Voltage & Frequency Control

Apr.18,2013

JICA Study Team

Contents

- New methodologies of system voltage control that can be applied to the Jakarta metropolitan area in addition to the installation of shunt capacitors
- Basic study of Phase Measurement Unit (PMU) in the future
- Recommendation for better frequency control

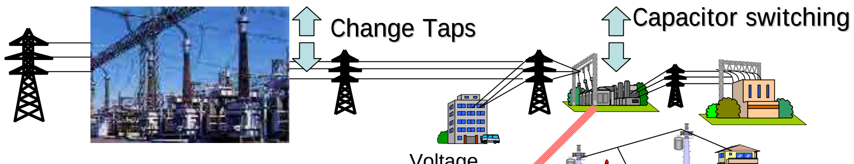
Growing Amount of Shunt Capacitors

Area	Result of P3B study		Year 2015	Year 2021
	Existing	On-going & planned		
Region 1	260	1,445	1,950	4,255 (6,055※)
Region 2	70	100	1,080	
Region 3	75	0	100	
Region 4	370	0	635	
Region 5	175	0	175	
Total	950	1,545	3,940	
Increase			1,445	315 (2,115※)

(MVA)

※ Including Shunt capacitors (1,800MVar) for Java-Sumatra 3,000MW HVDC transmission system

Increase of Voltage Control Cycle



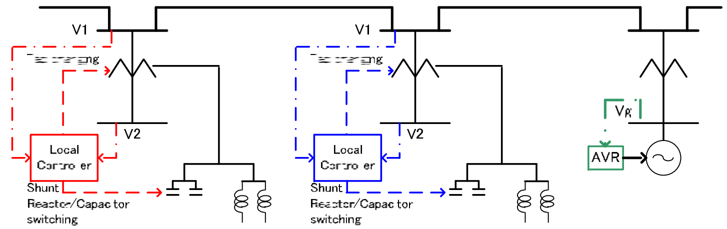
Voltage control cycle will increase by the expansion of the network scale and the demand.

Automatic voltage regulation may be essencial.

Control of Transformer Tap & Shunt Capacitors

Option	Countermeasures
A	In addition to the existing and planed shunt capacitors in Java Bali system, the following shunt capacitors are to be installed: ・By 2015 ; 1,445MVar (Total:3,940 MVar) ・By 2021 ; 315MVar + 1,800MVar for HVDC (Total:6,055 MVar) (HVDC means Java-Sumatera 3,000 MW HVDC transmission line.) Without additional Voltage Controller （Manually）
B	Countermeasure A （Additional Shunt Capacitors） + Installation of Local VQC to regulate voltage automatically
C	Countermeasure A （Additional Shunt Capacitors） + Installation of Centralized VQC to regulate voltage automatically

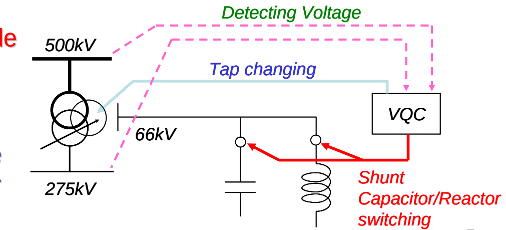
Local VQC Scheme



Control individually in each substation

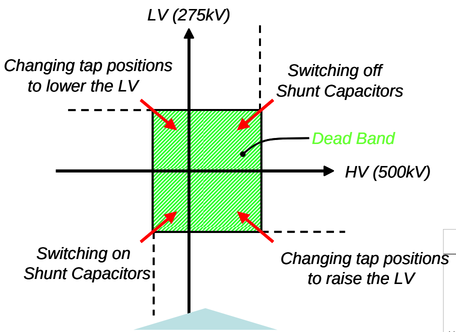
Regulate primary side with capacitors

Regulate secondary side with taps of transformer

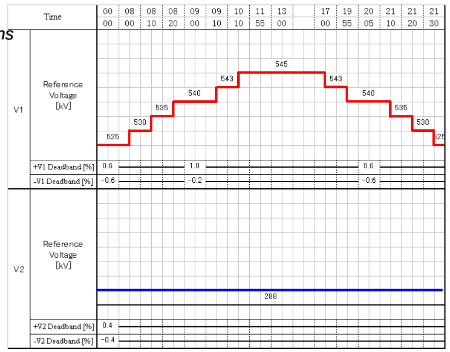


VQC;voltage reactive power controller

Operating characteristics of Local VQC



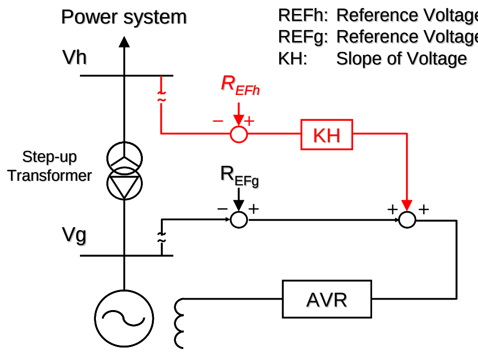
An example of voltage control pattern is shown in this figure. In this example, the primary voltage is varied up and down according to the demand fluctuation.



Within the dead band (green area), switching of shunt capacitors or changing tap positions does not work. If the voltages are out of range, they are controlled into the dead band.

PSVR control scheme

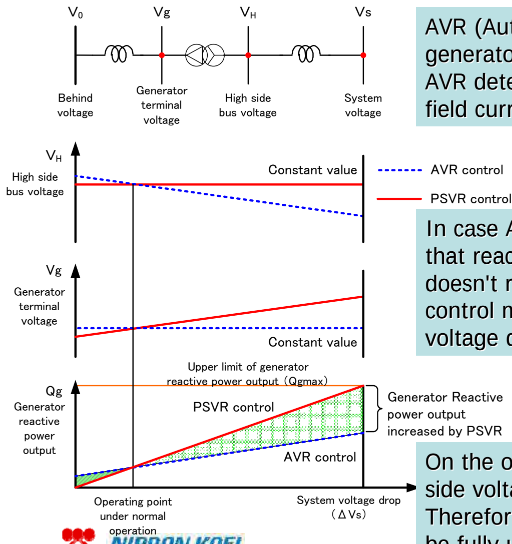
REFh: Reference Voltage of High-side Bus
REFg: Reference Voltage of Terminal Voltage
KH: Slope of Voltage



AVR (Automatic Voltage controller) controls generator's terminal voltage. AVR detects the terminal voltage and control field current of exciter.

On the other hand, PSVR controls the high side voltage of step-up transformer. Therefore reactive power of generator can be fully utilized.

Control Characteristics of PSVR and AVR

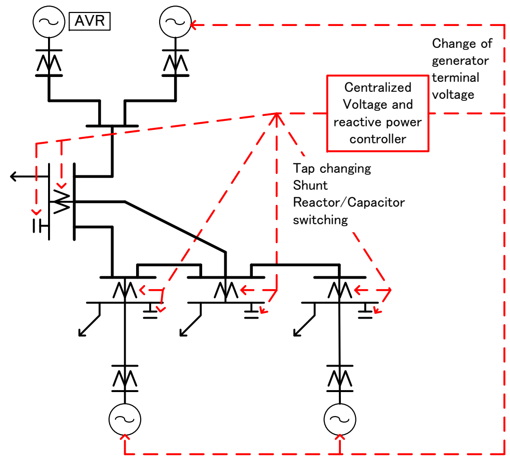


AVR (Automatic Voltage controller) controls generators' terminal voltage.
AVR detects the terminal voltage and control field current of exciter.

In case AVR is applied, it is often the case that reactive power output of the generator doesn't reach its upper limit and voltage control margin is remained even if system voltage drops.

On the other hand, PSVR controls the high side voltage of step-up transformer. Therefore reactive power of generator can be fully utilized.

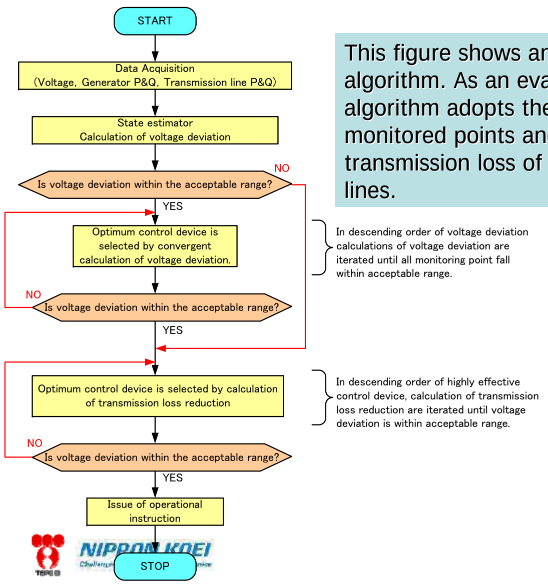
Centralized VQC Scheme



The conceptual diagram of Central VQC is shown in This Figure.

Based on the monitored online data, voltage control signal is sent out to the power stations and substations from central load dispatching center etc.

Example of the algorithm of Centralized VQC



This figure shows an example of Centralized 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.

Making Rule of Calibration

- Calibration of the input value to voltage controller
  - Voltage drop along the wiring from potential transformer should be calibrated.
- Making rules of calibration of detected voltage
  - Accuracy of potential transformer is not necessarily maintained because characteristics changes across the ages or under changing temperature.
  - Calibration rule is needed such as "If the detected value continuously differs more than 2 kV between neighboring busses in a substation, research and countermeasure should be taken."

Trend of PMU technology

- "PMU" is short for " Phasor Measurement Unit"

  can widely measure time synchronized voltage phase angle by using GPS (Global Positioning System) etc.

- At present ;WAMS (Wide Area Monitoring System)

  which PMU technology is based on is applied in many countries including Europe and the US and is utilized for real-time power system monitoring.

- Further more;WAMPAC (Wide Area Monitoring, Protection and Control)

  is being developed, which uses the monitored system information acquired by PMU.

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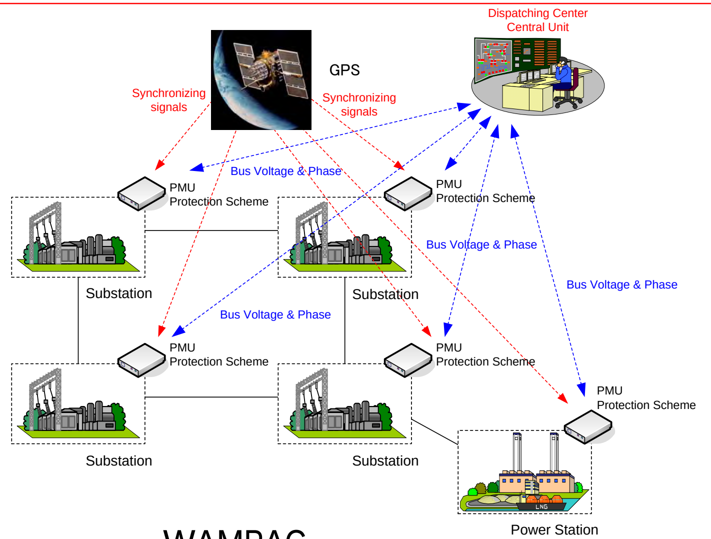
Conceptual Structure of Developed PMU System



WAMPAC (Wide Area Monitoring, Protection and Control)

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Synchrophasor Technology Roadmap (March 13, 2009)

By NASPI (North American Synchrophasor Initiative)

- By the year 2014 (WAMS)
  - 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

"Monitor by PMU"

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Synchrophasor Technology Roadmap (March 13, 2009)

By NASPI (North American Synchrophasor Initiative)

- By the year 2019 (WAMPAC)
  - 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

"Control by PMU"

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Accuracy improvement of State Estimation

EMS (Energy Management System) installed in JCC has the function of periodical Security Analysis on a real-time basis.

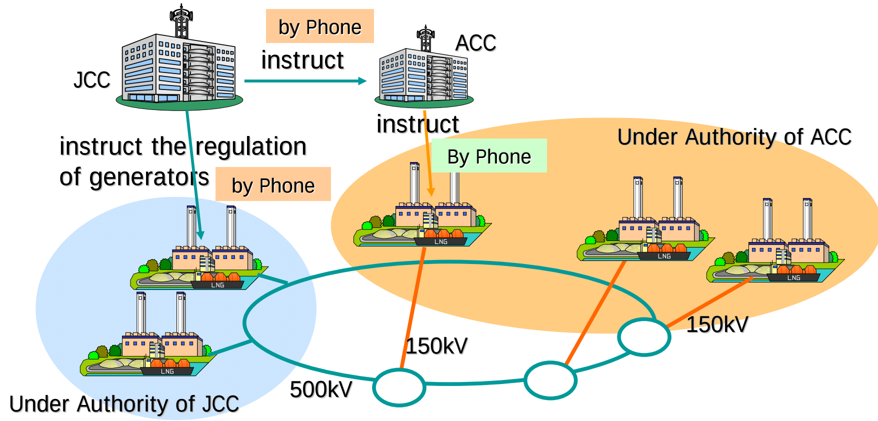
Introduction of PMU improve the accuracy as follows.

- State Estimation
- Contingency Screening

However, the following measures will be necessary along with the feasibility study on the introduction of PMU:

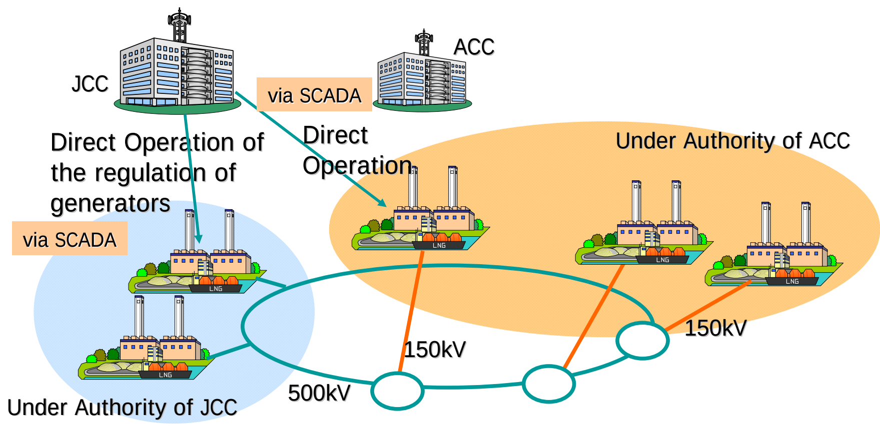
- To collect accurate network parameters
- To reduce missing data by the improvement of telecommunication facility

Present Conditions of Frequency Control



JCC operators instruct the regulation of generators directly by phone to the power stations connected to 500kV system, but instruct the p.s. connected 150 or 70 kV through ACCs.

Recommendation for Frequency Control



Study Team recommends direct dispatching of generators via SCADA of JCC, for quick response to the demand fluctuation.

Sharing The Knowledge for Frequency Control

Power Regulation is inhibited.

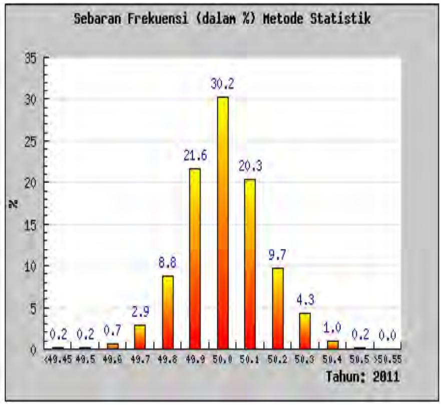
- When the number of mills is changed
- When the number of boiler feed pump changed
- During the hammering of Electrostatic Precipitator
- Valve Test etc.

Minimum output is raised.

- LNG equipment has Boil-Off gas
- When the LNG carrier arrives etc.

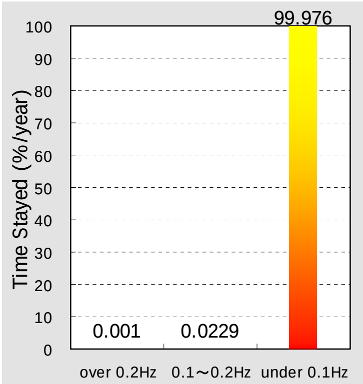
Conservative and Quiet Way
For Strategic Dispatching

【information】Frequency Distribution of Java Bali System



(SOURCE: Evaluasi Operasi Sistem Jawa Bali 2011)

Frequency Distribution of Jawa Bali System
on 2011 1.1-12.31



(SOURCE: Tokyo Electric Power Company)

Frequency Distribution of TEPCO
on 2010.4.1-2011.3.31

Involves on 2011.3.11；221 sec.out of 0.2Hz

Capacitor Bank Design Considerations

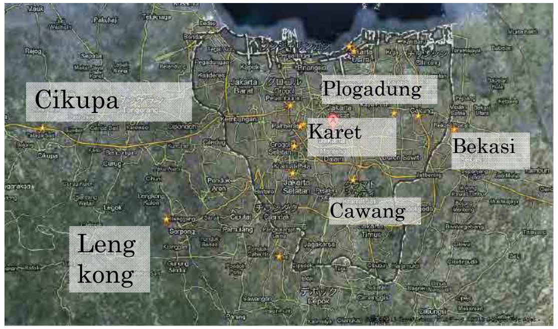
April. 18, 2013

JICA Study Team (Substation Design)
Takashi Wakabayashi
Eiji Matsuda

Capacitor Bank Installation

Objective: To develop a plan for capacitor bank installation, evaluate relevant designs and specifications, and review construction costs.

Photos: 500/150kV Kenbangan Substation



Capacitor Bank Installation Plan in near future

475 (on-going) +1070 (future) MVAR

= (approx.) 30 x 50MVAR Capacitor Banks

Japanese Typical Design for Capacitor Banks

Use of Power Cable for the flexibility of equipment location, because some substations was not designed to accommodate capacitor banks within.

