap positions to lower V2

Dead band

Changing tap positions to raise V2

V2 Mode

VQC Control Structure
(High Speed Control of SC/ShR)



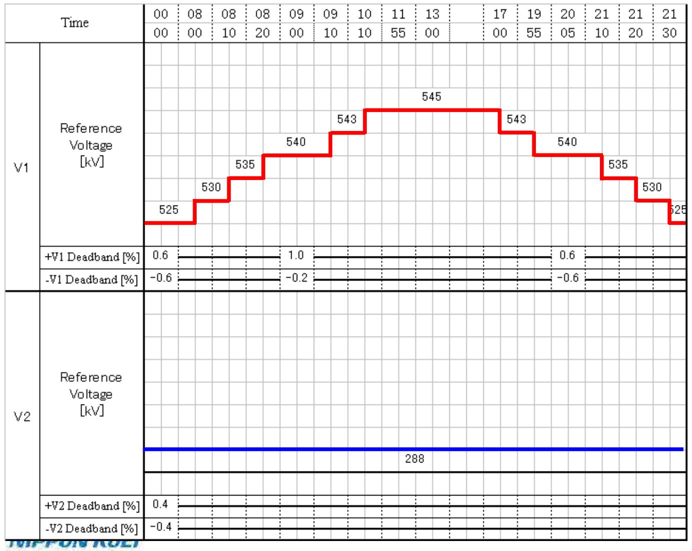
Switching off shunt capacitors
Switching on shunt reactors
(Switching off shunt capacitors has priority)

To prevent excessive rise of system voltage

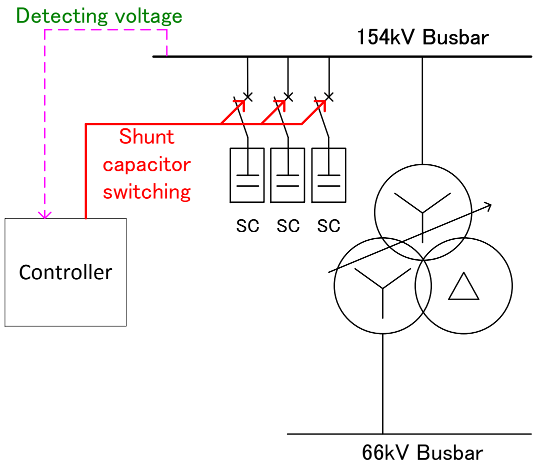
Switching off shunt reactors
Switching on shunt capacitors
(Switching off shunt reactors has priority)

To prevent excessive drop of system voltage

Voltage Control Patterns of VQC



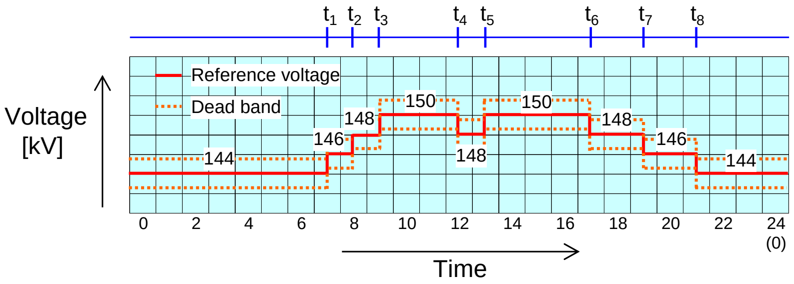
Shunt Capacitor Bank Controller



< Control Structure >

Shunt Capacitor Bank Controller (Voltage control mode)

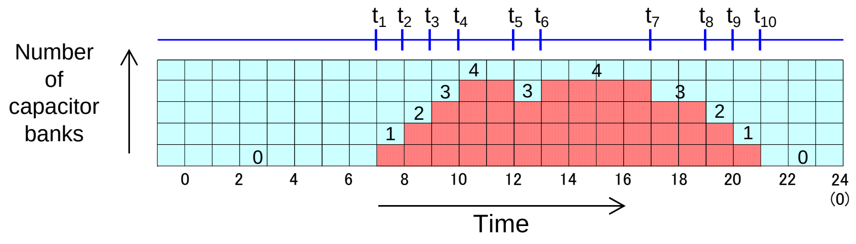
- Reference voltage: High-side voltages at each time can be pre-set.
- Dead band: Lower and upper limits of dead band at each time can be pre-set.



< Example of voltage control pattern >

- When high-side voltage become lower than the pre-set level, the controller orders a circuit breaker to switch on its shunt capacitor.
- When high-side voltage become high than the pre-set level, the controller orders a circuit breaker to switch off its shunt capacitor.