Example of Direct Wiring

Cubicle for Capacitor Banks (22kV) And Its Cable heads

Cable Head For Cirbuit Breakers to capacitors

Cable Head For Capacitor Banks (66kV 40MVA)

Typical Practices for Capacitor Banks

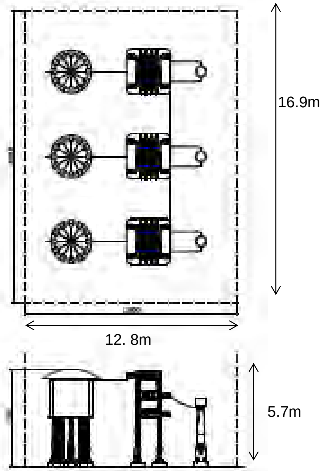
(Reference) TEPCO's Substation Design Philosophy:

- Securing areas for marshalling spaces, future substation expansion, rehabilitation, and renovations.
- Employing compact-type oil-immersed capacitor banks
- Enhanced seismic strength of facilities (0.3G with resonant sinusoidal three waves) = 0.2G in PLN
- Employing power cables for the flexibility for the equipment location
- Voltage control relay operates the OLTC tap and on/off of SCs and ShRs

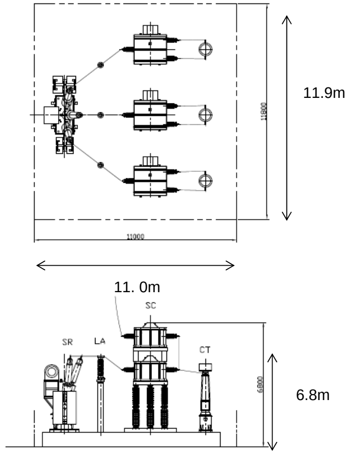
Japanese Typical Design for Capacitor Banks

Use of the Compact Type Capacitor Banks (154kV,25MVA)

Example of Condensor Banks (can type to oil-immersed type)



Expected Life of the Eelement: 10 yrs



Expected Life of the Eelement: 30 yrs

Transportation and Replacement in Substation

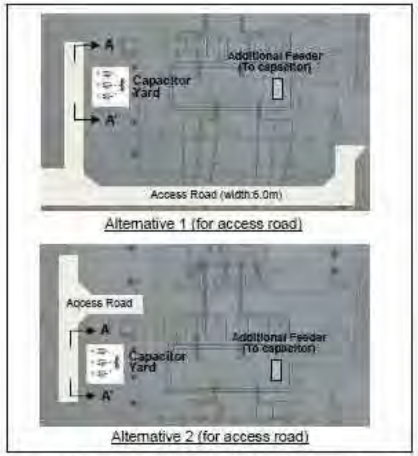


Figure Layout Plan of Additional Works for Capacitor Bank

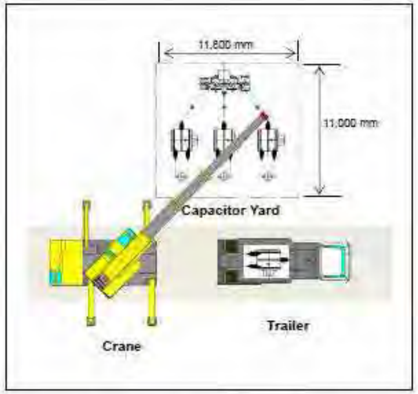
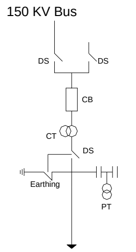


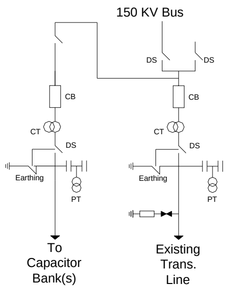
Figure Installation Method (Plan View A-A')

We should make sure that capacitor banks never become obstructions for future construction work

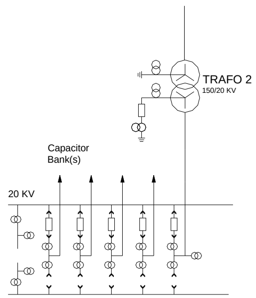
Capacitor Bank Connection



Feeder Addition



Modification of existing Feeder



in Case of GIS SS

Tertiary side connection could be possible in Transmission Substation if 66kV Tertiary side can be used.

Specifications for Reactive Power Source CBs

Circuit breakers for Capacitor Banks has typical operational requirements

- Frequent Operation during its lifetime
- Interruption of capacitive current : TRV specification

PLN already has a good equipment specification for Capacitor bank CB:

⇨ IEC M2 class circuit breaker with operation controller

The mechanical trouble in CB (M2+) for a Capacitor Bank in Bali system (6years after commissioning, operation 3 times a day)

Comparison of the specifications for capacitor CB

	PLN	TEPCO
Nominal Voltage,Capacity	154kV 50MVA (max.)	66kV 60MVA (max.)
CB Operation Duty	M2 Class (10,000+)	M2 Class (10,000+)
CB Controller	Necessary	Not for capacitive interruption. (only for inductive interruption)
Testing History for capacitive interruption	(Not specified)	Specified as a type test item

Environmental Change in Substation's Lifetime

TEPCO's expected Lifespan of the Substation's Equipment

65 years for 150kV+ transformers, Circuit breakers

Substation sites should be secured as long as it's possible

What'll happen in 40-60 years around substation ?

Ikebukuro, 45Years Ago

Ikebukuro, 2010

Future expansion of Substation (needs for land)

TEPCO is replacing the equipment installed 60+ years ago.

Substation Example:
154/66/22kV Substaton originally built in 1950s
With 12x 154kV ,17x 66kV ,13x 22kV Feeders.
Transformer: 200MVAx3, 45MVAx2

Next Page, We'll see the struggle for acquiring necessary land for the equipment replacements

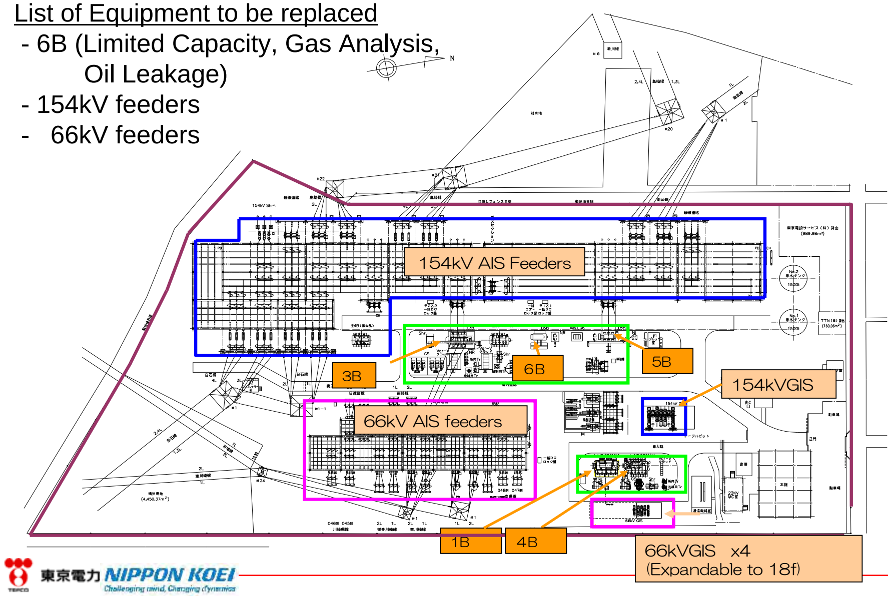
Conventional Air Insulated Substation

Gas Insulated Substation

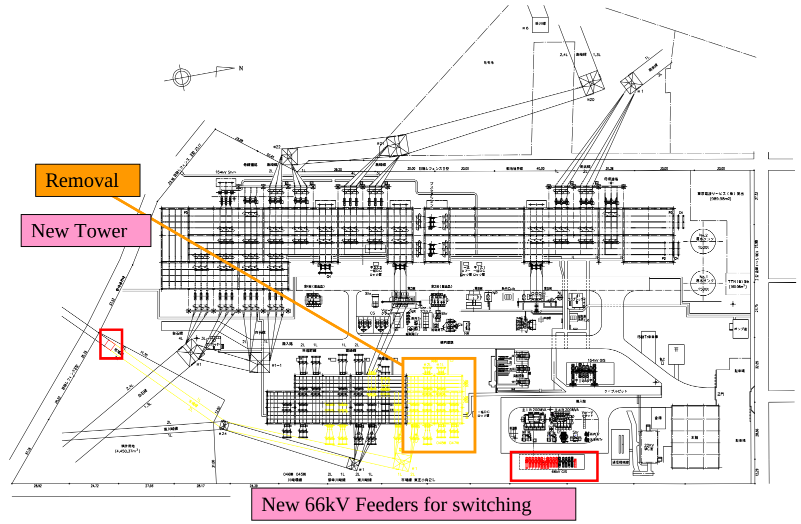
(EX.)Replacement Procedure in a Limited Space

List of Equipment to be replaced

- 6B (Limited Capacity, Gas Analysis, Oil Leakage)
- 154kV feeders
- 66kV feeders



(EX.) Replacement Procedure in a Limited Space



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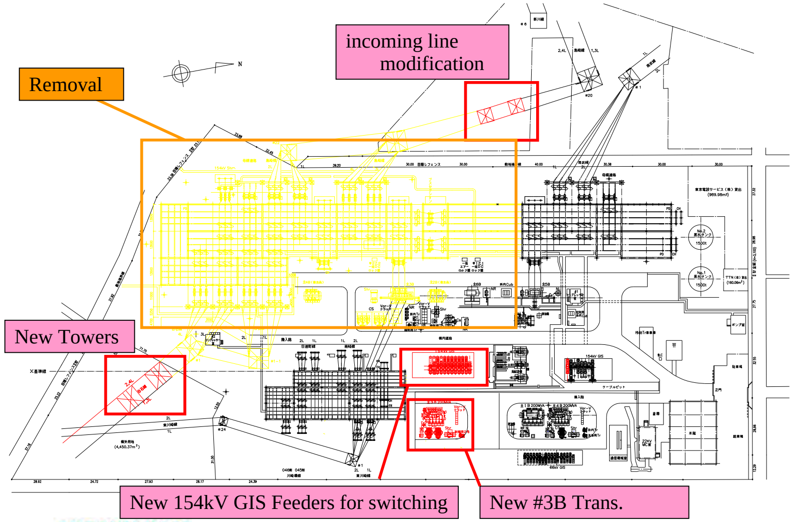
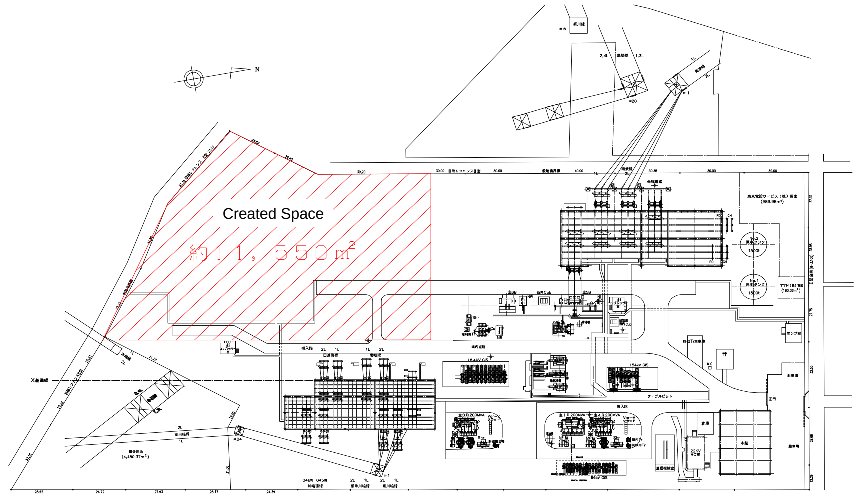
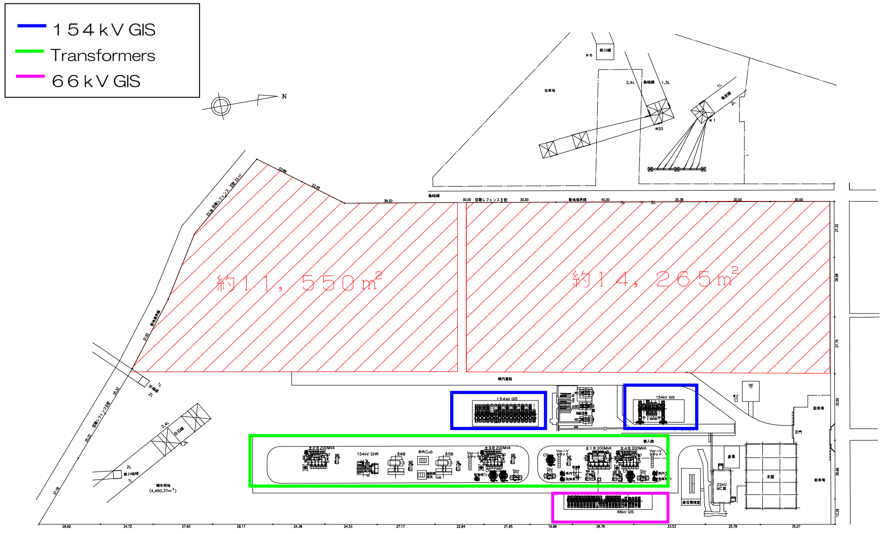


(EX.) Replacement Procedure in a Limited Space



(EX.) Final Form of the Replacement Plan



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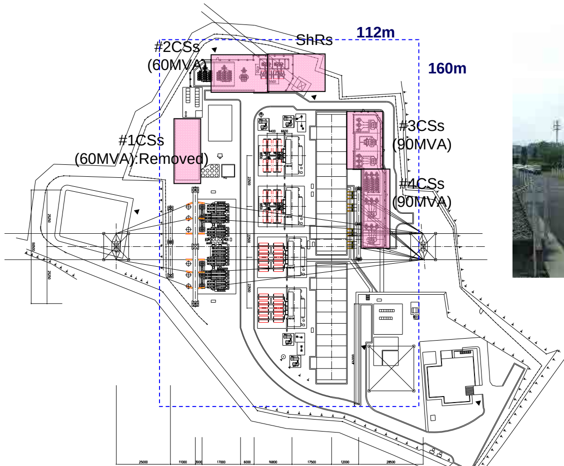
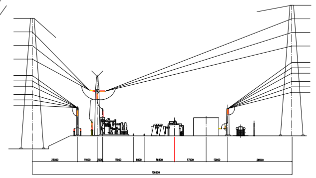
Challenging mind, Changing dynamics

How much is the minimum land area for Substation ?



An example of 275/66kV Substation
with
200MVA x 2 banks & 300MVA x 2 banks,
6x275kV GIS feeders, 20x66kV GIS and AIS Feeders



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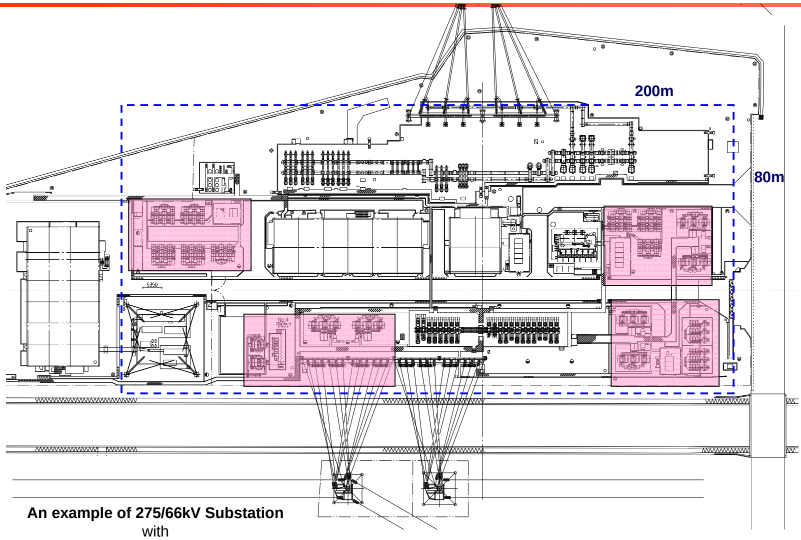
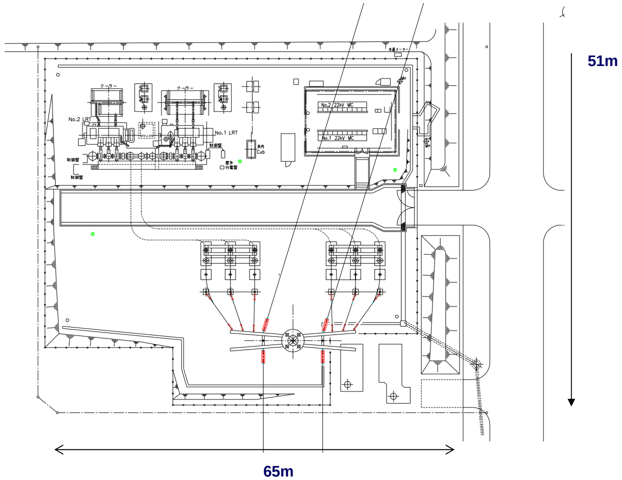
Challenging mind, Changing dynamics

How much is the minimum land area for GIS Substation ?



An example of 275/66kV Substation
with
300MVA x 4 Main Tr Bank, 500MVar SCs
7x275kV GIS feeders, 20x66kV GISFeeders

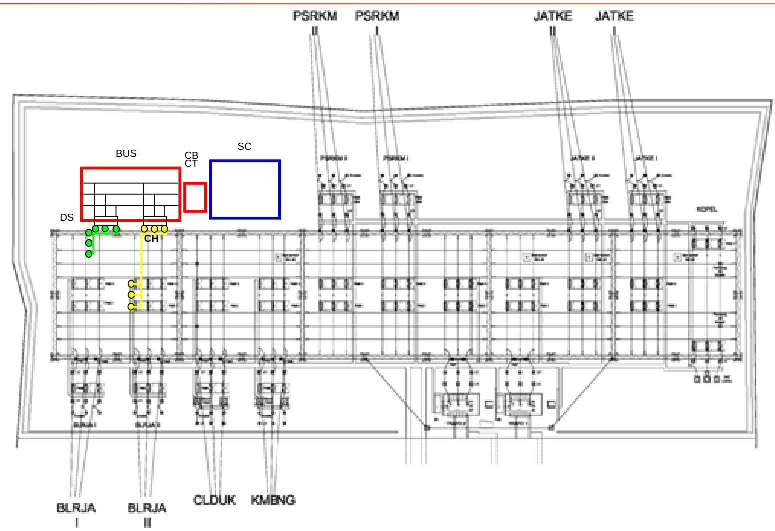
How much is the minimum land area for GIS Substation ?



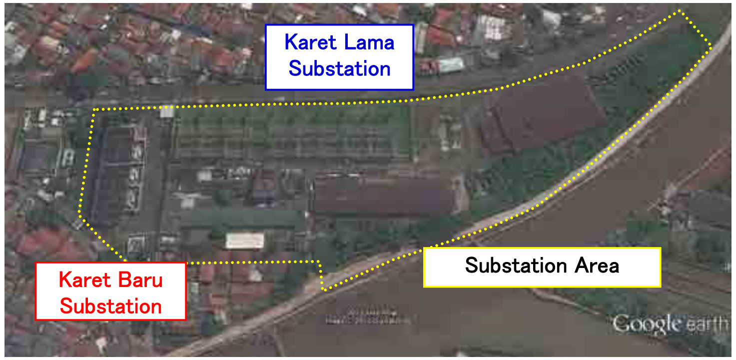
An example of 154/22kV Distribution Substation
with
30MVA x 2 banks, 2x154kV GIS feeders, 12x22kV Dist. Feeders

Discussion : Chikupa Substation

Yellow:
Substation
Area



Discussion : Karet Lama&Baru Future Expansion

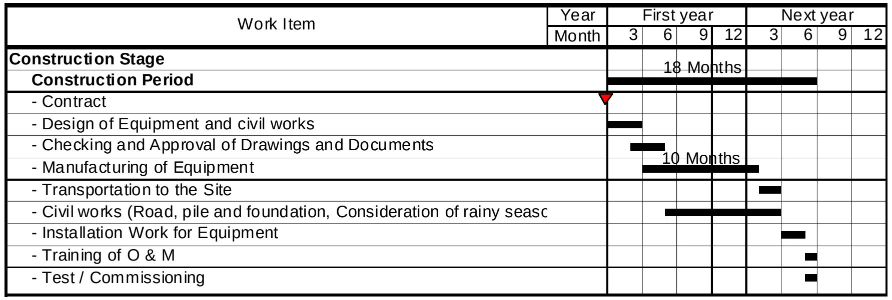


Consideration:

- Future expansion for 230 kV Substation ?
- Expansion of transformers ?
- New Office Building in City Center ?

Construction Work Planning

Implementation Schedule



Assumed Project Period	: 18 month
including	
Equipment Manufacturing	: 10 months
On-site Construction Work	: 5 months

Cost Comparison

kV	Unit size [MVar]	Electrical Works (Rp.)	Civil Works (Rp.)	Total (Rp.)
150	50	7,650,000,000	2,220,000 ,000	9,870,000 ,000
150	25	5,970,000,000	1,100,000,000	7,070,000,000
70	10	3,200,000,000	700,000,000	3,900,000,000
(22)	10	1,850,000,000	200,000,000	2,050,000,000

These cost estimation assumes

- Air insulated switchgears on 150kV
- Conventional Capacitor Bank (not compact)
- 22kV 10MVAR consists 5 x 2MVAR banks

If Compact type capacitor bank is selected, the equipment cost almost triples, but the expected lifetime will be also tripled (According to IEC) and has improved TRV.

Thus, in special case such as limited site availability, frequent operation of capactor banks, corrosive atmosphere, lifecycle cost of the compact capacitor bank will be beneficial to select the best form.

PT PLN (Persero)

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

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Technical Transfer Seminar

12th June. 2013

Tokyo Electric Power Company Inc.

Nippon Koei Co., LTD

Contents

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.

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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.

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Voltage Control Target in Japan

● **Electricity Utilities Industry Act**

100V → 101V ± 6V

200V → 202V ± 20V

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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

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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

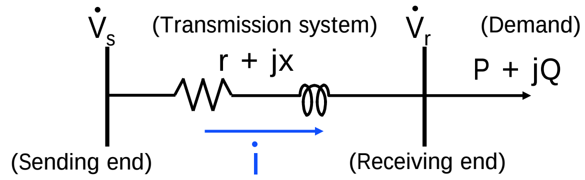
(4) Allowable voltage ranges for system security

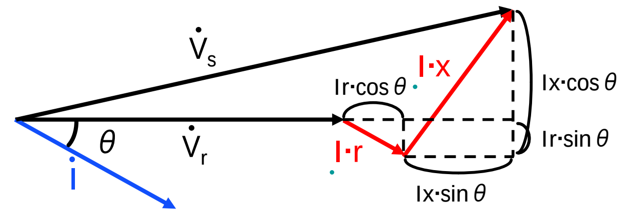
(5) Allowable voltage ranges to maintain supply voltages to customers

(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]

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

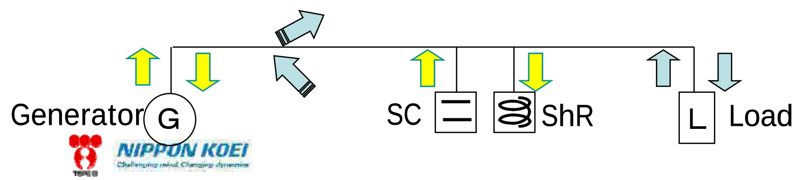
ΔQ fluctuates due to switchings of reactors / capacitors

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

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
Reactive power compensators	Shunt Reactor (ShR)	· Prevent over build-up of voltage by consuming reactive power	(A,D) Effective capacity fluctuates with system voltage (D) Only switching operation possible (not continuous)
Reactive power compensators	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 appolication for voltage stabilization (flickers etc) (A) Little need for maintenance (A,D) Inexpensive compared to SynC but more expensive than SC and ShR
Reactive power compensators	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

Voltage and Reactive Power Control

(1) Generator excitation control (leading, lagging)

(2) Shunt capacitors and shunt reactors

(3) Transformer tap changers

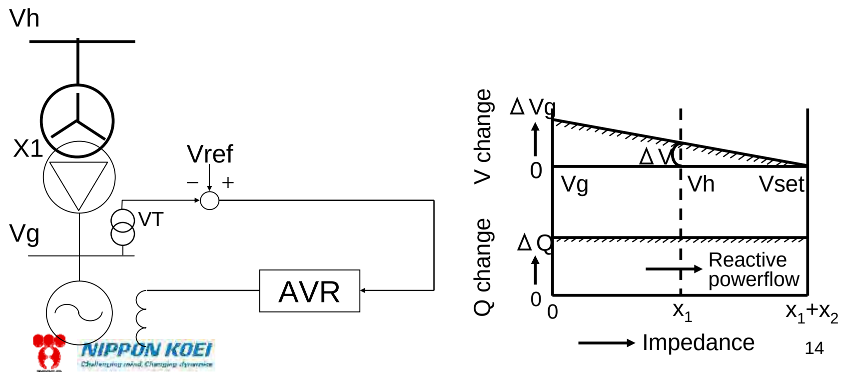
Generator Excitation Control

- **AQR (Automatic Q Regulator)**

  regulates reactive power flow in the system to setting values

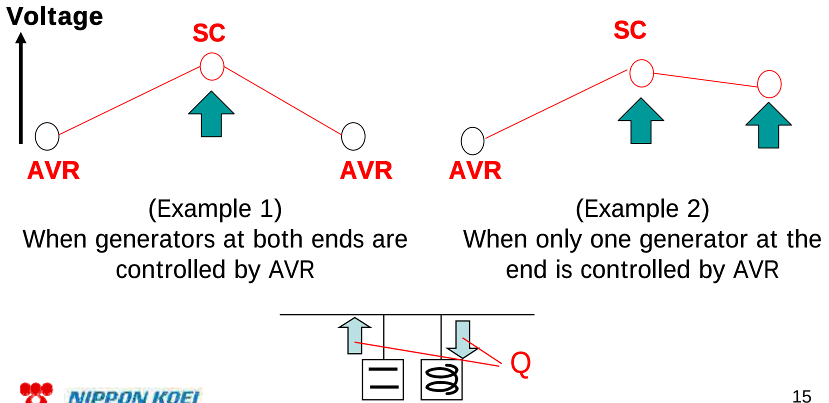
- **AVR (Automatic Voltage Regulator)**

  regulates generator terminal voltage to setting values



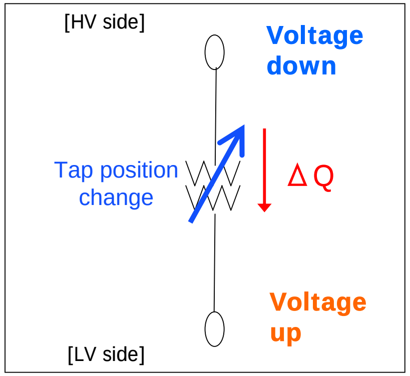
Shunt Capacitors and Shunt Reactors

Shunt capacitor supplies reactive power to the system



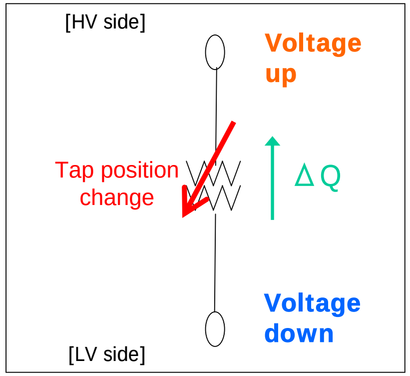
Transformer Tap Changers

When higher tap position is selected:



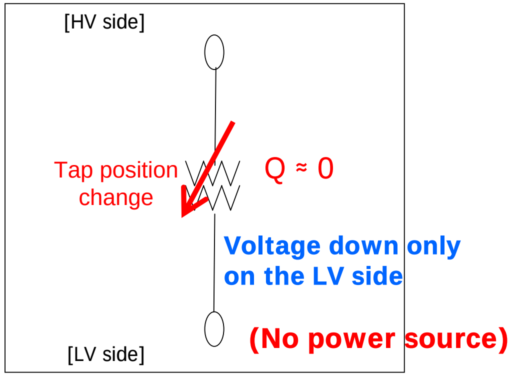
Transformer Tap Changers

When lower tap position is selected:



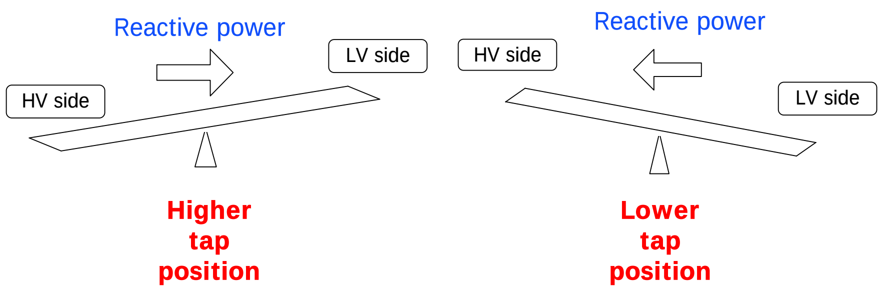
Transformer Tap Changers

When lower tap position is selected:
(without power source on the LV side)



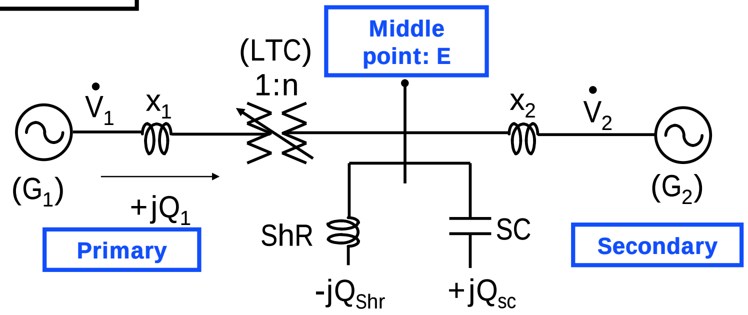
Transformer Tap Changers

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



Voltage and Reactive Power Control in a Model Network

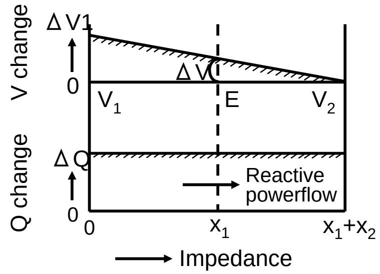
System model



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 ,

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

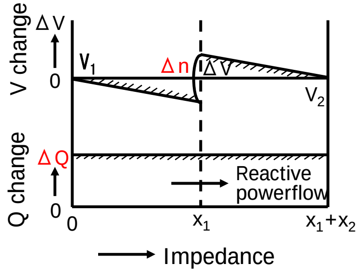


$$\frac{\Delta V}{\Delta V_1} = \frac{x_2}{x_1 + x_2} \qquad \frac{\Delta Q}{\Delta V_1} = \frac{1}{x_1 + x_2}$$

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.

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

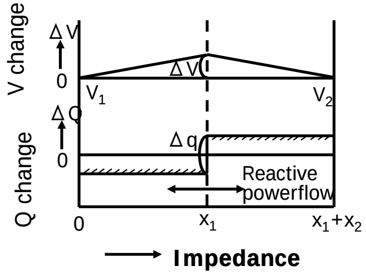


$$\frac{\Delta V}{\Delta n} = \frac{x_2}{x_1 + x_2} \qquad \frac{\Delta Q}{\Delta n} = \frac{1}{x_1 + x_2}$$

Shunt Capacitors and Shunt Reactors

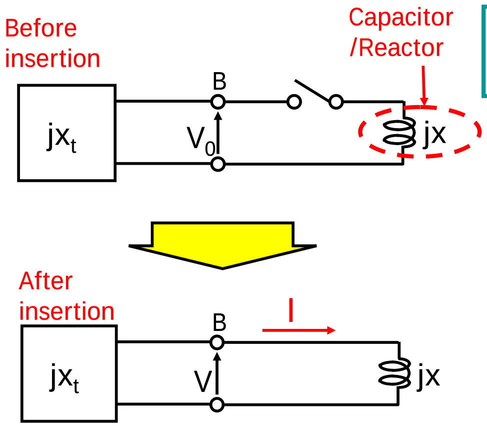
If SC is connected to the model system, voltage and reactive power changes are determined / distributed by the primary and secondary side impedance as shown in the figure.

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



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

Voltage Control by Shunt Capacitor / Reactor (Example)



x > 0: Reactor

x < 0: Capacitor

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

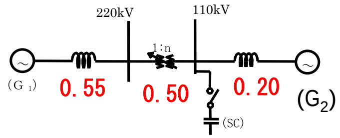
$$V = jx \cdot I = \frac{x}{x+x_t} V_0$$

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

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

Example 1

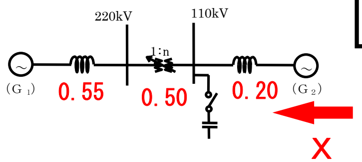
(1) When terminal voltage of generator G_2 is raised by 1%



Base: 1000MVA
220kV
110kV

Example 1

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



Base: 1000MVA
220kV
110kV

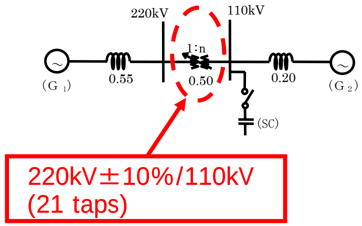
$$X = 0.20 + 0.50 + 0.55 = 1.25[PU]$$

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

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

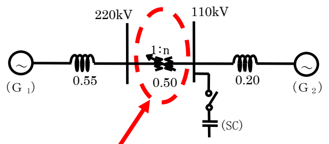
Example 2

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



Base: 1000MVA
220kV
110kV

Example 2



220kV±10%/110kV
(21 taps)

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

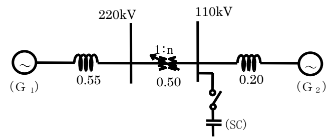
Base: 1000MVA
220kV
110kV

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



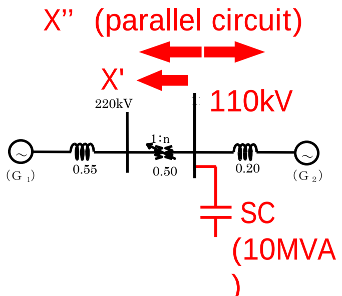
(3) When 10MVA SC is connected to 110kV busbar

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]

ΔV = X'' × Δq
= 0.168 × 0.01 = 0.00168[PU]
= 0.168[%]

JICA
The Study on Power Supply Reliability Improvement in Jakarta

- Voltage Stability -

Technical Transfer Seminar

12th June. 2013

Tokyo Electric Power Company Inc.

Nippon Koei Co., LTD

Contents

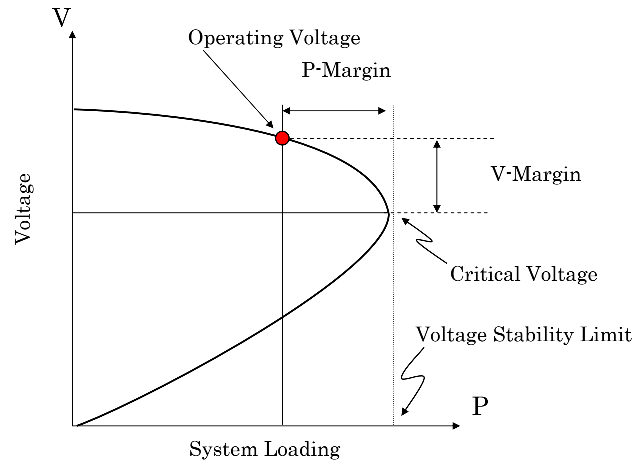
Basic Terms (1) Voltage Stability

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

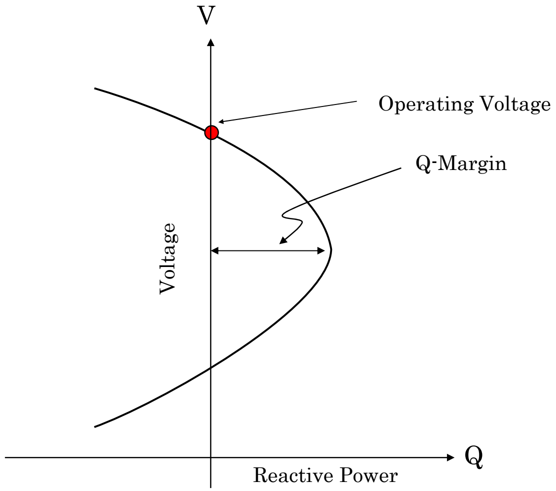
Voltage stability is the ability of a power system to maintain acceptable voltages at all buses in the system under normal condition and after being subjected to a disturbance.

Load characteristics also affect voltage stability.

Basic Terms (2) P-V Curve



Basic Terms (3) Q-V Curve



Static Load Models (1)

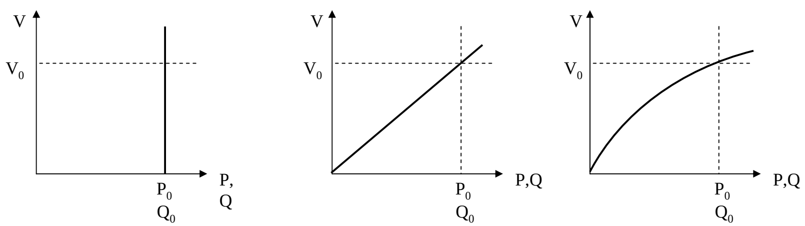
$$P = P_0 (V / V_0)^m \qquad (1)$$

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

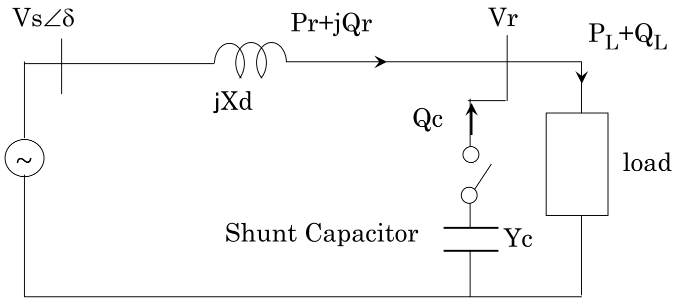
P : Active power load
Q : Reactive power load
V : Bus voltage
V_0 : Bus voltage in the initial operating condition
P_0 : Active power load in the initial operating condition
Q_0 : Reactive power load in the initial operating condition

Static Load Models (2)

(a) constant power	(b) constant current	(c) constant impedance
m,n = 0	m,n = 1	m,n = 2
$P = P_0 (V / V_0)^0$	$P = P_0 (V / V_0)^1$	$P = P_0 (V / V_0)^2$
$Q = Q_0 (V / V_0)^0$	$Q = Q_0 (V / V_0)^1$	$Q = Q_0 (V / V_0)^2$



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),

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

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

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

Preparation for P-V Curve (5)

From Equation(6) and (7),

$$\sin\delta = \frac{X_d P_L}{V_sV_r} \quad , \quad \cos\delta = \frac{X_d}{V_sV_r}\left(Q_L + \frac{V_r^{\,2}}{X_d} - Y_cV_r^{\,2}\right)$$

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

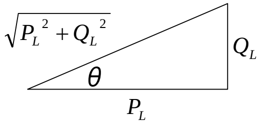
$$P_L^{\,2} + \left(Q_L + \frac{V_r^{\,2}}{X_d} - Y_C V_r^{\,2}\right)^2 = \frac{V_s^{\,2}V_r^{\,2}}{X_d^{\,2}} \qquad (8)$$

(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,

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

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

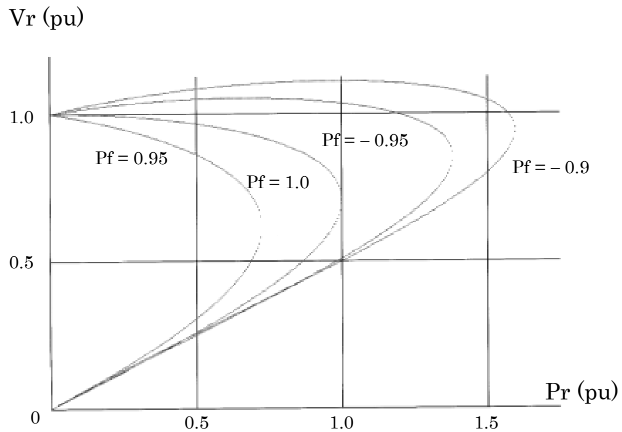
$$\left(\frac{1}{X_d} - Y_c\right)^2 V_r^4 + \left\{\frac{2\sqrt{1-f^2}}{f}\left(\frac{1}{X_d} - Y_c\right)P_L - \frac{V_s^2}{X_d^2}\right\}V_r^2 + \frac{P_L^2}{f^2} = 0 \qquad (11)$$