Shunt Capacitor Bank Controller (Time scheduling mode)

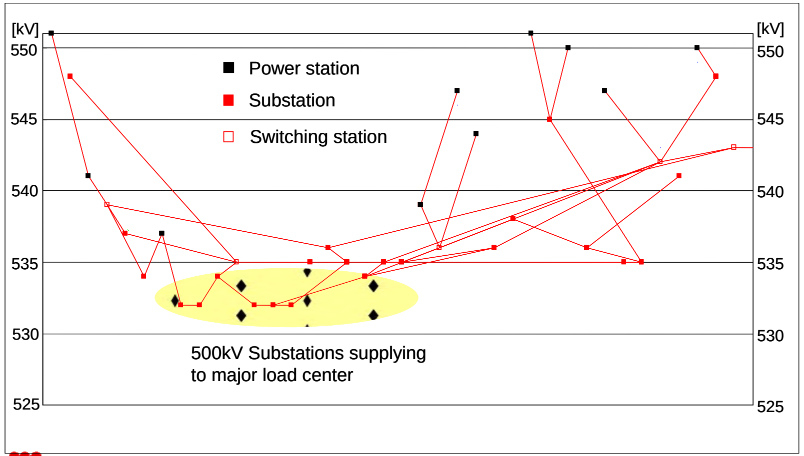


< Time scheduling mode >

Shunt capacitor banks are switched on and off independently from busbar voltage so that number of in-service shunt capacitor banks will be equal to pre-set value at each time.

Voltage Profile in 500kV System under Peak Demand

- Coordination of the reference voltage among the power stations and substations is necessary to ensure that the reactive power output from each station is adequate.



Coordinated Voltage Control in TEPCO

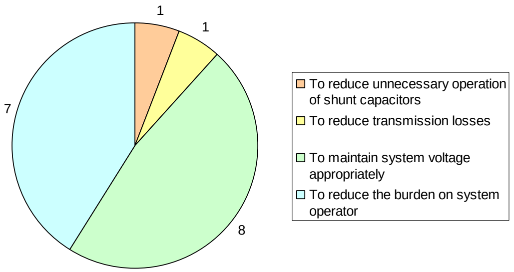
- Coordinated voltage control between bulk power system substation and local system substation
  - Most of shunt capacitor banks at 275kV or lower substations are in service during peak load periods.
  - Reactive power reserves are kept in bottom-up manner.
  - Voltage step at the time of change in reference voltage of VQC for bulk power substation should be coordinated so as to avoid the negative impact on secondary system voltage. (for smooth change in system voltage)

Coordinated Voltage Control in TEPCO

- Coordinated voltage control in whole bulk power system
  - VQC setting among bulk power substation should be coordinated in order to avoid imbalance in the distribution of in-service shunt capacitors. (system with voltage stability problems should not be generated)
  - Setting of voltage controllers should be coordinated between power stations and substations in bulk power system in order to avoid imbalance in the distribution of reactive power outputs of generators.
  - Reactive power reserve should be allocated as evenly as possible in whole bulk power system.

Need for New Voltage Control Scheme

- At present, terminal voltage control of generators, switching of shunt capacitors and changing tap position of transformers are done by manual operation according to the demand fluctuation
- Voltage control operation by the system operators will increase and ineffective operation of the voltage control equipment will be expected according to the expansion of the network scale of Java Bali system, increase of the controlled equipment and complication of system characteristics. To solve these problems, voltage control improvement is required.



Objective of Introduction of New Voltage Control Scheme

Reference : Questionnaire survey of Japanese electric power companies

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Voltage Control Scheme

Bulk Power System

	System configuration	Voltage and reactive power control scheme
A	**Meshed**	**Centralized**
B	**Meshed**	**Local**
C	**Meshed/radial**	**Local**
D	**Meshed/radial**	**Centralized**
E	**radial**	**Centralized**
F	**radial**	**Local**
G	**Radial/meshed**	**Local**
H	**Meshed**	**Block**
I	**Meshed/radial**	**Centralized**

Local Power System

	System configuration	Voltage and reactive power control scheme
A	**Radial (partially looped)**	**Local**
B	**Radial**	**Local**
C	**Radial**	**Local**
D	**Radial**	**Local**
E	**Radial**	**Local**
F	**Radial**	**Local**
G	**Radial**	**Local**
H	**Radial**	**Local**
I	**Radial (partially looped)**	**Local**