Preparation for P-V Curve (8)

defining V_r^2 as v,

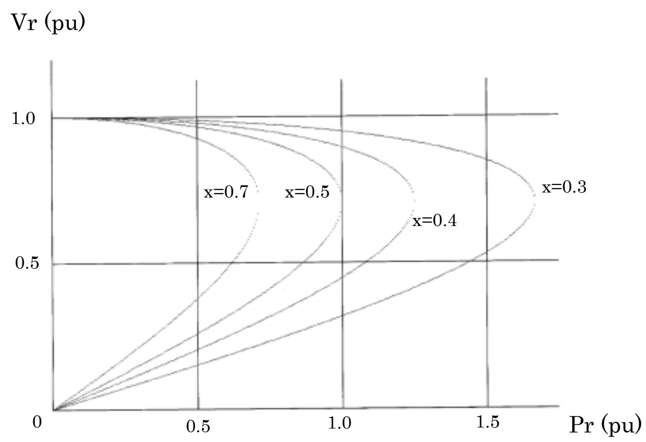
$$\left(\frac{1}{X_d} - Y_c\right)^2 v^2 + \left\{\frac{2\sqrt{1-f^2}}{f}\left(\frac{1}{X_d} - Y_c\right)P_L - \frac{V_s^2}{X_d^2}\right\}v + \frac{P_L^2}{f^2} = 0 \qquad (12)$$

P-V Curves (1)



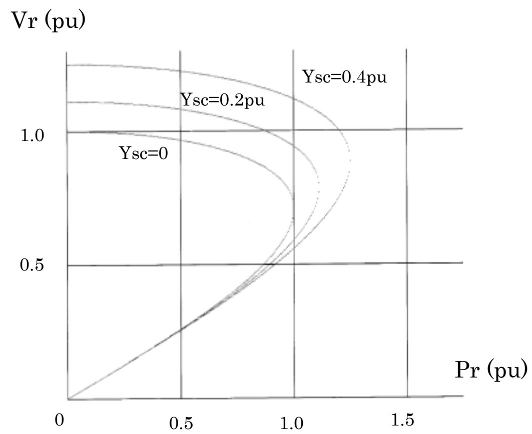
The relationship between Vr and Pr for different power factors of the load

P-V Curves (2)



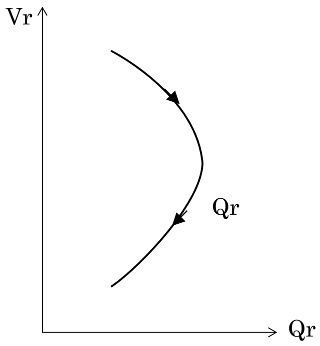
The relationship between Vr and Pr for different reactance Xd

P-V Curves (3)

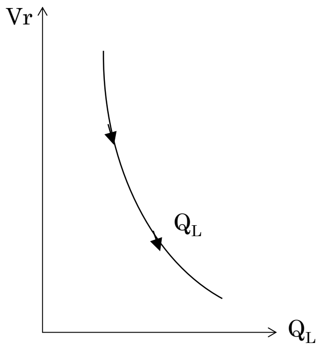


The relationship between Vr and Pr for different admittance Yc

Q-V Curves (1)

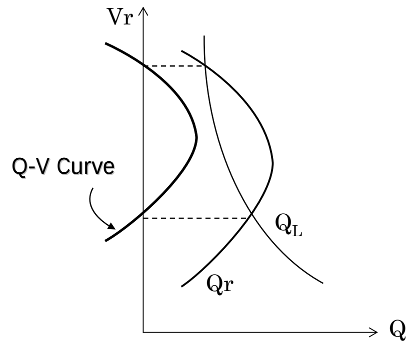


Reactive power
provided from power system



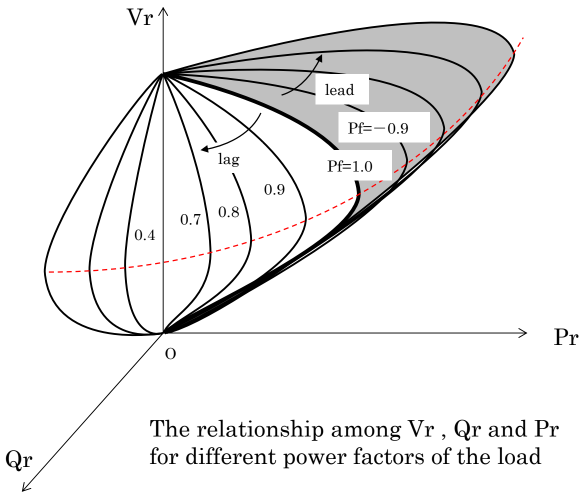
Reactive power
required by load

Q-V Curves (2)



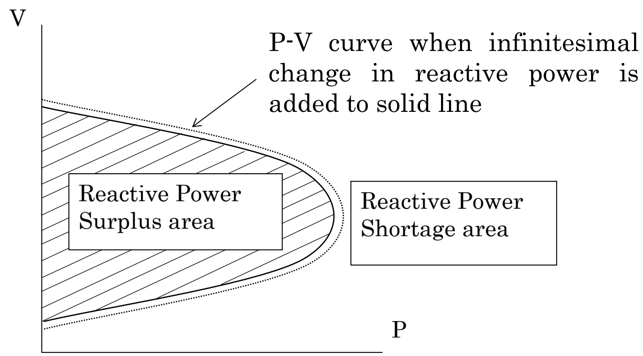
Difference between Qr and Q_L

P-Q-V Curve

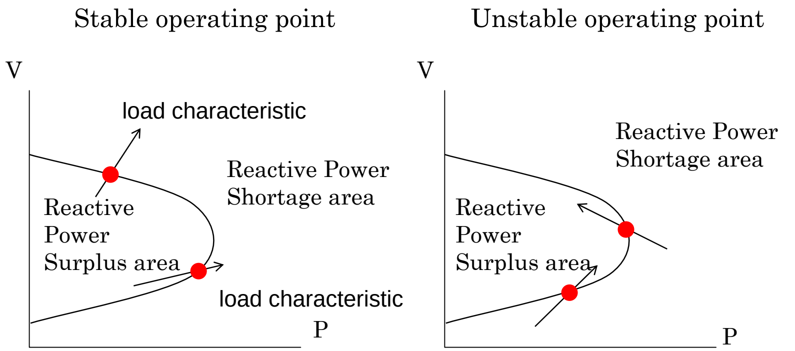


The relationship among Vr , Qr and Pr for different power factors of the load

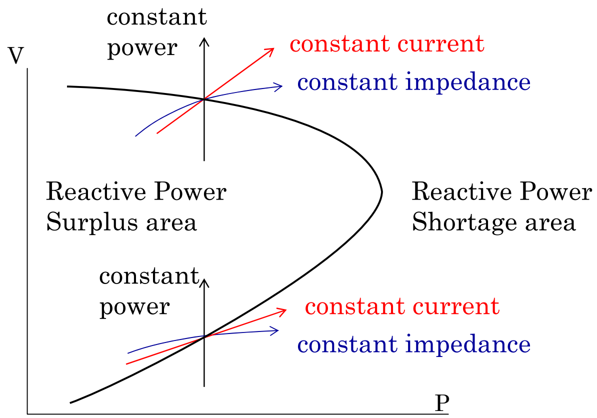
Static Voltage Stability (1)



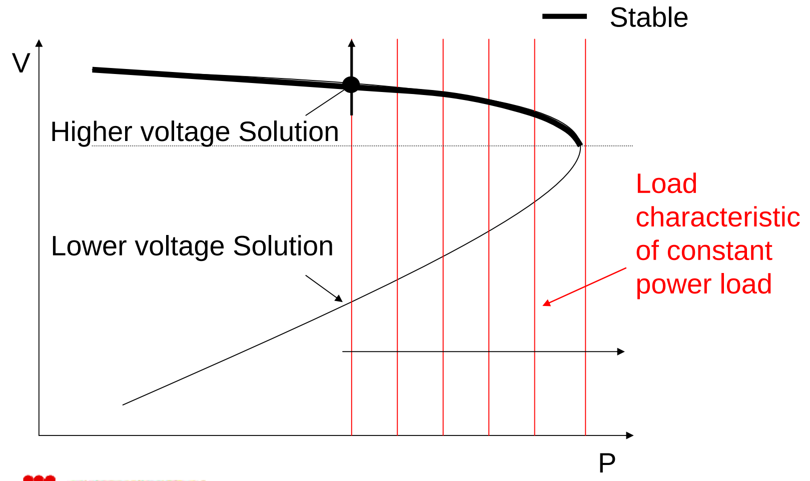
Static Voltage Stability (2)



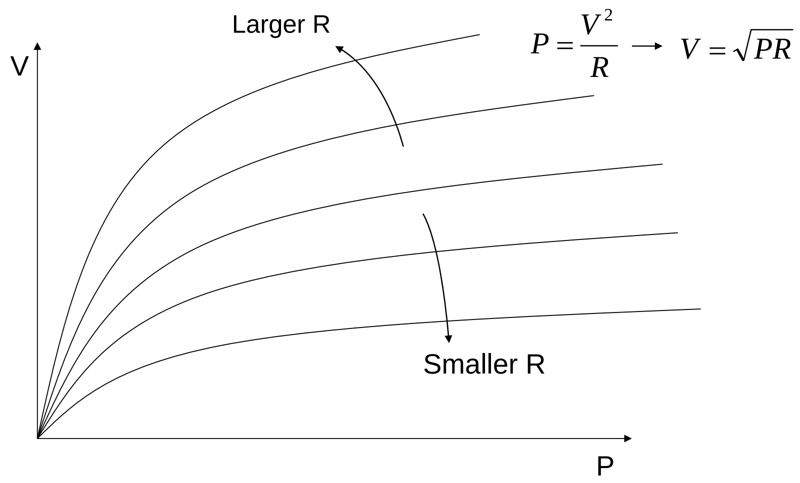
Static Voltage Stability (3)



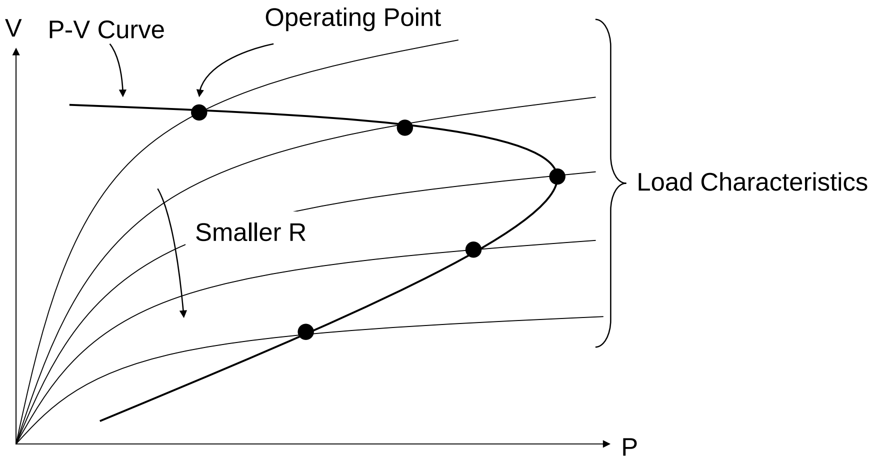
Operating Point and P-V Curve (1)



Operating Point and P-V Curve (2)



Operating Point and P-V Curve (3)



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The Study on Power Supply Reliability Improvement in Jakarta
- Reactive power compensation planning method
Technical Transfer Seminar

12th June. 2013
Tokyo Electric Power Company Inc.
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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.**

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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.**

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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

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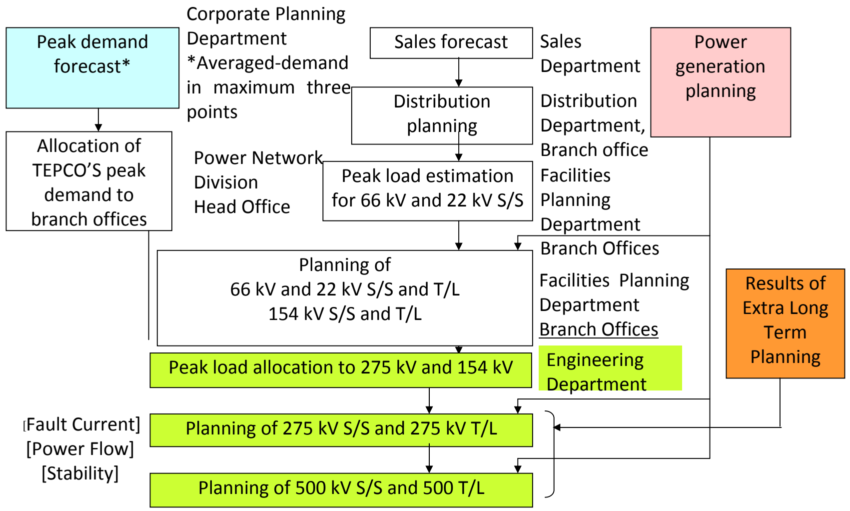
Power Network Planning of TEPCO

- **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)



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.**

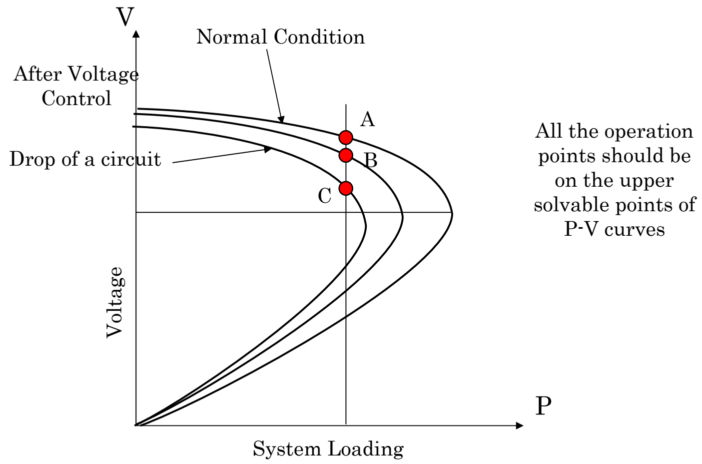
Demand Forecast Used for Planning of TEPCO

- **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



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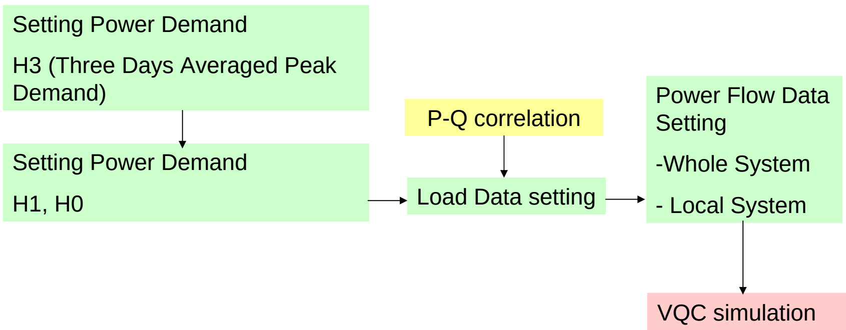
Procedure of Reactive Power Compensation Planning for Peak Demand



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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)**

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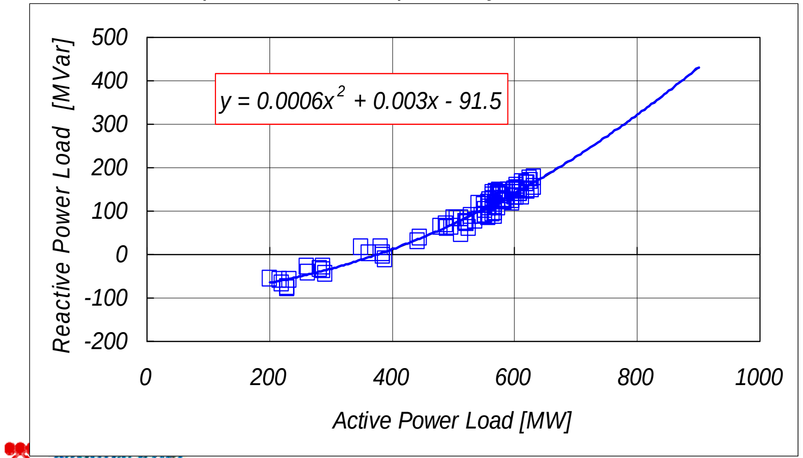
Studies for Ensuring Voltage Stability

- **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

Prediction of Reactive Power Load (An example)

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

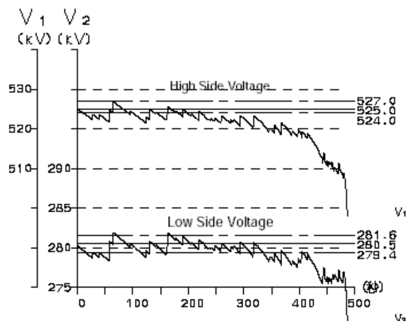


VQC Simulation Program Developed by TEPCO

- **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)

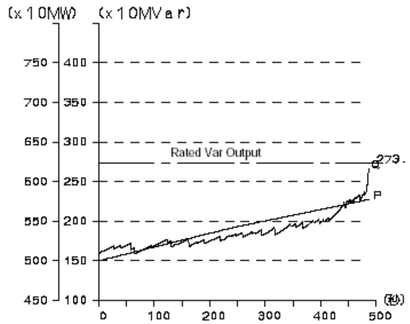
VQC Simulation Studies

500kV and 275kV Busbar Voltages



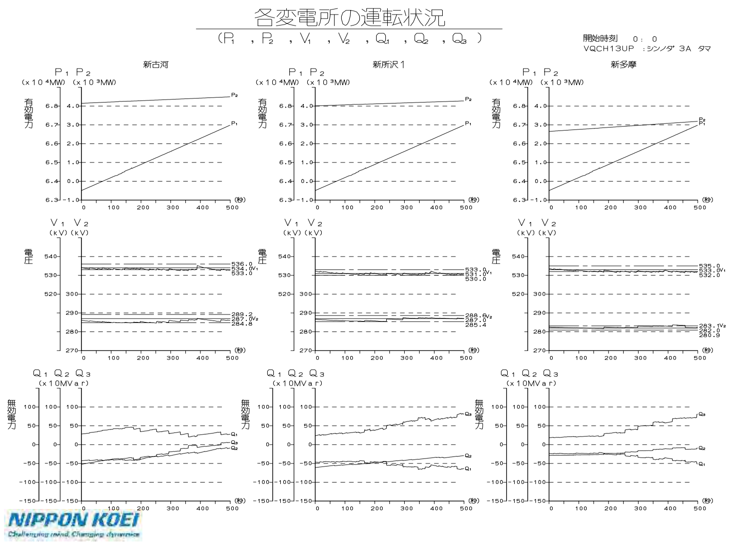
Demand Increasing

Increase in Active and Reactive Load Demand

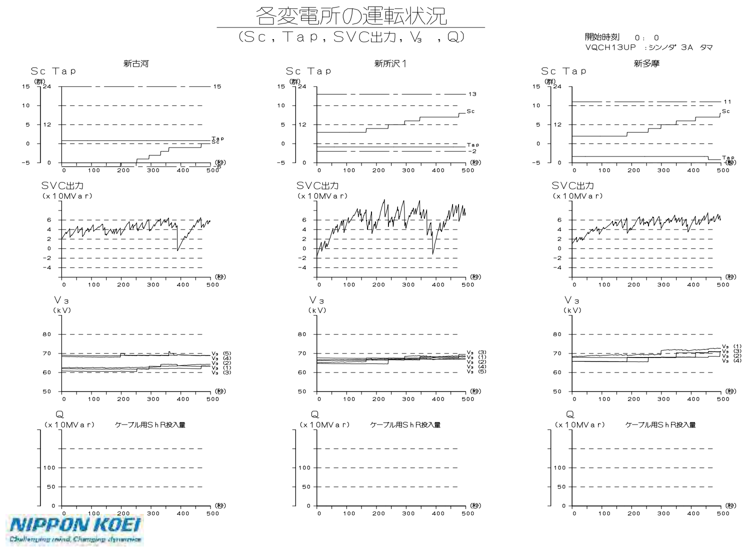


Demand Increasing

Output of VQC simulation (1)