Reference : Questionnaire survey of Japanese electric power companies

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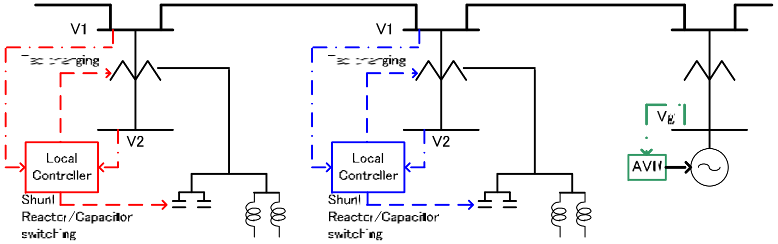
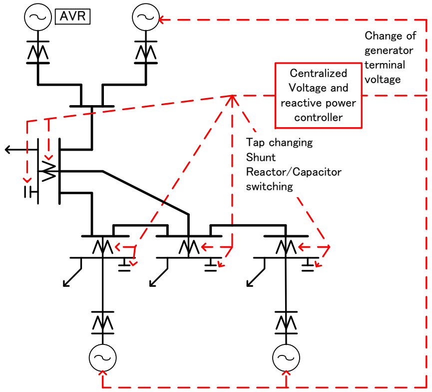
Local VQC

- The conceptual structure of Local VQC is shown in Figure 7.1. In this figure, generator terminal voltage is maintained constantly by AVR. Tap position of the transformers and ON/OFF status of shunt capacitors are coordinately controlled by Local VQC.
- Local VQC controls V & Q control equipment so as to keep the voltage and reactive power to the predetermined reference value in each substation.



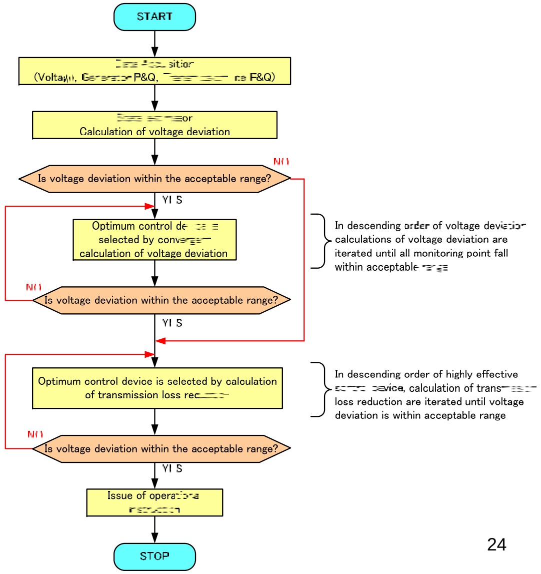
Centralized VQC

- The conceptual diagram of Central VQC is shown in Figure 7.7. Based on the monitored online data, voltage control signal is sent out to the power stations and substations from central load dispatching center etc.



Centralized VQC

- Figure 7.8 shows an example of Central VQC algorithm. As an evaluation function, this algorithm adopts the voltage deviation at the monitored points and minimization of transmission loss of the monitored transmission lines.



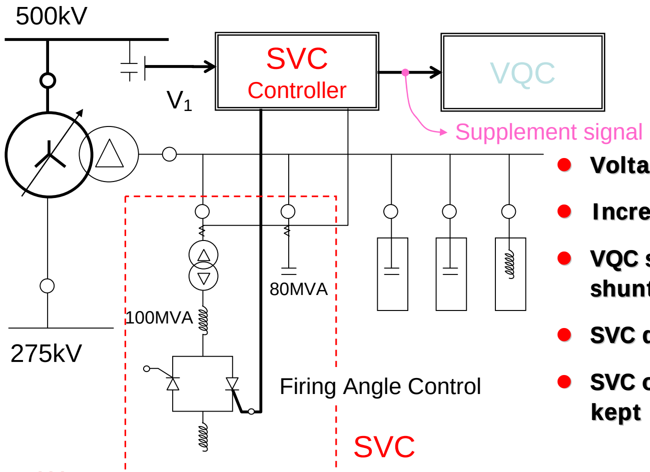
Comparison of Voltage Control Scheme

Manual	Local VQC	Centralized VQC
➢Operators have to Control the generators, Shunt Capacitors / Reactors, Taps of Transformers manually. **➢In response to the system complication, operation of voltage regulation will increase.** **➢Voltage regulation will depend on the operators Experience and Instinct, so the quality of voltage will not be equal or regulation might be late.**	**➢In case of large disturbance, VQCs will respond to the voltage deviation soon.** **➢Setting of each substation or power station has to be determined in coordination with other substations or power stations.**	**➢Because the control interval is 30 sec. to 2 minutes, in case of large disturbance, the recovery of the voltage fluctuation takes a certain extent of time.** **➢Setting of each substation has to be determined in coordination with other substation.** **➢It is possible to control the system voltage considering of minimize the active power loss of target point or all the system.** **➢As the premise of central control, state estimation has to be convergent.** **➢So a deficiency of telemetering or input data causes inadequate control.**