Output of VQC simulation (2)



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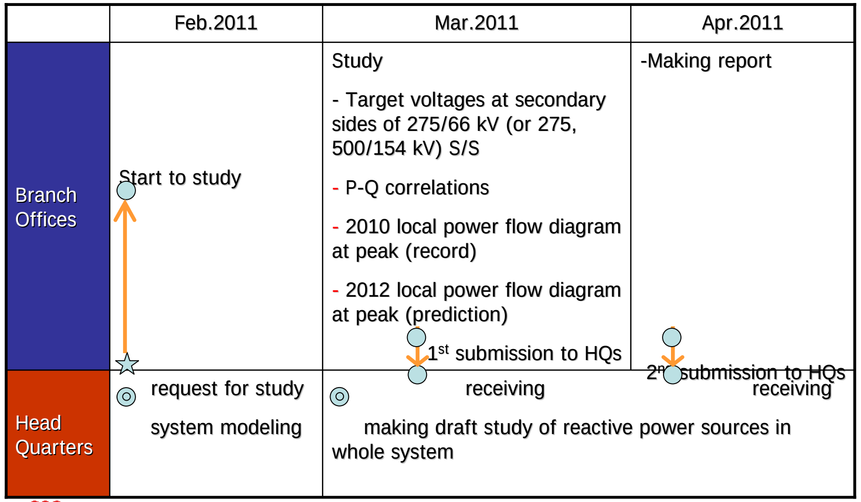
TEPCO's organization regarding power system plan and operation

- **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



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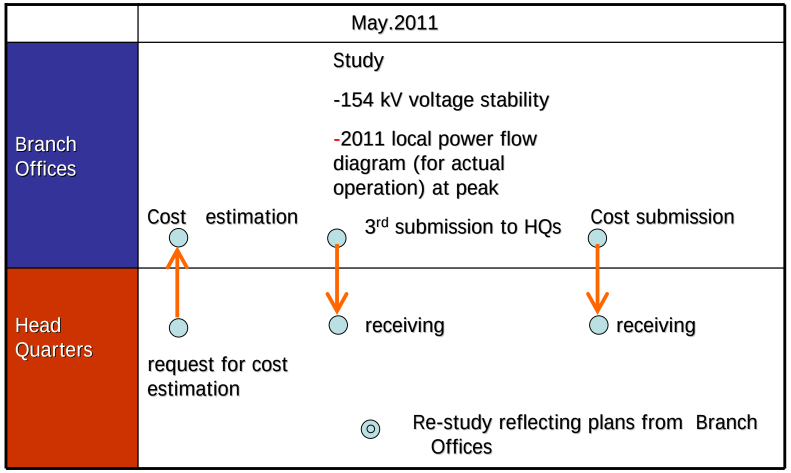

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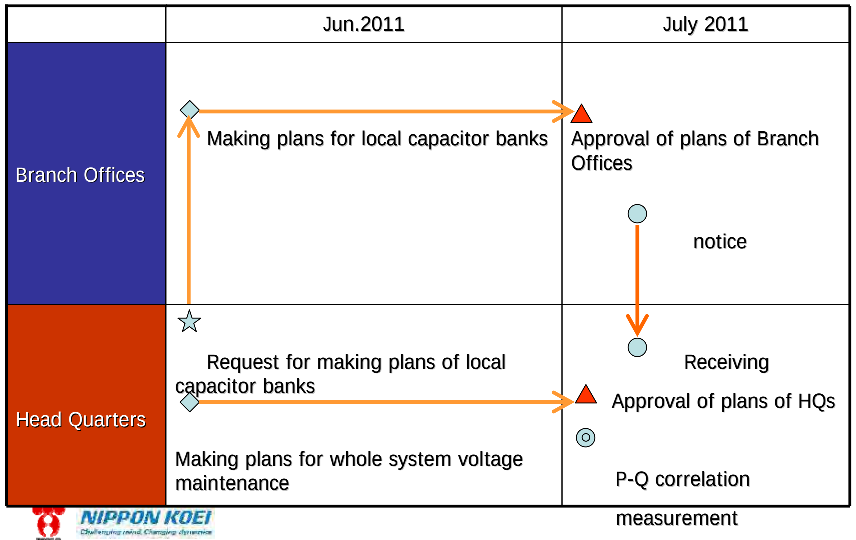

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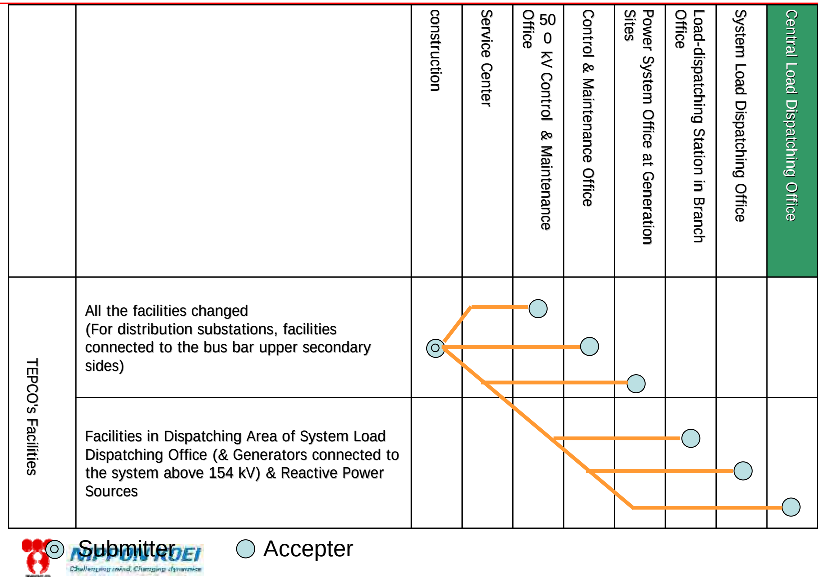
Information Exchange Flow of Facilities Change - TEPCO's Facilities



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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: Q/P
	Pumped Storage	%	%	a: MVar b: Q/P
	Reactive Power	%	%	a: MVar b: Q/P
	Test Energizing	at Output %-%-%	%	a: MVar b: Q/P
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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The Study on Power Supply Reliability Improvement in Jakarta

- Tokyo Blackout in 1987 -

Technical Transfer Seminar

13th June. 2013

Tokyo Electric Power Company Inc.

Nippon Koei Co., LTD

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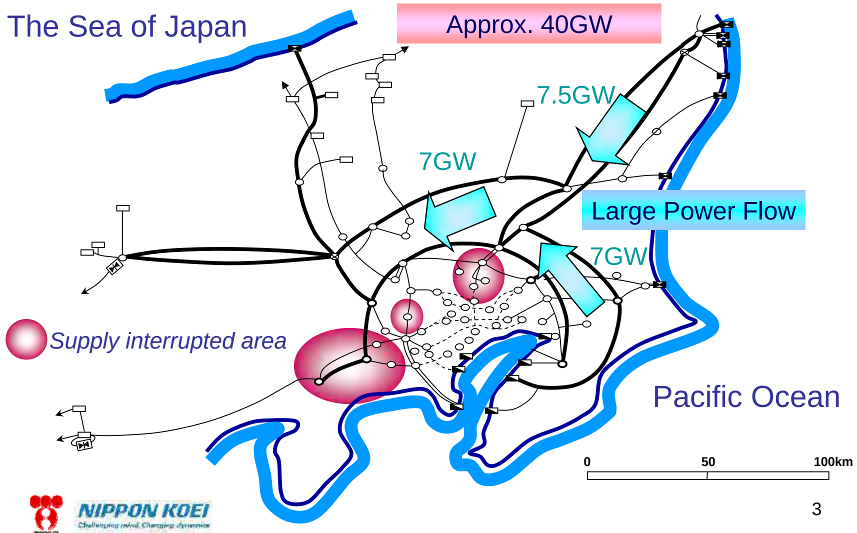
Importance of Appropriate Voltage Control

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

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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

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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

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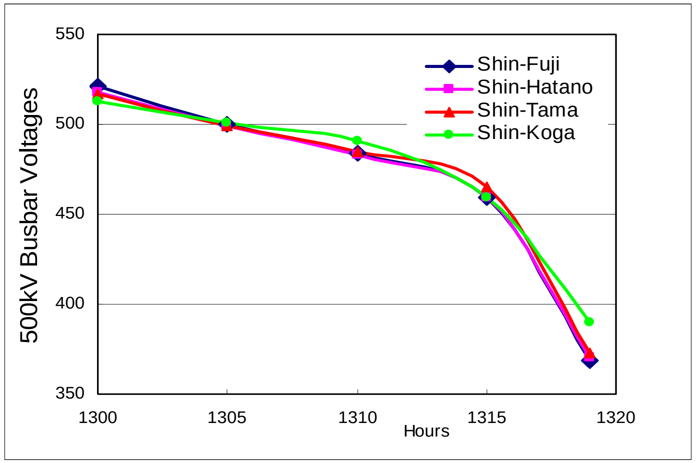
Busbar voltages at 500kV substations in the event of Voltage Collapse



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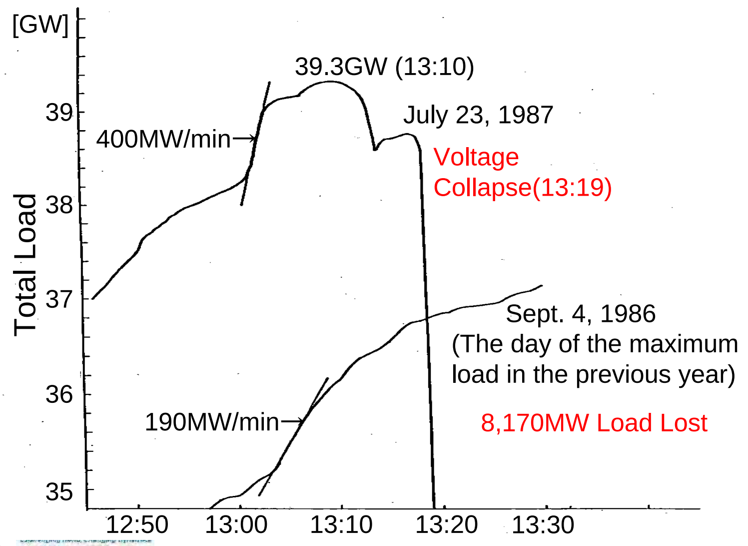
Load Curve (12:50 - 13:20)



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**

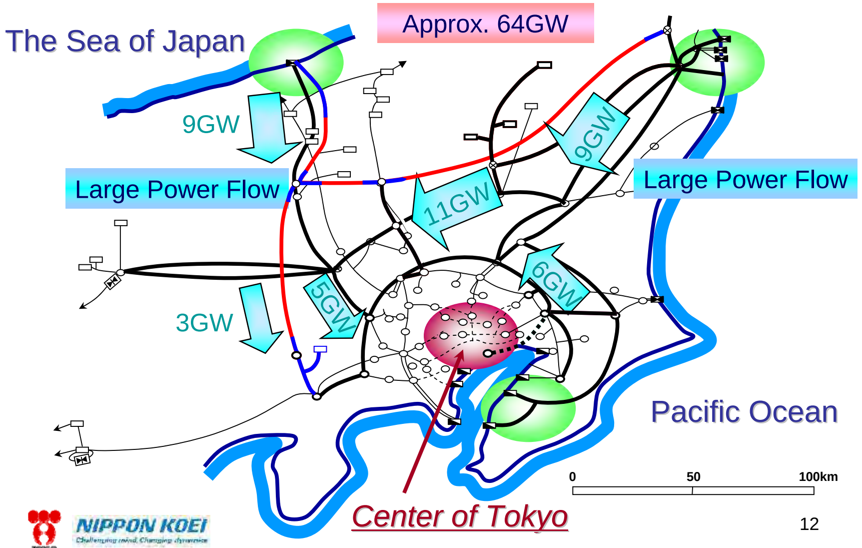
- **Insufficient practical knowledge on voltage instability phenomena**
- **Insufficient reactive power (Var) supply capability in terms of quantity and speed**

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



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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**

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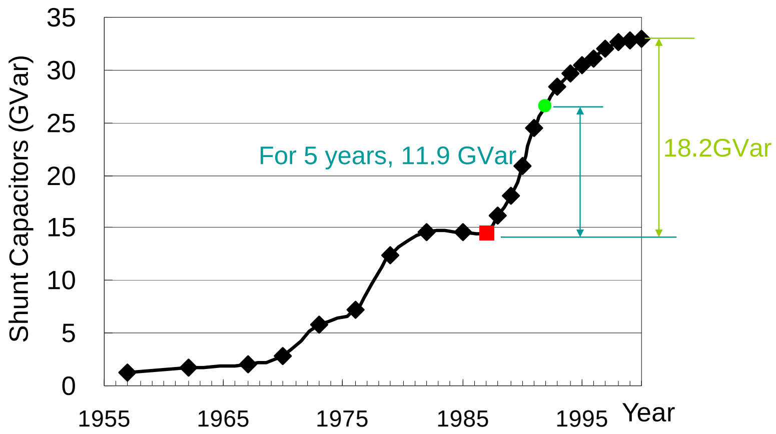
Shunt Capacitors installed in TEPCO power system



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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.

↓

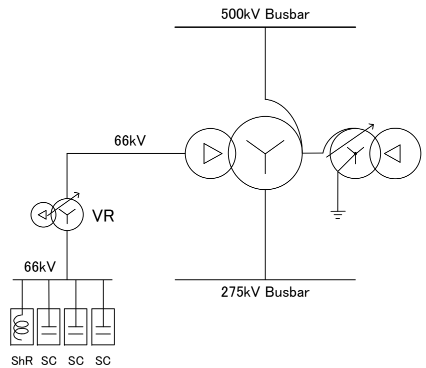
- The voltage at tertiary side exceeds the upper limit.

↓

- 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.



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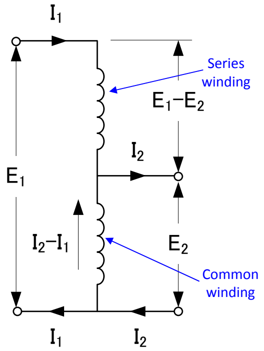
Connection Diagram of Auto Transformer

- 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**

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- Case study of wide area blackout in the United States and Canada in 2003
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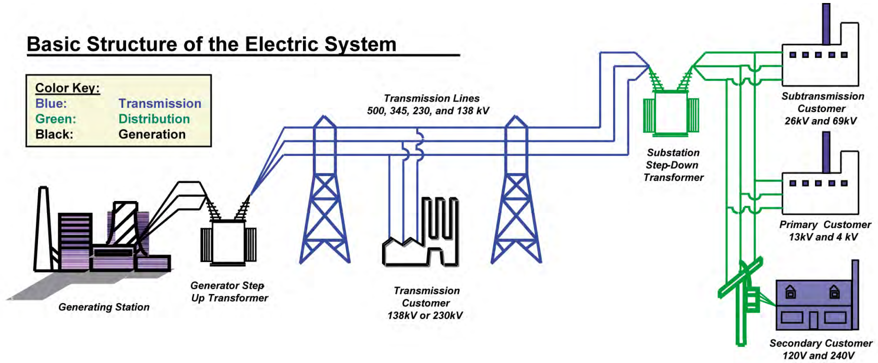
Power System Overview



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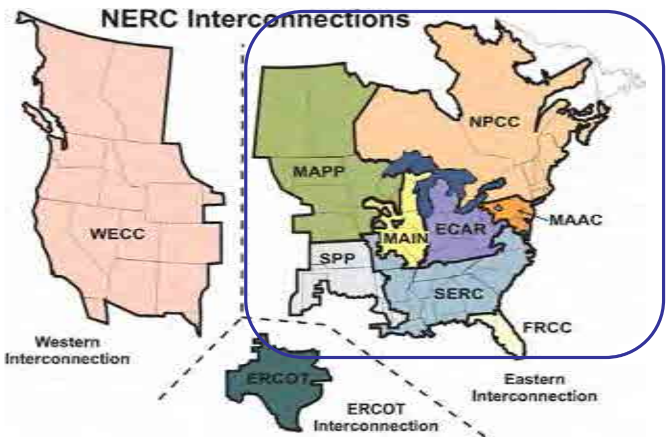
3 Interconnections / 10 NERC Regions

NERC's members are ten regional reliability councils.