SVC

- **Fast Var response**
- **Installed in 500kV S/Ss supplying to major load center**
- **Designed to react 500kV voltage during a steep rise in demand**
- **Coordinated Response with VQC**

SVC
- Control structure & Characteristics -



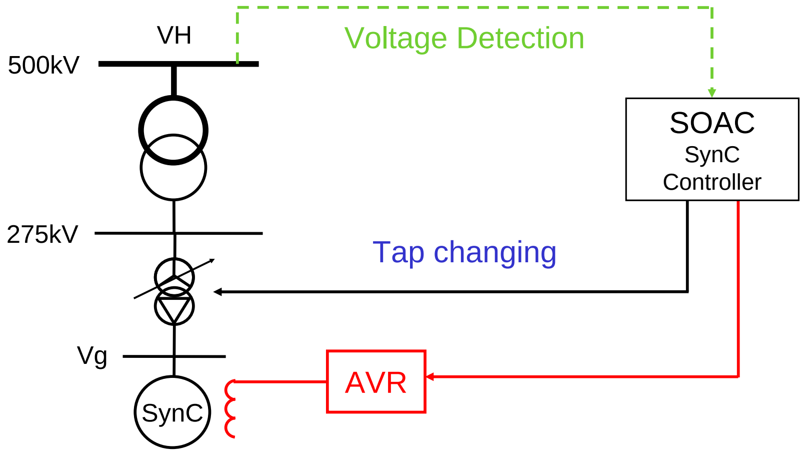
- **Voltage drop**
- **Increase in SVC output**
- **VQC switches on a shunt capacitor**
- **SVC decreases output**
- **SVC output reserve is kept**

Synchronous Condenser with SOAC

- **Fast Var response**
- **Installed in 500kV S/Ss supplying to major load center**
- **Designed to react 500kV voltage during a steep rise in demand**
- **Lower nose voltage which allows more voltage margin**

※ ‘SOAC’ is an acronym for ’System Oriented AVR Controller’

SOAC for Synchronous Condenser
- Control Structure -



Trend of PMU Technology

Trend of PMU Technology

- “PMU” is short for “ Phasor Measurement Unit”

  System that widely measures time synchronized voltage phase angle by using GPS signal.

⇒ Covered by IEEE C37.118-2005

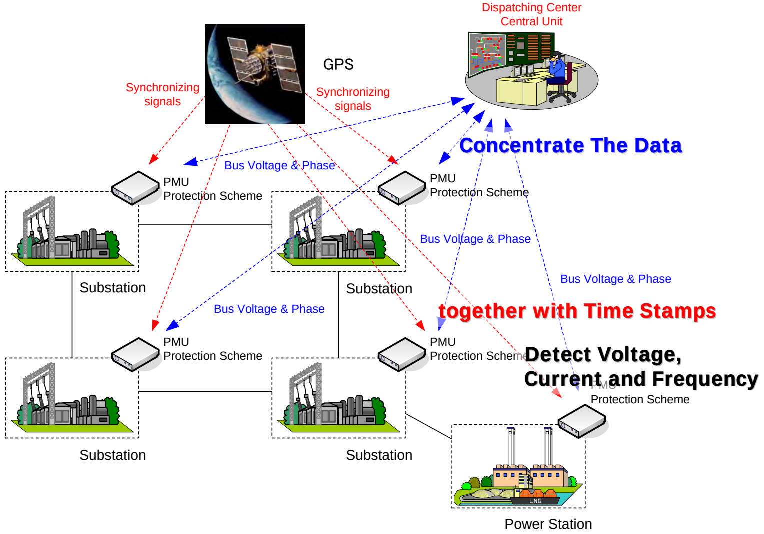
- WAMS (Wide Area Monitoring System)

  At present, real-time power system monitoring scheme goes main stream.
  WAMS’s consist of 2 to several tens of PMUs.

- WAMPAC (Wide Area Monitoring, Protection and Control)

  Many system operators and researchers set the target to install PMUs for protection or control in the future.