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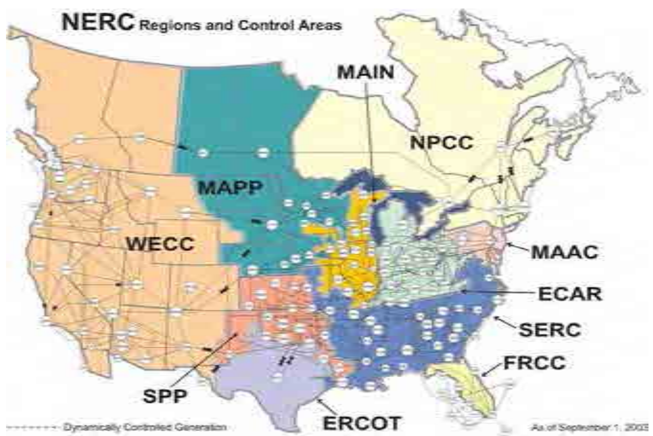
NERC Control Areas



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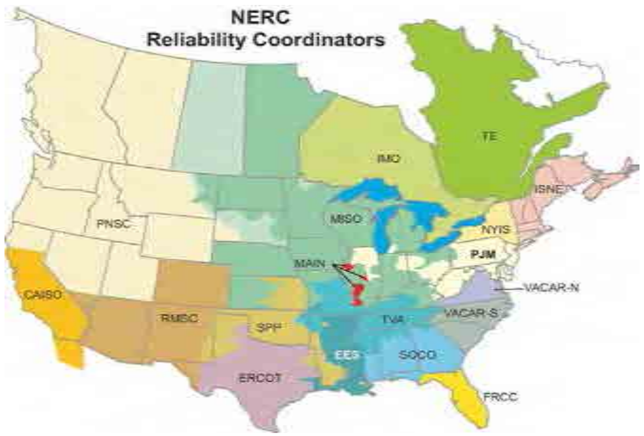
Control Area

- 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

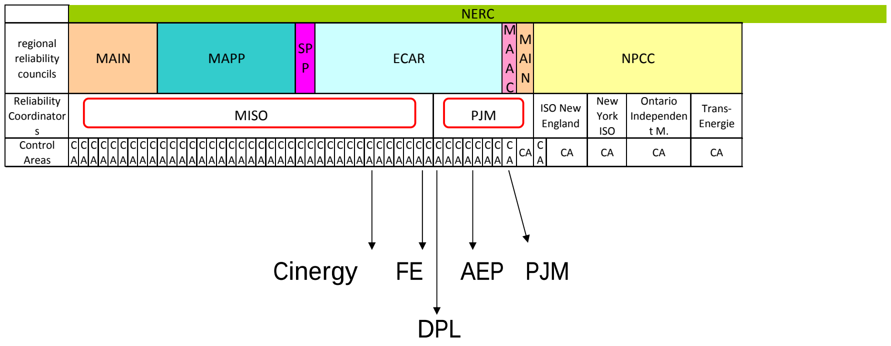
- They prepare reliability assessments, provide a wide-area view of reliability, and coordinate emergency operations in real time for one or more control areas. They may operate, but do not participate in, wholesale or retail market functions. There are currently 18 reliability coordinators in North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

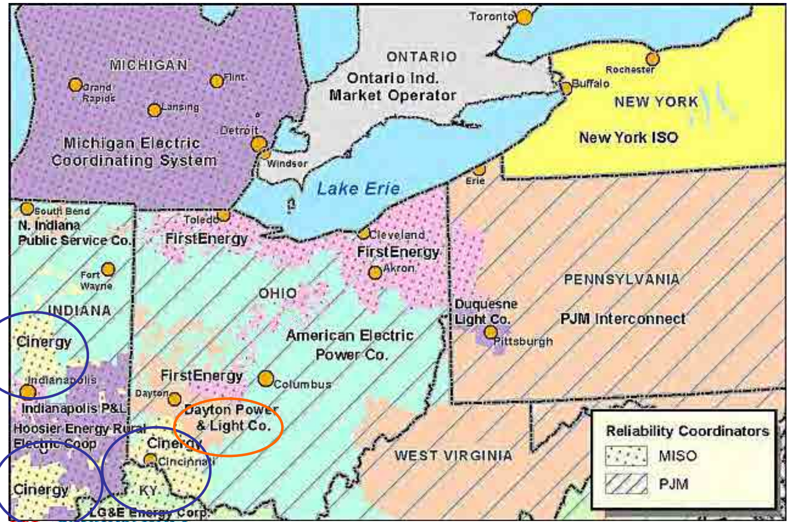


- **FirstEnergy (FE) consists of seven electric utility operating companies. Four of these companies, Ohio Edison, Toledo Edison, The Illuminating Company, and Penn Power, operate in the NERC ECAR region, with MISO serving as their reliability coordinator. These four companies now operate as one integrated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

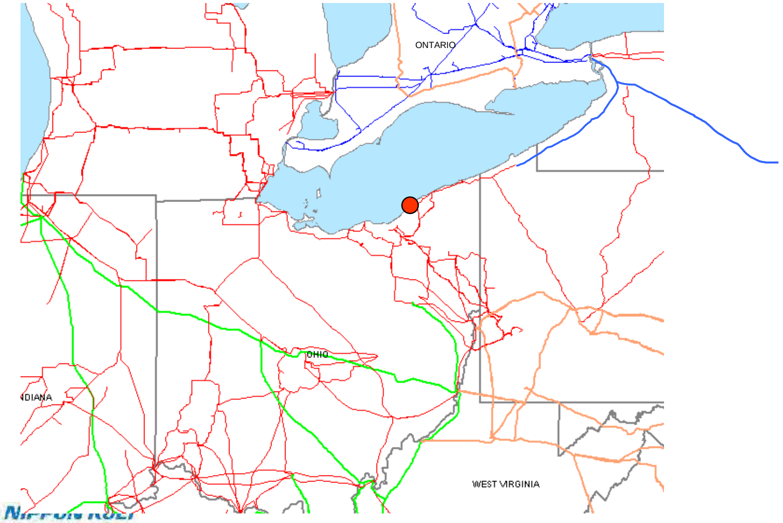
MISO State Estimator and Reliability Analysis

- 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**

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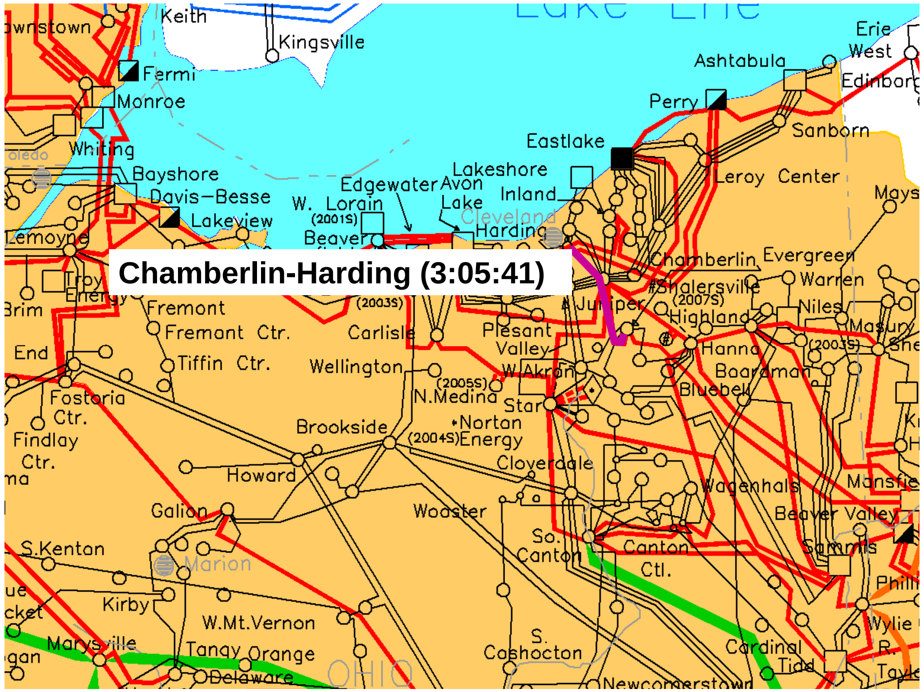

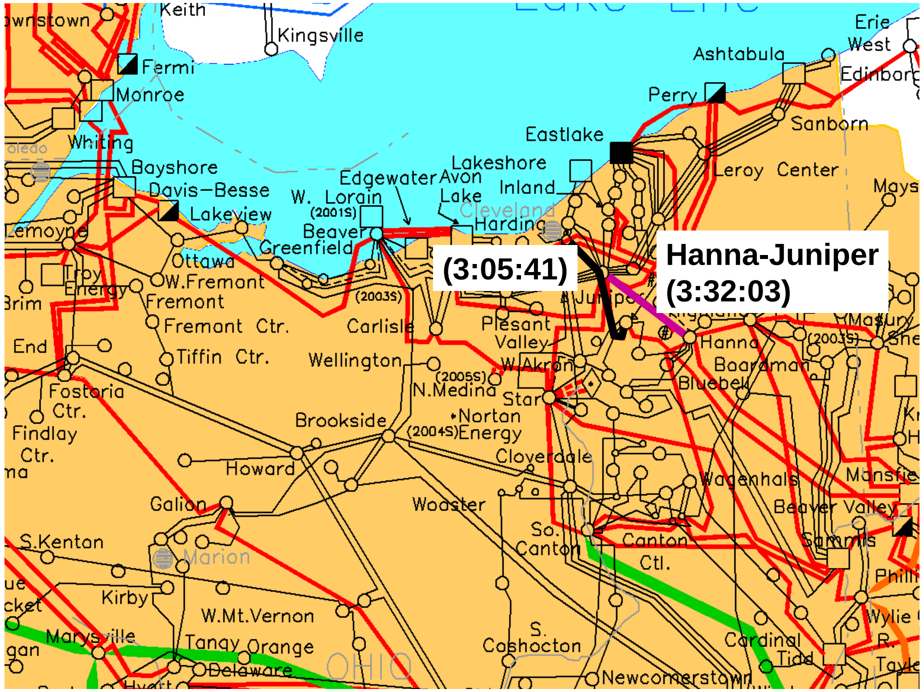

Hanna Juniper Confirmed as Tree Contact at Less than Emergency Ratings of Line

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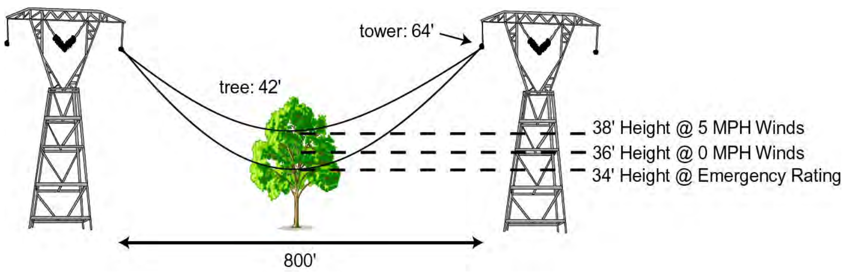
Effects of Ambient Conditions on Ratings



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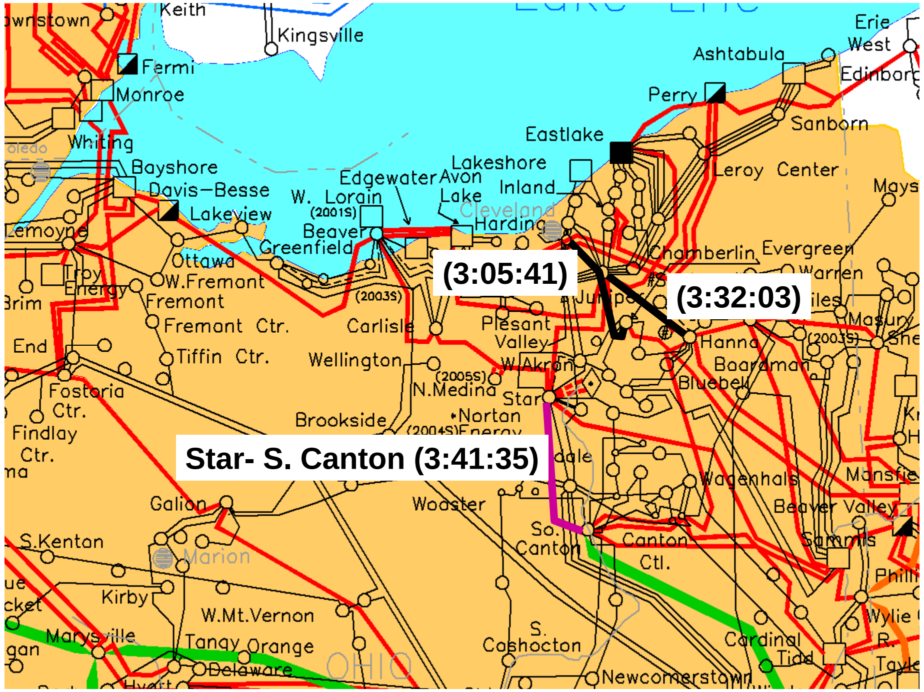
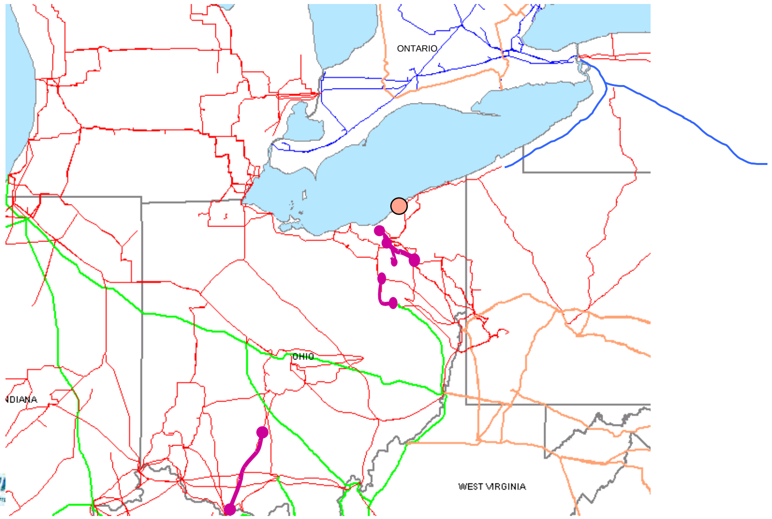


Situation after Initial Trips 3:05:41 – 3:41:35



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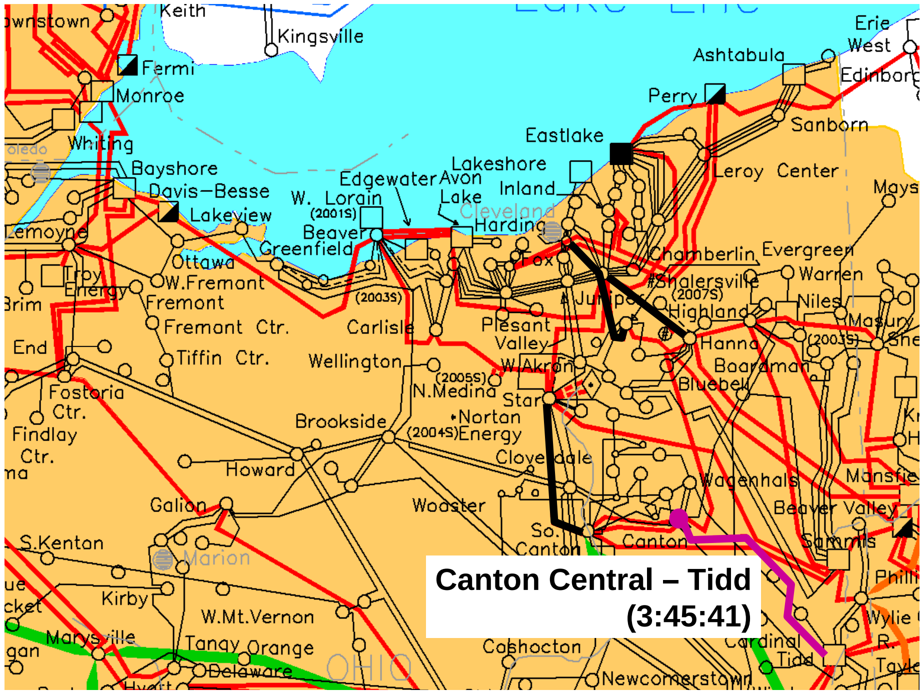
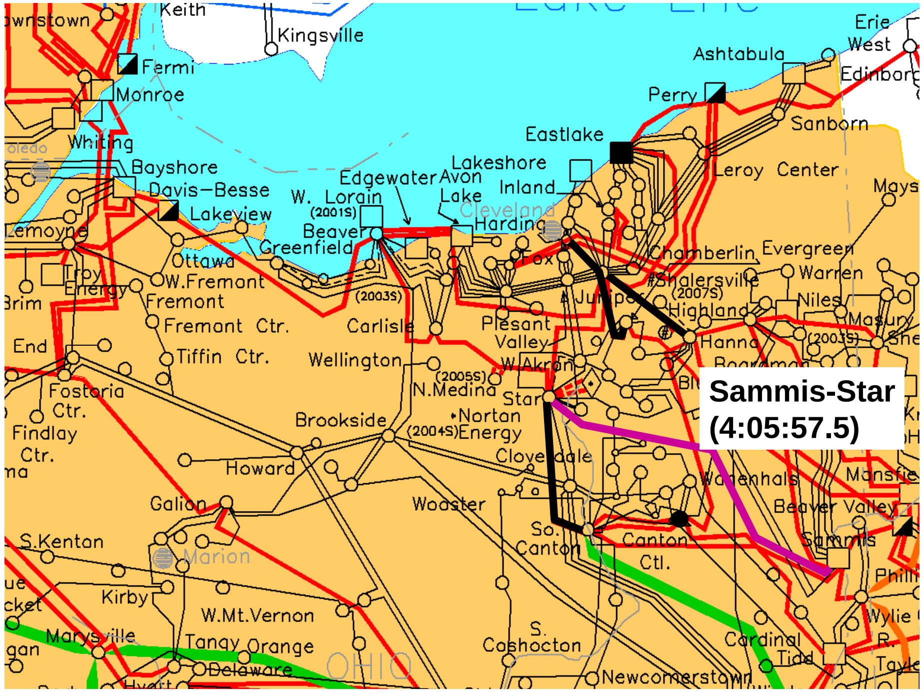
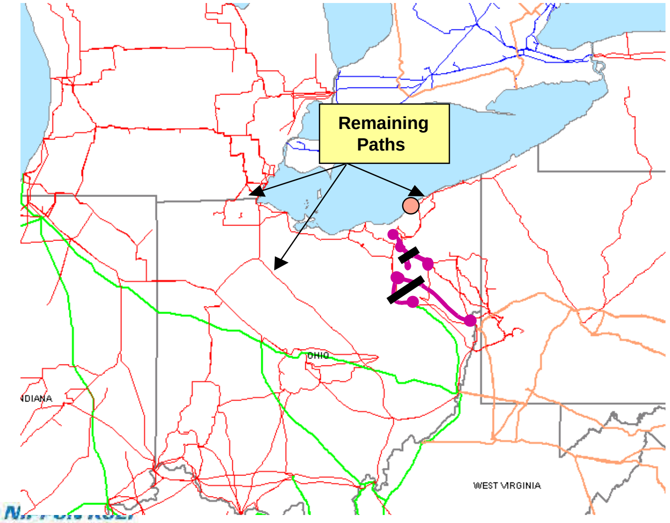
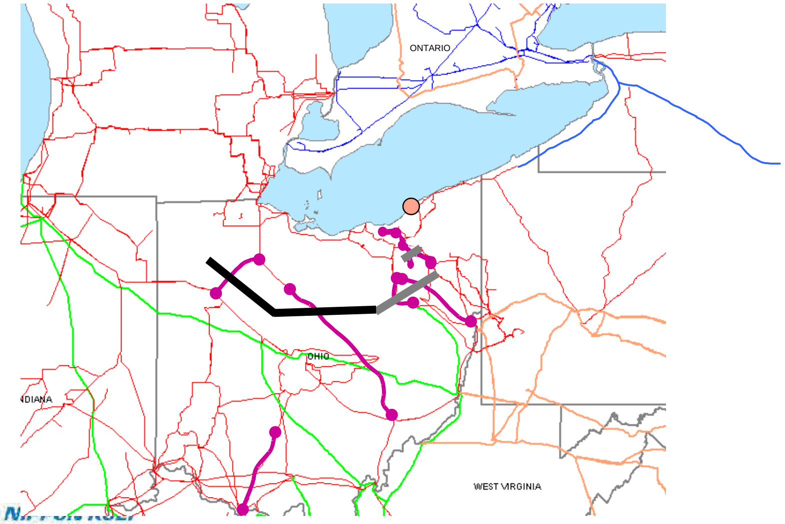




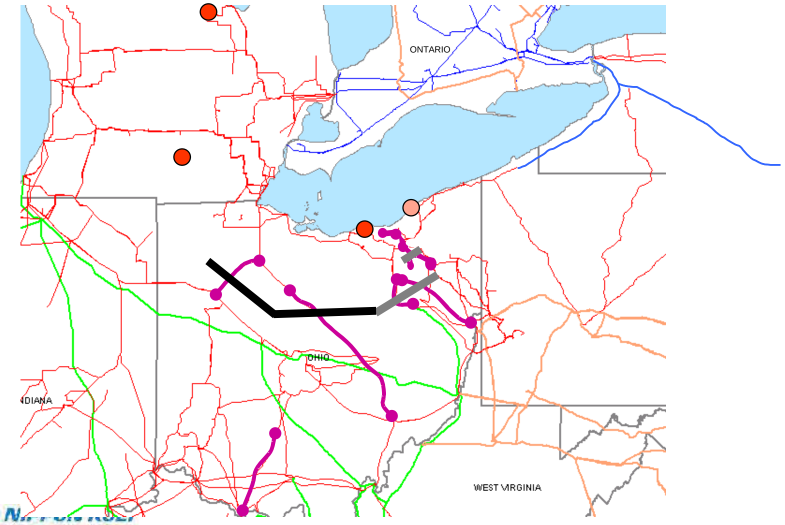
Major Path to Cleveland Blocked after Loss of Sammis-Star 4:05:57.5 PM