Conceptual Structure of Developed PMU System

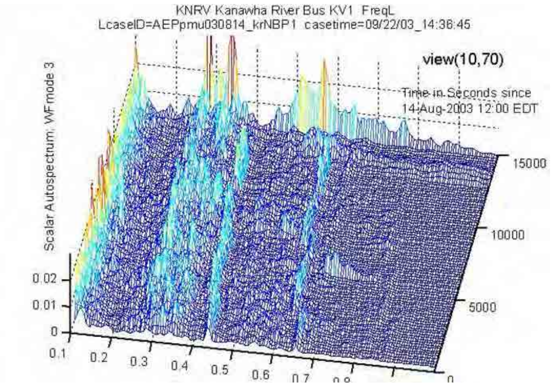


Example of WAMS in The World

Aim for Monitoring	Country, Entity
Dynamic Stability or Its Security Analysis	UCTE in Europe, Hydro Quebec in Canada, WECC in the US, TERNA in Italy, 10 universities in Japan, 3 universities in Sweden, Elkraft in Denmark, EGAT in Thailand, China, Nemmco in Australia, Hungary
Thermal Limitation	Switzerland, HEP in Croatia, APG in Austria
Voltage Stability or Its Security Analysis	HEP in Croatia, WECC in the US, TERNA in Italy , Elkraft in Denmark, China
Accuracy Improvement of State Estimation	WECC in the US, Eastern Interconnection in the US , Elkraft in Denmark , EGAT in Thailand, China, Nemmco in Australia

Source:Interim Report of the WECC Disturbance Monitoring Work Group1

WAMS Example of Eastern Interconnection in the U.S.



Here is the PMU data on 14th August in 2003.

This figure shows the time series analysis of oscillation frequency between 2 substations far away from each other.

This behavior suggests that the "swing frequencies" associated with inter-area modes were declining through increasing stress and network failures on the power system.

Source:Interim Report of the WECC Disturbance Monitoring Work Group1

Synchrophasor Technology Roadmap (March 13, 2009)

By NASPI (North American Synchrophasor Initiative)

- By the year 2014
  - Analysis after grid disturbances
  - Monitoring and visualization of angle differences, voltage stability, frequency, and thermal overloads
  - Power plant monitoring including windfarm, solar power and other dispersed generation
  - Power system restoration
  - Static model benchmarking
  - State estimation

Synchrophasor Technology Roadmap (March 13, 2009)

By NASPI (North American Synchrophasor Initiative)

- By the year 2019
  - ➢ Alarming for situational awareness tools
  - ➢ Day- and hour-ahead operations planning
  - ➢ Real-time automated grid controls and adaptive protection on a wide-area basis
  - ➢ Congestion management
  - ➢ Inter-area oscillation damping modulation controls
  - ➢ System integrity protection schemes
  - ➢ Dynamic model benchmarking
  - ➢ Dynamic line ratings and VAR support
  - ➢ Automatically manage frequency and voltage response from load
  - ➢ Distribution network monitoring, restoration and self-healing

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What is suitable to install the WAMPAC for ?

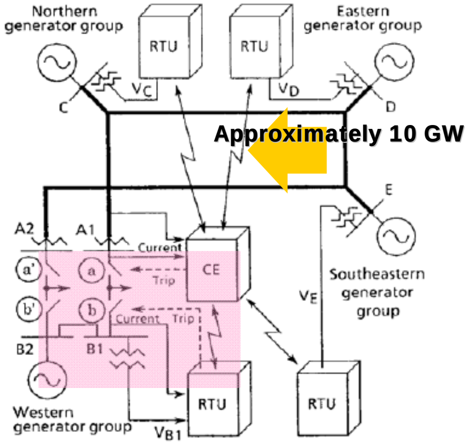
In the report of the WECC Disturbance Work Group, the WAMPAC is suitable to the following things.

- Continuous phenomena like oscillations and damping
- Under beyond N-1 contingency conditions, especially for multi- or cascading contingencies

However, basically the countermeasures against stability should be taken by SPSs (Special Protection Scheme) or RASs (Remedial Action Scheme) .

Source:Interim Report of the WECC Disturbance Monitoring Work Group1

Example Expected to Be Applied to WAMPAC



This scheme had been applied to the bulk system of TEPCO in 1990s.

Central Equipment (CE) continuously observes the variables of 2 substations.

When Step-out was predicted, the CE send out a trip signal to separate the system at proper point.

This scheme was applied to current differential relay.

It could be also implemented on a PMU base instead

Source:TEPCO

Request for the WAMPAC

In the report of the WECC Disturbance Work Group, the WAMPAC requests the following matters.

- Robustness

  They should be available on the different operational points, under different system conditions, on different time, etc.

- No Misbehavior in Contingency Situations.
- Modular Controller Design for System Control and Ancillary Services; Scalable for Different Control Ranges
- Dedicated Communication Channels

Source:Interim Report of the WECC Disturbance Monitoring Work Group1