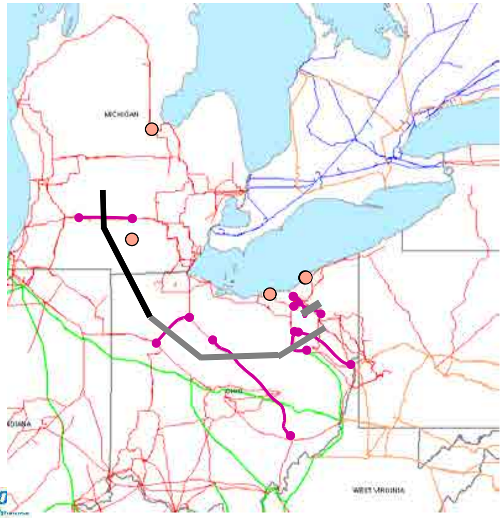
345 kV Lines Trip Across Ohio to West



Generation Trips 4:09:08 – 4:10:27 PM



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



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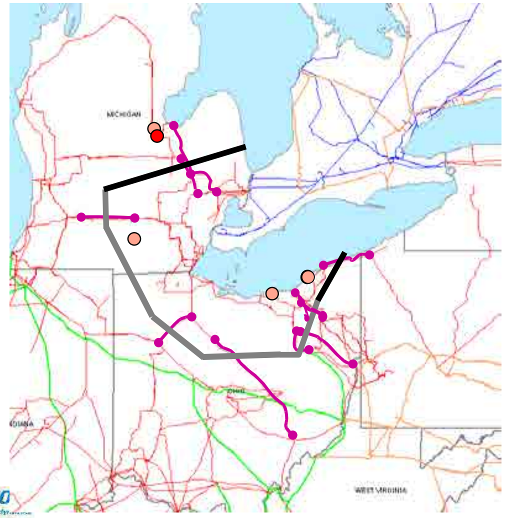
Northern Ohio and Eastern Michigan Served Only from Ontario after 4:10:37.5 – 4:10:38.6 PM



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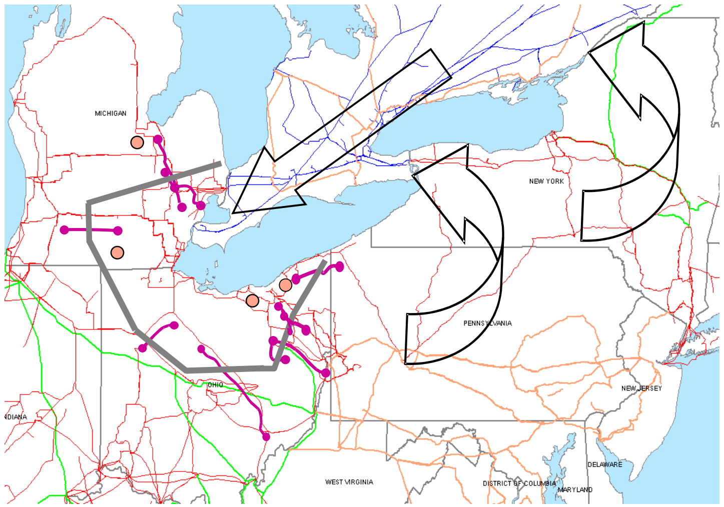
Power Transfers Shift at 4:10:38.6 PM



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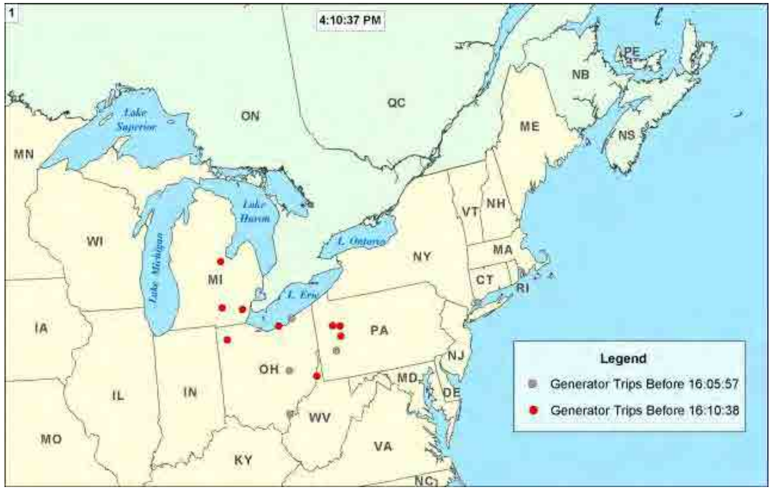
Generator Trips to 16:10:38



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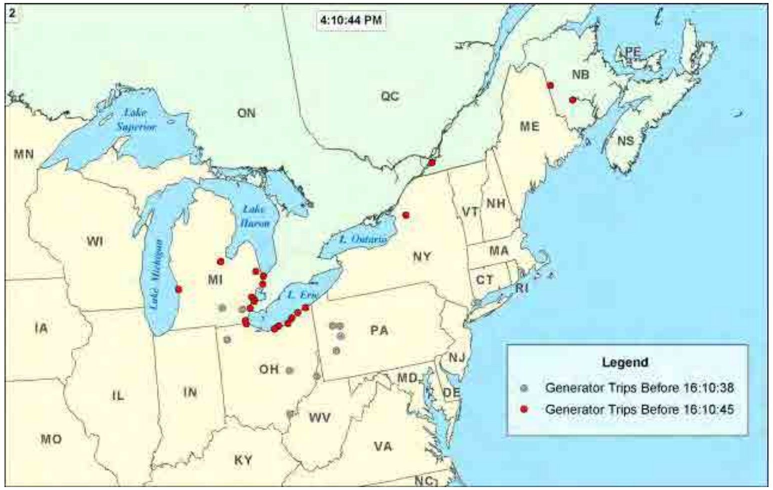
Generator Trips – Next 7 Seconds



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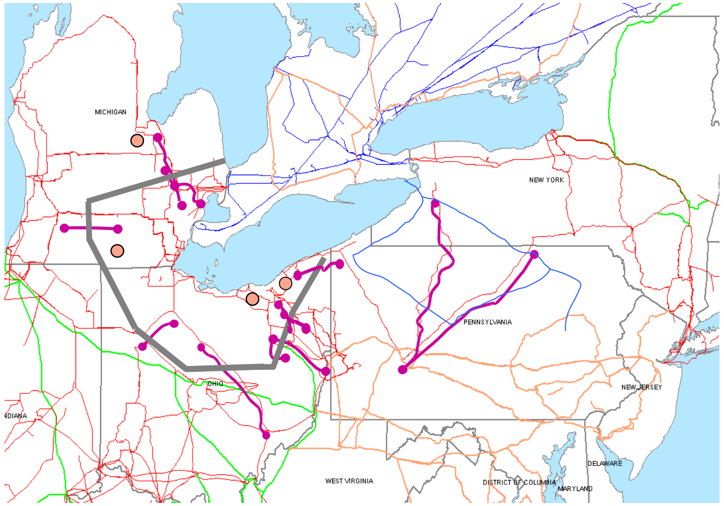
Overloads on PJM – NY Ties 4:10:39 PM



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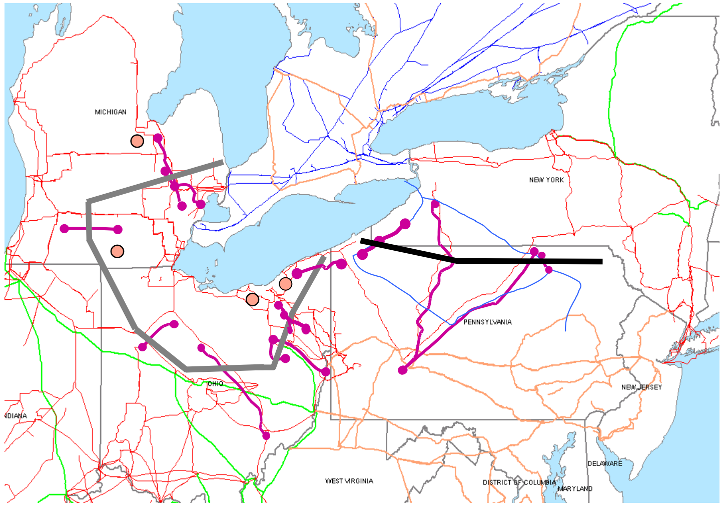
PJM – NY Separating 4:10:44 PM



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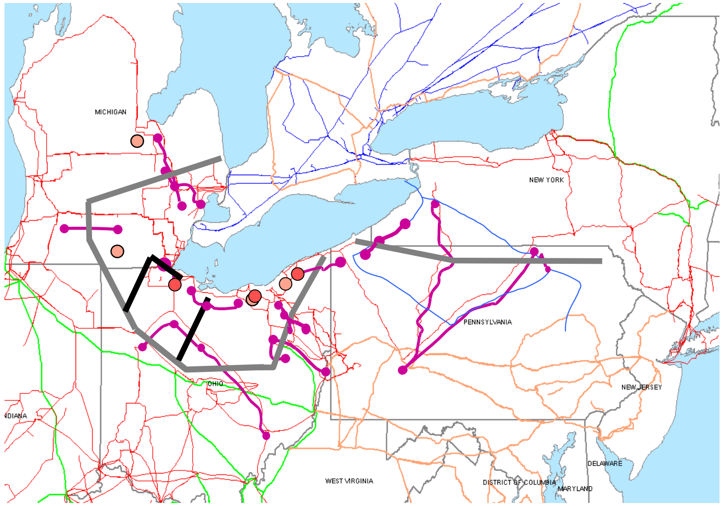
Cleveland – Toledo Island 4:10:39 - 4:10:46 PM Cleveland Blacks Out



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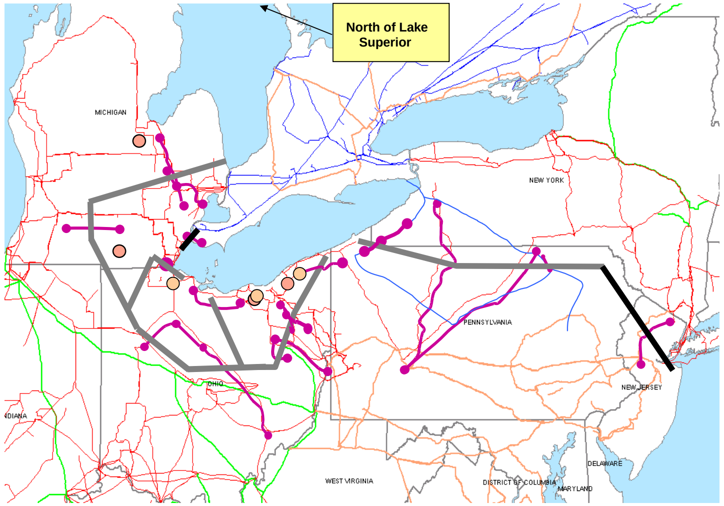
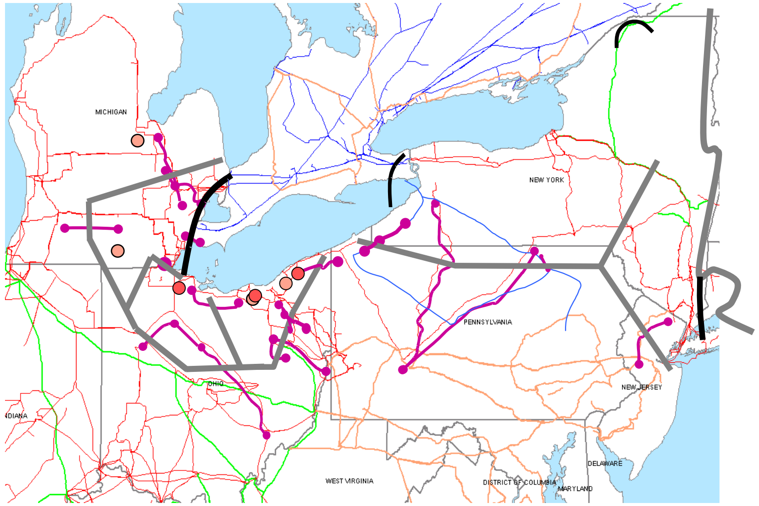
Northeast Completes Separation from Eastern Interconnection 4:10:43 – 4:10:45 PM



Island Breaks Up: 4:10:46 – 4:13 PM



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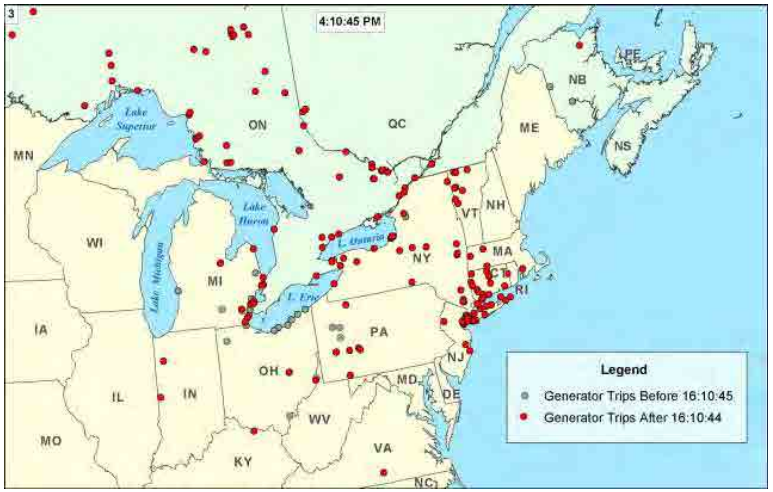
Generator Trips – After 16:10:44



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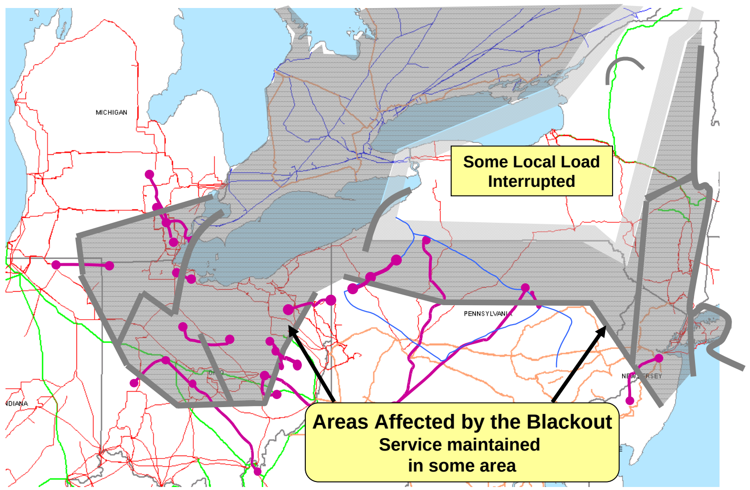
End of the Cascade



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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.

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- 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.

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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.

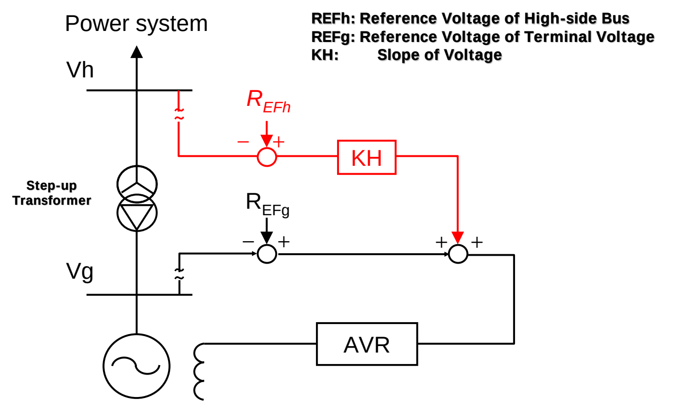
Nippon Koei Co., LTD

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)

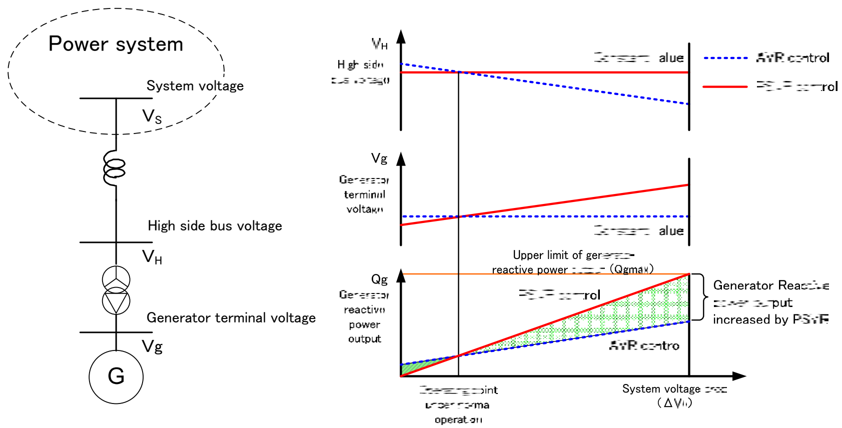
- Applied to all generators connected to 500 & 275kV system
- Regulate high-side busbar voltage VH at predetermined reference voltage



PSVR Control Structure

Power System Voltage Regulator (PSVR)

Control Characteristics of PSVR and AVR



Voltage Control Patterns of PSVR

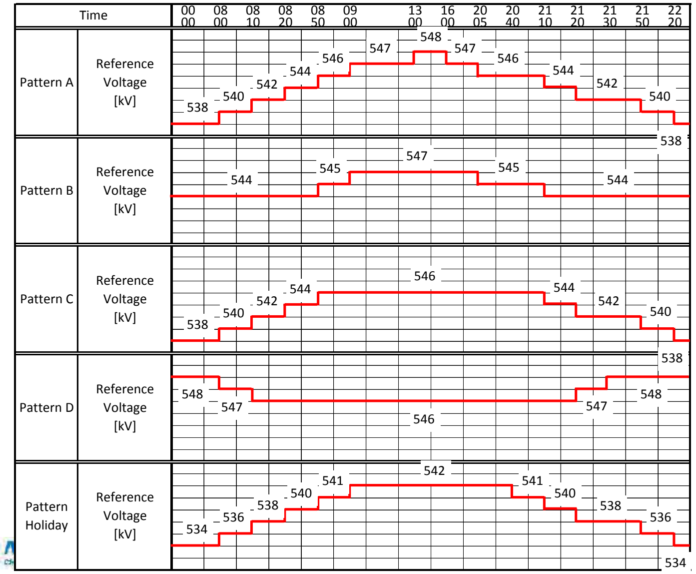
Application purpose of Each Control Pattern

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

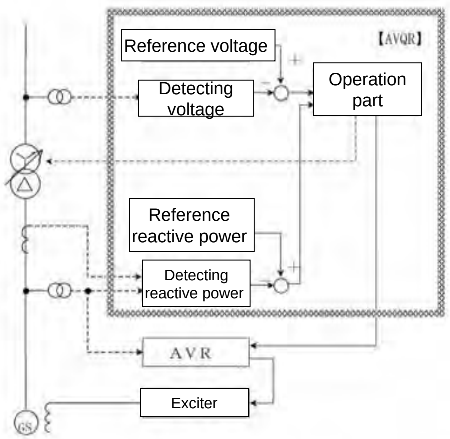
Control Patterns According to Peak Demand

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

Voltage Control Patterns of PSVR

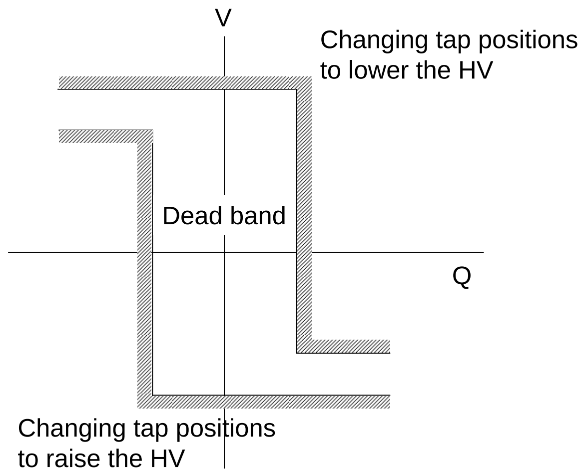


Automatic Voltage and Reactive Power Regulator (AVQR)



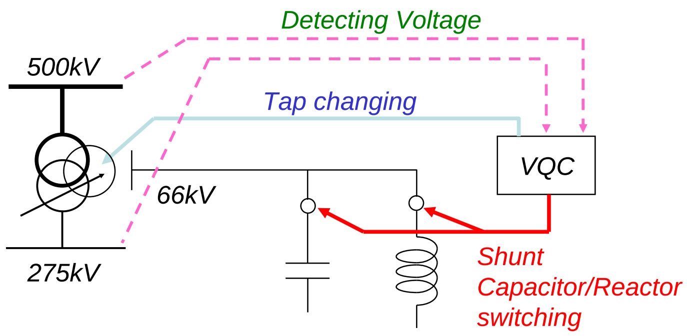
AVQR Control Structure

Automatic Voltage and Reactive Power Regulator (AVQR)



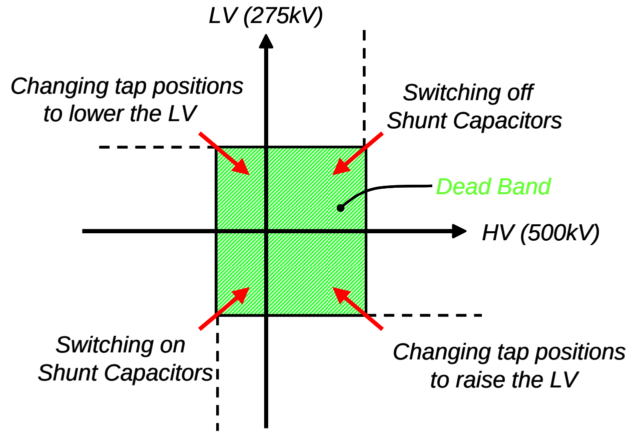
AVQR Control Structure

Voltage and Reactive Power Controller (VQC)



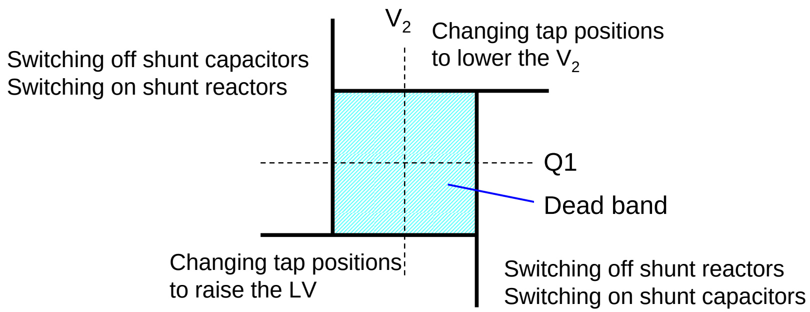
VQC Control Structure

VQC Control Structure (V1-V2 Mode)



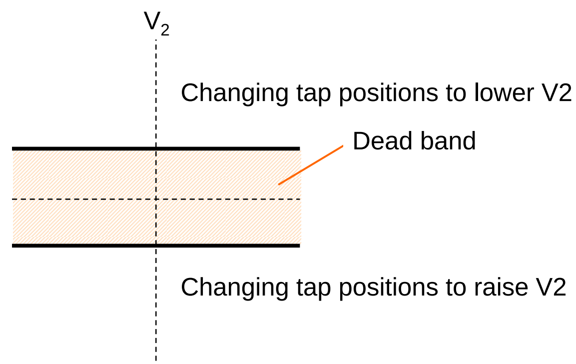
V1-V2 Mode

VQC Control Structure (V2-Q1 Mode)



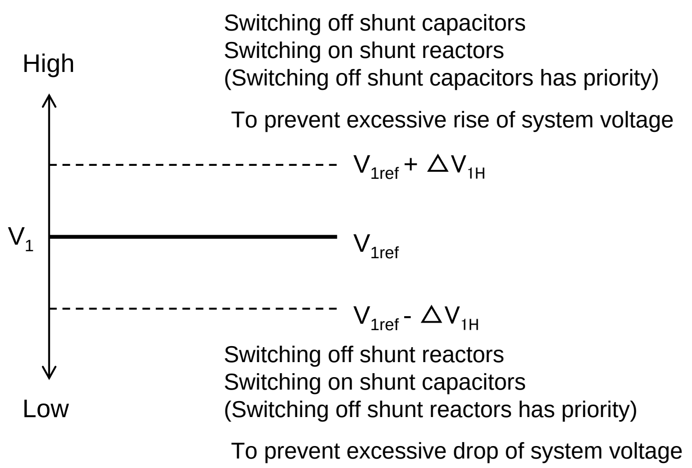
V2-Q1 Mode

VQC Control Structure (V2 Mode)

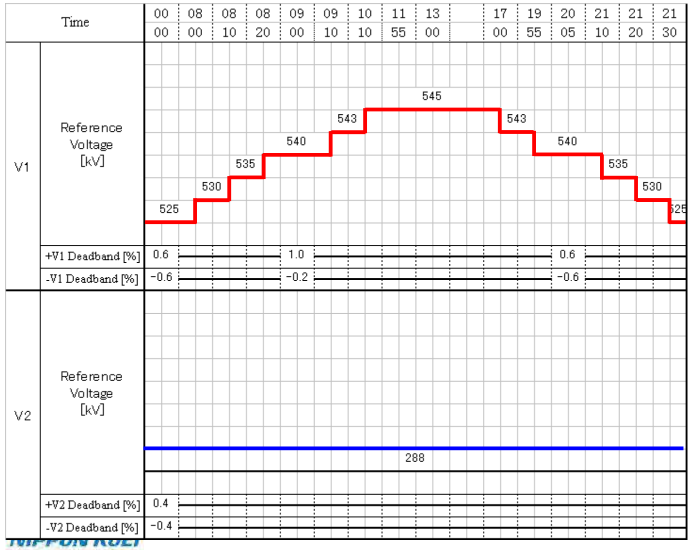


V2 Mode

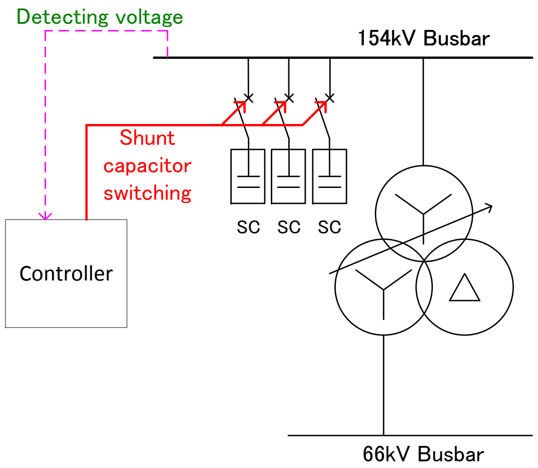
VQC Control Structure (High Speed Control of SC/ShR)



Voltage Control Patterns of VQC



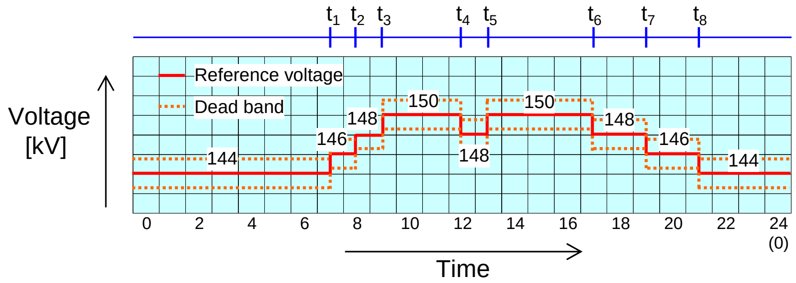
Shunt Capacitor Bank Controller



< Control Structure >

Shunt Capacitor Bank Controller (Voltage control mode)

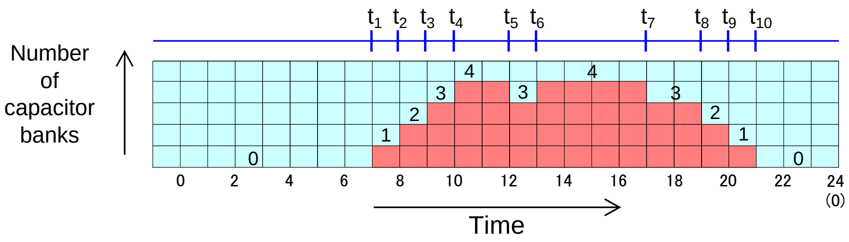
- Reference voltage: High-side voltages at each time can be pre-set.
- Dead band: Lower and upper limits of dead band at each time can be pre-set.



< 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)

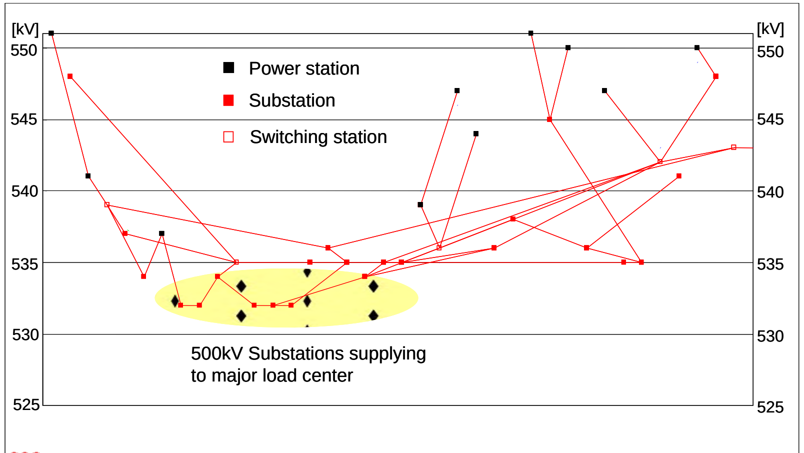


< Time scheduling mode >

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

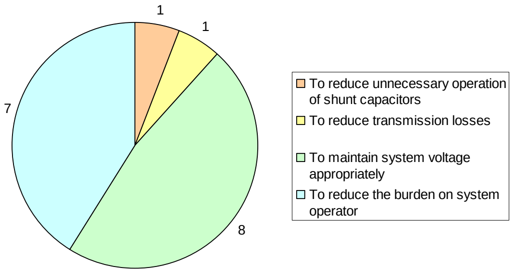
- Coordinated voltage control between bulk power system substation and local system substation
  - Most of shunt capacitor banks at 275kV or lower substations are in service during peak load periods.
  - Reactive power reserves are kept in bottom-up manner.
  - Voltage step at the time of change in reference 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

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

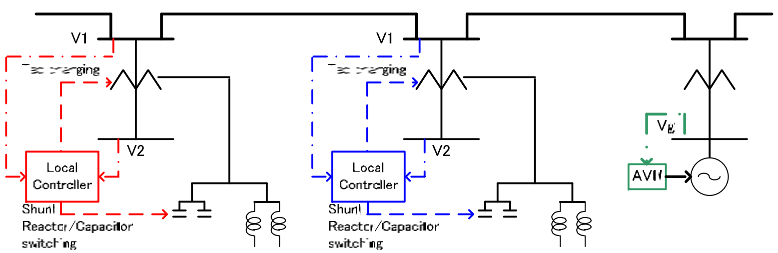
Local Power System

	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

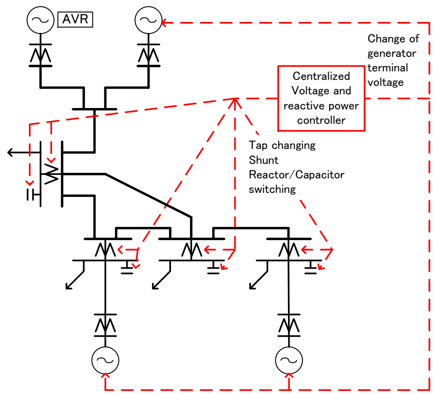
Local VQC

- 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.



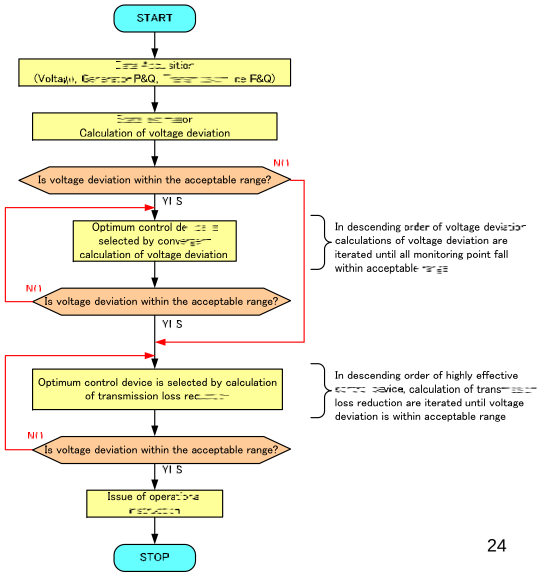
Centralized VQC

- 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.



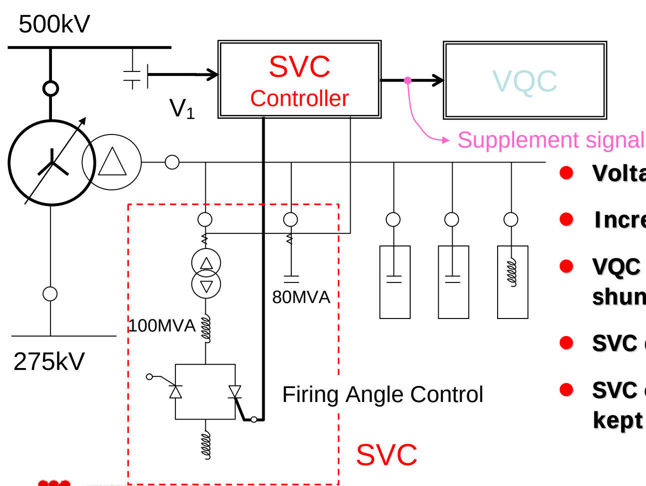
Comparison of Voltage Control Scheme

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 -



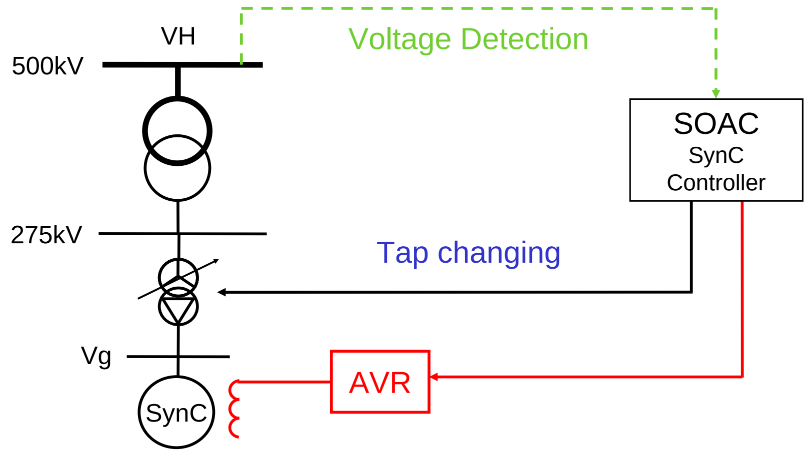
- Voltage drop
- Increase in SVC output
- VQC switches on a shunt capacitor
- SVC decreases output
- SVC output reserve is kept

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

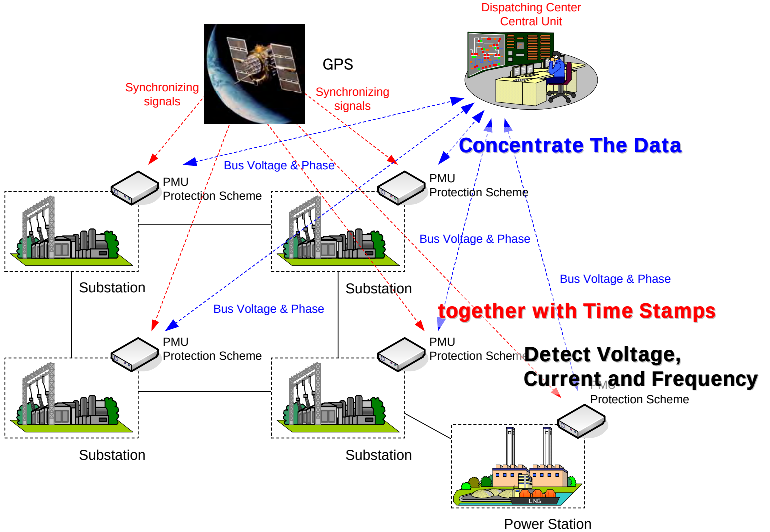
- WAMS (Wide Area Monitoring System)

  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

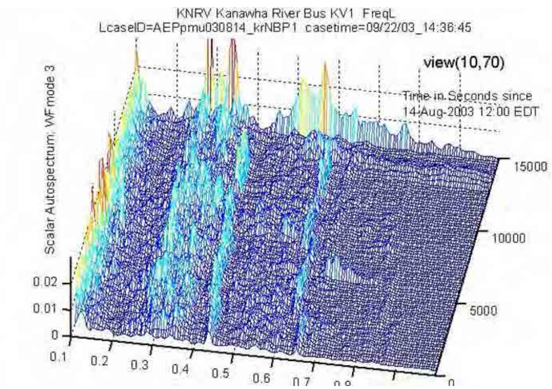


Example of WAMS in The World

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

What is suitable to install the WAMPAC for ?

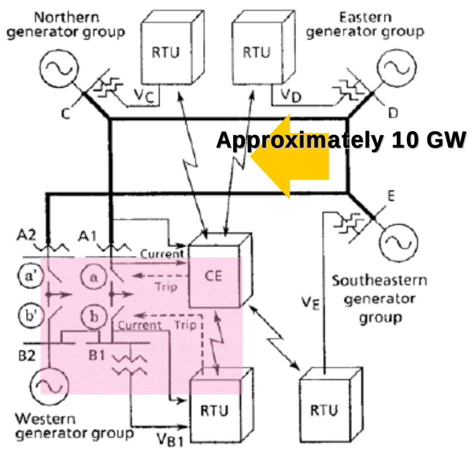
In the report of the WECC Disturbance Work Group, the WAMPAC is suitable to the following things.

- 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